

The National System Simulation Modelling (NSSM) Project

Phase 2 Report

Version 3, Final

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Executive Summary

Introduction

Water resources face mounting pressure over the next several decades, with expected increases in the UK's population providing upward pressure on demand, whilst water supplies will be affected by climate change. Meanwhile, many surface and groundwater resources are currently over-exploited, so restoring the resilience of the aquatic environment will mean abstracting less water. The emerging regional water resources plans (Jan 2022) show that England's water supplies face an additional 4000 Ml/d of pressure by 2050, of which environmental water needs contribute the most, followed by population growth and climate change. In response, the industry is acting to reduce demand and develop new water infrastructure to increase supply and meet future needs.

This report, commissioned by the Regulators' Alliance for Progressing Infrastructure Development¹ (RAPID) – a partnership of Ofwat, the Environment Agency and Drinking Water Inspectorate - and produced by a team comprising Oxford University, Ricardo, the University of Bristol, the Environment Agency and DHCR, details the output of the second phase of the project to develop a National Supply Simulation Model (NSSM) that incorporates solutions within the RAPID programme. Solutions within the RAPID programme ('RAPID water resource solutions', also known as Strategic Resource Options (SROs)) comprise large regional, and inter-regional supply options that have the potential to address the medium to long term water resource challenges. The solutions are those identified during the 2019 water resources management plan (WRMP) process and carried forward into the price review (PR19), to be allocated funding to progress through a gated process, overseen by RAPID, to achieve construction readiness in the 2025-30 period. The model gives a national scale platform to test the RAPID solutions to explore the implications of inter-regional drought coherence on large-scale transfers.

The project seeks to examine the resilience and benefits of individual RAPID solutions, different combinations of solutions and other policy decisions (e.g., water demand management) under different futures of climate change (water availability) and demand. The project is split into two phases and this report documents the findings from Phase 2².

This project is not intended to replace any regional or company modelling but provide a strategic, and independent, national view of the RAPID and regional solutions and explore the implications of inter-regional drought coherence (and other factors) on large-scale transfers. It aims to build on the work of the NIC report, National Framework, WRMP 19 and regional plans and will provide a quantitative independent evidence base for RAPID and its sponsor regulators, as well as help inform regional modelling where possible. Not all SROs were incorporated into this model as some are just being developed. However, some of the key SROs that featured in the emerging regional plans (Jan 2022) are in the simulator.

The Water Resources Model of England and Wales: WREW

The Phase 1 report² gave a detailed account of the Water Resources of England and Wales water resources model (WREW) model used in the NSSM project, its origin, and development. National water system simulation modelling is challenging, and involves integrating climate, hydrology, water infrastructure, and water demand modelling. WREW has been developed as a modelling tool that integrates these components allowing the exploration of the need for strategic water infrastructure alongside large-scale drivers of change, including climate, abstraction reform and changing demand. The model originated in the NERC-funded research project looking at drought and water scarcity in the UK, by a team led by Professor Jim Hall at Oxford University, using the software platform Wathnet. It was used and further developed in the 2016 Water UK Water Resources Long-Term Planning Framework study, and subsequent projects. It has been further developed and expanded for the NSSM project. The model simulates the key, large strategic sources in England; it does not simulate every source, therefore some sources are aggregated

¹ <https://www.ofwat.gov.uk/regulated-companies/rapid/>

² The Phase 1 report can be found here: [The National System Simulation Modelling \(NSSM\) - Project Phase 1 Report - December 2021 - Ofwat](#)

Since Phase 1, the model has been subject to extensive additional development and a second round of calibration, resulting in an improved model fit and performance against water company models. In addition, changes have been made to the RAPID Solutions, represented in the model, and new Solutions have been included. This has been facilitated through collaborative engagement with regional groups and water companies, who have shared invaluable data and insights.

The model will continue to be further developed beyond Phase 2, as set out below to continually improve its performance, and increase the level of confidence that can be placed in its output.

Simulating the Solutions

The Phase 2 outputs demonstrate the potential national resilience benefit gained as a result of the Solutions, working in combination with one other. Other water resource options (not RAPID Solutions) are in consideration by regional groups and water companies, which would also bring resilience benefit individually or in combination with the Solutions. The purpose of the NSSM project is to support RAPID's independent understanding of the Solutions within the RAPID gated programme (as of June 2022), hence the focus on these particular options.

A set of nine model scenarios were tested with WREW, as summarised in Table A. The scenarios fall into three categories each of which has a different aim:

- The **central scenario** is a reference scenario against which the outputs from other model scenarios can be compared. This scenario is configured to align as closely as possible with the regional water resources management plans. The drought resilience benefits associated with strategic solutions are reported by comparing results for a configuration of WREW without any strategic solutions implemented with results from the same scenario where the strategic solutions are operational.
- The **sensitivity scenarios** aim is to investigate whether the strategic solutions are sensitive to uncertainty in key components of water demand or availability. Changes in drought resilience benefit are reported by comparing the results for the central scenario and the stress test scenario, both configured with strategic solutions operational.
- The **stress test scenarios** explore the drought resilience implications at key areas of water stress when supply from the solutions is curtailed. The stress test scenarios are aimed at investigating the role individual solutions play in the broader set of schemes and whether any of the solutions act as a cornerstone for overall drought resilience benefits. The stress test scenario results are reported by isolating the difference in results between the central scenario and the stress test scenarios when configured with strategic solutions operational.

Three metrics have been used to describe the comparative drought resilience benefits associated with the strategic solutions:

- the probability of a supply shortfall occurring in any year
- the probability of a level 3&4 water use restriction occurring in any year
- the distribution of the size of supply shortfalls.

A supply shortfall occurs in the model when there is insufficient water available to meet demand. A supply shortfall would be considered as an extreme event, in real world terms, it would be the equivalent of customers' taps running dry and emergency methods of supply, such as water tankering, would be required. As a point of reference, a supply shortfall event is more severe than the different levels of operational water use restrictions that are more commonly used as a metric for water supply failure.

For the purpose of this report, the occurrence of level 3 and 4 water use restrictions are used to support the supply shortfall metric. The actions associated with level 3 restrictions include drought permits, drought orders and non-essential use bans. More extreme measures are implemented at level 4, which corresponds with emergency drought orders, when rota cuts and stand pipes might be introduced. Level 4 water use restrictions are commonly used by water companies as a metric for failure of the supply system and the frequency of these restrictions is used to define the level of

service for customers relative to Defra’s 1:500 drought resilience target by 2040 as defined in the water resources planning guidelines³.

One of the common themes across all the scenarios is the set of strategic solutions active in WREW, which follows the configuration considered in draft regional water resource management plans and documented in the regional reconciliation process report⁴. A summary of the solutions considered in this report is shown below in Table B.

It should be noted that the Thames-to-Affinity Transfer and Thames-to-Southern Transfer are also included in the set of solutions active in WREW, and were added following discussion with the strategic solution teams at Thames Water, Affinity Water and Southern Water.

Solution design is the same as for Phase 1 of the modelling, except for updates to the South Lincolnshire Reservoir and Fens Reservoir solutions and the Cheddar 2 Reservoir. Additionally, since Phase 1, two new strategic solutions have been developed, the Mendips Quarry scheme and the Upper Derwent Valley Reservoir Expansion scheme. Both solutions are now included in WREW.

Table A The model scenarios tested in WREW

Note: the red coloured cells show which variables have been adjusted for the sensitivity scenarios and the stress test scenarios, relative to the central scenario. ‘Regional reconciliation’ relates to the first round of reconciliation work carried out by the regional groups. ‘Regional Plan’ public water supply demand and level of environmental destination also refer to the data submitted by regional groups in January 2022. As part of this WRSE submitted a range of ‘Scenarios’: the one utilised for WREW is ‘Scenario 1’ and represents the most challenging future (high) scenario (Enhanced environmental destination, high population growth and high climate change scenario).

No.	Scenario Name	Strategic Solutions Active	Public Water Supply Demand	Level of Environmental Destination*	Climatology (w@h2 ensemble)
Central Scenario					
1	Central Scenario	Regional Reconciliation	Regional Plan – FP @2050	Regional Plan	Near Future
Sensitivity Scenarios					
2	High ambition environmental destination	Regional Reconciliation	Regional Plan – FP @2050	Enhanced	Near Future
3	High Public Water Supply demand	Regional Reconciliation	Regional Plan – FP @2050 with 50% reduction in leakage & PCC targets	Regional Plan	Near Future
4	Far Future Climate Change	Regional Reconciliation	Regional Plan – FP @2050	Regional Plan	Far Future
Stress Test Scenarios					
5	GUC Removed	Regional Reconciliation - GUC	Regional Plan – FP @2050	Regional Plan	Near Future
6	SESRO Removed	Regional Reconciliation - SESRO	Regional Plan – FP @2050	Regional Plan	Near Future
7	STT Supported Removed	Regional Reconciliation – support for STT	Regional Plan – FP @2050	Regional Plan	Near Future
8	STT Unsupported Removed	Regional Reconciliation – unsupported component of STT	Regional Plan – FP @2050	Regional Plan	Near Future
9	SLR Removed	Regional Reconciliation - SLR	Regional Plan – FP @2050	Regional Plan	Near Future

³ [Water resources planning guideline - GOV.UK \(www.gov.uk\)](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/61221/water_resources_planning_guideline.pdf)

⁴ The regional reconciliation process report can be found here: <https://wrse.uk.engagementhq.com/13777/widgets/39717/documents/22580>

Table B. The strategic solutions included in WREW

See glossary for a description of each solution. The Southern Water Services Water Desalination option (Fawley Desalination) was included in the original set of RAPID solutions and NSSM Phase 1. However, following the RAPID Gate 1 review, the desalination scheme was deemed no longer and has therefore been excluded from the analysis presented in this report.

Solution Name	Supporting options/solutions	Type	Water Resources Regional Group
Severn to Thames transfer (STT)	Severn Trent Sources (Minworth and Mythe) Minworth North West Transfer – Vyrnwy Aqueduct	Raw Water Transfer	WRW (donor) & WRSE (recipient)
South East Strategic Reservoir Option (SESRO)	-	New Reservoir	WRSE
London Reuse (LER) including Mogden, Beckton and Teddington Direct River Abstraction	-	Effluent Re-use	WRSE
Southern Water Havant Thicket Raw Water Transfer & Water Recycling	-	Raw Water Transfer & Effluent Re-use	WRSE
Thames to Southern Transfer (T2ST)	SESRO or STT	Raw Water Transfer	WRSE
Thames to Affinity Transfer (T2AT)	SESRO or STT & London Reuse	Raw Water Transfer	WRSE
Grand Union Canal (GUC)	Minworth	Raw Water Transfer	WRW (donor) & WRSE (recipient)
Cheddar 2	-	New Reservoir	WCWR
Mendip Quarries raw water reservoir	-	New Reservoir	WCWR
Poole Effluent Reuse	-	Effluent Re-use	WCWR
Fens Reservoir	-	New Reservoir	WRE
South Lincolnshire Reservoir (SLR)	-	New Reservoir	WRE
Upper Derwent Valley Reservoir Expansion (UDVRE)	-	Reservoir Enlargement	WRW
North West Transfer	UU Sources and Vyrnwy Aqueduct	Source re-deployment and new sources	WRW

Findings

Section 3.4 of this report goes through the results for particular scenarios and presents specific and detailed analyses. By way of a high-level summary, the key findings from the Phase 2 results are set out below.

- **Drought resilience benefit**

The set of strategic solutions being considered in the emerging regional plans (Jan 2022) is effective at preventing or greatly reducing the risk of failure at **key areas** of water stress in WRSE and WRE. The drought resilience benefit to WRSE is provided by a combination of solutions, including: South East Strategic Reservoir Option (SESRO), Severn Thames Transfer (STT), London Effluent Reuse (LER), Thames to Southern Transfer (T2ST), Grand Union Canal (GUC) and Thames to Affinity Transfer (T2AT). In contrast the benefit to WRE is driven by two solutions; the South Lincolnshire Reservoir (SLR) and Fens Reservoir solutions.

Analysis of time series for storage levels in SLR during drought events indicates that more water could be available for release to further increase the benefits with the WRE region.

The model calibration for **key areas** of water stress in the WCWR region means that it is not possible to confirm whether strategic solutions alone would be able to meet water needs.

- **Solutions are resilient against uncertainty in availability and demand**

Strategic solutions display limited sensitivity to scenarios with higher demand for water, both in terms of potable supply and for the environment, as well as a scenario with reduced supply due to more extreme climate change.

This suggests there are enough strategic options being considered in regional plans to provide benefits to **key areas** of water stress in the face of uncertain, but plausible, possible future conditions.

A notable increase in the probability of failure for WRZs in the Affinity Water Central region indicates that the boreholes providing the principal source of supply for the WRZs are susceptible to more extreme climate change.

The largest changes in drought resilience are brought about by a more extreme future of climate change. However, the simplified approach to other modelling scenarios, such as the environmental destination scenarios, may have influenced their impact on drought resilience.

The model calibration issues mentioned above for the WCWR region, prevent any conclusions being drawn around whether the strategic solutions would be able to meet additional pressures on water supply or demand for that region.

- **Stress tests**

Removing individual strategic solutions has been shown to have a limited impact on the overall drought resilience benefit of the set of solutions being considered in the WRSE regional plan. The increase in the scale of potential deficits when SESRO or the supported component of STT are removed is similar in size to the amount of water the missing solutions supply. Only a small increase in the size of supply shortfalls occurs when the unsupported component of the STT solution is removed, suggesting that this part of the STT solution is not available during the more severe droughts that cause failure in WRSE. Removing the GUC solution drives a more substantial increase in the size of supply shortfall compared with removing SESRO, or elements of STT. This result is a function of the inherent resilience of re-use options and how GUC is configured in WREW, with supply available at any time compared with STT and SESRO that must be triggered by reservoir drawdown.

The WRE regional plan is notably impacted by the removal of the SLR: this suggests the region is more susceptible to a potential change in solutions. When SLR is removed, the only remaining solution available for WRE is the Fens Reservoir, which supplies different parts of the region than SLR. The lack of connectivity with other regions, or the representation of other local supply options in WREW, means the missing supply from SLR cannot be replaced.

- **Effects of droughts on donor and recipient areas**

When looking at the probability of a supply shortfall, or water use restriction, occurring across all climate replicates (i.e. 2,340 years of different possible near future climate conditions after removal of replicates with a > 1:500 duration RP event), no marked trade-off in drought resilience is observed between the WRW areas that supply water and the recipient areas in WRSE. The overall occurrence of water use restrictions is slightly *less* frequent with the STT and GUC in place compared to the baseline situation. This indicates that the support options for these transfers deliver their intended function of maintaining resilience in donor areas.

Analysis of the sensitivity of solutions to specific spatial and temporal patterns of drought, focussed on the WRW and WRSE water resources regions, has revealed that the STT and GUC solutions are affected by a small number of droughts in the dataset. In these specific events in the modelling there are more water use restrictions with the solutions in place compared to the baseline. This is due to the balancing of storage across the zones to maintain river flows and customer demand in drought conditions under the transfers. However, in many other events, where there is not such a coincidence between droughts in WRSE and WRW there are fewer water use restrictions. This leads to an overall small reduction in frequency of water use restrictions with the solutions in place.

It should be noted that there are only five WRW-WRSE focussed droughts isolated from the near future w@h2 event set which show the effect of increasing water use restrictions. They represent only a small proportion of the 2,340 years simulated in WREW, with a likelihood of 1 in 468 years. By contrast there are 288 events that cause a water use restriction for WRZs in the WRW region, so these five events also represent a small proportion (2-5%) of the total of the drought events affecting WRW. These events represent more severe events in the w@h2 dataset, as the accumulated deficit-based return period can range up to 1:333.

The resilience impact of the WRW-WRSE focussed droughts is seen in WREW as an increase in the use water use restrictions for donor WRZs in the WRW region in these rare events. However, even this increase is likely to be caused by limitations in the WREW model setup. In reality further design considerations could be able to mitigate even these rare impacts if they were to be confirmed by more detailed modelling. This is beyond the detail considered in the WREW model but should be investigated as part of the SRO design.

Next Steps

The development of WREW will continue beyond Phase 2, with an aim to further improve the confidence in the model, where needed, and use the tool to better understand how the water supply system of England and Wales may behave under future socio-economic and climatic conditions.

Further model development

The model will be developed further, to act on the knowledge gleaned and additional data availability arising from engagement activities in Phase 2. The key areas for further development are as follows.

- **Improve the representation of London water system**

In Phase 3 efforts will be made to improve the representation of London's supply network in WREW. Proposed solutions include (a) splitting out WREW's London demand node into three demand centres to account for differences in system behaviour and sensitivity in the north; (b) adding the Thames-Lea Tunnel and Thames Water ring main to the model; (c) controlling model behaviour for the prioritisation of demand between London WRZ and the Teddington environmental constraints; (d) refining the 'licence of right' abstraction from the River Thames to Affinity Water's WRZ6 and investigating of groundwater behaviour within the water resource zone, and; (e) further analyse the hydrological inflows to WREW in the Thames Basin, with particular regard for the Colne and Wey catchments.

- **Refine sustainability reduction scenarios**

Further engagement with water companies in Phase 3 will help to better represent reductions in deployable output associated with specific licences in WREW and therefore improve confidence in the scenarios used to test RAPID's supply options.

- **Add supporting non-RAPID Strategic Supply Options and intra-regional transfers**

Non-RAPID supporting supply options to add to WREW in Phase 3 include intra-regional WRSE transfers which can distribute RAPID supply options around the region, and intra-regional imports and exports within WCWR. This is considered particularly important for the WRE region, where large volumes of desalination and/or re-use may be required to achieve resilience in addition to the Solutions.

- **Improve the representation of West Country's system**

Further work is required to ensure all missing and inaccurate water sources are accounted for. Improvement of the representation of the West Country's water supply network in WREW is necessary to improve confidence in the future simulation of WCWR supply options and identification of any real threats to the region's water supplies.

- **Analysis of WREW's empirical groundwater model during key historic droughts**

A third round of validation will be completed to assess the performance of WREW's empirical groundwater model during key historical drought events.

- **Improve the system representation of Dŵr Cymru Welsh Water**

Further improvements are necessary to build confidence in model outputs for the Welsh assets and demand centres. These further improvements include inclusion of operating rules, testing of reservoir release behaviour, better calibration of certain inflows, improved representation of abstractions and licence constraints and update WTW outputs and effluent returns in certain areas.

- **Further investigate the validity of WREW outputs using reservoir storage**

Despite the updates to the supply system representation in WREW that have been made during Phase 2, large differences in simulated storage between WREW and water company modelling remain for several reservoirs. These differences highlight areas of the model where WREW outputs cannot be fully validated and supply system behaviour could be better calibrated. However, they may also be a function of hydrological inputs or the fundamental difference in scale between national and water company models. Further work is planned to investigate and better understand the root cause of the differences in storage.

- **Investigate the relationship between drought characteristics and supply system failure**

The statistical analysis of the drought events in the w@h2 database allows for the characterisation of risk via a number of different metrics. For Phase 2, the accumulated deficit metric was used to filter out events >1:500. Applying a return period filter based on >1:500 duration events would yield a different event set with which to test the solutions. More work is needed to understand which drought metric best describes the impact of a drought event on the water supply system. In addition to assessing droughts based on climatological return period, the 1:500 system response standard (0.2% per annum system failure probability) should also be explored in WREW. This standard is preferable since it overcomes the issues of timing and duration when return period is evaluated using rainfall, and it captures aspects such as system constraints, conjunctive use capability and operational response.

Furthermore, the drought characterisation outputs from the w@h2 statistical analysis allow for a bottom-up analysis on the nature of droughts that cause supply system failure. For example, the drought events that cause supply shortfalls or water use restrictions can be described spatially, temporally and volumetrically and assessed for commonalities. This approach would provide insight on the type of droughts to which specific parts of the supply system are sensitive and if/how the RAPID solutions can act to mitigate these susceptibilities and improve resilience.

- **Undertake additional development activities**

Perform additional minor improvements to WREW to refine its representation.

Further use of the model

With water company supply networks and RAPID solutions now updated and built into the model, Phase 2 of the project has used the model to create national-scale evidence on the drought resilience benefits and trade-offs between cost, environmental risk, and drought resilience benefit, of the solutions in the RAPID programme. It should be noted that the scope of any further application of the WREW needs to be balanced with the accuracy of the model, taking into account limitations associated with the simplifying assumptions that have been made to create the model. The next project phases may utilise the model in the following ways to continue work against these objectives:

- Continue to work with the regional groups and RAPID solution teams on the emerging conclusions from Phase 2, and what this may mean for the development of the revised draft regional plans in spring 2023;
- Explore the benefits and trade-offs of the preferred portfolio of RAPID solutions, following the Regional Group's second round of reconciliation. This is especially important for the WRSE region, where the reconciliation is likely to output several different option combinations;
- The interaction of multiple Solutions with the River Trent is particularly complex and may benefit from further analysis using a modified model;
- Updating RAPID solutions to their preferred option configuration emerging from the draft regional plans and second round of reconciliation, and presented in RAPID solutions forthcoming Gate 2 submissions, as well as the proposals already submitted for accelerated Gate 2;
- Utilising modelled outputs to support regulators' review of published draft Water Resources Management Plans and Regional Plans;
- Use the model to test potential benefits from available resources and transfers not yet proposed in the RAPID programme or in WRMPs and or Regional Plans;
- Understanding the impact of drought events, with specific spatial and temporal characteristics, on the resilience of the preferred portfolio of RAPID solutions; and
- Testing RAPID-led queries and scenarios on the preferred portfolio of RAPID solutions, or on specific RAPID solutions configurations.

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Acronyms

BAU: Business As Usual

DECIPHeR: Dynamic fluxEs and Connectlivity for Predictions of HydRology

FP: Final Plan

GUC: Grand Union Canal

LER: London Effluent Reuse

LoS: Level of Service

NRW: National Resources Wales

NSSM: National System Simulation Modelling

P: Precipitation

Pe_{eff}: Effective precipitation

RP: Regional Plan

SESRO: South East Strategic Reservoir

SLR: South Lincs Reservoir

STT: Severn-Thames Transfer
SVT: Severn Trent Water
UDVRE: Upper Derwent Valley Reservoir Expansion
UU Sources: United Utilities Sources
w@h2: Weather at Home2
WINEP: Water Industry National Environment Programme
WCWR: West Country Water Resources (Regional Group)
WRE: Water Resources East (Regional Group)
WREW: Water Resources model for England and Wales
WRSE: Water Resources South East (Regional Group)
WRW: Water Resources West (Regional Group)
WRN: Water Resources North (Regional Group)
WUR: Water Use Restriction

Glossary

Accumulated drought deficit: The sum of the monthly deficits during a drought event.

Cheddar 2: Strategic supply solution part of West Country Sources, includes the development of a second reservoir at Cheddar, comprising a 9,400 MI bunded non-impounding reservoir alongside the existing Cheddar reservoir and a raw water pumping station. The reservoir would be filled by excess winter flows from Cheddar springs, within existing licenced abstraction rates.

Drought duration: Duration of a drought event, in months.

Drought event: A drought event can be defined as occurring when a single month, or several months in a row, has a positive effective precipitation deficit.

Drought intensity: Maximum monthly deficit of rainfall or effective precipitation during a drought event.

Drought threshold: Numerical threshold to identify drought events which fall below a fixed meteorological measure, such as Q20 precipitation or Q50 effective precipitation.

Ensemble: Collection of replicates (see Replicate), used to drive the water supply simulation model, WREW.

Far Future: Study simulation period from 1st January 2070 to 31st December 2099.

Fenland Reservoir: Strategic supply solution includes the development of a raw water storage reservoir (50,000 MI) in Water Resources East Region, supported by abstractions from potential sites on the River Great Ouse, including Bedford-Ouse at Earith, Ely-Ouse at Denver, Middle-Level at St. Germans and Storage in Ouse Washes.

Grand Union Canal (GUC): Strategic transfer option that utilises the existing canal infrastructure to transfer surplus water from the Midlands (treated wastewater at Minworth, Severn Trent) to WRSE (Affinity Water).

Level of Service (LoS): The average planned frequency (e.g. 1 in X year) of different types of water-use restrictions (WURs) or drought interventions that a water company can introduce during times of water shortage. In this report, the term level of service is used interchangeably with levels of water use restrictions e.g. LoS 1 refers to Level 1 restrictions. These cover a range of interventions from media messages to highlight the need for conservation of water through to Emergency Drought Orders. In WREW, these are split into four different levels of water use restrictions where specific types of restrictions are imposed. The planned frequency at which these restrictions are imposed will vary between water companies and are generally triggered by key system reservoir storage levels, surface water levels and/or groundwater levels:

Level (LoS) 1: The level of service (average planned frequency) for imposing level 1 restrictions which generally includes an intensive water saving media campaign.

Level (LoS) 2: The level of service (average planned frequency) for imposing level 2 restrictions which include temporary use bans (TUBs). TUBs allow for restrictions on a customer's water usage for activities such as using hosepipes to water gardens.

Level (LoS) 3: The level of service (average planned frequency) for imposing level 3 restrictions which include drought orders for non-essential use bans. This restricts customers' water usage further for activities such as cleaning the outside of buildings.

Level (LoS) 4: The level of service (average planned frequency) for imposing more extreme, level 4 restrictions which include emergency drought order (restricting demand), when rota cuts and stand pipes may be introduced as agreed with the company's customers.

London Effluent Reuse (LER): The London Effluent Reuse (LER) solution consists of four effluent reuse solutions including water from Mogden waste water treatment works (schemes of Teddington DRA, Mogden effluent reuse, Mogden South Sewer) and water from Beckton waste water treatment works. The solutions supply water directly to London and the greater London area.

Mendips Quarry: Strategic supply solution part of West Country Sources includes repurposing of a quarry in the Mendips into a reservoir (52800 MI with a usable net storage of 28700 MI) which will be filled by abstraction from the Bristol Avon (downstream of Bath) during high winter flows under either an existing or enhanced licence.

Mogden Effluent reuse: A strategic re use scheme where effluent from Mogden WwTW will be pumped to a new reuse treatment plant, "Hydes Field", which will then discharge treated effluent into the River Thames, whereafter intake pipes will transfer the water to the Lee Valley Reservoir Group.

Mogden South Sewer: A strategic reuse scheme where sewage will be abstracted from the South Sewer before it reaches Mogden WwTW, pumped into Hydes Field for treatment and the treated effluent discharged into the River Thames, whereafter intake pipes will transfer the water to the Lee Valley Reservoir Group.

Months of drought: The number of months in a drought event. A drought event can span a single month or several months in a row.

Near Future: Study simulation period from 1st January 2020 to 31st December 2049.

North West Transfer: A strategic solution that includes an engineering solution (new/altered pipeline of Vyrnwy Aqueduct) and new supply sources (previously known as "UU sources" which includes a range of surface water, groundwater supply and WTW options) to maintain service to the customers who would ordinarily be supplied from Vyrnwy Aqueduct in UU Strategic WRZ but cannot be when STT is actively using support from Vyrnwy reservoir. The new supply sources ("UU sources") can be utilised in UU Strategic WRZ not only when STT is active, but when resource is depleted in the WRZ in general; sources become available based on Haweswater Reservoir's resource state.

Poole effluent reuse: Strategic supply solution part of West Country Sources includes a proposed effluent re-use supply in Poole providing 30 MI/d which can be utilised in either WCWR (Poole and Bournemouth) or Southern Water (South Hampshire).

Probability of year with supply shortfall: The probability of any year in a given ensemble (see Ensemble) or replicate (see Replicate) of experiencing at least one day with a supply shortfall (see Supply shortfall).

Probability of year with water use restriction: The probability of any year in a given ensemble (see Ensemble) or replicate (see Replicate) of experiencing at least one day with a water use restriction.

Reduced ensemble: Curated collection of w@h2 replicates with drought events with a return period >1:500 removed.

Replicate: A specific combination of timeseries data, for a given period, used as input to the Water Resources model for England and Wales (WREW). One replicate input into WREW will contain daily water demand (public and non-public), groundwater levels and/ or precipitation data specific to the empirical groundwater model in WREW, and river flows generated using the DECIPHeR modelling framework and w@h2 climate outputs.

Scenario: The configuration of strategic resource options and the replicate or ensemble of replicates to be simulated in the Water Resources model for England and Wales.

Sensitivity test: Simulation exercise to test the reliability of supply in England and Wales when demand and/or climate inputs are varied.

Severn Thames Transfer (STT): A strategic transfer designed to convey raw water from the River Severn to the River Thames via an interconnector. There are multiple sources for the transfer (Minworth WwTW, Netheridge WwTW, Mythe WTW, River Severn at Deerhurst

abstraction, release of Shrewsbury licenced flow within the Severn, and Vyrnwy components (Vyrnwy Reservoir and North West Transfer (Vyrnwy Aqueduct and UU sources) which form their own enabling solutions, that will be utilized to support the solution when needed.

South East Strategic Reservoir (SESRO): A strategic supply option comprising of a proposed fully bunded reservoir in Abingdon, Oxfordshire. There are a range of possible capacities and yields, the max volume is 150,000 MI and a release of 321 MI/d.

South Lincolnshire Reservoir (SLR): Strategic supply option comprising of a 52,500 MI reservoir supported by an abstraction from the Witham near Boston and a transfer up to 300 MI/d from the River Trent.

Southern Water – water recycling (Havant Thicket): A strategic supply solution that includes Budds Farm WwTW, a proposed water recycling plant and a transfer of treated wastewater to Otterbourne water supply works. The solution supplies Southern Water’s South Hants and North Sussex WRZs, and Portsmouth Water.

Strategic Supply Option: Large regional and inter-regional water supply options that have the potential to address medium to long-term water resource problems in England and Wales. The strategic resource options are solutions identified by the RAPID programme.

Stress test: Simulation exercise to test the reliability of supply in England and Wales when one key Strategic Resource Option is removed from the final set of solutions.

Supply shortfall: Day within a simulation when the requested demand of a water resource zone exceeds the total supply available to the same water resource zone.

Teddington DRA: A strategic re-use scheme that involves treated effluent from Mogden WwTW being discharged into the River Thames upstream of Teddington Weir. Water would then be abstracted upstream of this effluent and pumped into the Thames Lee Tunnel for transfer to Lee Valley reservoirs in a “put and take” arrangement.

Thames to Affinity Transfer (T2AT): A strategic raw water transfer (up to 100 MI/d) from Thames Water to Affinity Water, facilitated by either abstraction from the River Thames (provided by SESRO/STT release) or through the shared use of future London Effluent Reuse (LER) supply.

Thames to Southern Transfer: A strategic raw water transfer (up to 110 MI/d) from Thames Water to Southern Water and South East Water, facilitated by abstraction from the River Thames (provided by SESRO or STT release).

Upper Derwent Valley Reservoir Expansion (UDVRE): A strategic supply option that includes expansion of the existing Upper Derwent Valley Reservoir (volume increase undecided). The increased storage proposed will provide additional raw water to support existing (Bamford and Rivelin WTWs) and/or new water treatment works operated by Severn Trent Water and Yorkshire Water through the bulk export agreement.

Water Use Restrictions: temporary restrictions on particular uses of water imposed during periods of water scarcity or drought.

Water Resources Management Plan (WRMP): A statutory document that all water companies must produce every 5 years. It sets out how a water company intends to achieve a secure supply of water for its customers while protecting and enhancing the environment.

Water Resources model for England and Wales (WREW): National scale Water Resource simulation model for England and Wales, developed using the software platform Wathnet.

weather@home2 (w@h2): The w@h2 modelling framework consists of a global climate model (GCM, HadAM3P) driven by observed or projected sea surface temperature (SST) and sea ice which is downscaled to a 25 km grid scale over the European domain by a regional climate model (RCM HadRM3P). The w@h2 near- and far-future ensembles are also forced with RCP 8.5 emissions scenario. This framework is used extensively by the climate modelling team at the University of Oxford to simulate climate conditions over Europe and generate long, validated, ensembles of spatially (nationally) coherent climate conditions for England and Wales.

1 Introduction

This report, commissioned by Ofwat's Regulatory Alliance for Progressing Infrastructure Development (RAPID) and produced by a team comprising Oxford University, Ricardo, the University of Bristol, the Environment Agency, and DHCR, details the second phase of a project to develop a National Supply Simulation Model (NSSM).

1.1 Objectives

The objectives of the NSSM project are to:

1. Create a national system simulation model that:
 - a) Represents the water company systems as of 2025, including their operational rules, at a level of detail that is sufficient to accurately approximate their behaviour, and hydrological inputs from national databases that are calibrated against water company models;
 - b) Includes the Solutions in the RAPID process, represented at an appropriate level of detail for national modelling and also considers potential operating rules and any key interdependencies;
 - c) Outputs 'real world' metrics such as reservoir levels and the number of days in a given level of water use restriction, and reports on environmental impact via a hydrological proxy;
 - d) Will be easily accessible by RAPID and the sponsoring regulators – allowing them to explore, edit and run the model over the course of the project and thereafter;
2. Use the national model to test the resilience and benefits of individual Solutions, and different combinations of Solutions, under different futures of climate change and demand scenarios spanning out to at least 2050:
 - a) Assess the relative drought resilience performance of the Solutions (individually and in combination) and how they trade-off against one another, in terms of cost, environmental risk, and drought resilience, by comparison with a baseline scenario;
 - b) Set up additional model runs to carry out a sensitivity analysis for the Solutions both individually and in combination;
 - c) Report on the spatial and temporal connection between large-scale physical droughts (climatological and hydrological drought) and human droughts (water supply system drought), using appropriate drought indices and water supply system metrics (e.g. number of days in water use restriction). Also, explore the inter-regional coherence of large-scale physical and human droughts and assess the implications for Solutions involving long transfer pathways; and
 - d) Deliver and communicate model outputs to feed into RAPID's gated assessments and assist with the decision-making process for continuation of Solutions within the RAPID process.

1.2 Overall approach

The overall approach to the NSSM project is set out in **Figure 1**. The project is split into two phases, with Phase 1 concentrating on data collation and workshops, updates to the "Water Resources of England and Wales" (WREW) water resources model, and incorporation and verification of each individual Solution. Phase 2 concentrates on stress testing individual and combinations of Solutions against drought, climate and demand scenarios.

The Phase 1 report⁵ gave a detailed account of the WREW model used in the NSSM project, its origin, and development. National water system simulation modelling is challenging, and involves integrating climate, hydrology, water infrastructure, and water demand modelling. WREW has been developed as a modelling tool that integrates these components allowing the exploration of the need for strategic water infrastructure alongside large-scale drivers of change, including climate, abstraction reform and changing demand. The model originated in the NERC-funded research project looking at drought and water scarcity in the UK, by a team led by Professor Jim Hall at Oxford University, using the software platform Wathnet.

⁵ [The National System Simulation Modelling \(NSSM\) - Project Phase 1 Report - December 2021 - Ofwat](#)

It was used and further developed in the 2016 Water UK Water Resources Long-Term Planning Framework study, and subsequent projects.

The project utilises the existing WREW model, and incorporates updates for WRMP24 planning, before building in Solution representations. The Solution representations have been agreed with the Solution leads at the relevant water companies, including expected operation and behaviour of the Solution, and any modelling simplifications required. Hydrological inflows to the model have derived from the DECIPHeR model (see Section River Flow 2.5), and climate scenarios from the w@h2 model (Section 2.4). Inputs to the model are verified using metrics within the model, such as comparing modelled reservoir drawdowns against historic records. Baseline performance of individual Solutions are also verified against metrics such as expected yields.

The output of Phase 1 informed and refined the Phase 2 scope, and including more complex improvements to Solution representations, and running stress test scenarios.

Phase 1	Update WREW for WRMP24	Supply system network updates & options inclusions
	Hydrology & model inputs preparation	Update & validate DECIPHeR inflows Weather@Home2 Climatology Demand Distribution Input updates
	Build in SRO representations	Consult with SRO teams Test & confirm operational behaviour
	Update Environmental constraints	Hands off flow updates Abstraction licence constraints inc. WINEP studies
	Individual SRO model runs	Analyse supply shortfall reduction as water resource benefit metric
	Phase 1 report and individual SRO performance analysis	[PHASE 1 OUTPUTS]
Phase 2	Model improvements	SRO representation updates Supply network representation improvements
	Combined SRO model runs	Analyse supply shortfall reduction as water resource benefit metric
	Scenario model runs	Environmental scenarios Demand scenarios
	Regional plan model run	Consult with regional groups Compare national water resource benefit
	Phase 2 report and SRO performance analysis	[PHASE 2 OUTPUTS]

Figure 1. Steps within the project's Phase 1 and 2

1.3 Phases 1 and 2

Phase 1 of this project covers Objectives 1 and 2a; Phase 2 covers Objectives 2b, c, and d.

The project's Phase 1 Report⁶ details the methods and data used to develop the Model and the incorporation of the regional water group's Strategic Resource Options. The Strategic Options present regional and inter-regional supply options that address increasingly pressured water resource challenges. The NSSM gives a national scale platform to stress test the Solutions and provide a quantitative

⁶ NSSM Phase 1 Report: <https://www.ofwat.gov.uk/publication/the-national-system-simulation-modelling-nssm-project-phase-1-report-december-2021/>

independent evidence base for RAPID and its sponsor regulators to explore the implications of inter-regional drought coherence⁷ on large-scale transfers. The reader is referred to the Phase 1 Report to find out about the context, background, and Phase 1 outputs for that stage of the project.

Phase 2 of the project focuses on the further development of the NSSM and its use to perform model simulations for different scenarios that explore possible futures with regard to changes in climate, water demand, and the potential benefits of certain Strategic Options. This report sets out the approach, results and findings from Phase 2 of the project.

⁷ Inter-regional drought coherence refers to spatially extensive drought events which affect multiple river basins and/ or water planning regions. A detailed description of inter-regional drought coherence and the implication to large-scale transfers can be found in [Murgatroyd & Hall \(2020\)](#).

2 Phase 2 NSSM Model Development

2.1 Introduction

This section outlines the further development, and changes made to WREW after the completion of Phase 1. The reader is referred to the Phase 1 Report⁶ to find out about the full context, background, and development of the model in Phase 1.

2.2 Engagement with stakeholders

A key part of the NSSM project involves carrying out updates to WREW, including ensuring the representation of the supply system is accurate, and appropriate for its national scale focus.

Throughout the project, the NSSM team have extensively engaged and collaborated with the regional groups and water companies in order to develop a shared understanding, and better align the national modelling with regional group/water company modelling.

The following sections set out the interactions with external stakeholders during Phase 2.

2.2.1 Modelling Advisory Group

The Modelling Advisory Group (MAG) meetings are run by the EA and RAPID and are attended by a wide range of delegates, including regional group technical/modelling leads, water company modellers, other regulators (Natural Resources Wales (NRW)), navigation authorities (Canal & River Trust (CRT)) and academic project partners (Universities of Oxford, Manchester and Bristol).

The meetings provide a forum where the various groups can share progress on the different modelling initiatives that are running in parallel, discuss technical issues, and work toward improving consistency and comparability between the regional models, as well as the regional and national modelling.

MAG meetings carried out during phase 2 of the modelling were used to provide progress updates on the project and discuss preliminary proposals for the scenarios to be tested in WREW. The meetings gave stakeholders opportunity to shape the scenario configurations and provide recommendations around the environmental destination scenarios.

2.2.2 Working Group

The NSSM working group includes representatives from the Regional Water Resources Planning groups and the All Company Working Group. The aim of the group is to provide a forum where regional groups and water companies can provide more specific technical feedback and input into the NSSM project. A series of meetings were held with the working group during Phase 2 of the modelling project. Discussions with the working group helped develop the model scenarios tested in Phase 2, as well as sense checking which of the strategic supply options solutions should be tested in WREW and their formulation.

Another key topic of discussion with the working group was around better understanding the w@h2 dataset, which is used in WREW. A twin track approach was settled on, including:

- The University of Oxford performing a statistical analysis of the w@h2 dataset to investigate the spatial, temporal and volumetric characteristics of the droughts in the dataset. This piece of work allowed for the identification of events in the w@h2 dataset with a return period >1:500, which could then be filtered out from the modelling results to better align the approach for regional water resources management plans; and
- Atkins performing a comparison between the w@h2 dataset and other climatology datasets including the regional groups weather generator, the advanced meteorology explorer and UKCP18 products.

2.2.3 Individual Solution teams

One of the most important tasks for updating WREW is to ensure the Solutions are represented in a simplified way that is appropriate for a national scale model, but which also allows for realistic behaviour. In order to achieve this task, NSSM team held further meetings in Phase 2 with the external Solution teams (water companies and consultants) up to April 2022. The process involved the NSSM team developing a conceptual understanding of any new Solutions, based on solution overview documentation or Gate 1 Submission reports provided to RAPID by water companies, and creating a preliminary representation of each new Solution in WREW. Any changes to existing Solutions were also discussed

with Solution teams and updated accordingly in WREW. Meetings with the Solution teams were used to confirm the conceptual understanding, review representations and gather feedback.

The Solution Meetings held in Phase 2 covered the following aspects:

- WCWR – updates to existing Solutions
- Mendips Quarry – addition of a new Solution
- UDVRE - addition of a new Solution
- Southern Solutions – updates to existing schemes
- T2AT – updates to existing scheme
- UU Sources (North West Transfer) – updates to existing scheme
- SLR and Fens Reservoirs – updates to existing schemes

2.2.4 Liaison over supply system representation

Since MaRIUS, WREW has been developed over several projects (WaterUK and the National Framework). Ensuring the model adequately represents the water supply infrastructure on a national scale has been achieved through engagement and information sharing with water companies. The engagement included the following people and / or topics:

- Severn Trent Water modelling specialists to discuss Severn regulation and abstractions on the River Severn
- United Utilities modelling specialists – updates to UU sources and Vyrnwy Aqueduct
- Welsh supply system representation – see Section 2.2.6
- Thames Water
- Canal and River Trust – discussion of the abstraction around Purton and rules around abstraction under Severn Regulation
- Affinity GW – see Section 2.6.2

2.2.5 Obtaining information and data

The NSSM project team made data requests to regional groups and their constituent water companies for a number of different topics including:

- Storage volumes of reservoirs simulated in their water resources models
- Environmental destination figures for scenarios that were not submitted as part of the regional reconciliation process (Enhanced and BAU+)
- Control curves, demand saving triggers and demand savings
- Regional group climate dataset

2.2.6 Welsh representation

The NSSM team engaged with technical modelling specialists in NRW and Welsh Water who work on the Dee and Wye water resources system in order to review the representation of the Welsh supply system in WREW. Information shared included the following:

- Abstraction rules around the Wye system
 - Mitcheldean/Lydbrook based on Redbrook Gauging Station
- Transfers between WRZs
- Elan Reservoir operational releases
- Abstraction rules around the Dee system

2.3 Comparison of generated climate data sets

The climate datasets used are the same as those used in Phase 1 of this project. They have been created from independent research at the University of Oxford, using Global and regional circulation models, as set out in the Phase 1 Report, and in Guillod *et al.* (2018).

They have been assessed by, Atkins, against other climate datasets currently being used. Here follows a summary of the analysis and its findings.

In January 2022, Atkins released the technical note '*Comparison between Regional Climate Data Tools (RCDT) and the W@h2 or MaRIUS data used by the Environment Agency RAPID project*'. This was commissioned by the water resources Regional Groups and sought to compare the MaRIUS data used by

NSSM against the Regional Climate Data Tools (RCDT) products used by water companies for their long-term planning. The Regional Climate Data Tools consist of (i) a stochastic weather generator for drought risk assessment based on the 20th Century climate and (ii) future climate change scenarios based on Met Office UKCP18 products. This report also compared MaRIUS against HadUK river basin average rainfall, and against the UKCP18 Global Climate Models (GCMs) and Regional Climate Models (RCMs) outputs.

In terms of 'baseline' precipitation (20th Century records), the MaRIUS data set performed very well both in terms of monthly averages, and against different drought metrics, significantly outperforming the baseline GCMs and providing a similar level of accuracy to the RCMs baseline. The mean error for equivalent historic periods was around 2.5%. Drought precipitation metrics were good for all 10 basins that were analysed. Direct comparisons against the water company stochastics were only possible for the Thames, South East, Anglian and Severn basins, as the water company RCDT generates spot location data rather than full gridded data sets, with limited spatial coverage in other basins. Within the South East and Thames basins MaRIUS did tend to be marginally drier than the RCDT and HadUK data, but only in the order of 3% for a 12-month drought. Drought precipitation totals for Anglian and Severn were very similar between the three data sets.

Baseline temperature was the only parameter where the MaRIUS data set deviated notably from the HadUK data set in comparison to the other models, although this was limited to the summer months (+0.5 to +1 Celsius). This was more than offset for the future climate analysis, with MaRIUS summer temperature increases between 2 and 3 Celsius lower than the equivalent RCP8.5 UKCP18 products.

Precipitation change factors under climate change were very similar to other RCP8.5 models used in the UKCP18 products, although it is notable that the combined impacts of baseline differences with change factors resulted in MaRIUS being drier overall than UKCP18, particularly for summer focused drought events.

The key advantage of the MaRIUS data over the RCDT data set is in its ability to match observed spatial correlation structures between basins. Whilst the RCDT correlation between South East and Thames was very good (reflective of the fact these were generated in a single model for the Water Resources in the South East Region), the correlations *between* drought basins outside of this were poor, even with correction methods applied. The MaRIUS data set, however, matched spatial correlation observations well and outperformed all other models, even the RCM. This is particularly important for the national scale modelling used by the NSSM.

In conclusion, MaRIUS performed well on all parameters and was considered to be a robust basis for national scale water resources modelling. It will tend to be marginally drier than the water company RCDT data sets in the baseline for the Thames and South East, so severe events will tend to be climatically worse in those areas when compared with the WRSE Regional Plan, but these differences are within the margin of error for estimation of severe drought deficits.

2.4 Drought characterisation of the w@h2 event set

The w@h2 dataset accounts for a wide range of uncertainty associated with future climate change and therefore includes some severe drought events. A recommendation from phase 1 was to better understand the severity of droughts in the w@h2 event set, compared with the target resilience to a 1:500 drought that water companies must meet as part of their water resources management plans. Any drought events >1:500 should be removed from the WREW analysis in order to align with approach taken by the water company and regional water resources plans, and avoid testing drought events beyond the design criteria of the RAPID solutions.

A statistical analysis of the w@h2 dataset was carried out to characterise the spatial patterns of droughts in the w@h2 event set. In terms of three metrics: the duration of the drought event; the maximum monthly deficit during the event; the accumulated deficit. The approach taken to identify droughts and characterise them is described in Appendix A.

Results from the analysis include the return period for each metric, as calculated relative to the dataset. The return period for the drought accumulated deficit metric was used to identify which of the 100 replicates in the near future (2020-2050) and far future (2070-2099) ensembles contain a drought event >1:500. The near future ensemble has 22 replicates with drought events >1:500, whereas the far future ensemble has 32 replicates. These replicates have been removed from WREW outputs and therefore the results presented in this report have been simulated using a reduced ensemble of 2,340 years (78 x 30-years) for the near future and 2,040 years (68 x 30-years) for the far future. It should be noted that filtering the w@h2 event set using the return period of a duration drought metric would likely exclude

different drought events, compared with the accumulated deficit metric used for this report (this is demonstrated in Figure 31, Appendix A. Further work is required to understand which drought metric is most appropriate for describing the severity of impact on the water resources system as outlined in Section 0.

2.5 River Flow

The river flow inputs are exactly the same as those used in Phase 1 of this project. This is a dataset generated from independent research conducted by the University of Bristol. It is different to the numerous data sets used by water companies in their own models. Below is a short description of how they were derived.

The MaRIUS model takes input data from the University of Bristol's DECIPHeR hydrological model (Coxon *et al.*, 2019a,b). DECIPHeR is a flexible hydrological modelling framework that can simulate flows across multiple catchments with different hydrological characteristics.

DECIPHeR groups together similar parts of the landscape into spatially connected hydrological response units (HRUs). This helps to minimize run times and enable the model to handle large ensembles of climate simulations and provide probabilistic flow simulations essential for risk analysis. HRUs are classified as hydrologically similar by (1) three classes of slope and accumulated area and (2) a 5-km² input grid to ensure the spatial variability of climatic inputs was represented.

DECIPHeR uses precipitation and potential evapotranspiration outputs from w@h2 downscaled to a 5-km grid using the same bias correction method as is presented in Guillod *et al.* (2018). It transforms these ensembles into river flows which are input data to the water resources supply model. In this way a national dataset of current and future river flows has been generated.

DECIPHeR has been applied to 1,366 flow gauges across Great Britain and shown to perform well for four different evaluation metrics covering high flows (Nash-Sutcliffe efficiency), water balance (bias in runoff ratio), low flows (bias in low flow volume), and flow variability (bias in the slope of flow direction curve) across a wide range of catchments (Coxon *et al.*, 2019). While model performance is generally good, it is important to note that model performance does vary across catchments and a more detailed analysis of model performance can be found in Coxon *et al.* (2019) and Dobson *et al.* (2020).

For WREW, ensembles of naturalized flows were generated for over 380 input points required by the water resources supply model. The ensemble of naturalized flows for each point consists of flows from the best parameter set, identified either by calibrating the model to daily naturalized flows obtained from the Environment Agency or transferring behavioural parameter sets from donor gauges where no naturalized flows were available.

For the model calibration, DECIPHeR was run for a 56-year period (1961–2015) using daily observed precipitation (CEH GEAR, Tanguy *et al.*, 2016) and potential evapotranspiration (CHES, Robinson *et al.*, 2016) data as input, and 10,000 parameter sets sampled in a Monte Carlo simulation using wide parameter ranges tested in previous studies (Coxon *et al.*, 2019a,b). There is no separate validation period, although we have implemented this in other studies (see for example Lane *et al.*, 2021).

The best parameter set for each point was defined as the top-ranked simulation for Nash-Sutcliffe efficiency and log Nash-Sutcliffe efficiency (using the rank sum) to gain simulations that can capture both high and low flows (particularly important for ensuring correct catchment storages in reservoirs). Thus, for each of the 338 input points, 100 90-year daily flow simulations (created using the best parameter set for each point) are generated from the w@h2 projections (covering the baseline, near-future and far future period).

We recognise the uncertainty associated with hydrological modelling from the datasets we use to drive and evaluate our hydrological models to the parameters and model structure used to derive hydrological projections. While we do consider these uncertainty sources in other research, the scope and time available on this project means that we were unable to consider and feed through all these uncertainty sources into the water resource system model. However, this is certainly an area for future model developments and research as highlighted in Section 4.2.1.1.

2.6 Groundwater

2.6.1 Empirical groundwater model

The groundwater inputs are exactly the same as those used in Phase 1 of this project, with the exception of inputs for Affinity Water (described in the next section). Below is a short description of how the groundwater inputs were derived.

There is currently no national-scale groundwater model that can be used to inform groundwater abstraction management. Even if it did exist, such a model could not be used directly for the thousands of years of simulation that have been conducted in this study. Whilst some water companies have developed regional groundwater models where groundwater is the dominant source, others rely on past borehole abstractions to estimate groundwater yields.

Incorporated within WREW is a national model of groundwater yields, given climatic conditions and antecedent withdrawal, which has been trained using information on groundwater licences within the national abstraction database. This empirical model describes the maximum abstraction rate from a borehole in a given month. This is achieved with a multivariate linear regression between antecedent rainfall, antecedent abstractions, and historic abstractions that were made under limiting conditions, for a given borehole of a given geological character. This model is based on the groundwater licence information from the Environment Agency's national abstraction database, which contains monthly reported public water supply abstraction for 900 boreholes greater than 1 Ml/day for at least 1 month in the record. More information on the approach can be found in Dobson *et al.* 2020.

While the current groundwater approach is basic, it does allow for time-variant groundwater times inputs, without the need for separate and more sophisticated groundwater modelling.

2.6.2 Groundwater modelling in Affinity Water's area

A recommendation from Phase 1 was to improve the representation of Affinity Water's (AFW) groundwater abstraction. Large parts of AFW's central region (WRZ 1, 2, 3, 4 and 5) rely heavily on groundwater supply and therefore the accuracy of model behaviour for these WRZs is limited by the default representation of groundwater in WREW.

Furthermore, the GUC, Thames to Affinity Transfer, and Anglian to Affinity Transfer Solutions all supply water to Affinity Water's area, which means that the groundwater representation has implications for reliability of the findings around drought scenarios.

The NSSM team led discussions with AFW and their partners, AECOM and HR Wallingford, to understand the discrepancies of outputs between WREW (empirical) and AFW's (lumped parameter) groundwater models, and to determine a way forward. After engagement, it was decided that to improve the accuracy of AFW's groundwater representation, the WREW climate data would be run through the AECOM groundwater lumped parameter models and the outputs would be used as groundwater inputs in WREW.

To do this, the $w@h2$ dataset was scaled to fit AFW's historic rainfall and PET datasets; these are the datasets that were used by AECOM to calibrate their lumped parameter models. The scaled $w@h2$ datasets (historic, baseline, near future and far future) were then provided to AECOM who ran them through their lumped parameter groundwater models to create outputs of groundwater levels for Chalfont, Elsenham and Lilley Bottom boreholes for the historic and range of futures. Chalfont, Elsenham and Lilley Bottom are observation boreholes used for AFW WRZs 1-5.

Groundwater levels for Chalfont, Elsenham and Lilley were converted to minimum deployable output (MDO) for WRZ 1-5 using algorithms provided by HR Wallingford. MDO was utilised in WREW instead of groundwater levels as it is taken to be more representative of the water available to be used in the system; WREW does not currently take into consideration pumping constraints, water quality issues, assets, treatment capability etc. Algorithms allowed conversion of groundwater level to return period, and from return period to a source MDO value. Where return period of the groundwater level was <2 , MDO values were taken as those at return period 2 to be consistent with AFW and HR Wallingford's outputs. It is to be noted that despite scaling of $w@h2$ data, bias may still exist in the AECOM outputs as the climate used is ultimately different to the climate data used to calibrate the lumped parameter models. Time variable groundwater MDO (monthly time step) for each WRZ was then combined with MDO from any 'fixed' sources which are considered drought resilient and reliable regardless of groundwater levels at the observation sites.

For input into WREW, MDO for AFW WRZs 1,2,4 and 3,5 was then aggregated to match the aggregation of these WRZs in the national model and converted to a daily time step in. Groundwater inputs for historic, baseline, near future and far future for demand nodes a) AFW 1,2,4 and b) AFW 3,5 was updated in WREW with these MDO datasets.

To sense check the groundwater levels output from lumped parameter models, the NSSM team engaged with AFW groundwater modelling specialists. The outputs demonstrated a sensible match between AFW observed historic groundwater levels and modelled ground water levels for a national scale water resources model.

AFW's level of service and drought triggers are entirely based on groundwater level/MDO and are therefore fixed based on climatology. As a result, the WREW model will not see any variability in the level of service irrespective of whether strategic supply options are turned on or off. Therefore, instead of using level of service as a metric to measure the performance of strategic supply options, the metric of supply shortfall is used for AFW WRZs.

2.7 Water demand

2.7.1 Potable water

Using historic data from the Environment Agency national abstraction and returns database (NALD), the WREW model has been populated with water demand from all abstractors over a 2 Ml/d cap.

Empirical data or standard assumptions have been used to derive non-consumed water volumes and/or effluent, returning it into the model downstream of the abstraction point.

Demand for public water supply in WREW was generally set at a water resource zone (WRZ) scale and at a daily time step. The most common set up within WREW has one demand node for each modelled WRZ. In some cases, larger WRZs have been broken down into multiple demand centres in order to represent the area more accurately; a few examples include United Utilities Strategic WRZ, Severn Trent Water Strategic Grid and Wessex Water.

Each demand node uses estimates of the annual demand in 2050, submitted by water companies as part of the regional planning process (Jan 2022 submission) and available from the Environment Agency. These estimates forecast water demand using projections for per capita consumption (PCC), leakage and population. For Phase 2, the WREW model has been updated to Regional Plan Final Plan Distribution Input for the Dry Year Annual Average climate scenario (1:500 event) and takes into consideration the water saved from achieving leakage and PCC targets. These targets are defined by policy and include 50% leakage reduction from 2017/18 levels and a PCC target of 110 l/h/d by 2050⁸. Data submissions show that these targets are mostly met at the regional scale by WRW, WRN and WCWR, however, the targets of constituent WRZs varies. In some cases, the PCC target is not met at a regional scale and is up to 120 l/h/d (WRE/WRSE).

Annual demand in 2050 was converted to daily time step using an annual profile of demand specific to WRZ or water company. If an annual profile was not available, the model uses a default annual profile, taken as the average across all available annual profiles.

Two different demand scenarios were run in Phase 2:

1. **Regional Plan – FP@2050:** Regional Plan Final Plan Distribution Input at 2050 including water saved from achieving 100% of leakage reduction and PCC targets (targets as above)
2. **Regional Plan – FP@2050 with 50% reduction in leakage reduction and PCC targets:** Regional Plan Final Plan Distribution Input at 2050 including water saved from achieving only 50% leakage reduction and PCC targets (targets as above)

WREW has the ability to run annually changing demand (not just at a 2050 time slice) in future phases. In Phase 2, the primary focus was to assess the benefits of Solutions, therefore using a static 2050 demand minimised the number of variables under exploration and allowed easier comparison of Solution benefits across the full near future period for each replicate.

⁸ See:

National Infrastructure Commission. Preparing for a drier future -England's water infrastructure needs, April 2018. <https://nic.org.uk/app/uploads/NIC-Preparing-for-a-Drier-Future-26-April-2018.pdf>

Environment Agency. Meeting our future water needs: a national framework for water resources, March 2020, [Meeting our future water needs: a national framework for water resources \(publishing.service.gov.uk\)](https://www.environment.gov.uk/publications/meeting-our-future-water-needs-a-national-framework-for-water-resources)

2.7.2 Non potable water demands

The inputs are the same as those used in Phase 1 of this project. Below is a short description of how the inputs were derived.

2.7.2.1 General approach

The WREW model uses data from the Environment Agency's national abstraction database on abstraction volumes taken for non-potable water supply. Due to the very large number of licences, non-public water abstraction processing is performed at a catchment scale to preserve computing resources. NPW abstractions connect to a river arc or groundwater source in WREW, and are typically located upstream of public water abstractions when appropriate.

Analysis undertaken to explore seasonality in non-public water and non-irrigation licence abstractions showed only small interannual variability. Therefore, demand has been assumed to be equal to the average abstraction over 1999 and 2015. Information was taken from NALD on the non-consumptive rates for each licence type; these percentages were used to ensure the appropriate return of non-consumed into the model downstream of the abstraction point.

2.7.2.2 Irrigated agriculture

Although <1% of abstracted surface water in England is used for irrigated agriculture, this usage is seasonal, highly spatially concentrated and a high-value use. As irrigation water demand is dependent on climatology, the WaSIM simulation model was used to determine irrigation water demand (Hess, 1996).

2.7.3 Effluent discharge

Water returned to rivers as treated effluent is represented according to information from water companies.

2.8 Environmental destinations and sustainability reductions

Environmental destination (ED) is a new term, originally introduced as environmental ambition through the Environment Agency's Water Resources National Framework published in 2020. Developed as part of regional planning into 'Environmental Destination', as it is referred to here, it is an opportunity for regional groups and water companies to consider and plan for the delivery of a long-term and sustainable 'destination' for water resources. This plan should address known and likely future environmental issues related to all aspects of water abstraction as well as proactively enhance the environment.

As part of regional planning, regional groups and water companies are expected to:

- Understand their environmental needs in the long term
- Work with regulators and other partners to develop a shared long-term destination on environmental ambition. This should ensure no deterioration, address unsustainable abstraction and improve environmental resilience in the face of climate change
- Develop a plan setting out actions they will take to reach the destination

The National Framework set out a broad ambition based on a range of scenarios including 'business as usual' ('BAU'), 'Enhanced' and 'Adapt'.

The BAU scenario is defined as the current regulatory approach remaining the same with protection of the same percentage of natural flows for the environment. The BAU scenario is also extended to a slightly higher level of environmental ambition denoted by the BAU+ scenario. There are a number of different definitions of BAU+, however, the data used in this report refers to the WRSE/WRE definition of BAU+, as set out below:

- **WRSE/WRE BAU+:** Business as usual including water needed to restore groundwater bodies that have been classed as uneconomic to recover (therefore includes all waterbodies). Beyond the regulatory minimum, provided protected areas, existing measures and deterioration have also been accounted for.

The 'Enhanced' scenario is defined by greater environmental protection for protected areas, SSSI rivers and wetlands, principal salmon and chalk rivers. In these water bodies the most sensitive flow constraint is applied, increasing the proportion of natural flow that is protected for the environment.

Under the 'Adapt' scenario, the level of protection is reduced in some less sensitive or modified water bodies to allow access to more water and considers that achieving current environmental objectives everywhere in a shifting climate may not be possible.

At the time of running Phase 2 model simulations, regional groups had put forward their expected environmental destination as part of the Regional Plan Reconciliation data submission (Jan 2022). At this point, there was a broad range of ambition and no set requirement of level of environment destination to strive for resulting in a range of ambition put forward including 'BAU', 'Enhanced', 'BAU+' and for WRW a '% of Enhanced' scenario. This in turn leads to an inconsistent national picture of environmental destination or a 'patchwork quilt' as highlighted in **Figure 2**.

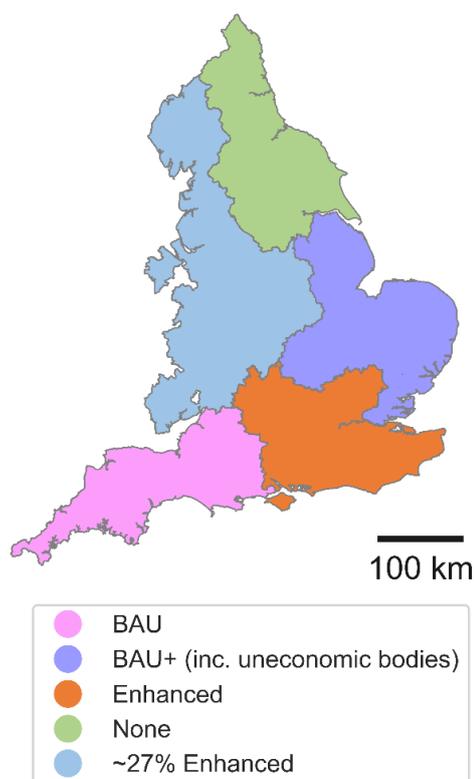


Figure 2. The range of environmental destination scenarios put forward by regional groups (WCWR, WRE, WRSE, WRN and WRW) as part of the regional plan reconciliation process (Jan 2022 submission)

Environmental destination figures - reductions in deployable output (due to reduction of abstractions) for each WRZ under each region's ED scenario – were submitted by regional groups to the Environment Agency as part of the regional planning reconciliation process (the "Jan 2022 submission"). The Jan 2022 submissions figures have been used in WREW as part of the Central Scenario.

A high environmental destination (ED) scenario was also created through request of additional data of some regional groups (WRE, WCWR), where deployable output reductions under the 'Enhanced' scenario are used for all regions in order to provide a more nationally consistent picture

Environmental destination figures (reductions in deployable output) were accounted for in WREW by adding the forecasted 2050 reduction in deployable output (MI/d) onto the forecasted daily demand for each WRZ (MI/d). This approach was taken instead of reducing individual licence abstractions in the national model due to time constraints as well as the limited information provided by water companies as to the breakdown of reductions in DO across specific licences.

It has since been confirmed by the Environment Agency that the minimum requirement for environmental destination in regional plans and WRMPs is an EA/NPF BAU+ scenario. EA/NPF BAU+ scenario is defined as business as usual but extended to a higher level of ambition which includes the further measures needed to recover flows in protected areas. The time frame for meeting this destination is from 2030 to 2050. Thus, it can be expected that sustainability reduction figures in our Central scenario would increase for WCWR, WRN and WRW in the future.

It is also worth noting that sustainability reductions set out in environmental destination scenarios are likely to be brought forward earlier than currently planned due to the recently announced licence capping approach. The approach will change time limited licences, setting the licenced amount back to recent actual usage in places.

2.9 Other updates

2.9.1 Control curves and demand saving levels

The majority of reservoirs and some groundwater sources in WREW include control curve information and associated strategic measures such as demand savings. However, some control curves, operational rules and/or demand saving measures were missing from the Phase 1 version of WREW. Additionally, some water companies have changed their control curves as part of the drought planning statutory process, which means that some of the existing control curves and demand savings in WREW needed to be updated in Phase 2.

At the start of Phase 2 the NSSM team made data requests to regional groups and their constituent water companies on control curves on all reservoirs simulated in their water resources models and corresponding demand savings levels. Information was also requested for demand savings associated with groundwater sources. If the information provided did not match the equivalent data in Phase 1's version of WREW, or was omitted entirely, the WREW model was updated. To aid this process, meetings were held with Thames Water, United Utilities, Severn Trent Water, Anglian Water, Affinity Water, Yorkshire Water, Dŵr Cymru Welsh Water and South West Water. Other companies provided written feedback.

Table 1 provides an overview of the updates to control curves and demand savings made to WREW in Phase 2.

Table 1. Phase 2 updates to WREW control curves and demand savings.

Water Company	Reservoir or groundwater source	Updated control curves	Updated demand saving levels
Anglian Water	Grafham Reservoir	– Resource state curve – Level 1-4	Level 1-4
	Rutland Reservoir	– Resource state curve – Level 1-4	Level 1-4
	Pitsford Reservoir	– Resource state curve	N/A
Affinity Water	Colne Groundwater Sources	– Drought zone 2-4	Level 2-4
	Lee Groundwater Sources	– Drought zone 2-4	Level 2-4
Bristol Water	Chew Valley Lake	– Resource state curve (Zone 2) – Zone 3-5	Level 1-3
	Cheddar Lake	– Resource state curve (Zone 2) – Zone 3-5	Level 1-3
	Blagdon Lake	– Resource state curve (Zone 2) – Zone 3-5	Level 1-3
SES Water	Bough Beech Reservoir	– Zone 2 & 3 – Emergency storage	Level 1 & 2
Severn Trent Water	Clywedog Reservoir	– Drought alert – Seek drought order – Drought order – Emergency storage	N/A
	Derwent Valley Reservoirs	– Curve C, E & F – Emergency storage	Level 2-4
	Carsington & Ogston Reservoirs	– Curve C, E & F – Emergency storage	Levels 2-4
	Elan Valley Reservoirs	– Curve C, E & F – Emergency storage	Level 2-4
	Draycote Reservoir	– Curve C, E & F – Emergency storage	Level 2-4
	Shropshire Groundwater Scheme	– Zone 1-3	N/A
South Staffs Water	Blithfield Reservoir	– Resource state curve – Drought program monitoring curve – Apply for drought order curve – Drought order curve – Emergency storage	Level 1-3
	Wimbleball Reservoir	– Zone B, C & D	Level 1-3

Water Company	Reservoir or groundwater source	Updated control curves	Updated demand saving levels
South West Water	Roadford Reservoir	– Zone B, C & D	Level 1-3
United Utilities	Haweswater Reservoir	– Resource state curve – Level 1-4	Level 1-4
	Thirlmere Reservoir	– Resource state curve	N/A
	Brenig & Celyn Reservoirs	– Level 1-4	Level 1-4
Yorkshire Water	Central Group Reservoirs	– Level 3 – Emergency storage	Level 3
	South West Group Reservoirs	– Level 3 – Emergency storage	Level 3
	South Group Reservoirs & Winscar Reservoir	– Level 3 – Emergency storage	Level 3
	North West Group Reservoirs & Grimwith Reservoir	– Level 3 – Emergency storage	Level 3

2.9.2 Improved calibration of United Utilities’ Strategic WRZ

A comparison of the simulated reservoir storage for the historic period from WREW, with the outputs from the United Utilities Aquator model in Phase 1, showed poor calibration and need for improvement for Haweswater Reservoir, which is the company’s key indicator of resource position.

In Phase 2 an investigation was carried out to assess and resolve this discrepancy, and thereby improve the calibration of the wider United Utilities’ Strategic WRZ. The NSSM team met with United Utilities and conducted a thorough examination of WREW’s representation of UU’s Strategic WRZ. Several differences between UU’s Aquator model and WREW were identified, including:

- a) Incorrect initial volume and active capacity of Thirlmere Reservoir
- b) Incorrect control curves for Thirlmere and Haweswater Reservoirs
- c) Incorrect capacities for Shap Pumping Station (below Haweswater Reservoir) and Haweswater gravity arcs
- d) Incorrect operating rules for the arc which connects Ullswater to Haweswater Reservoir
- e) Incorrect operating rules for the arc connecting Lake Windermere to Watchgate WTW
- f) Missing demand centres along the Dee and Vyrnwy Aqueducts (Wirral; Crewe & Vyrnwy Aqueduct customers)
- g) Missing groundwater sources that supply Wirral, Crewe & Vyrnwy Aqueduct customers
- h) Incorrect capacity of the Vyrnwy Aqueduct arc and Oswestry WTW
- i) Missing demand saving measures for all Strategic WRZ demand centres
- j) Various imbalances in arc costings across the Strategic WRZ

These issues were resolved with support from the UU water resource modelling team and the reservoir validation exercise was re-performed for Haweswater, Thirlmere, the Dee Reservoirs and Lake Vyrnwy (see Section 2.10.4). As a result, the simulation of water levels in Haweswater Reservoir has improved on the Phase 1 calibration, both across the full historic simulation period (1965-2015) and for individual drought events.

The additional calibration exercise also helped to improve confidence in WREW’s outputs for the United Utilities system and was important for understanding wider drought resilience impacts on the STT solution. The North West Transfer solution offsets the water normally abstracted from Lake Vyrnwy to United Utilities, allowing Lake Vyrnwy to support the STT instead. Improving the calibration of the United Utilities supply system in WREW is therefore important for assessing whether the use of Vyrnwy to support STT could result in a reduction in United Utilities’ resilience to drought events in Wales and north west England.

2.9.3 Severn Regulation and the River Severn Drought Order

The Severn Regulation was not included in WREW as part of Phase 1. This is particularly important to implement in the national model as it helps to improve the accuracy of the operation of the Severn Thames Transfer and its various enabling solutions such as Vyrnwy Reservoir, North West Transfer, Minworth, Netheridge, Mythe and the River Severn unsupported component).

At the beginning of Phase 2, the NSSM team met with South Staffordshire Water, Severn Trent Water and internal colleagues, to discuss how to best implement and simplify the Severn regulation and the River Severn Drought Order (RSDO) in WREW. The representation of supply sources and abstraction along the Severn were updated following the feedback provided. Features along the Severn that were updated

in WREW include Llandinam Gravel abstraction, Hampton Loade & Trimpeley abstractions, the Shropshire Groundwater Scheme (SGS), and the Gloucester & Sharpness Canal. The operational rules for Clywedog Reservoir were also updated, so that:

- When the drought order in force curve is crossed, Clywedog can release a maximum of 300MI/d
- When the emergency storage curve is crossed releases are capped at 1.5% of usable storage
- When the dead storage curve is crossed, releases are reduced to zero

During low flow conditions along the River Severn, the SGS is activated to help balance the demands of abstractors against the ecological needs of the river. When flow along the river drops below the first control curve, SGS can discharge a total of 75MI/d into the river. If flow along the river continues to fall to below the second control curve, SGS can discharge up to 150MI/d. During a RSDO, if SGS is active, releases from Clywedog are reduced by 70% of the total volume released from SGS.

A complete overview of the Severn regulation rules included in WREW are presented in Appendix B.

2.9.4 Anglian Water Strategic Pipeline Alliance

In an effort to build resilience to drought, Anglian Water is developing a network of pipelines to connect locations of water demand across its region. As the new network is expected to be complete by 2025, it has been included in the Phase 2 version of WREW.

Correspondence with Anglian Water informed the implementation of the pipeline network in WREW. The network includes a new supply source originating in East Lincolnshire and Cadney (DPC), and features connections between WRZs in Lincolnshire, Ruthamford, Fenland, Cambridge, and Suffolk.

2.10 Calibration and validation

2.10.1 Overview

A key task for Phase 2 was to carry out a more thorough validation of WREW to provide confidence in its outputs. This national level calibration is important because of the following reasons:

- a) The Environment Agency and RAPID wish to use the WRE national model to sense check outputs from regional water resource models and the regional reconciliation process, in order to better understand any benefits and implications and to challenge where necessary
- b) The Phase 2 simulations included sensitivity scenarios to explore uncertainty around Public Water Supply demand, environmental destination and climate change. In order to test these scenarios, it is important that both simulated historic reservoir storage levels and results from WREW's main/central scenario are reasonable when compared to water company simulations and forecasts.

2.10.2 Historic Calibration

The creation of the WREW model by the MaRIUS project and its subsequent development has been strengthened by interaction and collaboration with UK water industry practitioners, regulators, consultancies, regional water groups and the use of the model in various industry initiatives. The water system formulation in the model is based on communications with, and data sets provided by, these stakeholders.

A key period of industry-aligned parameterisation and calibration was during its use in the Water UK Water Resources Long-Term Planning Framework study (2016), when it was subject to intense scrutiny by water companies, consultants and regulators.

Since then, there has been continuous improvement by the University of Oxford, with input from Environment Agency staff, water companies and regional groups.

WREW's representation of water supply infrastructure operation has been successfully compared (Dobson *et al.* 2020) against the systems of the five largest English water companies, namely United Utilities, Anglian Water, Yorkshire Water, Thames Water and Severn Trent Water. The comparison was performed for major reservoirs, flows and transfer volumes and the simulation results found to be comparable to water company model outputs, with the lowest Nash-Sutcliffe efficiency of reservoir storage being 0.7 which is statistically proven good fit.

More recently, before the start of the NSSM project, the WREW model was used to undertake analyses that were used and published in the 2020 EA report "Meeting our Future Water Needs", were the first

national-scale assessment of the frequency and duration of current and future water shortages. The published estimates were broadly endorsed by water companies as being realistic representations of their systems.

Calibration and validation of the WREW model has taken place in both Phase 1 and 2 of the NSSM Project and the work undertaken in Phase 2 work is outlined in the following sections.

2.10.3 Validation of WREW outputs: supply-demand balance

To provide a national and holistic validation of the WREW model, its supply-demand balance outputs were compared to the data provided by regional groups to the Environment Agency, for the regional planning data submission in January 2022.

A supply demand balance metric for each WRZ was calculated from the regional planning data to compare against the WREW supply-demand balance outputs. This calculated metric removes outage and headroom volumes in order to match the WREW data (WREW does not represent these volumes). A main WREW scenario was simulated to provide a surplus/deficit figure for each WRZ for comparison. Further technical information on the metrics used can be seen in Appendix C. It should be noted that omission of headroom and outage in WREW will underestimate the probability of the frequency and severity of failure compared with the supply-demand balance from regional plans. Additionally, WREW is simulated with demand savings dynamically applied depending on the resource position within the model, whereas, in contrast the regional planning data omits benefits from demand savings. These factors should be considered in further work as outlined in **Section 4.2.1.6**. **Figure 3** presents maps that show WREW outputs compared to regional data. Panel A shows whether a supply shortfall is observed in WREW's main scenario by 2050 (without Solutions). Panel B shows whether a deficit is forecast in the Regional Plan in 2050. Panel C compares WREW outputs against the Regional Plan forecast. In Panel C, matches between WREW and RP are shown in pink and any discrepancies are shown in yellow. A tolerance threshold was applied whereby if the probability of the shortfall observed was very small (<0.5%), or the shortfall was within 10% of WRZ distribution input, then the discrepancy was deemed insignificant. The maximum absolute error accepted within the 10% DI tolerance was 14 MI/d. Appendix C has further detail on any WRZs that were within the tolerance threshold.

This analysis revealed seven discrepancies between regional plan forecasts and outputs from WREW, which are set out in **Table 2**. However, these make up a relatively small proportion of the national water resources system.

The main reason for the observed discrepancies between the regional plan forecast and WREW outputs is missing or inaccurate groundwater sources in WREW. Resolving these data gaps will be a feature of future phases of the NSSM project.

Of the seven discrepancies, only the Kennet Valley WRZ, is associated with a strategic solution (Thames to Southern transfer). As a result, caution must be taken with the analysis of model outputs for this area. For the majority of WRZs however, the analysis has shown that confidence can be put into the WREW model outputs, as they align with the regional plans.

2.10.3.1 Adjustments made to results following validation

2.10.3.1.1 Southern Water – Isle of Wight (SWS IoW)

It had been noted during engagement with Southern Water modelling specialists that if the Isle of Wight was to experience regular supply shortfalls in WREW (which it does), a supporting supply option (Sandown WRP providing 8.5 MI/d) should be added during post-processing of WREW results.

2.10.3.1.2 Wessex Water – Supply Area

A range of Solutions have been put forward by WCWR which predominantly benefit Wessex WRZ. Following the validation exercise, an audit of supply sources for the Wessex area in WREW took place which identified significant missing groundwater sources (~160 MI/d).

2.10.3.1.3 Affinity Water – Wey (WRZ 6)

There is a 0.2% chance of observing a supply shortfall in Affinity WRZ 6 (Wey) in contrast to no deficit expected in 2050 in the Regional Plan data submissions. The supply shortfall observed only occurs in 5 events across 3 replicates in the near future ensemble and is a result of surface water abstractions along the Thames at Wey dropping to 0 in very dry (rare) events (RP>200). In reality, this would never happen – Affinity WRZ 6 has priority of abstraction and there would ultimately be less water available downstream

on the Thames (London). This priority of abstraction is not represented accurately in the model and will look to be updated in the future.

Table 2. Discrepancies between regional plan forecasts and outputs from WREW

That is, the WRZs that do not correlate (those which are yellow in Figure 3)

Map ID	Water Company	WRZ	RP 2050 Deficit?	WREW Supply Shortfall?	Reason for outstanding discrepancy between RP and WREW
1	Severn Trent Water	Rutland	N	Y	Relies on bulk import from Rutland Reservoir – reservoir drops to 0 in WREW
2	Thames Water	Kennet Valley	N*	Y	Missing groundwater sources
3	Affinity Water	Wey	N	Y	Inaccurate model representation of surface water abstraction in very dry replicates (drops to 0). NB: This is rare behaviour that is only observed in 3 years across the whole ensemble (and are removed as a result), please refer to Section 2.10.3.1.3 for discussion.
4	Thames Water	Guildford	N	Y	Inaccurate groundwater inflows (3-4 MI/d too low) and surface water supply drops to 0 in WREW
5	South East Water	Tunbridge Wells	Y	N	Inaccurate GW inflows – 10 MI/d too high
6	Wessex Water	Supply Area	N	Y	Missing groundwater sources
7	South West Water	Roadford	N	Y	Missing groundwater and surface water sources

*NB: Correspondence from WRSE (June 2022) highlights that Kennet Valley will now have a RP 2050 Deficit due to surface water availability (not groundwater availability) under 1:500 conditions.

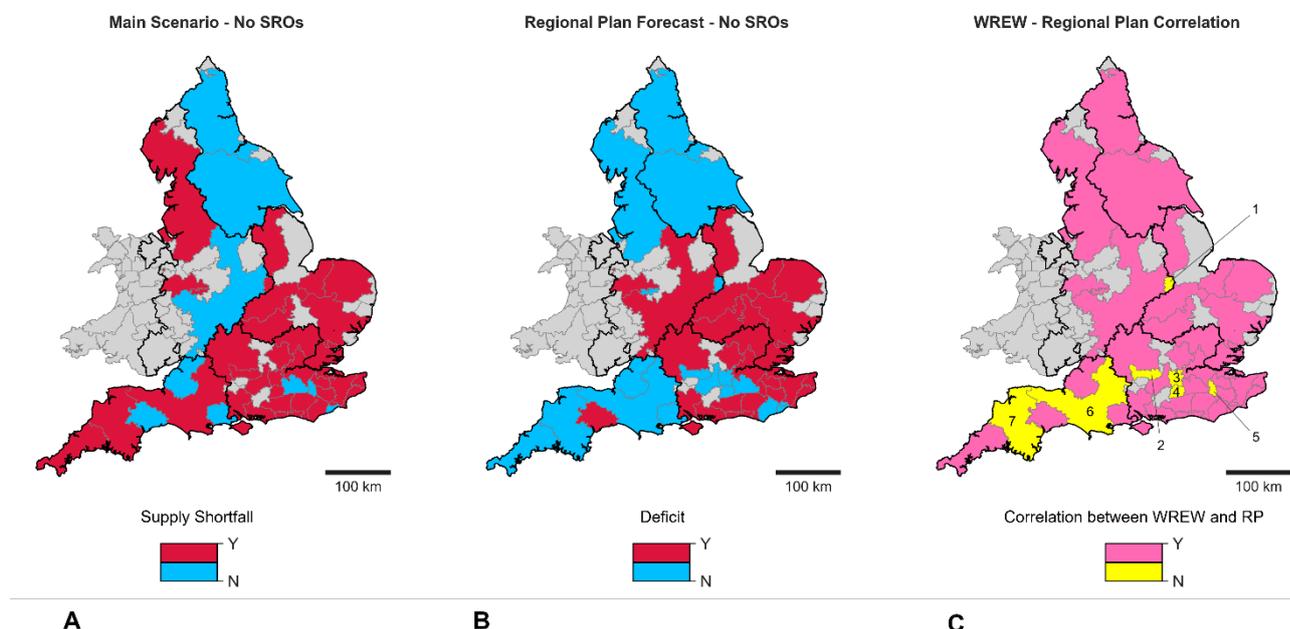


Figure 3. Maps comparing the WREW outputs against the Regional Plan forecasts

NB Panel A shows whether a supply shortfall ('Y'=yes and 'N'= no) is observed in the national model's main scenario at 2050 (without Solutions). Panel B shows whether a deficit (yes/no) is forecast in the Regional Plan in 2050. Panel C correlates WREW outputs against the Regional Plan forecast in a binary yes (pink) or no (yellow) NB: A tolerance threshold is applied, where discrepancies with shortfall within 10% of Distribution Input or shortfalls with a <0.5% probability were deemed acceptable and set to yes (pink). Grey areas represent WRZs that are not fully represented in WREW.

It is important to note that the observation of surface water abstractions (along the Thames at Wey) dropping to 0 in WREW may be a reflection of the underlying hydrology in the simulation model. Please

refer to Appendix D3 on the poor performance of the hydrological model, DECIPHeR, around the Wey Catchment. DECIPHeR does not perform as well in baseflow rivers, similar to the Wey, where the topographical areas don't match the contributing area. It is unknown whether hydrological flows around the Wey catchment are being under or over-estimated and thus whether they could be impacting the water available for abstraction.

In order to provide a clearer picture of the benefits of these Solutions and the supply-demand balance of the system in general for both WRZs, a correction filter (adjustment) was applied to both Wessex and SWS IOW WRZ WREW outputs (160 and 8.5 MI/d respectively) to account for the missing sources of supply. To correct for the rare supply shortfalls observed in Affinity WRZ 6 (Wey), the 3 replicates where this is observed were removed (thus, removing all shortfalls observed). The impact of the adjustment for IOW, Wessex and Affinity Water (Wey) on probability and absolute shortfall can be seen in **Figure 4**. NB The results presented in subsequent sections of this report for the SWS Isle of Wight, Wessex WRZ and Affinity WRZ 6 (Wey) have had this correction applied.

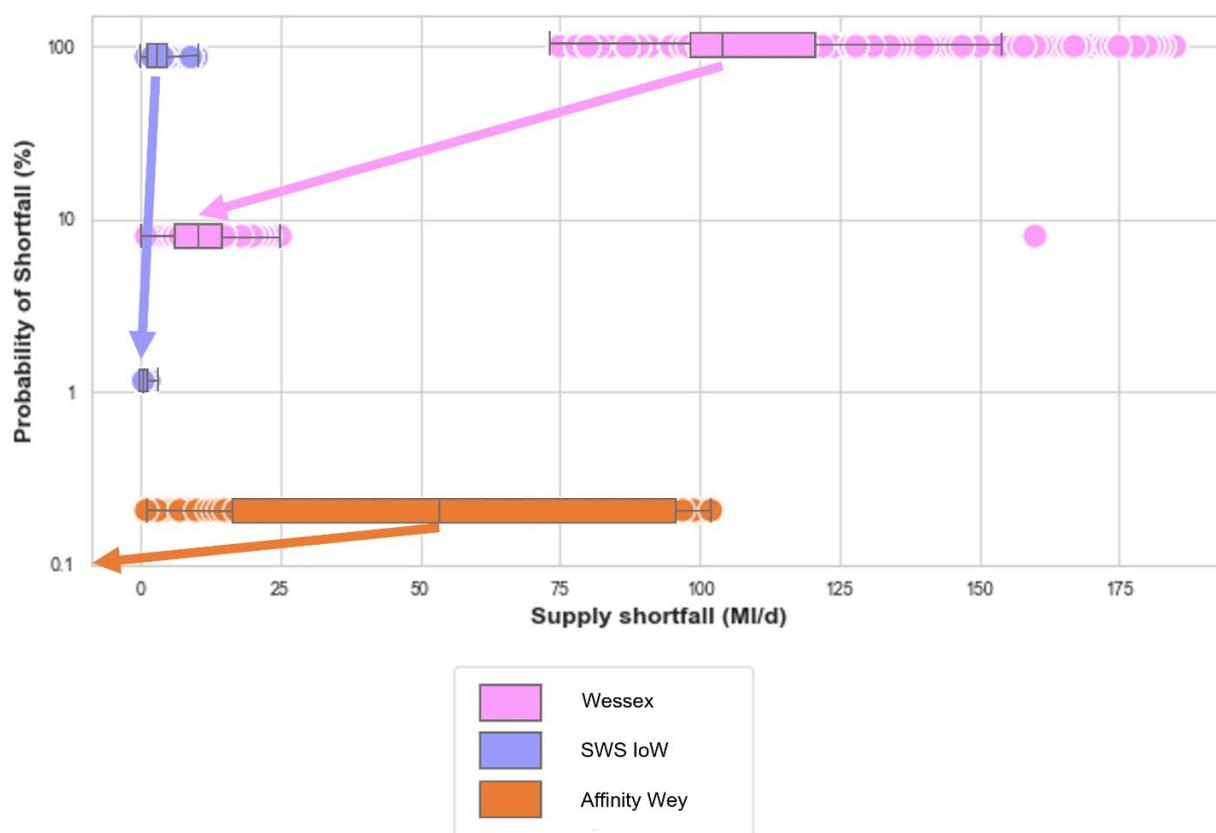


Figure 4. The probability and distribution of the size of supply shortfall observed in IOW, Wessex and Affinity Wey in WREW results

(Central Scenario, no Solutions) with and without the adjustment (correction filter) applied. Affinity WRZ 6 Adjusted not shown (at 0,0)

2.10.4 Validation of WREW outputs: reservoir storage

Reservoir storage levels are a useful metric for comparing the performance of water resource models. Water companies often use the storage levels in key reservoirs as an indication of their resource position and a basis for implementing drought actions in a WRZ. Additionally, from a modelling perspective, the large storage volumes of reservoirs act to smooth out temporal variability of input datasets and model behaviour, meaning that storage levels are a robust high-level metric for assessing model performance.

The spatial coverage of model validation carried out for Phase 1 was limited by the availability of simulated reservoir storage level outputs from water company modelling. In Phase 2 of the project more data was requested and provided by water companies which allowed for further validation.

Figure 5 shows the range of individual reservoirs from England and Wales chosen to perform a relative validation exercise, which involved comparing simulated reservoir storage levels from WREW with water company simulated reservoir storage. The results are presented in full in Appendix D. The reservoirs

were selected based on their size, and location, either directly supplying a solution or falling within the same area of the supply system as a solution. The availability of water company simulated storage also played a role in which reservoirs were chosen for validation. It is possible to produce additional plots for reservoirs not included in this report, provided the data are made available by water companies or regional planning groups.

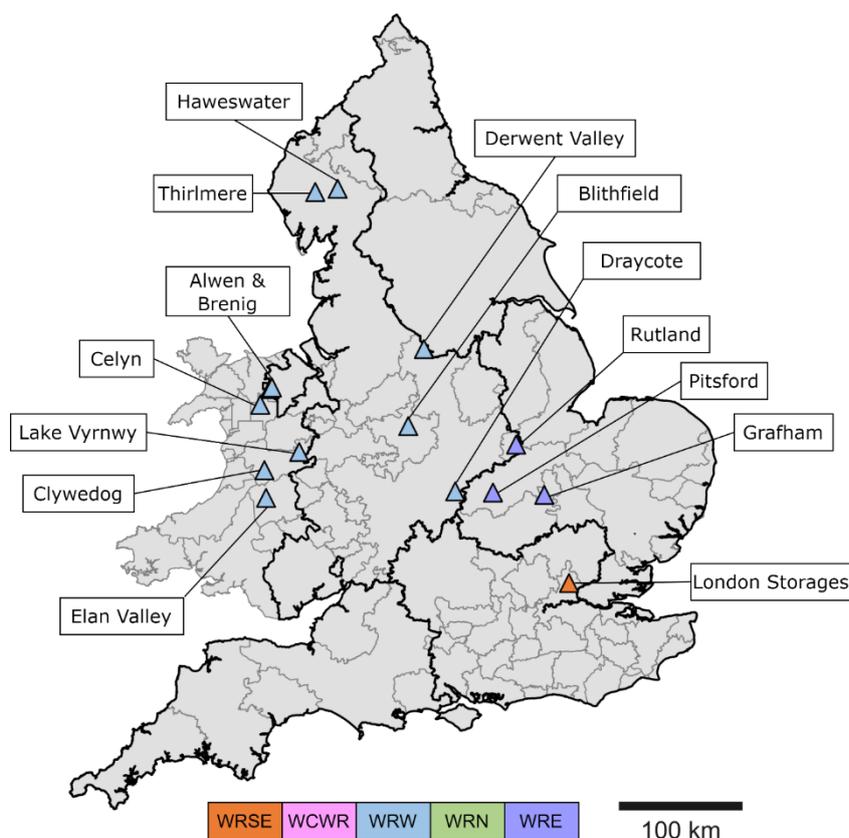


Figure 5. Reservoirs used in WREW Phase 2 validation exercise

In order to perform the relative validation exercise, the model scenarios tested in WREW and water company models were aligned as closely as possible to achieve an equal comparison: both were run for the historic period and using the same level of demand (i.e. the 2020-21 Distribution Input data from WRMP19).

In this way, the differences that arise are largely a result of model configuration, behaviour, and hydrological inputs (i.e., river flows). It must be noted however that there is a fundamental difference in scale between WREW (national scale) and water company models (local scale) and therefore factors such as the level of complexity at which the supply and hydrological system are represented will inevitably also drive differences in model results.

Simulated reservoir storage has been compared for the three drought events that caused significant drawdown of storage levels at each of the reservoir locations. The geographical distribution of the reservoirs and association with different hydrological systems means timing of these drawdown events varies between the reservoirs used for validation.

On the whole, the simulated storage from WREW compares well with the storage outputs from water company models, especially when considering the differences in scale between the approaches. In particular, WREW is able to capture the patterns of initial storage and the timing of drawdown over the course of a drought event. The majority of discrepancies between WREW and water company outputs are a result of the rate of refill or drawdown being under- or over-estimated. For the purpose of this report, the differences identified in reservoir storage are considered to be within error for a national scale model and therefore have not been taken into account in the analysis of model results around the resilience of the strategic solutions.

The results are presented in full in Appendix D. The differences observed in simulated storage highlight that there is still room for improvement in the calibration of WREW: further recommended work on model validation is outlined in Section 4.2.1.

2.11 The Strategic Regional Solutions

The Phase 1 Report gave a summary of each Solution and how they have been implemented in WREW. This section gives a high-level overview of the solutions, how they have been implemented in WREW, and describes changes to the Phase 1 representation of the solutions following further engagement with regional groups and water companies as the scheme details become further developed. Solution diagrams can be found on the RAPID website⁹.

2.11.1 West Country Water Resources (WCWR)

2.11.1.1 Update to Phase 1 WCWR Strategic supply options

Following Phase 1 and the submission of their Emerging Regional Plan in January 2022, WCWR's initially proposed strategic supply options have now shifted from an *inter*-regional to *intra*-regional focus. The requirements and uncertainty surrounding environmental destination highlighted in WCWR's Regional Plan demonstrates the need for the proposed strategic supply options to be utilised in their own region, rather than sharing inter-regionally.

As a result of this shift, the following updates were made to WCWR strategic supply options.

- a) **Roadford pumped storage scheme:** The initial scheme involved a transfer of 30 Ml/d from Roadford Reservoir to Southern Water's Hampshire WRZs to make better use of the existing Roadford Reservoir through pumped winter storage from River Tamar and the creation of a new long-distance transmission system. Following this shift from inter-regional to intra-regional focus - water will no longer be transferred inter-regionally to WRSE (Southern Water South Hampshire) and as such, the transfer has been updated to stop at Wessex WRZ (Warminster and Bournemouth and Poole and Bournemouth demand centres in WREW). Note that this scheme has gained Green Recovery funding and is going ahead outside of the RAPID process and is therefore no longer considered a strategic supply option. The scheme will continue to be included in WREW as part of the baseline configuration.
- b) **Cheddar 2:** The proposed new reservoir (Cheddar 2) initially included a new pipeline to Southern Water's Testwood WTW to allow this resource to benefit Hampshire WRZs. Following feedback from WCWR, Cheddar 2 has been updated in WREW to only be used intra-regionally (within WCWR – Wessex WRZ – Warminster and Salisbury demand centre in WREW), with the transfer to South Hampshire turned off in WREW. There is the potential to share with Southern Water in the future and this can be updated in WREW accordingly.
- c) **Poole Effluent Recycling and Transfer:** The proposed effluent re-use in Poole provides 30 Ml/d which can be utilised in either WCWR (Poole and Bournemouth) or Southern Water (South Hampshire). Based on feedback from WCWR, there is no change required in WREW from Phase 1, the option to share with Southern Water will be kept active in WREW but it is expected the water will be needed in WCWR and assumed the model will opt to transfer the water to WCWR.

⁹ Solution diagrams can be found on the RAPID website here: <https://www.ofwat.gov.uk/regulated-companies/rapid/the-rapid-gated-process/gate-one-submissions-and-final-decisions/> and here: <https://www.ofwat.gov.uk/regulated-companies/rapid/the-rapid-gated-process/accelerated-gate-two-submissions-and-new-solution-proposals/>

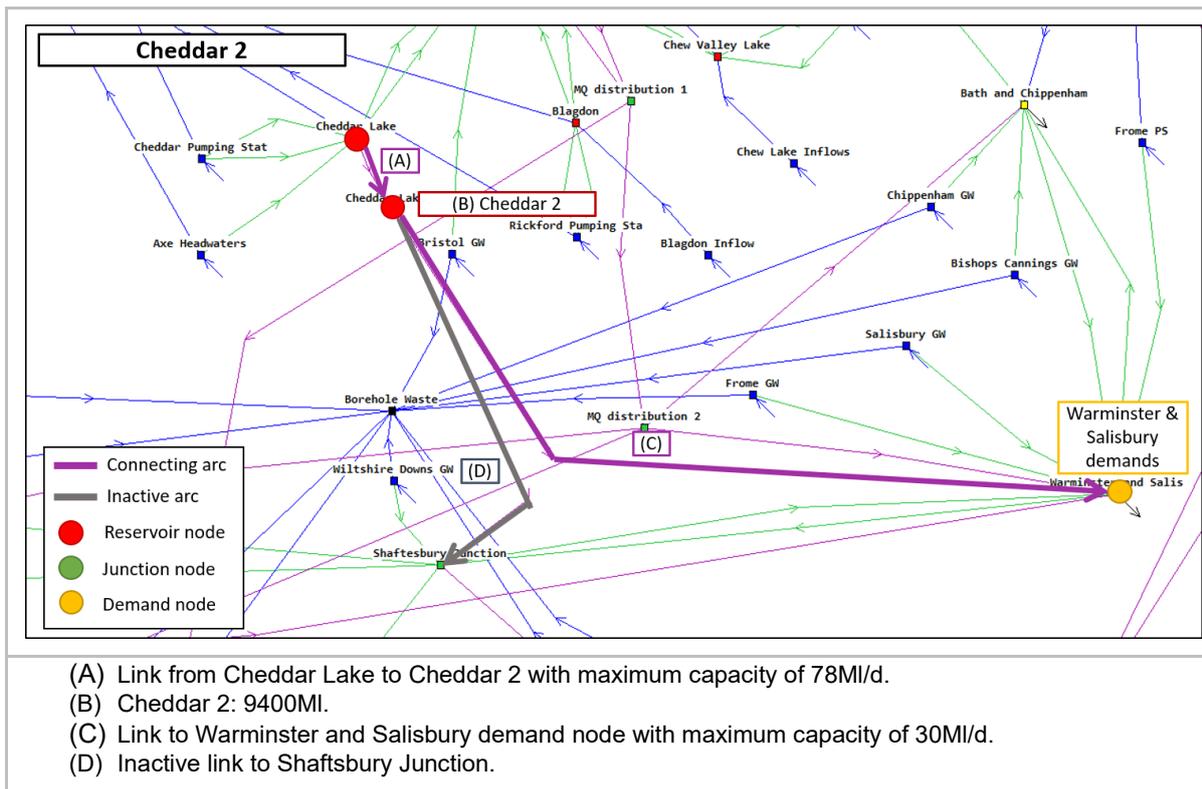


Figure 6. The representation of Cheddar 2 scheme in WREW

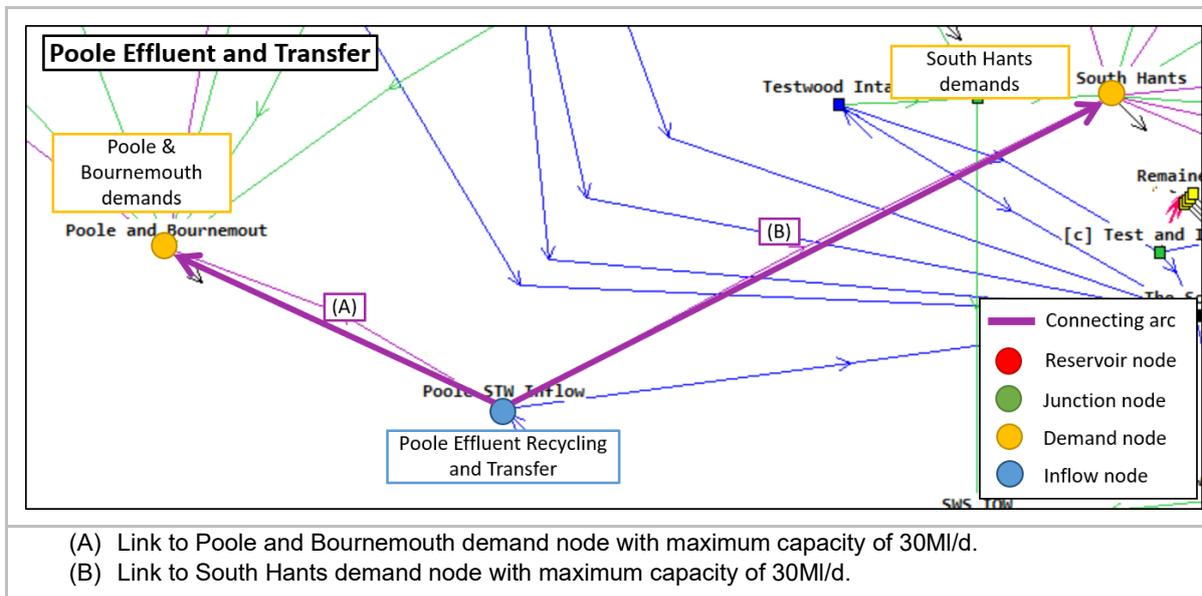


Figure 7. The representation of Poole Effluent and Transfer scheme in WREW

2.11.1.2 Mendips Quarry

Mendips Quarry is a new WCWR strategic supply option and was put forward for the Gate 1 Submission to RAPID in December 2021. The option includes the repurposing of a quarry in the Mendips into a reservoir (52800 MI with a usable net storage of 28700 MI) which will be filled by abstraction from the Bristol Avon (downstream of Bath) during high winter flows under either an existing or enhanced licence. The abstraction to fill Mendips Quarry was implemented in WREW using the potential enhanced licence option in order to observe the maximum possible benefit in the model (this comprises a maximum abstraction of 150 MI/d abstraction under high winter river flows subject to various HOFs which will provide ~90 MI/d yield from Mendips Quarry).

The Mendips Quarry Solution has 5 potential recipient locations including 3 intra-regional transfers and 2 inter-regional transfers:

1. Intra-regional: Mendips Quarry to Wessex Water Service Reservoir near Warminster
2. Intra-regional: Mendips Quarry to Chewton Mendip to join the Barrow Reservoirs and back feed into Bristol Water
3. Intra-regional: Mendips Quarry to River Stour (augment flow in Stour and re-abstract downstream at Bournemouth and back fed into Wessex WRZ if required)
4. Inter-regional: Mendips Quarry to Wessex Water Service Reservoir and onto Testwood (Southern Water)
5. Inter-regional: Mendips Quarry to Kennet and Avon Canal (for re-abstractation by Thames Water, South East Water and Affinity Water)

All options are not mutually exclusive and it is envisaged that all could run together.

The NSSM team engaged with WCWR to understand and simplify the representation of Mendips Quarry options for implementation in WREW. It was decided to include only the intra-regional transfers 1 to 3. These were simplified for representation in WREW as demonstrated in **Figure 8** whereby:

1. Mendips Quarry to Wessex Water Service Reservoir near Warminster
 - a. Service reservoir was not represented, water delivered (90 MI/d) direct to demand (Wessex Water network; Arcs C, E, F, G and H).
2. Mendips Quarry to Chewton Mendip to back feed into Bristol Water
 - a. Direct transfer to Bristol WRZ in WREW from Mendips Quarry (16 MI/d minus 5% losses from treatment ~15.2 MI/d). Simplified as WTW and Barrow reservoirs are not represented in WREW (Arc I)).
3. Mendips Quarry to River Stour
 - a. Direct transfer from Mendips Quarry to Poole & Bournemouth demand centre in WREW (30 MI/d). As this is put forward as a put and take option, NSSM team suggested avoiding the river network and send water direct to demand centres, in line with other strategic supply option implementation in WREW (Arc D).

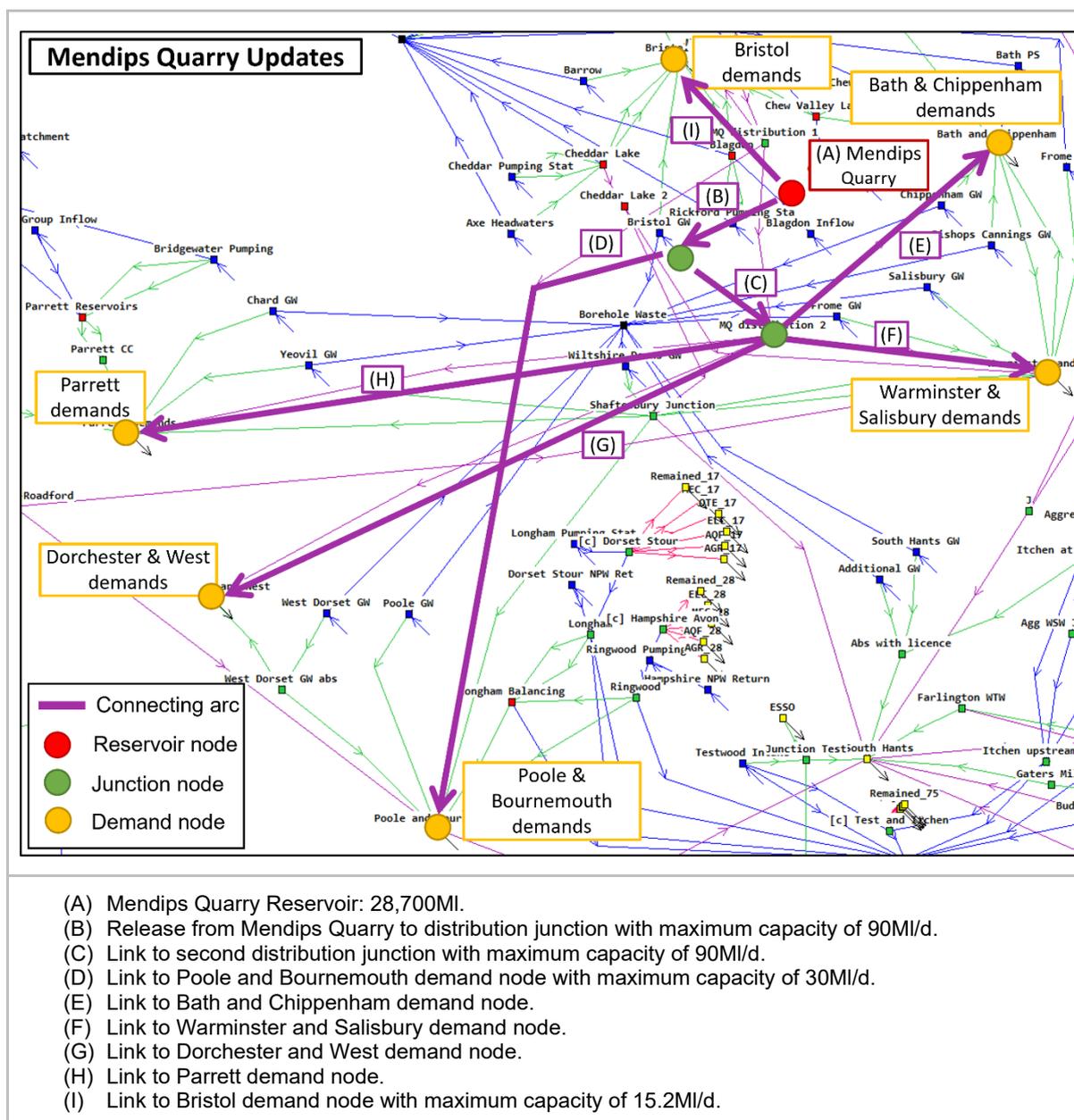


Figure 8. The representation of Mendips Quarry and links to nodes in WREW

2.11.2 Water Resources West and North (WRW & WRN)

2.11.2.1 Upper Derwent Valley Reservoir Expansion

Upper Derwent Valley Reservoir (UDVR) is an existing reservoir which has recently been proposed for expansion as part of a strategic supply option outlined in the Gate 1 Submission (December 2021). A schematic is shown in **Figure 9**. The increased storage proposed will provide additional raw water to support existing (Bamford and Rivelin WTWs) and/or new water treatment works operated by Severn Trent Water and Yorkshire Water through the bulk export agreement.

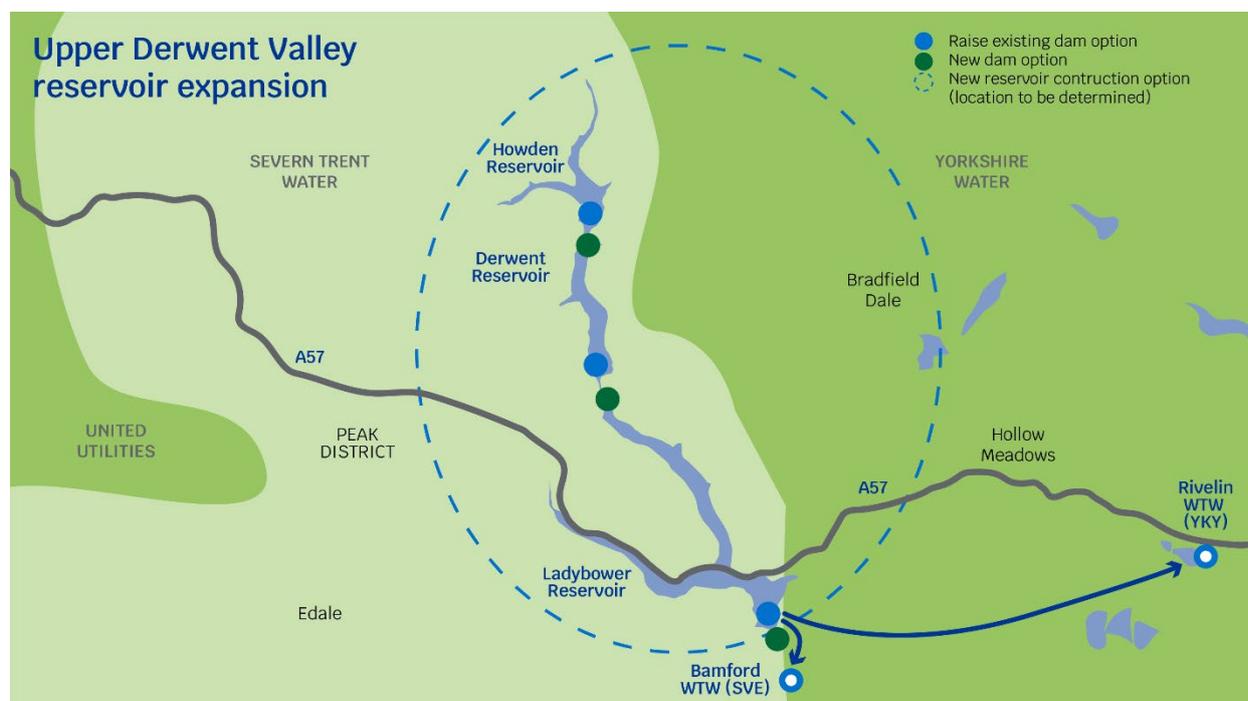


Figure 9. Upper Derwent Valley Reservoir Expansion solution schematic

Severn Trent Water currently has a WRMP24 feasible solution to stop their bulk export to Yorkshire Water by 2035, in order to reduce the supply-demand deficit in Severn Trent Strategic Grid WRZ. The expansion of UDVR would allow Severn Trent Water to maintain the export for the remainder of the existing agreement (2084). It would also negate the need for Yorkshire Water to develop its own in-region scheme to backfill the lost deployable output from Severn Trent Water.

The NSSM team led discussions with both Severn Trent Water and Yorkshire Water modelling specialists to understand and proceed with both updating the baseline representation of UDVR as well as the proposed expansion in WREW. Based on this engagement, WREW was updated (see **Figure 10**) as follows.

Baseline configuration:

- Up to date reservoir volumes, control curves and trigger levels for demand savings (Level 3) for Yorkshire Water's South Group
- Up to date reservoir volumes for Yorkshire Water's South West and Central Group
- Representation of Severn Trent Water to Yorkshire Water transfer
 - Previous implementation of transfer from UDVR to Yorkshire Water had a cost of 200. This was changed to 0 to incentivise transfer when required in Yorkshire Water.
 - Previous implementation of transfer was based on only one resource state of UDVR (resource state 2) with a transfer of 50 MI/d. Transfer was updated to vary with Derwent Valley Reservoir resource states 1 to 5 (range from 68 to 35 MI/d) (Label D).

UDVR Expansion update:

- Increase volume by 10,000 MI when strategic supply options are switched on in WREW, see Label (A).

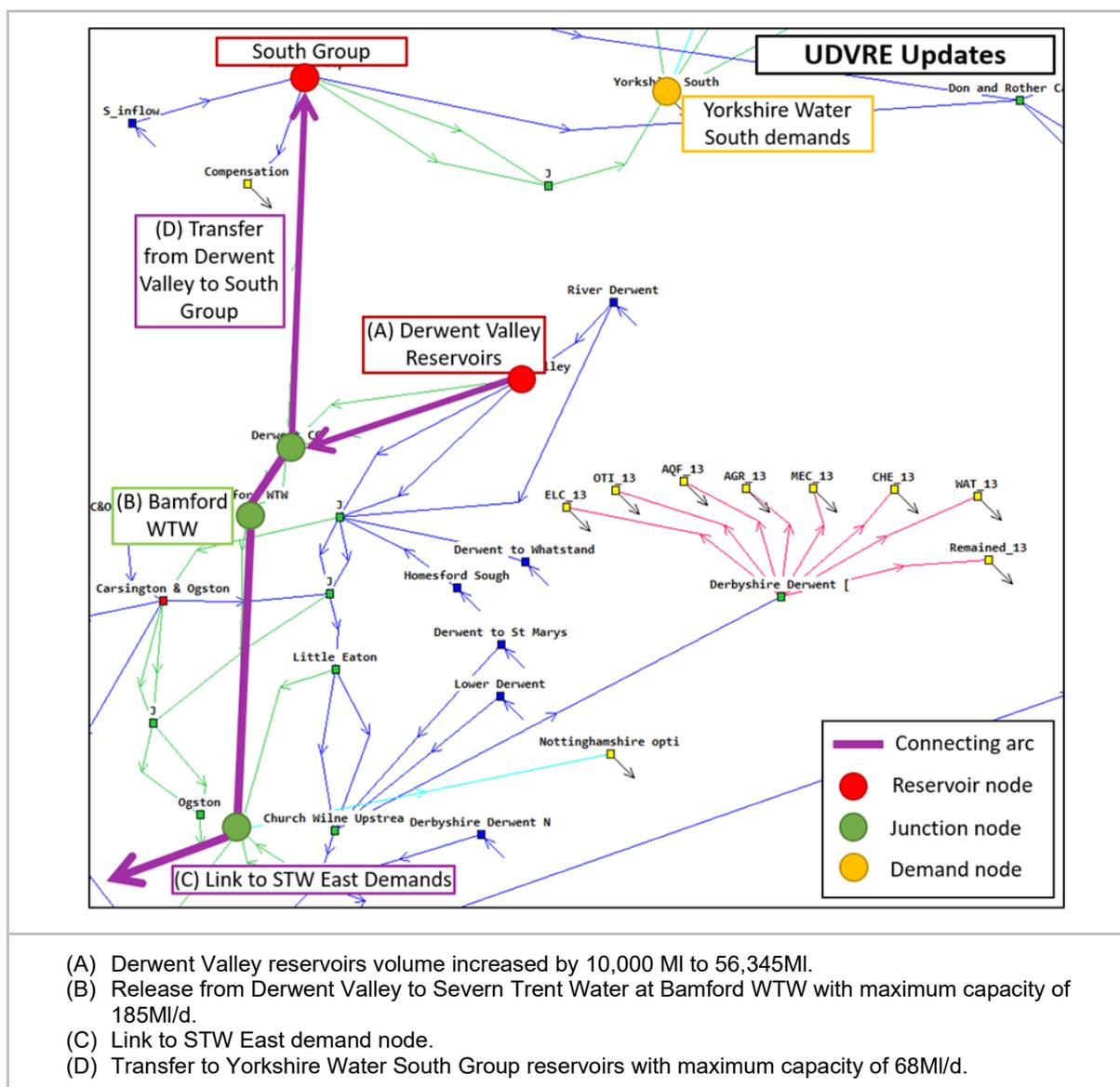


Figure 10. The representation of the Upper Derwent Valley Reservoirs Expansion (UDVRE) in WREW

2.11.2.2 North West Transfer (previously known as "UU Sources")

In Phase 1, the North West Transfer solution (previously known as "UU (United Utilities) sources") was represented as a simple aggregated bulk supply of 180 MI/d which would supply UU Strategic WRZ when STT was activated and the Lake Vyrnwy STT source was utilised. There has since been development of this solution, with an increased understanding of the capacity required to compensate for the transfer as well as the way in which the UU sources would come online and be distributed throughout the UU Strategic WRZ.

In the most recent regional reconciliation, the preferred solution included a 180 MI/d total Vyrnwy release with an additional 25 MI/d Shrewsbury export totalling to a 205 MI/d export (see arc A in **Figure 11**, Section 2.11.2.3). The additional 25 MI/d from Shrewsbury to STT was updated in WREW by taking 25 MI/d of licence at Shelton and releasing this to STT (see arc D in **Figure 11**) and subsequently diverting 25 MI/d from Dee Aqueduct to Shelton to backfill the water sent to STT (see arc B in **Figure 11**).

For this 205 MI/d total export/transfer, United Utilities would require 167 MI/d of options (UU sources) to compensate UU Strategic WRZ. It is also proposed that the 167 MI/d of options would be used outside of trading periods (not only when the Severn Thames Transfer is actively transferring).

At the time of running simulations, specific sources and capacities were still being finalised with no preferred set. Due to this and the national scale of the model, after engagement with the WRW Regional Group and their modelling specialists, it was decided to represent the sources in a simplified way where the 167 MI/d would be split across the Strategic WRZ. In WREW, UU's Strategic WRZ is split into nine demand centres, as shown in **Table 3**, in order to more accurately represent the large WRZ and its network. To represent UU sources, a bulk supply was added to each UU demand centre. The size of the bulk supply for each demand centre was set as a proportion of UU Strategic WRZ.

In order to represent when the UU sources would come online accurately (e.g. outside of trading periods), the use of the options was linked to the health of Strategic WRZ (when Haweswater Reservoir storage levels drop below the Haweswater resource state curve); not to the activation of Severn Thames Transfer (trading days) as it was in Phase 1.

The North West Transfer solution now includes the Vyrnwy Aqueduct solution that was originally proposed as a separate solution. The Vyrnwy Aqueduct solution proposes a new/altered pipeline that can transfer 170 MI/d to maintain service to the customers who would ordinarily be supplied from Vyrnwy Aqueduct but cannot be when STT is actively trading. This pipeline is represented in WREW as a 170 MI/d link between the Dee Aqueduct and the Vyrnwy Aqueduct when STT is actively transferring via Vyrnwy Aqueduct (see link C in **Figure 11**).

Table 3. North West Transfer (UU Sources) representation in WREW

UU Demand Centre	% of UU Strategic WRZ	Yield of UU Sources (MI/d) when online
South Cumbria	3.75	6.3
West Cumbria	3.3	5.5
Lancaster	2.1	3.5
Fylde	9.05	15.1
Liverpool	23.4	39.1
Wirral	5.28	8.8
Manchester	31.1	51.9
S. Pennines	12.65	21.1
Strategic 'Other'	9.3	15.5
Total	100	167

2.11.2.3 Severn Thames Transfer and enabling solutions

The Severn Thames Transfer (STT) is designed to convey raw water from the River Severn to the River Thames via an interconnector. There are multiple sources for the transfer, which form their own enabling solutions, that will be utilized to support the solution when needed.

The representation of the STT sources in WREW are shown in **Figure 11**. The representation of the Minworth Wastewater Treatment Works (WwTW) source (link G), Netheridge WwTW (link F), Mythe Water Treatment Works (link H) and abstraction from the River Severn at Deerhurst (link I) are unchanged from Phase 1.

The configuration of the Vyrnwy components of STT (links A, B, C, D and E) have been updated following consultation with United Utilities and Severn Trent Water. A 20% loss is deducted from the total volume of

water moved along Arc E, which reflects the estimated losses during the transfer of water from Vyrnwy. As established in the previous section, the Vyrnwy Aqueduct and North West Transfer solution is needed to avoid deterioration in United Utilities' Strategic Resource Zone as a result of the partial redeployment of Vyrnwy.

In Phase 1, the North West Transfer solution and Vyrnwy Aqueduct solutions were aggregated into one supply source in WREW that offset water supplied from Vyrnwy to the Severn-Thames Transfer. In Phase 2, the following changes were made:

- New arc between the Dee and Vyrnwy Aqueducts to represent water which will be back-pumped from the Dee to Vyrnwy Aqueduct when STT is active (link C);
- New arc from Dee Aqueduct to Severn at Shelton (link B) and STT Vyrnwy arc (link D) to represent Vyrnwy offtake to Shrewsbury demands; and
- Increased capacity of STT Vyrnwy arc (link E) from 180MI/d to 205MI/d.

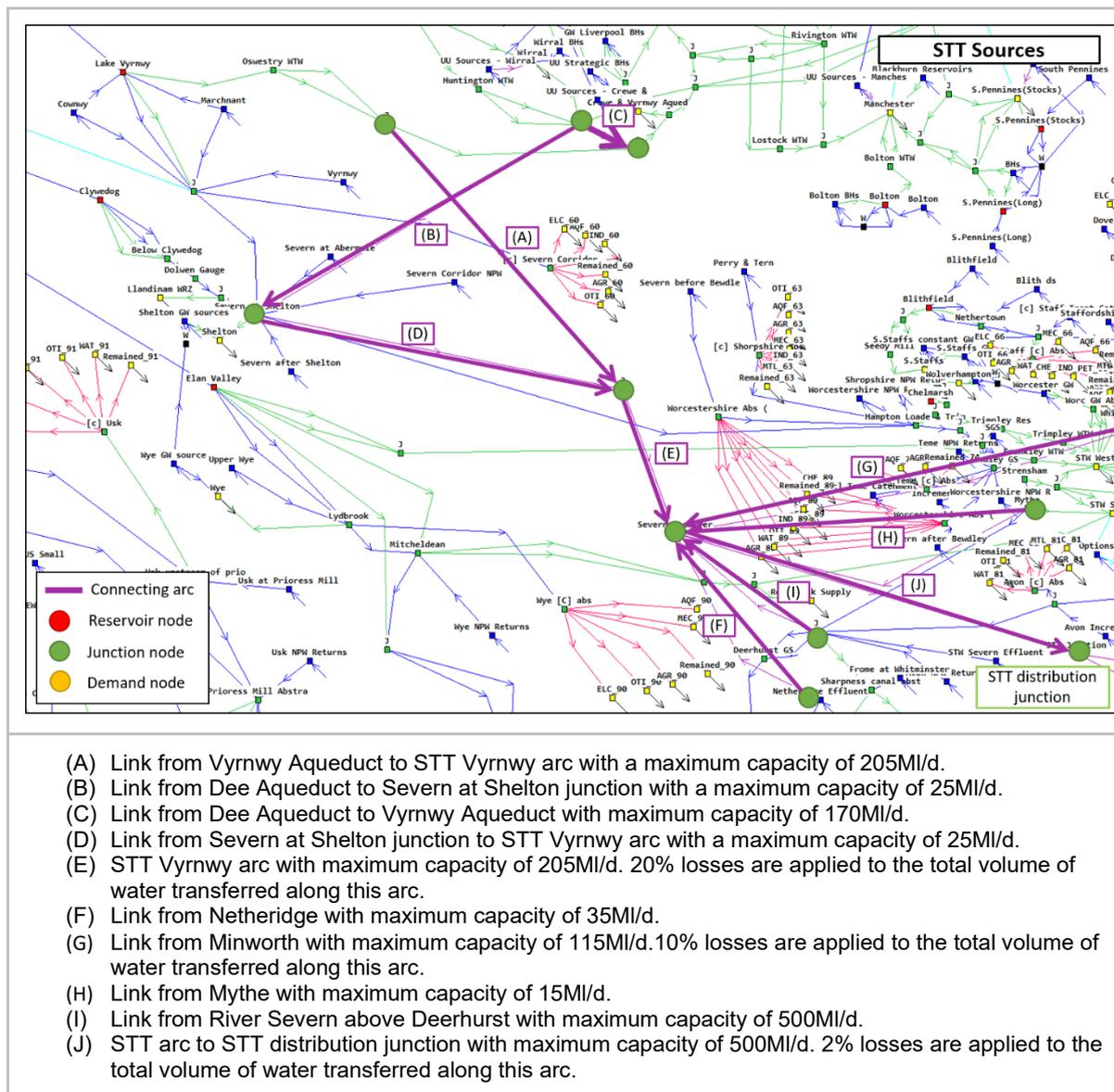


Figure 11. The representation of STT Sources in WREW

The distribution of water from STT remains largely unchanged from Phase 1. However, changes to the configuration of the Thames to Affinity Transfer (T2AT) and Thames to Southern Transfer (T2ST) resulted in some changes to distribution from both STT and SESRO sources, as shown in Figure 12. The changes made to the STT distribution include:

- New junction which combines flow from STT arc (link B) and SESRO arc to Affinity WRZs 1, 2 and 4;
- New arc from STT Southern arc (link C) to Thames Water's Kennet WRZ (link F); and
- New arc from STT Southern arc (link C) to South East Water WRZ 6 (link G).

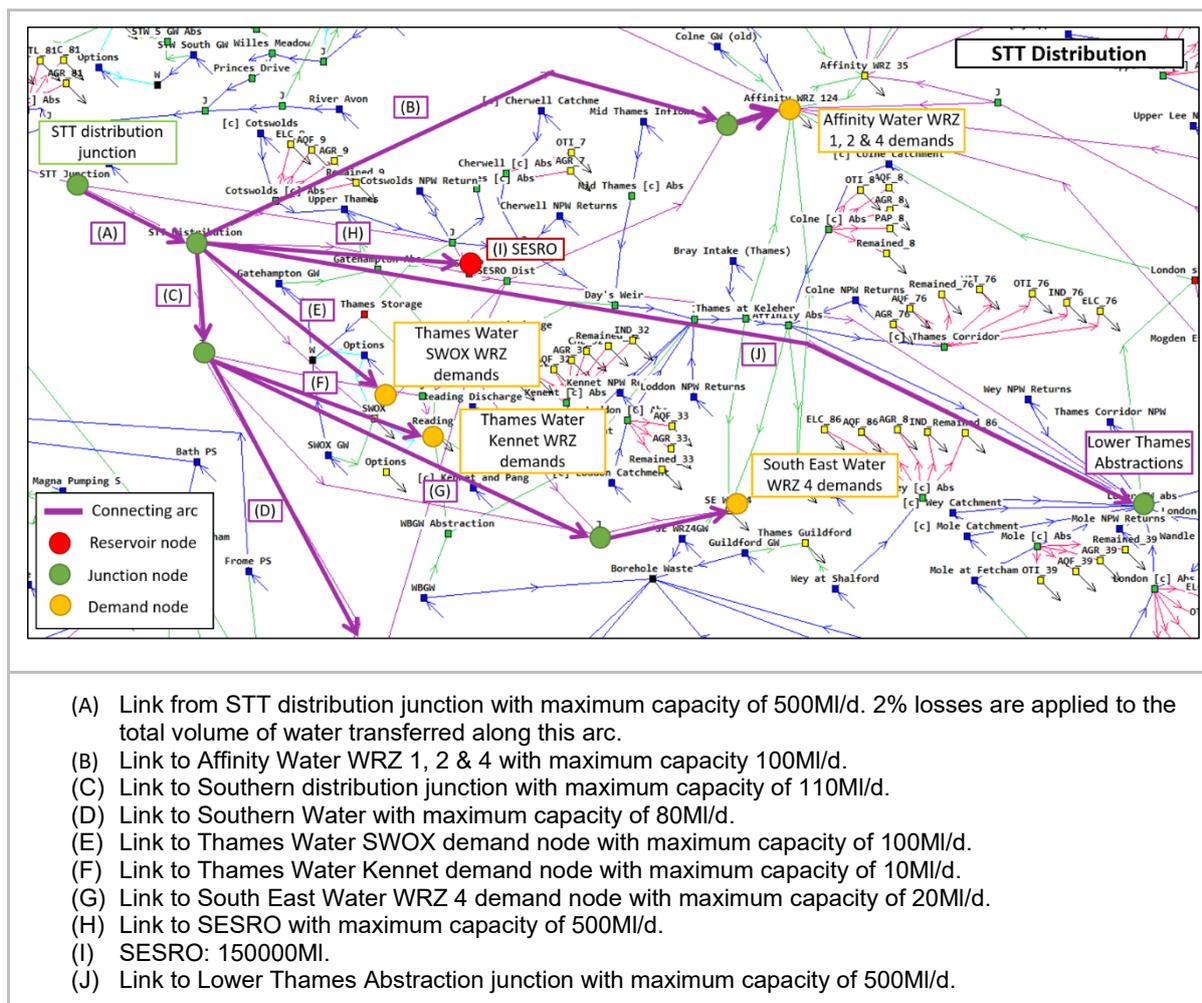


Figure 12. The representation of STT Distribution in WREW

2.11.3 Water Resources South East (WRSE)

2.11.3.1 South East Strategic Reservoir Option

SESRO is a proposed fully bunded reservoir 5 km south west of Abingdon, Oxfordshire. During periods of high flow in the river, water would be abstracted from the River Thames at Culham and transferred to the reservoir by pipeline for storage. During periods of low flow, water would be released back to the River Thames for re-abstraction further downstream.

Figure 13 shows the representation of the SESRO solution in WREW. The changes made to SESRO in Phase 2 arise following updates to T2AT and T2ST, described below:

- New junction which combines flow from the SESRO arc (link J) and STT arc to Affinity WRZs 1, 2 and 4;
- New arc from SESRO Southern arc (link F) to Thames Water's Kennet WRZ (link G); and
- New arc from SESRO Southern arc (link F) to South East Water WRZ 6 (link I).

Note: In reality there is a link from SESRO to Thames Water's Slough, Wycombe and Aylesbury (SWA) WRZ. The national model does not currently include SWA WRZ so this link cannot be represented.

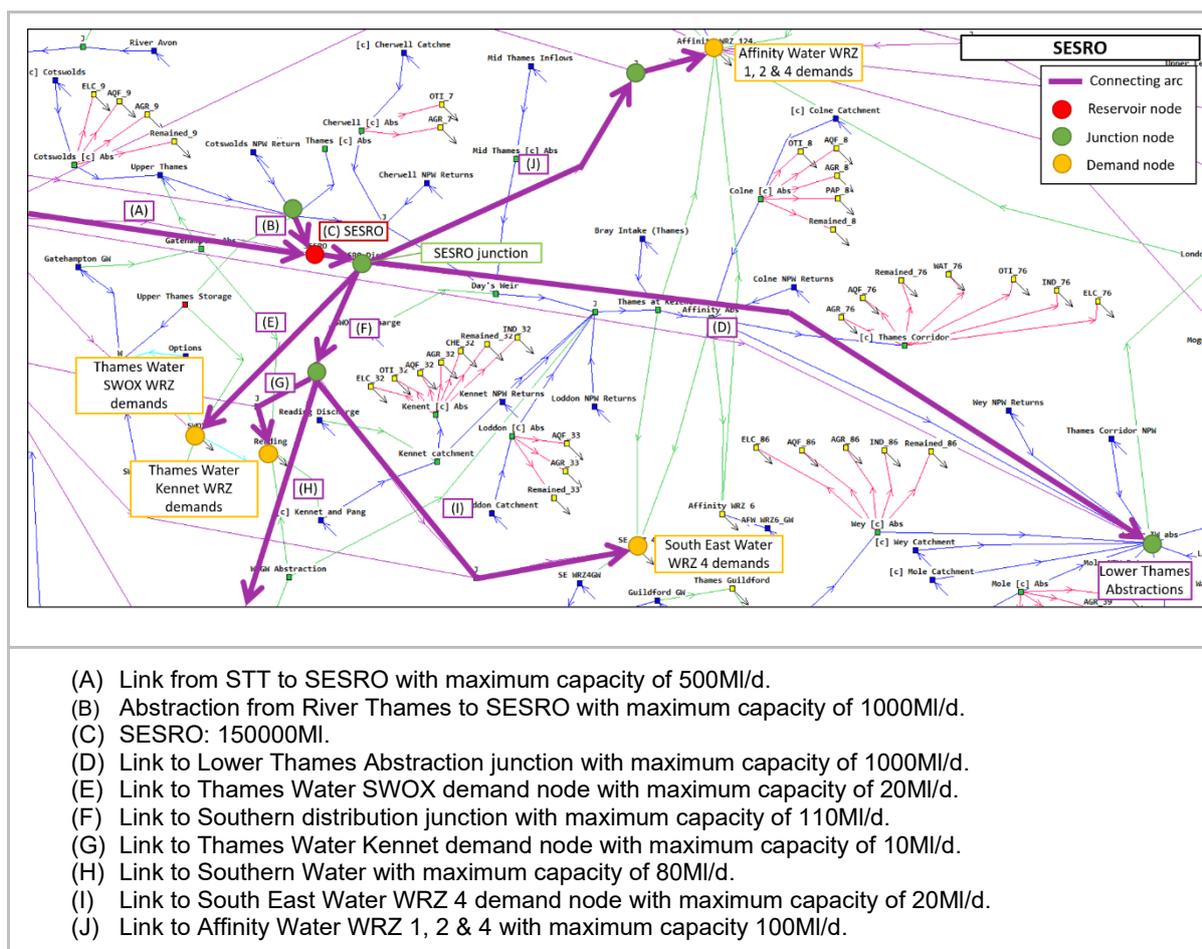


Figure 13. The representation of SESRO in WREW

2.11.3.2 London Effluent Reuse and GUC

The London Effluent Reuse (LER) solution consists of four effluent reuse solutions, as outlined in the Phase 1 report. The solutions supply water directly to London and the greater London area and are not dependent on any other solution. Water from Beckton effluent reuse can also supply Affinity WRZs 1, 2, 3, 4 and 5 via the Thames to Affinity Transfer. Following consultation with Affinity Water and Thames Water, the following changes were made to the configuration of the LER, **Figure 14**, and eastern route of T2AT in WREW:

- The eastern route of the T2AT is now only supplied by Beckton reuse (node H in **Figure 14**), which has a total yield of 300 MI/d and a max of 100 MI/d supplied to Affinity (link D).
- Connections between Beckton and Affinity demand nodes updated so the model can choose to send water to either Affinity 1, 2 and 4 (link C) or Affinity 3 and 5 (link B) demand nodes.

The Grand Union Canal (GUC) solution is an effluent reuse and strategic transfer solution to supply water from the Midlands to Hertfordshire and North West London. No changes were made to the representation of GUC in WREW in Phase 2.

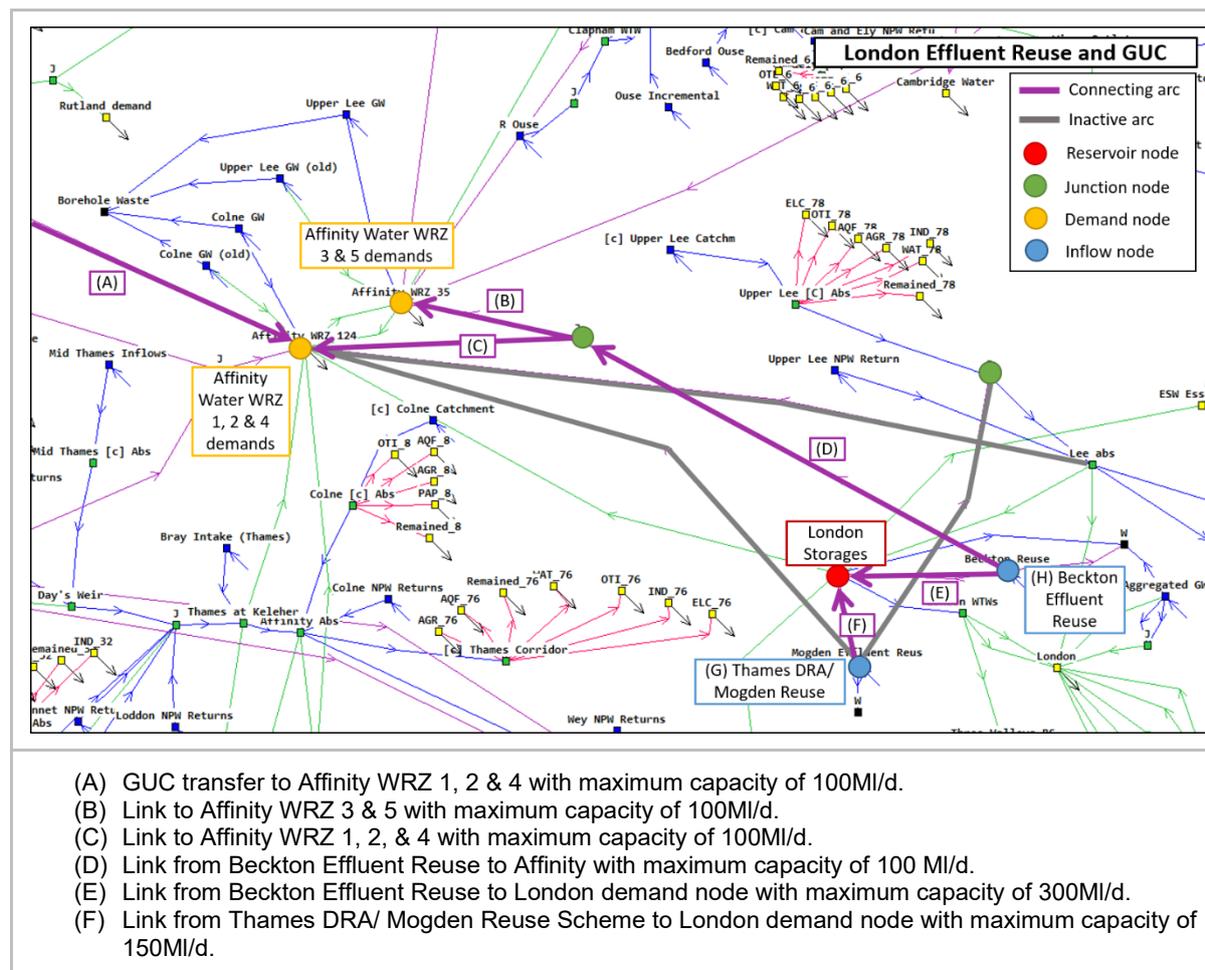


Figure 14. The representation of LER and GUC in WREW

2.11.3.3 Southern Water solutions

Southern Water Services' water recycling solution involves Budds Farm WwTW, a proposed water recycling plant and a transfer of treated wastewater to Otterbourne water supply works. The solution supplies Southern Water's South Hants and North Sussex WRZs, and Portsmouth Water.

Several changes were made to the representation of SWS solutions in WREW in Phase 2, **Figure 15**, described below:

- Water supplied from Havant Thicket (node A in **Figure 15**) to Portsmouth demand node redirected via Farlington WTW.
- Arc from Budds Farm (node B) to South Hants demand node switched off and water directed via Havant Thicket Reservoir and Farlington WTW.
- New arc from Havant Thicket to Hardham WTW (link B) to supply SWS North Sussex WRZ.
- Changed arc costing to ensure that T2ST prioritises supply to South Hants, whilst SWS reuse and Havant Thicket solutions prioritise North Sussex and Portsmouth.

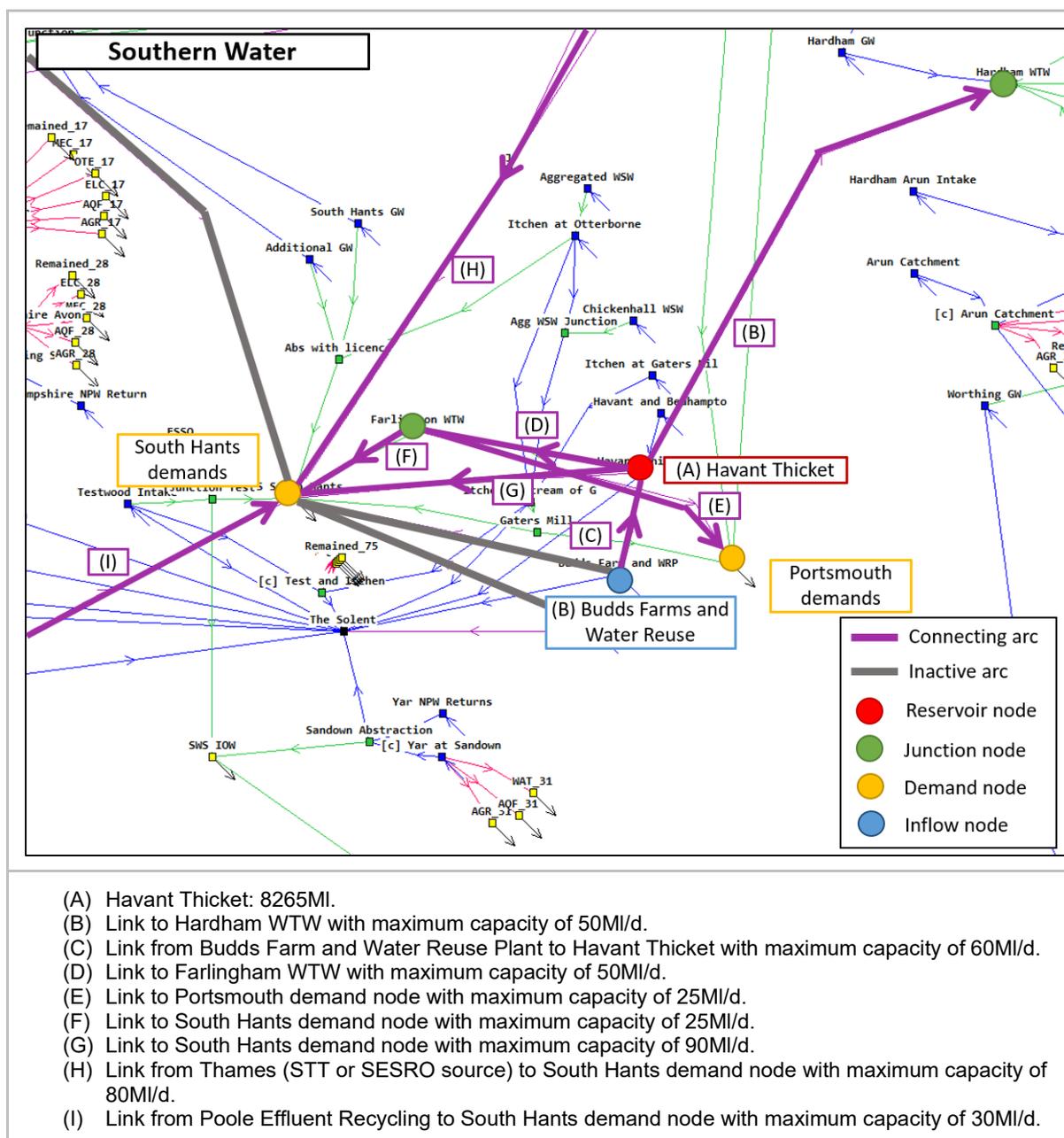


Figure 15. The representation of SWS Water Recycling and Havant Thicket in WREW

2.11.4 WRE – South Lincolnshire and Fenland Reservoirs network

The South Lincolnshire Reservoir (SLR) and Fenland Reservoir supply options are sources that were developed initially to support an Anglian-Affinity Transfer but, for the purposes of the regions second round of reconciliation, are now being considered solely to supply demand centres in Water Resources East. For this reason, the connecting arcs which linked sources within Anglian Water’s region to the Affinity Water network in Phase 1 have been switched off in WREW for Phase 2 simulations (the connections remain in place for future simulations if required).

Updates to the SLR and Fenland Reservoir supply network, **Figure 16**, have been made following feedback from Anglian Water, as follows:

- a) **South Lincolnshire Reservoir:** This option is linked to Ruthamford South (up to 100MI/d, 1st priority), Ruthamford North (up to 50MI/d, 2nd priority) and Cambs & West Suffolk¹⁰ (up to 100MI/d,

¹⁰ In WREW, the Cambs & West Suffolk demand node accounts for WRZs in Anglian Water that fall inside Cambridgeshire, Suffolk, Central and South Essex.

3rd priority) demand nodes. The reservoir can release up to 150MI per day. This capacity will increase to 250MI/d if the Anglian-Affinity Transfer is activated; and

- b) **Fenland Reservoir:** This option is linked to the Cambridge Water, Norfolk and Cambs & West Suffolk demand nodes, each with equal priority of supply. The Cambridge Water demand node is assigned a flat demand of 40MI/d, meaning it does not change day-to-day. The reservoir can release up to 40MI/d directly to the Cambridge Water node, and 30MI/d to be shared between the other two demand nodes.

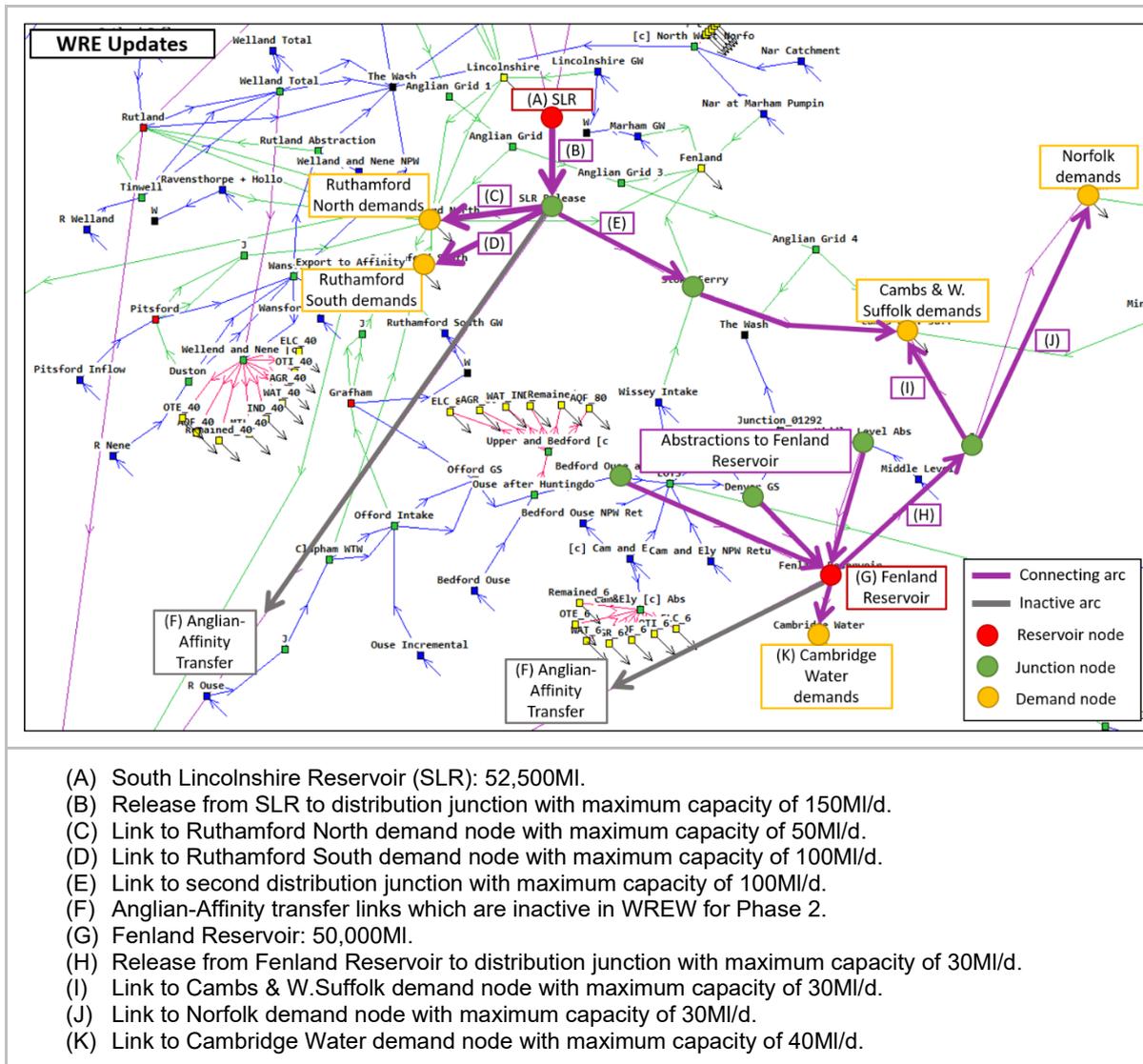


Figure 16. The representation of Water Resources East strategic supply options in WREW

3 Phase 2 outputs

The WREW model has been used to explore the impact of droughts on the water supply system under different model scenarios. The range of uncertainty associated with climate change and Public Water Supply demand (including population growth and policy on per capita consumption and leakage reduction), as well as the different possible supply system configurations, means that a very large number of model scenarios are possible.

Since the main focus of this study is to investigate the drought resilience benefits of the Solutions, it is practical to test Solutions in model scenarios where Public Water Supply demands are fixed at the end of the water resources planning horizon (2050) but uncertainty in future climate is considered. This approach yields a manageable number of scenarios under which Solutions can be assessed against nationally spatially coherent droughts.

The Phase 2 outputs demonstrate the potential national resilience benefit gained as a result of the Solutions working in combination with one other option. Other non-RAPID Solution options are in consideration by regional groups and water companies, which would also bring resilience benefit individually or in combination with the Solutions. These additional supply options from WRMP24 are not included in WREW, except for a new water re-use plant for the IOW WRZ, and the Anglian Water Strategic Pipeline Alliance. The purpose of this modelling project is to support RAPID's understanding of the Solutions within the RAPID gated programme, hence the focus on Solutions.

A detailed summary of the model scenarios and solutions tested are presented in the sections below.

3.1 Solutions tested

The Solutions tested have design configurations that incorporate different sub-options, many of which offer a range of capacities or yields for the solutions. In Phase 2, each Solution is tested at its maximum capacity or yield, unless dialogue with water companies suggested otherwise. The Solution design configurations are shown in **Table 4**. The table gives the solution name, type, sub-options associated with the solution, maximum sub- and total-option yield, the recipient of the solution, and the maximum yield received by the recipient from the solution. We note that the Thames to Affinity Transfer (T2AT*) and Thames to Southern Transfer (T2ST°) are not reported as individual solutions, but incorporated into Severn Thames Transfer (STT), South East Strategic Reservoir Option (SESRO) and London Effluent Reuse (LER) as these solutions act as a source for the inter-company transfers.

Unlike the modelling experiments conducted in NSSM Phase 1, all the solutions listed in **Table 4** are 'switched on' in the 9 model scenarios described in the next section.

3.2 Scenarios tested

A set of nine model scenarios were tested with WREW, as summarised in **Table 5**. The scenarios fall into three categories:

1. The **central scenario** is configured to align as closely as possible with the regional water resources management plans at the time of the 1st round of the regional planning reconciliation process (Jan 2022). It represents a reference scenario for comparison with the other scenarios considered in this report, as well as the modelling carried out in the regional water resource management plans. The formulation of the components of demand for public water supply and environmental destination are described in Sections 2.7 and 2.8 respectively.
2. The **sensitivity scenarios** have the same formulation as central scenario except for an increase in one of the demand variables, including:
 - Public Water Supply demands, where only 50% of the 2050 targets for the reduction of Per Capita Consumption and Leakage are realised (see Section 2.7.1). This scenario aims to investigate the risk of the ambition around PCC and Leakage reduction not being achieved;
 - Level of ambition around environmental destination, where all the water resources regions follow an enhanced level of environmental destination (see Section 2.8); and
 - Climate change, where river flows and groundwater levels input into WREW are forced by the far future ensemble of the w@h2 dataset (100 x 30-year, 2070-2099, forced with RCP8.5 emissions scenario), which provides a larger risk envelope for uncertainty associated with climate change.

- The **stress test scenarios** also have the same formulation as the central scenario except that each scenario involves the removal of an individual strategic solution, or a component of supply for a strategic solution.

Table 4. The Solutions tested in Phase 2

Solution Name	Type	Sub-option	Sub-option max yield (MI/d)	Max supply yield (MI/d)	Solution recipient	Recipient max yield (MI/d)
Severn Thames Transfer (STT) & Enabling Solutions	Water transfer (river/pipeline)	Unsupported component	500	500	Affinity Water*	100
		Vyrnwy component	205		Southern Water°	80
		Minworth component	115		South East Water°	20
		Mythe component	15		Thames Water	500
		Netheridge component	35			
South East Strategic Reservoir Option (SESRO)	Reservoir and water transfer (river)	-	-	321	Affinity Water*	100
		-	-		Southern Water°	80
		-	-		South East Water°	20
		-	-		Thames Water	321
London Effluent Reuse (LER)	Effluent Reuse	Beckton Reuse	200	350	Affinity Water*	100
		Teddington DRA, Mogden Effluent and Mogden South Sewer Scheme	150		Thames Water	350
Grand Union Canal (GUC)	Water transfer (canal)	-	-	100	Affinity Water	100
WRE Solutions	Reservoir and water transfer (pipeline)	South Lincolnshire Reservoir	150	220	Anglian Water	180
		Fenland Reservoir	70		Cambridge Water	40
Southern Water – Water Recycling	Reservoir, water recycling and transfer (pipeline)	Havant Thicket	-	165	Southern Water	140
					Portsmouth	25
West Country Sources (WCSS)	Reservoir, effluent reuse and water transfer (pipeline)	Cheddar 2 Reservoir	30	150	Wessex Water	150
		Poole effluent reuse	30		Bristol Water	15.2
		Mendips Quarry	90		Southern Water	30
Upper Derwent Valley Reservoir Expansion	Reservoir expansion	-	Reservoir capacity increase of 10,000MI	-	Severn Trent, Yorkshire Water	-
UU Sources	-	-	-	167	United Utilities	167
*Thames to Affinity Transfer (T2AT) Solution						
°Thames to Southern Transfer (T2ST) Solution						

The three categories of model scenarios have different aims. The **central** scenario is a reference scenario against which the outputs from other model scenarios can be compared. Its aim is to test the portfolio of strategic solutions selected in the regional reconciliation against nationally realistic droughts under climate change and with 'most likely' projections of future demands, as well as provide a means of comparing between the regional and national modelling. The aim of the **sensitivity** scenarios is to investigate whether the strategic solutions are sensitive to uncertainty in key components of water demand or availability. In contrast to the sensitivity scenarios, where additional pressure for water supply needs is spread evenly across England, the **stress test** scenarios explore the drought resilience implications at key areas of water stress when supply from the solutions is curtailed. The stress test scenarios are aimed at investigating the role individual solutions play in the broader set of schemes and whether any of the solutions act as a cornerstone for overall drought resilience benefits.

Where possible, efforts have been made to align the central scenario with the planning scenario of the emerging regional water resources management plans (Jan 2022). For example, the demand and leakage reduction options considered in emerging regional plans are included in the Public Water Supply demand component of the central scenario. However, it is important to note that, with the exception of the strategic solutions, a new water re-use plant for the IOW WRZ, the Anglian Water Strategic Pipeline Alliance (see Section 2.9.4) and a green recovery scheme on the River Tamar to support Roadford Reservoir, none of the other new supply options selected in the draft regional water resources management plans are represented in WREW. The Havant Thicket reservoir option from WRMP19 is represented in WREW since supply from the reservoir is increased by the Southern Water Service Havant Thicket Raw Water Transfer Solution. Some of the smaller supply options from regional plans would work to support the strategic solutions and enhance the overall benefit to the water resources regions. Unfortunately, the comparatively small size of these supply options makes it difficult to simplify them for representation in a way that is appropriate for a national scale model while also maintaining realistic behaviour. As a result, smaller scale supporting supply options from regional plans are omitted in WREW, however, it should be noted that the objective of the NSSM project's Phase 2 is to assess the drought resilience benefits of the preferred RAPID solution portfolio selected through the regional reconciliation process, not replicate the regional water resource management plans. Furthermore, the strategic solutions provide the principal component of new water supply for key areas of water stress in the South East, East and West Country water resources regions. It is therefore appropriate to use a national scale model to investigate the drought resilience benefits that strategic the solutions alone can provide to key areas of water stress.

Table 5. The model scenarios tested in WREW

Note: the red coloured cells show which variables have been adjusted for the sensitivity scenarios and the stress test scenarios, relative to the central scenario

No.	Scenario Name	Strategic Solutions Active	Public Water Supply Demand	Level of Environmental Destination	Climate (w@h2 ensemble)
Central Scenario					
1	Central Scenario	Regional Reconciliation	Regional Plan – FP @2050	Regional Plan	Near Future
Sensitivity Scenarios					
2	High ambition environmental destination	Regional Reconciliation	Regional Plan – FP @2050	Enhanced	Near Future
3	High Public Water Supply demand	Regional Reconciliation	Regional Plan – FP @2050 with 50% reduction in leakage reduction & PCC targets	Regional Plan	Near Future
4	Far Future Climate Change	Regional Reconciliation	Regional Plan – FP @2050	Regional Plan	Far Future
Stress Test Scenarios					
5	GUC removed	Regional Reconciliation - GUC	Regional Plan – FP @2050	Regional Plan	Near Future
6	SESRO removed	Regional Reconciliation - SESRO	Regional Plan – FP @2050	Regional Plan	Near Future
7	STT Supported Removed	Regional Reconciliation – support for STT	Regional Plan – FP @2050	Regional Plan	Near Future
8	STT Unsupported Removed	Regional Reconciliation – unsupported component of STT	Regional Plan – FP @2050	Regional Plan	Near Future
9	SLR Removed	Regional Reconciliation - SLR	Regional Plan – FP @2050	Regional Plan	Near Future

3.2.1 Strategic Solutions

One of the common themes across all the scenarios is the set of strategic solutions active in WREW, which follows the configuration considered in emerging regional water resource management plans (Jan 2022) and documented in the regional reconciliation process report¹¹.

It should be noted that the Thames-to-Affinity Transfer and Thames-to-Southern Transfer are also included in the set of solutions active in WREW, and were added following discussion with the strategic solution teams at Thames Water, Affinity Water and Southern Water.

The solution configuration reflects the regional reconciliation selection, as described in Section 2.9 and summarised in **Table 4**. The configurations were already represented as solution options in WREW from phase 1, except for two new solutions; the Mendips Quarry scheme and the Upper Derwent Valley Reservoir Expansion scheme, as described in Sections 2.11.1 and 2.11.2 respectively.

Each strategic solution in WREW is configured at the maximum yield or capacity stated in the regional reconciliation, which acts as an upper limit on supply in the model, rather than a constant level of supply. The WREW model's Network Flow Program optimises water assignments from the solutions up to this regionally reconciled maximum capacity. Solution behaviour is configured in WREW such that solutions are triggered when key stages in resource position of the surrounding supply system are reached, or so that they have the lowest priority compared with other sources of supply. While demand-led utilisation of solutions is simplistic, it is appropriate for a national scale model, especially given the uncertainty scheme operation and utilisation at this stage in the design process.

3.2.2 River flow and demand inputs

All the scenarios, except for the far future climate change sensitivity scenario, involve river flows and groundwater level inputs into WREW that are forced by the near future climate ensemble runs (100 x 30-year, 2020-2049) from the MaRIUS w@h2 dataset, while at the same time water demands for public water supply and the environment are held static at 2050 levels. The timing of the climatology and Public Water Supply demands used in WREW aligns with the 25-year planning horizon considered by the regional and water resources management plans.

The scenarios are configured in this way to isolate and explore the drought resilience behaviour of the water supply network during spatially coherent droughts and an uncertain future of climate change.

3.3 Key performance metrics

For the central scenario, drought resilience benefits associated with strategic solutions are reported by comparing results for a configuration of WREW without any strategic solutions implemented with results from the same scenario where the strategic solutions are operational.

Changes in drought resilience benefit under the sensitivity test scenarios are reported by comparing the results for the central scenario and the sensitivity scenario, both configured with strategic solutions in place.

The stress test scenarios are reported by isolating the difference in results between the central scenario and the stress test scenarios when configured with strategic solutions operational.

For the purpose of this report, three metrics have been used to describe the comparative drought resilience benefits associated with the strategic solutions:

- the probability of a supply shortfall occurring in any year;
- the probability of a level 3&4 water use restriction occurring in any year; and
- the distribution of the size of supply shortfalls.

Each metric is described in more detail below.

3.3.1 Supply Shortfalls – frequency and size

A supply shortfall occurs in the model when there is insufficient water available to meet demand. A supply shortfall would be considered as an extreme event: in real world terms it would be the equivalent of conditions where emergency methods of supply, such as standpipes or water tankering, would be

¹¹ The regional reconciliation process report can be found here:
<https://wrse.uk.engagementhq.com/13777/widgets/39717/documents/22580>

required. As a point of reference, a supply shortfall event is more severe than the different levels of operational water use restrictions that are more commonly used as a metric for water supply failure.

Supply shortfalls have been chosen as a metric for reporting results from WREW because they are one of the decision variables that the model's algorithm uses to optimise water assignments in the system. The Network Flow Program is solved to meet demand while also minimising cost (finding the lowest flow volumes in arcs with the lowest penalties (cost) for conveying a unit of water) and since a supply shortfall incurs the highest cost, the model will attempt to avoid this situation occurring. This behaviour means that despite a supply shortfall representing more of a 'model domain' metric it is a reliable way of measuring system performance. Additionally, supply shortfalls can be measured at any of the demand centres in the model, whereas level of water use restriction are only available at a few locations.

The probability of supply shortfall is calculated simply as the number of years that experience one or more days of supply shortfall, divided by the total number of years simulated in the ensemble. A total of 2,340 years in the w@h2 near future period (2020-2049) and 1,980 years in the far future period (2070-2099) are available for the Phase 2 simulations, following the exercise to filter out drought events with a return period >1:500. In this case, if a simulation using the near future ensemble reveals 100 years with a supply shortfall for a given WRZ, the probability of shortfall in that WRZ would be 100 divided by 2,340, or 0.043.

Reporting the change in probability of a supply shortfall occurring for any year simulated in WREW when the strategic solutions are implemented gives a good indication of how likely it is that a deficit will occur at any given demand centre in the model. However, the size of the supply shortfall is equally important as it helps to provide context on the scale of the risk and the challenge that key areas of water stress face. Both metrics are reported to compare results for a configuration of WREW without any strategic solutions implemented with results for the same scenario where strategic solutions are operational. The size of supply shortfall at a given demand centre is assessed using the distribution of the maximum shortfall for each year simulated in WREW. This combined approach has been taken to provide a more complete view on the drought resilience benefits associated with the strategic solutions.

3.3.2 Water use restrictions

Some of the demand centres in WREW that are supplied by strategic solutions are also connected to large reservoirs which include storage level triggers to impose different levels of water use restrictions. Water use restrictions in groundwater dominated regions are generally triggered by falling groundwater levels. Groundwater level triggers and associated demand savings are only imposed in Affinity Water's and Southern Water's WRZs in WREW. Groundwater is currently represented in WREW using a basic empirical model, making it difficult to rely on groundwater levels to impose restrictions. As Affinity Water groundwater levels have been updated in WREW using a lumped parameter model, there can be higher confidence in imposing restrictions and demand savings in WREW as a result. Southern Water's restrictions and demand savings are triggered on a combination of both groundwater and surface water (river) levels.

Whilst water use restrictions are used to apply demand savings and augment the behaviour of reservoir releases in WREW, they do not affect how the model's algorithm optimises water assignments in the same way that supply shortfalls do. As a result, at the locations in WREW where water use restrictions are available, they are reported in combination with supply shortfalls to provide a more complete picture on the drought resilience performance of the strategic solutions.

For the purpose of this report, the occurrence of level 3 and 4 water use restrictions are measured. The actions associated with level 3 restrictions include drought orders and the resulting non-essential use bans. More extreme measures are implemented at level 4, which corresponds with emergency drought orders, when rota cuts and stand pipes might be introduced. Level 4 water use restrictions are commonly used by water companies as a metric for failure of the supply system and the frequency of these restrictions is used to define the level of service for customers relative to Defra's 1:500 drought resilience target.

3.3.3 Metric limitations

A limitation of the supply shortfall metric is encountered when a demand centre in WREW does not experience any supply shortfalls in the results for the configuration of the model without strategic solutions implemented. In these situations, water use restrictions have been used, where they are available in WREW, as an alternative metric for assessing drought resilience benefit associated with the strategic solutions.

3.3.4 Assumptions and limitations of the modelling approach

WREW, which covers England and Wales, represents water supply infrastructure at a necessarily lower resolution than the regional and water company models used to inform water resources planning decisions more locally. It simplifies the system network in many ways to make it computationally efficient and manageable at a national scale with the data available.

As a result, there are some limitations to the national modelling approach which include:

- Due to the necessary lower resolution and simplistic nature of a national scale, WREW is modelled at a WRZ-scale with some WRZs also aggregated due to their high-level connectivity in reality. In other places in WREW, large WRZs may be broken down into multiple demand centres e.g. UU and SvT Strategic WRZs. Water company models are modelled at a much higher resolution and therefore can explore the intermediate detail between supply sources and demand centres, enabling identification of sub-zonal areas of water stress. In WREW, when a shortfall or water use restriction is observed in a WRZ, it could be that some areas of that WRZ do have enough supply to meet demand but the national model isn't sensitive to it;
- At a national scale, multiple reservoirs that supply single treatment works are occasionally aggregated to increase computational efficiency;
- Small sources may be omitted or aggregated; the lowest non-zero flow is 1 Ml/d
- Representation of water redistribution in unmodeled areas by allowing multiple sources/transfers to deliver water to the same demand node;
- Instantaneous flow travel time along arcs is assumed (except for aqueducts with known travel times);
- Where information on evaporation for reservoirs has not been provided, it is assumed that there is zero evaporation, this could be updated in the future;
- Where information on reservoir dead storage is not available, reservoir dead storage volumes are excluded for simplicity and modelled reservoir capacities represent the live storage only;
- WREW assumes that water quality is always acceptable and does not take into consideration any losses due to water quality issues;
- For simplicity, WREW does not take into consideration outage (caused by operational limitations or environmental constraints including water quality) and outputs are therefore likely to over-estimate the stability of water availability. It is assumed in the model that distribution networks can get water to wherever it is needed, whenever it is available at the supply works. Outage could be implemented in WREW in the future;
- Whilst WREW does take into consideration distribution losses (within the demand component), supply system process losses or inefficiencies (e.g. at WTWs or pumping stations) are only parameterised in WREW where information was available;
- WREW does not take into consideration headroom as it is defined in the water resources planning guideline, therefore uncertainty related to demand and supply is not accounted for. Uncertainty is accounted for in WREW with the range of possible future climatic drought conditions that the national system is tested against;
- Financial costings of strategic options are not directly included in the national model but where possible are accounted for by applying 'pseudo' cost to the sources of supply which are available to the algorithm that chooses how the water should be distributed within the network at each time-step;
- The national model is based on balancing supply and demand based on dry year annual averages and does not explore the impacts of critical periods specifically. However, a seasonal scaling profile is applied to DYAA demand to account for variation across the year;
- For simplicity and ease of interpretation, the national scenarios presented in Phase 2 are run at a 2050 time slice, rather than an annually changing, supply and demand. Similarly, strategic solutions are all considered to be 'switched on' by 2050, when in reality the solutions would ramp up and come online at various times up until 2050. Dynamic (time-variant) supply, demand and strategic options could be explored in scenarios in the future;
- Non-public water supply is represented well in WREW. WREW uses data from the Environment Agency's national abstraction database (NALD), due to the very large number of licences, non-public water abstraction processing is performed at a catchment scale to preserve computing resources. The NALD database is not exhaustive and some abstractors may not be represented, in general agriculture, chemicals, metals, industrial/commercial and energy (electricity) demands are represented;

- Demand for non-public water supply has been assumed to be equal to the average abstraction over 1999 and 2015; this is likely to have increased since then as well as increase in the future;
- Any new non-public water abstractors (since 2015) will not be represented in WREW.
- Data was taken from the NALD on the non-consumptive rates for each licence type; any non-consumed water was returned into the model downstream of the abstraction point.
- Abstractions for canals are only represented in a limited way and could be improved in the future with engagement with CRT;
- Updates to non-public water demands could be implemented in WREW in the future, when estimates of non-public water supply needs are available; and
- The impacts of ordinary and emergency drought orders are represented simplistically in WREW.. The demand savings associated with them are implemented in WREW, whereas the changes to abstraction licences (e.g. an increase in abstraction) under them are not.

3.4 Results and findings

3.4.1 Scale of the challenge

In order to better understand the results on drought resilience benefits of the strategic solutions presented in the subsequent sections, it is useful to first provide the context on the future challenges that key areas of the supply system face, and which the strategic solutions must attempt to meet.

The sections below on the central scenario and sensitivity scenarios demonstrate the size of the challenge, using results from a configuration of WREW without strategic solutions implemented.

3.4.1.1 Central Scenario

The spatial pattern of the probability of supply shortfalls occurring in the central scenario without solutions implemented is shown in **Figure 17**. The probability map of supply shortfalls for the central scenario should be considered in combination with the distribution of the size of maximum supply shortfalls at areas associated with the strategic solutions, as presented in **Figure 18**.

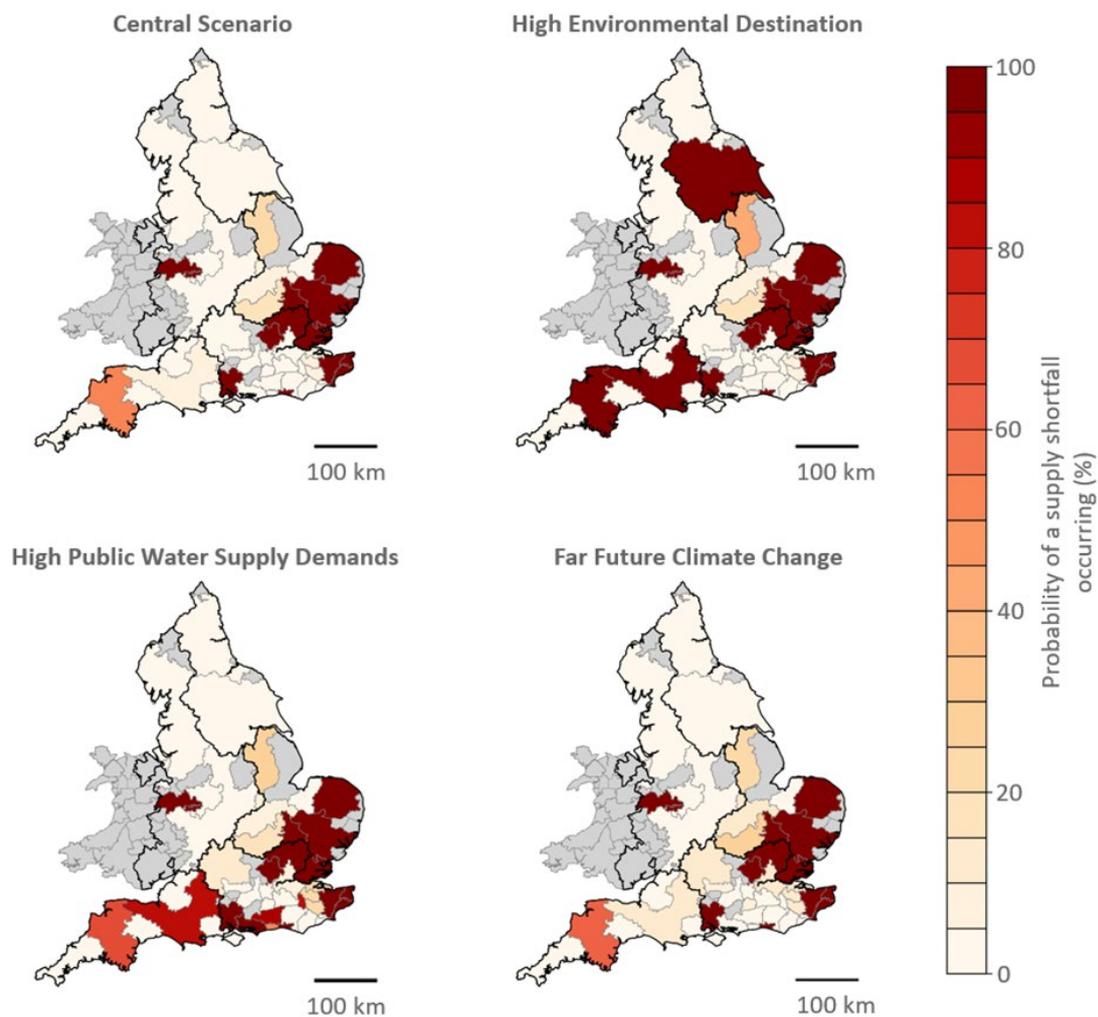


Figure 17. The spatial pattern of the probability of a supply shortfall occurring in any given year for the central scenario and the three sensitivity scenarios without any strategic solutions implemented

NB grey WRZs in England are not represented in WREW and those in Wales are omitted from the analysis.

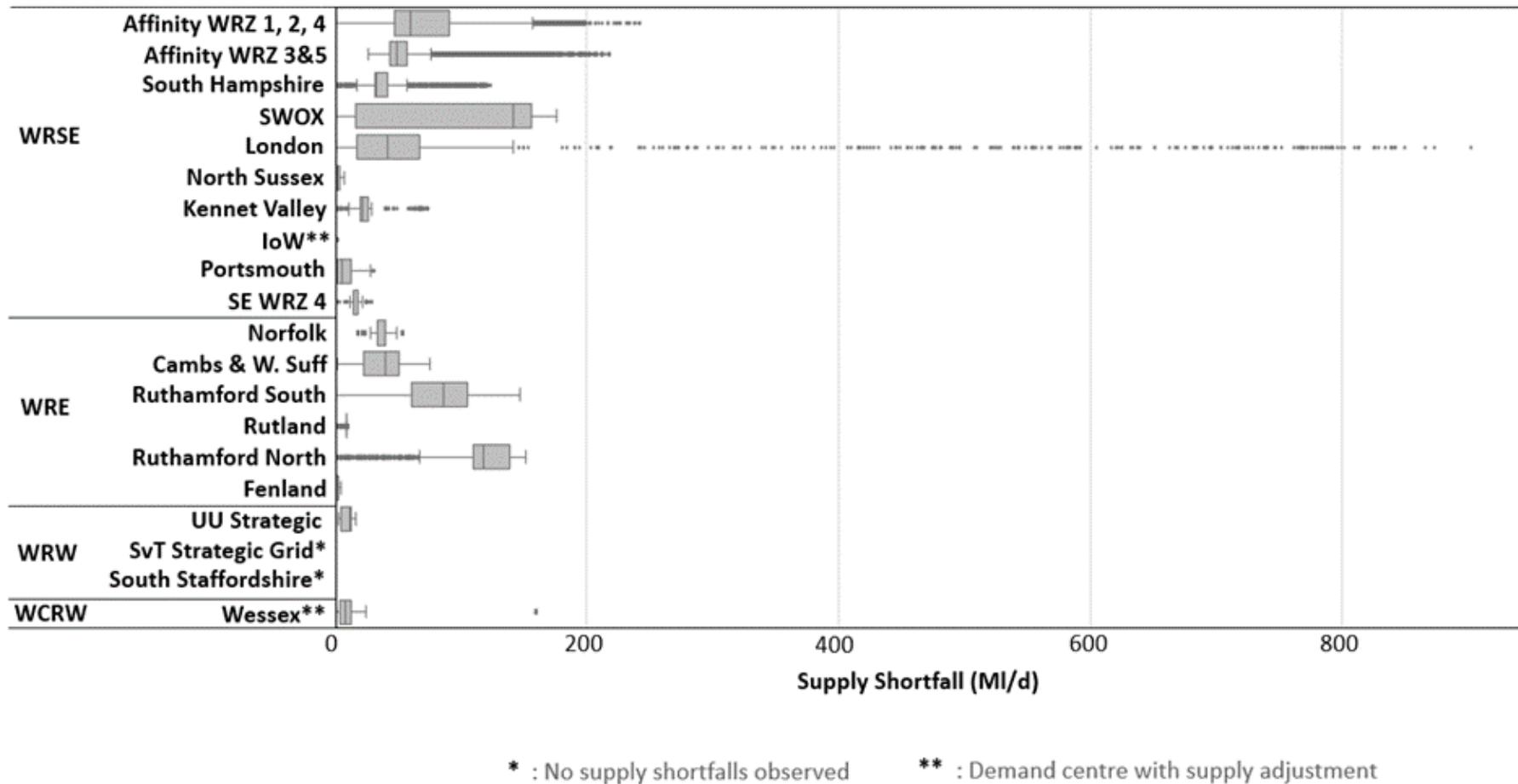


Figure 18. Distribution of the maximum daily supply shortfall observed in any given year with a shortfall under the central scenario configured without any strategic solutions implemented

The two figures demonstrate that the largest supply shortfalls occur in WRSE and WRE and that the probability of a supply shortfall occurring is also greatest in these regions. One of the areas of greatest water pressure in WRSE is the London WRZ, which several of the highest yield/capacity strategic solutions are designed to supply. As shown in **Figure 17**, the probability of a supply shortfall occurring for the London and SWOX WRZs is lower (~4%) in any given year compared with other areas of WRSE where a supply shortfall is observed every year, such as the South Hampshire demand centre (Hampshire Rural, Hampshire Winchester, Hampshire Southampton East and Hampshire Southampton West WRZs) or the Affinity WRZ 1,2,4 and Affinity WRZ 3&5 demand centres. However, the London WRZ shows a heavy-tailed distribution for the size of supply shortfalls, with shortfall events reaching up to 800 MI/d, approximately 600 MI/d greater than the events experienced by the Affinity WRZ 1,2,4, Affinity WRZ 3&5, and South Hampshire demand centres. The patterns observed for the London WRZ show that whilst the probability of a supply shortfall event occurring is lower than other demand centres in WRSE, the severity of these events is greater. This is caused by a combination of the very large demand in the London WRZ, and the hydrological nature of the supply. The London reservoirs have relatively little storage compared to demand and they are refilled by abstraction from the River Thames. Reservoir yield during a given drought event is therefore very sensitive to flow levels on the River Thames, which vary according to the severity of the event. It should be noted that although the ~4% probability of a supply shortfall event occurring for the London and SWOX WRZs is comparatively lower than other areas of WRSE, it is still greater than the 1:500 (0.2%) and 1:200 (0.5%) level of service thresholds.

Some of the demand centres shown in **Figure 18**, such as London WRZ, Affinity WRZ 1, 2, 4, Affinity WRZ 3&5, and South Hampshire, display a heavy-tailed distribution of the maximum daily size of supply shortfalls. Whereas, in contrast, a tail is not observed for the distributions of demand centres such as SWOX, Affinity WRZ 6, Cambs & W. Suffolk (WRZs: Bury Haverhill, Cheveley, Ely, Ixworth, Newmarket, Sudbury, Thetford, East Suffolk, South Essex and Central Essex), Ruthamford South (Ruthamford South, Central and West WRZs) and Ruthamford North. The implication of this observation only the demand centres with a heavy-tailed distribution in the maximum daily size of a supply shortfall have supply sources that are sensitive to particular spatial and temporal patterns of drought in the w@h2 dataset. Analysis of time series outputs from WREW during supply shortfall events for demand centres where a tail is absent, reveals that the maximum daily size of the shortfall is limited by consistent supply from groundwater or reservoir sources. The simple empirical approach used to estimate the maximum abstraction rates from a borehole in WREW (Section 2.6.1, results in a slightly reduced, but relatively consistent level of supply from groundwater sources over the course of a drought event. This behaviour means that groundwater supply is relatively resilient and therefore limits the size of supply shortfall that a demand centre can experience. The exception to this trend is the Affinity WRZ 1, 2, 4 and WRZ 3&5 demand centres that show a heavy tailed distribution, but also receive a significant proportion of supply from groundwater sources. Groundwater levels for these demand centres are estimated using a more robust lumped parameter modelling approach (Section 2.6.2), which captures greater variability in supply over a drought event.

Similarly, the Ruthamford South and North demand centres are supplied by Rutland and Grafham reservoirs. Release of water from these large reservoirs can be maintained at a low but consistent level during drought events when supply shortfalls occur. As a result, the size of maximum supply shortfall that the Ruthamford demand centres can experience is limited. In contrast, outlier events in the distribution of maximum size of supply shortfall are observed for other demand centres that rely on river abstractions, or where reservoir storage becomes depleted during a drought event.

3.4.1.2 Sensitivity Scenarios

The spatial pattern of the frequency of supply shortfalls under the three sensitivity scenarios, without solutions implemented, are shown in **Figure 17**.

The high environmental destination scenario displays an increase in the probability of a supply shortfall occurring, relative to the central scenario, for demand centres in the North and West Country water resources regions. This trend is to be expected since the two regions have a comparatively low starting point of environmental ambition (small, proposed changes to abstraction) in the central scenario and therefore the move to an enhanced level of environmental ambition in the high environmental ambition scenario represents a substantial decrease in supply. The configuration of the environmental destination scenarios for the central and high environmental destination scenarios is described in Section 2.6. A similar trend would be expected for Water Resources West, which also experiences a large decrease in supply associated with moving from the level of environmental destination in the central scenario to the enhanced level under the high environmental destination scenario. However, no change is observed between the central and high environmental destination probability maps for this region because the frequency of supply shortfall is either very small (e.g. United Utilities Strategic WRZ) or there are no supply shortfall events (Severn Trent Strategic Grid WRZ). The higher level of environmental ambition for

WRSE and WRE in the central scenario means there is little to no increase in the probability of a supply shortfall occurring under the higher environmental destination scenario. The high public water supply scenario, where only 50% of the 2050 targets for the reduction of Per Capita Consumption and Leakage are realised, acts to increase the probability of a supply shortfall occurring relative the central scenario for WRZs in the West and South East water resources regions. These regions include some of the most water stressed areas in England, where supply only marginally exceeds demand, and therefore any additional pressure on Public Water Supply demands can be expected to increase the probability of a supply shortfall occurring. An increase in the probability of a supply shortfall occurring between the central scenario and the far future climate change scenario is also observed for the West, South East and West Country water resources regions. However, the pattern of change is more subtle for the far future climate change scenario, where the increases in supply shortfalls are more spatially consistent, compared with the high environmental destination and high public water supply scenarios. For example, the increase in probability of a supply shortfall occurring under the high climate change scenario is smaller for WRWC and the south-west parts of WRSE compared with the high environmental destination scenario and the high Public Water Supply demand scenario. Similarly, a slightly larger increase in probability is observed for the London WRZ under the more extreme climate change scenario compared with the other sensitivity scenarios. This trend is to be expected since the additional pressure from climate change is based on physical systems that are more evenly distributed compared with the more spatially variable patterns of environmental destination or reduction in per capita consumption and leakage.

Looking at the results across all the sensitivity scenarios, the extra water demands associated with environmental ambition and public water supply, as well as the reduction in supply due to more severe climate change, only cause relatively small-scale increases in the probability of a supply shortfall occurring at the key areas of water stress that are supplied by the strategic solutions. For example, the London and SWOX WRZs display small increases in the probability of a supply shortfall occurring and the Cambs & West Suffolk, Affinity WRZ 1, 2, 4, Affinity WRZ 3&5 and the South Hampshire demand centres all experience a supply shortfall every year in the central scenario and therefore the probabilities of a supply shortfall occurring cannot increase under the sensitivity scenarios. The Wessex WRZ displays a more substantial increase in the probability of a supply shortfall occurring between the central scenario (8% probability) and the sensitivity scenarios (14-100% probability). However, results for this demand centre have been adjusted, as described in Section 2.10.3.1.2, and consequently any trends should be viewed with caution.

Although the additional pressures considered in the sensitivity scenarios only bring about small increases in the probability of a supply shortfall occurring for WRW demand centres, much larger changes are observed in the probability of water use restrictions, as shown in **Appendix G**. For example, the Severn Trent Strategic Grid demand centre experiences increases in the probability of level 3&4 water use restrictions occurring of 5% for the high public water supply scenario, 10% for the high environmental destination scenario and 20% for the high climate change scenario.

It should be noted that the maps in **Figure 17** only show the change in probability of a supply shortfall occurring. They do not reflect changes in the size of the risk for the sensitivity scenarios, or the change in probability of Level 4 restrictions, to which most of the storage-dependent water companies plan. Level 4 restriction impacts are discussed in the following scenario sections.

3.4.2 Central Scenario

When the set of strategic solutions being considered in the regional water resources management plans are implemented in WREW, there is a substantial reduction in the likelihood of a supply shortfall or level 3 & 4 water use restriction occurring at key areas of water stress in WRSE and WRE. The likelihood is even removed in some cases, as demonstrated by **Figure 19**, **Figure 20**, and **Figure 21**.

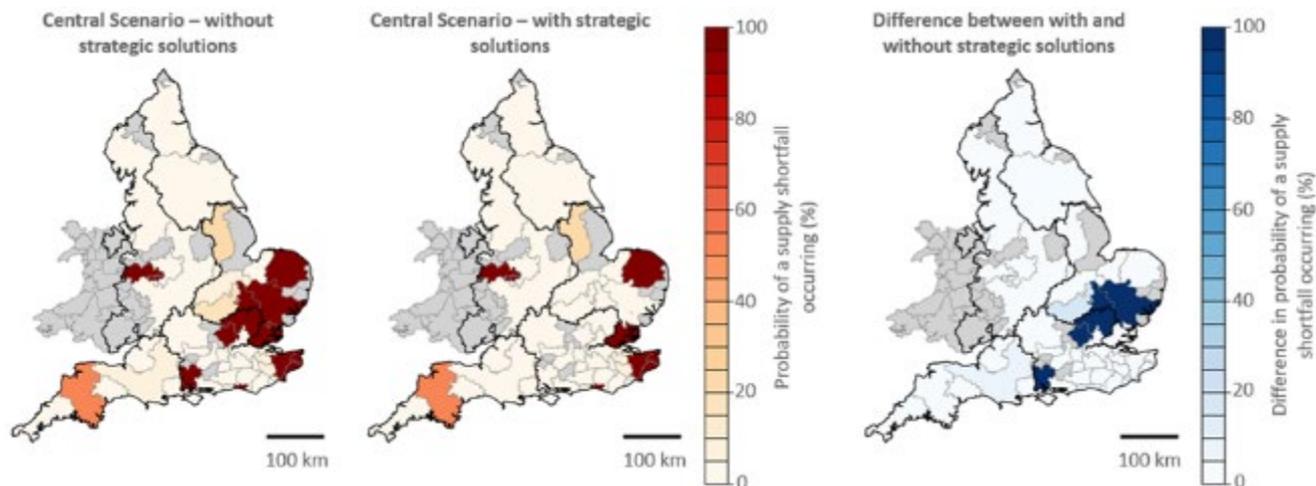


Figure 19. Spatial pattern of the probability of a supply shortfall occurring in any given year for the central scenario with, and without, any strategic solutions implemented in WREW

NB grey WRZs in England are not included in WREW and those in Wales are omitted from the analysis.

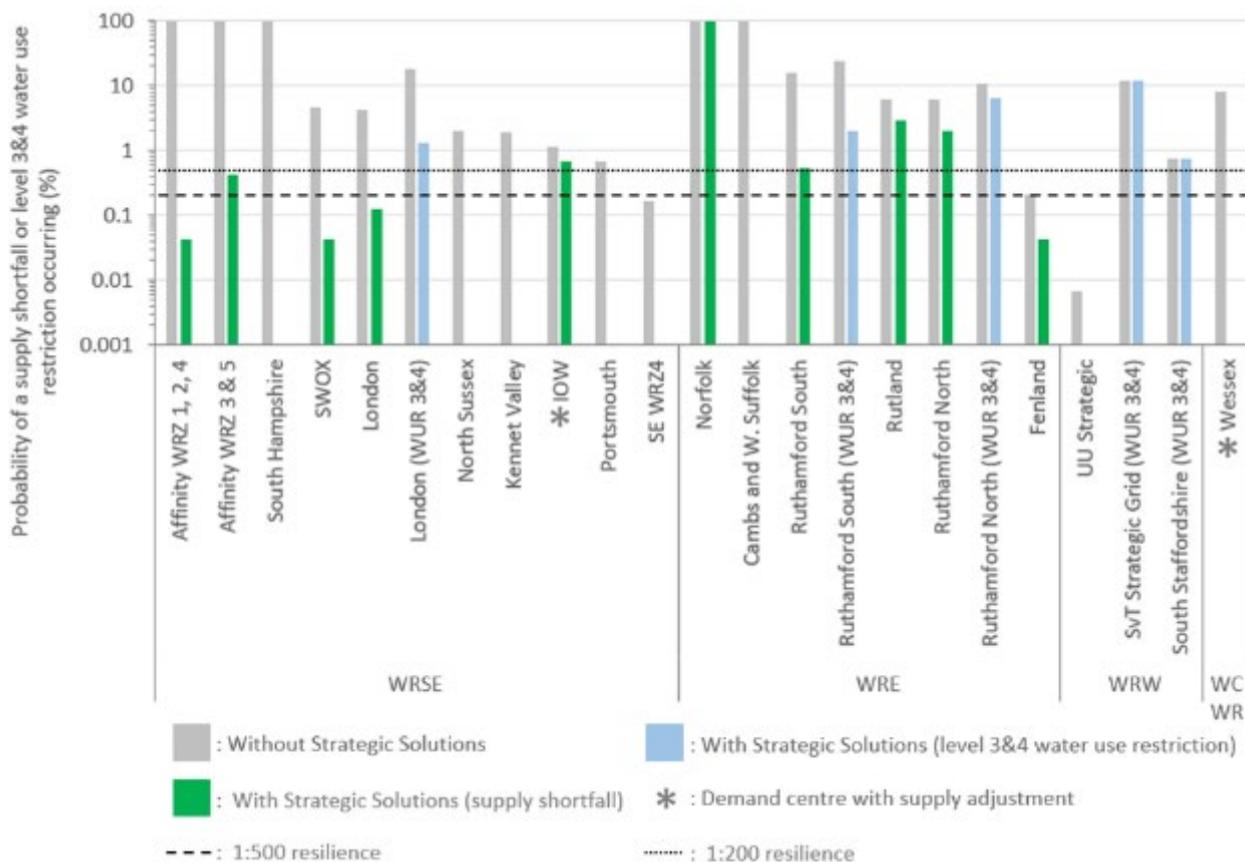


Figure 20. Difference in the probability of a supply shortfall or level 3 & 4 water use restriction occurring in the central scenario configured without (grey bars), and with (green & blue bars), strategic solutions activated in WREW

Note that demand centres suffixed with 'WUR 3&4' and shown with blue bars, represent the probability of a level 3&4 water use restriction occurring. All other demand centres on the figure show the probability of a supply shortfall occurring.

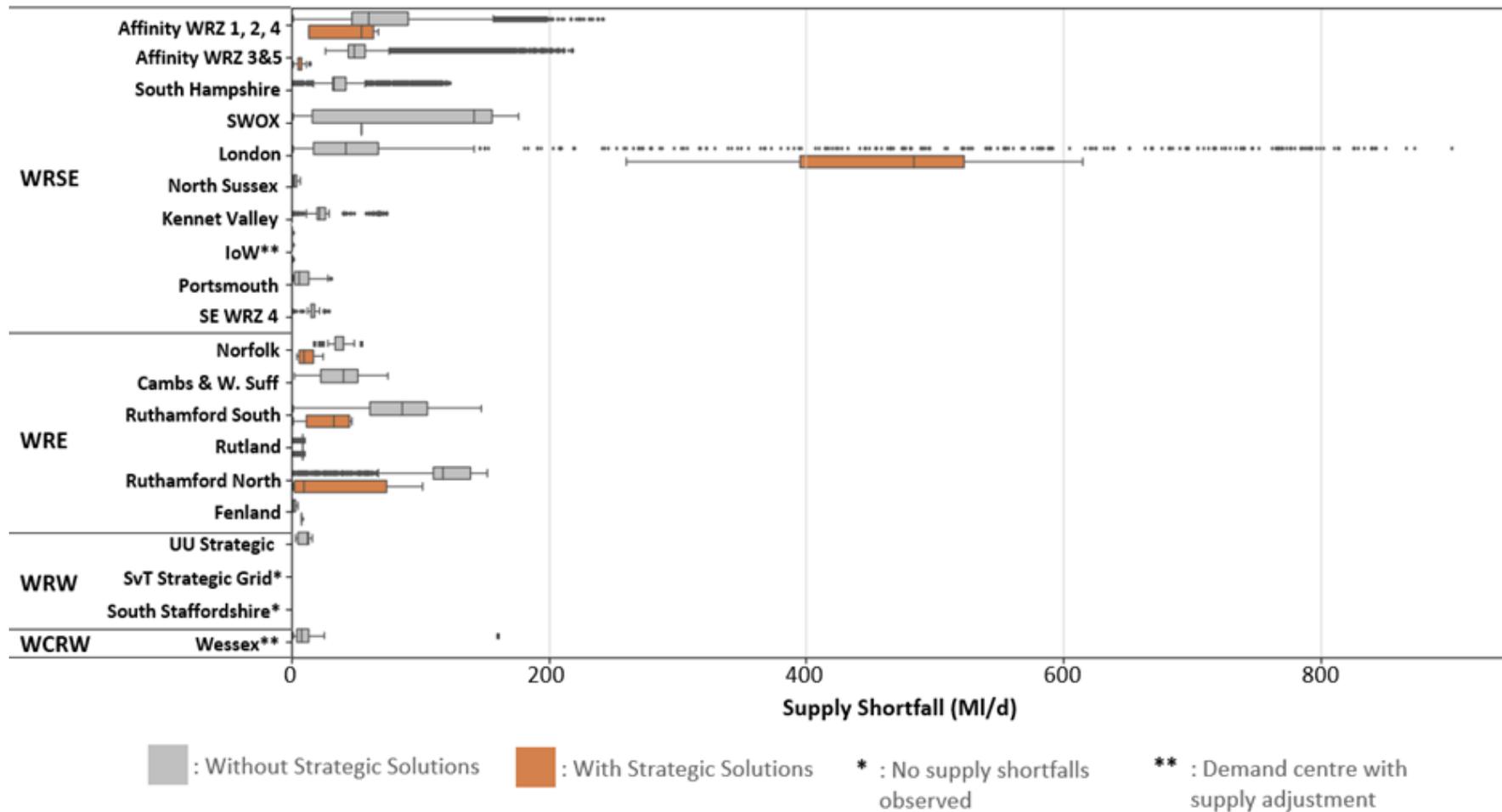


Figure 21. Distribution of the maximum daily supply shortfall observed in any given year with a shortfall under the central scenario configured without (grey), and with (orange), strategic solutions activated in WREW

For a comprehensive view on the drought resilience benefits associated with the strategic solutions, the probability of a supply shortfall, or level 3 & 4 water use restriction, occurring with and without strategic solutions operational, as shown in **Figure 20**, should be considered alongside the distribution of the maximum size of supply shortfall with and without strategic solutions operational, as shown in **Figure 21**.

Demand centres that experience the greatest drought resilience benefit are illustrated by the largest changes in the probability of a supply shortfall occurring between the configurations of WREW with and without solutions operational. The dark blue areas of the difference map shown in **Figure 19** correspond with two demand centres:

- Cambs & West Suffolk demand centre (WRZs: Bury Haverhill, Cheveley, Ely, Ixworth, Newmarket, Sudbury, Thetford, East Suffolk, South Essex and Central Essex); and
- South Hampshire demand centre (WRZs: Hampshire Rural, Hampshire Winchester, Hampshire Southampton East and Hampshire Southampton West).

The dark blue areas shows where a supply shortfall occurs every year without the strategic solutions and is removed when the solutions are implemented. The results for these two demand centres, the wider benefits of the solutions associated with them, and the benefits of other solutions supplying WRE and WRSE are explained in Sections 3.4.2.1 and 3.4.2.2 respectively. It should be noted that the probability of failure does not take into account the likely impact of failure. For example, a more densely populated WRZ will be impacted to a greater extent by failure compared with a rural zone. When the reduction in the probability of failure, shown in **Figure 20**, is combined with population, the largest impacts in order of size are observed for the Affinity 1, 2, 4, Affinity 3&5, Cambs and West Suffolk, South Hampshire, London and Ruthamford South demand centres. The findings for the Water Resources West Region, which mostly acts as a donor of water for other strategic solutions, are covered in Section 3.4.2.3, and have been combined with the findings on the West County Water Resources solutions. Unfortunately, the poor calibration of WREW for the Wessex demand centre, which is supplied by the majority of the West Country strategic solutions, means that only limited conclusions can be drawn on the drought resilience benefits of these solutions.

3.4.2.1 WRE

The SLR and Fens Reservoir solutions act to reduce or remove the probability of a supply shortfall or level 3&4 water use restriction occurring for key areas of WRE. For example, SLR acts to remove the probability of a supply shortfall occurring for the Cambs & West Suffolk demand centre, satisfying shortfalls of up to 75 MI/d, as shown in **Figure 19**, **Figure 20**, and **Figure 21**. The SLR solution also supplies the Ruthamford South Demand Centre (Ruthamford South, Central and West WRZs) and the Ruthamford North Demand Centre. However, it only acts to reduce the probability of a supply shortfall or level 3&4 water use restriction occurring at these demand centres, due to supply shortfalls exceeding supply from the solution (**Figure 20**). Limits on the amount of water released from the reservoir in WREW mean that supply shortfalls can only be reduced by 100 MI/d for the Ruthamford South demand centre and by 50 MI/d for the Ruthamford North demand centre (**Figure 21**). Similarly, the reservoir also indirectly supplies the Fenland demand centre (North Fenland and South Fenland WRZs) but cannot remove the probability of a supply shortfall occurring, despite the comparatively small supply shortfalls (~5-10 MI/d). This suggests that the majority of the 250 MI/d release from the reservoir is required by the Cambs & West Suffolk, Ruthamford South, and Ruthamford North demand centres. Interestingly, analysis of the simulated storage time series from WREW, for SLR during drought events, indicates that more water could be available for release and therefore the solution could provide more benefit to the Ruthamford North, Ruthamford South, and Fenland demand centres.

The Fens Reservoir solution supplies the Norfolk demand centre (WRZs: Happisburgh, North Norfolk Coast, North Norfolk Rural, South Norfolk Rural and Norwich and the Broads), which experiences a supply shortfall every year without the solution in place, and only receives a marginal reduction in the probability of a supply shortfall occurring when the solution is operational, as shown in **Figure 19**. Although only a limited drought resilience benefit is observed for the Norfolk demand centre, **Figure 21** shows that supply from the Fens Reservoir acts to reduce the size of supply shortfalls by ~30 MI/d.

It is important to note that a number of re-use and desalination options are considered in the WRE regional plan and the emerging Regional Plan indicates that these are required in quite large numbers across the region to further reduce any residual risk of a supply shortfall occurring at the Norfolk, Ruthamford North, Ruthamford South and Fenland demand centres. The WREW modelling therefore reconciles with this emerging regional view, but also suggests that extra benefit could be realised by increasing the volume of water released from the SLR and Fens Reservoir solutions.

3.4.2.2 WRSE

The RAPID solutions for WRSE selected through the regional reconciliation process are effective at removing or reducing the probability of a supply shortfall or level 3&4 water use restriction occurring. As outlined above, the greatest drought resilience benefits associated with the strategic solutions are illustrated by the largest changes in the probability of a supply shortfall occurring between the configurations of WREW with or without solutions operational. For the WRSE region, the South Hampshire demand centre experiences a supply shortfall occurs every year, which the strategic solutions remove, as shown by the dark blue shading on the difference map in **Figure 19** and the absence of a green bar in **Figure 20**. The South Hampshire demand centre is supplied by the Thames to Southern Transfer (T2ST) and the Southern Water Services Havant Thicket Raw Water Transfer, which is supported by the Southern Water Services Water Recycling solutions. These solutions can solve supply shortfalls up to of 123 MI/d, as shown in **Figure 21**. The solutions also supply the Kennet Valley, North Sussex, Portsmouth, and South East WRZ4 demand centres where they too remove the probability of a supply shortfall from occurring. A pre-existing water transfer between the South Hampshire demand centre and the Isle of Wight (IOW) demand centre establishes an indirect drought resilience benefit via the T2ST and Havant Thicket Raw Water Transfer solutions that supply South Hampshire. As a result, a small decrease in the probability of a supply shortfall occurring can be seen in **Figure 20** when the strategic solutions are operational. However, it should be noted that an adjustment has been made the results for the IOW demand centre to account for missing supply sources, as described in Section 2.10.3.1.1, and consequently the size of the drought resilience benefit observed should be viewed with caution.

The STT, London Effluent Reuse and SESRO solutions directly supply the London WRZ and the results demonstrate that when these solutions are operational in WREW the probability of a supply shortfall or level 3&4 water use restriction occurring is reduced. **Figure 21** shows that when solutions are activated in WREW they satisfy smaller supply shortfall events up to 265 MI/d and reduce the size of the largest supply shortfalls by ~275 MI/d (900 MI/d without solutions operational vs 625 MI/d when solutions activated). The solutions also remove the heavy tailed distribution for the maximum daily size of supply shortfalls, indicating that they improve the resilience of the London demand centre by reducing its sensitivity to particular spatial and temporal patterns of drought that would otherwise lead to very large shortfalls. Despite the large benefit that the solutions provide to the London WRZ, the residual shortfall events are still quite large and therefore additional supporting supply options would be required. The SWOX demand centre is also supplied by the STT and SESRO solutions and receives a similar scale of drought resilience benefit as the London demand centre when the solutions are activated in WREW, as shown by the reduction in the probability of a supply shortfall occurring when the solutions operational in **Figure 20**. Also, the size of supply shortfalls for the SWOX demand centre is reduced by ~100 MI/d when the solutions are active (see **Figure 21**).

The Thames to Affinity Transfer solution provides a significant drought resilience benefit to the Affinity WRZ 1, 2, 4 and Affinity WRZ 3&5 demand centres. This benefit is shown by the reduction in probability of supply shortfalls at the demand centres, when the solutions are operational, in **Figure 20**, as well a 200 MI/d reduction in the maximum daily size of supply shortfalls shown in **Figure 21**. Results for distribution of the maximum daily size of shortfall events show the tail of larger shortfall events is removed when the solutions are activated and suggests that the solutions improve the resilience of the Affinity WRZ 1, 2, 4 and Affinity WRZ 3&5 demand centres by reducing sensitivity to spatial and temporal patterns of drought that would otherwise lead to very large shortfalls.

3.4.2.3 WRW

Of all the strategic solutions, only the North West Transfer solution benefits the Water Resources West Region, it is effective at removing the probability of a supply shortfall occurring in the demand centres that make up United Utilities Strategic WRZ. This result is demonstrated in **Figure 20** where the very infrequent (0.006% probability) supply shortfalls for United Utilities Strategic demand centres are removed when solutions are operational. The Severn Trent Strategic Grid demand centre does not experience any supply shortfalls in the central scenario; however, level 3 & 4 water use restrictions do occur. Although the region acts as a donor of water for the Severn to Thames Transfer (STT) and Grand Union Canal solutions (GUC), the 'put and take' arrangement on which STT operates means that a reduction in drought resilience is not observed, as shown in **Figure 20**, by the bars of equal probability of a level 3 & 4 water use restriction occurring with and without solutions active for the Severn Trent Strategic Grid demand centre.

3.4.2.4 WCWR

The Mendips Quarry Raw Water Reservoir and Cheddar 2 solutions supply the demand centres in WREW that make up the Wessex WRZ. When these solutions are active the probability of a supply shortfall occurring is removed (**Figure 20**) and similarly supply shortfall events up to 25 MI/d are satisfied (**Figure 21**). It should however be noted that this demand node is poorly calibrated in WREW and that the results have been adjusted to account for a missing supply source, as described in Section 2.11.1. Consequently, the findings on the drought resilience benefits associated with the Mendips Quarry and Cheddar 2 should be viewed with a low level of confidence.

The Poole Effluent Re-use solution supplies the Poole and Bournemouth demand centre in WREW (Bournemouth WRZ). However, no supply shortfalls are observed for the demand centre, in the results for the configuration of WREW without strategic solutions and therefore the drought resilience benefits associated with the re-use solution cannot be commented upon. The draft regional plan for the West Country water resources region indicates that the Bournemouth WRZ faces deficits in the future due to sustainability reductions on abstraction licences. The lack of sensitivity in this area of WREW may be due to the simplified way in which the reduction in supply associated with environmental destination scenarios have been represented in the model.

3.4.3 Sensitivity Scenarios

Three sensitivity scenarios are tested in WREW, where one of the variables is increased relative to the central scenario. The aim of these scenarios is to explore whether uncertainty around climate change, Public Water Supply demands, and the water needs of the environment affect the drought resilience benefits associated with the strategic solutions. In each scenario, the extra pressures are applied nationally and therefore the solutions must attempt to maintain supply to key areas of water stress without being influenced by competing water needs, or reduction in water availability elsewhere. Overall, the results for the sensitivity scenarios show that the solutions can overcome the extra pressures on the supply system with only a small decrease in the drought resilience benefit they provide to key areas of water stress. This suggests that the solutions are resilient to uncertainty in demand and that there are enough strategic solutions being considered in regional plans to provide benefits in the face of uncertain but plausible futures. The main trends in the results are explained in more detail below.

Results from the sensitivity scenarios are shown in **Figure 22** and **Figure 23**, where the probability of a supply shortfall occurring in the central scenario, with strategic solutions operational, is compared with the probability of a shortfall occurring in each of the sensitivity scenarios when the solutions are operational. Assessing the size of the change in probability, between the central scenario and the sensitivity scenarios, at the key areas of water stress that the strategic solutions supply, gives an indication of how well the solutions can adapt to additional pressure from uncertainty in supply or demand in terms of drought resilience benefit.

Looking at the national scale, the difference maps in **Figure 22** show some large changes in drought resilience between the central and sensitivity scenarios. However, the majority of the demand centres where a significant change is observed are not supplied by the strategic solutions and therefore highlight where the supply system has limited capacity to mitigate the extra pressure and/or where the pressures are greatest. Only comparatively small-scale changes in the change in probability of a shortfall, or level 3 & 4 water use restriction, occurring are observed at the demand centres that the strategic solutions supply, as demonstrated by **Figure 23**.

This result must be viewed in context with the size of the additional challenge that the solutions face under the sensitivity scenarios, as presented and discussed in Section 3.4.1.2. For example, as the central scenario for WRSE already incorporates high environmental destination, the 'high environmental destination scenario does not result in any notable change for the region.

Although, when considered nationally, the demand centres supplied by the solutions are not amongst those most affected by the additional pressures in the sensitivity scenarios, they still show a ~2-3 fold increase in the probability of a supply shortfall occurring without solutions activated (Section 3.4.1.2, **Figure 23**). The fact that the difference in probability of a supply shortfall occurring with solutions operational is small suggests that the solutions have sufficient supply capacity to maintain a broadly comparable level of drought resilience benefits as for the central scenario. It is however also worth considering that whilst the solutions are able to limit the number of additional years in which a supply shortfall event occurs due to the extra pressures, it is likely that the pressure would still work to increase the size of the shortfall events when solutions are in place. In other words, the remaining supply shortfalls have increased in size.

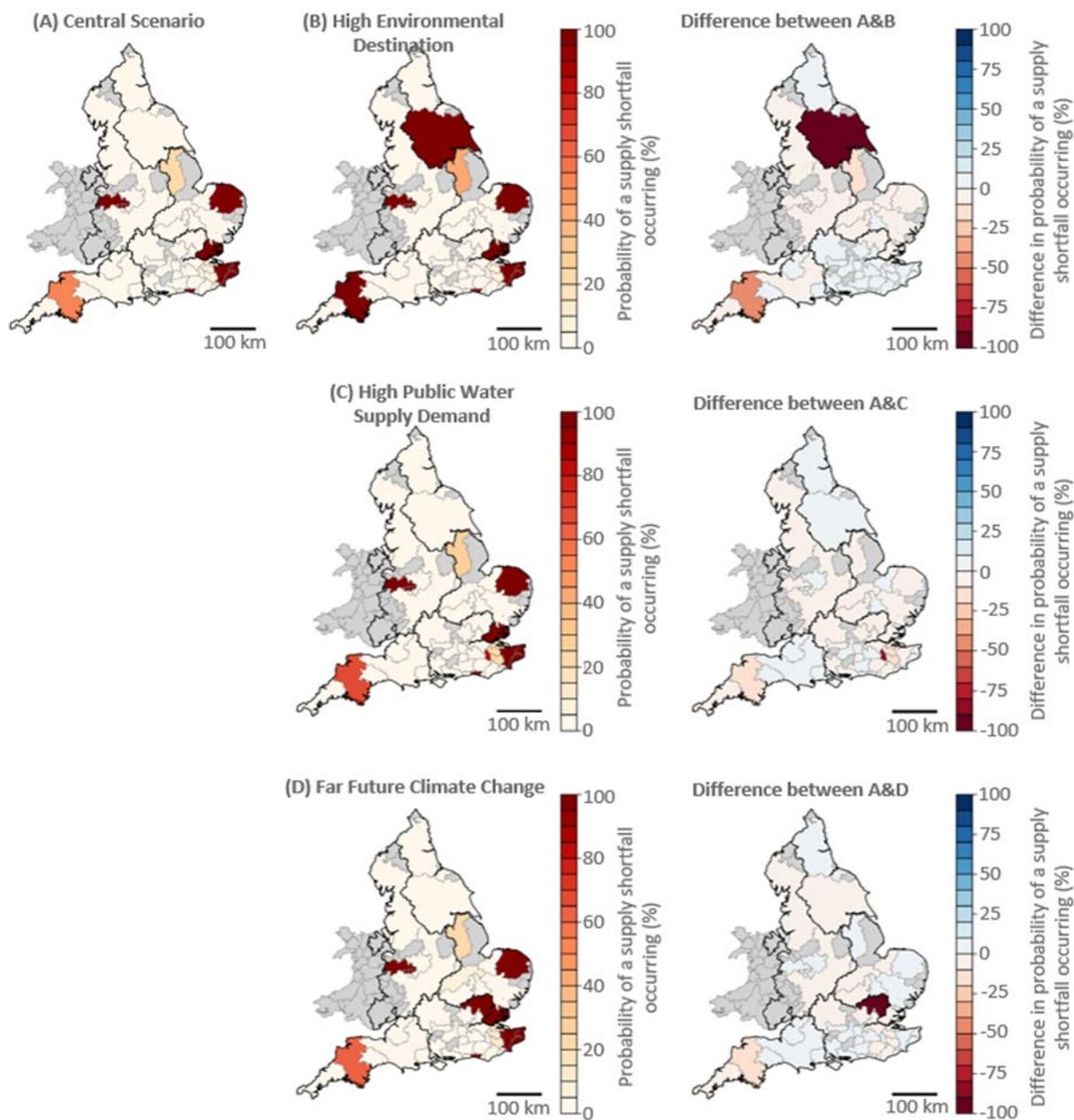


Figure 22. Spatial pattern of the probability of a supply shortfall occurring in any given year for the central scenario (A) compared with the sensitivity scenarios (B-D), when strategic solutions are operational

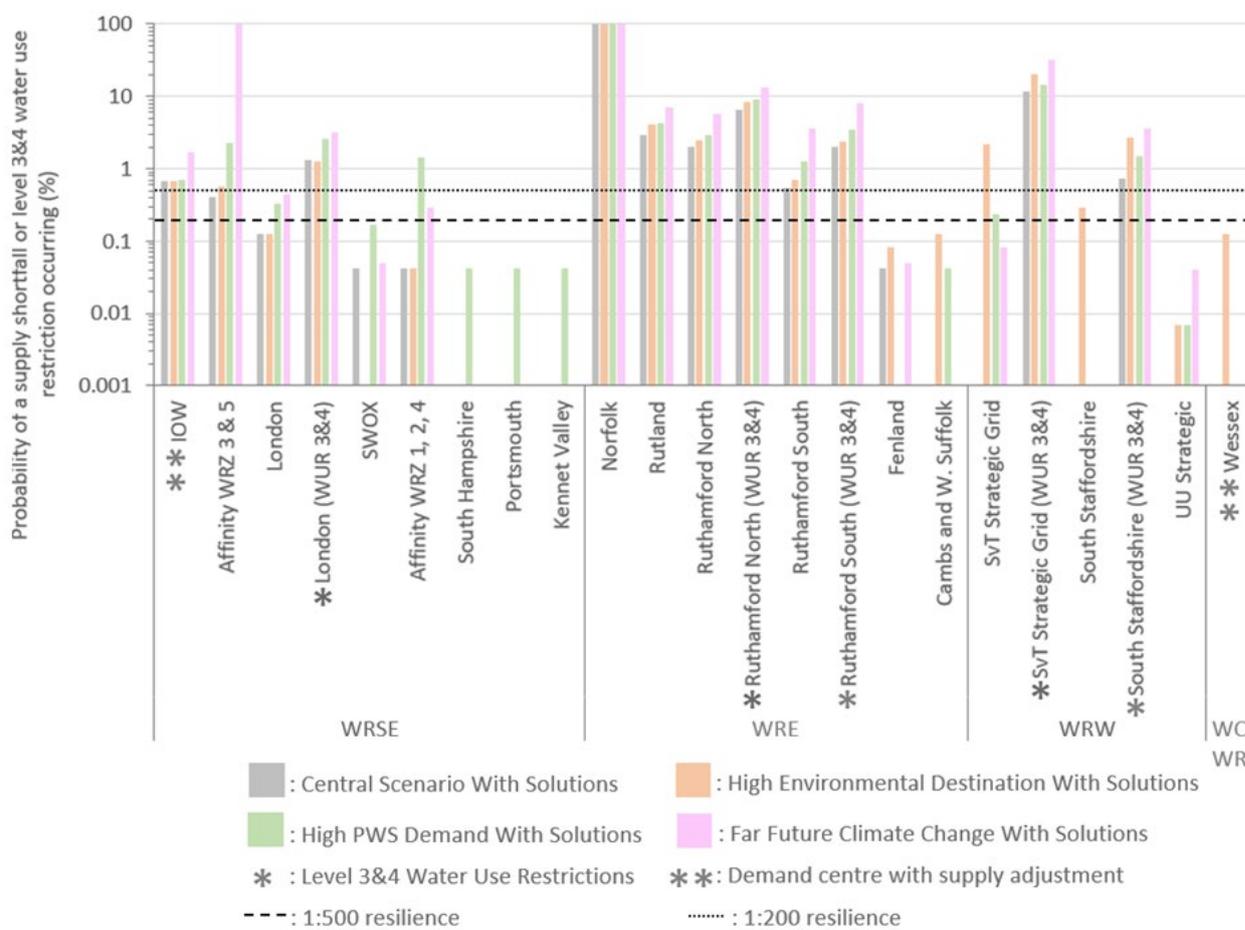


Figure 23. Difference in the probability of a supply shortfall or level 3 & 4 water use restriction occurring in the central scenario (grey bars) and the sensitivity scenarios (orange, green and pink bars) both with solutions operational in WREW

There are some exceptions to the trend highlighted above, which can be seen in **Figure 23**. For example, the Affinity WRZ 3&5 demand centre, where the extra pressure on supply associated with the far future climate change sensitivity scenario causes a significant increase in the probability of a supply shortfall occurring. A similar trend is observed for the Affinity 1, 2, 4 demand centre under the higher public water supply scenario and the far future climate change scenario. In both cases the extra pressures outstrip the supply from the T2AT and GUC strategic solutions. The result is to be expected, since the supply/demand position for these two demand centres is finely balanced, as demonstrated by a supply shortfall event occurring every year in the central scenario without solutions operational (see **Figure 22**). Any extra pressure on the Affinity system that is similar in scale to the amount of water supplied by the strategic solutions will therefore cause a large increase in the frequency of failure. The susceptibility of the Affinity WRZ 3&5 demand centre to climate change is a function of the hotter and drier climate reducing the yield of the ground water sources that form the primary supply source for this area of the system.

A small number of demand centres supplied by the strategic solutions, display an increase in the probability of a supply shortfall occurring under the sensitivity scenarios, even though shortfall events are removed by the solutions at these demand centres in the central scenario. This is the case for the South Hampshire, Portsmouth, Kennet Valley, and Cambs & West Suffolk demand centres, which experience a very small (0.03%) increase in probability of a shortfall event. This result highlights areas where the supply/demand position is finely balanced when the solutions are not active (e.g. South Hampshire and Cambs & West Suffolk which experience a supply shortfall every year in the central scenario without solutions active) and where the additional pressures are similar in size to supply from the strategic solutions. In these situations, the additional pressures act to increase the frequency of failure by reintroducing the supply shortfalls normally removed by the strategic solutions.

As outlined above in Section 3.4.2, when assessing probabilities of a supply shortfall occurring across results from the entire ensemble for the central scenario, no change in drought resilience is observed for

the demand centres in Water Resources West that donate water to the strategic solutions. In contrast, these demand centres show increases in the probability of a supply shortfall occurring in the sensitivity scenarios, as shown in **Figure 23**. However, analysis of time series outputs from WREW demonstrates that the observed reduction in drought resilience is a function of the extra pressures on the supply system, rather than any sensitivity associated with the operation of the strategic solutions. **Figure 23** also shows an increase in the probability of a supply shortfall occurring under the high environmental destination scenario for the Wessex demand centre. The volumetric reduction in abstraction licences associated with environmental destination scenarios is one of the key pressures identified in the draft West Country regional plan. However, as highlighted above in Section 3.4.2.2, the adjustment to the results for this demand centre limits the degree to which any conclusions can be made about the drought resilience benefits of the Mendips Quarry Raw Water Reservoir and Cheddar 2 solutions. This is especially true when exploring results around uncertainty in demand variables.

3.4.4 Stress Test Scenarios

Five stress test scenarios are explored in WREW, where one of the strategic Solutions, or a supply source for a strategic Solution, is removed from the model. In contrast to the sensitivity scenarios, where additional pressure for water supply needs is spread evenly across England, the stress test scenarios explore the drought resilience implications when supply from Solutions is curtailed at key areas of water stress. The stress test scenarios are aimed at investigating the role individual solutions play in the broader set of schemes and whether any of the solutions act as a cornerstone for overall drought resilience.

Results from the stress test scenarios are shown in **Figure 24**, where the increase in the probability of a supply shortfall, or level 3 & 4 water use restriction occurring, under the stress test scenarios has been isolated by subtracting the probability results from the central scenario, with solutions operational. The results for the scenario with the unsupported component of STT removed are presented because a change in probability is not observed.

Overall, the results show that removing a component of supply from STT and the SESRO solution, has limited impact on the drought resilience benefit that the remaining set of solutions can provide to the region. This is demonstrated by the ~1% increase in probability of a supply shortfall or level 3&4 water use restriction observed when the supported component of STT is removed or SESRO is removed. The ~1% relative change in probability should be considered in context with the absolute probability results for the central scenario where the complete portfolio of preferred solutions from the regional reconciliation process is activated, as shown in **Figure 24**. For example, under the central scenario the probability of a level 3&4 water use restriction occurring for the London demand centre is reduced from 18% to 1% when the full portfolio of solutions is operational. Similarly, the probability of a supply shortfall occurring for the Affinity WRZ 1, 2, 4 and Affinity WRZ 3&5 demand centres is reduced from 100% to 0.04% and 0.4%, respectively, when all of the preferred solutions are activated.

Larger reductions in drought resilience benefit are observed under the scenarios where GUC and SLR are removed from the set of strategic solutions tested in WREW. This result is to be expected since, the GUC solution represents 50% of the extra supply that the set of strategic solutions provide to the Affinity demand centres, and these are smaller in volume than the London WRZ, so losses of additional water are proportionally more significant. Similarly, the SLR solution is the only solution that supplies some of the demand centres in the Water Resources East region, or that acts as the principal source of new supply for others.

In addition to changes in the probability of failure brought about by the stress test scenarios, it is also important to consider changes in the size of supply shortfall. A large change in the scale of potential deficits would suggest that the solution removed from the portfolio is particularly effective at increasing drought resilience. Results for the STT Supported Removed and SESRO Removed stress test scenarios, compared with the central scenario, reveal that the maximum daily size of supply shortfall increases across the WRSE region, by a similar amount to the supply removed. This pattern suggests that both solutions can provide a drought resilience benefit commensurate with design yield. Changes in the distribution of size of supply shortfalls at the sub-regional level are also important and show that removing SESRO has the greatest impact on the London demand centre. In contrast, removing the supported component of STT impacts demand centres supplied by the T2ST and T2AT solutions. These sub-regional impacts might reflect solution behaviour, or, more simply how the model chooses to allocate water. Further work, including the analysis of time series outputs from WREW, is required to investigate these emerging results.

Removing the unsupported component of STT only marginally increases the size of maximum daily supply shortfall observed across WRSE, which suggests that flow levels on the River Severn are low during the more severe droughts that cause a supply shortfall in WRSE, and consequently only a small

amount of unsupported water is available for transfer to WRSE. Interestingly, removing GUC from the regional reconciliation solution portfolio increases the size of the supply shortfall across WRSE by approximately three times the yield of the GUC solution. The large increase in the size of supply shortfall, compared with the amount of supply removed, is a result of the type of option removed and the configuration of GUC in WREW. Supply from re-use options, especially as represented in WREW without outage or operational constraints, is disassociated with the hydrological system and therefore inherently resilient to drought. Furthermore, supply from the GUC solution is available at all times in WREW, but as the lowest priority (highest cost) source. This means that the model can utilise GUC more frequently than STT, SESRO and LER solutions, which are triggered by storage levels of London reservoirs, and consequently the impact of removing GUC is greater. It is likely that a larger increase in the size of supply shortfall would be observed for removing SESRO (supported) or STT, if the solutions followed demand led utilisation in WREW, rather than the storage trigger on London reservoirs. Sub-regional trends show that a substantial part of the increase in size of supply shortfall when GUC is removed is observed for the London demand centre. This trend is to be expected since, when GUC is removed, the Affinity 1, 2, 4 demand centre must rely more heavily on abstraction from the River Thames and therefore less water is available for abstraction further downstream at London. It is important to note that the observations on the change in size of supply shortfall under the stress test scenarios described above are made across the 2,340 years simulated in WREW. Whilst the results give an indication of the maximum scale of change in the size of potential deficits, the aggregated view across all simulated years means that the changes might occur at different times. A more accurate picture of how removing a solution impacts the water balance would be achieved by assessing the change in the size of supply shortfalls across each drought event in the w@h2 ensemble.

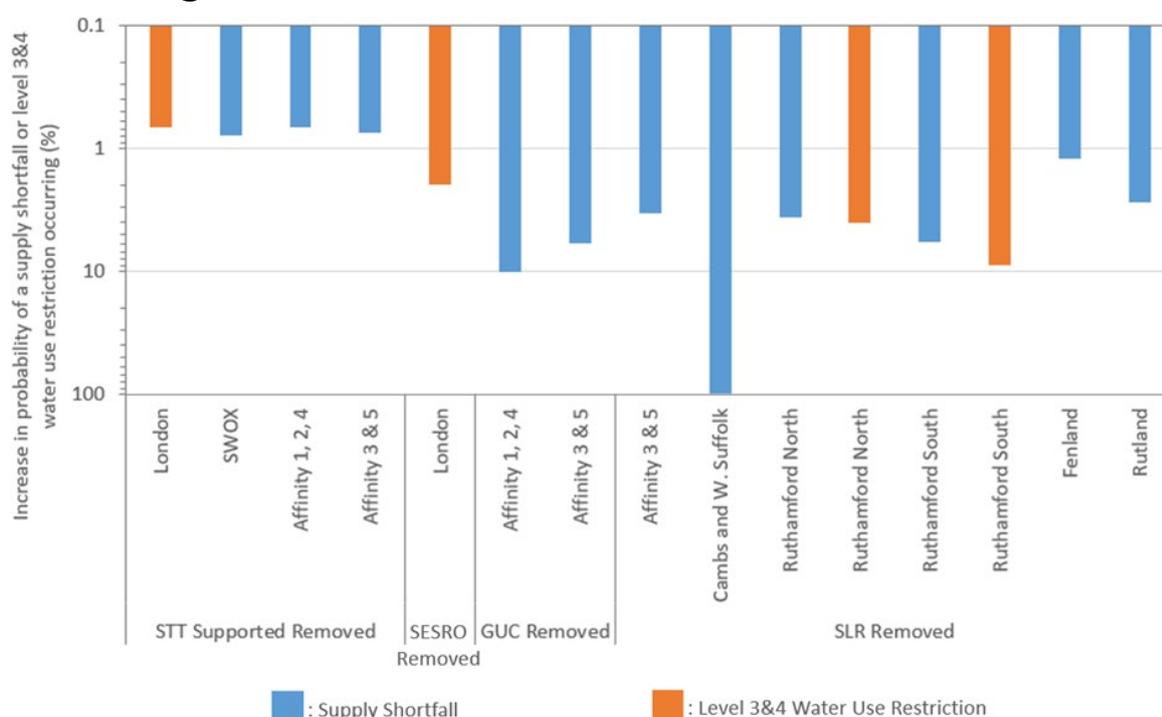


Figure 24. Reduction in the probability of a supply shortfall or level 3&4 water use restriction occurring in stress test scenarios compared with the central scenario with solutions operational

3.4.5 Specific droughts

As well as looking at summary statistics across all of the replicates in the w@h2 ensemble (i.e., probabilities of a supply shortfall occurring over 2,340 years of near future possible climate after removal of replicates with a > 1:500 RP event), it is possible to isolate specific types of drought event in the w@h2 dataset both temporally and spatially. This was made possible by statistical interrogation of the w@h2 drought event set undertaken by University of Oxford. Drought events are identified for river basins in England and Wales, as defined by the UKCP18 river basin regions. The approach is outlined in Appendix A.

For use in Phase 2, the NSSM team have identified four types of drought including:

1. National 24-month long droughts;

2. National 12-month long droughts;
3. WRE/WRSE focussed drought; and
4. WRW/WRSE (+/- WRE) focussed drought.

A fifth type of drought (WRW focussed) was searched for, but no drought event could be found where a drought was occurring in Severn, Dee and North West England basins at the same time without the same event impacting another basin (generally WRE: Anglian basin).

These 5 types of drought events were generally selected in order to explore the impact of nationally spatially coherent drought events and how they interact with and/or impact the behaviour and performance of different supply options. These spatially coherent drought events are particularly useful to explore specific solutions that have an inter-regional focus including strategic transfers such as Severn Thames Transfer and the Grand Union Canal. Exploring impacts of nationally spatially coherent droughts is particularly important in light of recent results from the eFLaG project that suggest widespread summer droughts across the UK are predicted to become more common (Tanguy, in prep.). This has the potential to impact summer water transfers considerably.

National drought events provided dry conditions that were equally distributed across the nation spatially and allowed testing of the full 'set' of supply options put forward by the regional groups and give an indication of the performance (resilience, effectiveness, yield) of the solutions under a nationally stressed system. This could be tested with shorter, sharper droughts (12-month) or longer (24 month) droughts.

WRE/WRSE focussed drought events ensured supply options that are intended to benefit the East/South East were performing as expected and allowed exploration of any limits/excess or sensitivities of specific options.

WRW/WRSE focussed drought events were primarily chosen to investigate the impacts of a drought in both the donor and recipient region at the same time; this way any trade-offs between the two could be identified and mitigated if necessary. These inter-regional focussed drought events allowed exploration of their impact on resilience (effectiveness) of large-scale transfers and subsequent sensitivities of yields.

The criteria for the drought events (the only basins where a drought event is observed) are outlined in **Table 6**, with corresponding **Figure 25** highlighting the geographical extent of the basins referred to in the table. The criteria for each type of drought event are based upon seeing a drought in only the basins listed (assumed a 'drought' when normalised accumulated deficit for the basin > 0.007).

To explore the impact of these specific drought events on WRZs with and without strategic supply options, the percentage difference of days in supply shortfall or days in water use restrictions with strategic supply options (under the Central Scenario) was calculated over the course of each drought event.

The national 24 and 12 month long and WRSE/WRE focussed drought events demonstrated similar results to those found across the whole ensemble where, for the majority of these drought events, a 100% reduction in days of supply shortfall or days in water use restriction when Solutions are operational is observed in WRSE, for the most part in WRE, and with more variability in Ruthamford North.

In a similar way to the main results, the WRSE trend in particular suggests that the solutions put forward offer a high level of resilience and that it is possible that either a) not all solutions would be required b) their overall yield could be lowered, or c) the water could be shared more broadly across the region.

Whilst the overarching trend of resilience behaviour is similar to the main results, specific model behaviour should be investigated in the future including an audit of hydrological flow levels and reservoir storage levels during specific drought events. The results presented for WRSE explore an 'Enhanced' environmental destination scenario which reflects a significant reduction in abstraction; however, this does not take into account any future changes to licence capping or changes in environmental destination scenarios for other regions. These are likely to be more extreme reductions in abstraction than ran in these simulations, potentially lowering the resilience of solutions put forward.

Furthermore, the way in which sustainability reductions were applied in WREW is simplistic and un-dynamic (added to each demand centre) and has the potential to underestimate the impact on supply. Further work in Phase 3 aims to apply sustainability reductions at a licence level.

Table 6. Specific drought events searched for and isolated in the w@h2 dataset

Drought Event	WR Regions	River basins
24 month national	All	<ul style="list-style-type: none"> •WRSE: Thames & South East England; WCWR: South West England •WRE: Anglian •WRW: Severn, Dee, North West England, *Solway •WRN: Northumbria & Humber
12 month national	All	<ul style="list-style-type: none"> •WRSE: Thames & South East England; WCWR: South West England •WRE: Anglian •WRW: Severn, Dee, North West England, *Solway •WRN: Northumbria & Humber
WRW focussed*	WRW	•Severn, Dee, North West England
WRE & WRSE focussed	WRE & WRSE	•Anglian, South East England, Thames
WRW & WRSE focussed	WRW & WRSE (+/- WRE)	•Severn, Dee, North West England, South East England, Thames, +/- Anglian



Figure 25. The river basins used in the drought analysis in relation to the regional group boundaries. River basins are defined using the river basin regions identified in UKCP18¹².

¹² <https://github.com/ukcp-data/ukcp-spatial-files>

3.4.5.1 Summary of WRW and WRSE (+/- WRE) focussed drought events

Two of the five WRW and WRSE (+/- WRE) focussed drought events that were isolated in the w@h2 dataset are highlighted in **Figure 26**. The figure demonstrates for each of the two drought events, the intensity (measured in mm/month), the duration of the event in each river basin and the combined impact of intensity and duration which is the total accumulated deficit across a drought year (measured in mm).

Please refer to **Appendix A** for more information on how drought events are characterised within the distribution of all drought events in the w@h2 dataset. Please refer to **Appendix F** for spatial and temporal patterns of other WRW/WRSE focussed drought events and their impacts on the water system.

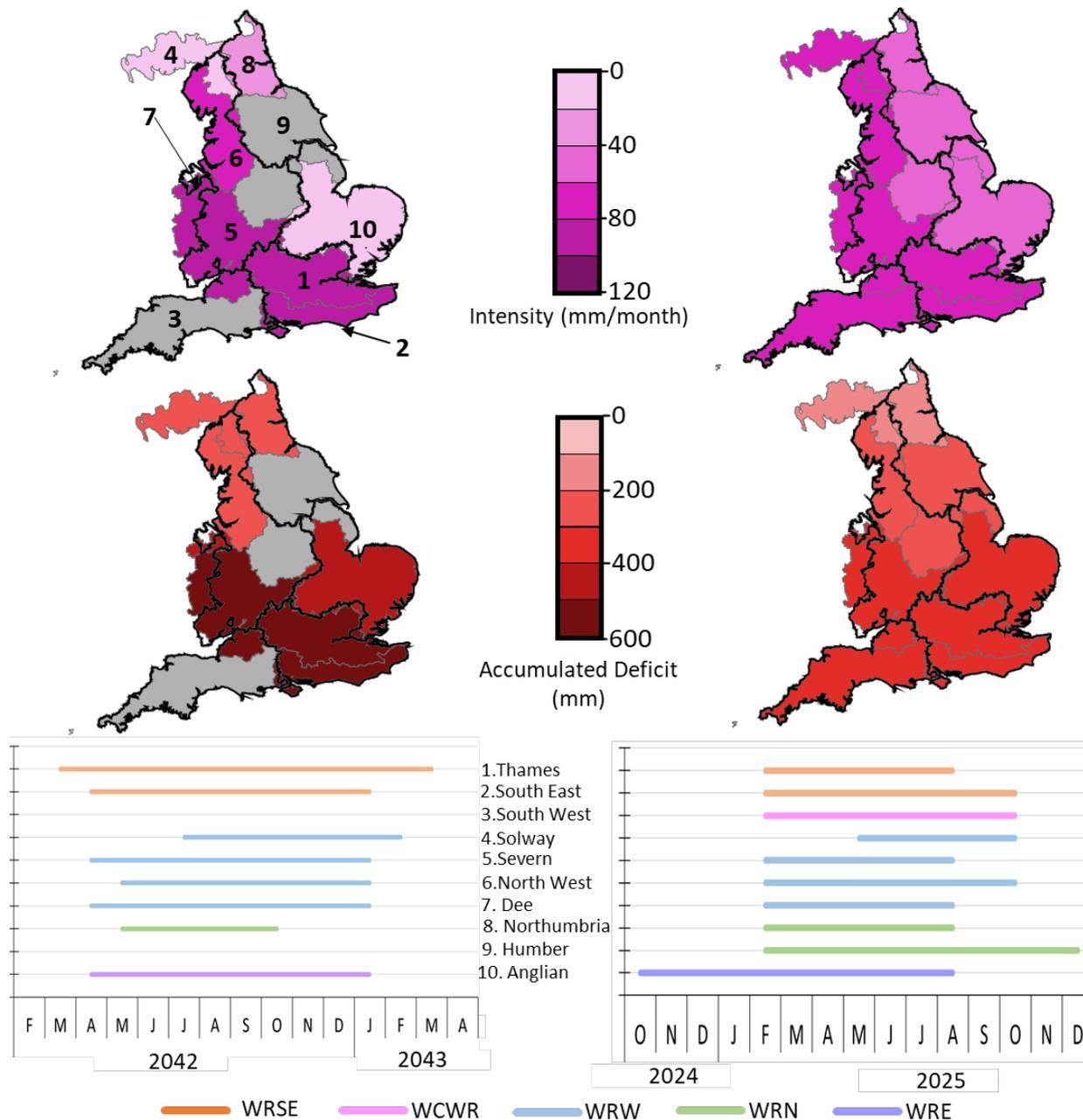


Figure 26. Isolated WRW/WRSE (+/- WRE) drought events in the w@h2 dataset.

NB Spatial and temporal patterns of drought events observed in replicate NF10 (left) and NF2 (right). For other WRW/WRSE events, refer to Appendix F

3.4.5.1.1 Likelihood and severity of drought events that impact WRW

To provide context to the West/South East focussed drought events analysed, it should first be considered how frequently drought events in the dataset cause an issue in Severn Trent and United Utilities Strategic zones. **Table 7** demonstrates the number of years that Severn Trent and UU Strategic Zones experience

water use restriction in the w@h2 dataset. It should be caveated that this number could be an over or underestimate and therefore does not directly correlate to the number of drought events e.g. one year could have more than 1 event; for a full explanation of how drought events are defined within the w@h dataset, please refer to Appendix A. Since the WREW model is simulating a 2050 scenario without WRMP options in place, it should also be noted that the frequency of water use restrictions noted here does not correspond to levels of service reported in companies WRMPs or drought plans. However, used in a comparative way, the figures do provide an indication of the change in likelihood of droughts impacting Water Resources West region across different WREW scenarios and stress tests.

The five WRW/WRSE focussed events explored that impact WRW and WRSE basins represent only 0.2% of the 2,340 year data set (1 in 468 years) and only 1.7% of the total years (288 years) that WRW see an impact (water use restriction). The accumulated deficit-based return period of the events can range up to 1:333. Return period in this context does not always provide a clear indication of duration specifically as it is predicated upon the accumulated deficit of the event. It is for this reason that both the duration and accumulated deficits (mm) of the events are explored individually. In the 5 events, the average accumulated deficits across each WRW and WRSE basin can range from 305 to 540 mm which represent the more severe end of accumulated deficits observed in the dataset. On average, the accumulated deficits observed in all drought events across the ensemble in these basins is 101 mm. Up to a maximum of ~775 mm accumulated deficit is observed across these basins. In terms of duration, the drought events in each basin range from a minimum of 6 months and up to 24 months.

Further work in Phase 3 aims to characterise the droughts observed in the 288 years to understand both the number of drought events that are causing this impact as well as the return period based on duration and intensity) of the events.

Table 7. The total number of years and the probability of a water use restriction in WREW (Level of water use restriction (WUR) > 0 for UU; Level of water use restriction (WUR) > 3 for SvT) in the near future ensemble under the Central Scenario

WCO	WRZ	Central Scenario (no Solutions)		Central Scenario (with Solutions)	
		Total # years with a water use restriction	Probability of a water use restriction (%)	Total # years with a water use restriction	Probability of a water use restriction (%)
Severn Trent Water (SvT)	Strategic Grid	288	11.9	286	11.8
United Utilities (UU)	Strategic WRZ	106	4.38	106	4.38

NB After removal of replicates with a > 1:500 RP event; 2340 years in ensemble (78 replicates x 30 years)

3.4.5.1.2 Impacts observed during WRW/WRSE events

Under the five isolated WRW/WRSE (+/- WRE) focussed drought events, and when Solutions are switched on under the Central Scenario, there is a negative impact (disbenefit) observed in WRW (Severn Trent Strategic Grid +/- United Utilities Strategic WRZ). This impact is an increase in the number of days in water use restriction in the model, of between 13% and >100% as shown in **Figure 27**. In absolute terms, WREW shows an increase in the number of days in WUR level > 3 of up to 54 days for Severn Trent Strategic Grid and WUR level > 0 up to 34 days for United Utilities Strategic WRZ¹³. Throughout these events, WRSE and WRE are generally benefiting with a 100% reduction of days in either supply shortfall or water use restriction.

The model behaviour observed for WRW is under the Central Scenario with Solutions switched on. Under this Central Scenario, sustainability reductions in 2050 (submitted environmental destination figures from the regional planning reconciliation) are included but WRMP supporting options to offset these reductions are not included. It is important to highlight that, under this scenario, WRW submitted Deployable Output (DO) reductions corresponding to ~27% of Enhanced. If this DO reduction were to increase, the water companies would select more WRMP supporting options to offset the impact. This would result in a different system configuration which would need further testing in WREW. Without further modelling it is not possible to assess the impact of this in on the transfers.

Although there is an impact under the five specific drought events, overall, this behaviour is not observed in the high-level statistics (over years) across the whole ensemble as observed in **Table 7**.

¹³ Note that inclusion of LoS 1 + 2 for United Utilities here was the result of direct request from WRW (e.g. does WREW show that UU has to implement TUBs more often when STT is in operation?)

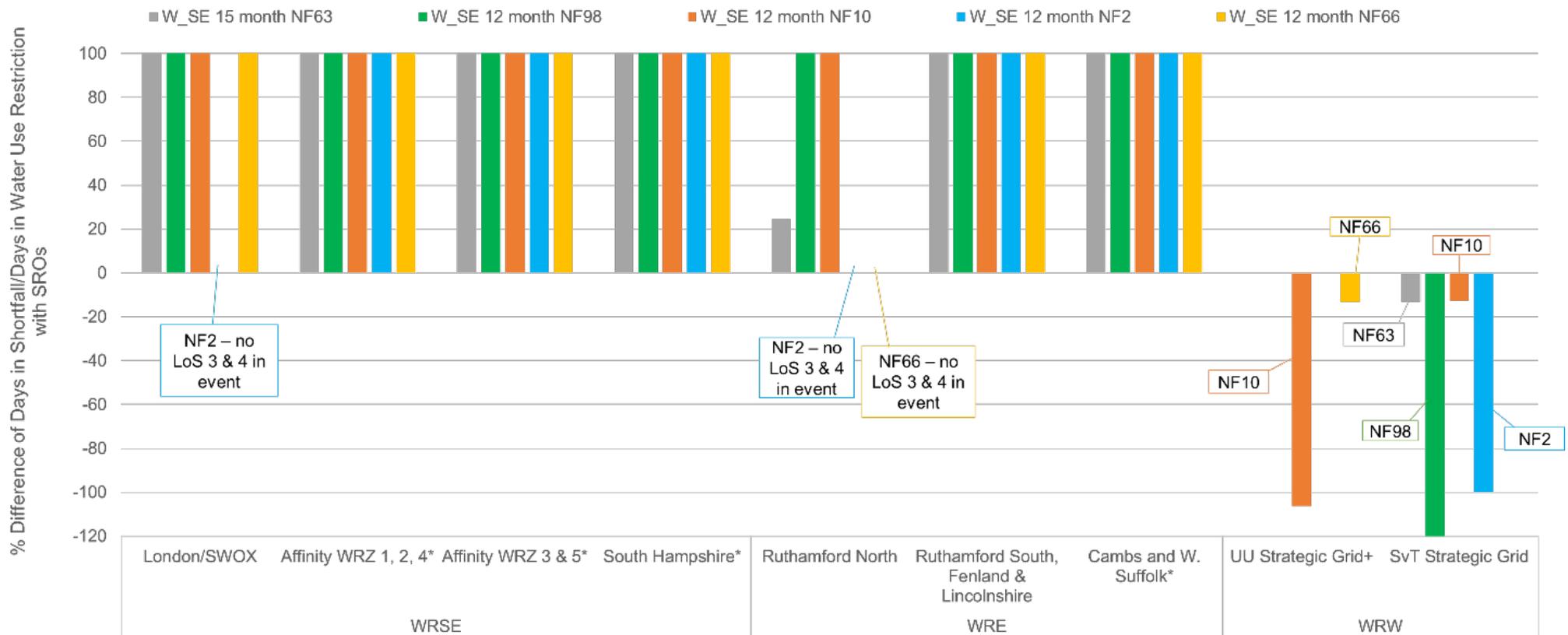


Figure 27. Impact of strategic supply options during specific WRW/WRSE (+/- WRE) drought events under the Central Scenario

This is shown as the change in number of days in supply shortfall or days in water use restriction, expressed as a %

NB WRZs with a * reflect supply shortfall, without reflect water use restriction LoS 3 + 4 and those with a + reflect water use restriction LoS 1 + 2.

3.4.5.2 Model behaviour

It is important to understand why effects are observed in the model, as many of the modelled impacts across WRW are actually a result of the model setup, which favours transfers for the Solutions and flows in the River Trent above the preservation of WRW resource base. This is compared against the likely reality of impacts in the next section.

3.4.5.2.1 Severn Trent Water

All isolated WRW/WRSE drought events were interrogated through time series of specific arcs and nodes in result output files. All events showing a disbenefit to Severn Trent Water Strategic Grid WRZ exhibited similar model behaviour as demonstrated in **Figure 28 A** and **B**.

In order to understand the model behaviour around WRW/WRSE during these specific drought events when Solutions are switched on, the baseline model topology should be first understood (without Solutions, **Figure 28 A**). In WREW, there is a connection that exists between Severn Trent reservoirs (Carsington & Ogston and Melbourne) and the River Trent. These reservoirs have the ability to send water to the River Trent via spill (at a cost) or compensation (incentivised with reduced cost). Water is consistently being released to the River Trent over time, not just in isolated drought events. As well as reservoir releases, water from Minworth (aggregated with other STW effluent) is also discharged into the River Trent; both ultimately link to WRE further downstream where they abstract water to serve PWS in Lincolnshire and fill Rutland and South Lincolnshire Reservoir when Solutions are switched on.

Severn Trent Water reservoirs Carsington & Ogston and Melbourne, as well as Derwent Valley, all serve as sources of supply to Severn Trent Water's Strategic WRZ (Strategic East demand centre; Strategic WRZ is split into 3 demand centres in WREW).

During these specific drought events in WREW, SvT's Strategic WRZ is already in WUR Level 3 + 4 and the HOF (2650 MI/d) at North Muskham (downstream on the River Trent) is reached with no strategic supply options switched on (e.g. flow levels drop below the HOF (2650 MI/d), to a minimum of 2460 MI/d). This is the result of:

- 1) Drawdown of Melbourne Reservoir as it sends more water over to the River Trent in drought, so less available from Melbourne to send to STW East demands; and
- 2) Drawdown of Carsington & Ogston to compensate for lack of water available from Melbourne. Drawdown so much that control curves are triggered and SVT Strategic goes into WUR Level >2.

When strategic supply options are switched on in WREW, the impacts to STW are exacerbated (see **Figure 28 B**). With water from Minworth now being diverted to support STT and GUC, less is available for the River Trent. This in turn means more water is sent over to the Trent from Melbourne to compensate for the lack of water available from Minworth. This draws down Melbourne further and therefore even less available to be sent to STW East. More water is subsequently sent down the Derwent Valley Aqueduct from Carsington & Ogston and Derwent Valley Reservoirs to compensate for lack of water in Melbourne. This results in even further drawdown of Carsington & Ogston so that control curves are hit more frequently, sending STW Strategic into higher LoS and/or more frequent days in WUR Level > 2. The North Muskham HOF is further invalidated (flow levels drop more, to a minimum of 2320 MI/d across the events) when strategic supply options are turned on.

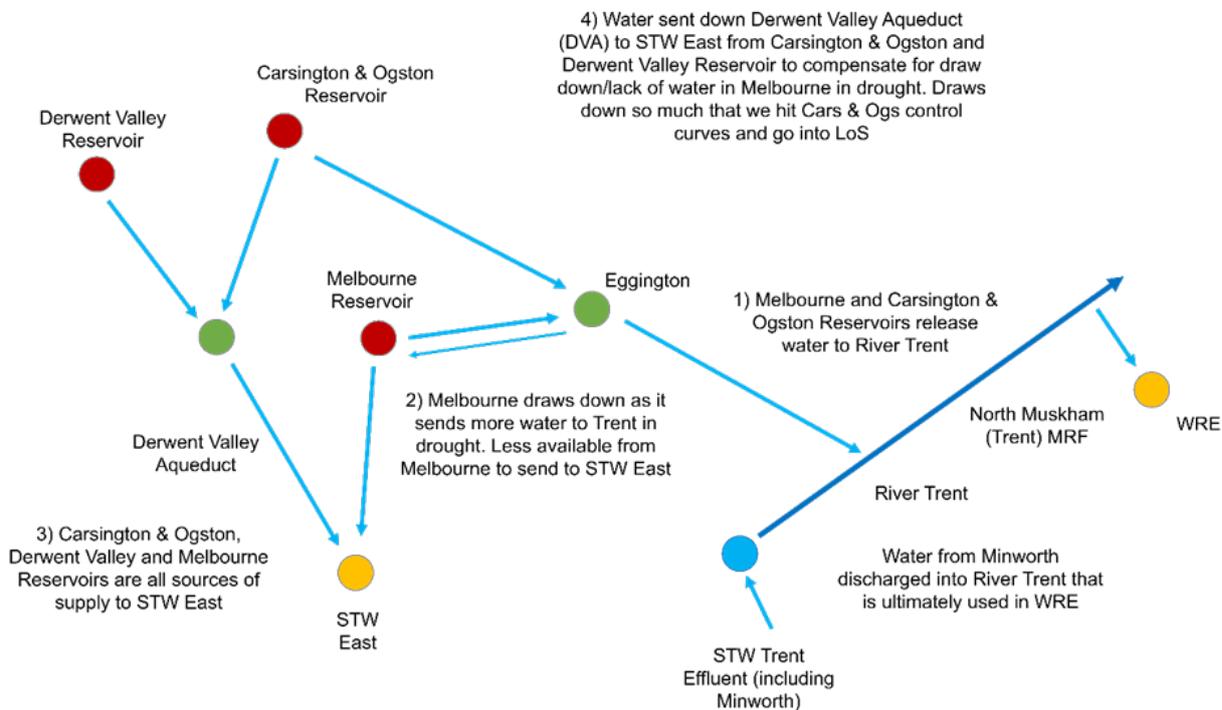
As part of the event interrogation, impacts on behaviour from other strategic supply options including South Lincolnshire and Upper Derwent Valley reservoirs were also investigated.

Across all events, storage in South Lincolnshire Reservoir (SLR) never drops to zero and abstractions to fill SLR on the Trent always stop when flow levels drop below the HOF at North Muskham <2650 MI/d, indicating that the filling of SLR is not causing water to be released to the Trent from SvT.

When strategic supply options are switched on, Derwent Valley Reservoir's storage increases by 10,000 MI. This is likely to be buffering the behaviour and ensuring water is available in STW Strategic Grid for longer, if this Solution was not switched on, it is likely the situation in SVT Strategic would be worse. To investigate this in a future Phase of the modelling project, the same Central Scenario with Solutions but with Upper Derwent Valley Reservoir Expansion Solution switched on should be run.

Further review of the model configuration with Severn Trent water resources modellers indicated that flows in the River Trent, or the crossing of North Muskham HoF do not affect compensation releases or storage in Melbourne, Carsington & Ogston reservoirs. Therefore, the observed behaviour appears to be an artefact on the model configuration in WREW rather than a genuine effect.

A) Without SROs:



B) With SROs:

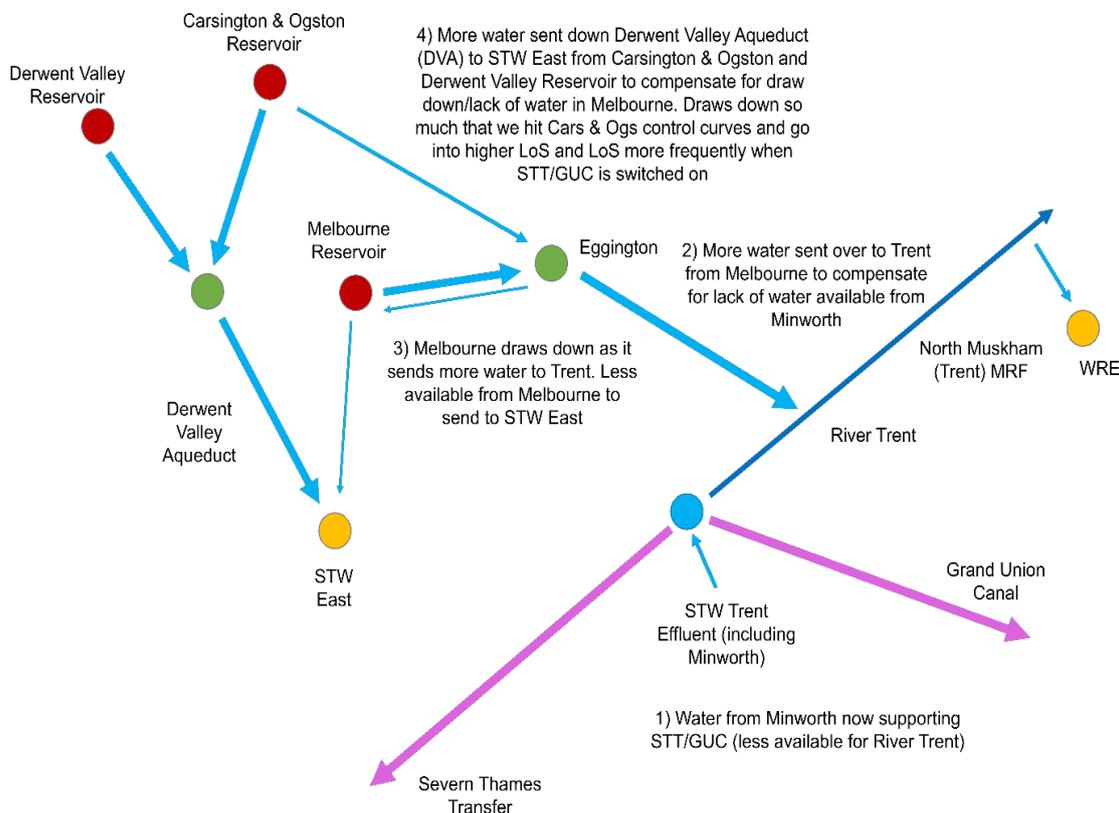


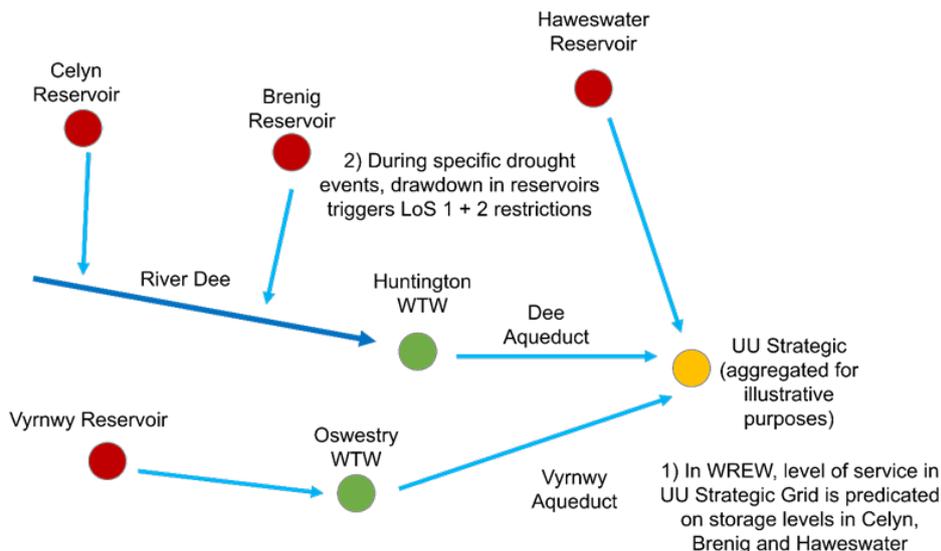
Figure 28. Model behaviour around WRW/WRSE/WRE in WREW (A) without and (B) with strategic supply options

3.4.5.2.2 United Utilities

In WREW, level of water use restriction/level of service triggers in UU Strategic WRZ are based on storage levels observed across Dee Group Reservoirs (Celyn & Brenig) and Haweswater (Figure 29 A).

The increase in days of water use restriction (Levels 1 + 2) observed in UU Strategic when strategic supply options are switched on are the result of increased drawdown observed in WREW at Dee reservoirs. When STT is switched on, water from Vyrnwy is diverted to the SE, with less water available from this source for UU's Strategic WRZ (Figure 29 B).

A) Without SROs:



B) With SROs:

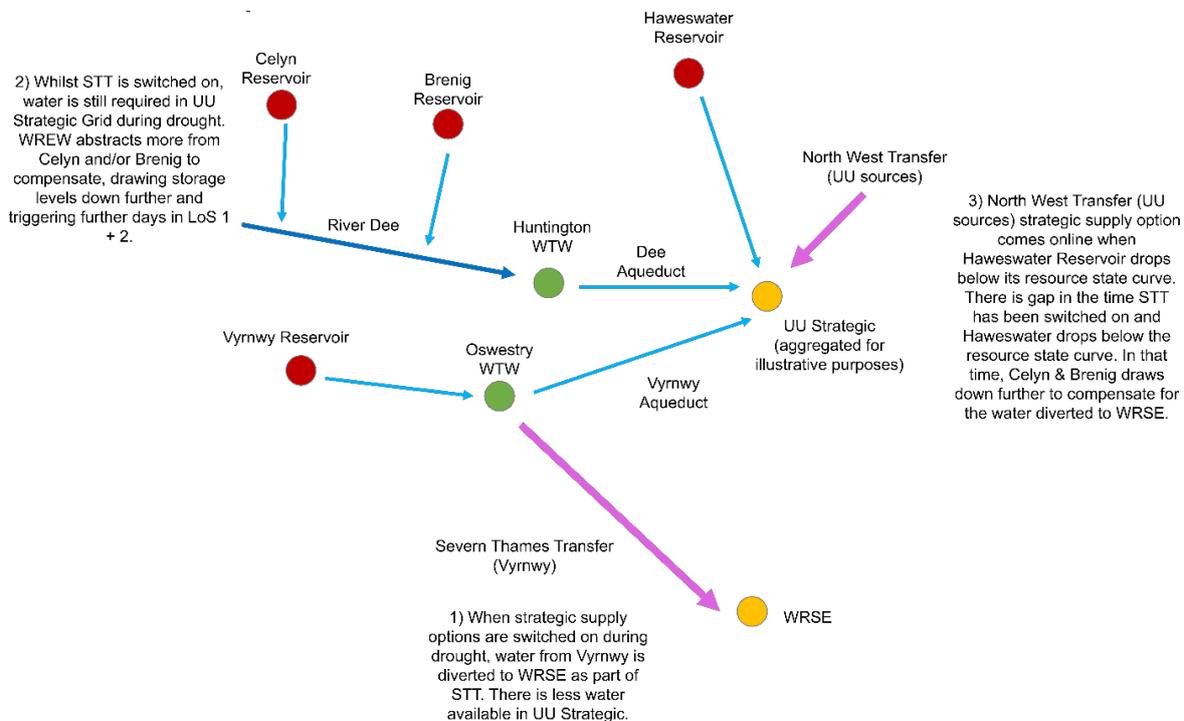


Figure 29. Simplified representation of the baseline model behaviour experienced in WREW surrounding the United Utilities Strategic WRZ in specific WRW/WRSE/WRE drought events (A) without and (B) when strategic supply options have been switched on

North West Transfer (UU sources) strategic supply option has been put forward as a way to compensate for this water being sent to WRSE. In WREW, North West Transfer is implemented to come online if Haweswater Reservoir storage drops below the resource state curve. In these specific drought events, STT has been switched on, sending water to WRSE but in drought, the water is still required in UU Strategic WRZ. Haweswater has not yet dropped below the resource state curve so UU sources have not yet come online to fill the gap. WREW instead, abstracts more from Celyn and/or Brenig to compensate, drawing storage levels down and triggering further days in levels of WUR 1 + 2 in UU Strategic WRZ.

3.4.5.3 Likely actual impacts

It is important to note that the model behaviour of disbenefit observed in WRW when Solutions are switched on is strictly an artefact of the national model's topology and priorities (for more information see Section 3.4.5.2.1). In reality, this disbenefit to WRW would **not** be observed (e.g. operationally there would **not** be more days in water use restriction observed in SvT/UU's system) and instead there would be:

Severn Trent System:

1. Additional time below the North Muskham HOF as water is transferred to WRSE via STT/GUC. Flow on the Trent would drop further than already observed in these drought events (which may not be acceptable in light of protecting the environment, navigational purposes or other abstractors) and this would result in less water available for abstractors further downstream on the Trent; or
2. Changes to the use of Minworth supporting STT and GUC to avoid these effects. There may simply be less water available to send to WRSE/WRE from Minworth as part of STT and/or GUC (and ultimately, we would expect lower performance of STT/GUC in WRSE during these drought events).

The sensitivities observed around North Muskham and Minworth are corroborated by more detailed environmental flow modelling that is currently taking place within the Environment Agency. Further work is needed to explore these impacts and identify options for mitigation (e.g. lowering the HOF, using bankside storage to release water when HOF is reached), these options could be tested in additional scenarios in WREW in the future.

United Utilities System:

1. The location or connectivity of North West transfer sources would be located within United Utilities network in areas that provide more benefit to Dee storage, and less benefit to Haweswater. This would balance the system better than the representation in the WREW model and avoid the effects described above; and/or
2. Operational control rules within United Utilities system would be reviewed to balance the system and have the same effect as 1; (e.g. operationally, North West Transfer (UU sources) would likely come online earlier, not only if/when Haweswater Reservoir storage drops below the resource state curve, or west to east transfers within United Utilities system could be used in a different way); or
3. In the unlikely event that 1 or 2 did not achieve the desired effect, less water could be available to send to WRSE from Lake Vyrnwy. Optimisation across WRW and WRSE could provide a different balance in terms of likelihood and duration of water use restrictions, while protecting levels of service for all the water companies involved.

4 Conclusions and Next Steps

The Phase 2 results presented in this report improve on, and go beyond, the preliminary results presented in the NSSM Phase 1 report. The results demonstrate the key utility of the WREW model in exploring the behaviour of RAPID strategic supply options against a wide range of future conditions and providing key insights for decision makers.

4.1 Conclusions

The Phase 2 outputs demonstrate the potential national resilience benefit gained as a result of the Solutions either in isolation or in combination with other Solutions. The key findings from the detailed results and analysis presented in Section 3 are set out below.

4.1.1 Drought resilience benefit

The set of strategic solutions being considered in regional planning is effective at removing or greatly reducing the risk of failure at **key areas** of water stress in WRSE and WRE. The drought resilience benefit to WRSE is provided by a combination of solutions, including: SESRO, STT, LER, T2ST and T2AT. In contrast the benefit to WRE is driven by two solutions; the SLR and Fens Reservoir solutions. The drought resilience benefits associated with the preferred portfolio of RAPID solutions is observed under a scenario, including:

- 2050 levels of Public Water Supply demand, including demand-side options for meeting a water company target of 110 l/h/d level of PCC and 50% leakage reduction targets;
- Environmental destination as per emerging regional plans (Jan 2022);
- An event-set of $\leq 1:500$ duration drought events, spanning 2,340 years of possible future climate between 2020 and 2050.
- Analysis of time series for storage levels in SLR during drought events indicates that more water could be available for release to further increase the benefits with the WRE region.

The lack of model calibration for key areas of water stress in the WCWR region means that it is not possible to confirm whether strategic solutions alone would be able to meet water needs. **Solutions are resilient against uncertainty in supply and demand.**

Strategic solutions display limited sensitivity to scenarios with higher demand for water, both in terms of potable supply and for the environment, as well as a scenario with reduced supply due to more extreme climate change. This suggests there are enough strategic options being considered in regional plans to provide benefits to **key areas** of water stress in the face of uncertain, but plausible, possible future conditions. A notable increase in the probability of failure for WRZs in the Affinity Water Central region indicates that the boreholes providing the principal source of supply for the WRZs are susceptible to more extreme climate change.

The largest changes in drought resilience are brought about by a more extreme future of climate change. However, the simplified approach to other modelling scenarios, such as the environmental destination scenarios, may have influenced their impact on drought resilience.

The model calibration issues mentioned above for the WCWR region, prevent any conclusions being drawn around whether the strategic solutions would be able to meet additional pressures on water supply or demand.

4.1.2 Stress tests

Removing individual strategic solutions has been shown to have a limited impact on the overall drought resilience benefit, in terms of probability of failure, of the set of solutions being considered in the WRSE regional plan. The increase in the scale of potential deficits when SESRO or the supported component of STT are removed is similar in size to the amount of water the missing solutions supply. Only a small increase in the size of supply shortfalls occurs when the unsupported component of the STT solution is removed, suggesting that this part of the STT solution is not available during the more severe droughts that cause failure in WRSE. Removing the GUC solution drives a more substantial increase in the size of supply shortfall compared with removing SESRO, or elements of STT. This result is a function of the inherent resilience of re-use options and how GUC is configured in WREW, with supply available at any time compared with STT and SESRO that must be triggered by reservoir drawdown.

The WRE regional is notably impacted by the removal of the SLR: this suggests the region is more susceptible to a change in a potential change in solutions. When SLR is removed, the only remaining

solution available for WRE is the Fens Reservoir, which supplies different parts of the region than SLR. The lack of connectivity with other regions, or the representation of other local supply options in WREW, means the missing supply from SLR cannot be replaced.

4.1.3 Effects of droughts on donor and recipient areas

When looking at the probability of a supply shortfall, or water use restriction, occurring across all climate replicates (i.e. 2,340 years of different possible future climate conditions), no marked trade-off in drought resilience is observed between the WRW areas that supplies water and the recipient area (WRSE). The overall occurrence of water use restrictions is slightly *less* frequent with the STT and GUC in place compared to the baseline situation. This indicates that the support options for these transfers deliver their intended function of maintaining resilience in donor areas.

Analysis of the sensitivity of solutions to specific spatial and temporal patterns of drought has revealed that the STT and GUC solutions are affected by five WRW-WRSE focussed droughts due to the interaction of Minworth and the River Trent. The resilience impact of the solutions is seen in WREW as an increase in use of water use restrictions for donor WRZs in the WRW region in these five droughts. However, in reality the resilience of the donor region would likely be maintained. The increase in water use restrictions is likely to be an artefact of the WREW model configuration, or in any case could be mitigated through changes to design of the SROs or wider system optimisation. Mitigation measures, such as bankside storage, may be required to maintain supply from Minworth to STT and GUC, whilst also ensuring security of supply for downstream non-public water supply abstractors.

It should be noted that the five WRW-WRSE focussed droughts isolated from the w@h2 event set are relatively rare events. They represent only a small proportion the 2,340 years simulated in WREW, with a likelihood of 1 in 468 years. By contrast there are 288 events that cause a water use restriction for WRZs in the WRW region, so these five events also represent a small proportion (2-5%) of the total of the drought events affecting WRW. These five events represent more severe events in the w@h2 dataset, since the accumulated deficit-based return period for these events can range up to 1:333 but are notably still below 1:500. Overall, the Solutions provide benefit to resilience for both WRW and WRSE.

4.2 Next steps

The development of WREW will continue beyond Phase 2, with an aim to further improve the confidence in the model, where needed, and use the tool to better understand how the water supply system of England and Wales may behave under future socio-economic and climatic conditions.

The sections below describe possible Phase 3 development activities and outline the intended future use of the model.

4.2.1 Further model development

4.2.1.1 Improve the representation of London water system

Engagement with Thames Water identified several components in WREW's representation of the London Water system which could be improved. The current representation in WREW has several limitations:

- WREW currently uses a single demand node to represent London demand and a single reservoir node to represent the London Storage Reservoirs. The Thames Water Aquator model, in contrast, has five demand nodes and three reservoir nodes. In comparison, WREW oversimplifies of the London network;
- Over-simplification of the network means that the WREW model may not pick up sub-WRZ issues for example should there be large sustainability reductions on the River Lee (as the environmental destination guidance suggests);
- Over-simplification of abstractions and effluent returns along the Lower Thames is likely affecting the simulation of flows downstream at Teddington and Fieldes Weir. Misrepresenting these flows by +/-10% will have repercussive impacts on other parts of the model;
- WREW is missing the Thames-Lea Tunnel, which can transport 400Ml/d under London to Walthamstow. This tunnel will play an important role in supplying water to North London if sustainability reductions in the Lee Valley are large;
- The primacy of abstraction from the Thames to Affinity Water Resource Zone 6 is unlicensed in WREW, which will likely exacerbate impacts on the Thames London reservoirs; and
- Over-estimation of storage in the London Reservoirs may be caused by differences in hydrology, particularly in the Colne and Wey catchments.

In Phase 3 efforts will be made to improve the representation of London's supply network in WREW. Proposed solutions include:

- (a) splitting out WREW's London demand node into three demand centres to account for differences in system behaviour and sensitivity in the north;
- (b) adding the Thames-Lea Tunnel and Thames Water ring main to the model;
- (c) Controlling model behaviour for the prioritisation of demand between London and the Teddington environmental constraints;
- (d) refining the 'licence of right' abstraction from the River Thames to Affinity Water's WRZ6, and further investigation of groundwater behaviour within the water resource zone, and;
- (e) further analysis of DECIPHeR inflows to WREW in the Thames Basin, with particular regard for the Colne and Wey catchments, and also how well DECIPHeR simulates high baseflow rivers.

4.2.1.2 Refine sustainability reduction scenarios

The number of scenarios used to test RAPID's Strategic Supply Options was increased in Phase 2 to allow for testing of uncertainty in potable demand and water needs of the environment.

As explained in Section 2.8, the Phase 2 work used data submitted by regional groups and water companies to develop multiple environmental destination scenarios. However, as a result of the broad range of ambition and no mandatory level of environment destination to achieve, there is an inconsistent national picture of environmental destination. This 'patchwork quilt' has made it difficult to reduce individual licences in WREW, so instead environmental destination figures (reductions in deployable output) were accounted for in WREW by adding them onto the demand volume for each WRZ. Further engagement with water companies in Phase 3 will help to better represent reductions in deployable output across specific licences in WREW and therefore improve confidence in the scenarios used to test RAPID's supply options. Add supporting non-RAPID Strategic Supply Options and intra-regional transfers

Whilst best efforts have been made to include all planned changes to water companies supply networks (e.g., Anglian Water's Strategic Pipeline Alliance, United Utilities' Sources), various future supporting supply options are not included in WREW.

Non-RAPID supporting supply options to add to WREW in Phase 3 include inter-regional WRSE transfers which can distribute RAPID supply options around the region, and intra-regional imports and exports within WCWR. This is particularly significant for the WRE region, which indicates large volumes of desalination and/or re-use are required to achieve resilience in addition to the Solutions.

4.2.1.3 Improve the representation of West Country's system

Simulation exercises conducted in Phase 2 revealed a persistent water supply deficit of ~160 Ml/d across the Wessex region, causing shortfalls in Bath and Chippenham, Warminster and Salisbury, Dorchester and West, and Parrett demand centres. Further investigation revealed inaccurate and missing groundwater sources in WREW's Wessex Water network, and missing sources in South West Water's Roadford WRZ.

In Phase 2 this issue was accounted for when post-processing the simulation results. However, in Phase 3 further work is required to ensure all missing and inaccurate water sources are accounted for. Improvement of the representation of the West Country's water supply network in WREW is necessary to improve confidence in the future simulation of WCWR supply options and identification of any real threats to the region's water supplies.

4.2.1.4 Analysis of WREW's empirical groundwater model during key historic droughts

In Phase 2 the geographic coverage of model validation was extended to include more reservoirs across England and Wales. In addition, a validation exercise was conducted to compare WREW supply-demand balance outputs with regional planning data.

In Phase 3 a third validation exercise will be completed to assess the performance of WREW's empirical groundwater model during key historical drought events. This will be important for evaluation of strategic supply options which supply regions that rely heavily on groundwater sources during critical periods. Furthermore, the analysis will help to understand trends observed in Phase 2 simulation experiments, such as the supply-demand validation exercise presented in Section 2.10.3 which revealed discrepancies in the supply-demand balance of several groundwater-reliant WRZs.

In addition, longer-term solutions for improving the representation of groundwater in WREW will be scoped in Phase 3. For example, the simple empirical approach for modelling groundwater inputs in WREW could be replaced with more sophisticated lumped or distributed modelling approaches.

4.2.1.5 Improve the system representation of Wales' water resource system

Key areas of Wales' water supply system are represented in WREW, including the Alwen/ Dee WRZ, Lake Vyrnwy, Clywedog and Elan Valley Reservoirs, the Twyi and SE Wales Conjunctive Use System, and the WRZs in the River Wye region.

As described earlier in the report, the control curves for various Welsh reservoirs were updated in Phase 2, in addition to improvements to the Severn regulation rules. Whilst these updates have improved calibration of the Welsh system, further improvements are necessary to build confidence in model outputs for the Welsh assets and demand centres. These further improvements include:

- Inclusion of the Dee General Directions (DGD) operating rules for the Dee Reservoir Group (including Alwen Reservoir, Llyn Brenig, Llyn Celyn and Llyn Tegid) and testing of reservoir release behaviour (NB: UU control curves and operating rules around the Dee Reservoir group are already implemented in WREW);
- Better calibration of Dee inflow at Chester, which appear ~30% higher than historic observed flows;
- Improved representation of abstractions and license constraints along the River Wye; and
- Update WTW outputs and effluent returns in the Wye region.

4.2.1.6 Further investigation on the validity of WREW outputs using reservoir storage and comparison with regional planning data

Despite the updates to the supply system representation in WREW that have been made during phase 2, large differences in simulated storage between WREW and water company modelling remain for several reservoirs. These differences highlight areas of the model where WREW outputs cannot be fully validated and supply system behaviour could be better calibrated. However, they may also be a function of hydrological inputs or the fundamental difference in scale between national and water company models. Further work is required to investigate and better understand the root cause of the differences in storage, including:

- Testing simulations in WREW using water company inflow data, in order to assess the degree to which hydrological inflows are responsible for the observed differences in storage;
- Comparing simulated storage from WREW with observed storage levels, which represent a more robust dataset for validation against; and
- Explore whether the greatest discrepancies in simulated storage correlate with specific spatial and temporal patterns of drought.

In addition to reservoir validation, further work is required to improve the national level validation of WREW outputs against the supply-demand balance from region plans. A fairer comparison could be achieved by accounting for headroom and outage in WREW as well as omitting benefits from demand savings. Investigation of the relationship between drought characteristics and supply system failure

The statistical analysis of the drought events in the w@h2 database allows for the characterisation of risk via a number of different metrics. For the purpose of this report the accumulated deficit metric was used to filter out >1:500 severity events to test against the RAPID solutions in WREW. Applying a return period filter based on >1:500 duration events would yield a different event set with which to test the solutions. More work is needed to understand which drought metric best describes the impact of a drought event of the water supply system. In addition to assessing droughts based on climatological return period, the 1:500 system response standard (0.2% per annum system failure probability) should also be explored in WREW. This standard is preferable since it overcomes the issues of timing and duration when return period is evaluated using rainfall, and it captures aspects such as system constraints, conjunctive use capability and operational response.

Furthermore, the drought characterisation outputs from statistical analysis of the w@h2 dataset allow for a bottom-up analysis on the nature of droughts that cause supply system failure. For example, the drought events that cause supply shortfalls or water use restrictions can be described spatially, temporally and volumetrically and assessed for commonalities. This approach would provide insight on the type of droughts that specific parts of the supply system are sensitive to and if/how the RAPID solutions can act to mitigate these susceptibilities and improve resilience.

Emerging results from the eFLaG project suggest that widespread summer droughts across the UK will become more common (Tanguy, in prep). This has the potential to impact summer water transfers considerably and so the national scale droughts in the w@h2 event set should be compared with those

identified in the latest eFLaG products. Any similar events can be tested in WREW to explore the implications for long-distance transfers such as STT.

4.2.1.7 Account for Outage

The configuration of the water supply network in WREW means that supply is limited only by the availability of water and operational rules that constrain the system. In reality, supply can also become temporarily reduced by planned events, such as maintenance, and unplanned events, such as power failures or pollution events. These short-term losses of supply and source vulnerability should be accounted for in WREW since they represent an additional risk for maintaining security of supply.

4.2.1.8 Additional development activities

Continued stakeholder engagement in Phase 3 will help make the following minor improvements to WREW:

- Refinement of Anglian Water's water supply network and licencing of surface water sources;
- Calibration of South Staffordshire's supply network, including the system response to changes in Hampton Loade licencing;
- Updates to the configuration of United Utilities future supply options;
- Updates to the configuration of the Upper Derwent Valley Reservoir Expansion;
- Analysis and calibration of Affinity Water's Lilley Bottom groundwater sources during critical drought events; and
- Analysis and calibration of the Gloucester-Sharpness Canal, with a focus on behaviour of abstraction during critical drought events.

4.2.2 Further use of the model

With water company supply networks and RAPID solutions now updated and built into the model, Phase 2 of the project has marked a shift toward using the model to create national-scale evidence on the benefits and trade-offs of the solutions in the RAPID programme.

Whilst further development of the model and the solutions will continue, such as set out above, the model is considered to be sufficiently robust and be used to meet the objectives of the NSSM project set out in Section 1.1. The next phases of the project may utilise the model in the following ways to continue work against these objectives:

- **Continue to work with the regional groups and RAPID solution teams on the emerging conclusions from Phase 2, and what this may mean for the development of the regional plans**

This includes concluding reasons behind lower benefits observed in WCWR, maintaining resilience in WRW's region in addition to supporting inter-regional transfers, and the resilience of WRE's plan in sensitivity scenarios.

- **Explore the benefits and trade-offs of the preferred portfolio of RAPID solutions, following the Regional Group's second round of reconciliation**

This may follow similar approaches to the Phase 2 work, which explored the preferred portfolio emerging from the first round of reconciliation. This will involve using utilisation as a way of examining how individual solutions contribute to the performance of the portfolio as a whole, as well as combining cost and drought resilience benefit for a more complete view on solution performance. The model may also allow for insight on which type of solution (e.g., re-use, transfers, reservoirs) can provide the greatest drought resilience benefit.

- **Updating RAPID solutions to their preferred option configuration emerging from the Regional Group's second round of reconciliation, and presented in RAPID solutions forthcoming Gate 2 submissions**

This will support the independent evidence base behind RAPID's assessment of the solution submissions at Gate 2.

- **Utilising modelled outputs to support regulators' review of published draft Water Resources Management Plans and Regional Plans**

Model outputs may allow for examining the number and types of options presented in the plans, and justify the need for low utilised options.

- **Use the model to test potential benefits from available resource and transfers not yet proposed in the RAPID programme or in WRMPs and Regional Plans.**

Specifically, this may explore benefits associated with a transfer from Kielder to WRE/WRW by using the WERE model to see if it supports the evidence from regional modelling as to why this transfer is not selected.

- **Understanding the impact of regionally and nationally-focused drought events on the resilience of the preferred portfolio of RAPID solutions**

Including the benefits and trade-offs of inter-regional transfers during regionally-focused severe droughts. This furthers the analysis started in Phase 2, detailed in Section 3.4.4. Additional analysis is also required on how national scale droughts might affect water transfers, since recent results from the eFLaG project suggest these events are likely to become more common.

- **Testing RAPID-led queries and scenarios on the preferred portfolio of RAPID solutions, or on specific RAPID solutions configurations**

Specifically, this may look at trade-offs between shared supporting solutions, such as Minworth supporting STT or GUC, multiple regions calling on STT resource, and the role of RAPID solutions that have otherwise not been selected in the preferred portfolio of solutions. The interactions of multiple schemes with the River Trent (GUC, STT and SLR) is particularly complex and would benefit from analysis using WREW.

Appendices

Appendix A – Statistical interrogation of the w@h2 drought event set

Work has been undertaken by the University of Oxford, which replicates the drought characterisation method developed by CEH (2019, draft) to identify drought events across the w@h2 baseline, near future and far future ensembles.

A.1 Calculation of drought risk

A1.1 Calculation of monthly deficit from drought threshold per region per scenario

Calculation of monthly precipitation and effective precipitation deficits follows the method outlined by the Centre for Ecology and Hydrology (Svensson and Mastrantonas, in prep), following the steps described below:

1. Drought events were extracted based on occurrences below a threshold of two meteorological variables: 1) precipitation, and 2) effective precipitation, ($P_{eff} = \text{precipitation} - \text{potential evapotranspiration}$) for the UKCP18 river basin regions.
2. Gridded monthly values of precipitation and P_{eff} were aggregated spatially for each region, r .
3. Two drought thresholds were used for each meteorological variable as the 50th and 20th percentiles from the baseline w@h2 scenario¹⁴.
4. For each climate scenario, cc , region, r , calendar year, y , and month, m , and b , deficits were calculated as the deviation of precipitation or P_{eff} from the monthly mean across the W@H2 baseline record, b . :
 - $D_{50,cc,r,y,m} = (\text{precipitation}/P_{eff, 50,cc,r,y,m} - \text{precipitation}/P_{eff, b,r,m}) (-1)$
 - $D_{20,cc,r,y,m} = (\text{precipitation}/P_{eff, 20,cc,r,y,m,r} - \text{precipitation}/P_{eff, b,r,m}) (-1)$

A1.2 Definition of a drought event

A drought event is defined as occurring when a single month, or several months in a row, have a positive effective precipitation deficit. The total accumulated drought deficit is defined as the sum of the monthly deficits during the event. However, a short spell above the threshold may not be considered a sufficient reason to keep two short drought events separate, rather than merging them into a single, longer event. For the present study, shorter droughts were pooled together into a single longer drought under the following circumstances (after CEH (2019, draft)):

1. Drought events separated by only a single month of surplus were pooled together, as long as the surplus of this one month was smaller than the total accumulated deficit of the preceding drought event;
2. The total deficit of the pooled event is the sum of the accumulated deficits for the two drought events, minus the surplus during the month that separates them;
3. When two events were pooled and there was again a single month of surplus between this and the next drought event, then the accumulated deficit of the already pooled event was compared with the next surplus, and the new drought event was added to the already pooled event provided that the total deficit of the already pooled event exceeded the surplus; and

This procedure was repeated as necessary. Only events with an accumulated deficit greater than 0.01 were included in the analysis.

A1.3 Drought event risk output

Each drought event was characterised by three metrics:

- The duration of the drought event [unit: months];
- The accumulated deficit during the event [unit: mm]; and

¹⁴ Q20 and Q50 are the monthly precipitation / effective precipitation totals that are surpassed 80 and 50 per cent of the time, respectively.

- The maximum monthly deficit during the event [unit: mm/month].

Drought events generated across the 100 w@h2 ensembles provide an event set where the maximum return period is equivalent to the number of years simulated by a given climate scenario (e.g., 30 years for Near Future scenario) multiplied by the number of ensemble runs (i.e., 100).

A.2 Results

Results are presented for the UK as a whole, and also for the regions shown in **Figure 30**.



Figure 30. The UKCP18 river basins used to spatially split the statistical analysis of the w@h2 dataset¹⁵

A2.1 Return periods

Figure 31 and **Figure 32** are provided as examples¹⁶ of the outputs generated from the analysis. The figures show the return period for each metric. The maximum return period shown on the charts is 3,000 years (30 years (2020-2050) * 100 ensembles).

The start of a drought episode is characterised by the month in which precipitation or Peff is lower than the drought threshold (Q20 or Q50).

Each figure shows three separate charts, as follows:

¹⁵ The supporting data can be accessed via: <https://github.com/ukcp-data/ukcp-spatial-files>

¹⁶ The full set of results can be found here: <https://ricardo.box.com/s/xlcg7kv1m6nbutlqqghz2cwnhzdiz7ov>

- The first chart, “*Months of drought*” shows droughts with different length in the near future event set such that each dot represents an event and its scarcity in the dataset; and
- The second chart, “*Intensity*”, shows the maximum monthly deficit over the period of each drought event, measured in mm/month.
- The third chart, “*Accumulated deficit*”, is the volume of deficit over the period of the drought, measured in mm. It is therefore a function of both drought duration and intensity.

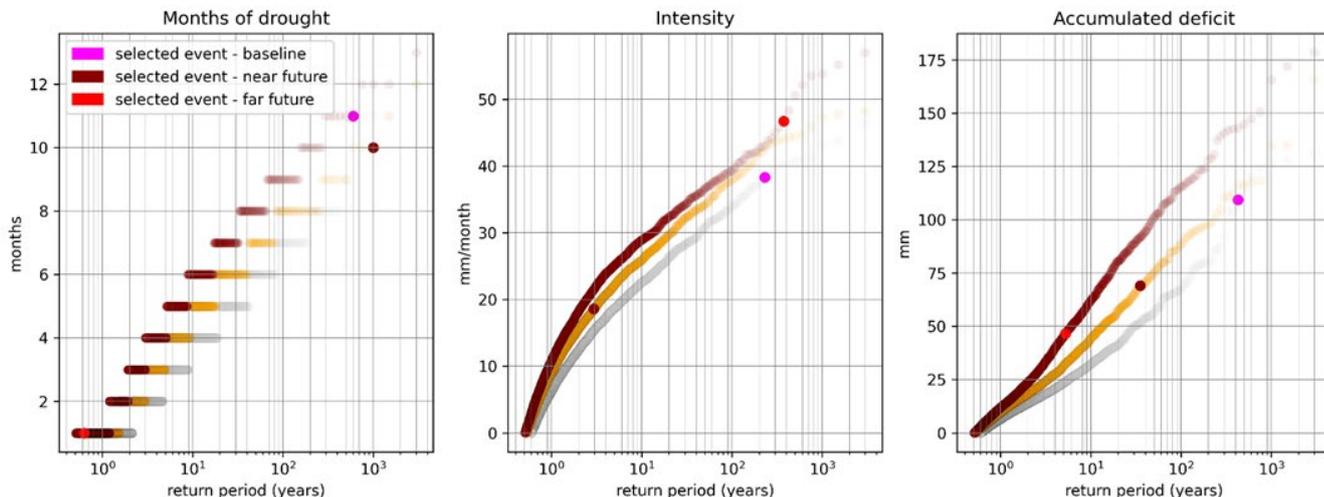


Figure 31. Example plot showing the same drought event expressed across each metric

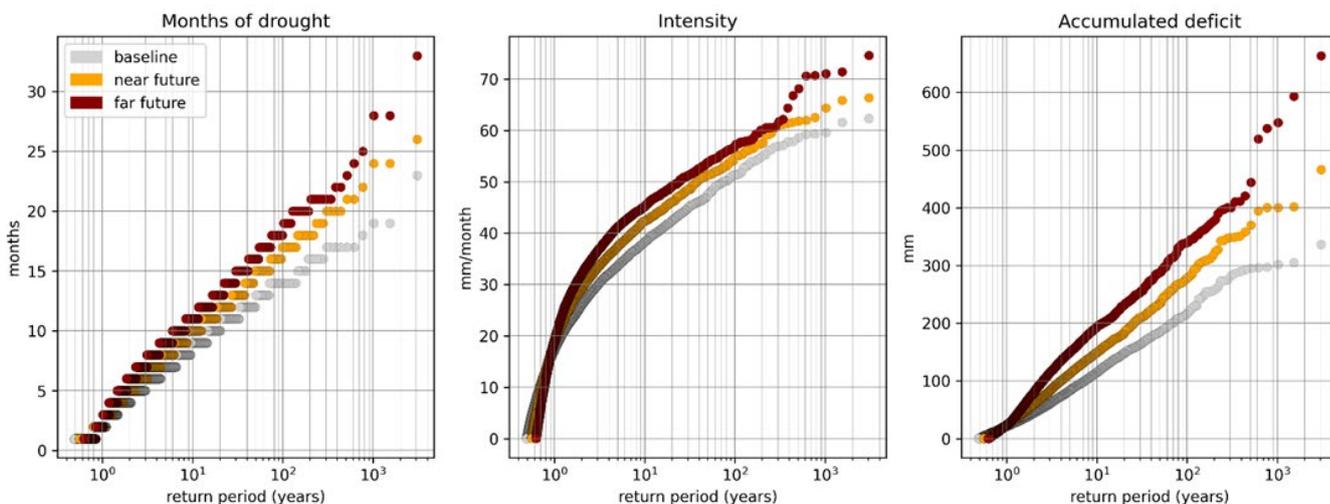


Figure 32. The results for the three metrics for the UK as a whole, showing the 50th percentile (Q50%) of effective precipitation (Peff) from the baseline W@H scenario

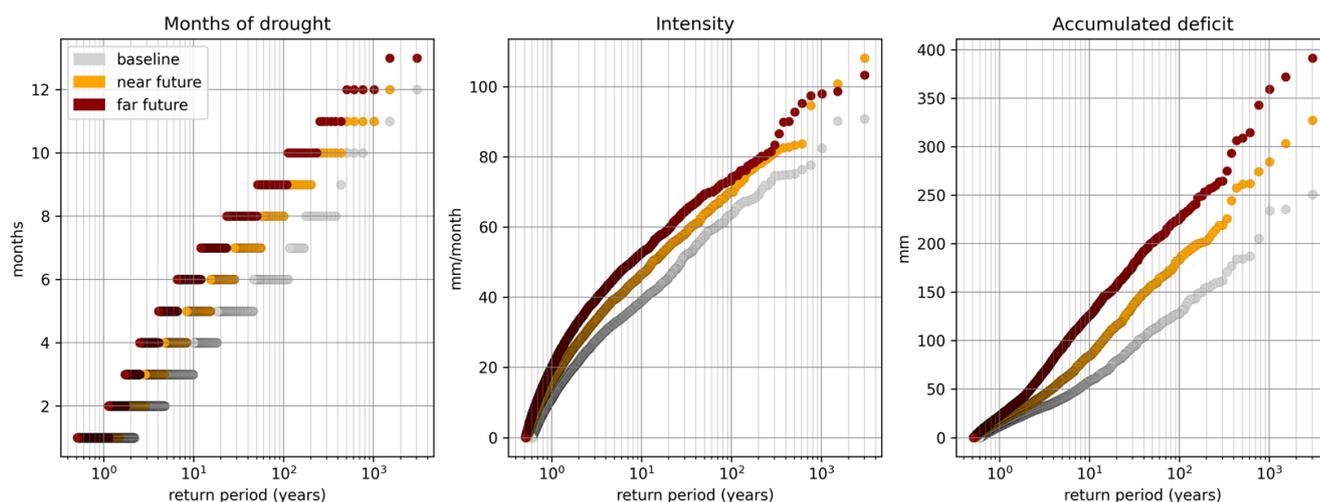


Figure 33. The results for the three metrics for the SE England region, showing the 20th percentile (Q20%) of effective precipitation from the baseline W@H scenario

Figure 31 shows the results of the three metrics with a particular event that represents the same event, characterised by the three different metrics. One can observe that a given drought event may be relative extreme in terms of one metric and less extreme in terms of another.

For the UK as a whole, both **Figure 31** and **Figure 32** show that the drought metrics become increasingly severe in the near and far future, when compared to the baseline. **Figure 31** shows that the w@h2 event set includes a drought of >30 months in duration, which has a return period of 1:3,000.

Table 8 shows the extracted 200- and 500-year drought events in terms of their duration for each region.

Additional results¹⁶ from the analysis include the identification of all identified drought events, i.e., driven by precipitation and effective precipitation, based on two different thresholds (Q50 and Q20), across three climate scenarios (baseline, near future and far future) – characterised by the three different metrics (duration, intensity and accumulated deficit). The outputs include the timing of each drought event, the corresponding region, the magnitude (number of months for duration, mm/month for intensity and mm for accumulated deficit) as well as their return period. These results can be used to understand how drought events correlate between regions, their likelihood, extent and duration or severity now and in the future, based on the w@h2 dataset.

Table 8. The extracted 200- and 500-year drought events in terms of duration (in months)

<i>Region</i>	<i>Baseline</i>	<i>Near Future</i>	<i>Far Future</i>
200-year return period			
Duration of event (months)			
<i>Anglian</i>	14	16	18
<i>Argyll</i>	13	13	14
<i>Clyde</i>	13	13	15
<i>Dee</i>	13	15	18
<i>Forth</i>	13	13	16
<i>Humber</i>	13	16	17
<i>NE Scotland</i>	13	14	15
<i>North Highland</i>	13	13	13
<i>Northumbria</i>	14	14	16
<i>NW England</i>	13	14	16
<i>SE England</i>	14	15	18
<i>Severn</i>	14	16	19
<i>Solway</i>	14	15	15
<i>SW England</i>	14	16	18
<i>Tay</i>	13	14	16
<i>Thames</i>	14	16	18
<i>Tweed</i>	13	14	15
<i>UK</i>	15	16	18
<i>West Highland</i>	13	13	13
<i>West Wales</i>	13	15	17
500-year return period			
<i>Anglian</i>	16	18	20
<i>Argyll</i>	14	15	15
<i>Clyde</i>	16	15	16
<i>Dee</i>	15	16	20
<i>Forth</i>	16	16	18
<i>Humber</i>	15	17	19
<i>NE Scotland</i>	15	16	17
<i>North Highland</i>	15	15	15
<i>Northumbria</i>	15	16	18
<i>NW England</i>	14	16	18
<i>SE England</i>	17	18	21
<i>Severn</i>	14	17	21
<i>Solway</i>	15	16	17
<i>SW England</i>	15	17	20
<i>Tay</i>	16	15	17
<i>Thames</i>	16	18	21
<i>Tweed</i>	15	16	16
<i>UK</i>	17	17	20
<i>West Highland</i>	15	15	14
<i>West Wales</i>	15	16	20

A.3 Application to WREW

For the purpose of Phase 2, drought events have been characterised using the effective precipitation meteorological variable at Q50 threshold from the overall drought event risk outputs described above.

The accumulated deficit of the drought event was used to calculate return period.

Appendix B – Severn Abstraction Licences included in WREW

As stated in Section 2.9.3, the Severn Regulation has been included in WREW as part of Phase 2. **Table 9** presents an overview of the abstraction licences included in the model.

Table 9 Overview of Severn abstraction licences included in WREW

Abstraction Name	Volume abstracted under normal conditions (MI/d)	Volume abstracted under maximum regulation (MI/d)**	Volume abstracted when River Severn drought order is in force (MI/d)	Volume abstracted when Clywedog emergency storage curve is crossed (MI/d)
Llandinam Gravel	18	N/A	17.1	14.4
Shelton	40.45	N/A	38.42	32.36
Hampton Loades & Trimpley*	431	303	287.5	242.4
West Upton /Strensham	167	165	156.75	132
Mythe	120	109	103.55	87.2
Gloucester and Sharpness Canal	245	210	197	168

*Normal conditions include Bewdley above the minimum required flow (MRF). Volumes have been simplified and aligned with Severn Trent Water modelling for the purposes of running a national scale model and may not reflect reality (could be an overestimate of ~31 MI/d).

**Maximum regulation includes 100-day river regulation. Regulation is based on releases from Clywedog and SGS. In reality, releases from Vyrnwy waterbank are also used for regulation, but are omitted from the Severn Regulation rules modelled in WREW.

Appendix C – Further WREW-Regional Plan Validation:

C.1 Technical Notes

A regional plan supply demand balance (SDB) metric was calculated in order to allow a fairer comparison between RP submission data and WREW shortfalls. This is defined as:

- Available Headroom + Demand Savings (PCC Reductions + Leakage Reductions) + *Process Losses*
 - Available Headroom = Total WAFU – Distribution Input
 - Total WAFU = (DO + Baseline forecast changes to DO – *Process Losses*) + Total water imported – Total water exported
 - Process losses (outage & treatment losses) added on to remove them from SDB metric as WREW does not take outage into consideration (which makes up the larger portion of this process losses figure)
 - Not using typical planning table SDB metric (Available headroom – target headroom) as WREW does not take into consideration target headroom

The WREW scenario used for comparison is a near future ensemble, using 2050 DI (including demand savings from PCC and leakage reductions) and 2050 sustainability reductions (using submitted sustainability reductions (patchwork of SR scenarios, mix of BAU+, Enhanced and none)), and no RAPID Solutions are switched on. This is to allow direct comparison to RP figures. Replicates that contain >1:500 RP events have been removed prior to analysis.

C.2 Discrepancies within tolerance

The tolerance threshold for accepting a discrepancy between WREW outputs and Regional Plan forecasts (e.g. observing a shortfall in WREW but no deficit forecast in Regional Plan and vice versa) includes:

- The probability of a shortfall occurring in WREW <0.005 (0.5%)
- Supply shortfall observed in WREW or deficit in Regional Plan Forecast is within 10% of the Distribution Input of the WRZ (at 2050)

Table 10 highlights the WRZs that have an absolute discrepancy between WREW outputs and Regional Plan forecast but were deemed acceptable as they fall within the tolerance threshold stated above.

Table 10 The WRZs that have an absolute discrepancy between WREW outputs and Regional Plan forecast but were deemed acceptable

WCO	WRZ	RP 2050 Deficit?	WREW Supply Shortfall?	Reason for Adjustment (Tolerance)
South West Water	Wimbleball	Y	N	RP SDB metric within 10% of DI (0.06 MI/d)
Severn Trent Water	Wolverhampton	N	Y	Shortfall within 10% of DI (1.8 MI/d)
South West Water	Colliford	N	Y	Probability of shortfall <0.005
Severn Trent Water	Strategic Grid	Y	N	RP SDB metric within 10% of DI (3.5 MI/d)
United Utilities	Strategic	N	Y	Shortfall within 10% of DI (14 MI/d)
South East Water	Bracknell	N	Y	Probability of shortfall <0.005
South East Water	Eastbourne	N	Y	Probability of shortfall <0.005

Appendix D – Reservoir validation

D1 Water Resources East

Water Resources East has a number of important reservoirs including Grafham Water, Rutland Water and Pitsford Water. **Figure 34** and **Figure 35** show the simulated storage levels between WREW and water company modelling for Grafham and Rutland Water. **Figure 36** presents storage levels for Pitsford Water.

The results show that the WREW model exhibits a mixed performance in the WRE region. In Grafham, storage levels are underestimated in 1976, 1991 and 1997, and overestimated in 1996 and 1990. In Rutland, storage levels are consistently overestimated. The mismatch between levels in both reservoirs suggests that the balance of supply across the WRE region may be incorrectly represented in WREW. Further work is required to understand why WREW simulates the drawdown of Grafham at a faster rate than Rutland during drought events.

Despite the disbalance between storage levels, the shape of storage profiles simulated in WREW are similar to the simulated company storage. This suggests that WREW does respond to periods with drier hydrological inputs by drawing down two key reservoirs in the region, and is able to replicate similar stresses to those observed in the water company models.

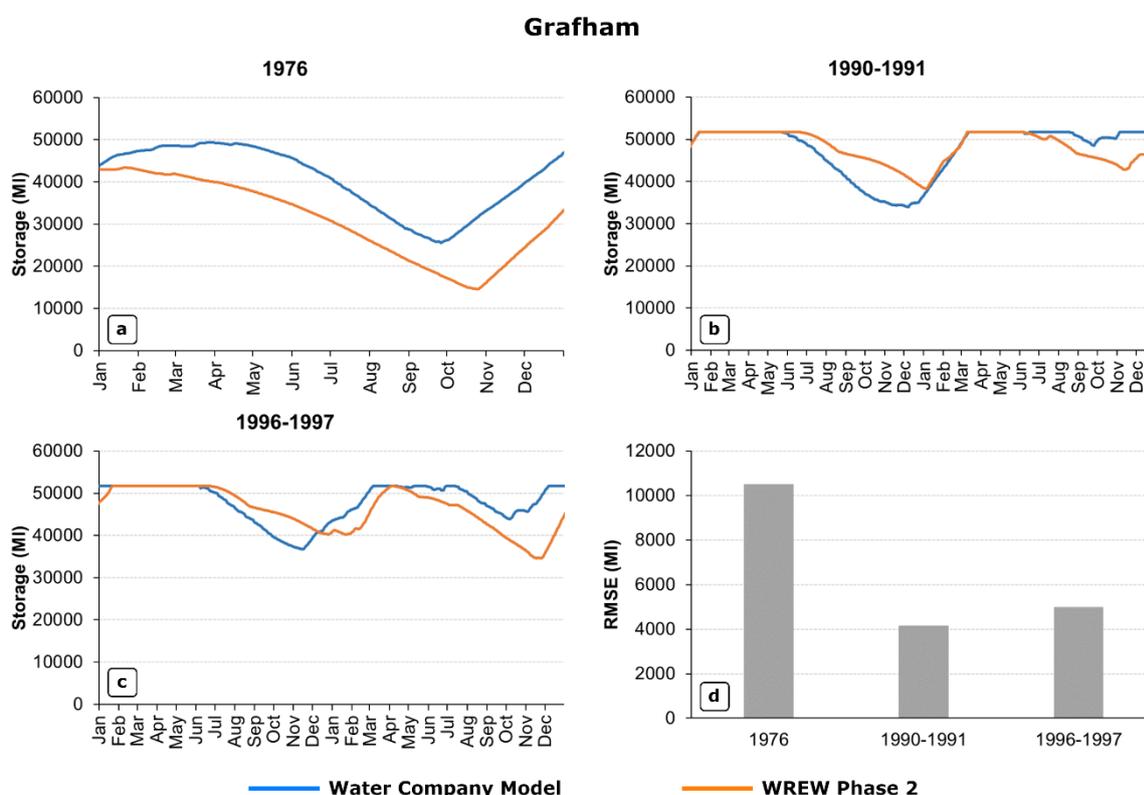


Figure 34. Comparison of Grafham simulated storage from WREW and water company models

Panels a-c show three historic drought events; panel d shows root mean square error (RMSE) between Phase 2 WREW and water company simulated storage for the drought events.

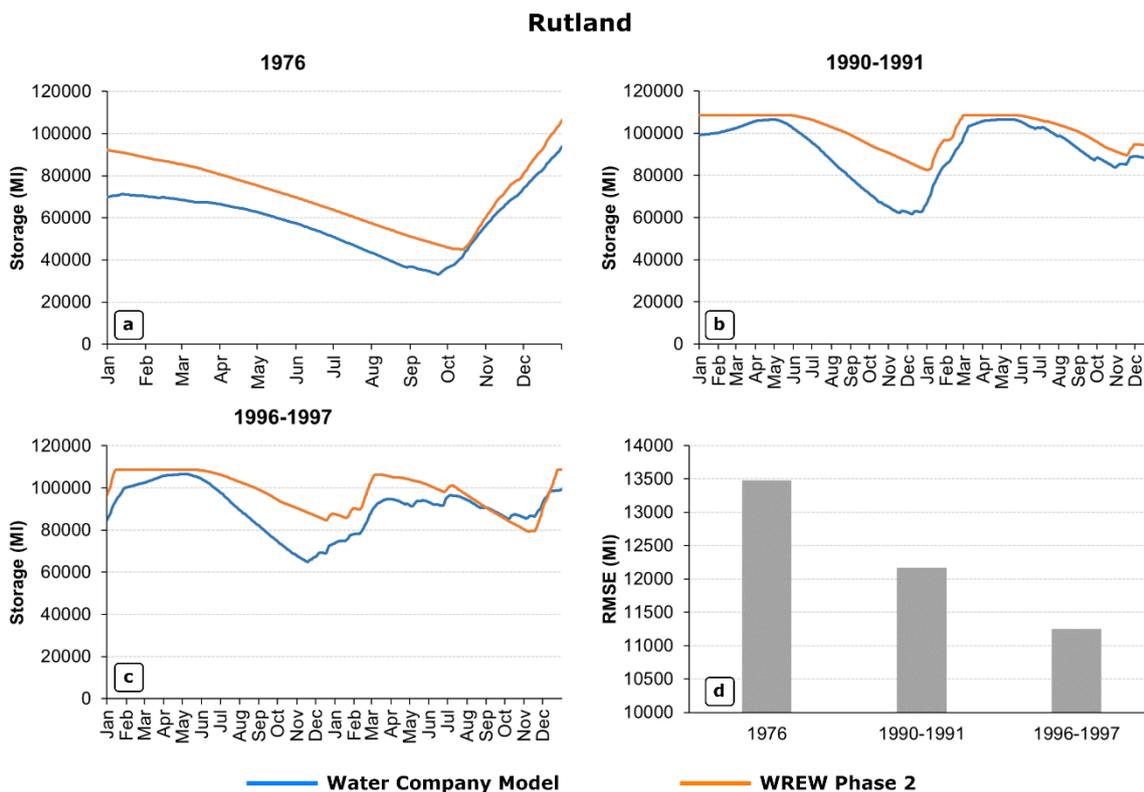


Figure 35. Comparison of Rutland simulated storage from WREW and water company models
 Panels a-c show three historic drought events; panel d shows root mean square error (RMSE) between Phase 2 WREW and water company simulated storage for the drought events.

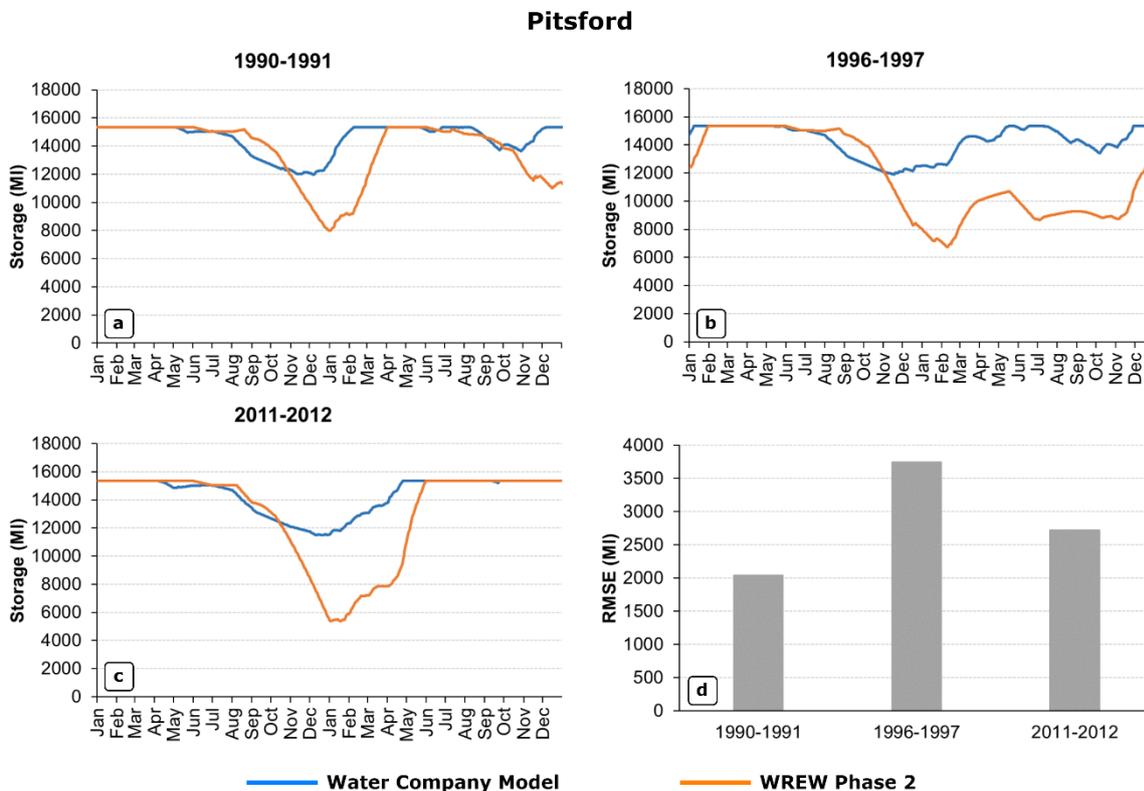


Figure 36. Comparison of Pitsford simulated storage from WREW and water company models.
 Panels a-c show three historic drought events; panel d shows root mean square error (RMSE) between Phase 2 WREW and water company simulated storage for the drought events.

D2 Water Resources West

Water Resources West has a number of reservoirs, with storage in United Utilities, Severn Trent Water, South Staffordshire Water and Dŵr Cymru Welsh Water. Four of Water Resources West’s reservoirs were evaluated in the NSSM project Phase 1 Report: Elan Valley, Derwent Valley, Lake Vyrnwy and Haweswater. These reservoirs have been carried through in the Phase 2 validation exercise, with the additional of Clywedog, Thirlmere and Alwen. Validation plots for Brenig, Celyn, Draycote and Blithfield are also presented in Section D2.7.

D2.1 Haweswater

Haweswater is a key reservoir for the United Utilities Strategic WRZ. **Figure 37** shows simulated storage levels from WREW and water company model. In Phase 1, WREW showed a poor calibration, with storage levels consistently than the water company model. In Phase 2 efforts have been made to improve calibration of Haweswater in WREW, with varied success.

Storage levels better match the water company model during spring, autumn and winter, and are closer in summer when reservoir drawdown occurs. The greatest improvement is observed in the 1995-1996 drought, where simulated storage levels in WREW match water company modelled outputs well. The model still underestimates drawdown in the 1976 and 1984 droughts: the difference in drawdown in 1984 is about 150 – 200 MI/d (similar scale to an SRO). Further improvements can be made, as outlined in Section 4.2.1.6.

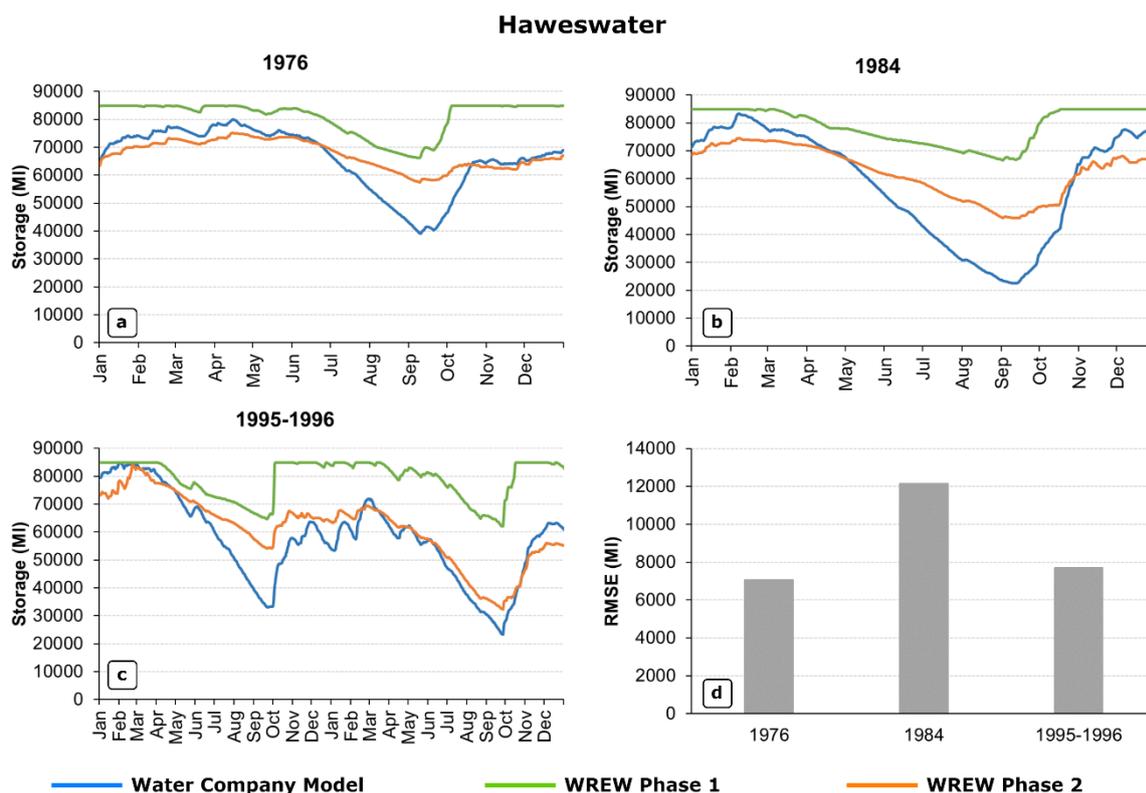


Figure 37. Comparison of Haweswater simulated storage from WREW Phase 1, WREW Phase 2 and water company models

Panels a-c show three historic drought events; panel d shows root mean square error (RMSE) between Phase 2 WREW and water company simulated storage for the drought events.

D2.2 Thirlmere

Thirlmere Reservoir was not evaluated in Phase 1. However, given its important role alongside Haweswater in supplying United Utilities Strategic WRZ it was included in the Phase 2 validation exercise.

Figure 38 shows a good agreement between the simulated storage levels from WREW and the water company modelling for the 1976 and 1984 droughts, and a very good agreement in the 1995-1996 drought. WREW follows the drawdown pattern of the water company model storage in the late summer and autumn months, with minor deviations when the reservoir reaches its lowest levels.

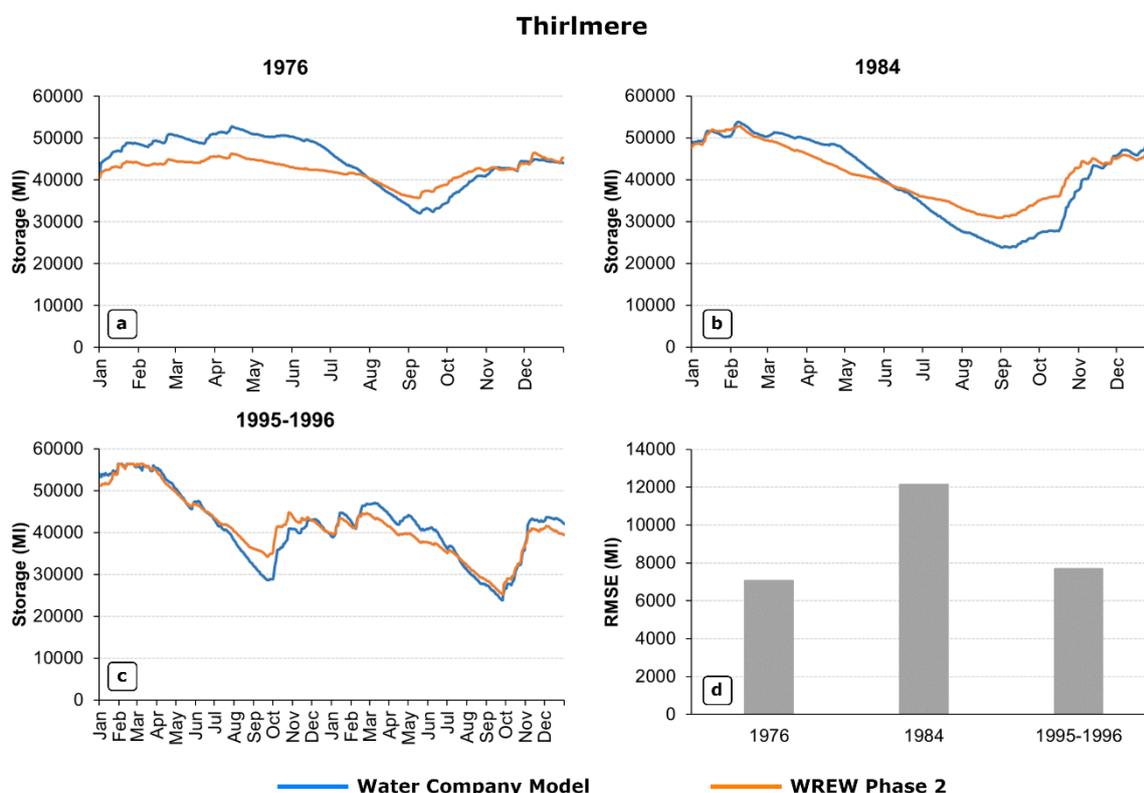


Figure 38. Comparison of Thirlmere simulated storage from WREW and water company models

Panels a-c show three historic drought events; panel d shows root mean square error (RMSE) between Phase 2 WREW and water company simulated storage for the drought events.

D2.3 Alwen, Brenig and Celyn

Alwen, Brenig and Celyn are three of four reservoirs in North Wales' Dee Valley represented in WREW, supplying customers along the Dee and in the southern part of United Utilities Strategic WRZ via the Dee Aqueduct.

Figure 39 shows that WREW's representation of Alwen has good agreement between simulated storage levels from the water company model over the three main drought events, and especially in the 1984 drought. More specifically, the pattern of simulated storage from WREW captures the storage level immediately before the drawdown, as well as the drawdown over the course of a drought event, particularly well. The main discrepancies are the rate of refill being over- or under-estimated. For example, storage is overestimated for the 1976 drought, and underestimated for the 1995-1996 drought. This may arise from other reservoirs along the Dee Valley in WREW, such as Brenig (**Figure 40**), Celyn (**Figure 41**), and Tegid, being utilised differently in the WREW model to the water company model.

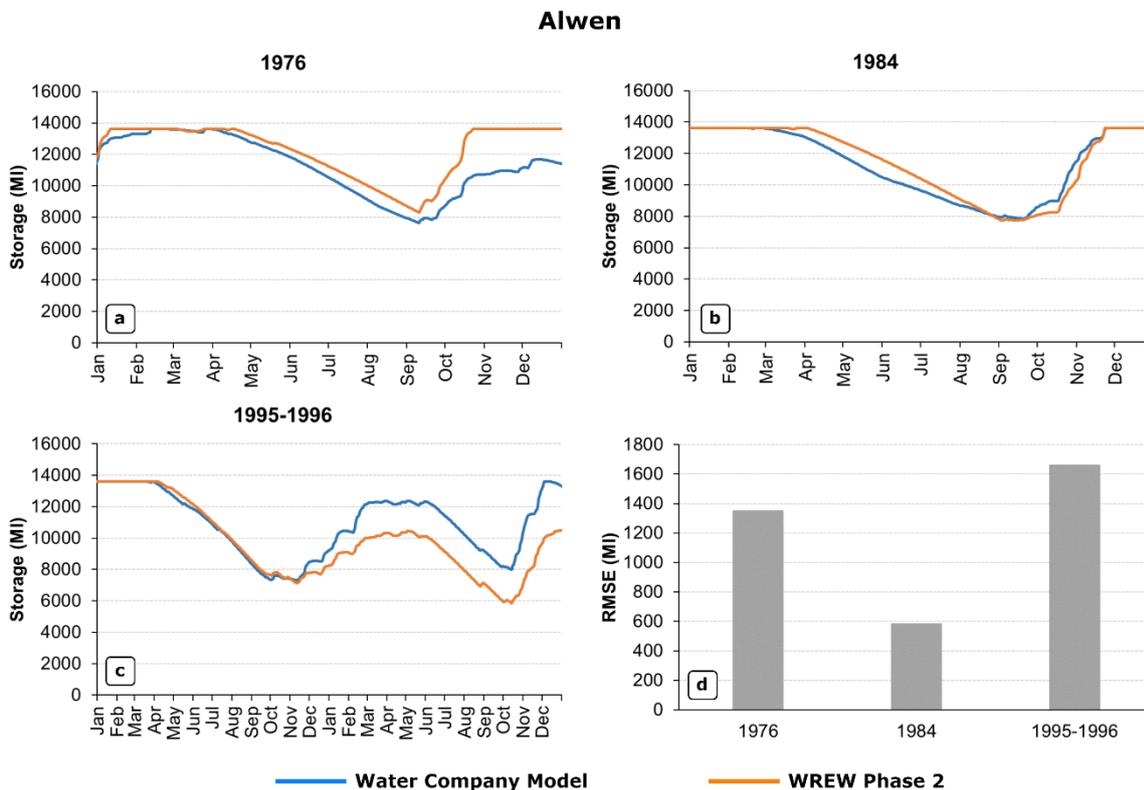


Figure 39. Comparison of Alwen simulated storage from WREW and water company models

Panels a-c show three historic drought events; panel d shows root mean square error (RMSE) between Phase 2 WREW and water company simulated storage for the drought events.

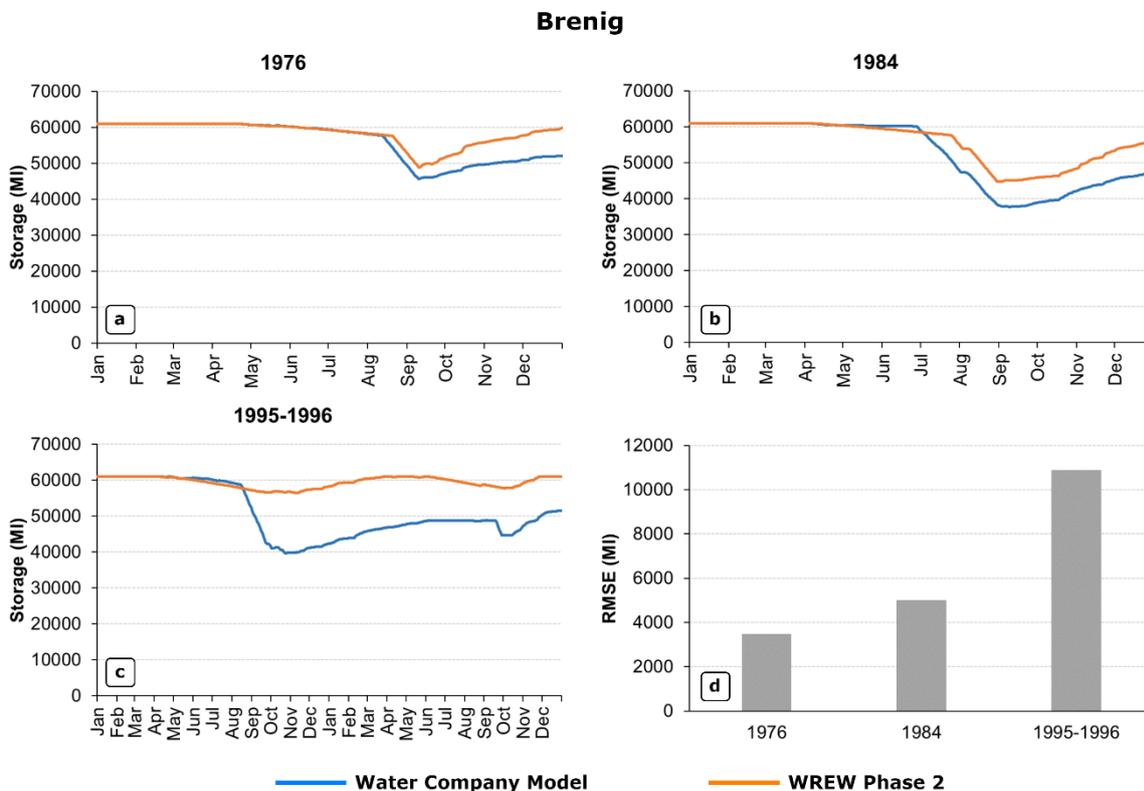


Figure 40. Comparison of Brenig simulated storage from WREW and water company models.

Panels a-c show three historic drought events; panel d shows root mean square error (RMSE) between Phase 2 WREW and water company simulated storage for the drought events.

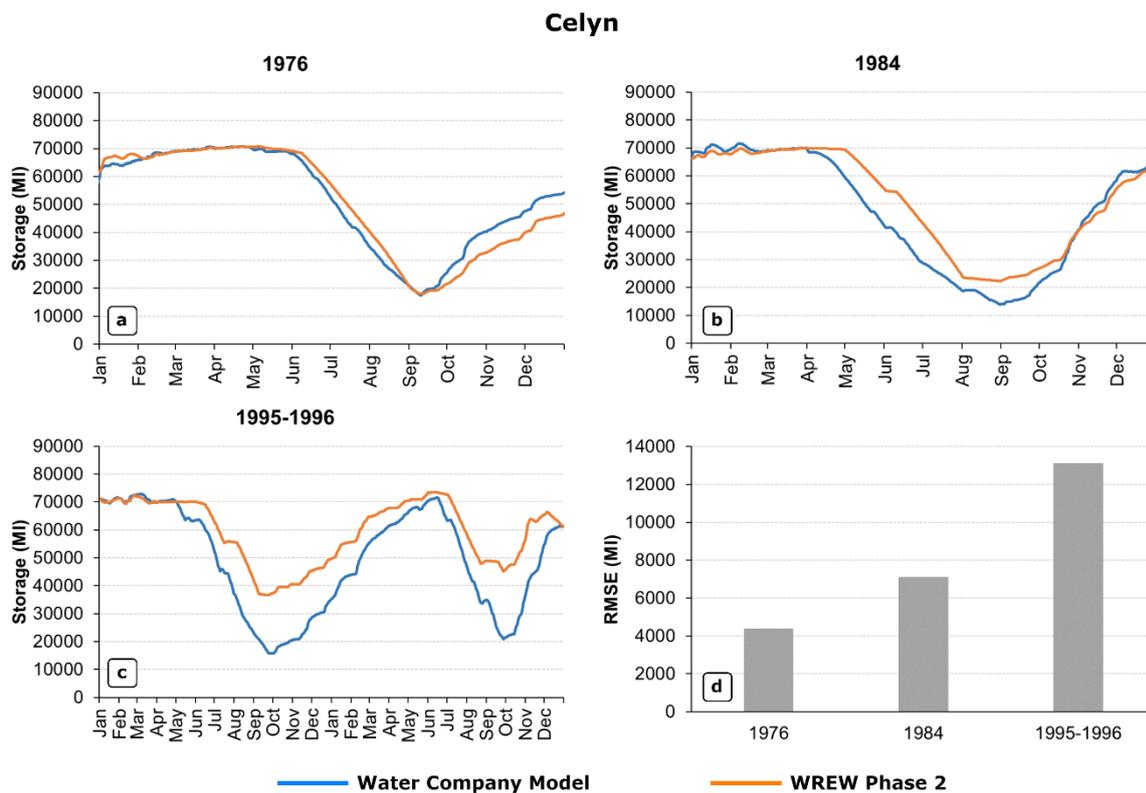


Figure 41. Comparison of Celyn simulated storage from WREW and water company models.

Panels a-c show three historic drought events; panel d shows root mean square error (RMSE) between Phase 2 WREW and water company simulated storage for the drought events.

D2.4 Lake Vyrnwy

Lake Vyrnwy reservoir is an important part of United Utilities water supply infrastructure, supplying customers in the Strategic WRZ via the Vyrnwy Aqueduct. Simulated storage levels were evaluated as part of the Phase 1 validation exercise, revealing poor calibration during late summer and autumn. In Phase 2 efforts were made to improve simulated storage levels, with significant improvements achieved for the 1976 and 1984 droughts. The 1995-1996 drought shows some small improvements, with more realistic drawdown of the reservoir during the autumn months. **Figure 42** indicates there is still room for improvement in the calibration of Lake Vyrnwy. Further work on model validation is outlined in Section 4.2.1.6. In Phase 1 it was hypothesised that the mismatch between simulated storage levels may be a result of ‘wetter’ hydrological inflows input into WREW from the DECIPHeR model. However, investigations in Phase 2 revealed a strong agreement between DECIPHeR inflows to Vyrnwy and a naturalised inflows dataset by the EA, as shown in **Figure 43**. This suggests the parameterisation of the Vyrnwy and wider UU system, and not the hydrological inflows, are the likely cause of the issue.

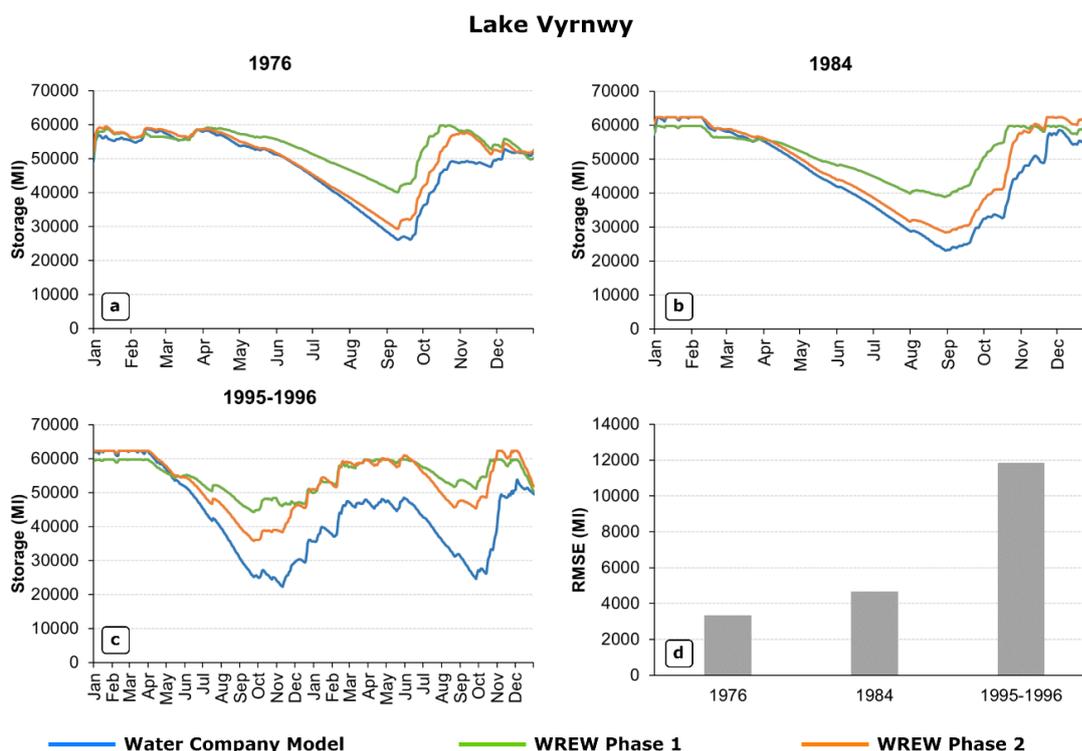


Figure 42. Comparison of Lake Vyrnwy simulated storage from WREW Phase 1, WREW Phase 2 and water company models

Panels a-c show three historic drought events; panel d shows root mean square error (RMSE) between Phase 2 WREW and water company simulated storage for the drought events.

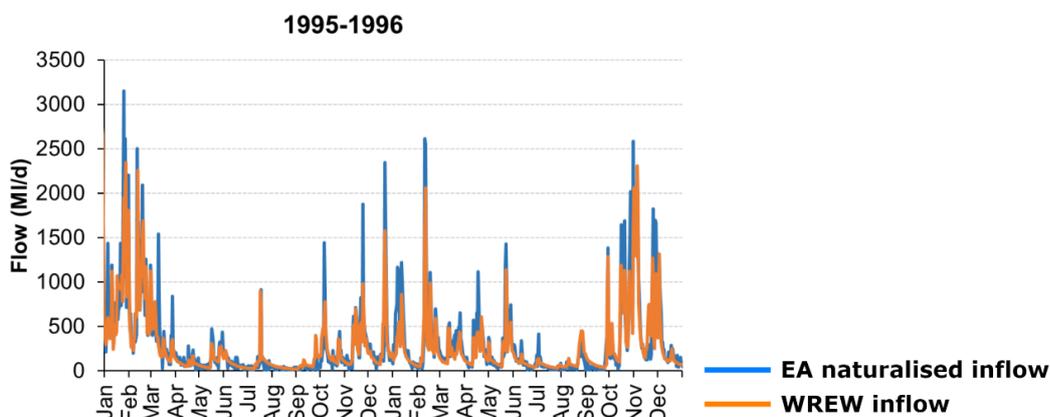


Figure 43. Comparison of Lake Vyrnwy simulated inflows from the hydrological model DECIPHeR and Environment Agency naturalised flow (smoothed) for the 1995-1995 drought

D2.5 Elan Valley and Clywedog

Elan Valley Reservoirs and Clywedog Reservoir sit in the headwaters of the Severn Basin and are important for supply to Severn Trent Water's Strategic Grid WRZ.

The Elan Valley Reservoirs are a group of five reservoirs: Claerwen, Caban Coch, Craig Goch, Pen-y-Garreg and Garreg Ddu. Phase 1 validation showed good agreement for all three drought events between the simulated storage levels from WREW and the water company modelling.

Figure 44 shows that work in Phase 2 has further improved the calibration, most notably in the 1976 and 1984 droughts. Drawdown is more closely aligned for the summer and autumn periods, giving a higher confidence in the WREW outputs.

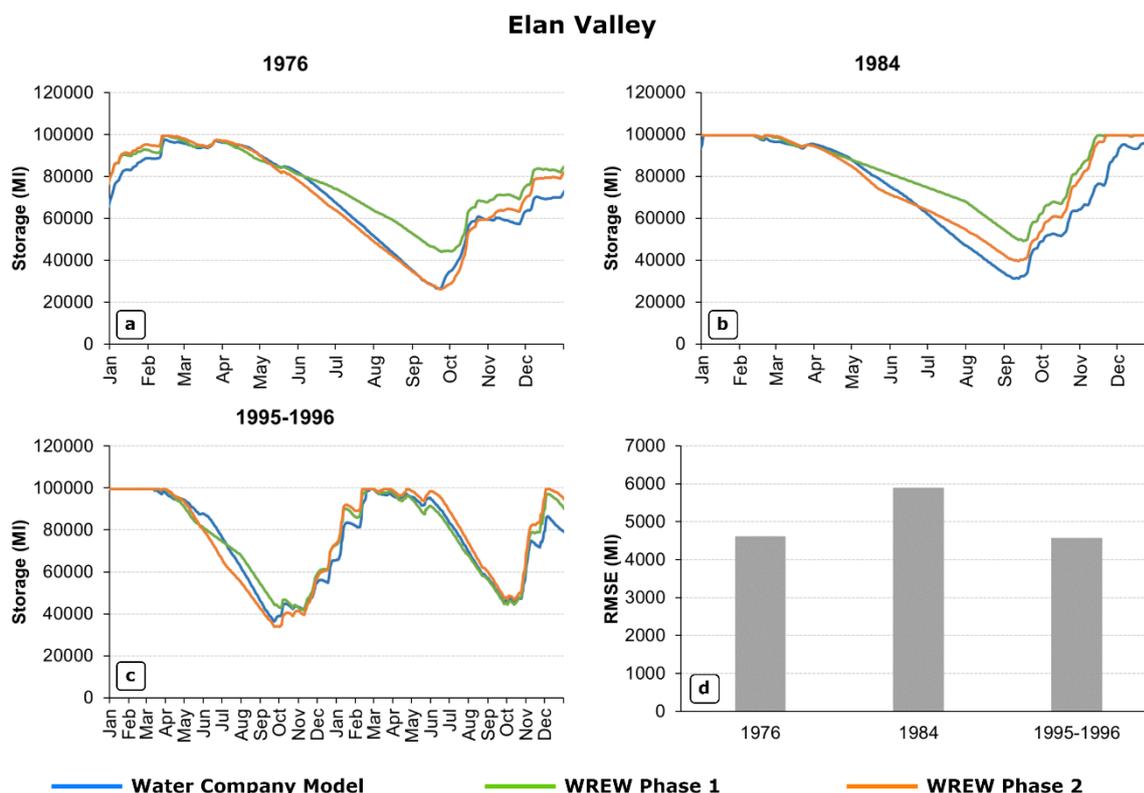


Figure 44. Comparison of Elan Valley Reservoirs simulated storage from WREW Phase 1, WREW Phase 2 and water company models

Panels a-c show three historic drought events; panel d shows root mean square error (RMSE) between Phase 2 WREW and water company simulated storage for the drought events.

Clywedog is important for regulation of flows along the River Severn. The WREW simulated storage of Clywedog matches well with water company model outputs for all three drought events investigated, as shown in **Figure 45**. Minor discrepancies emerge in the refill periods of the 1976 and 1995-1996 drought, and drawdown period in 1984, however the overall pattern of WREW's Clywedog drawdown and refill closely mirrors those emerging from the water company's modelled storage.

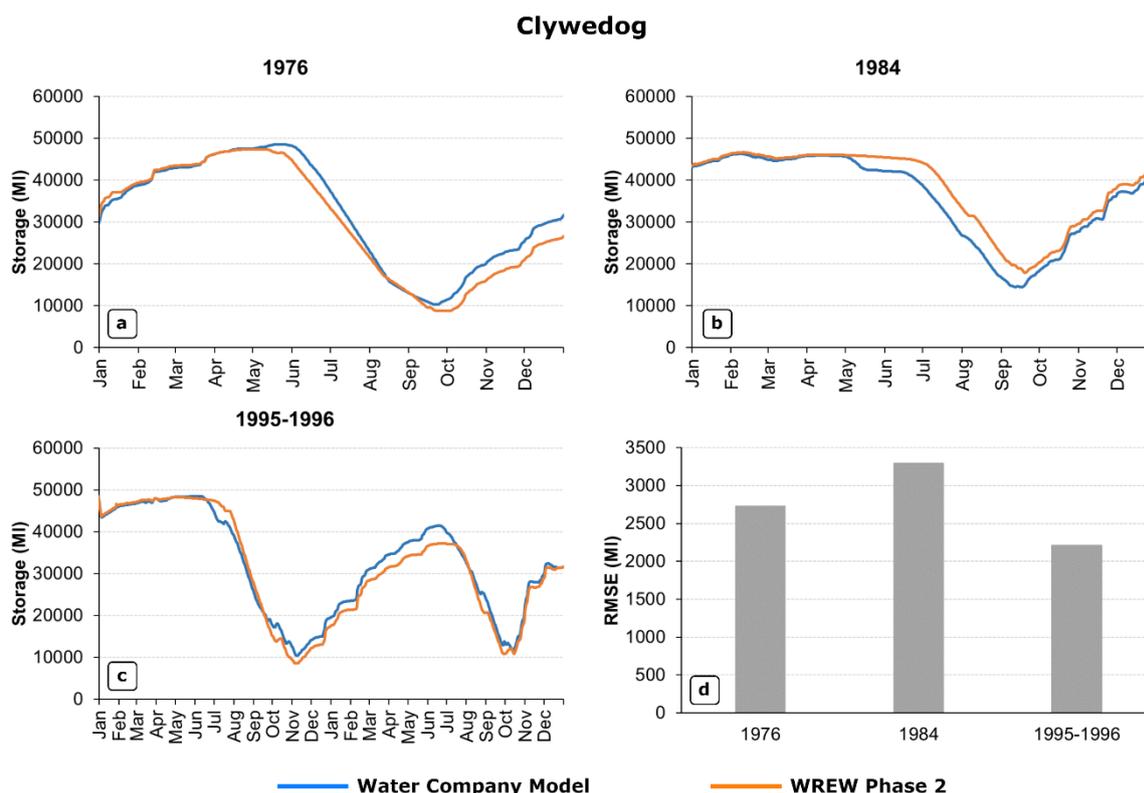


Figure 45. Comparison of Clywedog simulated storage from WREW and water company models

Panels a-c show three historic drought events; panel d shows root mean square error (RMSE) between Phase 2 WREW and water company simulated storage for the drought events.

D2.6 Derwent Valley

The Derwent Valley Reservoirs are a group of three reservoirs: Derwent, Ladybower and Howden. The reservoirs directly supply customers in Severn Trent Water's Strategic Grid WRZ and indirectly supply customers in Yorkshire Water via a transfer from Derwent Valley.

Figure 46 shows that the outputs from Phase 1 and Phase 2 demonstrate good agreement between simulated reservoir storage levels from WREW and water company modelling for the 1976 and 1984 droughts. Whilst the lowest storage levels for both drought events are not reached in WREW simulations, the pattern of drawdown and refill matches the water company profile well. The results suggest that modifications made to WREW in Phase 2 have not impacted calibration of the Derwent Valley Reservoirs.

The longer 1995-1996 drought is less well captured by WREW, with an overestimation of reservoir storage in the autumn and winter of 1995. This suggests that multi-year droughts in this region of England could be less well represented in WREW; a feature which requires further investigation in future phases of the NSSM project.

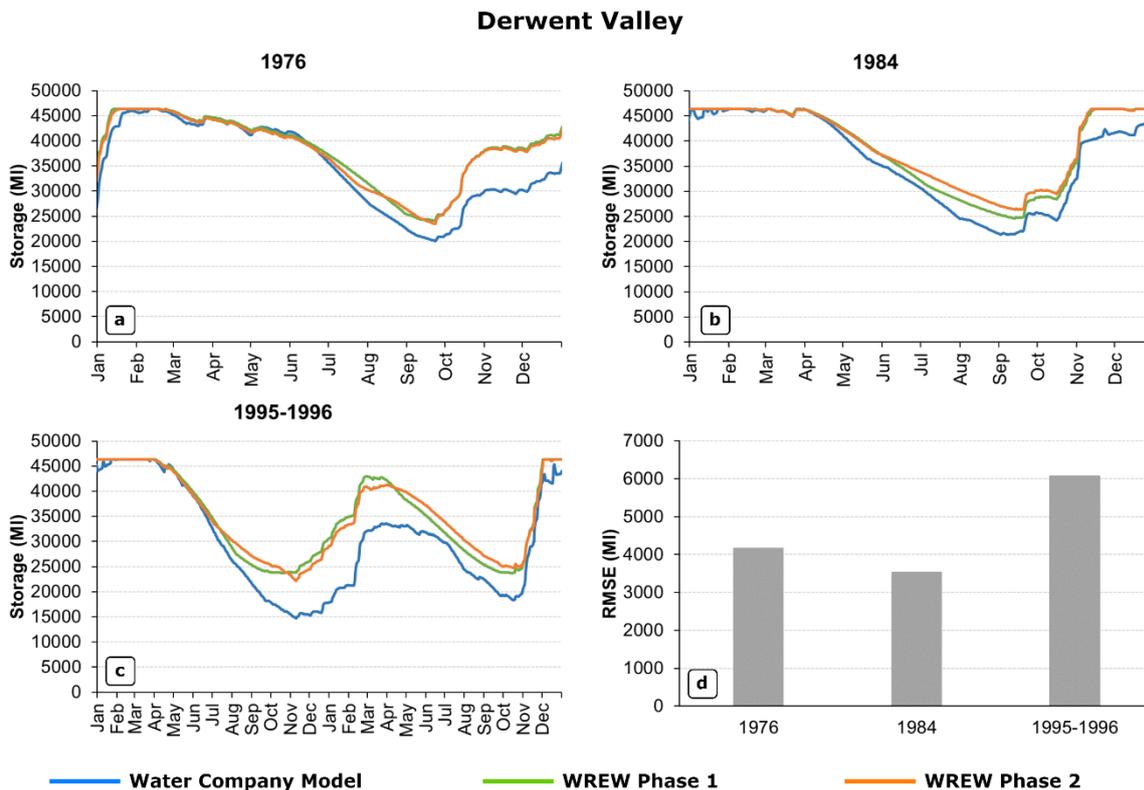


Figure 46. Comparison of Derwent Valley Reservoirs simulated storage from WREW Phase 1, WREW Phase 2 and water company models

Panels a-c show three historic drought events; panel d shows root mean square error (RMSE) between Phase 2 WREW and water company simulated storage for the drought events.

D2.7 Draycote and Blithfield

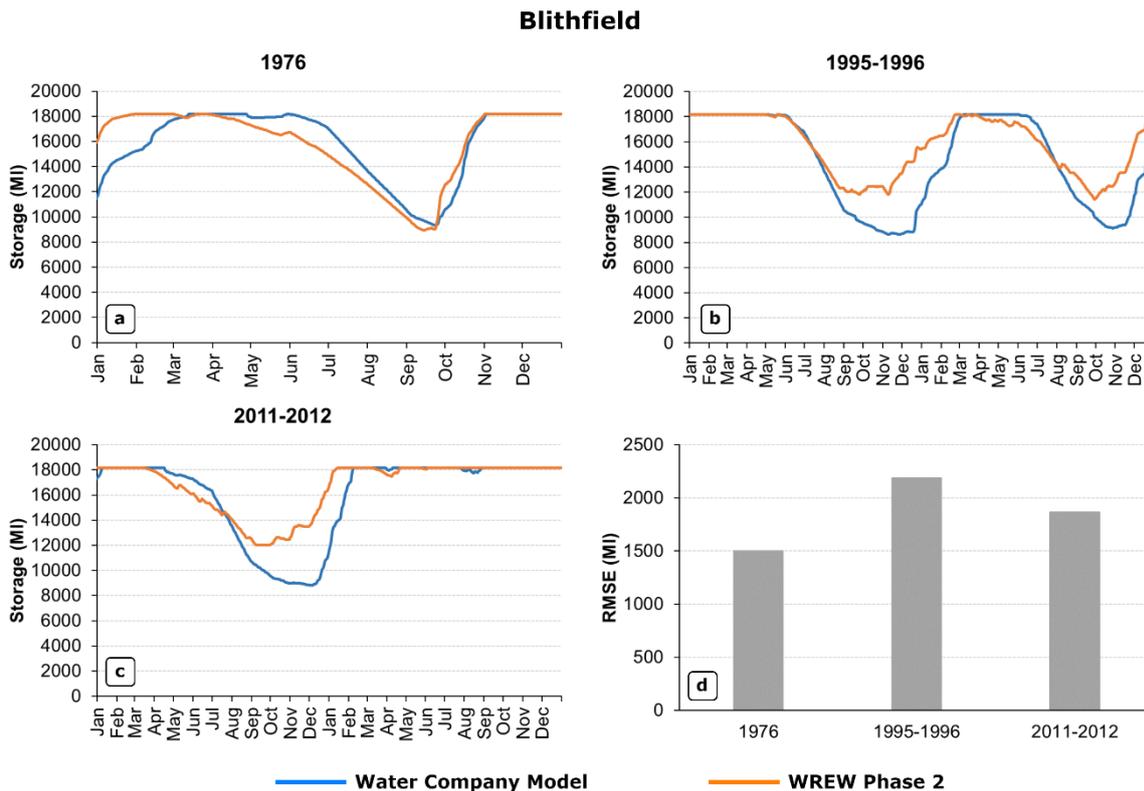


Figure 47. Comparison of Blithfield simulated storage from WREW and water company models.

Panels a-c show three historic drought events; panel d shows root mean square error (RMSE) between Phase 2 WREW and water company simulated storage for the drought events.

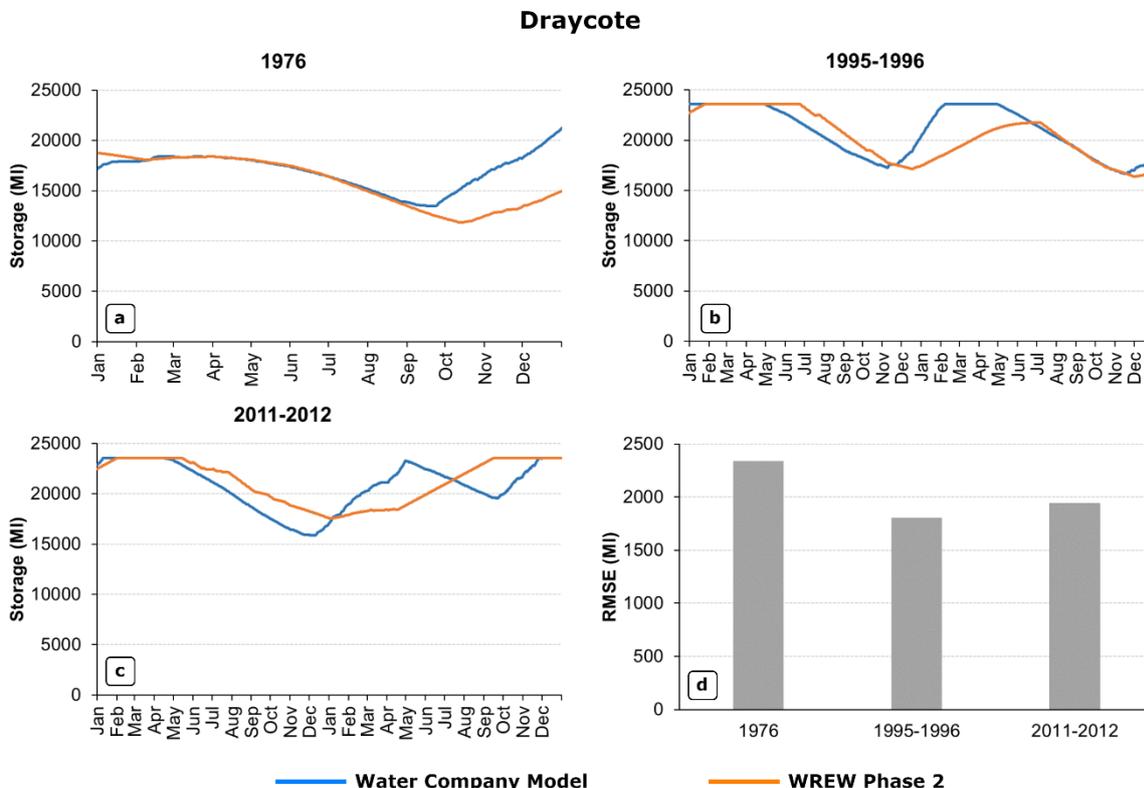


Figure 48. Comparison of Draycote simulated storage from WREW and water company models.

Panels a-c show three historic drought events; panel d shows root mean square error (RMSE) between Phase 2 WREW and water company simulated storage for the drought events.

D3 Water Resources South East

The London Storages Reservoirs are a group of reservoirs which supply Thames Water's London WRZ. In WREW the individual reservoirs within the London WRZ are aggregated into one large reservoir, which directly supplies water users. The reservoir is fed by the Lower Thames Abstraction and abstractions from the River Lee.



Figure 49 shows the simulated reservoir storage levels between WREW and water company modelling. The WREW model captures the general pattern of reservoir drawdown and refill during the 1976 and 1997 droughts, but experiences a delay when the reservoir storage hits its lowest level in the drought. In both droughts reservoir drawdown is smoother than the water company model; a possible consequence of simplified reservoir operating rules in WREW. The 2011-2012 drought event is poorly captured by WREW, with an overestimation of simulated storage in the autumn and winter months.



Figure 49. Comparison of London Storages simulated storage from WREW and water company models

Panels a-c show three historic drought events; panel d shows root mean square error (RMSE) between Phase 2 WREW and water company simulated storage for the drought events.

The validation exercise indicates that WREW's representation of the London Storages may be less sensitive to winter drought events. This bias may affect the WREW outputs, as the London WRZ in WREW is likely more resilient to low-flow events than is the case in reality. There are two possible causes for the observed difference: poor calibration of the London system in WREW and difference in hydrological inputs. **Figure 50** shows the performance of the hydrological model, DECIPHeR, for various gauging stations in the Thames Basin that are represented in WREW. Many of the gauges show good to excellent model performance, with a Nash Sutcliffe efficiency (NSE) greater than 0.6. However, the model performs less well for the Colne Catchment and poorly for the Wey Catchment. This makes it difficult to disentangle exactly what is causing the overestimation of storage in WREW. Further investigation is required to better understand London Storages, with particular regard to the Wey and Colne catchments.

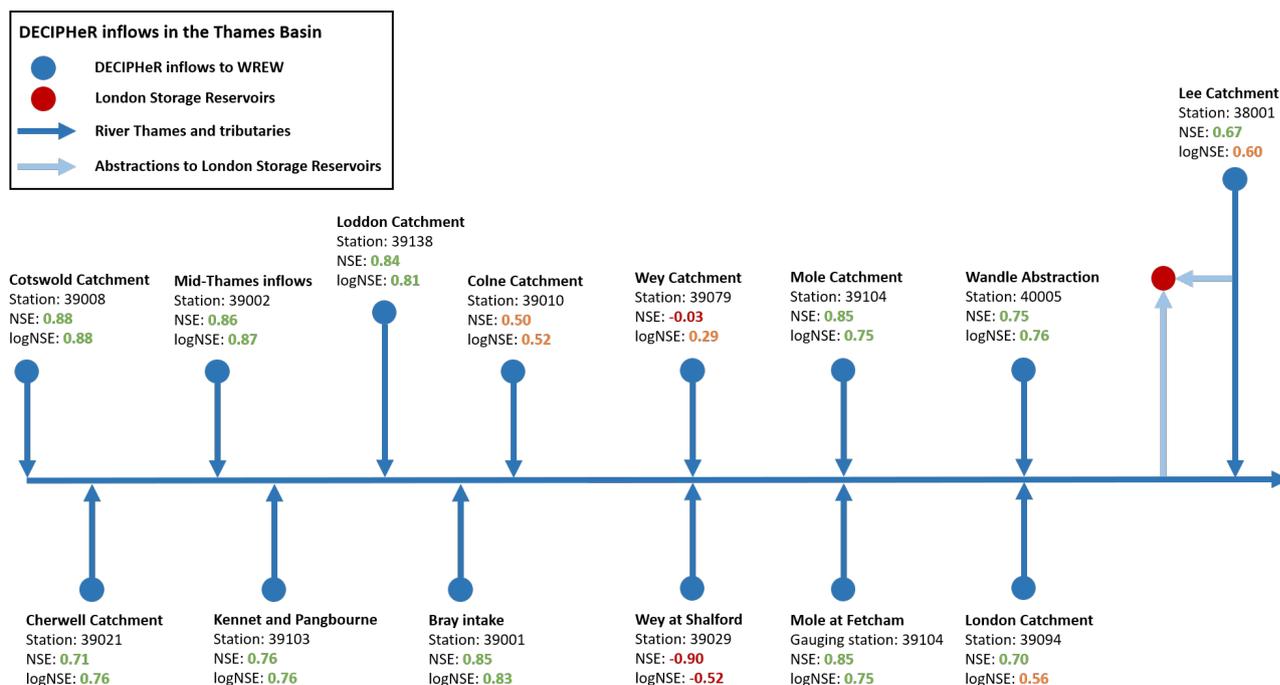


Figure 50. Performance of DECIPHeR model at gauging stations in the Thames Basin, measured as NSE and logNSE
 Data from Coxon et al. (2019b)

Appendix E – Characterising specific WRW/WRSE drought events within the w@h2 dataset

The figures below demonstrate how the WRW/WRSE (+/-WRE) specific drought events that were isolated sit within the distribution of all drought events in the w@h2 dataset in terms of duration (months of drought), intensity (mm/month) and accumulated deficit (mm).

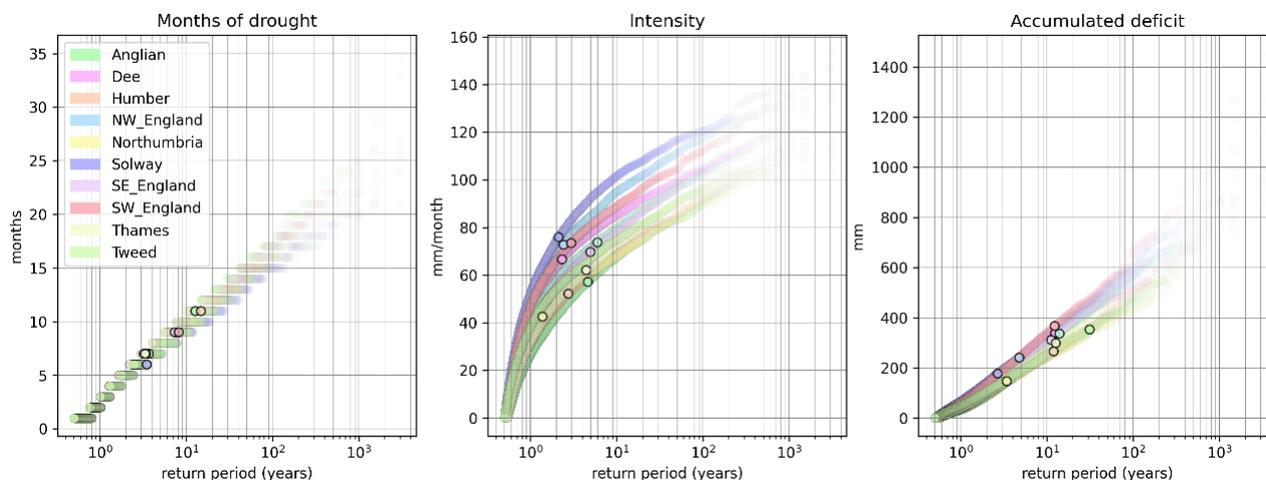


Figure 51. Characterisation of a WRW/WRSE drought event isolated in replicate NF2

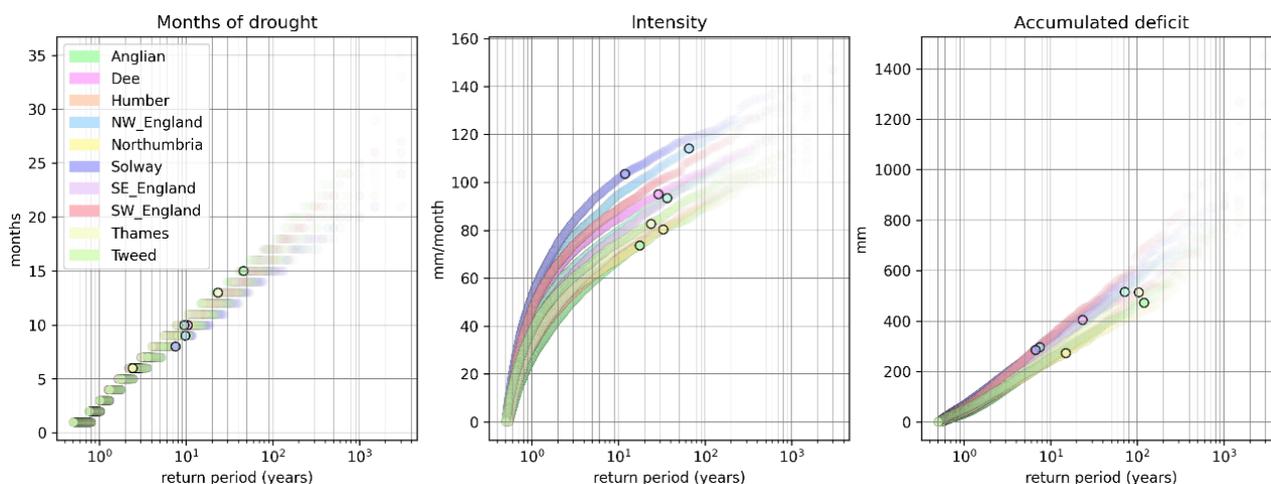


Figure 52. Characterisation of a WRW/WRSE drought event isolated in replicate NF10

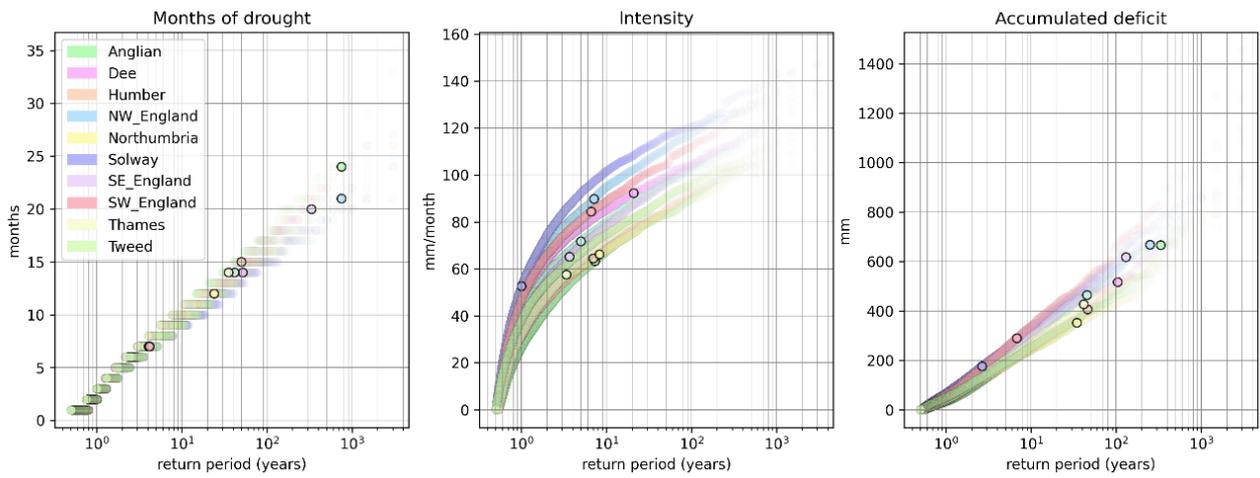


Figure 53. Characterisation of a WRW/WRSE drought event isolated in replicate NF63

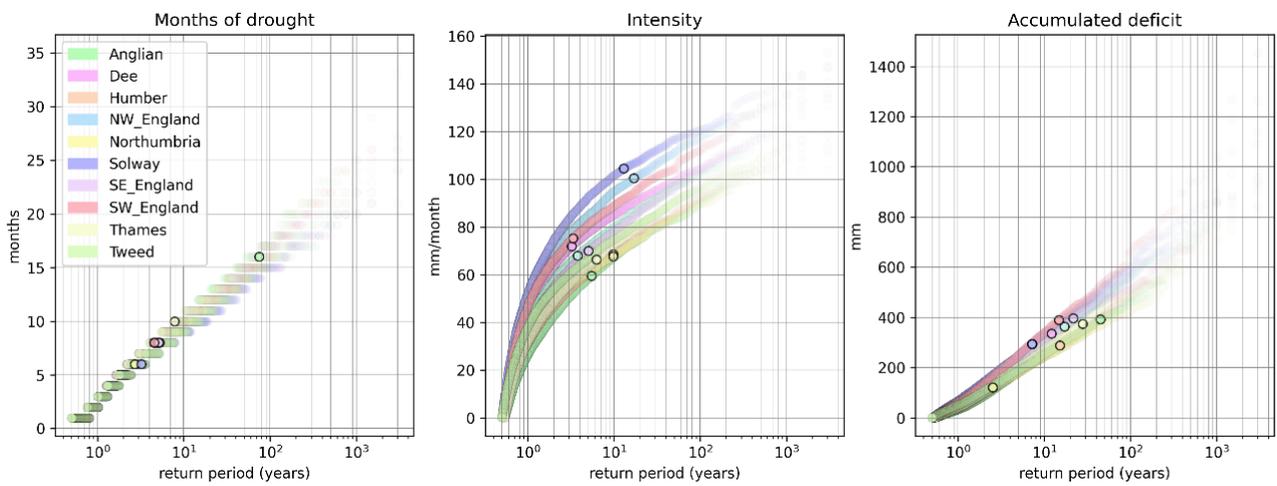


Figure 54. Characterisation of a WRW/WRSE drought event isolated in replicate NF66

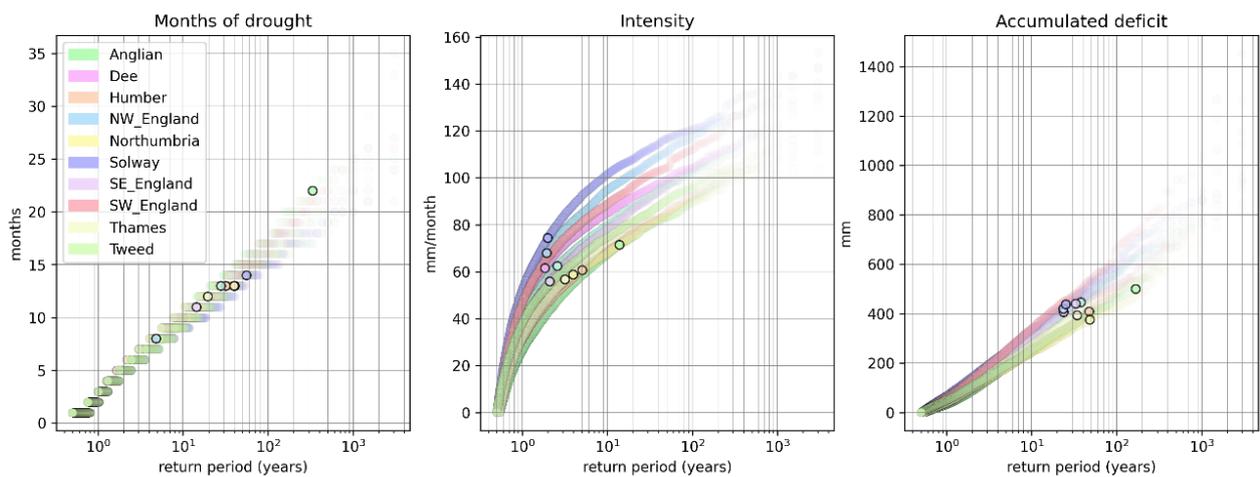


Figure 55. Characterisation of a WRW/WRSE drought event isolated in replicate NF98

Appendix F – Spatial and temporal patterns of specific drought events & their impacts

F.1 National, 24 month long droughts

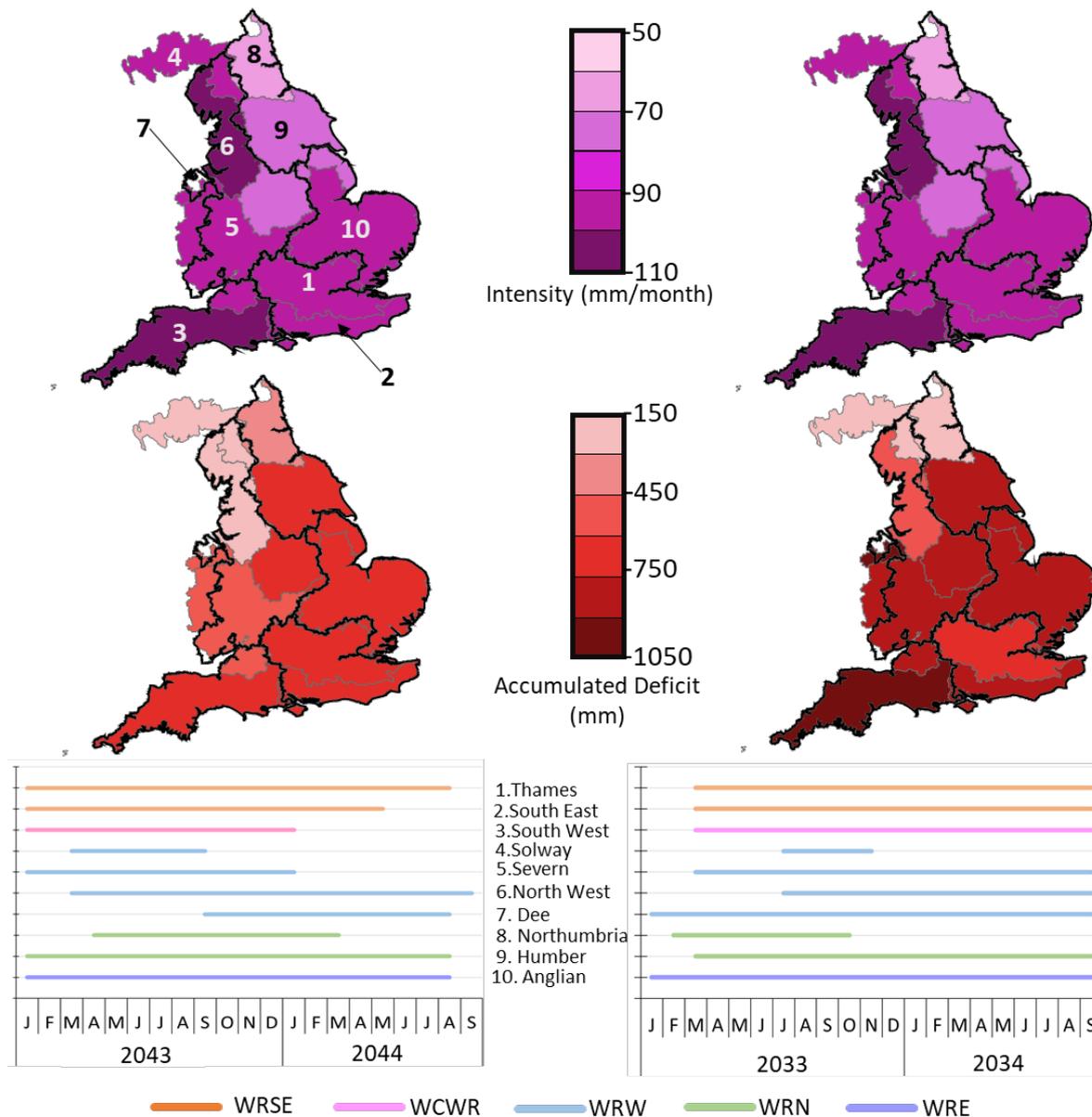


Figure 56. National 24 month drought events observed in replicates NF21 (left) and NF49 (right)

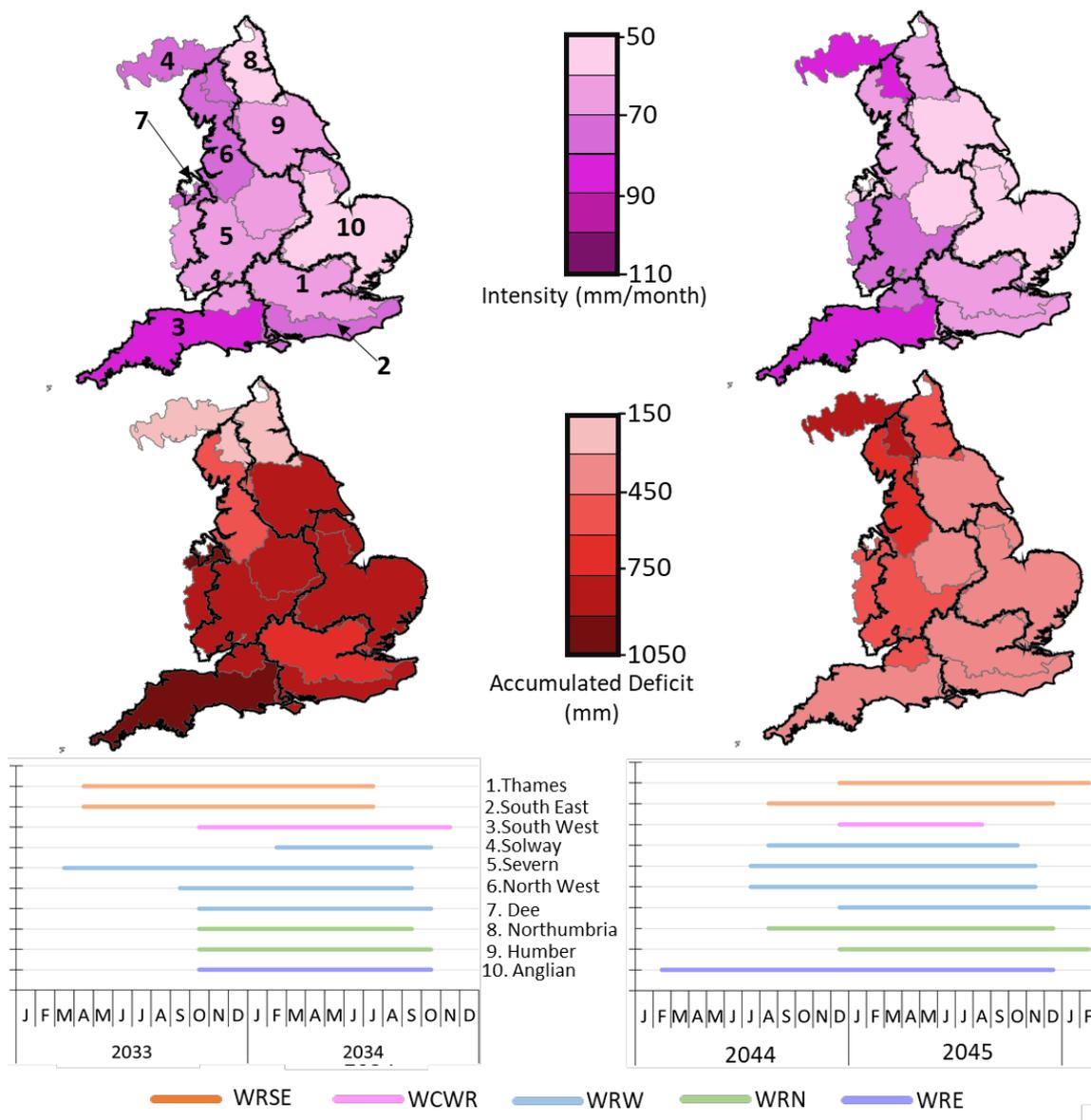


Figure 57. National 24 month drought events observed in replicates NF72 (left) and NF35 (right)

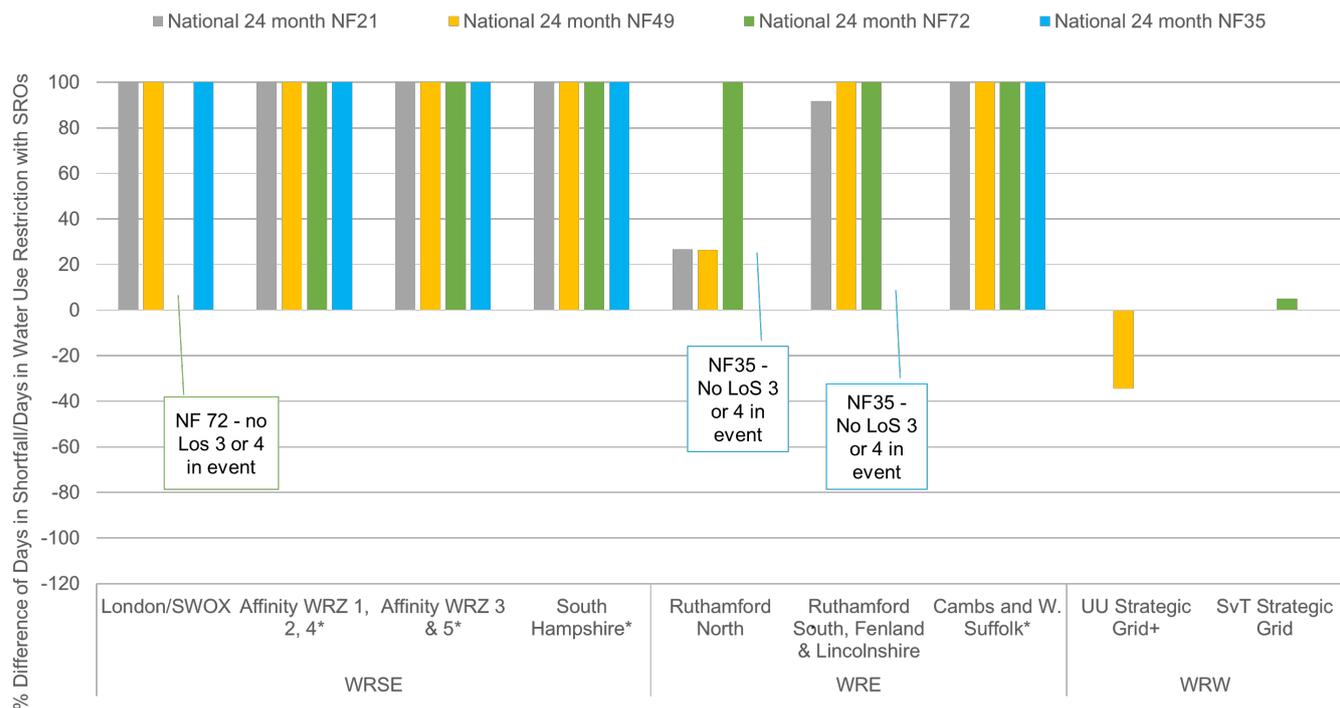


Figure 58. Impact of strategic supply options during specific national 24 month drought events under the Central Scenario

Shown as the change in number of days in supply shortfall or days in water use restriction, expressed as a %. WRZs with a * reflect supply shortfall, without reflect water use restriction LoS 3 + 4 and those with a + reflect water use restriction LoS 1 + 2.

F.2 National, 12 month long droughts

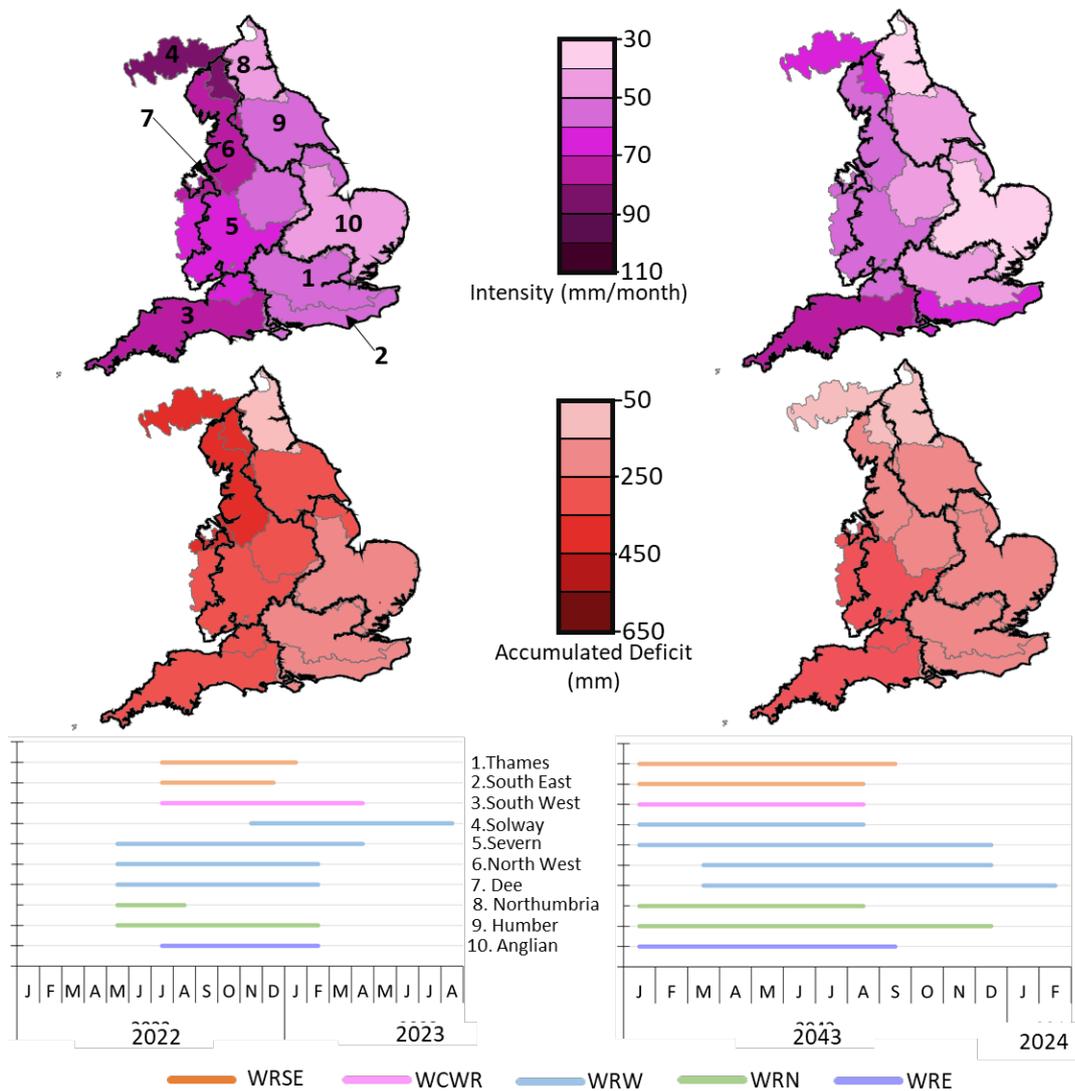


Figure 59. National 12 month long drought events observed in replicates NF51 (left) and NF40 (right)

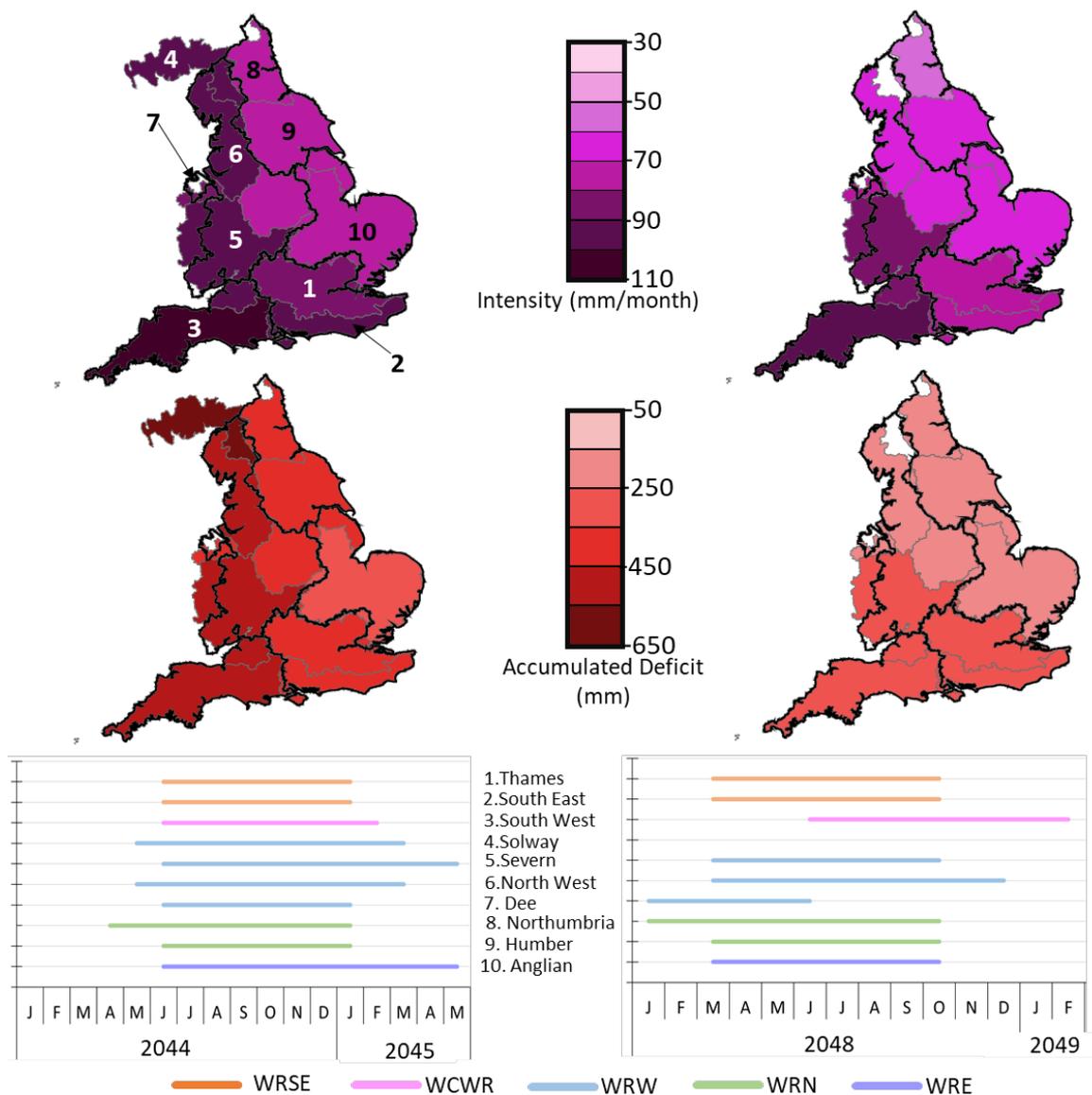


Figure 60. National 12 month drought events observed in replicates NF35 (left) and NF8 (right)

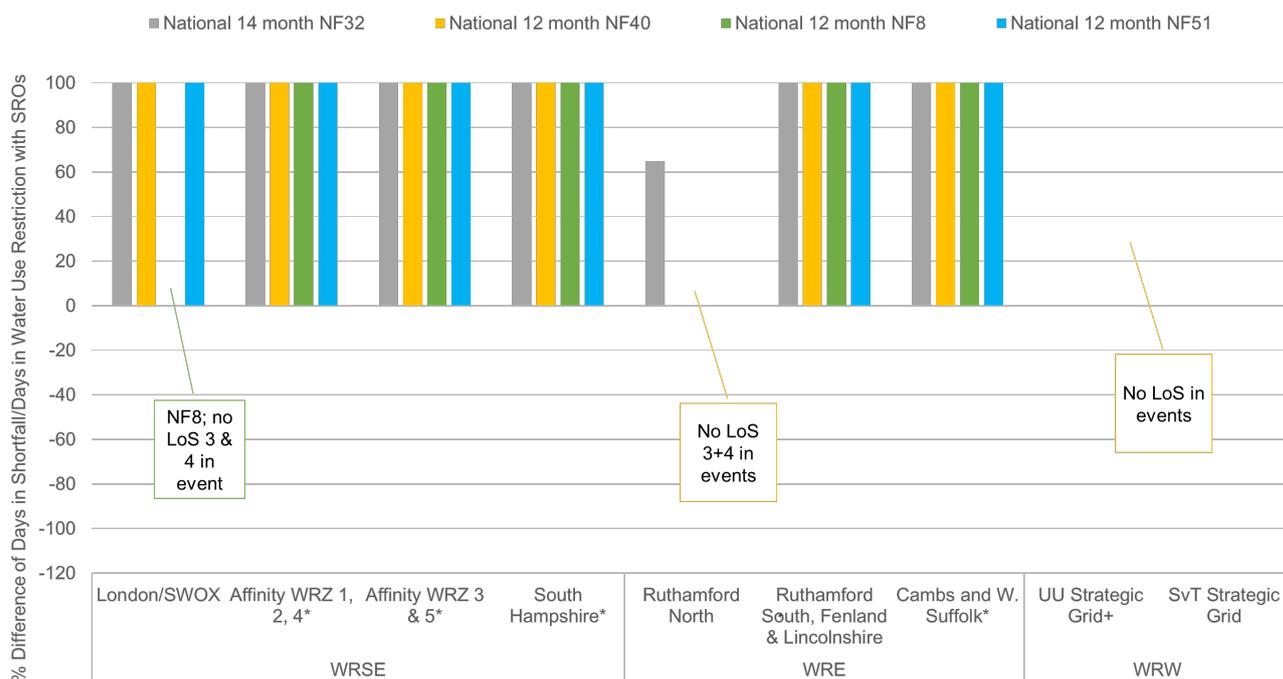


Figure 61. Impact of strategic supply options during specific national 12-14 month drought events under the Central Scenario

*This is shown as the change in number of days in supply shortfall or days in water use restriction, expressed as a %. WRZs with a * reflect supply shortfall, without reflect water use restriction LoS 3 + 4 and those with a + reflect water use restriction LoS 1 + 2.*

F.3 WRSE/WRE Focussed

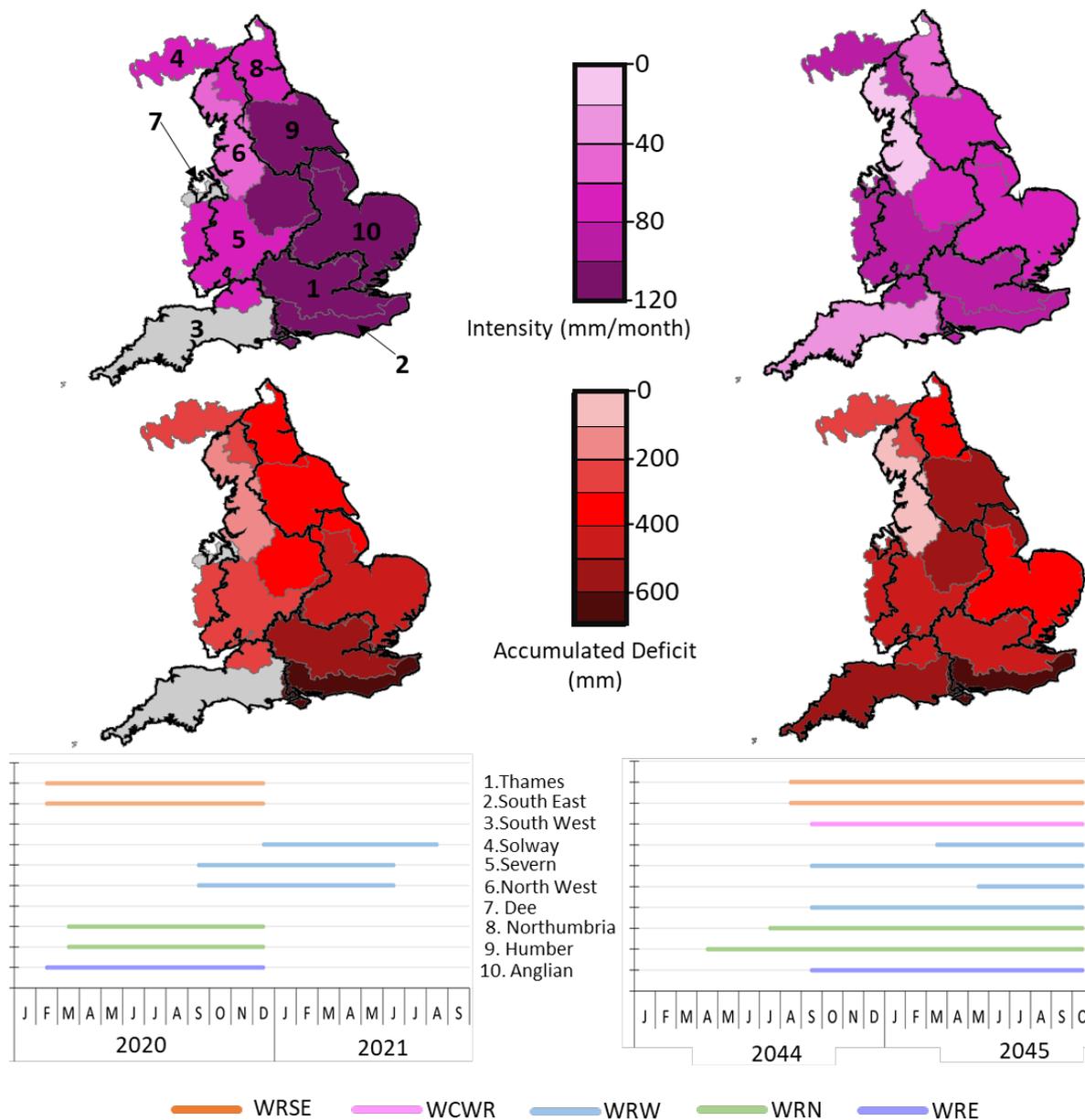


Figure 62. WRSE/WRE focussed drought events observed in replicates NF87 (left) and NF54 (right)

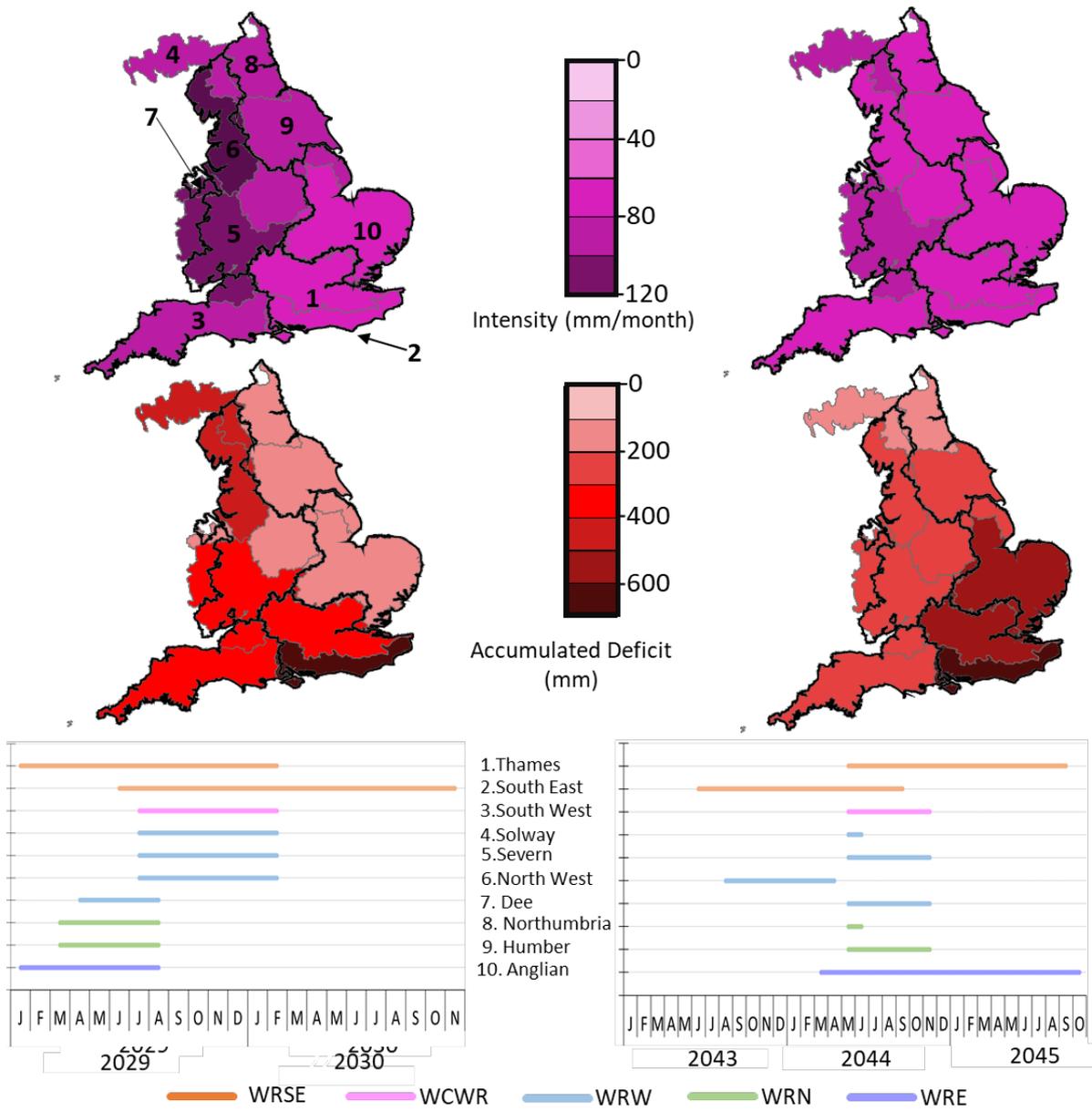


Figure 63. WRSE/WRE focussed drought events observed in replicates NF12 (left) and NF38 (right)

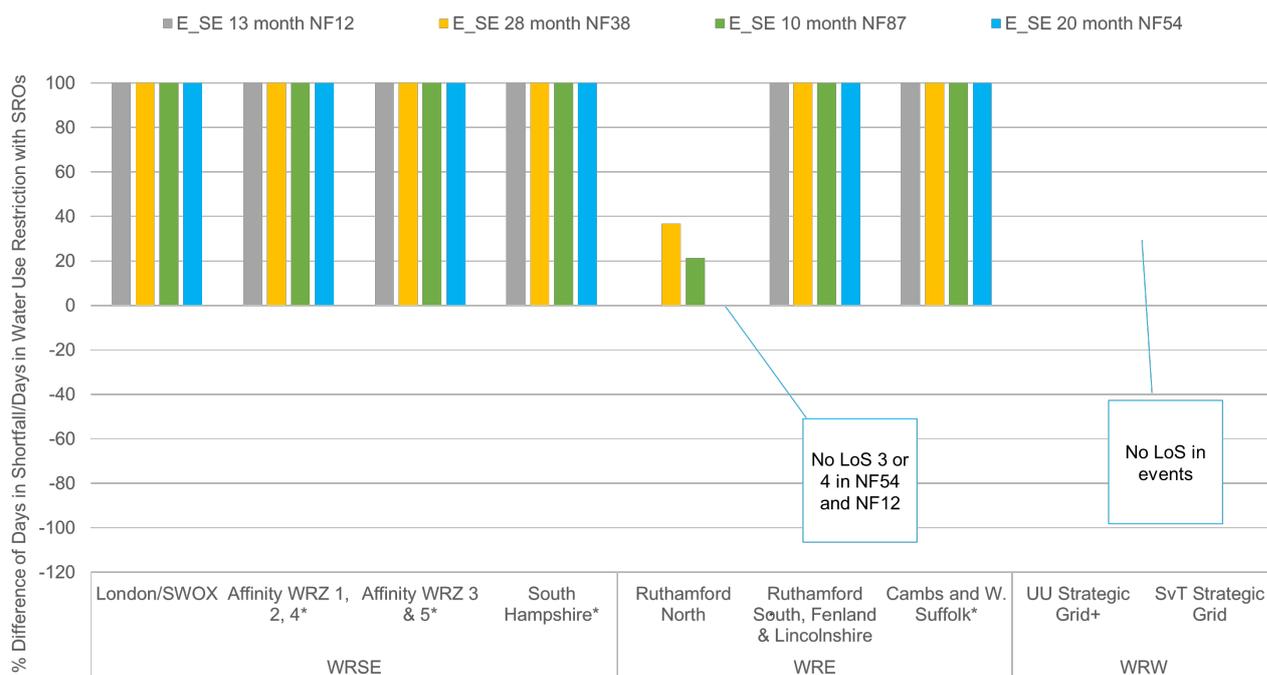


Figure 64. Impact of strategic supply options during specific WRE/WRSE focussed drought events under the Central Scenario

*This is shown as the change in number of days in supply shortfall or days in water use restriction, expressed as a %. WRZs with a * reflect supply shortfall, without reflect water use restriction LoS 3 + 4 and those with a + reflect water use restriction LoS 1 + 2.*

F.4 WRW/WRSE (+/- WRE) Focussed

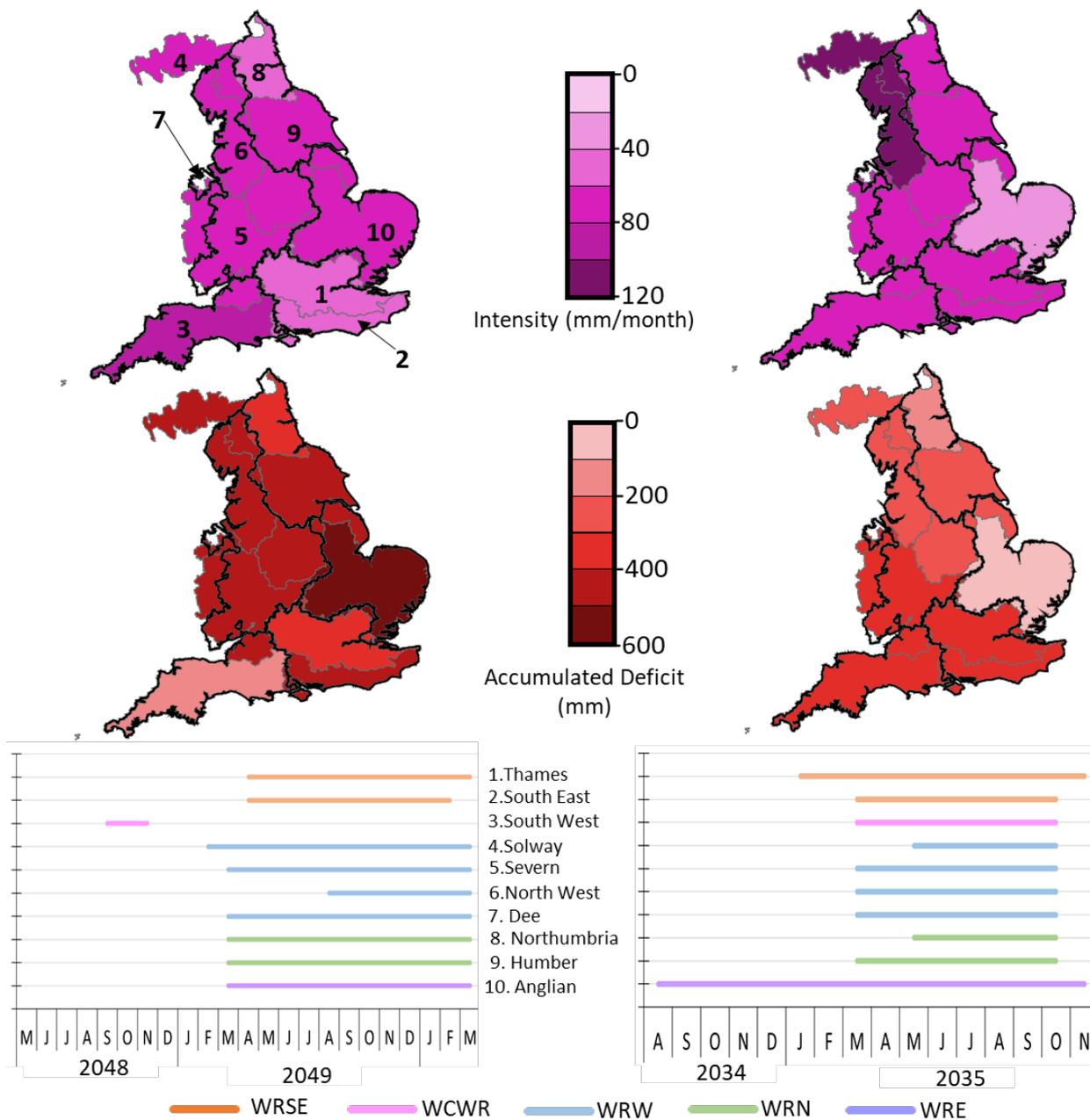


Figure 65. WRW/WRSE/WRE focussed drought events observed in replicates NF98 (left) and NF66 (right)

Appendix G – Sensitivity Scenarios

The figure below demonstrates how the additional pressure on water supply, explored in the sensitivity scenarios, acts to increase the probability of failure (supply shortfall or level 3&4 water use restriction) at key areas of water stress in England.

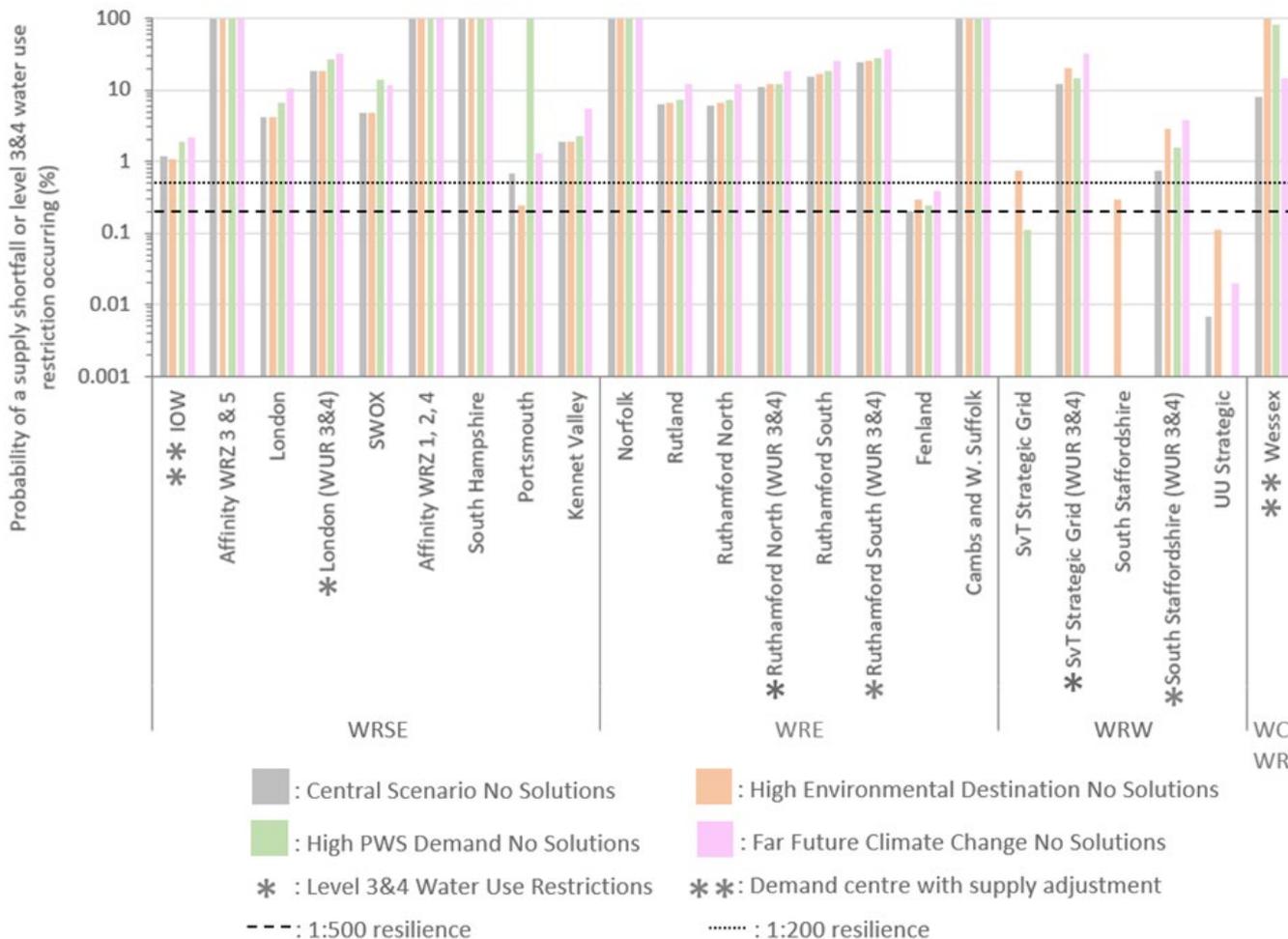


Figure 66. Difference in the probability of a supply shortfall or level 3 & 4 water use restriction occurring in the central scenario (grey bars) and the sensitivity scenarios (orange, green and pink bars) both without solutions operational in WREW

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