The National System Simulation Modelling (NSSM) Project

Phase 1 Report

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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.

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 Regulator's Alliance for Progressing Infrastructure Development (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 first phase of a project to develop a National Supply Simulation Model (NSSM) that incorporates solutions within the RAPID programme. Solutions within the RAPID programme 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 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 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 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 the first phase, which focusses around investigating the resilience benefits of individual solutions. This project is not intended to replace any regional or company modelling but provide a strategic national view of the 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 National Framework and will provide a quantitative independent evidence base for RAPID and its sponsor regulators, as well as help inform regional modelling where possible.

The Water Resources Model of England and Wales: WREW

Through the NERC-funded MaRIUS project (2014-2020), the first national scale Water Resource simulation model for England and Wales (WREW) was developed using the software platform Wathnet, by a team led by Professor Jim Hall at Oxford University. Climate and hydrological inputs were also developed though the MaRIUS project, in partnership with the Met. Office and the University of Bristol.

WREW's water system representation and its subsequent development has been strengthened by interaction, collaboration, and data provided by UK water industry practitioners, regulators, consultancies, regional water groups and the use of the model in various industry initiatives. The model was used to provide inputs to the 2016 Water UK Water Resources Long-Term Planning Framework study, and the 2020 EA report "*Meeting our Future Water Needs*".

At the start of this NSSM project, the WREW implementation included a simplified representation of all major water supply infrastructure that are connected to England and Wales' wider water network via any river or significant transfer. It covered more than 90% of England and Wales' population and public water demand with non-public water users represented at catchment scale, and included abstraction licence conditions, operational preferences, control curves and asset locations.

A significant amount of Phase 1 has been focused on the further development of WREW, including ensuring the representation of the supply system is correct, updating the baseline configuration of the supply system to 2025 and adding the solutions. The model was run to test its performance against available data of real-world system such as water company model outputs; adjustments were made when needed in a reiterative nature. Due to the academic use of the model before this project, a key area of focus has been the Thames catchment and water network infrastructure (for example, see Hall *et al*. 2019, Mortazavi *et al*. 2019).

A further validation exercise examining storage used four key reservoirs revealed that the shape of the WREW simulated reservoir storage level curves are very similar to those from the water company models. This validation exercise builds on a previous round of model validation that involved a broader geographic spread of reservoirs and was carried out for the 2016 Water UK Water Resources Long-Term Planning Framework study. While there is good match by WREW in matching the outputs of water company models, there are areas where further investigation of input data and model configuration is needed in Phase 2 to provide greater confidence in the outputs of this national-scale model. The RAPID solutions are represented in WREW are based on information available at the time of this project's Phase 1 and are therefore a snapshot of scheme design.

The project team have extensively engaged with regional groups and water companies in order to develop a shared understanding, and better align the national modelling with regional group/water company modelling. This process involved providing water companies with model documentation on the supply system topology and requesting feedback on the representation of the network, as well as any changes required for 2025. Due to time and scope limitations, not all of the feedback provided could be implemented in Phase 1; further development of the WREW model will occur in Phase 2.

Simulating the solutions

WREW can be 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 personal consumption and leakage), 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 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.

A total of 17 solution proposals have been submitted by water companies and accepted into the gated process at the time of Phase 1 modelling[1]. Some of these solutions are not standalone and only work to support other SROs; these have been grouped together as 'enabling' and 'dependent' solutions. Additionally, some have the same supply yield and work in same way, and consequently be considered as one solution for the purposes of modelling. Some solutions involve sub-options that have been explored in the model, see Figure A.

Phase 1 scenarios have focussed on testing benefits from individual solutions (but including enabling or dependent SROs). This provides a baseline against which to determine changed benefit from strategic combinations of solutions that will be explored further in Phase 2. Overall, a total of 16 scenarios have been performed, comprising 14 individual solution scenarios with an additional 2 combination scenarios, see Table A. Each scenario involves a different solution, keeping public water supply demand and future climate ensemble consistent. Details of the model inputs and scenarios are covered in more detail in Section 5.1. Each solution or sub-option is tested at maximum capacity/yield and configured to be triggered when key stages in resource position of the surrounding supply are reached, or so that they have the lowest priority compared to other sources of supply, i.e., the solution is the last supply source available to the model for meeting demand.

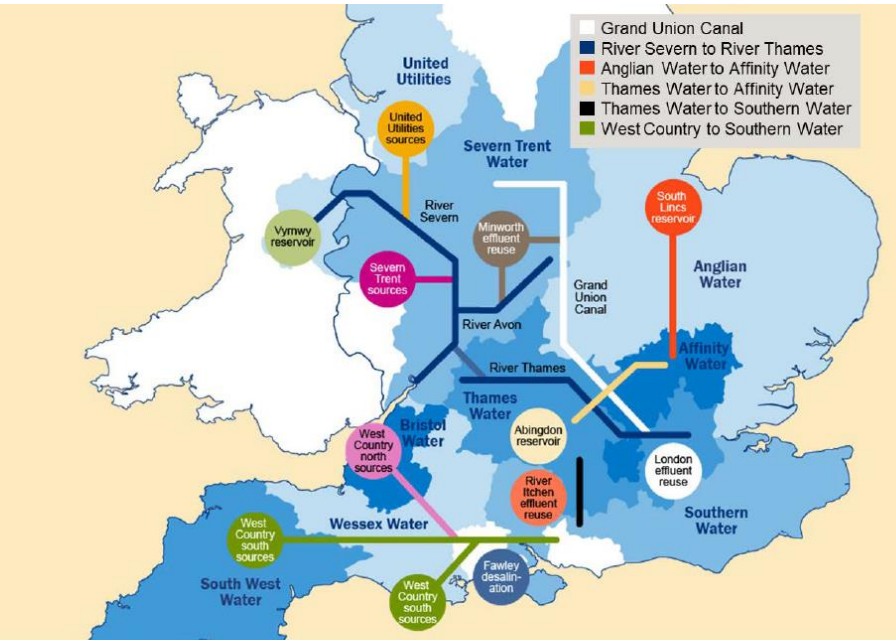

Figure A: The location of the Gate 1 Phase 1 solution[2]:

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[1] *Phase 2 of the project will reflect changes proposed in the Draft Determinations*

[2] From: RAPID (2021) Standard Gate One Themes and Assessment Overview

Table A The Phase 1 solution 'enabled' configurational scenarios tested in WREW

No.	Solution name	Sub-options	Type	Area supplied
Individual Scenarios				
1	Severn Thames Transfer (STT) & Enabling SROs	All sources activated (Vyrnwy Reservoir, Vyrnwy Aqueduct, UU Sources, Minworth Effluent Reuse and Severn Trent Sources) and Deerhurst pipeline[3]	Water transfer (river/pipeline)	Thames Water
2	South East Strategic Reservoir Option (SESRO)	None	Reservoir and water transfer (river)	Thames Water
3	London Effluent Reuse (LER)	Beckton reuse source	Effluent Reuse	Thames Water
4	Thames to Affinity Transfer (T2AT)	SESRO source	Reservoir and water transfer (river/pipeline)	Affinity Water
5		STT source	Water transfer (river/pipeline)	Affinity Water
6		LER (Beckton) source	Water reuse and transfer (pipeline)	Affinity Water
7	Anglian to Affinity Transfer (A2AT)	SLR source	Reservoir and water transfer (pipeline)	Affinity Water
8	Grand Union Canal (GUC)	None	Water transfer (canal)	Affinity Water
9	Thames to Southern Transfer (T2ST)	SESRO source	Reservoir and water transfer (pipeline)	Southern Water
10		STT source	Water transfer (river/pipeline)	Southern Water
11	Southern Water – Water Recycling	Water recycling plant and Havant Thicket Transfer	Water recycling, reservoir and water transfer (pipeline)	Southern Water
12		Water recycling plant only	Water reuse and transfer (pipeline)	Southern Water
13	West Country South Sources (WCSS) and West Country to Southern Transfer (WC2ST)	Roadford transfer	Reservoir and water transfer (pipeline)	Southern Water
		Poole effluent reuse	Effluent reuse and transfer (pipeline)	Southern Water
14	West Country North Sources (WCNS)	None	Reservoir and water transfer (pipeline)	Southern Water
Combination Scenarios				
15	SESRO and STT	None	Water transfer (river/pipeline) and reservoir	Thames Water
16	GUC and STT	None	Effluent Reuse and water transfer (river/pipeline)	Thames Water & Affinity Water

Note: All simulations use the same demand profile (Distribution Input for 2020-21 from WRMP19) and 100 climate scenarios from the MaRIUS project (Near Future ensemble (2020-2049) generated by Weather@home2).

Where solutions have multiple options or configurations, the option/configuration giving the highest capacity has been chosen for these phase 1 model runs.

Findings

Different ways of exploring the benefits of the solutions were explored in Phase 1. In this report, the benefit provided by the solution has been assessed as the relative change in the probability of a supply shortfall occurring when a solution is implemented. 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, especially when compared to the different levels of operational water use restrictions, such as temporary use bans and drought orders, which are imposed to prevent demand from outstripping supply in

[3] STT is also investigating an option to route via the Cotswold Canal. The Phase 1 model runs have selected solutions options which allow testing of the highest capacity configuration. Therefore the capacity which reflects the Deerhurst pipeline (500 Ml/d) has been set up for the purpose of this modelling.

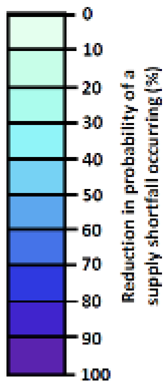
times of developing drought. The regional groups and water companies rely on different metrics, such as level of service, for assessing the drought resilience of the current and future supply system.

Reduced probability of a supply shortfall

The solutions act to reduce the probability of a supply shortage occurring. It is however important to note that the benefits associated with solutions are not unique, groups of other supply options could provide a similar benefit. Table B shows the reduction in this probability for each of the solution model scenarios tested in WREW. Note that where a cell contains a dash not a percentage value, this indicates that a supply shortfall was not observed for this zone in the baseline before the solution was incorporated into the model.

Table B The effect of the solutions in reducing the relative probability of a supply shortfall occurring
A dash in a cell indicates that no change in the probability of a supply shortfall relative to the baseline was observed for this zone.

Scenario number	SRO	WREW Demand Centre/WRZ						
		Thames Water		Affinity Water		Anglian Water		Southern Water
		London	SWOX	Affinity WRZ 1, 2, 4	Affinity WRZ 3 & 5	Ruthamford North	Ruthamford South	South Hampshire
1	STT	60-70%	90-100%	0-10%	0-10%	-	-	-
2	SESRO	70-80%	50-60%	0-10%	0-10%	-	-	-
3	LER	80-90%	0-10%	0-10%	0-10%	-	-	-
4	T2AT (SESRO)	70-80%	50-60%	90-100%	90-100%	-	-	-
5	T2AT (STT)	60-70%	90-100%	90-100%	90-100%	-	-	-
6	T2AT (LER)	80-90%	0-10%	90-100%	90-100%	-	-	-
7	A2AT (SLR)	10-20%	0-10%	90-100%	90-100%	80-90%	20-30%	-
8	GUC	0-10%	0-10%	90-100%	90-100%	-	-	-
9	T2ST (SESRO)	60-70%	50-60%	0-10%	-	-	-	90-100%
10	T2ST (STT)	50-60%	90-100%	0-10%	0-10%	-	-	90-100%
11	SW - WR + HT	-	-	-	-	-	-	70-80%
12	SW - WR	-	-	-	-	-	-	90-100%
13	WCSS & WC2ST	-	-	-	-	-	-	70-80%
14	WCNS & Transfer	-	-	-	-	-	-	60-70%
15	SESRO + STT	90-100%	90-100%	0-10%	0-10%	-	-	-
16	GUC + STT	60-70%	90-100%	90-100%	90-100%	-	-	-



Individual solutions that primarily supply Southern Water and Affinity Water are capable of removing the chance of a supply shortage occurring relative to the baseline infrastructure configuration of the model, whereas the larger deficits for the Thames Water London WRZ mean that solutions must be combined in order for the same level of benefit to be realised. The scale of resilience benefit presented here is proportional to the frequency of supply shortfalls triggered in the baseline configuration of the model. It is therefore likely that where model validation tests have highlighted further baseline model configuration improvements could be made, such as the Affinity Water supply system, the drought resilience performance of solutions may be overestimated or underestimated by understating baseline supply shortfalls. Investigation of these improvements will be examined in Phase 2 (see Section 6).

Interaction v standalone

Solutions that involve interaction with a river network offer less drought resilience benefit than those that are standalone. For example, the STT has a yield of up to 500 Ml/d, however flow level constraints on the River Severn can act to remove the unsupported flow component of the transfer and similarly, hydrological constraints on the River Trent can limit the amount of water that Minworth Effluent Reuse can provide to support the transfer. It is however likely that real world operational constraints would act to reduce the static yield behaviour and associated drought resilience benefit observed for standalone solutions in WREW, whose yield is not impacted by hydrological variability.

Observed in-combination drought resilience benefit

An in-combination drought resilience benefit is associated with some in-combination scenarios (source and transfer, and two transfers). These results, and whether any additional benefit is realised beyond combining schemes, will be further explored as part of the Phase 2 modelling.

Despite the notable reduction in the relative probability of a supply shortfall, the solutions do not remove the risk entirely. Any residual risk is likely a function of coincident droughts between the Thames and Severn Catchments that act to reduce STT transfer capacity as mentioned above and also demonstrate the scale of demand for the London WRZ.

Supporting multiple areas

When the SESRO and STT solutions are configured to also support the T2AT and T2ST solutions, they notably reduce the relative probability of a supply shortfall for Southern Water and Affinity Water, while maintaining the same performance benefit for the Thames Water WRZs. The lack of a negative trade-off for sharing water supplied by supporting solutions indicates that the transfer configurations may allow for overall more efficient and effective resource use, notwithstanding any real world operational constraints.

Benefit of supporting SROs

Some of the solutions are supplied water by supporting solutions, which are in turn connected with other areas of the hydrological and supply system network. The supporting solutions have been shown to be utilised during droughts events in enabling the receiving solutions (such as STT) to deliver its benefits to the receiving WRZs. The supporting solutions are designed to cause no change to resilience in the supplying or donor WRZs, but the lack of supply shortfalls observed in these WRZs means we were limited in our ability to measure and conclude this. This circumstance has also limited the ability to conclude indirect resilience benefits to supply system-connected adjoining WRZs, that supporting or receiving solutions may have been otherwise expected delivered.

Next Steps

The Phase 1 results presented in this report investigates solution performance simulated over 2,500 years of near future climate projections, which include many different spatial and temporal patterns of drought. It is clear that the WREW model is an extremely useful tool with which to explore the behaviour and drought resilience benefits of each solution and combination of solutions.

Nevertheless, as with all models, there can be continuous development and improvement of different aspects. Below are a number of areas where further development of the model would be useful to improve confidence and enable a greater understanding how the solutions behave under different drought events, especially those that are geographically widespread, and more severe.

The recommended areas for further work in Phase 2 ae set out below.

Model Improvements

Improve model behaviour and supply system calibration for United Utilities' network

A comparison of the simulated reservoir storage for the historic period from WREW with the outputs from the Aquator models of United Utilities shows an imperfect calibration of Haweswater Reservoir, which is a key indicator of resource position for the company. Improving the calibration of this reservoir, and consequently the behaviour and drought resilience characteristics of the United Utilities system in WREW, is important for understanding wider resilience impacts on STT.

Improve the representation of Affinity Water's groundwater abstraction

Large parts of Affinity Water'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 current representation of groundwater in WREW. A more robust approach, for modelling groundwater under drought conditions using lumped parameter models, should be adopted to improve behaviour of the Affinity Water's central region in WREW.

Improve model behaviour linked to reservoir storage

Reservoir storage is an important component of supply system infrastructure since storage levels give a reliable indication of the resource position for a WRZ. Improving the behaviour of reservoir storage and the associated underlying supply system representation in WREW will help improve model behaviour during drought events.

Scenarios and Analysis

Greater scenario testing

In Phase 1, the scenario configurations held steady all parameters except climate to isolate the drought resilience benefits of the solutions relative to baseline. The next phase of the project should involve a more robust stress test of the solutions through comprehensive scenario testing and sensitivity analysis, exploring uncertainty in potable demand and the water needs of the environment. Additionally, Phase 2 of the project should focus on investigating the drought resilience benefits associated with combinations of solutions, including the portfolio of solutions provisionally selected in regional plans.

Updates to strategic solutions

The representation of the RAPID solutions in WREW is based on the information available at the time of Phase 1 and is consequently a snapshot of scheme design. Since then, solutions have been further developed as part of the of the RAPID and regional planning process, which has brought about changes in scheme design. In the next phase of the project, any important changes to the solution design should be taken into account by updating the representation in WREW.

Inter-regional drought correlation

The hydrological model used for this analysis is driven by spatially coherent climate simulations, which means that inter-regional drought correlations are well represented. In Phase 2 it will be possible to examine in more detail how inter-regional drought events affect surface and groundwater resources and supply system behaviour, and consequently the resilience benefits of the solutions.

Different drought resilience metrics

A supply shortfall metric has been used in Phase 1 to measure the drought resilience performance benefit associated with the solutions. However, many of the indirect benefit and potentially impacted demand centres do not experience a supply shortfall event in the drought event set used, and therefore a benefit or dis-benefit cannot be measured. An alternative metric could be used: level of service and associated water use restrictions. This metric should generate outputs that allow investigation of how the solutions promote drought resilience.

Comparison of climatological input data

The modelling approach used in this study is different to the approach taken by the regional groups in that it takes a national-scale approach and spatially consistent datasets, particularly with climatological inputs. However, insights from the national modelling can be used to help sense check the findings of regional models and aid reconciliation between them. For this process to work with confidence, there needs to be an understanding of the extent to which any differences are observed are a function of the modelling (i.e. climatological input data or modelling approach) or real-world behaviour.

Test against specific types of drought events

Some of the WRZs examined in Phase 1 did not show any demand deficit against the simulated droughts, limiting the examination of additional indirect benefits of the solutions to associated areas. It would be useful to assess the performance of the solutions against more challenging droughts in order to stress test existing and proposed infrastructure and ascertain the direct and indirect benefits of new solutions on a nationally coherent scale.

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 methods to develop the first phase of a National Supply Simulation Model that incorporates regional water group's solutions within the rapid programme. The solutions present regional and inter-regional supply options that address increasingly pressured water resource challenges. The model gives a national scale platform to stress test the solutions and provide a quantitative independent evidence base for RAPID and its sponsor regulators to explore the implications of inter-regional drought coherence on large-scale transfers.

1.1 Water resource and regulation

The demand for water is set to increase over the next several decades, with the population of the UK rising from 67 million to 75 million by 2050[4]. The environment needs more water too, in order to protect rare habitats, which are ecologically vital, as evidenced by the 2020 EA report "*Meeting our Future Water Needs*". At the same time, the water available to supply those needs is expected to decrease by 10-15%[5], due to climate change. In order to address the combined effects of growth and climate change the industry is acting to reduce demand and develop new water infrastructure to increase supply and meet future needs.

In the face of these long-term and large-scale challenges around water resources, water companies are collaborating to produce regional water resources plans that will feed into individual water company Water Resource Management Plans (WRMPs). Five regional water resource planning groups currently exist in the South East, the East, the West Country, the West and the North. These plans will be presented to the regulators and stakeholders for scrutiny. The regional plans aim to transcend company boundaries and look beyond the requirements of just public water supply to identify optimum solutions for the region as a whole.

In the PR19 final determination, Ofwat has made £469m of development funding available to water companies to investigate and develop new large-scale solutions that will form part of future WRMPs, regional plans and business plans. Based on company submissions for Ofwat's Price Review 2019 (PR19) process, Ofwat initially identified 17 solutions for further investigation and development. These solutions are listed in the final determinations for PR19 and involve different source-type solutions including reservoirs, effluent reuse, and six transfer-type solutions, utilising river, canal and pipeline transfer routes.

Delivery of the solutions is subject to a formal gated process, coordinated by a new cross regulatory unit: the water Regulators' Alliance for Progressing Infrastructure Development (RAPID). The alliance consists of the three water regulators; Ofwat, the Environment Agency and the Drinking Water Inspectorate.

The vision of RAPID is for resilient, timely, high-quality, environmentally beneficial and affordable water resources. The team is focussed on the delivery of three objectives:

- To facilitate the timely and co-ordinated development of solutions;
- To make recommendations for the frameworks for the future that best support the delivery of the vision on an enduring basis; and
- To provide a seamless regulatory interface for the solution proposers and regional groups.

1.2 The problem

The solutions being considered as part of the RAPID gated process aim to be 'construction ready' within the 2025-2030 period and will provide resilience to future supply challenges arising from climate change, along with other factors that influence water demand. The benefit of water resource solutions will therefore be vital over the next five to 15 years. Water resource models are required to reliably account for uncertainty in water availability and demand and fully explore the risk, interdependencies

[4] Office for National Statistics, National population projections: 2018 based

[5] Sir James Bevan (2019) Escaping the jaws of death: ensuring enough water in 2050, Environment Agency Waterwise conference

and sensitivities of these solutions. Several of the solutions comprise of inter-regional transfers utilising river, canal and pipeline transfer routes. These inter-regional solutions demonstrate the scale of the water resource supply and demand challenges that we face and highlight the need for a national perspective, evidenced by a national modelling approach.

Many of the regional groups are building regional scale water resource simulation models to test the solutions to help inform regional plans and WRMPs, and follow the water resources planning guidelines. Whilst efforts are being made to ensure a consistent approach is taken to regional modelling and that model outputs are comparable, fundamental differences in approach and complexity mean that there are difficulties when combining these outputs into a fully representative national picture.

One of the major sources of uncertainty for water resources planning is around how climate change will affect water availability and the consequent impacts on the benefits provided by large regional solutions. For example, what will large scale droughts look like under climate change? The regional groups are using regional drought library datasets in their models, to test droughts under climate change. These datasets are spatially coherent in each region, but not necessarily outside, which means that generally the impact of large-scale droughts cannot be assessed without additional work. This is especially relevant for solutions involving large-scale transfer pathways, where sensitivities and risk associated with inter-regional drought coherence must be understood and quantified.

The interdependencies between solutions potentially extend across multiple catchments stretching the full length of the country, from Thirlmere in the north and Lake Vyrnwy in the west, to the south coast. A national-scale model is required to test the solutions and understand their benefits and risks at the national level. Such a model will help to identify key areas of water resource uncertainty and focus regulatory scrutiny of the regional and company processes. It will also allow for more robust stress testing of solutions involving inter-regional transfers by exploring the risk around uncertainties in inter-regional drought coherence.

1.3 The National System Simulation Modelling project

This project is intended to examine the resilience and benefits of individual 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 outcomes will help inform RAPID's recommendations to Ofwat around future funding and investment through the gated process, and support the regulators provide feedback to regional and company plans. This approach will give RAPID an independent and strategic national-level viewpoint of the risks and benefits of the solutions.

This project will rely on a system simulation modelling approach to ensure the interdependencies of solutions and the impact of environmental constraints from solutions and regulators investigations are incorporated, as well as maintaining comparability and consistency with regional and company models.

This project is not intended to replace any regional or company modelling, but rather provide a strategic national view of the solutions and the explore the implications of inter-regional drought coherence (and other factors) on large-scale transfers. It does aim to build on the work of the National Framework and will provide a quantitative independent evidence base for RAPID and its sponsor regulators, as well as help inform regional modelling where possible.

The project also recognises that there are feasible supply options being considered by regional groups and water companies to address water resource challenges that are not solutions in the RAPID programme. The model is a tool to support the RAPID process investigating the national benefit of the solutions, rather than a promotion of the solutions over any other options. Where options that are not solutions in the RAPID programme begin to be selected with confidence through planning processes, as standalone options or to support solutions, this modelling project may look to incorporate these as appropriate to reflect likely current and future planning scenarios.

The objectives of the 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 enough to accurately approximate their behaviour,

assessed via comparison of simulated reservoir storage with water company models and observations;

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 performance of the solutions (individually and in combination) and how they trade-off against one another, 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.

Phase 1 of this project covers all of Objective 1 and Object 2a. Phase 2 of the project will see the further development of the representation of the water infrastructure within WREW and cover Objectives 2b to 2d.

2 Background

2.1 The MaRIUS project

Through the NERC-funded MaRIUS project[6] (2014-2020 'Managing the Risks, Impacts and Uncertainties of drought and water Scarcity'), the first national scale Water Resource simulation model for England and Wales (WREW) was developed by a team led by Professor Jim Hall at Oxford University, using the software platform Wathnet.

The work undertaken within the MaRIUS project, developed a risk-based approach to the management of droughts and water scarcity, drawing upon global experiences and insights from other hazards to society and the environment.

MaRIUS used a multi-disciplinary approach to understanding the risk and consequences of drought and water scarcity, using an end-to-end process starting with climatological drivers and exploring the effects on water quantity and quality, ecology, the economy, energy systems, agriculture, and the implications for humans and society.

By underpinning a risk-based approach to management of water scarcity, the MaRIUS project developed an integrated suite of models of drought processes and impacts of water scarcity. Of relevance for this work, are the WREW water resources model, the DECIPHeR hydrological model, and the large, validated, ensembles of spatially (nationally) coherent climate conditions for England and Wales (from the Weather@Home2 climate modelling system), which contain many drought sequences. These outputs are described in the sections below.

2.2 Water resource modelling: WREW

National water system simulation modelling is challenging, and involves integrating climate, hydrology, water infrastructure, and water demand modelling. Though coupled simulation models have existed at catchment and water company scales, until recently it has proved too challenging to apply this approach at a national scale.

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. It is configured to perform simulations on a daily time-step.

The WREW formulation includes a simplified representation of all major water supply infrastructure (reservoirs, boreholes, transfers, water treatment works, pumped storage, desalination plants, and river abstraction points) that are connected into England and Wales's wider water network via any river or transfer of significance (defined as >2 Ml/day for the purposes of this model).

It also includes licence conditions which regulate water abstractions, operational rules, control curves, and asset locations where necessary (locations are needed for river abstractions or boreholes). It covers more than 90% of England and Wales's population and public water use, with non-public water users represented at catchment scale).

The model contains national level climate and hydrology data, abstraction volumes and returns, environmental flow thresholds, groundwater information, water infrastructure relevant up to 2014, some of the (>20 Ml/d) supply side options from WRMP 2019, and operational rules.

A full description of the WREW model can be found in Dobson *et al*. 2020[7].

Figure 1 gives an overview of the WREW workflow, showing the main data sources, models and outputs which are colour coded to show how they input to other models.

[6] See: http://www.mariusdroughtproject.org/
[7] See: https://doi.org/10.1029/2020WR027187

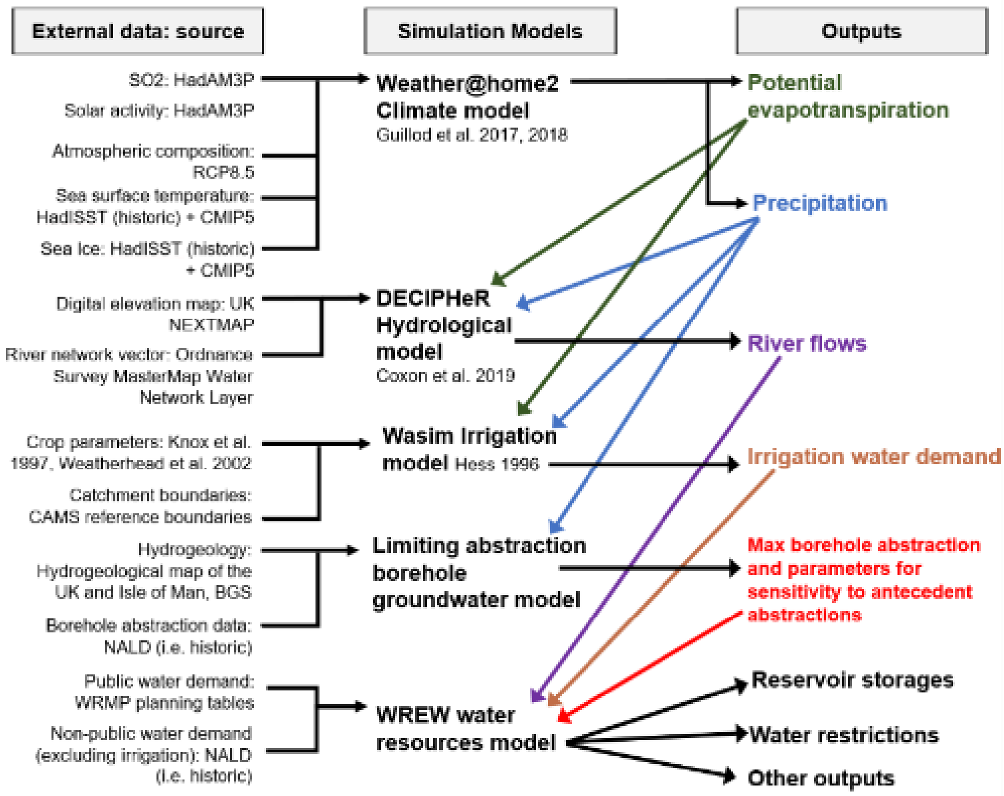


Figure 1 An overview of the workflow, showing the main data sources, models and outputs which are colour coded to show how they input to other models.

2.2.1.1 The WATHNET Modelling software

WREW is based on the proprietary WATHNET water resource simulation software.

This software solves a mass balance optimization problem and allocates water between model nodes, via arcs, under both constraints inherent to mass balance and constraints set out by the water system's formulation (e.g. pipe capacities and minimum flows). The solver minimizes a set penalty associated with each model arc, performed by network linear programming; the penalty reflects operational preferences.

Wathn*et al*lows a relatively high degree of customisation in order to accommodate the large variety of water resources systems that exist. Bespoke scripts can be written to create the customisation required to allow custom rules, detailed implementation of operator preferences and complex abstraction licences.

2.3 Hydroclimatic modelling and outputs

2.3.1 Climatology

The MaRIUS project created a new ‘event set' of past and possible future hydroclimatic drought conditions, which enables extensive testing of drought scenarios at national scales. This dataset enables analysis of drought in a spatially coherent way for all of the catchments in the WREW model domain.

These long, validated, ensembles of spatially (nationally) coherent climate conditions for England and Wales were created using the Weather@home2 modelling framework[8]. This framework is used

[8] For data from the MaRIUS project and associated projects, see: *Full index of datasets (aboutdrought.info)*

extensively by the climate modelling team at the University of Oxford to simulate climate conditions over Europe.

The weather@home2 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).

Sets of 100 time series have been generated for each of (i) a historical baseline (1900–2006), (ii) five near-future scenarios (2020–2049) and (iii) five far-future scenarios (2070–2099) (Guillod *et al*., 2017, 2018). The five scenarios in each future time slice all follow the Representative Concentration Pathway 8.5 (RCP8.5) and sample the range of sea surface temperature and sea ice changes from CMIP5 (Coupled Model Intercomparison Project Phase 5) models.

The validation of the historical baseline showed good performance for temperature and potential evaporation. There are substantial seasonal biases in mean precipitation which have been corrected using a linear approach. For extremes in low precipitation over a long accumulation period (>3 months) and shorter-duration high precipitation (1–30 days), the time series generally represents past statistics well. Future projections show small precipitation increases in winter but large decreases in summer on average, leading to an overall drying, consistently with the most recent UK Climate Projections (UKCP09) but larger in magnitude than the latter. Both drought and high-precipitation events are projected to increase in frequency and intensity in most regions, highlighting the need for appropriate adaptation measures.

It should be noted that the simulations produced by the weather@home2 modelling framework are driven by the high emissions or ‘business as usual’ RCP8.5 climate emissions scenario, which is the same emissions scenario used in the Met Office UKCP18 climate scenarios.

The MaRIUS validated climate dataset contains a total of 9,000 years of synthetic weather, containing many severe droughts that have been calibrated and validated against long series of observed weather data within the MaRIUS project. The use of these coherent and bias corrected climate model outputs means that combinations of variables (e.g. to estimate evapotranspiration) are physically consistent, allowing drought and periods of water scarcity to examined on a like for like basis on a regional and national scale. This physical consistency cannot be guaranteed with the use of weather generators, which means that the datasets used by each regional water resource planning group may not be inter-comparable on a like for like basis. This potentially causes uncertainty when assessing the possibility of supplying water from one region to another. The datasets used by water companies and regional water resource planning groups use an approach that perturbs existing climate data for assessing climate change risk, as set out in the water resources planning guidelines. In contrast, the MaRIUS validated climate dataset is generated from a regional climate physical system simulation model, similar to the Met Office’s UKCP process. This dataset offers benefits at the national scale by being spatially consistent, but does not align with the water resources planning guidelines, as it was produced before they were created.

2.3.1.1 Use in this modelling project

The 100x30year near future (2020-2049) climate ensemble runs were used to generate river flows using the DECIPHeR hydrological modelling framework (see next section). There are a range of drought durations and intensities in the climate ensemble reaching beyond 1:200 year return periods and including extreme events. Generally, the baseline (historic) climate ensemble maps well onto observed droughts, and the near- and far-future droughts include longer and drier events compared to the baseline.

Further analysis of the drought ensemble will be performed for Phase 2 in order to identify particular drought sequences of interest, be that based on drought location, coverage, duration, intensity and other factors, in order to allow assessment of the performance of the water supply infrastructure under different pressures. In addition, Phase 2 will also see a national comparison of the climate scenarios used in this project to those used by water companies and regional groups, as well as the UKCP18 dataset, to give insights into any variances or differences. Separate to this project is a climate comparison project funded by the regional groups, that focusses on several key river basins to examine the different regional climate datasets being used and which will also consider the climate dataset used in this project. It is hoped that the results will be available to report within Phase 2 of this project.

2.3.2 River Flow

Within the MaRIUS model, the University of Bristol built the DECIPHeR hydrological model (Coxon *et al.,* 2019a,b). DECIPHeR is a flexible hydrological modelling framework, based on general hydrological principles applicable to a broad spectrum of different catchment types, that can simulate flows across multiple catchments with different hydrological characteristics, and can be applied to a range of space and timescales.

The DECIPHeR model flexible framework allows the simulation and prediction of hydrologic flows and connectivity from spatial scales of small headwater catchments to entire continents, and to test different spatial resolutions, spatial configurations, levels of hydrologic connectivity, and process representation. The underlying code has been optimized to run large ensembles and enable model uncertainty to be fully explored. This is particularly important given inherent uncertainties in hydro-climatic datasets (Coxon et al., 2015) and impact on model calibration, regionalization and evaluation.

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-km^2 input grid to ensure the spatial variability of climatic inputs was represented.

It groups together hydrologically similar points in the landscape into spatially connected hydrological response units to minimise run times. This enables it to run large ensembles of climate simulations and provide probabilistic flow simulations essential for risk analysis.

DECIPHeR uses precipitation and potential evapotranspiration outputs from weather@home2 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

DECIPHeR has been applied to 1,366 flow gauges across Great Britain and tested to assess its performance against a range of hydrological parameters. It has been shown to perform well for four different evaluation metrics: (a) high flows (Nash-Sutcliffe efficiency), (b) water balance (bias in runoff ratio), (c) low flows (bias in low flow volume), and (d) flow variability (bias in the slope of flow direction curve). Good performance is shown across a wide range of catchments characteristics but particularly in wetter catchments in the west and north of Great Britain (Coxon *et al*., 2019a,b). In this way a national dataset of current and future river flows has been generated and is publicly available[9]. More information on the approach can be found in Coxon *et al*., 2019a.

For input to the WREW model, ensembles of naturalized flows were generated for 338 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 the best available daily naturalized flows obtained from the Environment Agency or by 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 (CHESS, 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). Given the inherent uncertainty associated with hydrological modelling, 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 weather@home2 projections (covering the baseline, near-future and far future period).

2.3.2.1 Use in this modelling project

The only change to the above datasets for this modelling project was to run DECIPHeR for an additional point on the River Tamar at Gatherley for the West Country South Sources & West Country – Southern Transfer solution.

[9] The DECIPHeR model code is open-source and freely available under the terms of the GNU General Public License version 3.0. The model code is written in Fortran and is provided through a Github repository: https://github.com/uob-hydrology/DECIPHeR.

2.3.3 Groundwater

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.

2.3.4 Water demand

2.3.4.1 Potable water

Using historic data from the Environment Agency national abstraction and returns database, 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 is generally set at water resource zone (WRZ) scale. The most common setup within WREW is to have one demand node for each modelled WRZ. However in some cases, where a WRZ is large or the supply system is more complex, WRZs are divided into several smaller demand nodes. Each demand node uses demand data from water company PR19 planning tables available from the Environment Agency (2019) (Distribution Input for the Dry Year Annual Average climate scenario, on a monthly profile for each WRZ).

2.3.4.2 Non potable water demands

2.3.4.2.1 General approach

WREW uses data from the Environment Agency's national abstraction database on abstraction volumes taken for non-public 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.

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

2.3.4.2.2 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) (see Figure 1).

2.3.4.3 Effluent discharge

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

2.4 Calibration and validation

2.4.1 Representation within WREW

At the start of the National System Simulation Project, the WREW implementation included all major public water supply infrastructure (300 reservoirs, boreholes, transfers, water treatment works, pumped storage, desalination plants and river abstraction points) that are connected into England and Wales' wider water network via any river or significant transfer (> 2Ml/d).

It includes abstraction licence conditions, operational preferences, control curves and asset locations where necessary. It covers more than 90% of England and Wales' population and public water demand with non-public water users represented at catchment scale.

In order to build a computationally efficient model, a number of assumptions have been made, as follows:

- Aggregation of multiple reservoirs that supply single treatment works and/or < 2 Ml volume, part of the same hydrological system, and located proximal to one another;
- The omission or aggregation of small sources; the lowest nonzero flow is 1 Ml/day;
- 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 (except for aqueducts with known travel times);
- Zero evaporation for reservoirs (except where relationships have been provided)
- Zero incident rainfall on reservoirs; and
- Assumed acceptability of water quality and exclusion of reservoir dead water storage volumes.

Figure 2A: shows a depiction from the accompanying GIS representation of the water resources set-up showing nodes and arcs against large rivers and the EA management regions.

2.4.1.1 Welsh representation

Key areas of Wales' water supply system are represented in WREW, as shown in Figure 2B: including:

- The Alwen/Dee WRZ and associated Dee Reservoir Group (Alwen Reservoir, Llyn Brenig, Llyn Celyn and Llyn Tegid);
- Lake Vyrnwy, Clywedog Reservoir and the Elan Valley Reservoirs;
- The Twyi Conjunctive Use System and SE Wales Conjunctive Use System and associated reservoirs (Llyn Brianne, Llandegfedd Reservoir, Usk and Crai Reservoirs, Lliw and Ystradfellte Reservoirs, SE Wales Conjunctive Use System Small Reservoirs and SE Wales Conjunctive Use System Large Reservoirs); and
- The Wye demand centre, which includes the Elan/Builth Wells, Llyswen and Monmouth WRZs as well as other Dŵr Cymru WRZs that are located in England but also supplied by abstraction from the River Wye.

The first two areas are included in WREW due to their important role in the regulation of the River Dee and River Severn, as well as supplying water to Severn Trent Water's Strategic Grid WRZ and United Utilities' Strategic WRZ. The two WRZs in South Wales cover some of the most densely populated areas in the country and are represented in WREW because of the associated high levels of water demand. The Wye demand centre contains the Elan Valley Reservoirs, which supply Severn Trent Water's Strategic Grid WRZ and also play a key role for regulation on the River Wye. It is important to note that some of the water demands from other Welsh WRZs are aggregated into the demand centres in WREW listed above.

All of the Welsh assets and demand centres currently included in WREW were implemented via consultation with Natural Resources Wales and Welsh Water during the 2016 Water UK Water Resources Long-Term Planning Framework study. The supply system has not been updated as part of the NSSM project. Model validation was carried out for the Water UK study by comparing simulated storage levels from WREW with water company modelling outputs for Lake Vyrnwy and Elan Valley Reservoirs. This analysis has been updated and is shown in section 4.1.2.

As part of the solution development process, water companies are working with Natural Resources Wales to ensure that relevant solutions comply with Welsh Legislation and will not affect the environment or security of supply for the people of Wales. The current incomplete representation of the Welsh supply system in the model, means that assessing how/if the solutions affect reliability of water supply in Wales is beyond the scope of the NSSM project. The relationship between solutions and resilience and the environment in Wales is expected to be demonstrated by modelling undertaken by water companies and / or regional groups.

2.4.2 Historic calibration of model

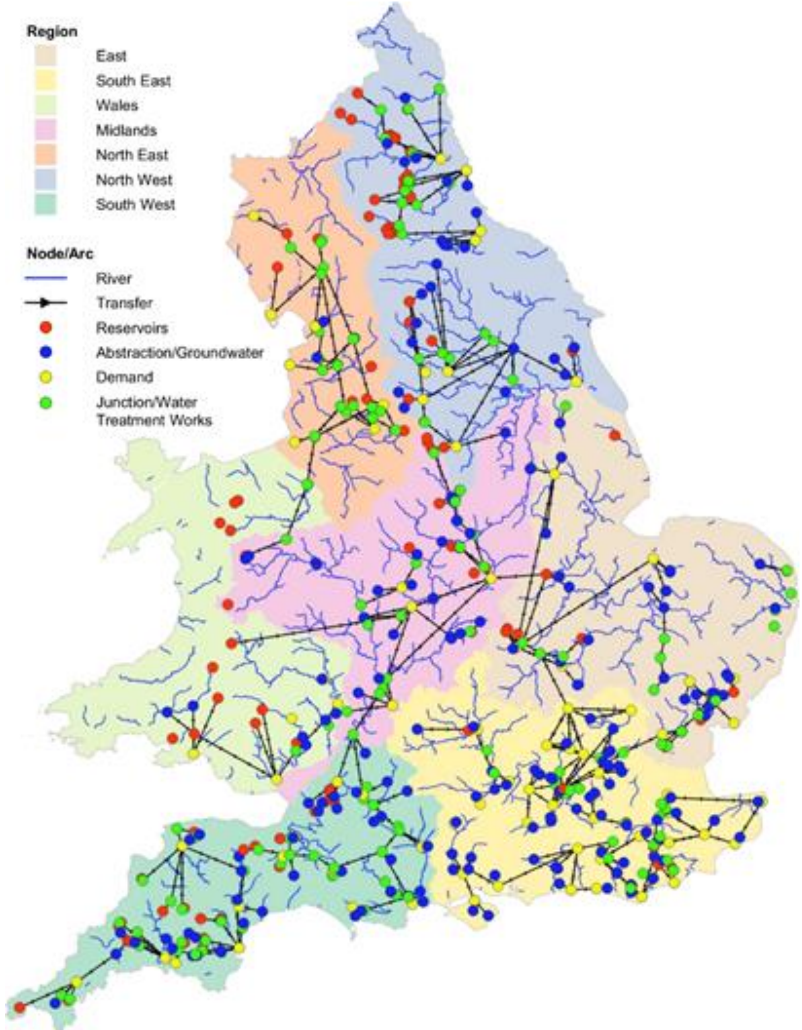
The creation of the WREW model by the MaRIUS project and its subsequent development has been strengthened by interaction and collaboration with UK water industry practitioners, regulators, consultancies, regional water groups and the use of the model in various industry initiatives. The water system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

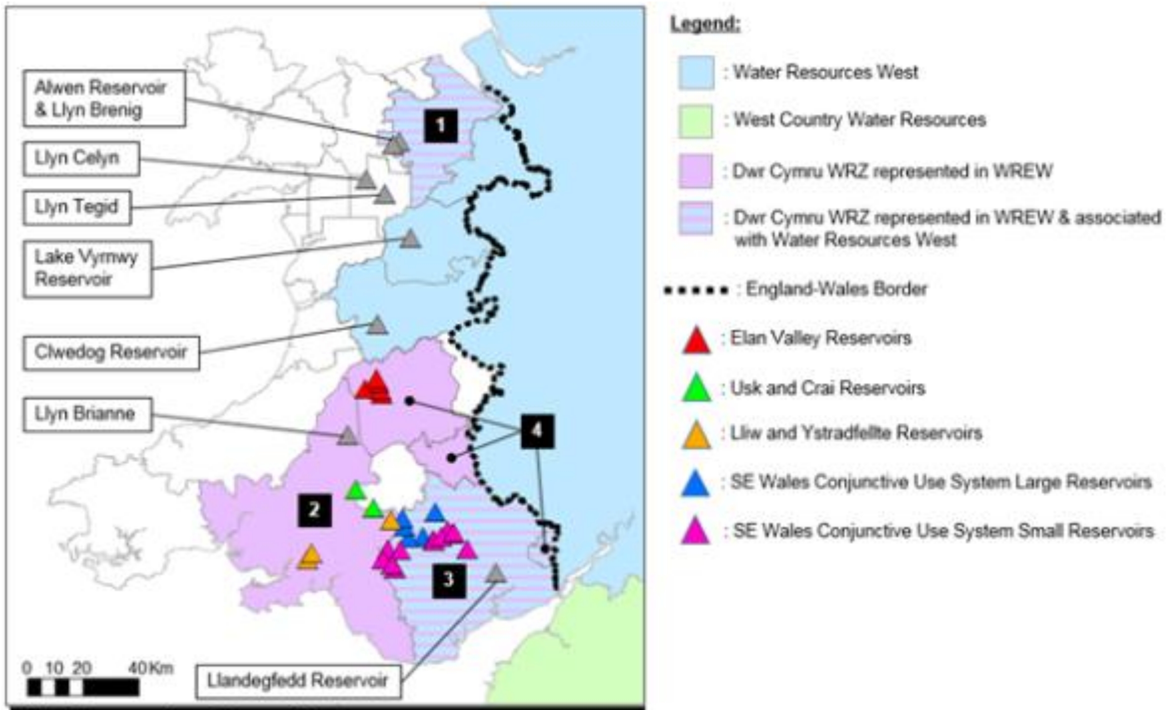
A key period of industry-aligned parameterisation and calibration was during its use in the Water UK Water Resources Long-Term Planning Framework study (2016), when it was subject to intense scrutiny by water companies, consultants and regulators.

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. For example, when comparing the goodness of fit between the WREW model and companies-own operation supply model for changes in different reservoir storage volume of key reservoir groups, the Nash-Sutcliffe efficiency value ranged from 0.97 to 0.69; a good fit. More information on this, and charts can be found in Dobson *et al.* (2020) particularly the supplementary information to the paper.

Most 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.





Water Resource Zones/Demand Centres

	Name	Company
1	Alwen/Dee	Dwr Cymru
2	Twyi Conjunctive Use System	Dwr Cymru
3	SE Wales Conjunctive Use System	Dwr Cymru
4	Wye	Dwr Cymru

Figure 2A: A GIS depiction of WREW showing nodes and arcs against large rivers and the EA management regions.

Figure 2B: An overview map of the WRZs and reservoirs in Wales in WREW

Figure 2 The representation of infrastructure in the water resources supply model, WREW, at the start of the NSSM project

3 Overall approach, industry liaison, and the SROs

3.1 Overall approach

The overall approach to the NSSM project is set out in Figure 3. The project is split into two phases, with Phase 1 concentrating on data collation and workshops, updates to the WREW model, and incorporation and verification of each individual solution. Phase 2 then concentrates on stress testing of individual and combinations of solutions against drought, climate and demand scenarios. This report reflects Phase 1 tasks, with recommendations for Phase 2.

The project utilises the existing WREW model (detailed in Section 3.2 above), 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 been updated and verified using the DECIPHeR model, and climate scenarios from the Weather@Home2 model (Section 3.3). 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 Phase 1 tasks will inform recommendations to refine Phase 2 scope, including more complex improvements to solution representations, and stress test scenarios to run.

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 3 Steps within the project's Phase 1 and 2

3.2 Liaison with stakeholders

A key part of the national system simulation (NSSM) project involves carrying out updates to WREW, including ensuring the representation of the supply system is correct, updating the baseline configuration of the supply system to 2025 and adding the solutions.

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.

3.2.1 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) and 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 regional and national modelling.

Over 2020-2021, the NSSM team shared preliminary plans for the national modelling, gathered feedback on areas of concern and agreed data requests with MAG, all of which helped refine the project ensure a collaborative way of working. The key decisions taken as a result of discussion at the MAG meetings include:

- Align the representation of the supply system in the baseline WREW model scenario with regional and water company modelling by updating WREW to include any major (>20 Ml/d) new supply options signed off as part of WRMP19;
- Investigate the extent to which the climatology datasets and hydrological modelling approaches used in the NSSM project, will drive differences in the water resources modelling results, compared with water company and regional models, by:
    - Comparing simulated storage levels for key reservoirs in WREW with those from regional/water company modelling. Any significant differences in simulated storage would warrant further investigation around flow data;
    - Carrying out a comparison between the weather@home2 climatology, used in the NSSM project, and the regional group weather generator climatology dataset (to be undertaken in Phase 2, see Section 6.1.7); and
- Further engagement by the NSSM team with the regional groups to get information with which to complete the above actions.

3.2.2 Working group

Liaison with the working group and discussions with members were very useful for the project and modelling process. Advice was given on validation, including the identifying reservoirs at would be suitable for this purpose. IT also facilitation wider access to aligned discussions and other commissioned work for example on comparing climatological datasets for example.

3.2.3 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 meetings with the external solution teams (water companies and consultants) between January and June 2021. The process involved the NSSM team developing a conceptual understanding of the solutions, based on solution overview documentation provided to RAPID by the water companies, and creating a preliminary representation of each solution in WREW. Meetings with the solution teams were used to confirm the conceptual understanding, review the preliminary representations and gather feedback.

The simplified nature of WREW compared with the complexity of solution design resulted in the NSSM team adopting an iterative approach for representing the solutions in the model and required multiple meetings with the external solution teams. Some solutions are inherently more complex and therefore required a greater number of iterations on the representation, as well as detailed sense-checking of behaviour, before a solution was agreed. This process allowed the NSSM team to gain assurance that the solutions are represented satisfactorily in WREW.

3.2.4 Liaison over supply system representation

Since MaRIUS, WREW has been developed over several projects (WaterUK[1] and the National Framework[2]), which involved consultation and engagement with water companies on the representation of the supply system. The timing of consultation and phases of work previously carried out on the national model meant that the supply system in WREW was configured to represent the network as of WRMP14, with some additional large supply options from WRMP19 added for the National Framework[2] and for academic research (Dobson *et al.* (2020)).

Water companies and regional groups have updated the supply systems in their models to a baseline year of 2025, it follows that WREW would similarly be updated, to align with regional and water company models. Furthermore, ensuring that that supply system is represented as accurately as possible in WREW is important since this is the baseline network into which the solutions are implemented and tested relative to.

The NSSM team engaged with the water companies around the representation of the supply system in WREW. This process involved providing water companies with model documentation on the supply system topology and requesting feedback on the representation of the network, as well as any changes required for 2025. Meetings were held with Thames Water, United Utilities and Severn Trent Water, all other companies provided written feedback. Due to time and scope limitations, not all of the feedback provided by water companies could be implemented in Phase 1. Instead, the feedback was compiled and prioritised according to straightforward but high-impact changes. Further development of WREW will occur in Phase 2 to incorporate remaining water company feedback, as detailed in Section 6.

3.2.5 Obtaining information and data

The NSSM made data requests to regional groups and their constituent water companies for storage volumes of all reservoirs simulated in their water resources models, as well as, providing access to the regional group climate dataset.

3.3 Representation of the solutions in the RAPID programme

This section gives a high-level summary of the solutions and how they have been implemented in WREW. Representing the solutions within a national scale model allows exploration of their inter-regional drought benefits and the impact on the water supply system.

3.3.1 Severn to Thames Transfer (STT) and enabling solutions

During periods of drought in the South East, the Severn to Thames Transfer (STT) would convey raw water from the River Severn into the River Thames via an interconnector. There are currently two possible conveyance options: a pipeline from the River Severn at Deerhurst that discharges into the middle River Thames near Culham, Oxfordshire (300-500 Ml/d); or the use of the Cotswolds Canal infrastructure, plus a pipeline to move water between Deerhurst and Culham (300 Ml/d). There are multiple sources, which form their own enabling solutions, which will be utilized to support the solution when needed, namely: Lake Vyrnwy; Minworth Wastewater Treatment Works (WwTW) (also a potential source for the Grand Union Canal transfer SRO), Netheridge WwTW, and Mythe Water Treatment Works (WTW).

The primary recipient water resource zone is London with the Swindon and Oxfordshire (SWOX) WRZ is a secondary recipient (both Thames Water).

This solution is a possible source for the Thames-Southern transfer and the Thames-Affinity transfer.

Following consultation with solution leads in water companies, a number of decisions were made to best represent the solution within WREW. The following representation decisions and simplifying assumptions were agreed:

- The upstream operation of the solution involves transfer of water along river reaches. However, in WREW the STT is configured as a virtual transfer (i.e., water is not discharged into or transferred via the river network) since all of the sources (except for the unsupported flow available for abstraction on the River Severn at Deerhurst) work on a 'put and take basis' (i.e., do not support flow in the river systems). Support from Vyrnwy reservoir to STT has been represented in WREW as a virtual transfer from Oswestry Water Treatment Works. This configuration was chosen for simplicity and as a means of intercepting water that Lake Vyrnwy normally supplies to United Utilities, when STT is not in operation. Considerations around raw or treated water are not important for the virtual transfer setup in WREW. In reality, raw water releases would be made into the river system, either directly from the dam or via a new pipeline upstream of Oswestry Water Treatment Works;

- The solution is triggered when London Storage drops below the control curve where Teddington Target Flow transitions from 800 Ml/d to 600-700 Ml/d;

- The downstream operation of the solution involves release at Culham and transfer of water via the River Thames. However, releasing water at Culham in WREW would allow other demand centres (WRZs) that have abstraction points on the Thames to benefit. Although this may be possible in the future, for this project's context, the STT should just supply London, SWOX, Affinity (via Thames- Affinity Transfer) and Southern (via the Thames – Southern Transfer). Therefore, the downstream part of the solution is configured as a virtual transfer, and not released at Culham, but instead sent directly to the target demand centres;

- Although the supply sources for the STT are configured as virtual transfer, losses have been implemented to represent the expected behaviour of the relevant river systems the transfer would use in reality. The virtual transfer from Minworth Effluent Reuse to Deerhurst has a 10% loss associated with transfer along the River Avon. The virtual transfer from Lake Vyrnwy to Deerhurst has a 20% loss associated with transfer along the River Severn. Losses on all rivers are assumed to be constant, in the absence of other information at this time. A 2% loss has been added to the Deerhurst pipeline;

- The Trent effluent reuse node is used to represent Minworth in WREW. This is an aggregation of all sewage treatment works along the River Trent, which has a combined output of ~800Ml/d in WREW (~1006 Ml/d in reality). This simplification will not impact the behaviour of Minworth solution as dry weather flow at Minworth is ~400 Ml/d;

- The unsupported flow component of supply for the STT is represented in WREW as an abstraction on the River Severn at Deerhurst. Information provided by the solution team was used to configure abstraction rules in WREW that control the volume of water available for abstraction at different flow levels on the River Severn;

- Due to the close proximity of the two possible conveyance options, via the restored Cotswold Canals, or a new pipeline, both are simulated as one arc with full capacity; and

- The Vyrnwy Aqueduct and UU Sources solution (North West Transfer) solution is needed to avoid deterioration in United Utilities' Strategic Resource Zone as a result of the partial redeployment of Vyrnwy. The UU Sources and Vyrnwy Aqueduct solutions have been aggregated into one supply source in WREW that offsets water Vyrnwy supplies to the Severn-Thames Transfer. The volumes between the UU Sources & Vyrnwy Aqueduct Solutions and the Vyrnwy component of STT are linked so that up to 110 Ml/d can be supplied to United Utilities when Vyrnwy sends 180 Ml/d to STT.

Figure 4 shows the schematic map of the solution, and Figures 5 and 6 show the WREW representation.

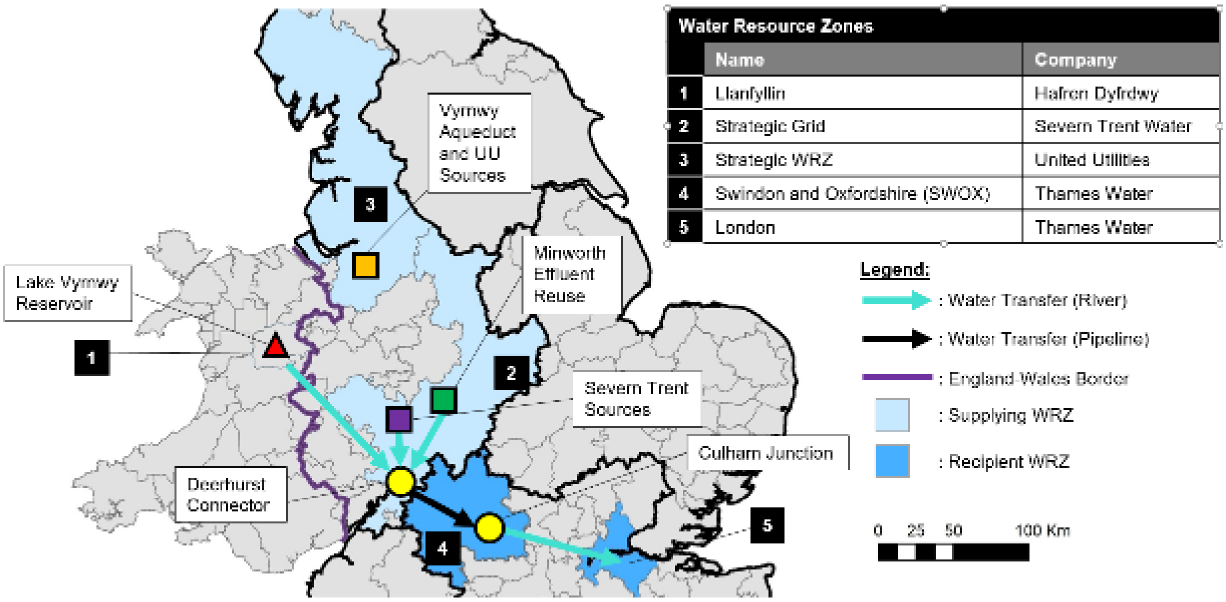
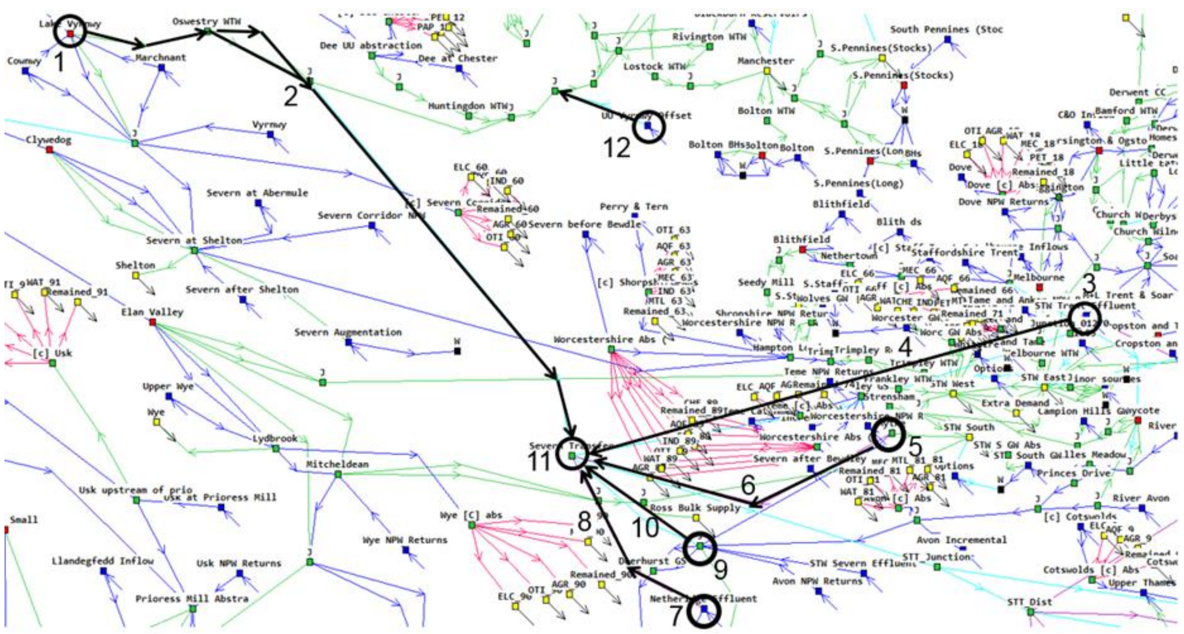


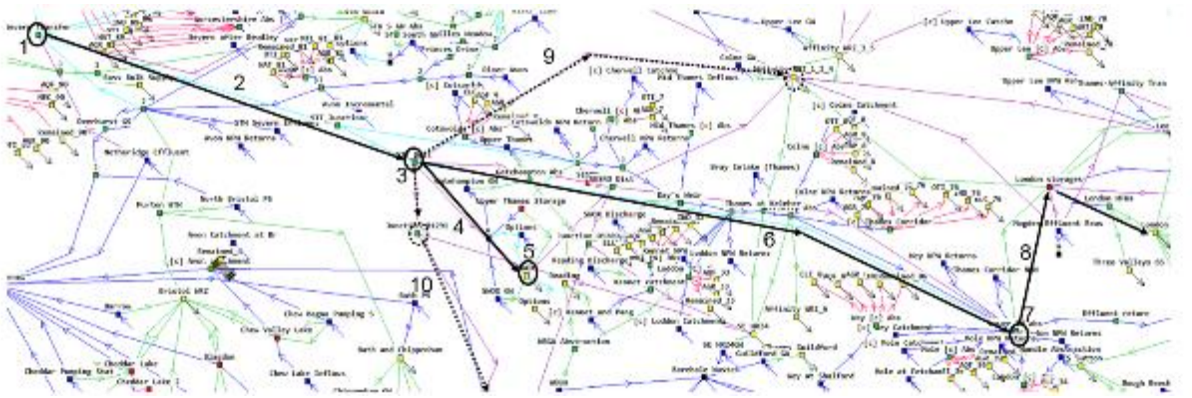
Figure 4 A schematic map of the STT including supporting solutions and transfer route



Where:

1. A single node to represent Lake Vyrnwy
2. Arc to represent the 180 Ml/d transfer from Lake Vyrnwy to the Deerhurst Junction, via Oswestry Water Treatment Works (Node 9). The transfer arc is set with 20% losses.
3. Node to represent Minworth Wastewater Treatment Works.
4. Arc transferring 115 Ml/d from Minworth WwTW to the Deerhurst Junction (node 11). The transfer arc is set with 10% losses.
5. Junction node to represent Mythe Water Treatment Works.
6. Arc transferring 15 Ml/d from Mythe to the Deerhurst Junction (node 11).
7. Node representing Netheridge Wastewater Treatment works.
8. Transfer of 35 Ml/d from Netheridge WwTW to Deerhurst junction (node 11).
9. Node representing abstraction from the River Severn at Deerhurst (this is the unsupported flow supply component of STT – the volume available for abstraction is subject flow level at Deerhurst).
10. Arc transferring unsupported flow to Deerhurst Junction (node 11).
11. Node to represent the Deerhurst Junction where virtually transferred supply sources and unsupported flow component are combined.
12. Node to represent UU Sources and Vyrnwy Aqueduct solutions, which offset the water sent from Lake Vyrnwy to STT.

Figure 5 The representation in WREW for the upstream section



Where:

1. Represents the Deerhurst Junction, the discharge point for the supply sources supporting this transfer
2. A transfer of 300 to 500 Ml/d from Deerhurst to the Culham junction located on the Thames. This arc represents both the Deerhurst pipeline interconnector and the Cotswold Canal interconnector sub-option.
3. Discharge point at Culham, from here water can be distributed to meet supply shortfalls in London, SWOX and support the Thames-Affinity and Thames-Southern transfer.
4. A transfer of 100 Ml/d from the Culham junction to the SWOX demand node.
5. A single demand node representing the water resource zone Swindon and Oxfordshire (SWOX)
6. A transfer of 300-500 Ml/d to the Lower Thames abstraction (node 7), from here it can be distributed to meet supply shortfalls for London.
7. A node representing the abstraction from the lower Thames River.
8. The arcs which move water to the London Storages Reservoirs and onward to the London demand centre.
9. This dashed arc represents the Thames-Affinity transfers which are sourced from the STT.
10. This dashed arc represents the Thames-Southern transfers which are sourced from the STT.

Figure 6 The representation in WREW for the downstream section

3.3.2 South East Strategic Reservoir Option (SESRO)

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.

The primary recipient water resource zones are London; and Swindon and Oxfordshire (SWOX) (both Thames Water); Affinity Water's WRZ4 (via the Thames to Affinity Transfer SRO); and Southern Water (via the Thames to Southern Transfer SRO).

SESRO has a range of possible capacities (75-150 Mm^3) and yields[10]. It is not dependent on any other solution.

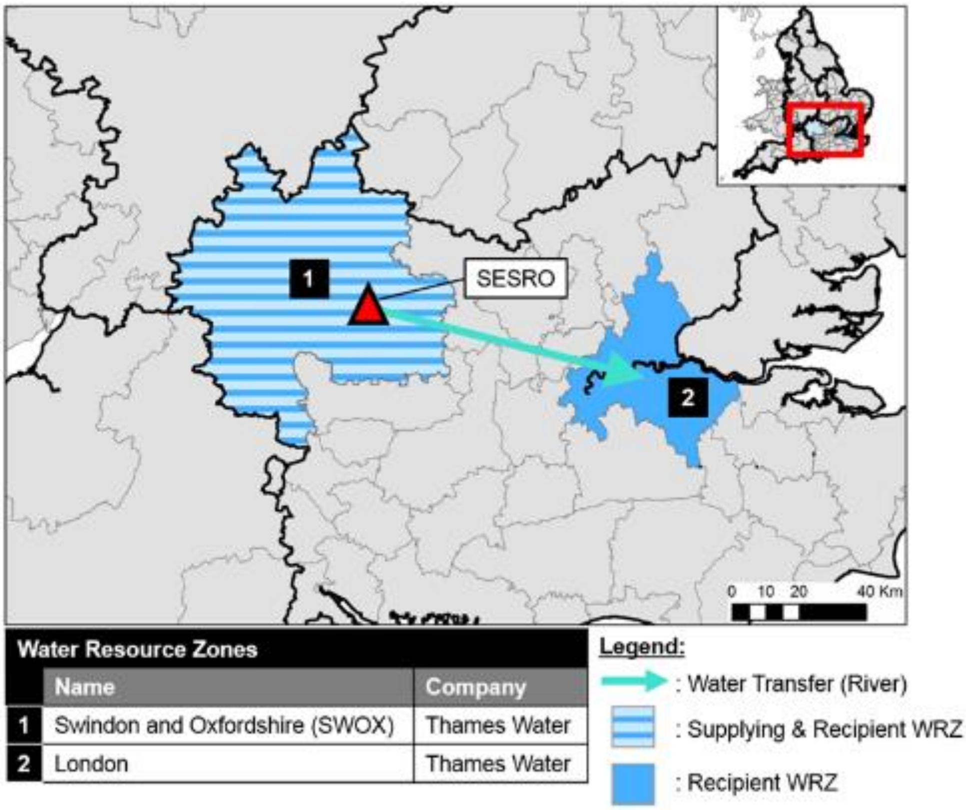
Following consultation, a number of decisions were made to best represent the solution within WREW. The following representation decisions and simplifying assumptions were agreed:

- SESRO could have a range of possible capacities and yields but WREW only simulates the solution using the maximum volume of 150 Mm^3 and a release of 321 Ml/d;
- The solution is triggered when London Storage drops below the control curve where Teddington Target Flow transitions from 800 Ml/d to 600-700 Ml/d;
- SESRO has a lower priority than the Lower Thames Reservoirs for abstracting water. However, if the trigger point for the solution has been reached then SESRO has priority;

[10] On the difference between "yield" and "capacity". Water supply options have a specific design capacity: this may not be the same as its deployable output. The option's *design capacity* is the maximum output the option can provide, according to engineering and licensing constraints. The same option's *deployable output*, or reliable *yield*, may be less than its capacity, due to environmental factors, such as droughts. Further, when considering the deployable output of a whole system, additional factors may reduce the *system's* reliable yield such that it is less than the sum of the *options'* deployable outputs. These factors include aspects such as network connectivity, conjunctive benefits with other sources and levels of service.

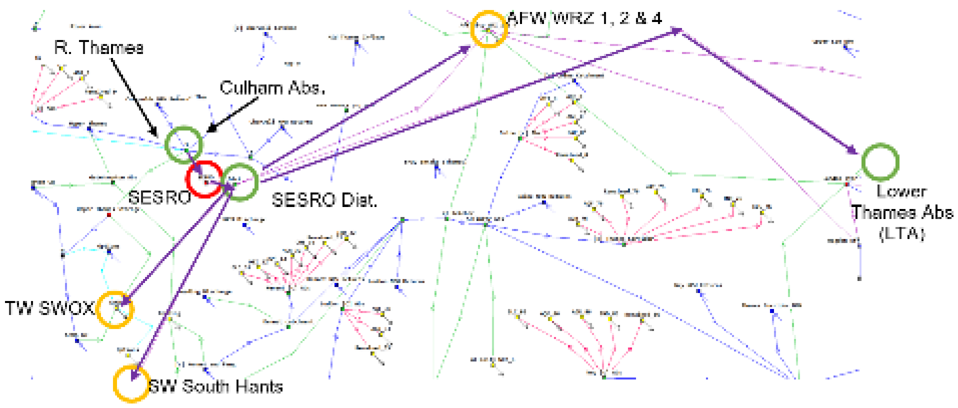
- Instead of releasing water into the River Thames at Culham, WREW transfers water from SESRO direct to demand nodes (SWOX; AFW 1,2&4; South Hants) to ensure the water is not used by other demand nodes on route; and
- Instead of releasing water direct to demand node of London (as this would go against licencing restrictions/agreements) – water is transferred to Lower Thames Abstraction point to be utilised there (e.g., used to fill London Storage and subsequently transferred to London).

Figure 7 shows the schematic map of the solution, and Figure 8 shows the representation in WREW.



Water Resource Zones		
	Name	Company
1	Swindon and Oxfordshire (SWOX)	Thames Water
2	London	Thames Water

Figure 7 A schematic map of SESRO



- Arc from River Thames at Culham Junction to SESRO to fill (*capacity of 1000 Ml/d if switched on*)
- Reservoir node for SESRO (*capacity of 150,000 Ml*)
- Arc from SESRO to SESRO Dist. (*capacity of 321 Ml/d*)
- Arc from SESRO Dist. to SWOX (capacity of 20 Ml/d)
- "SESRO to London" - Arc from SESRO Dist. to Lower Thames Abstraction (up to 321 Ml/d) to be distributed to fill London Storage and subsequently/potentially transferred to London.
- Arc from SESRO Dist. to SW South Hants demand node for Thames-Southern Transfer supplied by SESRO.
- Arc from SESRO Dist. to Affinity WRZ 1, 2, 4 for Thames-Affinity Transfer supplied by SESRO.

Figure 8 The representation in WREW for SESRO

3.3.3 London Effluent Reuse (LER)

This solution relates to four effluent reuse solutions: those dependent on Mogden WwTW for the source of water; and one dependent on water from Beckton WwTW.

3.3.3.1 Using water from Mogden WwTW

This relates to three effluent reuse solutions: Teddington Direct River Abstraction (DRA), Mogden Effluent Reuse, and Mogden South Sewer, the main source of water is Mogden Sewage Treatment Works (WwTW):

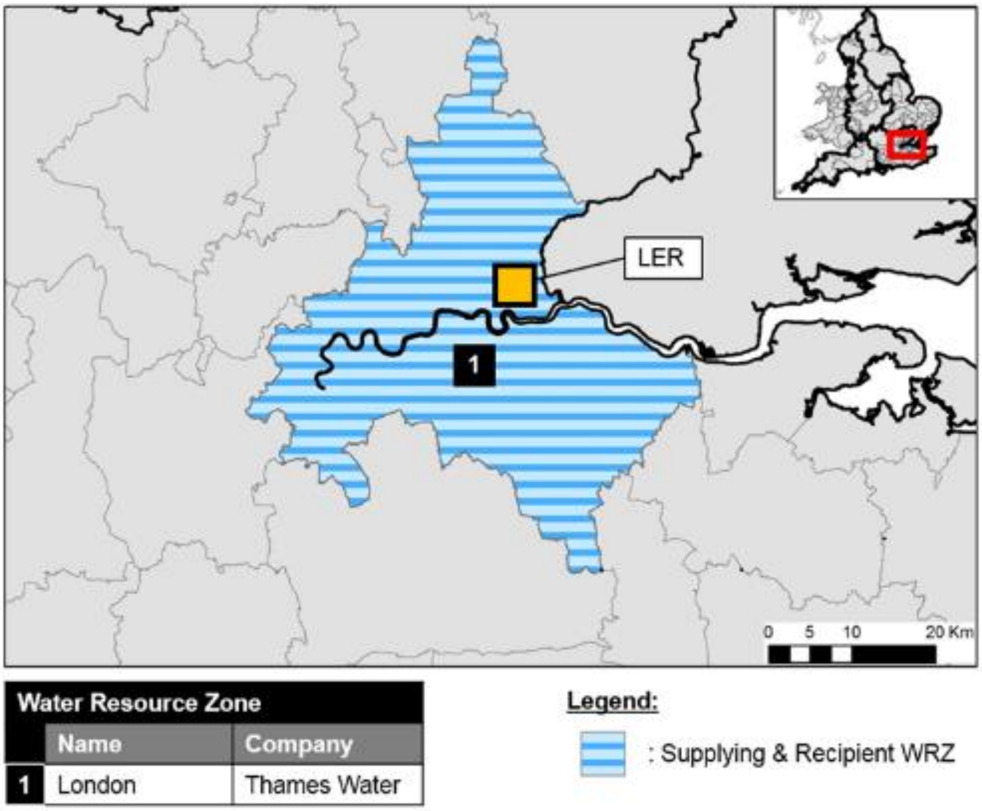
- **Teddington DRA**- Treated effluent from Mogden WwTW would be discharged into the River Thames upstream of Teddington Weir. Water would be abstracted upstream of this effluent discharge location and pumped into the Thames Lee Tunnel for transfer to the Lee Valley reservoirs. This is a "take & put" arrangement. There is a range of potential capacities: 50, 75, 100 and 150 Ml/d;
- **Mogden Effluent reuse**- 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. There is a range of potential capacities: 50, 100, 150 and 200 Ml/d; and
- **Mogden South Sewer-** Sewage will be abstracted from the South Sewer, before it reaches Mogden WwTW, and pumped to 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. The maximum capacity of the solution is 50 Ml/d.

The solutions serve London and the greater London area. It is not dependent on any other solution.

Following consultation, a number of decisions were made to best represent the solution within WREW. The following representation decisions and assumptions were agreed:

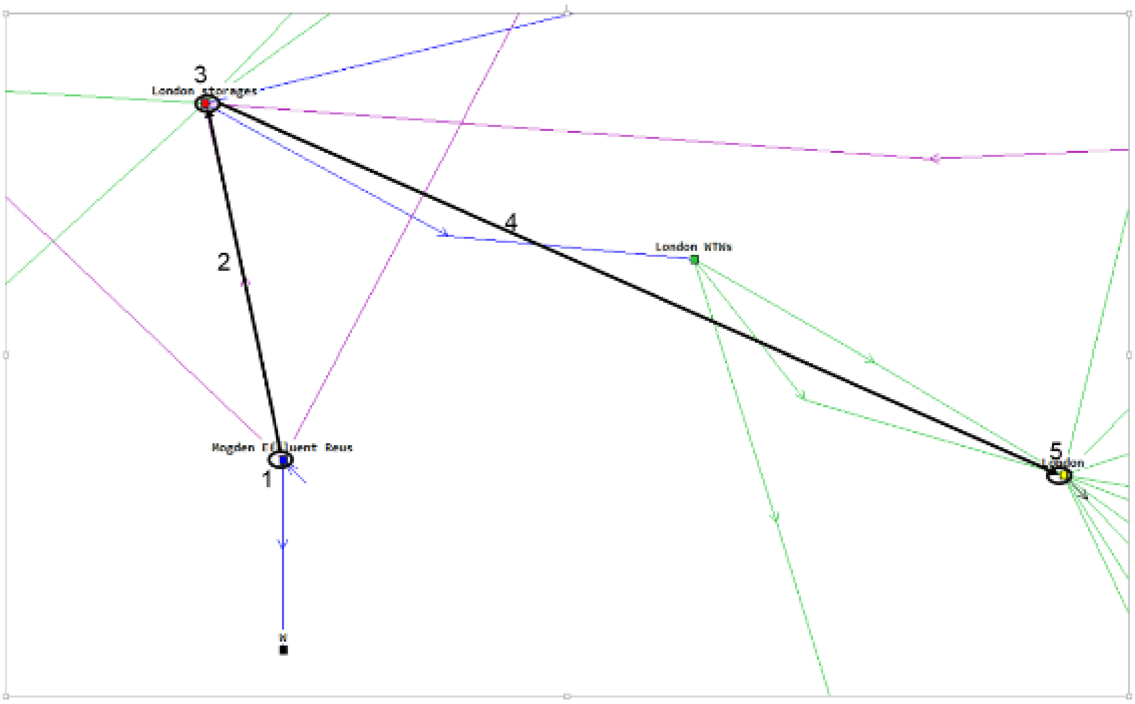
- Although the three solutions work in different configurations around Mogden WwTW, the behaviour is the same when considered at the scale of WREW and therefore the solutions can be simplified into one Effluent Reuse supply node with yield ranging from 50-200 Ml/d);
- As the Mogden Effluent and South Sewer solutions operate on a 'put and take' arrangement, and therefore do not support flow in the River Thames, the effluent reuse node is connected straight to the London Storage Reservoir group in WREW, which includes the Lee Valley Reservoirs. It is recognised that while this more direct representation would require more treatment, it is not an important factor from a national scale WR modelling perspective;
- The Mogden and Teddington DRA solutions can be implemented together, however the maximum in combination yield is 200 Ml/d, where the limiting factors is the amount of effluent available for treatment; and
- The trigger at which the solutions are activated is the point at which London Storage drops below the control curve where Teddington Target flow transitions from 800 to 600/700 Ml/d.

Figure 9 shows the schematic map of the solution, and Figure 10 shows the representation in WREW.



Water Resource Zone		
	Name	Company
1	London	Thames Water

Figure 9 A schematic map of London Effluent Reuse



Where:

1. Hydes Field and Mogden treatment works have been aggregated into one node allowing WREW to represent all three solutions in one design.
2. An arc is used to transfer water from the Mogden Reuse node to the London Storage node and can represent the various capacities for each one of the solutions (50, 75, 100, 150 and 200 Ml/d).
3. When the solution is activated, water will be delivered to the aggregated London Storage node to top up reservoir storage.
4. Water will then be transferred from London Storage to the London demand node (Point 5) to meet the /supply shortfalls.

Figure 10 The representation in WREW for LER using water from Mogden WwTW

3.3.3.2 Using water from Beckton WwTW

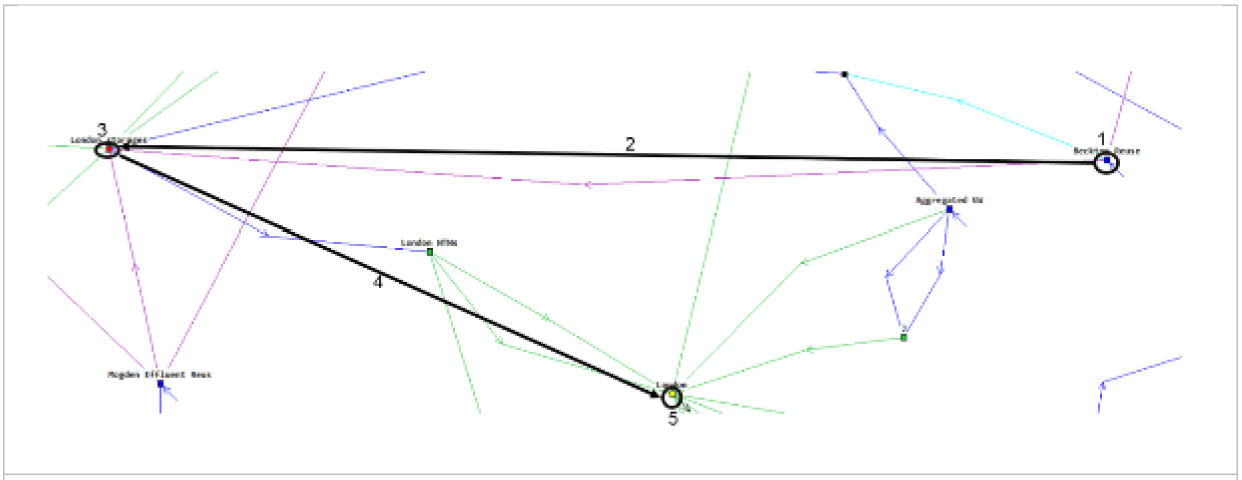
This relates to one effluent reuse solution. Effluent from Beckon WwTW will be transferred to and treated at a reuse treatment plant at the same site, before being pumped to a new discharge location on the River Lea, above the inlet for King George V Reservoir. Offtake of treated effluent from the River Lea into King George V Reservoir would then supplement raw water supply to the Lee Valley Reservoirs.

The solution serves London and the greater London area. The primary source of water for this solution is Beckton WwTW. There is a range of potential capacities: 50, 100, 150, 200, 250 and 300 Ml/d.

Following consultation, decisions were made to best represent the solution in WREW. The following assumption was agreed:

- The trigger point is when London Storage goes below the line where Teddington Target flow transitions from 800 to 600/700 Ml/d.
- Beckton Reuse supplements raw water storage in the Lee Valley Reservoirs. Since the Lee Valley Reservoirs are included in the aggregated London Storage Reservoir node in WREW the solution can be represented using a direct link between Beckton Reuse and London Storages, rather than via discharge into the River Lee.

Figure 9 shows the schematic map of the solution, and Figure 11 shows the representation in WREW.



Where:

1. A single node represents both Beckton WwTW and the water recycling plant.
2. The arc from Beckton to London Storage can represent the possible yields (50, 100, 150, 200, 250, 300 Ml/d).
3. When the solution is activated, water will be supplied to the aggregated London Storage Reservoir node. From here water can be distributed via an arc (Point 4) to meet demand/supply shortfall in the London demand centre (Point 5).

Figure 11 The representation in WREW for LER using water from Beckton WwTW

3.3.4 Thames to Affinity Transfer (T2AT)

This raw water transfer from Thames Water to Affinity Water is facilitated by either: (a) a new abstraction from the River Thames (SESRO/STT) transferred to Affinity Water for treatment and distribution or through the shared use of existing Lower Thames Reservoirs; or (b) the shared use of future London Re-use solution resources.

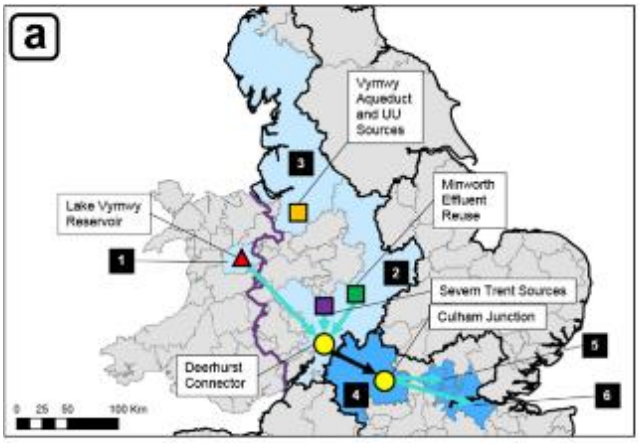
Therefore 3 sub-options have been configured in WREW so that the source water for the T2AT solution can be supplied by SESRO, STT, or LER.

The solution can yield 50 or 100 Ml/d and serves Affinity Water's WRZ 4. The solution is dependent on other solutions since the source of water for the transfer comes from SESRO, London Reuse solutions or via the Severn Thames Transfer (STT). The different supply option configurations for the transfer are mutually exclusive.

Following consultation, a number of decisions were made to best represent the solution within WREW. The following representation decisions and assumptions were agreed:

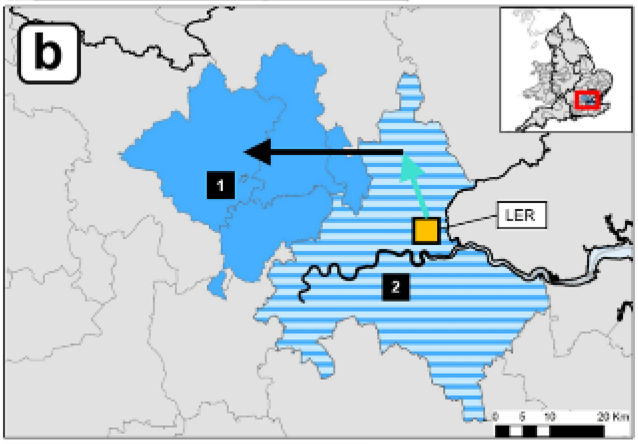
- Affinity Water WRZs 1, 2 and 4 are aggregated into one demand centre in WREW. Although the Thames-Southern Transfer would mainly supply WRZ 4 it is assumed that inter-zonal transfers would allow water from the Thames-Southern Transfer to be distributed to Affinity WRZ 1 and 2, as well as WRZs 3 and 5, which are connected with the Affinity WRZ 1, 2, 4 demand node in WREW;
- As Affinity Water is heavily dependent on groundwater sources, water use restriction levels are based on groundwater levels. The simplified representation of groundwater in WREW means that it is not possible to track water use restrictions for Affinity Water and therefore restriction levels cannot be used to trigger the Thames-Affinity transfer. Instead, the solution is used as the last source of supply when demand is high enough;
- The 50 or 100 Ml/d transfer capacities can be supplied by any of the sources. All of the source solutions can also supply their primary demand centres (SWOX and London WRZs) whilst supplying the Thames-Affinity Transfer.

Figure 12 shows schematic maps of the solution, and Figure 13 and Figure 14 show the representation in WREW.



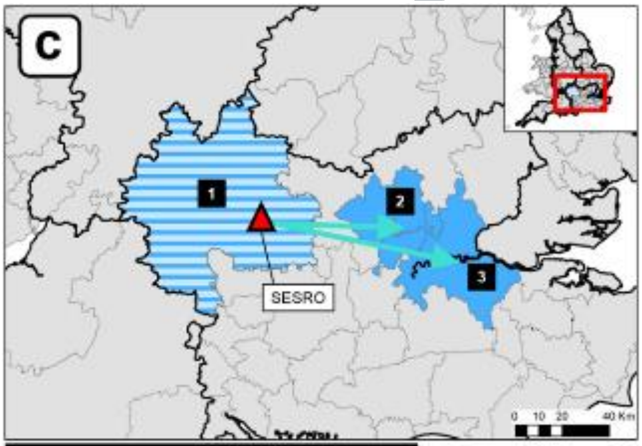
	Water Resource Zones	
	Name	Company
1	Llanfyllin	Hafren Dyfrdwy
2	Strategic Grid	Severn Trent Water
3	Strategic WRZ	United Utilities
4	Swindon and Oxfordshire (SWOX)	Thames Water
5	Misbourne, Colne and Pinn	Affinity Water
6	London	Thames Water

Legend:
: Water Transfer (River)
: Water Transfer (Pipeline)
: England-Wales Border
: Supplying WRZ
: Recipient WRZ



	Water Resource Zones	
	Name	Company
1	Misbourne, Colne and Pinn	Affinity Water
2	London	Thames Water

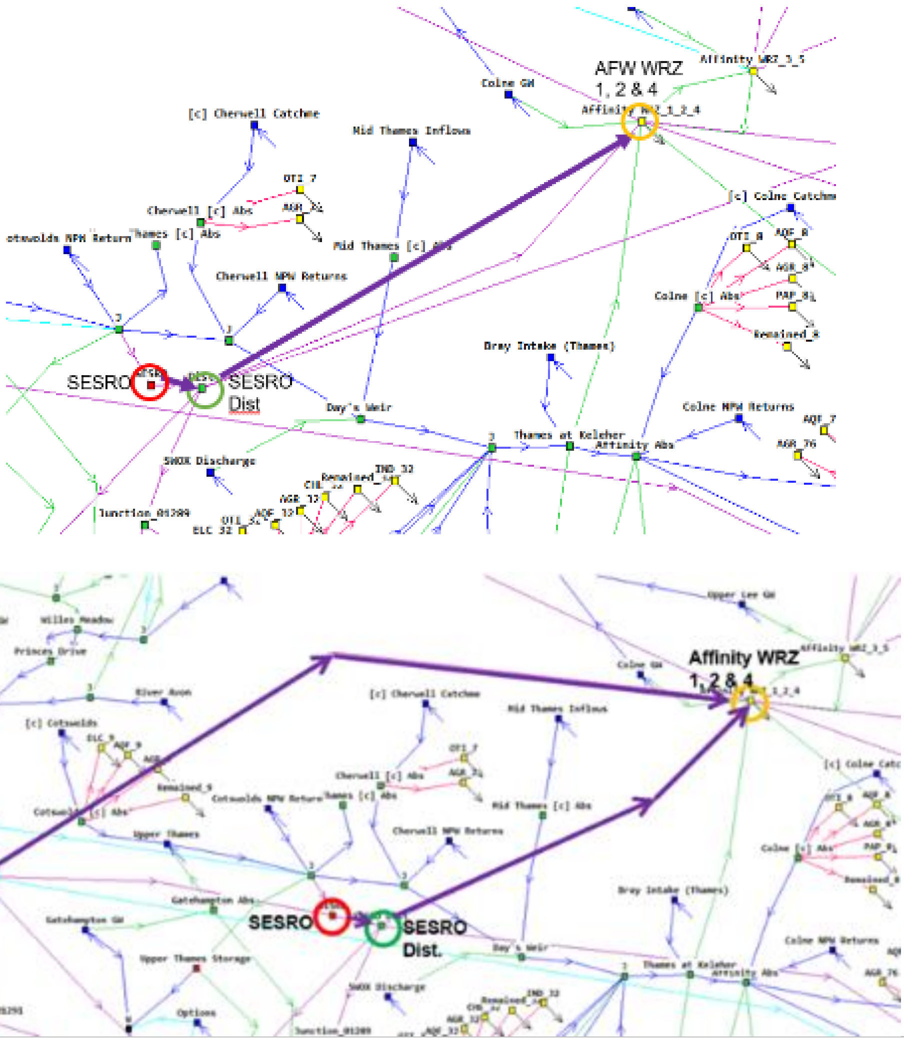
Legend:
: Water Transfer (River)
: Water Transfer (Pipeline)
: Supplying & Recipient WRZ
: Recipient WRZ



	Water Resource Zones	
	Name	Company
1	Swindon and Oxfordshire (SWOX)	Thames Water
2	Misbourne, Colne and Pinn	Affinity Water
3	London	Thames Water

Legend:
: Water Transfer (River)
: Supplying & Recipient WRZ
: Recipient WRZ

Figure 12 Schematic maps of the Thames to Affinity Transfer and three possible supply configurations: (a) supply by STT; (b) supply by LER; (c) supply by SESRO



- Represents Thames-Affinity Transfers sub-options 1-3 and sub-option 4 (involving STT or SESRO)

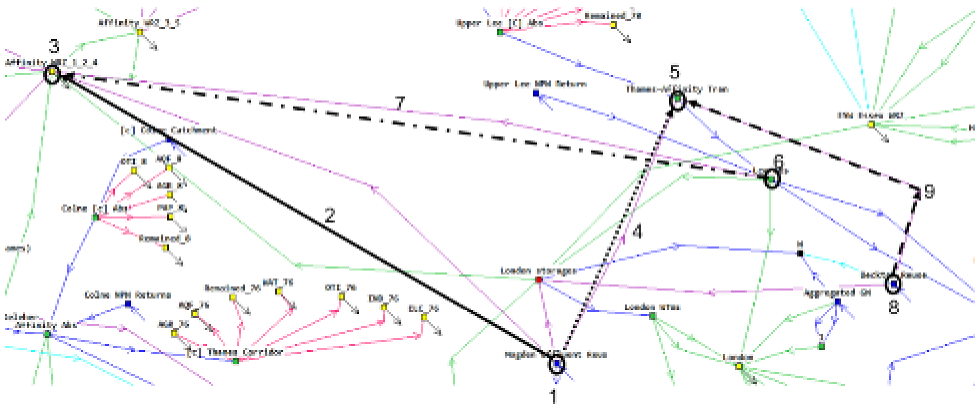
SESRO:

- Water is transferred via an arc from SESRO (red circle) to the junction node SESRO Distribution (green circle).
- Water is then transferred from SESRO Distribution to the Affinity WRZ 1, 2 & 4 demand centre (orange circle)

STT:

- Water is transferred via an arc from the STT Distribution junction node (blue circle) to the Affinity WRZ 1, 2 & 4 demand centre (orange circle)

Figure 13 The representation in WREW for the Thames to Affinity Transfer with SESRO /STT as the source



Sub-Option

- Represents Thames- Affinity sub-option 4 (involving Mogden Reuse and sub-option 5)
- The source is effluent from Mogden WwTW (node 1).
- 50 or 100 Ml/d is transferred (arc 2) directly from Mogden WwTW to meet demand in the Affinity supply area (node 3), primarily benefitting WRZs 1, 2 and 4.

Sub-Option

- Represents Thames-Affinity Transfer sub-option 6.
- The source is effluent from Mogden WwTW (node 1).
- 50 or 100 Ml/d is transferred (arc 4) from the source to the River Lea (node 5).
- Water is discharged upstream of the abstraction to Lee Valley Reservoirs and provides support to flow levels on the River Lea.
- Water is then abstracted at the abstraction on the River Lee for the Lee Valley Reservoirs (node 6) and transferred (arc 7) to meet demand in Affinity resource zones 1, 2 and 4 (node 3).

Sub-Option

- Represents Thames-Affinity Transfer sub-option 7.
- The source is effluent from Beckton WwTW (node 8).
- 50 or 100 Ml/d is transferred (arc 9) from the Beckton WwTW to the River Lea (node 5).
- Water is then abstracted (node 6) and transferred (arc 7) from the Lea to meet demand in Affinity resource zones 1, 2 and 4 (node 3).

Figure 14 The representation in WREW for the Thames to Affinity Transfer with the London Effluent Reuse solution as the source

3.3.5 Anglian to Affinity Transfer (A2AT)

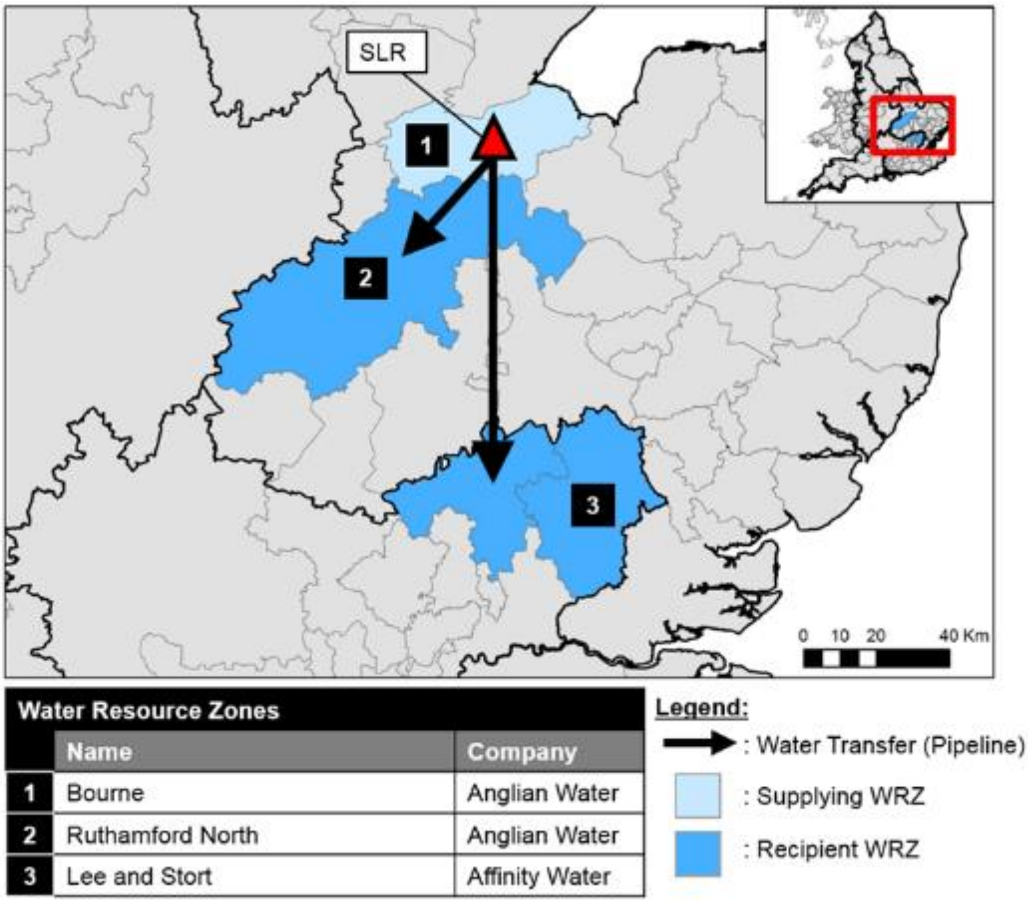
The aim of the Anglian to Affinity transfer is to transfer water from sources within Anglian Water's region to the Affinity Water network. There are three sub-options:

- **River Trent Sub-Option**- Rutland Water is the source and can support a transfer of 50 or 100 Ml/d. In order to balance the water transferred from Rutland reservoir to Affinity Water, an abstraction from the River Trent will be used to support reservoir levels
- **South Lincolnshire Reservoir Sub-Option**- The proposed South Lincolnshire reservoir (SLR) is the source and can support a transfer capacity of 50 or 100 Ml/d. It is proposed that the reservoir is filled by abstraction from one or more of several potential sources including the River Nene, Welland, Witham, Trent and South Forty Foot Drain. As this is sub-option is dependent on the construction of the South Lincolnshire Reservoir solution, it will be unviable if the reservoir is not constructed; and
- **Fenland Reservoir Sub-Option**- The proposed Fenland Reservoir is the source and can transfer up to 70 Ml/d. It is proposed that the reservoir is filled by Abstraction from four 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.

The solution will benefit Affinity Water's WRZ 3 (Lee) and WRZ 5 (Stort). The River Trent Sub-option supplies WRZ 3, the South Lincolnshire Reservoir Sub-option supplies WRZ 5 or WRZ 3 and the Fenland Reservoir Sub-option can only supply WRZ 5. Inter-zonal transfers would allow the water from the transfer to be distributed to other parts of the Affinity Water's supply network including WRZs 1, 2 and 4.

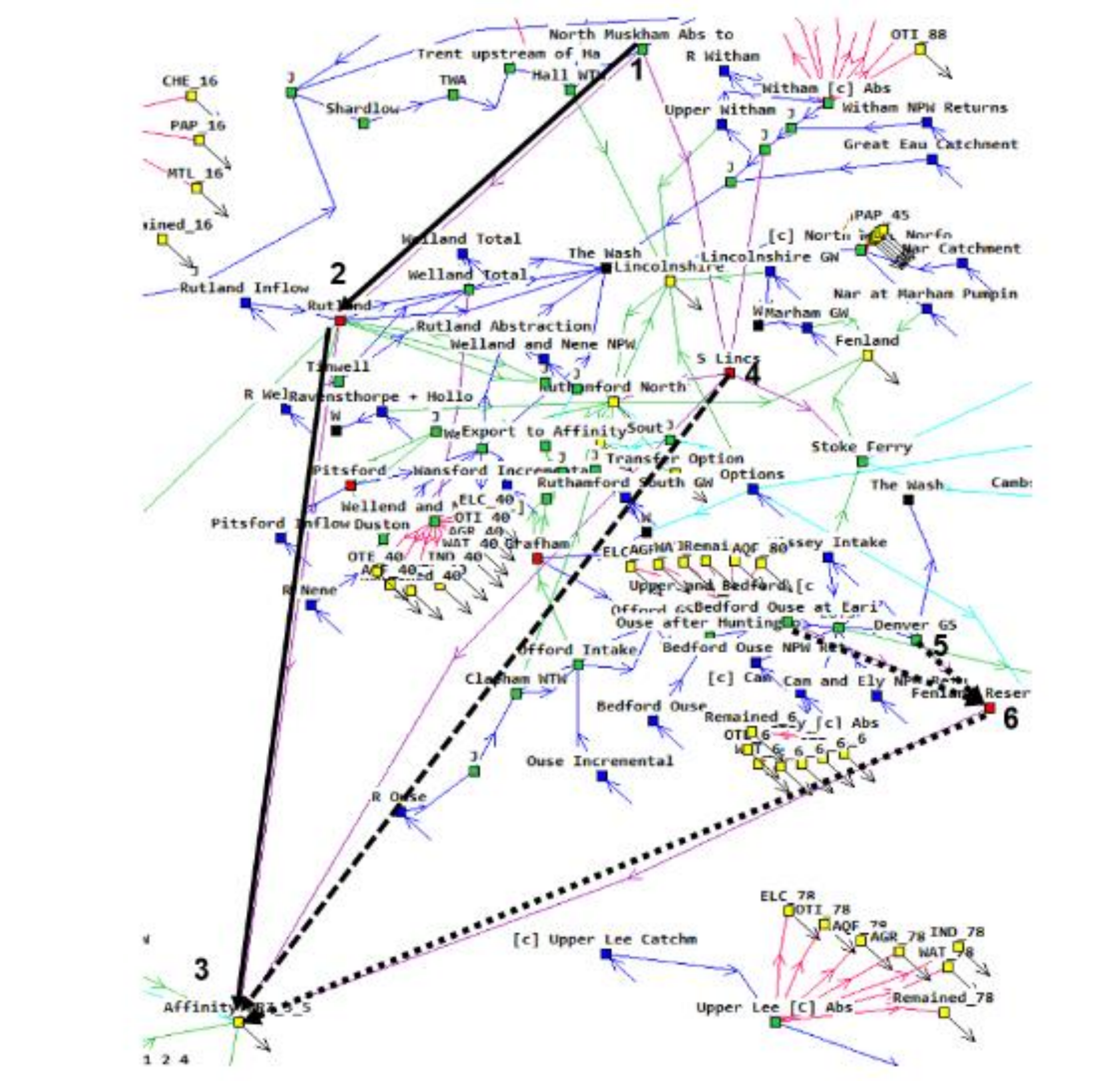
Following consultation, a number of decisions were taken made to best represent the solution within WREW including abstraction rules and triggers. The following representation decisions and assumptions were agreed:

- The transfer uses numerous pumping stations and water treatment works to deliver water. These assets will not be a constraint on the transfer and so they do not need to be included in the solution representation, instead the transfers can be represented as moving water directly from the source to the demand centre;
- Sub-options for the transfer can supply either Affinity WRZ 3 or WRZ 5. These two WRZs are aggregated in WREW into the Affinity WRZ 3 & 5 demand centre. It is assumed that Inter-zonal connections would allow the transferred water to be distributed between WRZs 3 and 5, and onward to other parts of the Affinity Water system (WRZs 1, 2 & 4);
- The artificial network of waterways in the Fens is used for drainage with complex pumping and operational management. It is therefore difficult to model the flow regime of the Middle Level at St Germans: a key source for the Fenland Reservoir. Therefore, a Middle Level flow input has been approximated in WREW by applying a scaling factor to the nearby Cam and Ely Ouse inflow.
- The three major abstractions for the Fenland Reservoir (Bedford Ouse, Ely Ouse and the Middle Level) have been represented; the Ouse Washes source is not represented since it provides a smaller volume and is heavily managed; and
- At the timing of representing the SLR in WREW ~10-15 potential sites for abstraction were under consideration on the Rivers Nene, Welland, Witham and Trent. In reality not all of these sites and sources would be used, for the purposes of WREW, only River Trent and Witham sources were represented as they provide the largest volume of water.



Water Resource Zones		
	Name	**Company**
1	Bourne	Anglian Water
2	Ruthamford North	Anglian Water
3	Lee and Stort	Affinity Water

Figure 15 A schematic map of the A2AT solution



- River Trent Sub-Option is represented by the solid black line. An abstraction placed near North Muskham (node 1) will transfer up to 300 Ml/d to Rutland Water (node 2). A transfer of 50 or 100 Ml/d is drawn off Rutland Water to meet demand in Affinity Water WRZ 3 & 5 (node 3).
- South Lincolnshire Reservoir Sub Option is represented by the dashed black line. 50 or 100 Ml/d from South Lincolnshire Reservoir (node 4) can be transferred to Affinity Water's WRZ 3 & 5 (node 3).
- Fenland Reservoir Sub Option is represented by the dotted black line. Abstraction points along the River Ouse will supply Fenland Reservoir (node 6) with water (node 5); 70 Ml/d can then be transferred to Affinity Water WRZs 3 & 5 (node 3).

Figure 16 The representation in WREW for the A2AT solution

3.3.6 Grand Union Canal (GUC)

The aim of this effluent reuse & strategic transfer solution is to supply water from the Midlands to Hertfordshire and North West London. The GUC will transfer treated wastewater supplied by Minworth WwTW to Affinity Water's region. Water will be transferred via the existing canal infrastructure (the GUC & the Coventry/Oxford Canal).

The solution is configured to transfer either 50 or 100 Ml/d of treated effluent and will benefit the Affinity Water's Misbourne, Colne and Pinn zones (WRZ 1, 2 & 4, respectively); and be distributed within the company's network to meet demand in other areas e.g., the Lee and Stort WRZs (WRZ 3 & 5, respectively).

Minworth WwTW is the only source of water for this solution; this plant is also listed as a source for the STT solution. Investigations are ongoing to ascertain whether Minworth can simultaneously supply STT and GUC solutions, whilst also supporting flows on the River Trent.

Following consultation, a number of decisions were taken made to best represent the solution within WREW including abstraction rules and triggers (demand within Affinity's resource zones). The following representation decisions and assumptions were agreed:

- Affinity resource zones 1, 2, and 4 are the primary beneficiaries of the transfer. The end point of the transfer is WRZ 4, however, abstraction points are being considered around Hemel Hempstead, which could supply WRZs 1 and 2. These three WRZs are aggregated in WREW into the Affinity WRZ 1,2 & 4 demand centre;
- The transfer pathway involves water treatment works and service reservoirs, however these assets are not represented in WREW as their function is for water quality rather than water resources;
- The Trent effluent reuse node, which represent Minworth WwTW, is an aggregation of all sewage treatment works along the River Trent;
- A number of sub-options exist for different routes that the transfer could take between Minworth WwTW and discharge to the Grand Union Canal. However, transfer capacity does is the same for all sub-option locations and therefore the transfer pathway is simplified in WREW by using only one arc from Minworth Effluent Reuse to the Affinity WRZ 1, 2 and 4 demand centres, with a capacity of 50 or 100 Ml/d;
- It is assumed that travel time for transfer of water along the canal network is instantaneous, which is appropriate for a national scale model with a daily time-step; and
- Pumping is required to enable the transfer. This process has not been represented in WREW since it is not important for water resources modelling.

Figure 17 shows the schematic map of the solution, and Figure 18 shows the representation in WREW

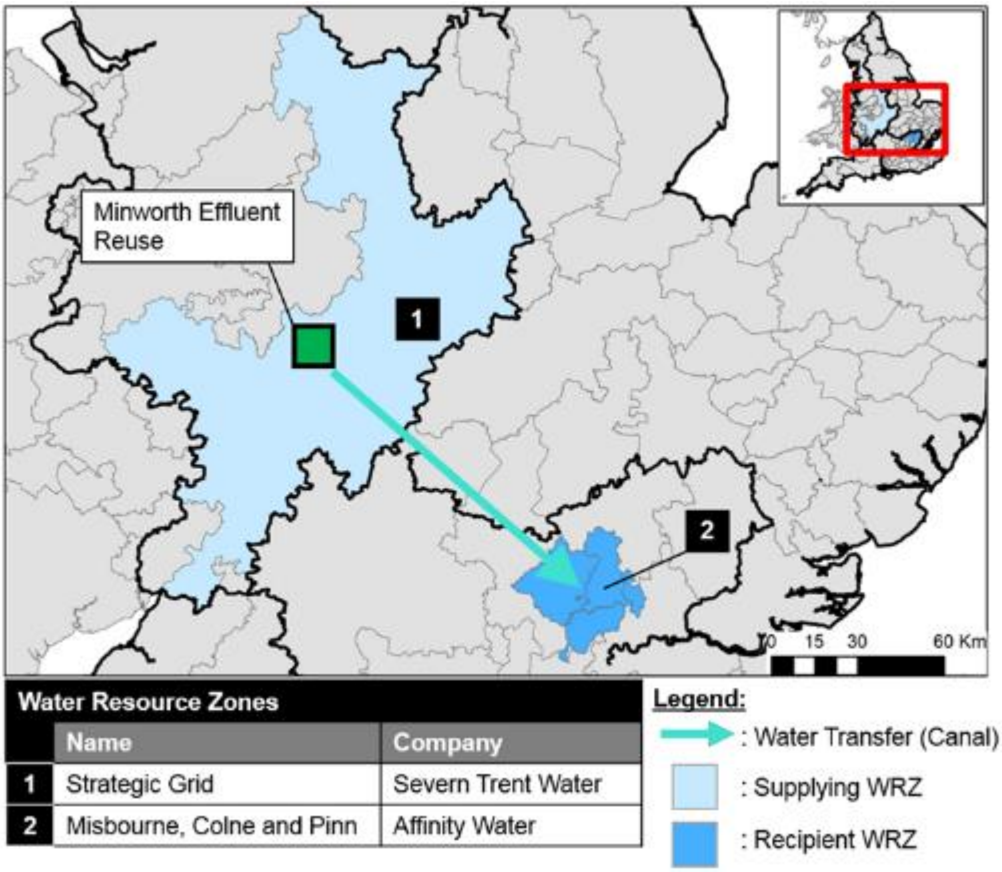
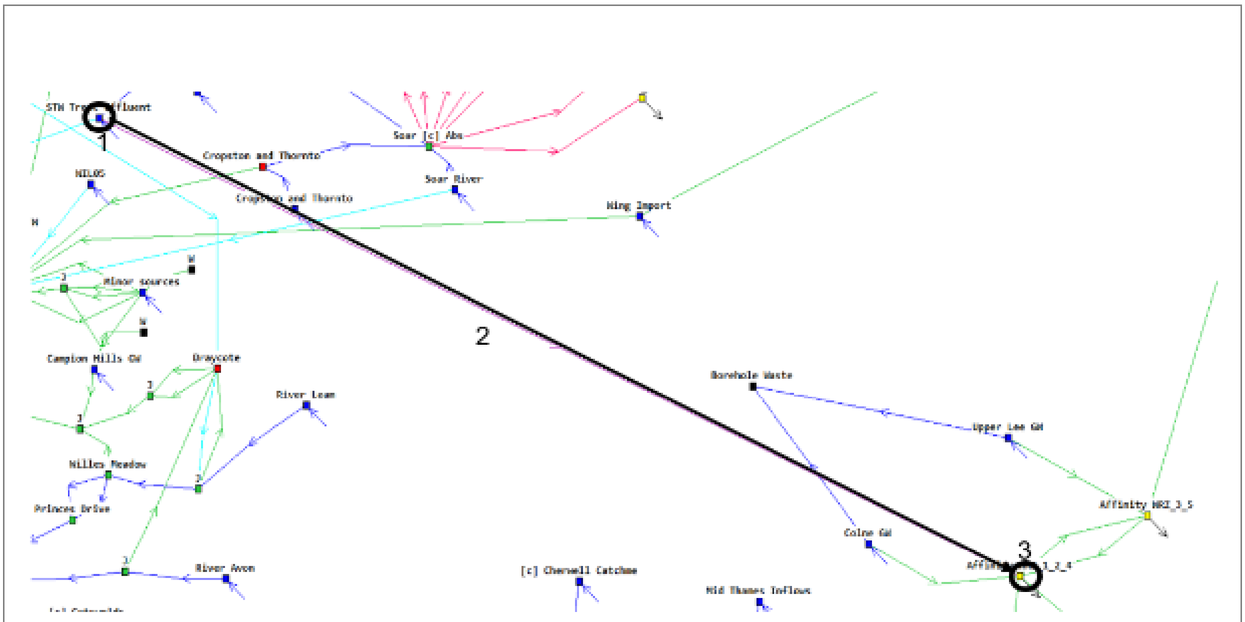


Figure 17 A schematic map of the Grand Union Canal SRO



- WwTW Trent Effluent (node 1) represents Minworth WwTW, the source of water for this solution.
- Water is passed through one arc (arc 2) for all of the sub options.
- This arc has a capacity of 50 or 100 Ml/d, and transfers water to the Affinity Water WRZ 1, 2 & 4 demand centre (node 3).

Figure 18 The representation in WREW for the Grand Union Canal

3.3.7 Thames to Southern Transfer (T2ST)

The source of water for this transfer from Thames Water to Southern Water's Hampshire WRZs is dependent on the SESRO or STT solution. Therefore, 2 sub-options have been configured in WREW so that the water can be supplied by either source.

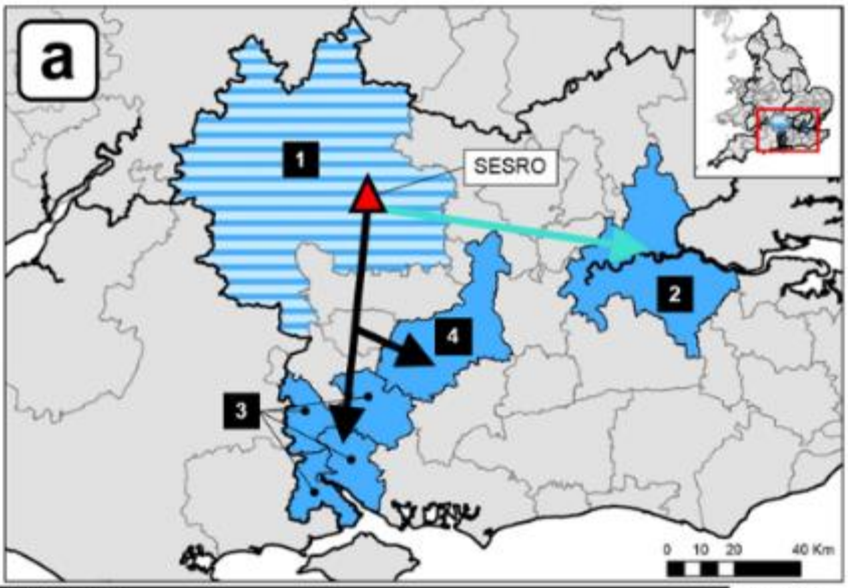
There are two potential intakes, Culham or Reading, resulting in six transfer options (all of which allow smaller branch connections to South East Water (Basingstoke) and Southern Water's north Hampshire zones (Andover/Kingsclere).

The potential transfer volume includes 50, 80 and 120 Ml/d. An offtake volume of 10-20 Ml/d can be transferred to Kingsclere/Andover, and to South East Water.

Following consultation, a number of decisions were taken made to best represent the solution within WREW including abstraction rules and triggers. The following representation decisions and assumptions were agreed:

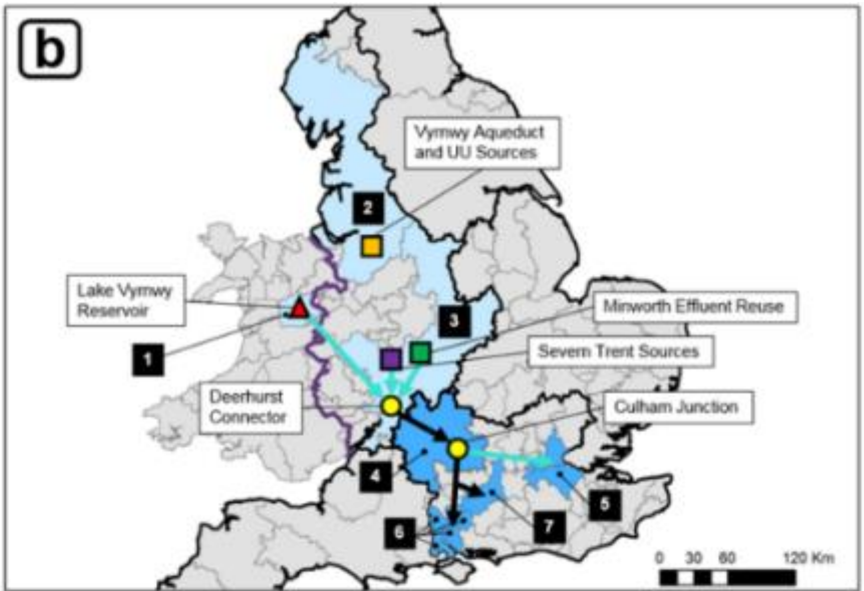
- The Hampshire WRZs are aggregated as a 'South Hants' demand node which includes Hampshire Southampton East, Hampshire Southampton West, Hampshire Winchester and Hampshire Rural;
- The 10-20 Ml/d offtakes to the Hampshire Andover & Kingsclere WRZs are not represented as these demand centres are not included in WREW. A decision was made to not add the Hampshire Andover and Kingsclere WRZs into WREW because they rely on other supply sources, which would have required additional modelling. Furthermore, the demand for these WRZs is much lower (~20 Ml/d) than the Hampshire Southampton East and West WRZs (~120 Ml/d), which the Thames-Southern Transfer also supplies;
- The 10-20 Ml/d offtake to SE WRZ4 (Northgate) is represented only as the maximum 20 Ml/d;
- No WTWs are represented for this solution as they do not limit the solution capacity;
- In reality, sub options could include the transfer of raw or potable water however this distinction is not needed.

Figure 19 shows the schematic map of the solution, and Figure 20 shows the representation in WREW



	Water Resource Zones	
	Name	Company
1	Swindon and Oxfordshire (SWOX)	Thames Water
2	London	Thames Water
3	Hampshire Southampton East, Hampshire Southampton West, Hampshire Rural and Hampshire Winchester	Southern Water
4	Bracknell	South East Water

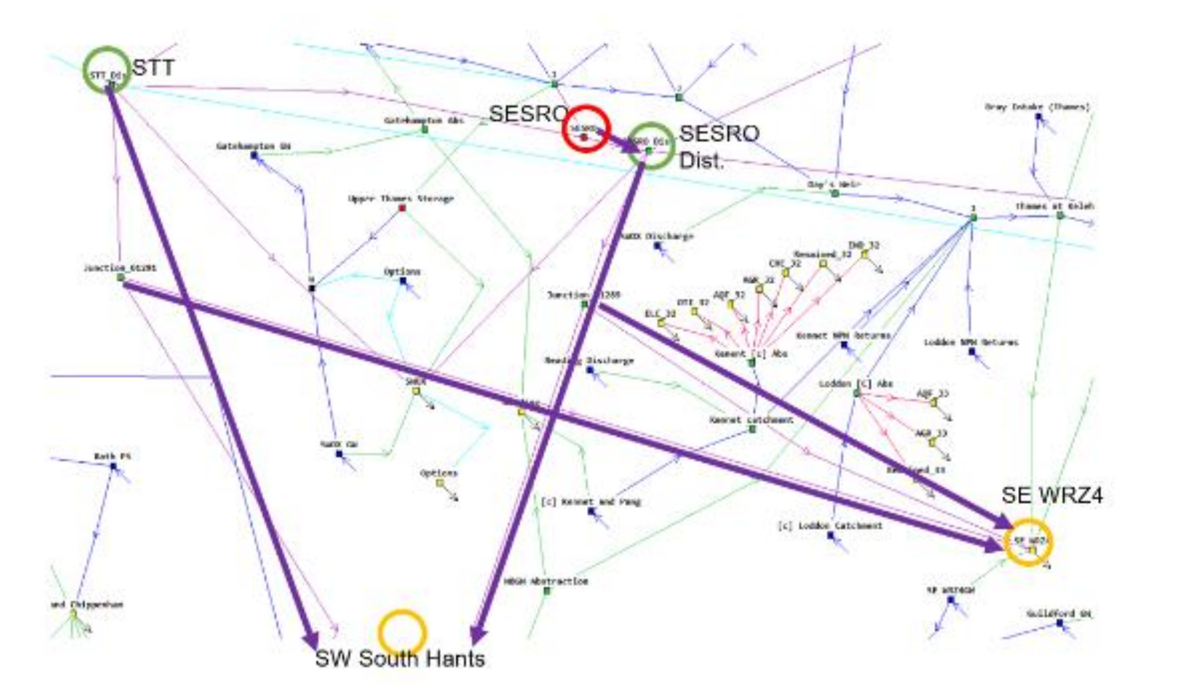
Legend:
: Water Transfer (Pipeline)
: Water Transfer (River)
: Supplying & Recipient WRZ
: Recipient WRZ



	Water Resource Zones	
	Name	Company
1	Llanfyllin	Hafren Dyfrdwy
2	Strategic Grid	Severn Trent Water
3	Strategic WRZ	United Utilities
4	Swindon and Oxfordshire (SWOX)	Thames Water
5	London	Thames Water
6	Hampshire Southampton East, Hampshire Southampton West, Hampshire Rural and Hampshire Winchester	Southern Water
7	Bracknell	South East Water

Legend:
: Water Transfer (River)
: Water Transfer (Pipeline)
: England-Wales Border
: Supplying WRZ
: Recipient WRZ

Figure 19 Schematic maps of the Thames to Southern Transfer with two supply configurations: (a) supply by SESRO; (b) supply by STT.



Supply by SESRO:

- Arc from SESRO Reservoir (red circle) to SESRO Distribution (green circle): capped at 321 Ml/d
- Arc from SESRO Distribution (green circle) direct to Southern Water South Hants demand node (50, 80, 120 Ml/d) (orange circle)
- Arc from SESRO Distribution (green circle) to SE WRZ 4 (20 Ml/d) (orange circle)

Supply by STT:

- Arc from STT Distribution (green circle) direct to Southern Water South Hants demand node (50, 80, 120 Ml/d) (orange circle)
- Arc from STT Distribution (green circle) to SE WRZ 4 (20 Ml/d) (orange circle)

Figure 20 The representation in WREW for the Thames to Southern Transfer

3.3.8 Southern Water – Water Recycling Solution

This solution involves the Budds Farm wastewater treatment works, a proposed water recycling plant (WRP), and transfer of treated wastewater to Otterbourne water supply works (WSW) for distribution to the Southern Water supply area, via the company's new grid network benefitting the Hampshire WRZs.

There are 4 sub-options under consideration to determine the best way to transfer water from the WRP to Otterbourne WSW.

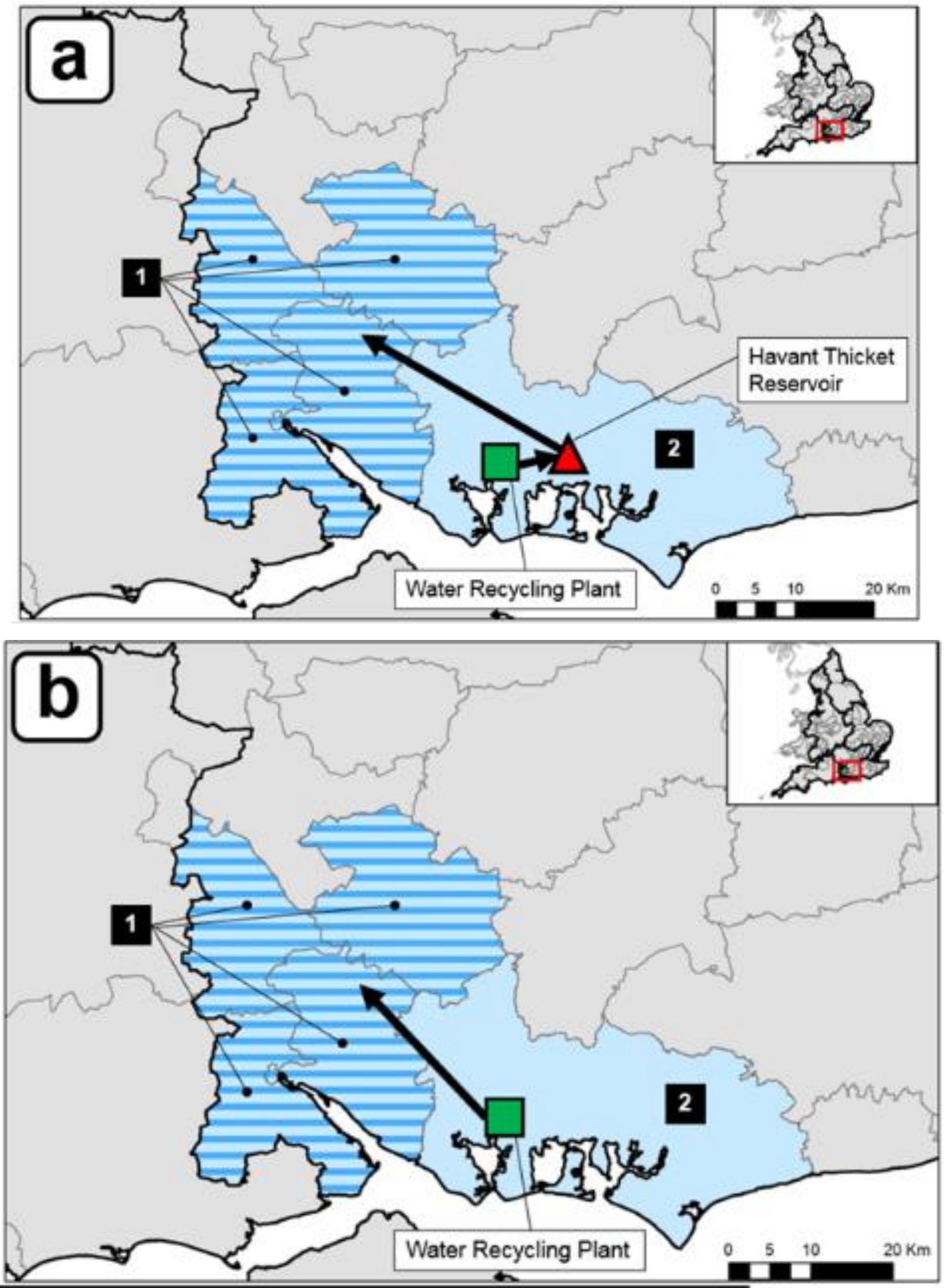
- Sub-Options 2 and 5- Will transfer water from the WRP to Otterbourne WSW via an Environmental buffer. The total capacity for sub-option 2 is 61 Ml/d whilst, sub-option 5 has a capacity of 75 Ml/d;
- Sub-Option 3 - A total of 61 Ml/d will be transferred via a direct route from the water recycling plant to Otterbourne WSW; and
- Sub-Option 4 - This option is dependent on the new Havant Thicket Reservoir and involves a bulk transfer of 61 Ml/d from the WRP to Havant Thicket Reservoir followed by a 61 Ml/d transfer from the reservoir to Otterbourne WSW, via a direct pipeline.

(The original Sub-Option 1, involving transfer to the Lower Itchen, has been removed from the RAPID process and therefore is not included in WREW.)

Following consultation, a number of decisions were taken made to best represent the solution within WREW including abstraction rules and triggers (demand within Affinity's resource zones). The following representation decisions and assumptions were agreed:

- Budds Farm WwTW and the WRP will work together and are therefore not expected to independently limit solution yield. For this reason, the two assets have been aggregated into a single node in WREW;
- The environmental buffer involved along the transfer route for sub-options 2 and 5 only operates on a 24-hour basis and is unlikely to be a constraining/limiting factor on the solution. For the purpose of national modelling, the representation of the transfer pathway for sub-options 2 and 5 is simplified as a direct transfer, the same as for sub-option 3. As a result, sub-options 2, 3, & 5 have been aggregated into one representation with two capacities: 61 Ml/d for sub-options 2 and 3, and 75 Ml/d for sub-option 5;
- The solution supplies Otterbourne WSW, which is located in Southern Water's Hampshire Southampton East WRZ. The Hampshire Southampton East WRZ is aggregated in WREW into the South Hants demand node along with the Hampshire Southampton West, Hampshire Rural and Hampshire Winchester WRZs. There are however plans for the Southern Water Hampshire WRZs to be connected with one another and therefore the aggregated Hampshire WRZs demand node in WREW is appropriate;
- Otterbourne WSW is not represented in WREW as it would not be a limiting factor on the solution yield; and
- The solution is demand led but only to be used during peak demand periods and as the lowest priority/last source of supply.

Figure 21 shows the schematic map of the solution, and Figure 22 shows the representation in WREW.



	Water Resource Zones	
	Name	**Company**
1	Hampshire Southampton East, Hampshire Southampton West, Hampshire Rural and Hampshire Winchester	Southern Water
2	Portsmouth	Portsmouth Water

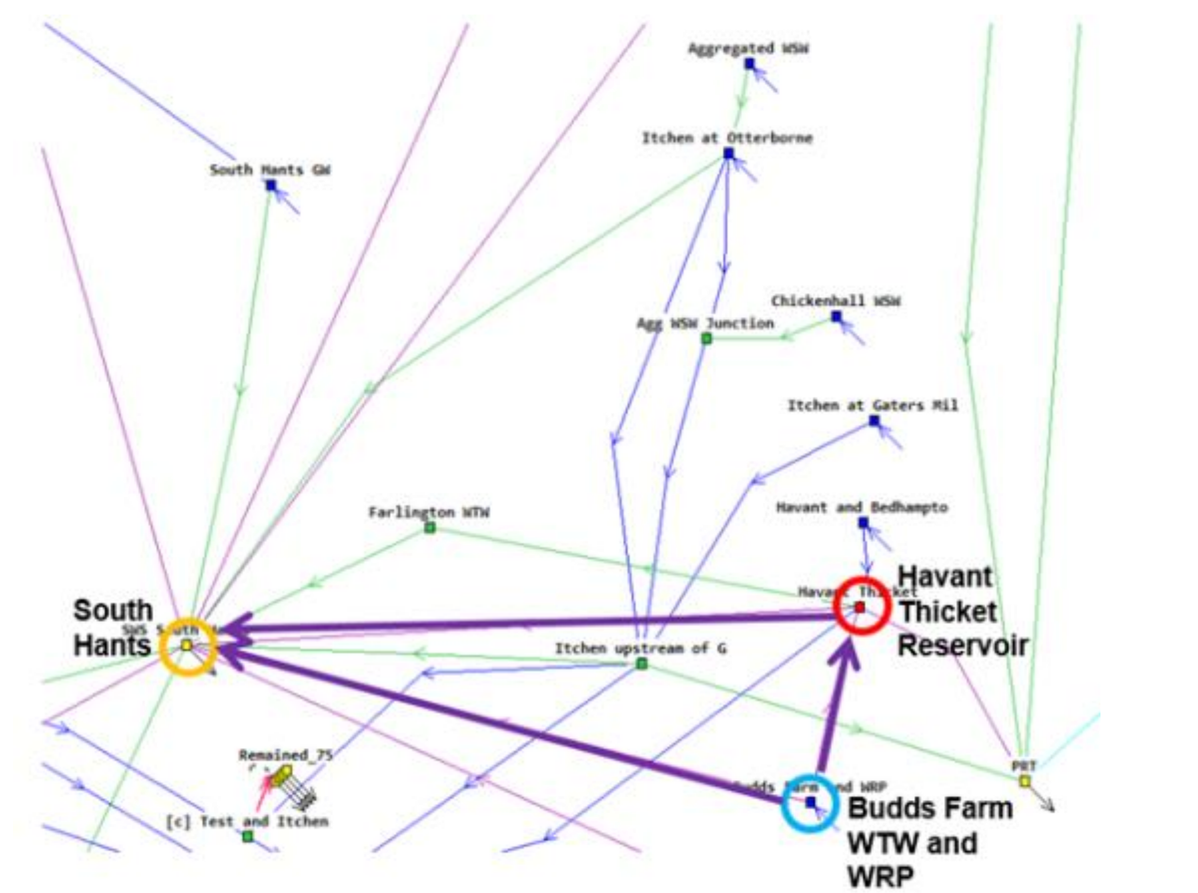
Legend:

: Water Transfer (Pipeline)

: Supplying & Recipient WRZ

: Supplying WRZ

Figure 21 Schematic maps of the Southern Water – Water Recycling solution with two sub-option configurations: (a) Havant Thicket Raw Water Transfer solution SESRO; (b) Water Recycling Plant Direct.



Where:

Sub-options 2, 3 & 5:

- A single node representing the Budds Farm wastewater treatment works and the water recycling plant (blue circle). As these two plants interact with one another and do not affect the capacity of the solution we have aggregated them into one node. Yield is 61 Ml/d for sub-options 2 & 3 and 75 Ml/d for sub-option 5.

An arc transferring 61 Ml/d (sub-options 2 & 3) or 75 Ml/d (sub-option 5) from Budds Farm WwTW and the WRP (blue circle) to the South Hants demand centre (orange circle). The South Hants demand centre includes Southern Water's Hampshire Southampton East, Hampshire Southampton West, Hampshire Winchester, Hampshire Rural WRZs.

Sub-option 4:

- A single node representing the Budds Farm wastewater treatment works and the water recycling plant (blue circle). Yield is 61 Ml/d.
- An arc transferring 61 Ml/d from Budds Farm WwTW and the WRP (blue circle) to the Havant Thicket Reservoir (red circle). The reservoir has a capacity of 8700 Ml with 5% dedicated to emergency storage.
- An arc transferring 61 Ml/d from Havant Thicket Reservoir (red circle) to meet demand/supply shortfalls for the South Hants demand centre (orange circle)

Figure 22 The representation in WREW for the River Itchen Reuse Solution

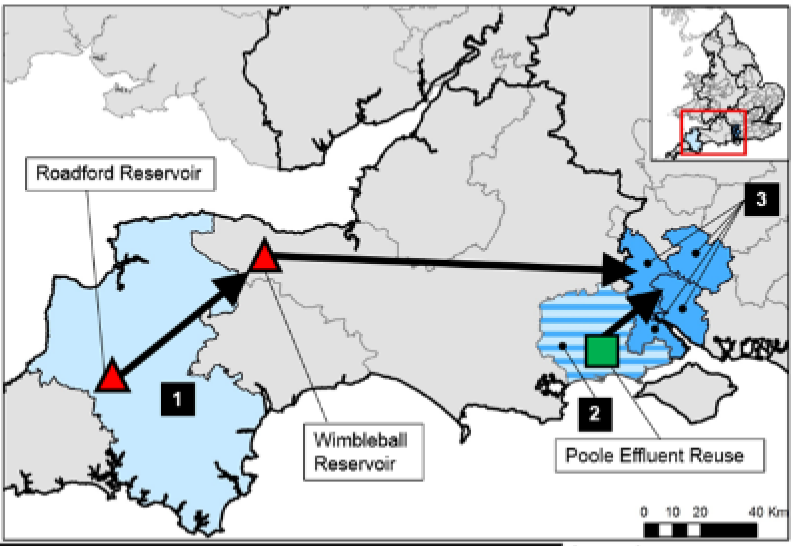
3.3.9 West Country South Sources (WCSS) & West Country to Southern Transfer (WC2ST)

This standalone transfer solution comprises of two 30 Ml/d supply sources and a new long-distance transmission system. The first supply source involves making better use of existing storage capacity in the Roadford Reservoir, where up to 15,000 Ml of storage could be utilised by pumping water from the River Tamar to the reservoir, during high flows. The second supply source is effluent reuse from Poole Sewage Treatment Works. There is also the potential for additional configurations of the existing distribution system. The beneficiary will be Southern Water's Hampshire WRZs: Southampton and Andover.

Following consultation, a number of decisions were taken made to best represent the solution within WREW, including triggers, and licence conditions. The following representation decisions and assumptions were agreed:

- Southern Water Hampshire WRZs are aggregated in WREW as a 'South Hants' demand node which includes Hampshire Southampton East, Hampshire Southampton West, Hampshire Winchester and Hampshire Rural;
- The transfer route includes the Shaftesbury Junction, which has existing connectivity with the Warminster and Salisbury demand centre and the Parrett demand centre. It is therefore possible that some of the water transferred from Roadford Reservoir could be used to supply these demand centres as well as the South Hants demand centre. Supply priorities in WREW have been set so that supply to the South Hants demand centre takes precedence;
- WTW and pumping stations are omitted from representation as they are not constraining/limiting factors to the SRO;
- Inflow at Gatherley has been run through the DECIPHeR hydrological model;
- Abstraction limits and timings for the Gatherly abstraction on the River Tamar have been included in WREW using information provided by the solution team;
- Created a new arc to transfer water from Roadford Reservoir to Wimbleball Reservoir – in reality, the Roadford Reservoir enhancement planned as part of the solution would actually reduce the use of the current transfer from Wimbleball Reservoir to Roadford WRZ, which would free up water in Wimbleball Reservoir that could then be transferred to Wessex Water and on to Southern Water. However, it is suggested to leave the existing transfer from Wimbleball Reservoir to Roadford WRZ (rather than reduce it) and create a new transfer that takes the extra water stored at Roadford Reservoir, as part of the solution, over to Wimbleball Reservoir; and
- The transfer pathway for water from Poole Sewage Treatment Works is complex and involves discharging water into the Dorset Stour and abstracting on a "put and take" basis, pumping to an intermediate station and finally pumping to lakes at Testwood Water Treatment Works. It was agreed that, for the purposes of national scale modelling, these aspects would not constrain the solution and therefore the transfer pathway in WREW has been simplified using a direct connection from Poole Sewage Treatment works to the South Hants demand centre. Additionally, the solution has also been configured so that the 30 Ml/d of water from Poole Sewage Treatment Works is also available to the Bournemouth demand centre, however, supply priorities in WREW have been set so that the South Hants demand centre takes precedence.

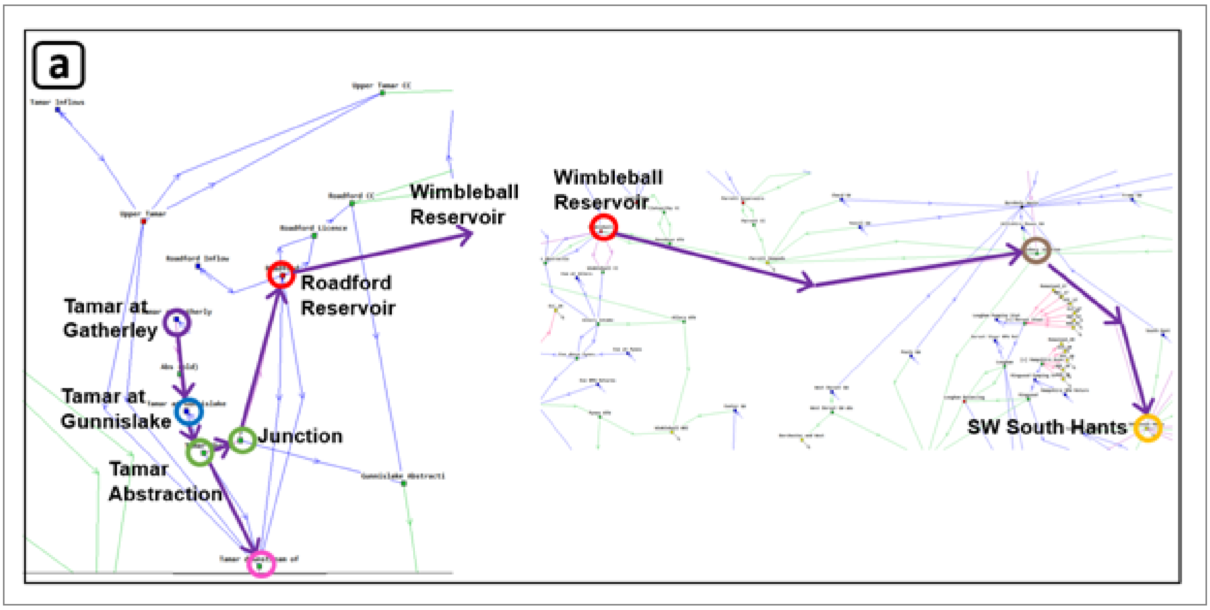
Figure 23 shows the schematic map of the solution, and Figure 24 shows the representation in WREW.

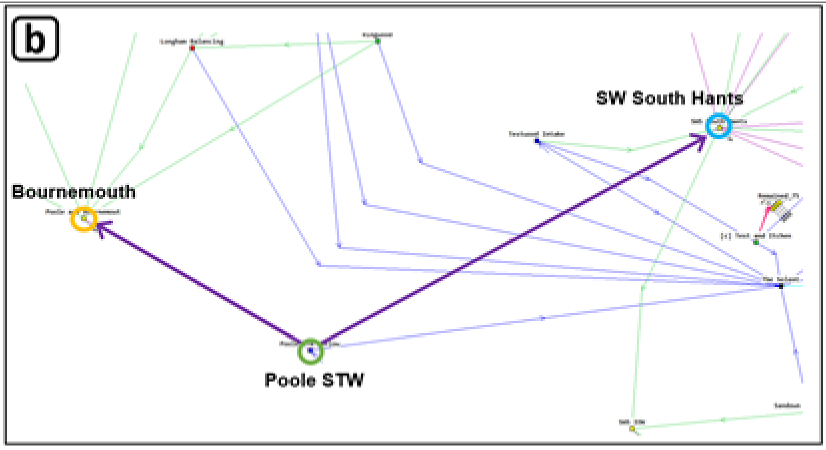


Water Resource Zones		
	Name	**Company**
1	Roadford	South West Water
2	Bournemouth	South West Water
3	Hampshire Southampton East, Hampshire Southampton West, Hampshire Rural and Hampshire Winchester	Southern Water

Legend:
- : Water Transfer (Pipeline)
- : Supplying & Recipient WRZ
- : Recipient WRZ
- : Supplying WRZ

Figure 23 A schematic map of West Country South Sources and West Country – Southern Transfer





Panel a:

- New inflow (Tamar at Gatherley) (purple circle)
- Arcs between Tamar at Gatherley and Tamar at Gunnislake (blue circle)
- (Historic) abstraction node (Tamar Abs.) and junction node (green circles)
- Arc connecting Tamar flows to Tamar downstream (to discharge of any surplus) (pink circle)
- New arc from Junction Node to Roadford Reservoir (red circle)
- New arc from Roadford Reservoir to Wimbleball Reservoir
- New arc from Wimbleball Reservoir to Shaftesbury Junction (brown circle)
- New arc from Shaftesbury Junction to Southern Water South Hants demand node (orange circle)

Panel b:

- New node for Poole Sewage Treatment Works (green circle)
- New arc from Poole Sewage Treatment Works to Bournemouth demand node (orange circle)
- New arc from Poole Sewage Treatment Works to Southern Water South Hants demand node (blue circle)

Figure 24 The representation in WREW for the West Country to Southern Transfer - South Sources: Roadford Pumped Storage

3.3.10 West Country North Sources and Transfer

This standalone solution comprises a second 9,400 Ml reservoir alongside the existing Cheddar reservoir and a raw water pumping station to transfer water via a new pipeline to Southern Water's Testwood WTW, to benefit Southern Water's Hampshire WRZs.

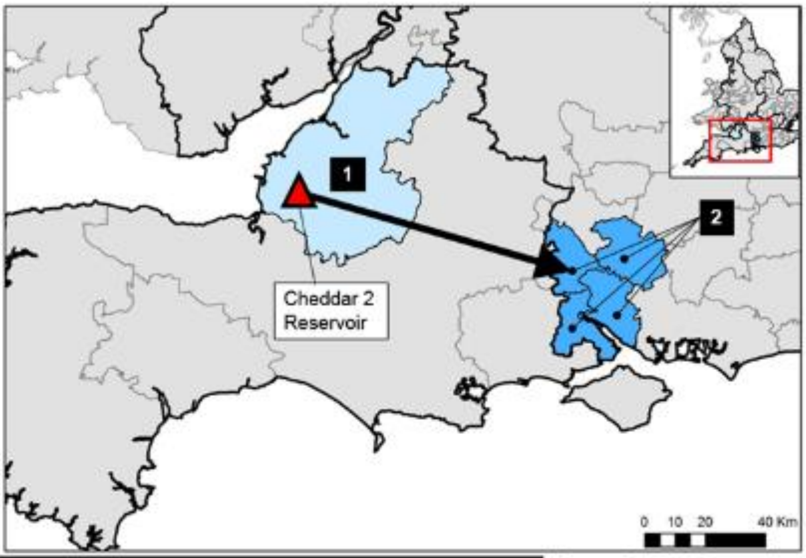
The transfer will either occur as base flow or in drought triggered by low flows on the River Itchen.

Like the existing reservoir, Cheddar 2 would be filled by flow from Cheddar springs, within existing licenced abstraction rates; a range of transfer capacities are under consideration from 16 Ml/d to 40 Ml/d.

Following consultation, a number of decisions were taken made to best represent the solution within WREW, including reservoir filling rules and priority, capacity, yields and triggers. The following representation decisions and assumptions were agreed:

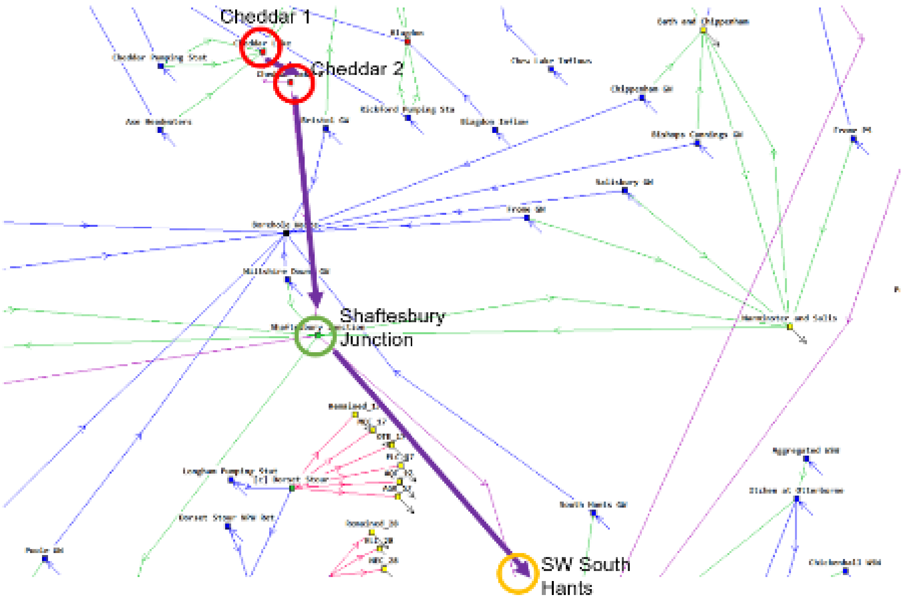
- Southern Water Hampshire WRZs are aggregated as a 'South Hants' demand node which includes Hampshire Southampton East, Hampshire Southampton West, Hampshire Winchester and Hampshire Rural;
- The transfer route involves the Shaftesbury Junction, which has existing connectivity with the Warminster and Salisbury demand centre and the Parrett demand centre. It is therefore possible that some of the water transferred from Cheddar 2 Reservoir could be used to supply these demand centres as well as the South Hants demand centre. Supply priorities in WREW have been set so that supply to the South Hants demand centre takes precedence;
- WTW and pumping stations are omitted from representation as they are not constraining/limiting factors to the SRO;
- Cheddar 2 will be filled when the solution is on, and Cheddar Lake is 90% full. There will be no recharge of Cheddar 2 if Bristol Water's resource state is above the Level 2 trigger threshold;
- Cheddar 1 and 2 would not be 'directly connected' in reality – the design is for different top water levels. Further, Cheddar 1 and 2 would not be operated in series e.g. "fill and spill" – they would be used as a single conjunctive water store; and
- WREW assumes the maximum transfer of 40 Ml/d.

Figure 25 shows the schematic map of the solution, and Figure 26 shows the representation in WREW.



Water Resource Zones		
	Name	Company
1	Bristol	Bristol Water
2	Hampshire Southampton East, Hampshire Southampton West, Hampshire Rural and Hampshire Winchester	Southern Water

Figure 25 A schematic map of West Country North Sources and Transfer



- Historic reservoir node for Cheddar 1 (Cheddar Lake) and new reservoir node for Cheddar 2 (red circles)
- New arc connecting Cheddar 1 and Cheddar 2.
- New arc connecting Cheddar 2 to Shaftesbury Junction (green circle)
- New arc connecting Shaftesbury Junction to Southern Water South Hants Demand node (orange circle)

Figure 26 The representation in WREW for the West Country to Southern Transfer - North Sources: Cheddar 2

4 Phase 1 Activity

4.1 Updating WREW with WRMP24 data

4.1.1 Representation of the water supply system in England and Wales

At the start of the NSSM project, the WREW model contained water infrastructure and operational rules relevant to the 2014 Price Review submission, with their representation suitable for national scale simulations. It also included some of the (>20 Ml/d) supply side options from WRMP 2019. Representation of six solutions was also included.

The information needed to further develop the model for the NSSM project includes all infrastructure and operational information on water company supply networks as of 2025, and the solutions, at a level appropriate for national scale modelling.

There has been much liaison with the water industry and many discussions held with key water resource technical staff of the regional groups and water companies to review the outputs of the WREW model. These discussions were invaluable to getting agreement over the set-up of WREW and identifying changes to the national scale model to produce a better representation.

4.1.2 Validation of WREW Outputs

It is important to assess the validity of outputs from WREW as this gives insight into their reliability and consequently the level of confidence that can be placed in the modelling results. Model validation can be achieved in a relative sense by comparing WREW outputs with those from other water resources models, and in absolute sense by comparing with observations.

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.

As stated in Section 2.4.2, before this project, the ongoing development of the WREW model by Oxford University involved the assessment of performance against the systems of the five largest English water companies, namely United Utilities, Anglian Water, Yorkshire Water, Thames Water and Severn Trent Water. A timeseries comparison of storage in key reservoir groups showed the good performance of the WREW model. More information on this, and charts, can be found in Dobson *et al.* (2020) particularly the supplementary information to the paper.

Further to the above, for this project, a set of four individual reservoirs from England and Wales were chosen for comparing simulated reservoir storage levels from WREW with simulated reservoir storage from water companies (Figure 27) to perform a relative validation exercise. 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. Additionally, the availability of water company simulated storage also played a role in which reservoirs were chosen for validation. 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 (2020-21 Distribution Input data from WRMP19). In this way, the differences that arise are largely a result of are 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 drive differences in model results.

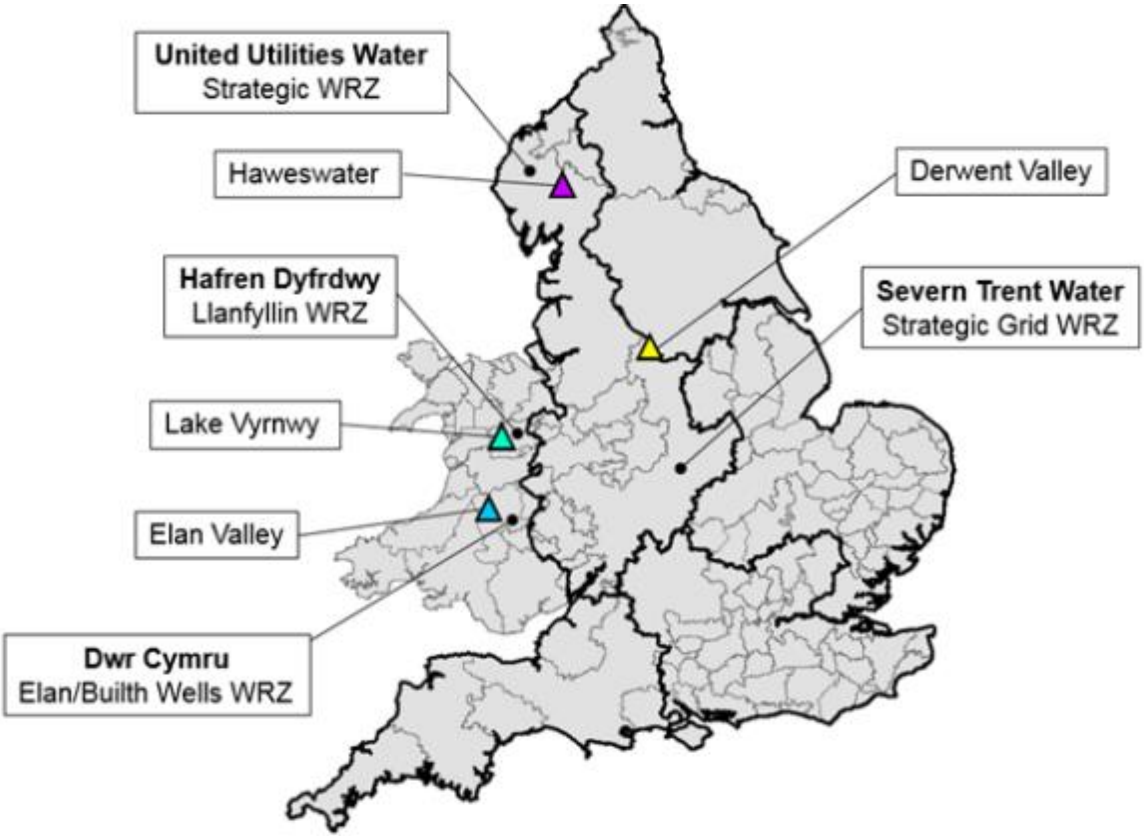


Figure 27 The four reservoirs used in the WREW validation exercise

Since the focus of this study is assessing the performance benefit of solutions under drought events, it is sensible to validate the model during drought events observed in the historic record. With this in mind, simulated reservoir storage has been compared for the three drought events that caused the most significant drawdown of storage levels at each of the four reservoir locations. The geographical distribution of the reservoirs and association with different hydrological systems means timing of these drawdown events varies between the four reservoirs used for validation.

4.1.2.1 Haweswater

Haweswater is a key reservoir for the United Utilities Strategic WRZ and is used to assess the resource position for the zone.

Figure 27 shows the simulated reservoir storage levels between WREW and water company modelling. The WREW model over-estimates the water levels relative to water company models over the three main drought events (1976, 1985 and 1996), with WREW displaying a 16,000-28,000 Ml deviation from water company outputs, equivalent to 20-34% of the total storage volume of Haweswater. Storage levels are consistently higher in WREW than in the water company model and the difference is greatest during summer and autumn when reservoir drawdown occurs. For example, the WREW storage levels display a drawdown of ~20,000 Ml over the course of the drought events, whereas the drawdown observed in the water company storage levels is much greater at ~50,000 Ml[11].

Despite these differences, the shape of the storage profiles is similar and suggests that the relative patterns of supply system behaviour or rainfall/river flows are well represented in WREW. The continuous offset between WREW and water company simulated storage levels is not observed for the other reservoirs validated in this study and suggests that operational rules for this area of the model are incorrectly configured, river flows are too high and/or the demand for water is too low.

Haweswater is an important part of the Strategic WRZ system and therefore the mismatch in simulated storage has implications for how well calibrated the wider United Utilities system is in WREW. The issue has been discussed with United Utilities. It was agreed that although confidence in this part of the model would be low until Haweswater is better calibrated, the more important factor for the NSSM modelling results around STT is the extent to which the United Utilities Sources and Vyrnwy Aqueduct solutions have been represented in WREW. The current configuration of the United Utilities solutions means that STT transfer behaviour is not sensitive to the resource position in United Utilities. Two actions were agreed to rectify these issues, as noted in section 4.3. and 4.5.

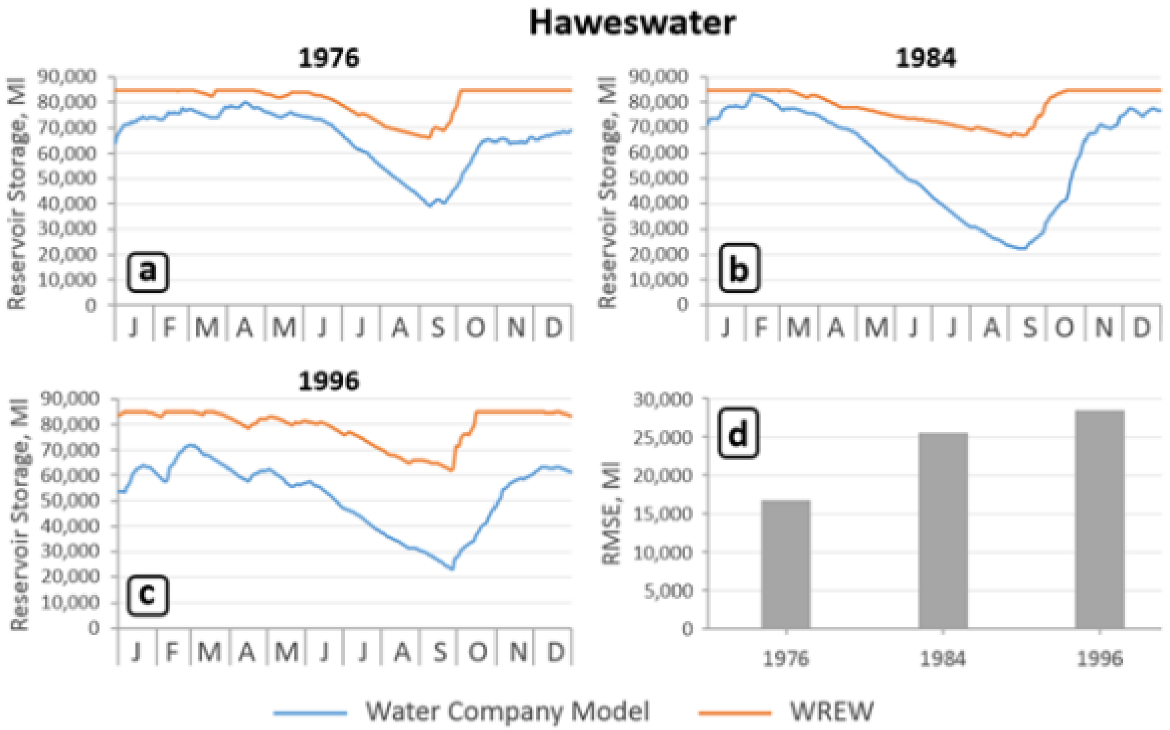


Figure 28 Comparison of Haweswater simulated storage from WREW and water company models

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

[11] For context, a volume of 30,000 Ml over 6-month drought draw-down period would be approximately equivalent to 170 Ml/d

4.1.2.2 Lake Vyrnwy

Lake Vyrnwy reservoir is an important part of the United Utilities water supply infrastructure, supplying demand centres in the southern part of the company's strategic WRZ. Releases from the reservoir provide the largest volume component of supported flow for the STT solution; these are enabled by the Vyrnwy Aqueduct and UU Sources solutions, which replace water normally supplied to UU from Vyrnwy.

Figure 29 shows the simulated reservoir storage levels between WREW and water company modelling. The WREW model over-estimates the water levels relative to water company modelling over three drought events (1984, 1988 and 1995-96) with WREW displaying an 8,000-14,500 Ml deviation from water company outputs, equivalent to 14-24% of the total storage volume of Lake Vyrnwy. Most of the observed error accumulates over the summer and autumn season of the 1984 and 1988 drought events and over a longer period spanning from the summer of 1995 to the autumn of 1996, for the 1995-96 event. Over these intervals, simulated storage from WREW shows ~17,000 Ml of drawdown, which is much lower than the ~38,000 Ml of drawdown seen in water company modelled storage[12].

The difference in WREW and water company simulated storage levels for Lake Vyrnwy follows a similar trend to that observed for Haweswater, with the greatest difference during late summer and autumn. This pattern may be a result of 'wetter' hydrological inputs but could also be caused by the extent to which the wider United Utilities system is calibrated in WREW. For example, Vyrnwy is one of the Welsh reservoirs that supplies demand centres in the United Utilities Strategic WRZ, which are also supplied by Cumbrian reservoirs, including Haweswater. The relatively poor calibration of Haweswater could therefore impact on the simulated storage behaviour for Vyrnwy. Discussion with United Utilities confirms that more work is required on the calibration of the Cumbrian reservoirs in WREW and two actions have been agreed to rectify the issues, as described in section 4.3. and 4.5.

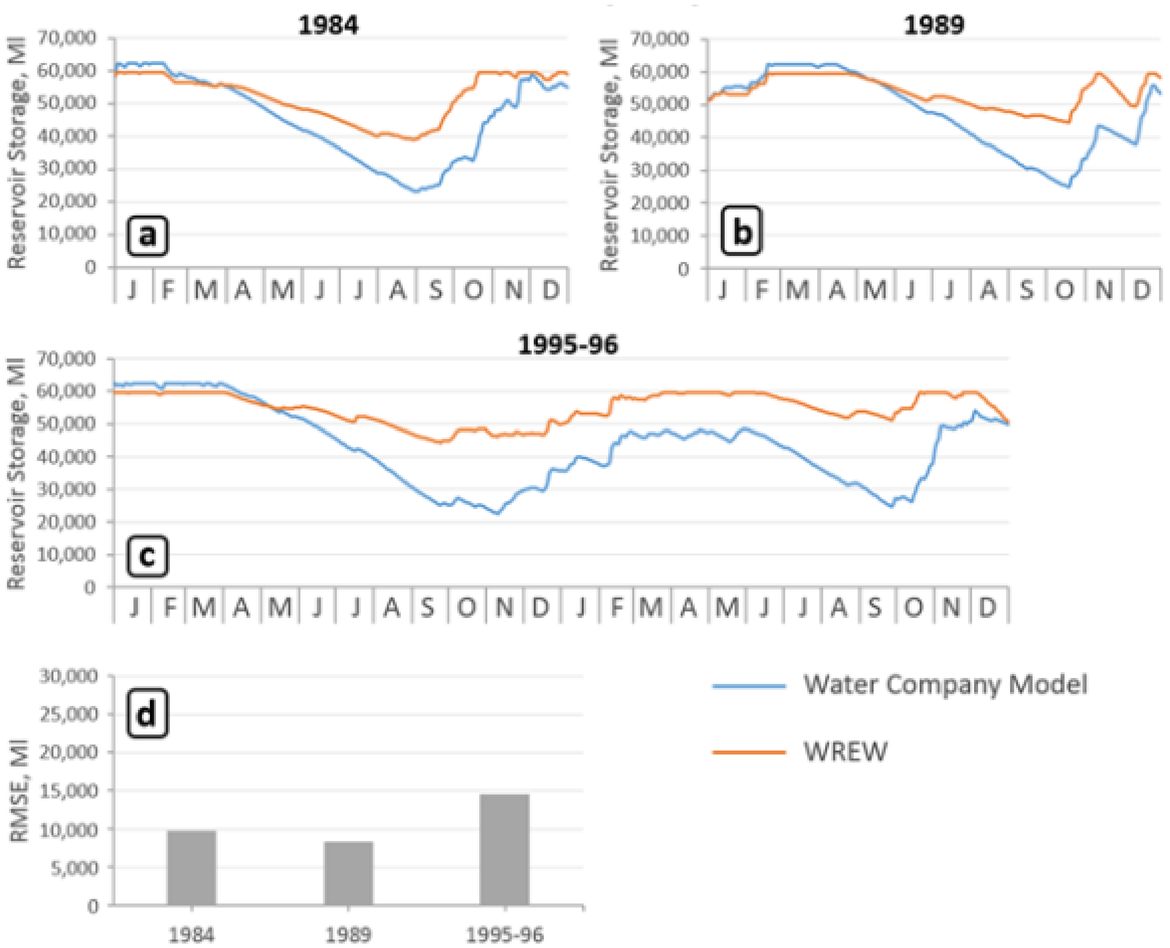


Figure 29 Comparison of Lake Vyrnwy simulated storage from WREW and water company models
Panels a-c show the three worst historic drought events; panel d shows root mean square error (RMSE) between WREW and water company simulated storage for the drought events.

12 For context, a volume of 21,000 Ml over 6-month drought draw-down period would be approximately equivalent to 120 Ml/d, in addition to the 170 Ml/d difference noted at Haweswater reservoir in the same zone.

4.1.2.3 Elan Valley Reservoirs

The Elan Valley Reservoirs are a group of 5 reservoirs, including Claerwen, Caban Coch, Craig Goch, Pen-y-Garreg and Garreg Ddu, which supply water to Birmingham in Severn Trent Water's Strategic Grid WRZ.

Figure 30 shows a good agreement between the simulated reservoir storage levels from WREW and water company modelling for 1976 and 1984 drought events and a very good correlation for the 2004 event. The simulated storage from WREW deviates from water company outputs by 4,100-12,250 Ml, which is equivalent to 4-12% of the aggregated reservoir storage volume. While the storage levels for the 2003 event are in agreement, the error observed for the 1976 and 1984 events accumulates over the summer – autumn period, when WREW storage levels are drawn down by ~53,000 Ml compared to the ~70,000 Ml of drawdown observed for the water company modelled storage[13]. A similar trend is observed for Haweswater and Vyrnwy and although the differences are less pronounced for the Elan Valley reservoirs.

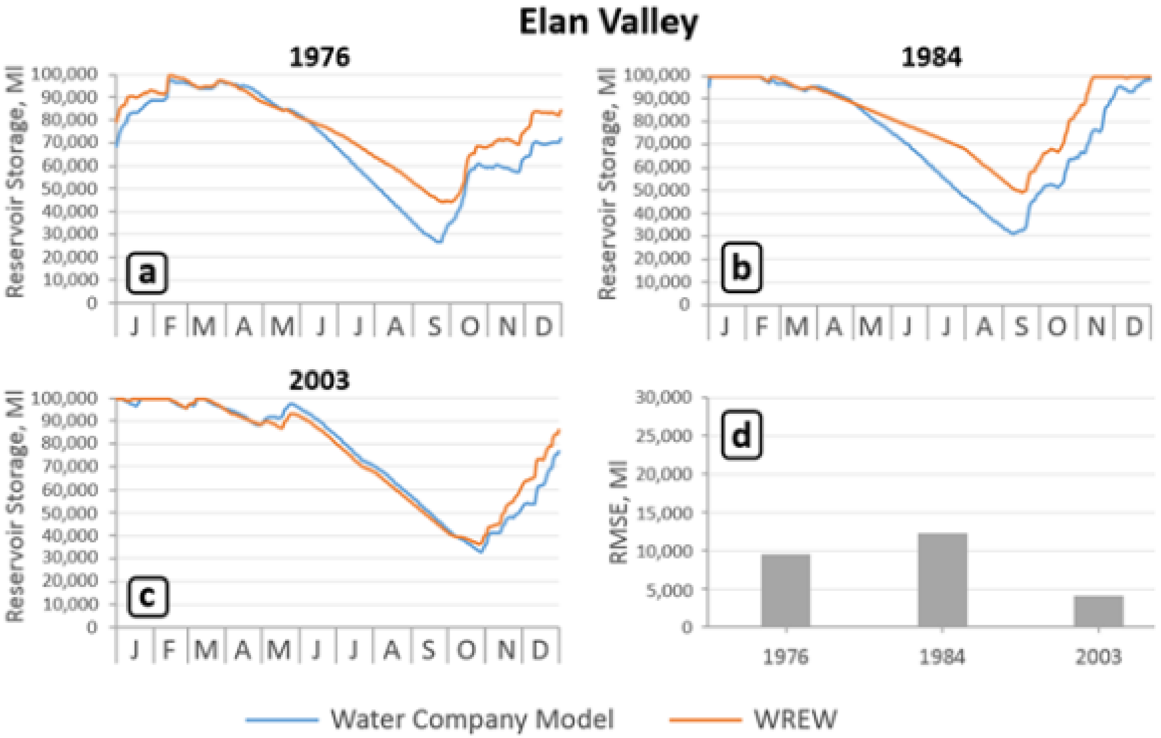


Figure 30 Comparison of Elan Valley simulated storage from WREW and water company models

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

[13]For context, a volume of 17,000 Ml over 6-month drought draw-down period would be approximately equivalent to 90 Ml/d

4.1.2.4 Derwent Valley Reservoirs

The Derwent Valley Reservoirs are a group of three reservoirs including Derwent, Ladybower and Howden, which supply a number of demand centres in the Severn Trent Water Strategic Grid WRZ.

Figure 31 shows a relatively good agreement between the simulated reservoir storage levels between WREW and water company modelling over the three main drought events (1976, 1995-96 and 2003), with WREW displaying a 3,000-6,150 Ml deviation from water company outputs, equivalent to 6-13% of the aggregated reservoir storage volume (Figure 31). Most of the observed error accumulates over the summer and autumn season for the 1976 and 2003 drought events and from the late summer of 1995 to the spring of 1996, for the 1995-96 event. Over these intervals simulated storage from WREW shows ~22,500 Ml of drawdown, whereas the water company outputs show ~28,500 Ml of drawdown[14].

While WREW simulated storage compares well with water company outputs for the 1976 and 2003 events there is a much longer period of mismatch for the 1995-96 event. The same pattern is observed for the 1995-96 event at Lake Vyrnwy, which suggests this more prolonged drought event is not well captured by the climatological or hydrological inputs.

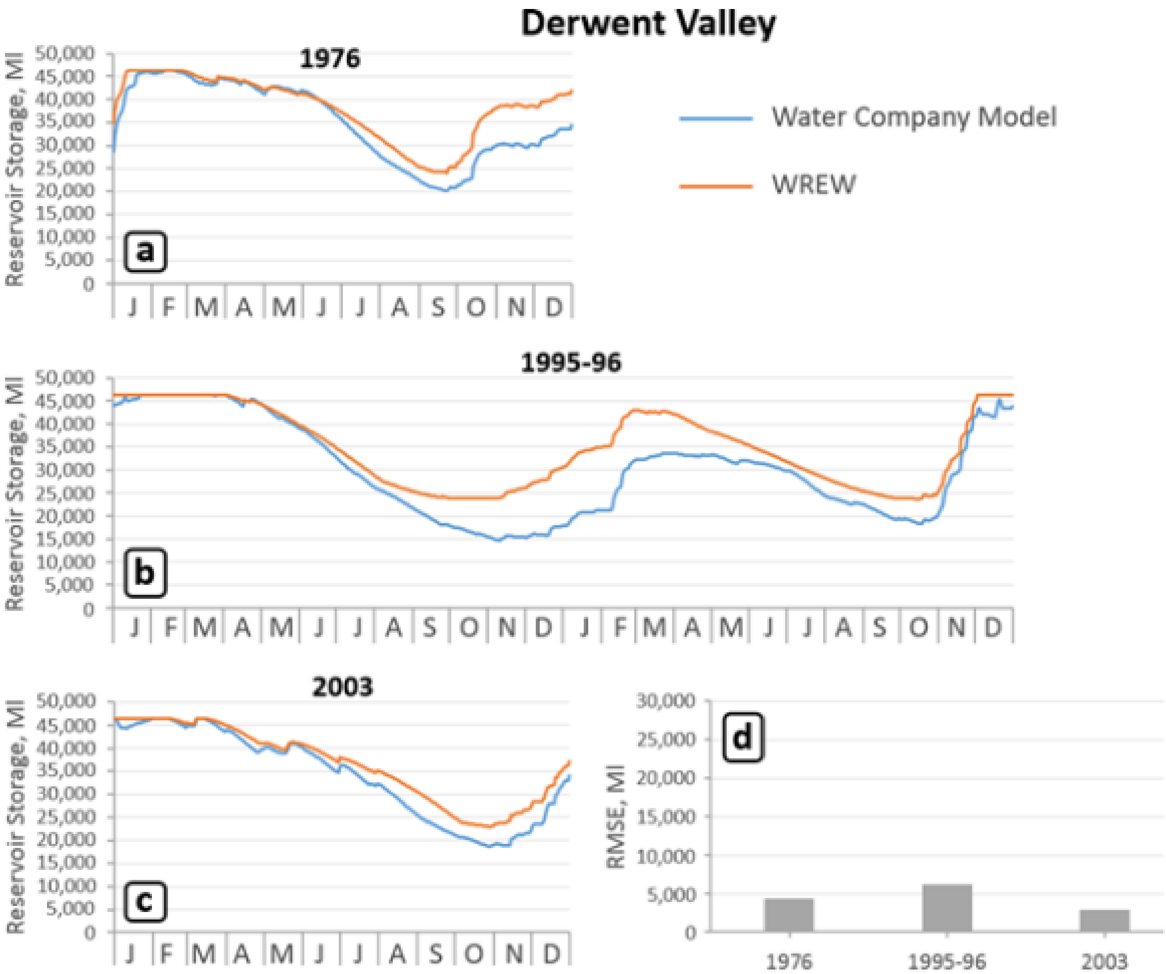


Figure 31 Comparison of Derwent Valley simulated storage from WREW and water company models

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

[14] For context, a volume of 6,000 Ml over 6-month drought draw-down period would be approximately equivalent to 30 Ml/d, in addition to the 90 Ml/d difference noted at Elan in the same zone

4.1.2.5 Common theme

A common theme across all of the reservoirs and drought events for which storage levels have been compared is that the shape of the WREW simulated reservoir storage level curves are similar to those from the water company models. This trend suggests that the relative patterns of supply system behaviour or rainfall/river flows are well represented in WREW although further work is required to investigate and reduce the observed offset with water company simulated storage. The level of discrepancy between WREW and water company simulated storage represents an area of further development for Phase 2 of the project, as described in Sections 6.1.1 and 6.1.8. Additionally, the spatial extent of validation should be extended for Phase 2 of the project, as described in Section 6.1.2,

The majority of the discrepancy between WREW and water company outputs is a function of lower levels of drawdown in WREW reservoir storage, especially over the summer and autumn period, which implies that hydrological inputs used in the national model may be ‘wetter’ than the water company input datasets. It is only possible to test this hypothesis by running water company flow series through WREW. This has not been possible within Phase 1 of this project, but such a validation exercise was carried out for the WaterUK project[1] which involved using water company flow data through an earlier version of the WREW model. The analysis included a group of reservoirs in the north of the United Utilities area (including the Haweswater reservoir) and showed much smaller errors for the 1976, 1985 and 1996 events compared to the results discussed above, equivalent to 2.3, 0.7 and 3.4% of the total aggregated storage volume (~254,000 Ml), respectively.

It is important to note that this validation work was based on a larger group of reservoirs, used a different version of WREW and a different demand scenario. However, the results suggest that the differences observed between WREW and water company modelled reservoir storage levels in this study might be a function of the climatological and hydrological input datasets.

5 Phase 1 outputs

WREW can be 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 personal consumption and leakage), 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 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 1 outputs demonstrate the potential national resilience benefit gained as a result of the solutions inclusion, in isolation or in combination with other solutions. Other options that are not solutions in the RAPID programme 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 this modelling project is to support RAPID's understanding of the solutions within the RAPID gated programme, hence the focus on solutions. Through Phase 2 and beyond, where options that are not solutions in the RAPID programme begin to be selected with confidence through planning processes, either as standalone options or to support solutions, this modelling project may look to incorporate these as appropriate to reflect likely current and future planning scenarios.

A detailed summary of the model scenarios is presented in the sections below.

5.1 Scenarios tested

A set of 16 model scenarios were tested in WREW, as summarised in Table 1 . Note that each scenario involves a different solution, while the public water supply demand and the future climate ensemble remain consistent.

A total of 17 solution proposals have been submitted by water companies, however, some of the solutions only work as supply sources for other solutions (i.e., they are not standalone solutions). solutions of this nature have been grouped together as 'enabling' and 'dependent' solutions. Additionally, the Southern Water desalination solution and Southern Water's water recycling solution have the same supply yield and work in same way, when simplified for representation in WREW, and can consequently be considered as one solution for the purposes of national modelling. Taking these additional considerations into account reduces the number of individual solutions tested to 10, but as some involve sub-options the total number of individual solution scenarios performed equals 14, with two in-combination scenarios also simulated. More details on the solution setup can be found in section 7.2.

5.1.1 River flow and demand inputs

The river flows for the model scenarios described in Table 1 , are simulated using the DECIPHeR hydrological modelling framework (Coxon *et al.,* 2019a) which uses the 100x30year near future (2020-2049) climate ensemble runs from the MaRIUS weather@home2 dataset (Guillod *et al*., 2017, 2018).

Public water supply demand is parameterised using the 'dry year annual average distribution input' (DYAA DI for 2020/21 from WRMP19), which represents the annual average amount of potable water entering the distribution system within the area of supply, for a dry year. In this case, the area of supply is a water resource zone (WRZ). A monthly demand profile is applied to the annual DI values to give a monthly water demand for each WRZ, and therefore each demand node in the model.

5.1.2 Controls on solution operation

Many of the solutions have design configurations that incorporate different sub-options, many of which offer a range of capacities or yields for the solutions. The sub-options increase the complexity and total number of solution model scenarios that could be tested with WREW. In an effort to keep the number of model scenarios manageable, we have chosen to test each solution at its maximum capacity or yield. In the majority of cases this approach removes sub-options with different yields/capacities and allows for one model scenario per solution. However, some solution sub-options are different enough in their design that a separate model scenario is required. The solution design configurations for each scenario are shown in Table 1 .

Solution behaviour is configured in WREW such that solutions are triggered when key stages in resource position of the surrounding supply are reached, or so that they have the lowest priority compared with other sources of supply, i.e., the solutions are the last supply source available to the model for meeting demand. While demand-led utilisation of solutions is simplistic, it is appropriate for a national scale model, especially given the uncertainty around operation and utilisation at this stage in the solution design process. Solutions that supply Southern Water and Affinity Water are triggered when demand is sufficiently high; solutions that supply Thames Water are activated when the storage volume of aggregated reservoirs for London dips below a particular threshold i.e., when Teddington Target Flow drops from 800 Ml/d to 600/700 Ml/d.

Table 1 The solution model scenarios tested in WREW

Note: All simulations use the same demand profile (Distribution Input for 2020-21 from WRMP19) and 100 climate scenarios from the MaRIUS project (Near Future ensemble (2020-2049) generated by Weather@home2)

No.	Solution name	Sub-options	Type	Area supplied
Individual Scenarios				
1	Severn Thames Transfer (STT) & Enabling SROs	All sources activated (Vyrnwy Reservoir, Vyrnwy Aqueduct, UU Sources, Minworth Effluent Reuse and Severn Trent Sources) and Deerhurst pipeline	Water transfer (river/pipeline)	Thames Water
2	South East Strategic Reservoir Option (SESRO)	None	Reservoir and water transfer (river)	Thames Water
3	London Effluent Reuse (LER)	Beckton reuse source	Effluent Reuse	Thames Water
4	Thames to Affinity Transfer (T2AT)	SESRO source	Reservoir and water transfer (river/pipeline)	Affinity Water
5		STT source	Water transfer (river/pipeline)	Affinity Water
6		LER (Beckton) source	Water reuse and transfer (pipeline)	Affinity Water
7	Anglian to Affinity Transfer (A2AT)	SLR source	Reservoir and water transfer (pipeline)	Affinity Water
8	Grand Union Canal (GUC)	None	Water transfer (canal)	Affinity Water
9	Thames to Southern Transfer (T2ST)	SESRO source	Reservoir and water transfer (pipeline)	Southern Water
10		STT source	Water transfer (river/pipeline)	Southern Water
11	Southern Water – Water Recycling	Water recycling plant and Havant Thicket Transfer	Water recycling, reservoir and water transfer (pipeline)	Southern Water
12		Water recycling plant only	Water reuse and transfer (pipeline)	Southern Water
13	West Country South Sources (WCSS) and West Country to Southern Transfer (WC2ST)	Roadford transfer	Reservoir and water transfer (pipeline)	Southern Water
		Poole effluent reuse	Effluent reuse and transfer (pipeline)	Southern Water
14	West Country North Sources (WCNS)	None	Reservoir and water transfer (pipeline)	Southern Water
Combination Scenarios				
15	SESRO and STT	None	Water transfer (river/pipeline) and reservoir	Thames Water
16	GUC and STT	None	Effluent Reuse and water transfer (river/pipeline)	Thames Water & Affinity Water

5.2 Key performance metrics

Drought resilience benefits associated with solutions are reported by comparing results for the baseline configuration of WREW (i.e., model configuration without any solutions implemented) with results from each of the model scenarios shown in Table 1 , where the solutions are operational.

For the purpose of this report, the metric used to assess performance is the relative change in probability of a supply shortfall occurring when a solution is implemented. 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, especially when compared to the different levels of operational water use restrictions, such as temporary use bans, which are imposed to reduce demand and prevent demand from outstripping supply in times of developing drought.

Whilst it is possible for different levels of water use restrictions to be imposed in WREW, they do not affect how the model's Network Flow Program optimizes water assignments in the system. Instead, the Network Flow Program is solved to meet demand while also minimising total cost (i.e., find the path of interconnecting arcs between supply and demand notes, which involves using the lowest flow volumes in arcs with the lowest penalties (cost) for conveying a unit of water). Since a supply shortfall incurs the highest cost, the model will attempt to avoid this situation occurring, unless it is physically impossible to satisfy demand. This behaviour means that, despite supply shortfall representing more of a 'model domain' metric, it is a more reliable means of measuring system performance than water use restrictions.

Some solutions are dependent on supply from other solutions. There are two main types of dependencies:

- those where 'enabling' solutions only provide water for the 'dependant' solution (i.e., are not standalone SROs), rather than supplying a demand centre. For example, Severn Trent Sources only supplies water to the Severn Thames Transfer; and
- those where enabling solutions can supply their own demand centres (i.e. run as standalone SRO) while also providing water for other solutions. For example, SESRO can supply water to Thames Water SWOX and London WRZs, as well as supply water for either the T2AT or T2ST solutions.

In order to document this interlinked behaviour of the solutions, the results presented for some of the solution scenarios include benefits at the principal demand centre(s) supplied by a solution, as well as the demand centres supplied by any supporting solutions.

Additionally, the interconnected nature of the supply and hydrological networks in WREW means that a solution can alter the broader water balance in the model and therefore indirectly affect the amount of water supplied to other demand centres, as well as affect their drought resilience characteristics. For example, SESRO supplies London and SWOX WRZs, which are also supplied by abstraction from the River Thames. When SESRO supplies water to London and SWOX the volume of water abstracted from the River Thames for these demand centres could reduce, allowing more water to be available for abstraction from the river for the Affinity Water and South East Water demand centres. The drought resilience behaviour of demand centres which are associated with the same hydrological/supply system and solutions, and which may therefore be indirectly affected by the solution, are included in results for the relevant scenarios.

5.2.1 Metric limitations

Using relative change in supply shortfalls as a metric allows an assessment of the change in the ability to meet demand as a result of introducing the solution. Focussing on relative change from the baseline is appropriate for this national scale model, as it accommodates the possibility that, although broadly representative, the timing and magnitude of the supply shortfalls is unlikely to compare precisely with water company projections, due to the national model's simplified representation of some of the supply network and demand centres.

However, a limitation in the relative change metric is where WRZs do not experience any supply shortfalls in the baseline scenario, as this means that the benefit of introducing the solution cannot be measured. The model outputs analysis in Section 5.3 describes where this limitation has influenced the conclusions of the resource benefit that a solution brings to a WRZ.

This limitation can also hinder the ability to demonstrate any change in the ability to meet demand in areas which provide the supply support to the solutions. However, as the solutions involving water transfers are designed such that they do not affect the drought resilience of the donor areas, the model was not used to examine this potential change.

Where this limitation has occurred, investigations have been undertaken to determine whether the absence of a baseline supply shortfalls is appropriate for the WRZ, reflecting its real-world resilience, or whether improvements to the WRZ configuration within the model may be required to better represent where supply shortfalls would be expected to occur. This may involve checks on whether there is an excess amount of water available or an under-representation of demand in the WRZ. Section 6 details where the need for such improvements has been identified and which will be carried out in Phase 2.

Section 6 also details tasks for Phase 2 of the project which include using an additional metric to identify relative change in supply shortfalls; focussing on level of service; and examining associated water use restrictions. This will give insights into the relative change of restrictions that are less severe than supply shortfalls, such as Temporary Use Bans and Drought Order restrictions.

5.3 Outputs

5.3.1 Individual solution outputs

Ten individual solutions were tested in WREW, three of which involve sub-options. Together with two combination scenarios, this made a total of 16 scenarios modelled (see Table 1). The results for each scenario are set out below.

5.3.1.1 STT & Supporting Solutions

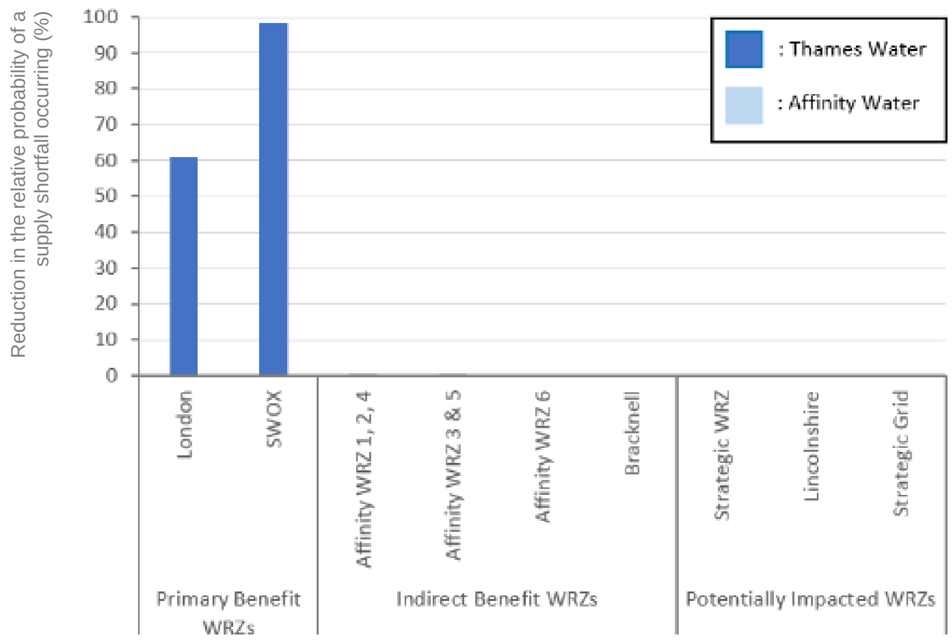


Figure 32 Reduction in the relative probability of a supply shortfall occurring under Scenario 1: STT & Enabling SROs

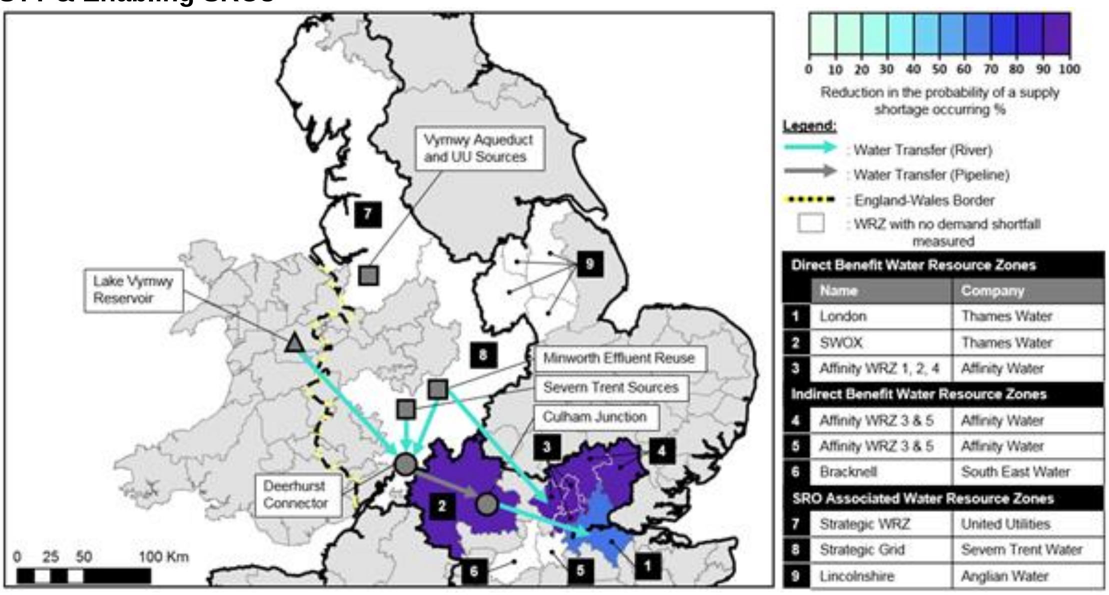


Figure 33 Spatial reduction in the relative probability of a supply shortfall occurring under Scenario 1: STT & Enabling SROs

The largest drought resilience benefit associated with STT (and supporting solutions) is for the Thames Water SWOX WRZ, as demonstrated by Figure 32 and

Figure **33**. This result is to be expected as the solution configuration involves an offtake to Thames Water's SWOX WRZ of up to 100 Ml/d from the Culham Junction, where up to 500 Ml/d of water transferred from Water Resources West enters the River Thames. The supply shortfall events experienced by SWOX WRZ are commonly 10-60 Ml/d, with the largest up to 150 Ml/d, which explains how the 100 Ml/d of water available to SWOX from STT provides such a significant reduction in the relative probability of a supply shortfall occurring, relative to the baseline scenario. A benefit is also observed for the Thames Water London WRZ, however, this WRZ has the highest water demands (1945-2131 Ml/d) and largest supply shortfalls (up to 700 Ml/d), which cannot all be solved by STT, especially when the 100 Ml/d transfer connection to SWOX leaves only ~400 Ml/d available for London WRZ.

There is a negligible (~1%) indirect benefit for Affinity Water's WRZ 1, 2, 4 and WRZ 3 & 5 associated with the STT, which is a modelling artefact driven by small differences in the water balance solution between the baseline and STT scenario (see Figure 27 – indirect benefit). More generally, this result is a function of the STT being configured as a virtual transfer in WREW, which means other abstractors cannot directly benefit from the transfer. An indirect benefit could be observed if supply from the STT were to be offset the amount of water abstracted from the River Thames by the London and SWOX WRZs, thereby leaving more water available for abstraction by other WRZs. However, hydrological conditions when the solution is activated, and more importantly when supply shortfalls are measured, prevent this situation from occurring. The solution is only triggered when London Storage drops below the control curve when the Teddington Target Flow transitions from 800 Ml/d to 600/700 Ml/d, which coincides with low flow levels on the River Thames. Furthermore, the supply shortfalls events used to assess performance only occur during more severe drought events when flow levels on the River Thames are extremely low. The high demands in the London and SWOX WRZs mean that these WRZs still abstract what little water is available from the River Thames, even when they receive additional supply from the STT, and therefore no additional water is freed up for abstraction by other WRZs.

Other abstractors on the River Thames (Affinity Water WRZ 6 and South East Water Bracknell WRZ) do not experience any reduction in the relative probability of a supply shortfall. Similarly, none of the WRZs which supply water to STT, or share a supply source with the STT, show any change in the relative probability of a supply shortfall occurring. The Affinity and STT supply WRZs do not experience supply shortfalls in the baseline scenario, limiting the ability to measure relative benefits, as described in Section 5.2.1. However, the solutions involving water transfers are designed so that they do not impact upon the drought resilience of the areas that supply water, and the majority of the supply sources for the transfer solution operate on a 'put and take basis'. The unsupported flow component on the River Severn and releases from Lake Vyrnwy Reservoir are also both subject to hydrological constraints. A link in behaviour is observed between the amount of water that Minworth Effluent Reuse can supply to STT and the extent to which Minworth is required for supporting flow on the River Trent, via discharge into the River Tame, a tributary of the River Trent. At times when flow levels on the River Trent are low and/or the minimum flow requirements are breached, the support Minworth provides to STT drops to 0 Ml/d. Although this behaviour is only observed during a handful of drought events in the near future weather@home2 climate ensemble, it does have implications for how hydrological controls can limit STT yield.

5.3.1.2 SESRO

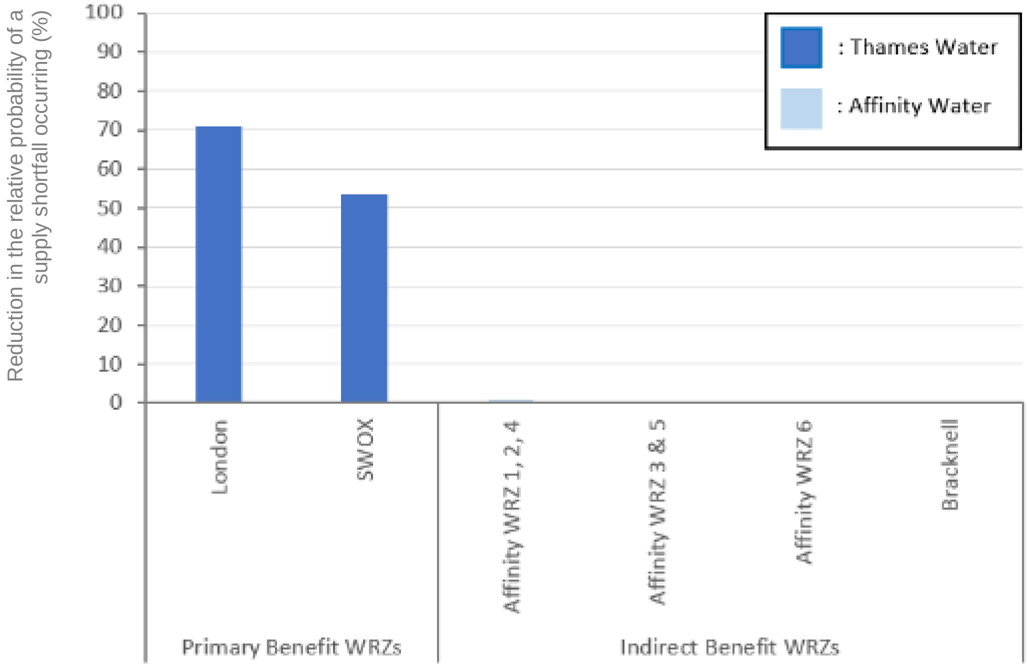


Figure 34 Reduction in the relative probability of a supply shortfall occurring under Scenario 2: SESRO

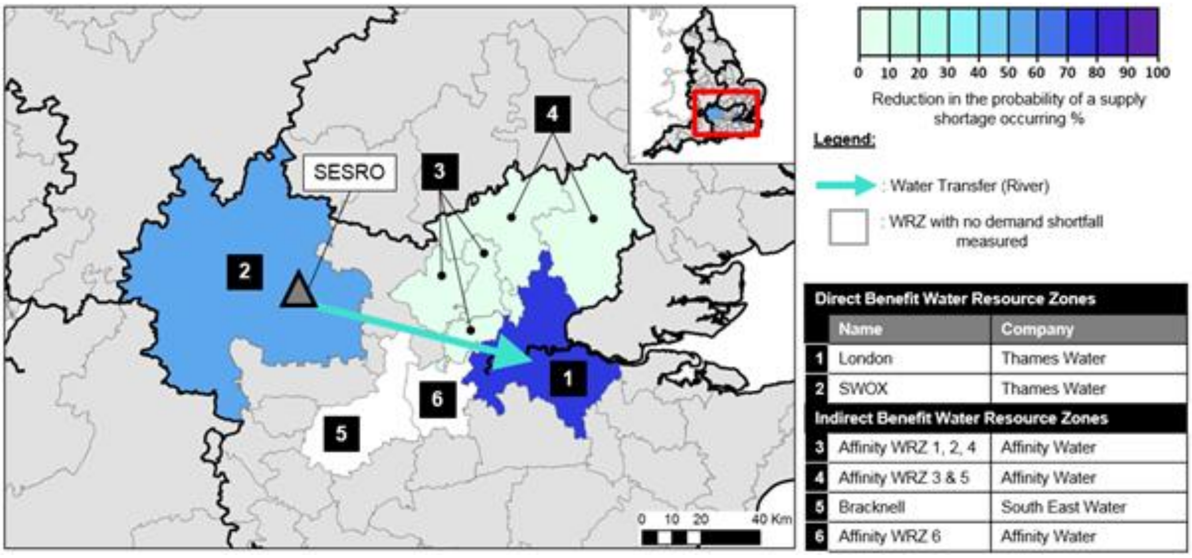


Figure 35 Spatial reduction in the relative probability of a supply shortfall occurring under Scenario 2: SESRO

Of the two Thames Water WRZs that SESRO primarily supplies, London and SWOX, the former receives the greatest resilience benefit with ~70% reduction in the relative probability of a supply shortfall (Figure 34 and Figure 35). The comparatively smaller benefit of a 50% reduction relative probability of a supply shortfall for the SWOX WRZ can be explained by the 20 Ml/d limit on capacity of the connection between SESRO and the WRZ. For example, the 20 Ml/d that SESRO can supply to the SWOX WRZ provides a 50% reduction in the relative probability of a supply shortfall, indicating that the majority of the supply shortfall events experienced by the WRZ are <=20 Ml/d. Similarly, the 321 Ml/d that SESRO can supply to the London WRZ provides a 70% reduction in the relative probability of a supply shortfall, which is to be expected since the WRZ experiences supply shortfalls of up to ~700 Ml/d.

Comparison with results for STT, demonstrates that while supplying an overall lower yield, SESRO generates a larger benefit for the London WRZ (compare Figure 32 and Figure 34), whereas STT provided the larger benefit to SWOX WRZ. These differences are observed to be the result of the extra resilience afforded by reservoir storage, which allows for the maximum supply yield to be maintained over a drought event. Additionally, although the STT can theoretically supply more water than SESRO, a significant proportion of the water transferred is from unsupported flow on the River Severn which is subject to hydrological constraints and therefore unlikely to be available during severe and widespread drought events. Similarly, Similarly, if drought conditions in the Thames Catchment coincide with those in the Trent Catchment, when flow levels on the River Trent are very low and/or the minimum required flow level is breached, the support that Minworth Effluent Reuse provides to STT is reduced, as is transfer yield. A reduction in transfer yield at these times will act to reduce the drought resilience benefit of the STT.

A negligible (~1%) indirect benefit associated with SESRO is observed for Affinity Water's WRZ 1, 2, 4, which abstracts water from the River Thames, and WRZ 3 & 5. The small value observed is a modelling artefact driven by slight differences in the water balance solution between the baseline and SESRO scenario. Overall, this result is a function of SESRO being configured as a virtual transfer in WREW, which means other abstractors cannot directly benefit from water released from the reservoir. An indirect benefit could be observed if supply from SESRO were to offset the amount of water abstracted from the River Thames by the London and SWOX WRZs, thereby leaving more water available for abstraction by other WRZs. However, hydrological conditions when SESRO is activated, and more importantly when supply shortfalls are measured, prevent this situation from occurring. The solution is only triggered when London Storage drops below the control curve when the Teddington Target Flow transitions from 800 Ml/d to 600/700 Ml/d, which coincides with low flow levels on the River Thames. Furthermore, the supply shortfall events used to assess performance only occur during the more severe drought events when flow levels on the River Thames are extremely low. The high demands in the London and SWOX WRZs mean that these WRZs still abstract what little water is available from the River Thames, even when they receive additional supply from SESRO, and therefore no additional water is freed up for abstraction by other WRZs.

Other abstractors on the River Thames (Affinity Water WRZ 6 and South East Water Bracknell WRZ) do not experience any reduction in the relative probability of a supply shortfall. However, the WRZs do not experience supply shortfalls in the baseline scenario, limiting the ability to measure relative benefits, as described in Section 5.2.1. The propriety of this observation will be explored further in Phase 2 of this project.

5.3.1.3 London Effluent Reuse (LER)

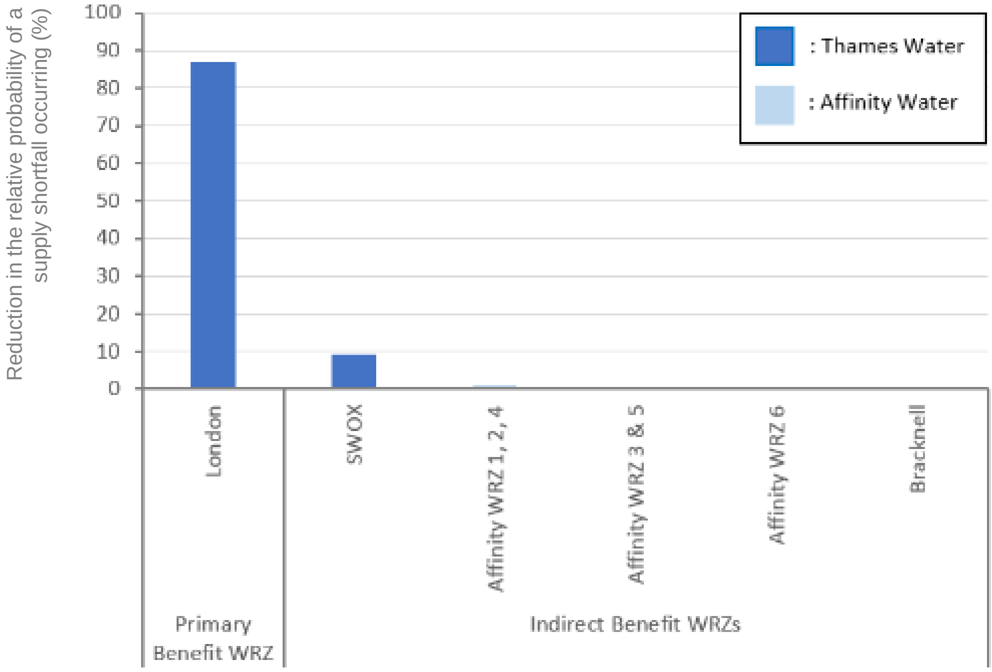


Figure 36 Reduction in the relative probability of a supply shortfall occurring under Scenario 3: LER

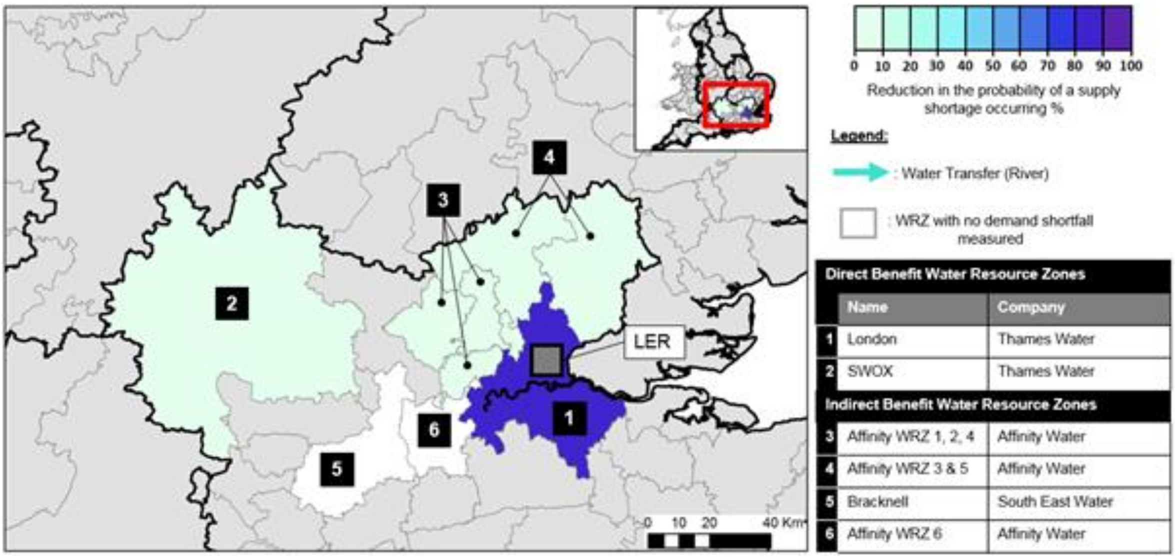


Figure 37 Spatial reduction in the relative probability of a supply shortfall occurring under Scenario 3: LER

The LER solution directly supplies water to Thames Water's London WRZ only, generating an 86% reduction in the relative probability of a supply shortfall (Figure 36 and Figure 37). This benefit is achieved by the solution providing a maximum yield of 300 Ml/d, with supply shortfalls for the London WRZ reaching up to ~700 Ml/d. The yield of LER is not subject to hydrological constraints, such as river flow availability, instead, all the water is available and transferred directly into London Storage.

A ~9% reduction in the relative probability of a supply shortfall is observed for Thames Water's SWOX WRZ. While this indirect benefit is relatively small compared with the London WRZ, it is much larger than the ~1% indirect benefit received by Affinity Water WRZ 1, 2, 4 from LER. The extra benefit is observed to be a result of the demand saving measures linked to the different levels of water use restrictions that are triggered by reservoir storage levels in the London WRZ, but are also applied to the SWOX WRZ. As LER supplies water to the London WRZ, it will act to slow progression through the levels of water use restriction and consequently increase the duration over which demand savings are in place for both London and SWOX WRZs.

Similar to the STT and SESRO scenarios, a very negligible (~1%) indirect benefit is observed for Affinity Water's WRZ 1, 2, 4, which abstracts water from the River Thames. The small value observed is a modelling artefact driven by slight differences in the water balance solution between the baseline and SESRO scenario. Overall, this result is a function of LER supplying water directly to London Storage, which means other WRZs do not have access to the water. An indirect benefit could be observed if supply from LER were to offset the amount of water abstracted from the River Thames by the London WRZ, thereby leaving more water available for abstraction by other WRZs. However, hydrological conditions when LER is activated, and more importantly when supply shortfalls are measured, prevent this situation from occurring. The solution is only triggered when London Storage drops below the control curve when the Teddington Target Flow transitions from 800 Ml/d to 600/700 Ml/d, which coincides with low flow levels on the River Thames. Furthermore, the supply shortfalls events used to assess performance only occur during the more severe drought events when flow levels on the River Thames are extremely low. The high demands in the London WRZ mean that the WRZ still abstracts what little water is available from the River Thames, even when additional supply is received from LER, and therefore no additional water is made available for abstraction by other WRZs.

Other abstractors on the River Thames (Affinity Water WRZ 6 and South East Water Bracknell WRZ) do not experience any reduction in the relative probability of a supply shortfall. However, the WRZs do not experience supply shortfalls in the baseline scenario, limiting the ability to measure relative benefits, as described in Section 5.2.1. The propriety of this observation will be explored further in Phase 2 of this project.

5.3.1.4 Thames to Affinity Transfer (T2AT) (SESRO Source)

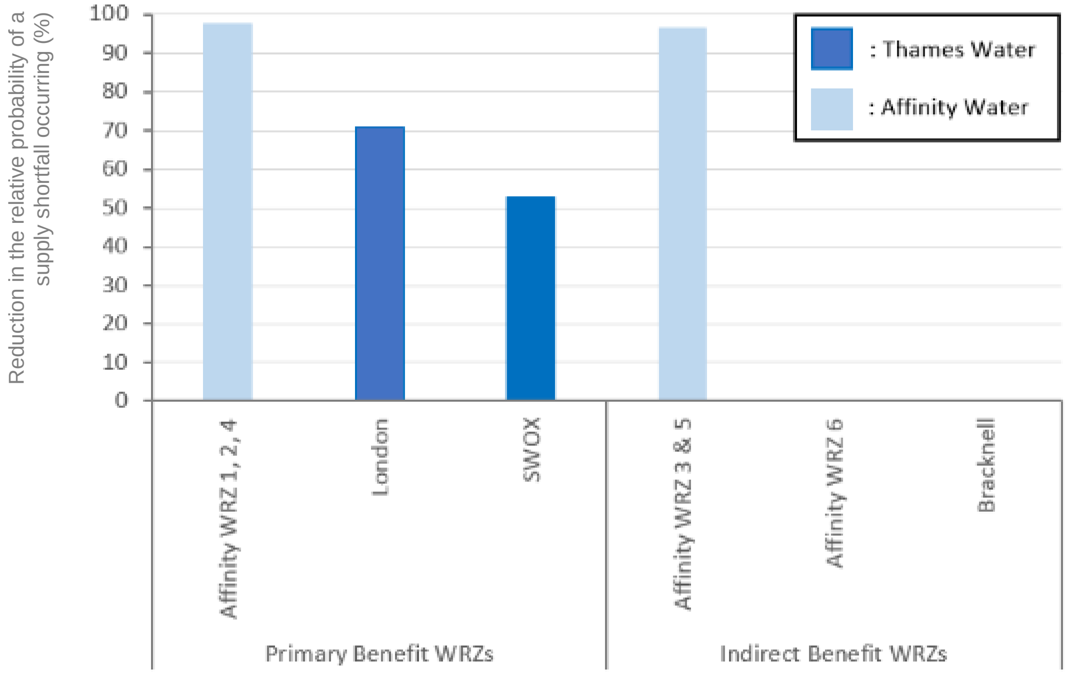


Figure 38 Reduction in the relative probability of a supply shortfall under Scenario 4: T2AT (SESRO Source)

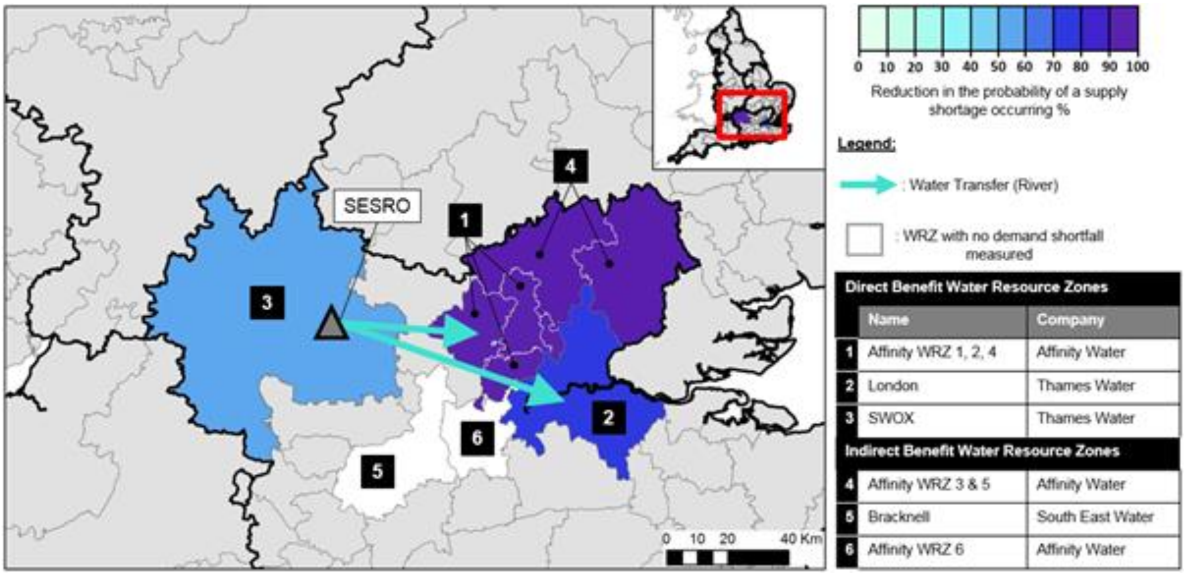


Figure 39 Spatial reduction in the relative probability of a supply shortfall occurring under Scenario 4: T2AT (SESRO Source)

The T2AT supplied by SESRO almost entirely removes the relative probability of a supply shortfall in comparison to the baseline scenario for both Affinity Water's WRZ 1, 2, 4 and WRZ 3 & 5 (see Figure 38 and Figure 39). Although the solution primarily supplies water to Affinity WRZ 1, 2, 4 a transfer exists between this demand centre and Affinity WRZ 3 & 5, which allows the drought resilience benefit to be shared between the two demand centres.

Since the supply source for the transfer is SESRO, water is also supplied to the Thames Water London and SWOX WRZs as part of the standard configuration of SESRO under the T2AT scenario. The reduction in relative probability of a supply shortfall for London and SWOX WRZs is the same for the T2AT supplied by SESRO, as it is for the standalone configuration of SESRO (compare Figure 34 and Figure 38). This is due to the transfer being configured so that it can supply water to Affinity WRZ 1, 2, 4 at any time and is used by the model as a last priority supply source, when demand levels are great enough. In contrast to this demand-led behaviour, supply from SESRO to SWOX and London WRZs is only activated when London Storage drops below the control curve when the Teddington Target Flow transitions from 800 Ml/d to 600/700 Ml/d. Allowing operation of the transfer in this way means that water can be supplied to Affinity WRZ 1, 2, 4 independent of resource position in the London WRZ. Furthermore, the London and SWOX WRZs are linked to reservoir storage, which acts to offset the timing of supply shortfalls relative to Affinity WRZ, 1, 2, 4 and therefore reduces the likelihood of the T2AT supplying Affinity Water at the same time as Thames Water. These two factors act to maintain the drought resilience benefits observed for the primary demand centres of the supporting solution.

Other abstractors on the River Thames (Affinity Water WRZ 6 and South East Water Bracknell WRZ) do not experience any reduction in the relative probability of a supply shortfall. However, the WRZs do not experience supply shortfalls in the baseline scenario, limiting the ability to measure relative benefits, as described in Section 5.2.1. The propriety of this observation will be explored further in Phase 2 of this project.

5.3.1.5 Thames to Affinity Transfer (T2AT) (STT Source)

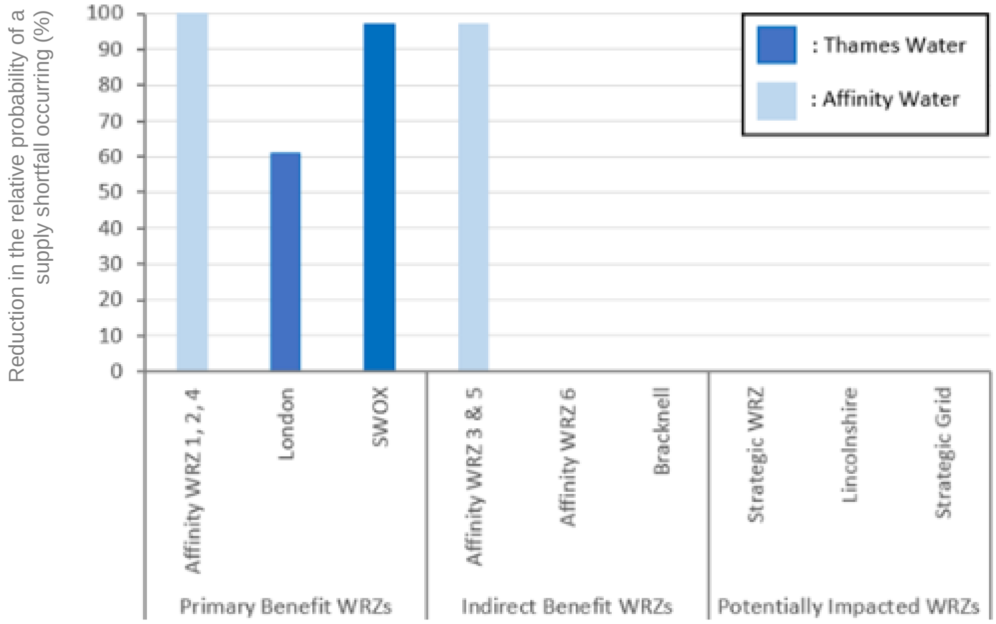


Figure 40 Reduction in the relative probability of a supply shortfall under Scenario 5: Thames to Affinity Transfer (STT Source)

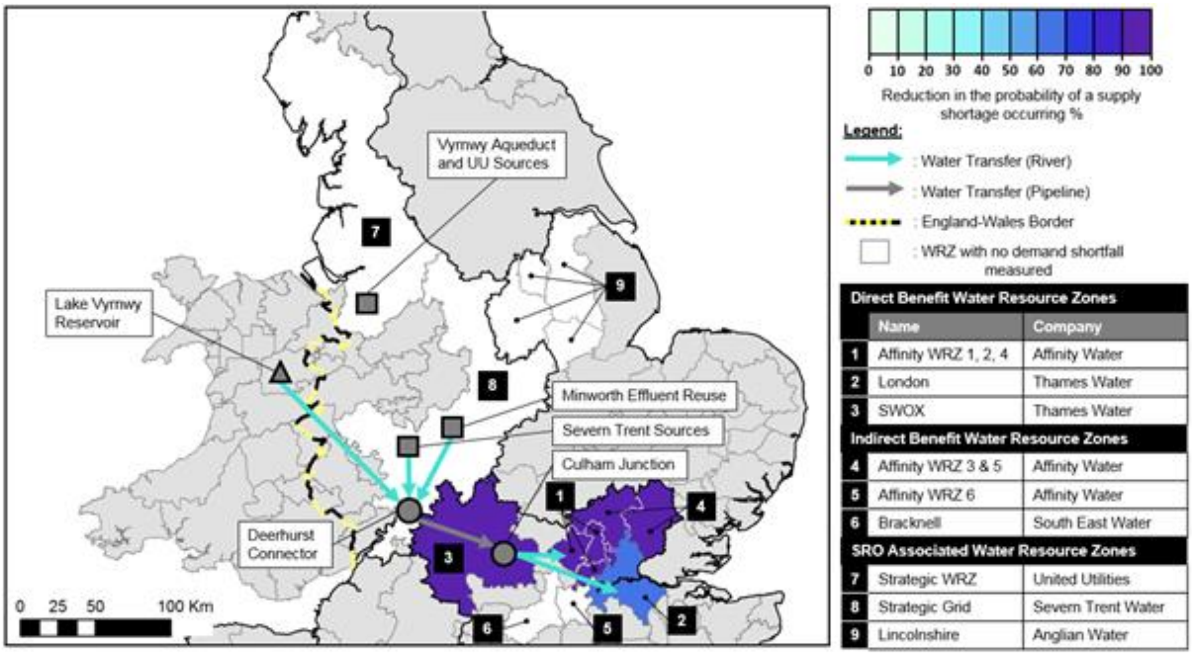


Figure 41 Spatial reduction in the relative probability of a supply shortfall under Scenario 5: Thames to Affinity Transfer (STT Source)

The T2AT supplied by STT completely removes the relative probability of a supply shortfall occurring in comparison to the baseline scenario for Affinity Water's WRZ 1, 2, 4 and reduces the probability by 97% for Affinity WRZ 3 & 5 (see Figure 40 and Figure 41). Although the solution primarily supplies water to Affinity WRZ 1, 2, 4 a transfer exists between this demand centre and Affinity WRZ 3 & 5, which allows water, and the resulting drought resilience benefit, to be shared between the two demand centres.

Since the supply source for the transfer is STT, water is also supplied to the Thames Water London and SWOX WRZs as part of the standard configuration of STT under the T2AT scenario. The reduction in the relative probability of a supply shortfall for the Thames Water SWOX and London WRZs under the T2AT (STT supply) is the same as for the standard configuration of the STT scenario (compare Figure 32 and Figure 40). this is due to T2AT being configured so that it can supply water to Affinity WRZ 1, 2, 4 at any time and is used by the model as a last priority supply source, when demand levels are great enough. In contrast to this demand-led behaviour, supply from STT to SWOX and London WRZs is only activated when London Storage drops below the control curve when the Teddington Target Flow transitions from 800 Ml/d to 600/700 Ml/d. Allowing operation of the T2AT in this way means that water can be supplied to Affinity WRZ 1, 2, 4 independent of resource position in the London WRZ. Furthermore, the London and SWOX WRZs are linked to reservoir storage, which acts to offset the timing of supply shortfalls relative to Affinity WRZ, 1, 2, 4 and therefore reduces the likelihood of T2AT supplying Affinity Water at the same time as Thames Water. These two factors act to maintain the drought resilience benefits observed for the primary demand centres of the supporting solution.

Other abstractors on the River Thames (Affinity Water WRZ 6 and South East Water Bracknell WRZ) do not experience any reduction in the relative probability of a supply shortfall. Similarly, none of the WRZs which supply water to STT, or share a supply source with the STT, show any change in the relative probability of a supply shortfall occurring. However, the Affinity and STT supply WRZs do not experience supply shortfalls in the baseline scenario, limiting the ability to measure relative benefits, as described in Section 5.2.1. However, change in probability of a shortfall in supplying WRZs is considered unlikely since the majority of the supply sources for the transfer solution operate on a ‘put and take basis’ and the STT unsupported flow component is subject to hydrological constraints.

5.3.1.6 Thames to Affinity Transfer (T2AT) (LER Source)

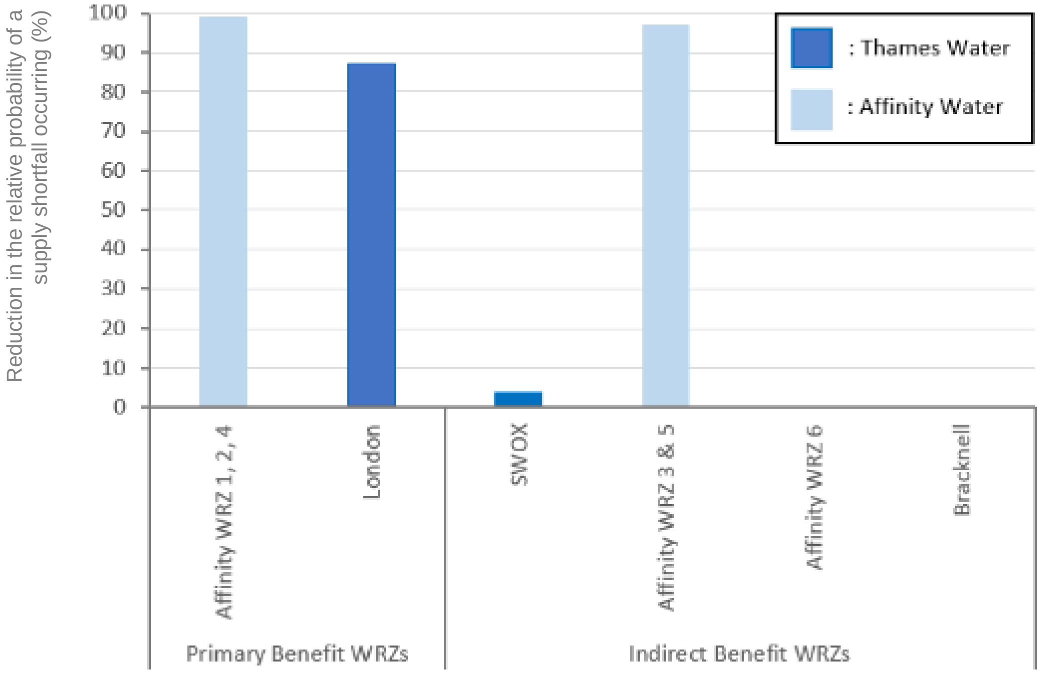


Figure 42 Reduction in the relative probability of a supply shortfall under Scenario 6: Thames to Affinity Transfer (LER source)

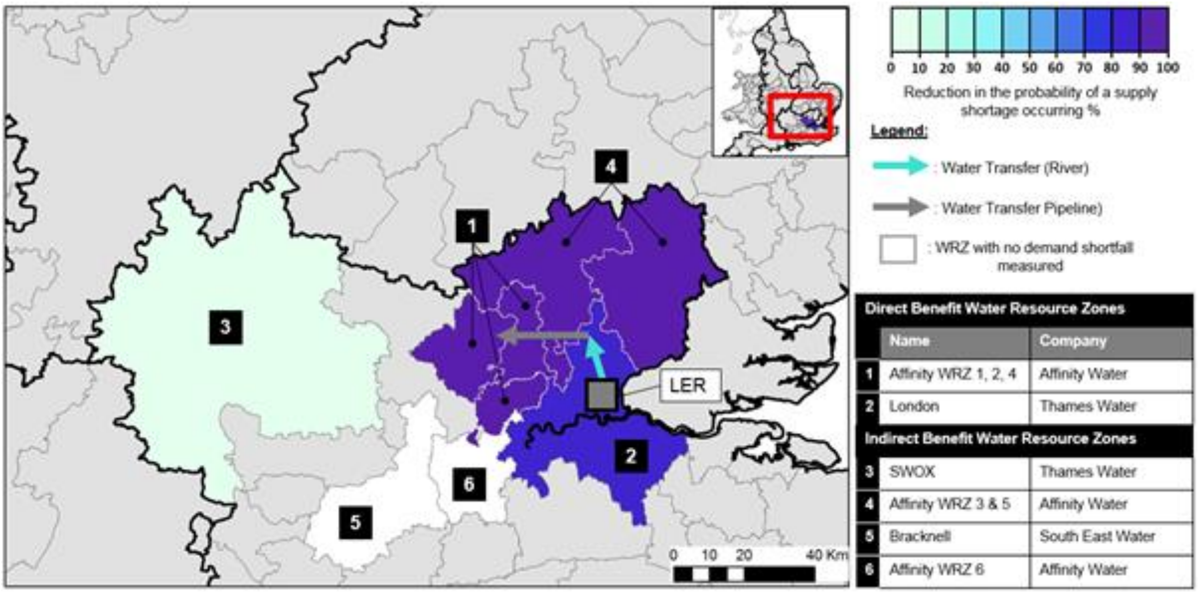


Figure 43 Spatial reduction in the relative probability of a supply shortfall under Scenario 6: Thames to Affinity Transfer (LER Source)

The T2AT when configured with supply from LER almost completely removes the relative probability of a supply shortfall in comparison to the baseline scenario for both Affinity Water's WRZ 1, 2, 4 and WRZ 3 & 5 (see Figure 42 and Figure 43). Although the solution primarily supplies water to Affinity WRZ 1, 2, 4 a transfer exists between this demand centre and Affinity WRZ 3 & 5, which allows the drought resilience benefit to be shared between the two demand centres.

Since the supply source is the LER solution, water is also supplied to the Thames Water London WRZ as part of the standard configuration of LER under the T2AT scenario. The reduction in the relative probability of a supply shortfall for London WRZ is the same for the T2AT supplied by LER, as it is for the standalone configuration of LER (compare Figure 36and Figure 42). This is due to the transfer being configured so that it can supply water to Affinity WRZ 1, 2, 4 at any time and is used by the model as a last priority supply source, when demand levels are great enough. In contrast to this demand-led behaviour, supply from LER to London WRZ is only activated when London Storage drops below the control curve when the Teddington Target Flow transitions from 800 Ml/d to 600/700 Ml/d. Allowing operation of the transfer in this way means that water can be supplied to Affinity WRZ 1, 2, 4 independent of resource position in the London WRZ. Furthermore, the London WRZ is linked to reservoir storage, which acts to offset the timing of supply shortfalls relative to Affinity WRZ, 1, 2, 4 and therefore reduces the likelihood of T2AT supplying Affinity Water at the same time as Thames Water. These two factors act to maintain the drought resilience benefits observed for the primary demand centre of the supporting solution.

A ~3% reduction in the relative probability of a supply shortfall occurring is observed for Thames Water's SWOX WRZ. While this indirect benefit is relatively small compared with the London WRZ, the SWOX WRZ is not supplied directly by the transfer solution. The extra benefit is observed to be a result of the demand saving measures linked to the different levels of water use restrictions that are triggered by reservoir storage levels in the London WRZ but are also applied to the SWOX WRZ. As LER supplies water to the London WRZ, it will act to slow progression through the levels of water use restriction and consequently increase the duration over which demand savings are in place for both London and SWOX WRZs. The 3% reduction in probability observed for SWOX WRZ under the T2AT supplied by LER scenario is lower than the 9% reduction observed under the standalone LER scenario. Although the difference is small it is caused by slight changes in the water balance and combined use with Affinity WRZ 1, 2, and 4.

Other abstractors on the River Thames (Affinity Water WRZ 6 and South East Water Bracknell WRZ) do not experience any reduction in the relative probability of a supply shortfall. However, the WRZs do not experience supply shortfalls in the baseline scenario, limiting the ability to measure relative benefits, as described in Section 5.2.1. The propriety of this observation will be explored further in Phase 2 of this project.

5.3.1.7 Anglian to Affinity Transfer (A2AT)

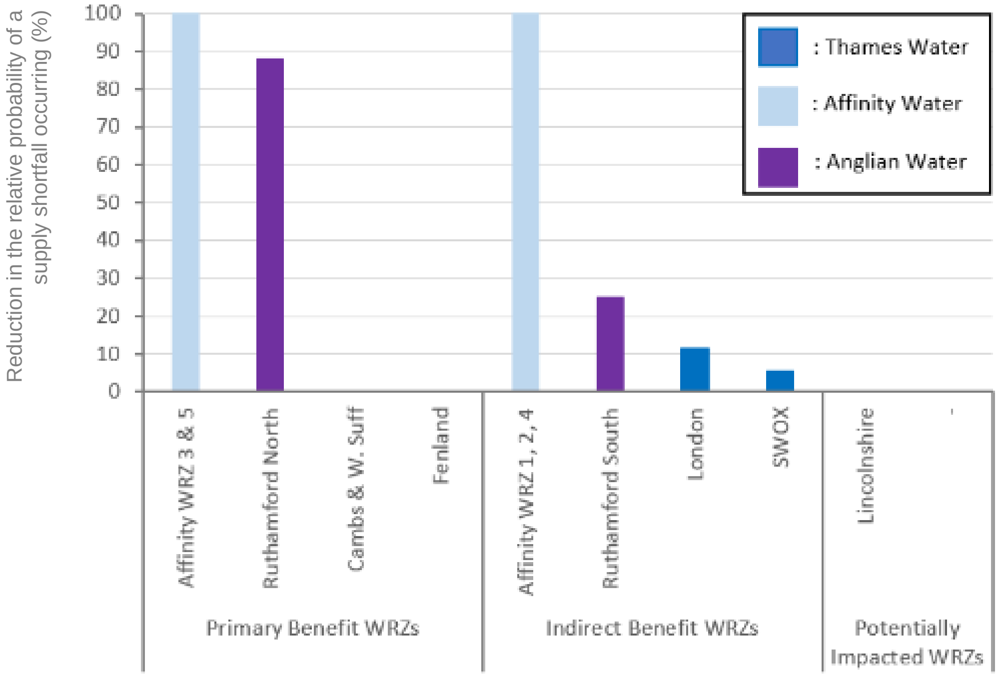


Figure 44 Reduction in the relative probability of a supply shortfall occurring under Scenario 7: A2AT

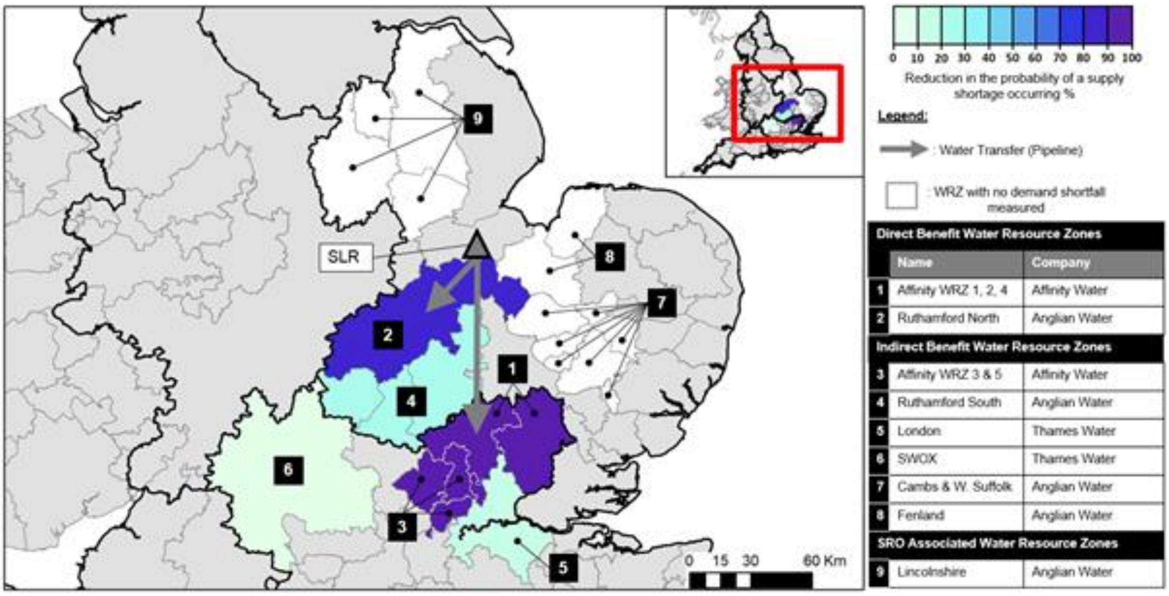


Figure 45 Spatial reduction in the relative probability of a supply shortfall under Scenario 7: A2AT

The A2AT completely removes the relative probability of a supply shortfall in comparison to the baseline scenario or both Affinity Water's WRZ 1, 2, 4 and WRZ 3 & 5 (see

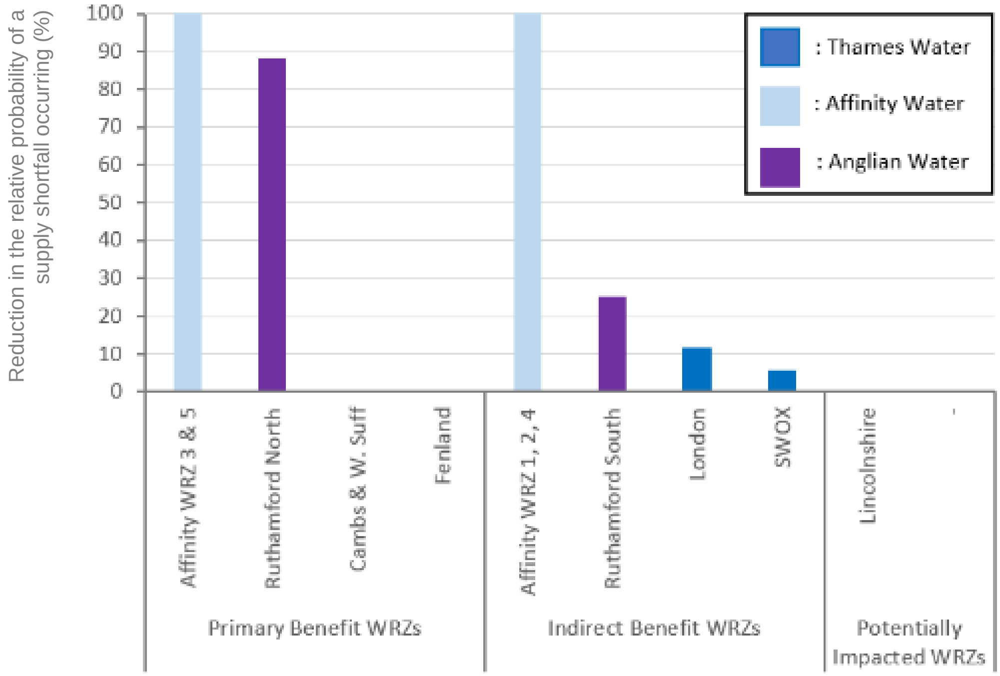


Figure **44** and Figure 45

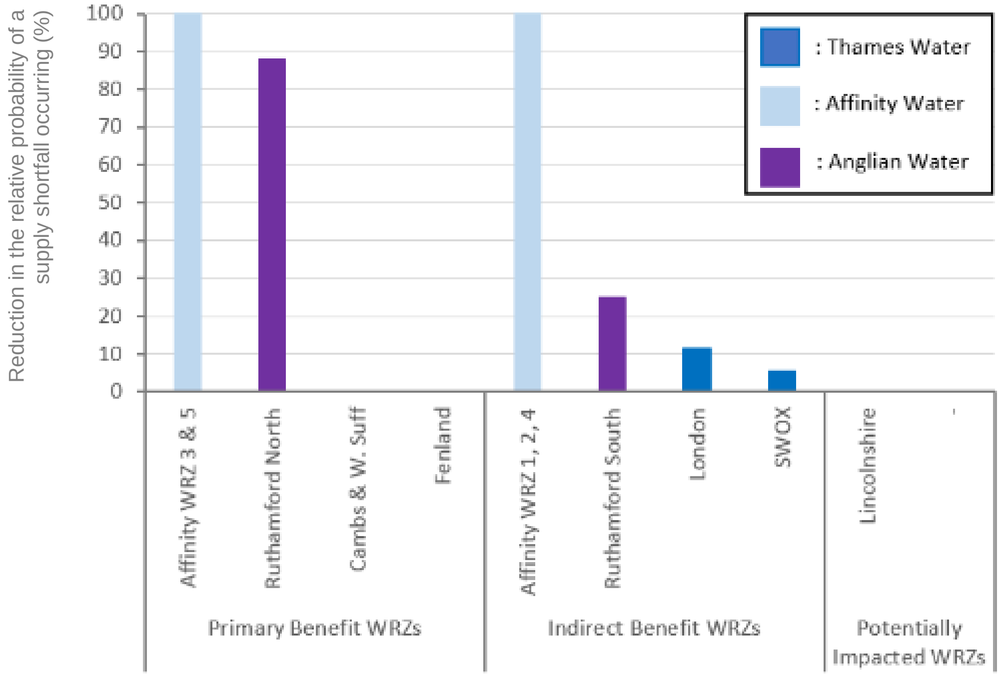


Figure 44). Although the solution primarily supplies up to 100 Ml/d water to Affinity WRZ 3 & 5, a transfer exists between this demand centre and Affinity WRZ 1 ,2, 4, which allows the water and associated drought resilience benefit, to be shared between the two demand centres. The A2AT also supplies up to 50 Ml/d to Anglian Water's Ruthamford North WRZ, reducing the relative probability of a supply shortfall by 88%. In a similar way to the Affinity WRZs, Ruthamford North and Ruthamford South (Ruthamford South, for the purposes of simplification in WREW, amalgamated with Central and West WRZs) are connected by a transfer, which allows water from SLR to be shared between the two demand centres. The capacity of the transfer (50 Ml/d) and comparatively higher demands associated with Ruthamford North explain why a greater benefit is observed here.

Both Thames Water SWOX and London WRZs receive a reduction in relative probability of a supply shortfall under the A2AT scenario, although neither WRZ is supplied by the solution. The indirect benefit observed is a result of the model using the A2AT to supply more water that is required to satisfy the relatively small supply shortfall events experienced by Affinity WRZ 3 & 5 and WRZ 1, 2, 4, reducing the amount of water abstracted from the River Thames by Affinity WRZ 1, 2, 4 and consequently making more water available for the London and SWOX WRZs. There is also an element of the observed indirect benefit that can be explained by the A2AT reducing the utilisation of the import from London Storage to

Affinity WRZ 1, 2, 4. Stopping or reducing this transfer frees up the water for maintaining reservoir storage levels in London, slowing the progression through level of service triggers and extending the duration of associated demand savings during drought events. The level of water use restrictions and demand savings applied to the SWOX WRZ are determined by the resource position of the London WRZ. This linked behaviour may explain why a benefit is observed for both London and SWOX WRZs.

As part of the A2AT, up to 100 Ml/d water can be supplied to two Anglian Water aggregated demand centres; the Cambs & W. Suffolk demand centre, which includes the Bury Haverhill, Cheveley, Ely, Ixworth, Newmarket, Sudbury and Thetford WRZs, and the Fenland demand centre, which includes the North Fenland and South Fenland WRZs. This transfer represents part of the Anglian Grid system and can occur when if and when Affinity WRZ 1, 2, 4 can satisfy demand with available local supply. However, neither of these demand centres experiences a supply shortfall in the simulation, limiting the ability to measure relative benefit, as described in Section 5.2.1. The same is true for the Anglian Water Lincolnshire aggregated demand centre (Central Lincolnshire, South Lincolnshire and Nottinghamshire WRZs), which abstracts water from the same sources as the SLR (River Trent and River Witham) and therefore could be affected by the A2AT. These WRZs with a 0% probability of a supply shortfall occurring do not represent a non-benefit or dis-benefit associated with the A2AT, but rather an area of the model that is not sensitive to drought events.

5.3.1.8 Grand Union Canal

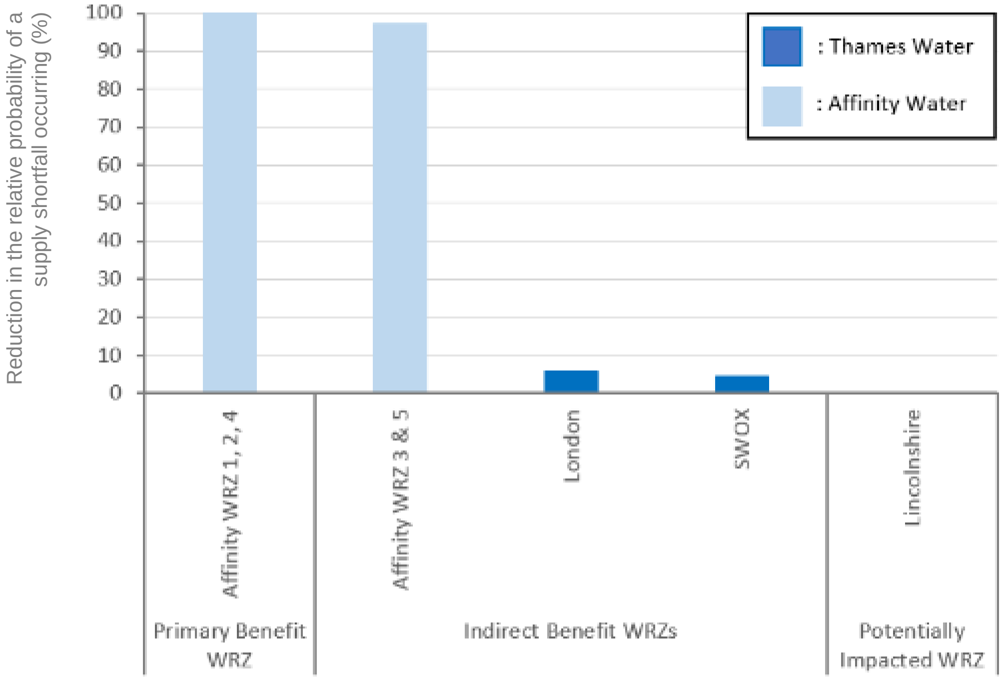


Figure 46 Reduction in the relative probability of a supply shortfall occurring under Scenario 8: GUC

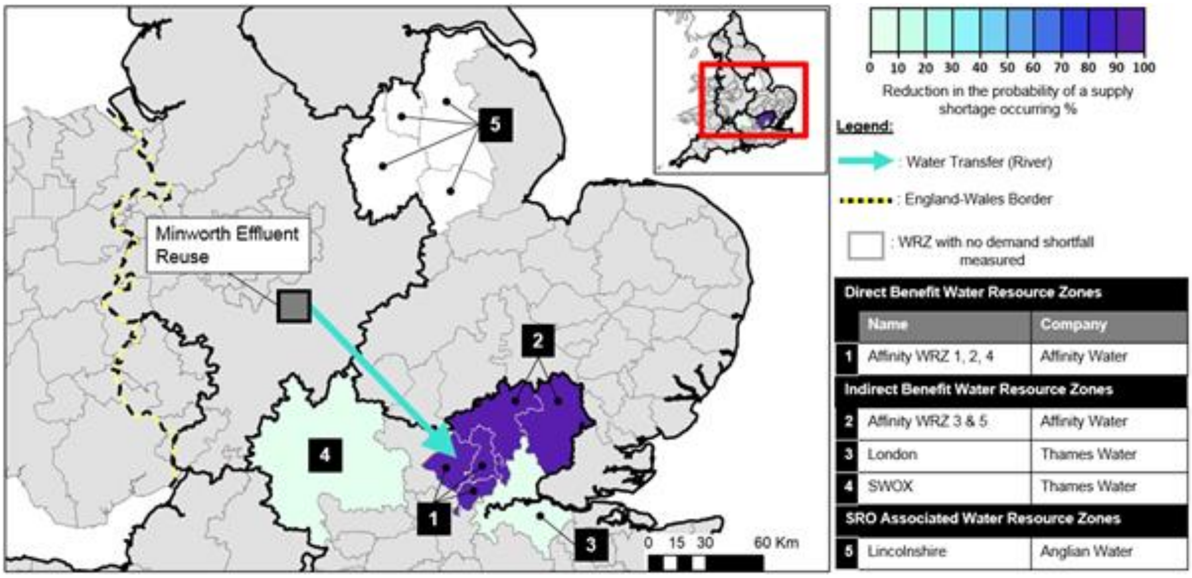


Figure 47 Spatial reduction in the relative probability of a supply shortfall under Scenario 8: GUC

The GUC solution removes all probability of a supply shortfall year occurring for Affinity Water in comparison to the baseline in WRZ 1, 2, 4 and almost all chance for Affinity WRZ 3 & 5 (see Figure 46 and Figure 47). Although the solution primarily supplies up to 100 Ml/d water to Affinity WRZ 1, 2, 4 a transfer exists between this demand centre and Affinity WRZ 3 & 5, which allows the water and associated drought resilience benefit, to be shared between the two demand centres.

Both Thames Water SWOX and London WRZs receive a small reduction (~5%) in the relative probability of a supply shortfall under the GUC solution, although neither WRZ is supplied by the solution. The indirect benefit observed is a result of the model using the A2AT to supply more water that is required to satisfy the relatively small supply shortfalls experienced by Affinity WRZ 3 & 5 and WRZ 1, 2, 4. This reduces the amount of water abstracted from the River Thames by Affinity WRZ 1, 2, 4 and consequently makes more water available for the London and SWOX WRZs. There is also an element of the observed indirect benefit that can be explained by the GUC solution reducing the frequency at which the import from London Storage to Affinity WRZ 1, 2, 4 is utilised by the model. Stopping or reducing this transfer frees up the water for maintaining reservoir storage levels in London, slowing the progression through level of service triggers and extending the duration of associated demand savings during drought events. The level of water use restrictions and demand savings applied to the SWOX WRZ are determined by the resource position of the London WRZ. This linked behaviour may explain why a benefit is observed for both London and SWOX WRZs.

The GUC is supplied by Minworth Effluent Reuse, which supports flow on the River Tame and in turn the River Trent. It is possible that by Minworth supplying water to the GUC, less water would be available for abstraction on the River Trent, which could affect supply to the Anglian Water Lincolnshire aggregated demand node (Central Lincolnshire, South Lincolnshire and Nottinghamshire WRZs). However, this demand centre did not experience supply shortfalls in the baseline scenario limiting the ability to measure relative benefit, as described in Section 5.2.1.

5.3.1.9 Thames to Southern Transfer (T2ST) (SESRO Source)

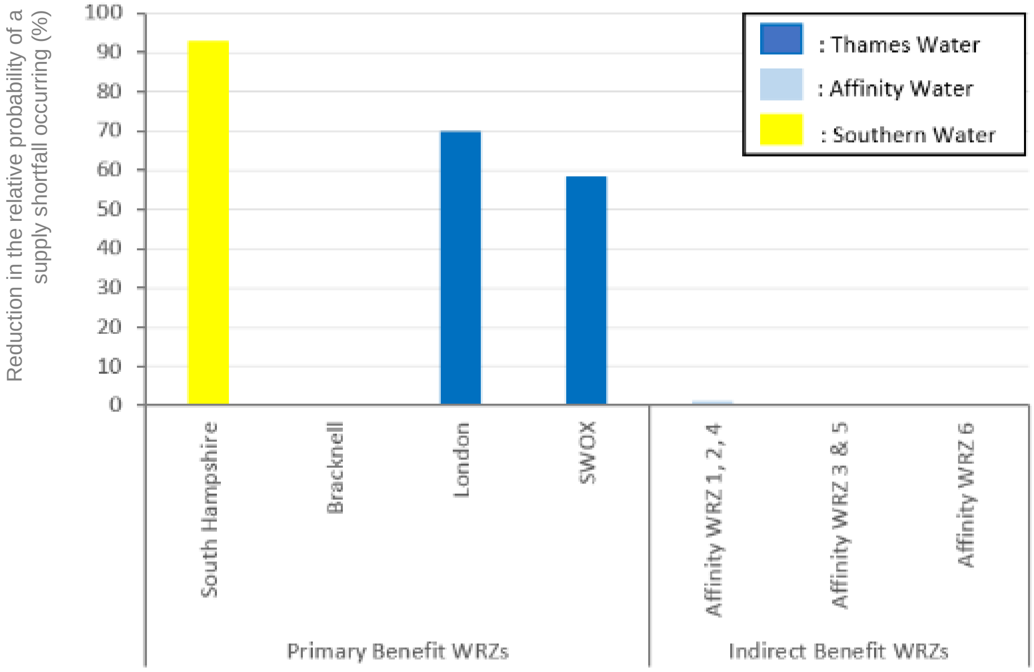


Figure 48 Reduction in the relative probability of a supply shortfall under Scenario 9: T2ST (SESRO Source)

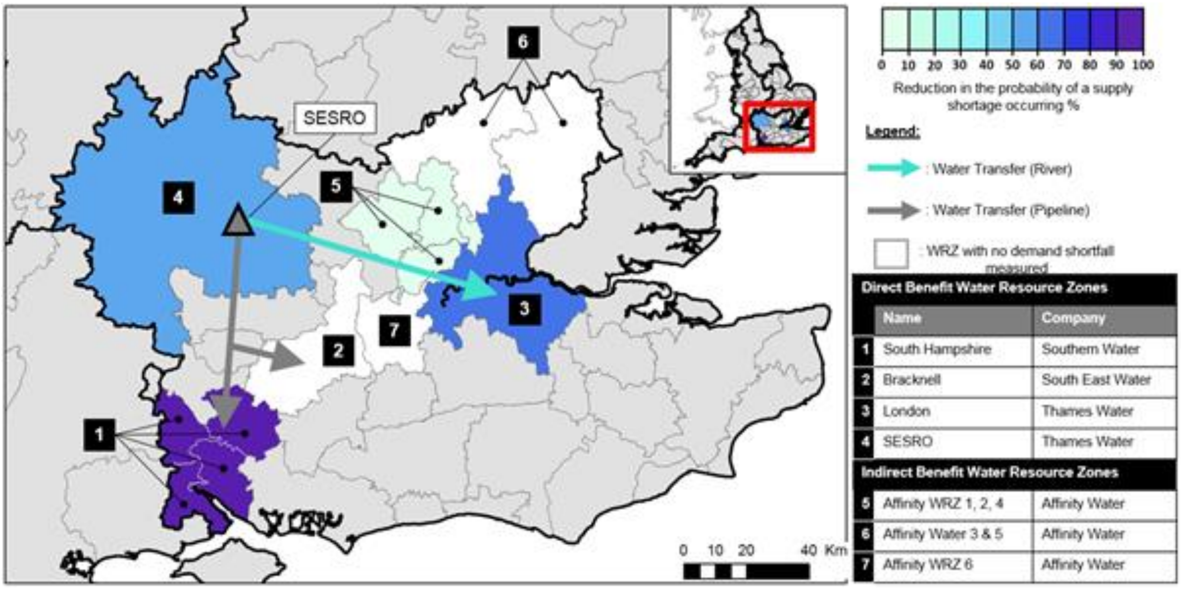


Figure 49 Spatial reduction in the relative probability of a supply shortfall under Scenario 9: T2ST (SESRO Source)

The T2ST supplied by SESRO almost completely removes (92%) the relative probability of a supply shortfall in comparison to the baseline for the Southern Water South Hampshire aggregated demand node (Hampshire Southampton West, Hampshire Southampton East, Hampshire Rural and Hampshire

Winchester WRZs), see

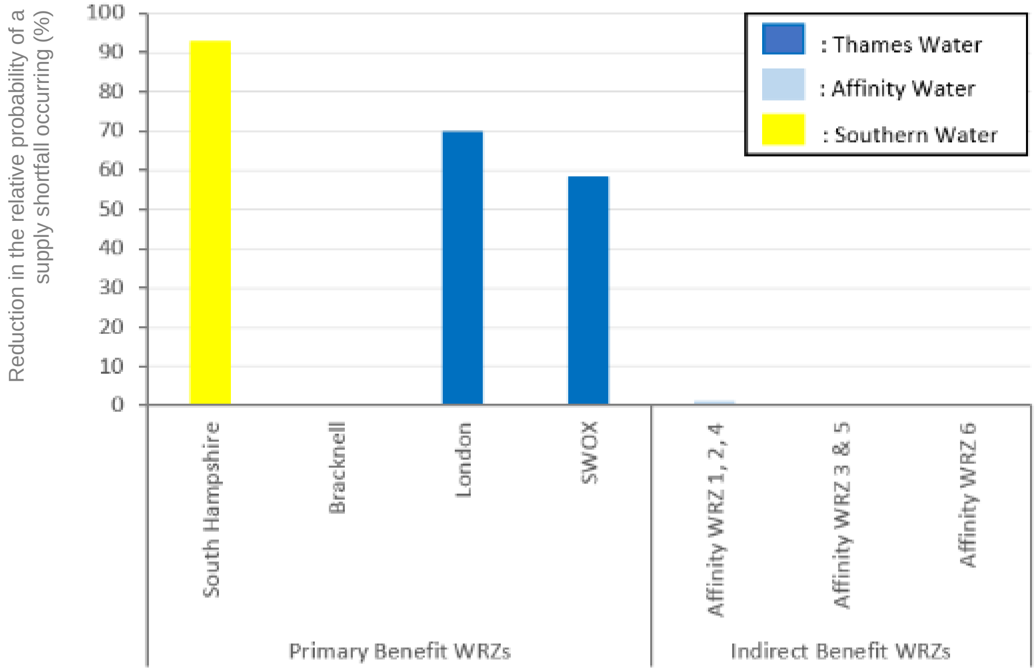


Figure **48** and Figure 49. Since the supply source for the transfer is SESRO, water is also supplied to the Thames Water London and SWOX WRZs as part of the standard configuration of SESRO under the T2STscenario. The reduction in the relative probability of a supply shortfall for London and SWOX WRZs is the same for the T2STsupplied by SESRO, as it is for the standalone configuration of SESRO (compare Figure 34 and

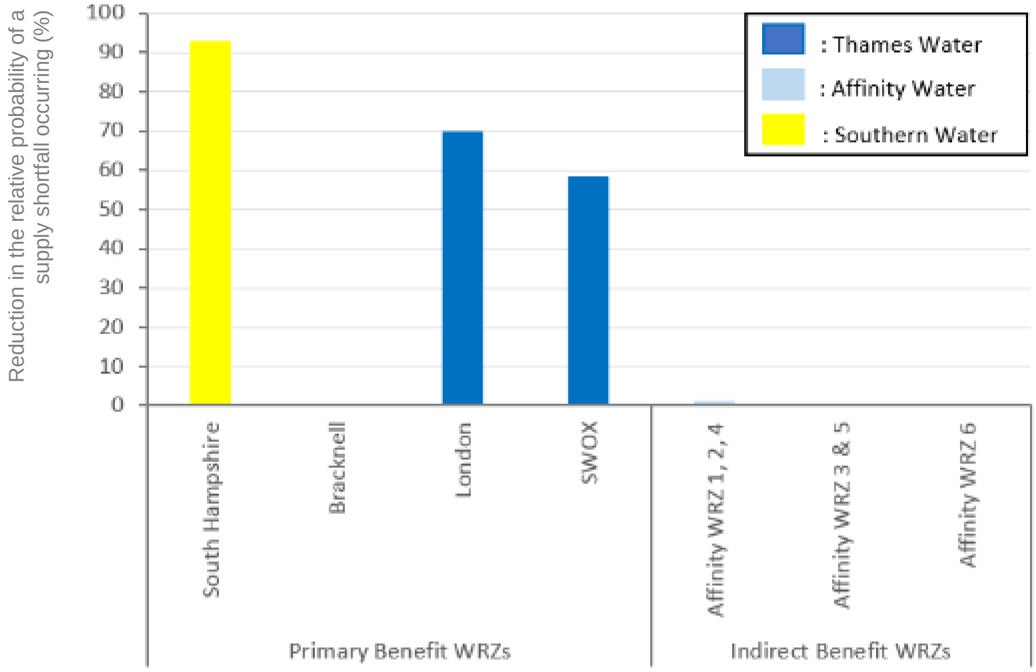


Figure **48**). This is due to the T2ST being configured so that it can supply water to South Hampshire at any time and is used by the model as a last priority supply source when demand levels are great enough. In contrast to this demand-led behaviour, supply from SESRO to SWOX and London WRZs is only activated when London Storage drops below the control curve when the Teddington Target Flow transitions from 800 Ml/d to 600/700 Ml/d. Allowing operation of the transfer in this way means that water can be supplied to Southern Water independent of resource position in the London WRZ. Furthermore, the London and SWOX WRZs are linked to reservoir storage, which acts to offset the timing of supply shortfalls relative to South Hampshire and therefore reduces the likelihood of T2ST supplying Southern Water at the same time as Thames Water. These two factors act to maintain the drought resilience benefits observed for the primary demand centres of the supporting solution.

A negligible (~1%) indirect benefit associated with SESRO is observed for Affinity Water's WRZ 1, 2, 4, which abstracts water from the River Thames. This result is a function of SESRO being configured as a virtual transfer in WREW, which means other abstractors cannot directly benefit from water released from the reservoir. An indirect benefit could be observed if supply from SESRO were to offset the amount of water abstracted from the River Thames by the London and SWOX WRZs, thereby leaving more water available for abstraction by other WRZs. However, hydrological conditions when SESRO is activated, and more importantly when supply shortfalls are measured, prevent this situation from occurring. The solution is only triggered when London Storage drops below the control curve when the Teddington Target Flow transitions from 800 Ml/d to 600/700 Ml/d, which coincides with low flow levels on the River Thames. Furthermore, the supply shortfalls events used to assess performance only occur during the more severe drought events when flow levels on the River Thames are extremely low. The high demands in the London and SWOX WRZs mean that these WRZs still abstract what little water is available from the River Thames, even when they receive additional supply from SESRO, and therefore no additional water is freed up for abstraction by other WRZs. The small benefit observed for Affinity WRZ 1, 2, 4 can be discounted as a minor difference in total water balance between the baseline and T2ST (SESRO) scenarios (i.e., this is an immaterial result and within the model tolerance).

As observed for other solution scenarios involving the River Thames system, other abstractors on the river (Affinity Water WRZ 6) do not experience any reduction in the relative probability of a supply shortfall. Similarly, the T2ST (SESRO source) supplies up to 20 Ml/d to the South East Water Bracknell WRZ, which does not show a drought resilience benefit. However, the WRZs do not experience supply shortfalls in the baseline scenario, limiting the ability to measure relative benefits, as described in Section 5.2.1. The propriety of this observation will be explored further in Phase 2 of this project.

5.3.1.10 Thames to Southern Transfer (T2ST) (STT Source)

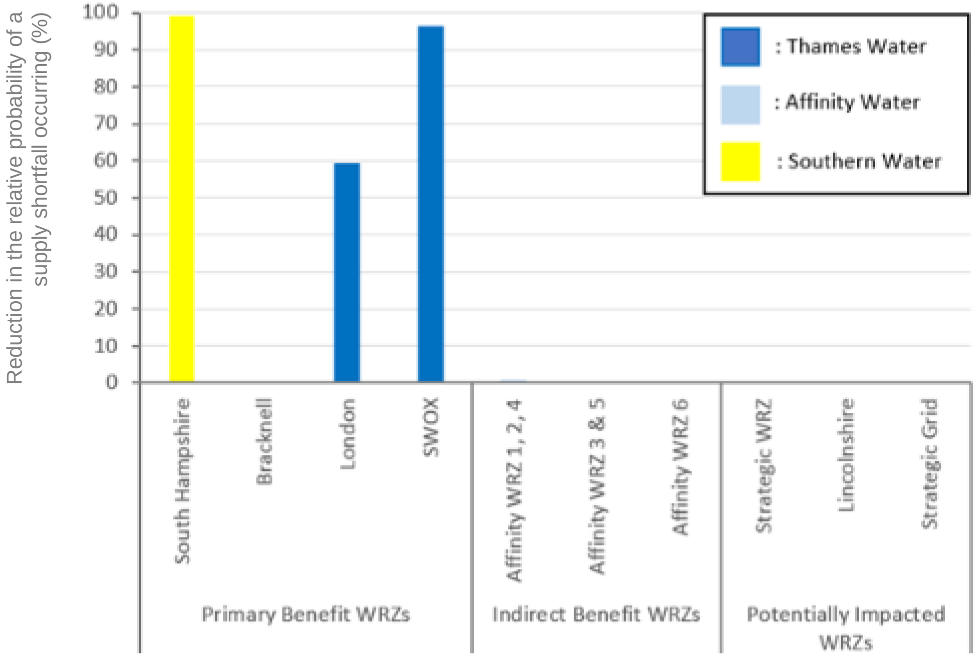


Figure 50 Reduction in the relative probability of a supply shortfall under Scenario 10: Thames to Southern Transfer (STT Source)

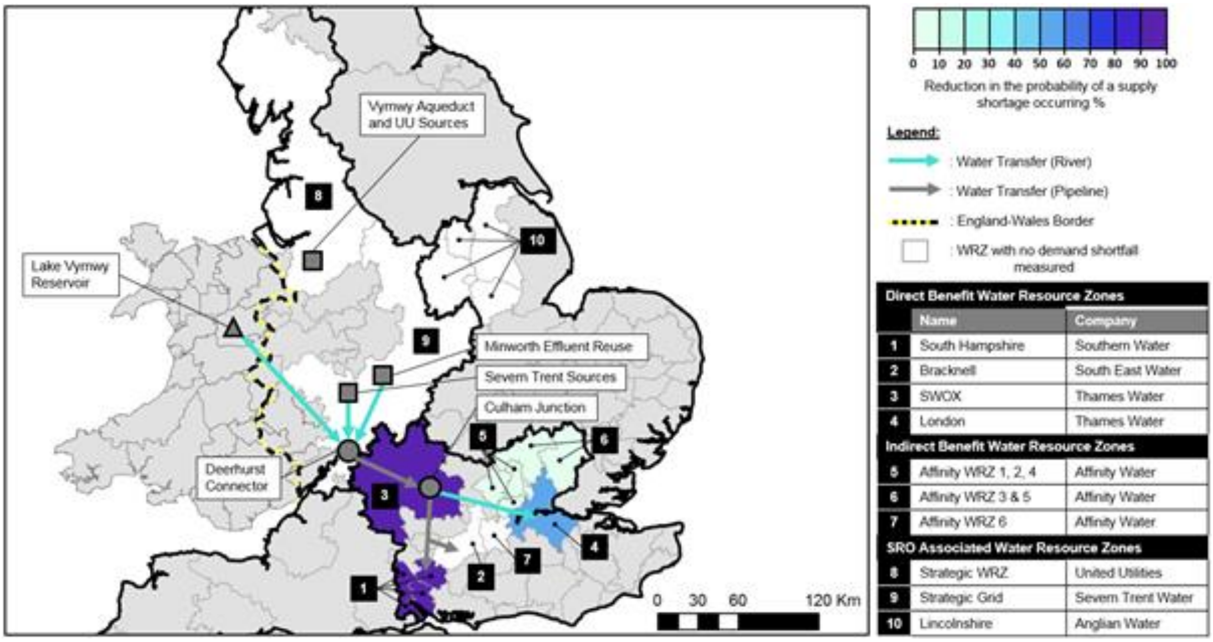


Figure 51 Spatial reduction in the relative probability of a supply shortfall under Scenario 10: T2ST (STT Source)

The T2ST supplied by STT almost completely removes the relative probability of a supply shortfall (99%) for the Southern Water South Hampshire aggregated demand node (Hampshire Southampton West, Hampshire Southampton East, Hampshire Rural and Hampshire Winchester WRZs), see Figure 50 and Figure 51. Since the supply source for the transfer is STT, water is also supplied to the Thames Water London and SWOX WRZs as part of the standard configuration of STT under the T2ST scenario. The reduction in the relative probability of a supply shortfall for London and SWOX WRZs is the same for the T2ST supplied by STT, as it is for the standalone configuration of STT (compare Figure 32 and Figure 50). This is due to the T2ST being configured so that it can supply water to South Hampshire at any time and is used by the model as a last priority supply source when demand levels are great enough. In contrast to this demand-led behaviour, supply from STT to SWOX and London WRZs is only activated when London Storage drops below the control curve when the Teddington Target Flow transitions from 800 Ml/d to 600/700 Ml/d. Allowing operation of the transfer in this way means that water can be supplied to Southern Water independent of resource position in the London WRZ. Furthermore, the London and SWOX WRZs are linked to reservoir storage, which acts to offset the timing of supply shortfalls relative to South Hampshire and therefore reduces the likelihood of T2ST supplying Southern Water at the same time as Thames Water. These two factors act to maintain the drought resilience benefits observed for the primary demand centres of the supporting solution.

A negligible (~1%) indirect benefit associated with STT is observed for Affinity Water's WRZ 1, 2, 4, which abstracts water from the River Thames. This result is a function of STT being configured as a virtual transfer in WREW, which means other abstractors cannot directly benefit from water released from the transfer. An indirect benefit could be observed if supply from STT were to offset the amount of water abstracted from the River Thames by the London and SWOX WRZs, thereby leaving more water available for abstraction by other WRZs. However, hydrological conditions when STT is activated, and more importantly when supply shortfalls are measured, prevent this situation from occurring. The solution is only triggered when London Storage drops below the control curve when the Teddington Target Flow transitions from 800 Ml/d to 600/700 Ml/d, which coincides with low flow levels on the River Thames. Furthermore, the supply shortfalls events used to assess performance only occur during the more severe drought events when flow levels on the River Thames are extremely low. The high demands in the London and SWOX WRZs mean that these WRZs still abstract what little water is available from the River Thames, even when they receive additional supply from SESRO, and therefore no additional water is freed up for abstraction by other WRZs. The very small benefit observed for Affinity WRZ 1, 2, 4 can be discounted as a minor difference in total water balance between the baseline and Thames – Southern (STT) scenarios (i.e., this is an immaterial result and within the model tolerance).

As observed for other solution scenarios involving the River Thames system, other abstractors on the river (Affinity Water WRZ 6) do not experience any reduction in the relative probability of a supply shortfall. Similarly, the T2ST (STT source) supplies up to 20 Ml/d to the South East Water Bracknell WRZ, which does not show a drought resilience benefit.

The WRZs which supply water to STT, or share a supply source with the STT, do not experience supply shortfalls in the baseline scenario, limiting the ability to measure relative benefits, as described in Section 5.2.1. However, change in probability of a shortfall in supplying WRZs is considered unlikely since the majority of the supply sources for the transfer solution operate on a 'put and take basis' and the STT unsupported flow component is subject to hydrological constraints.

5.3.1.11 Southern Water – Water Recycling solution and Havant Thicket

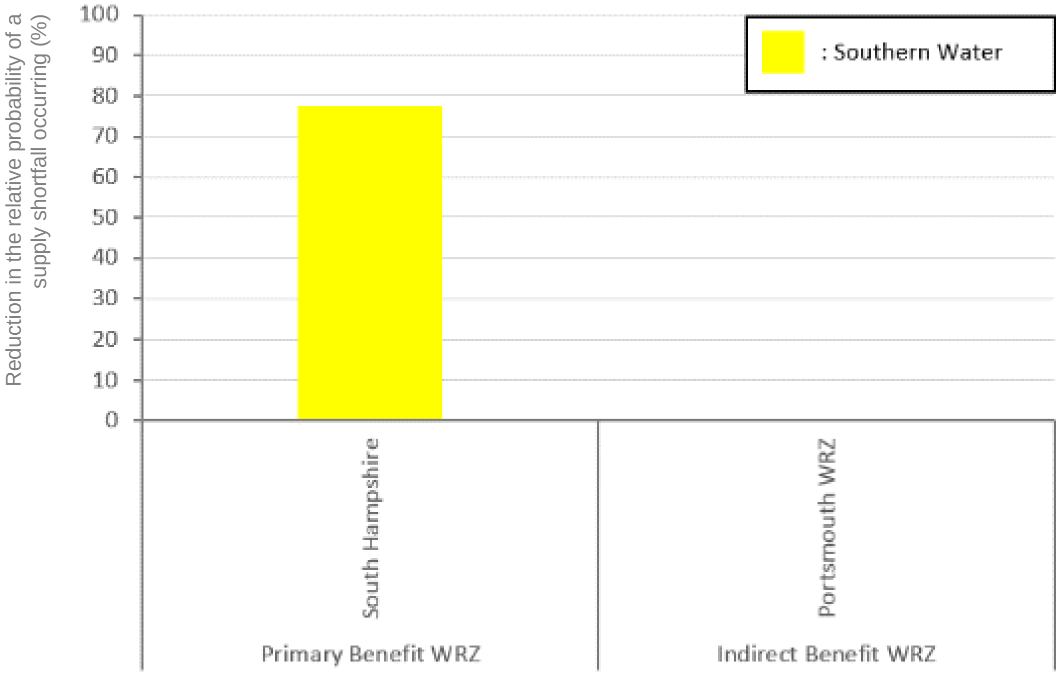


Figure 52 Reduction in the relative probability of a supply shortfall under Scenario 11: Southern Water - Water Recycling solution and Havant Thicket

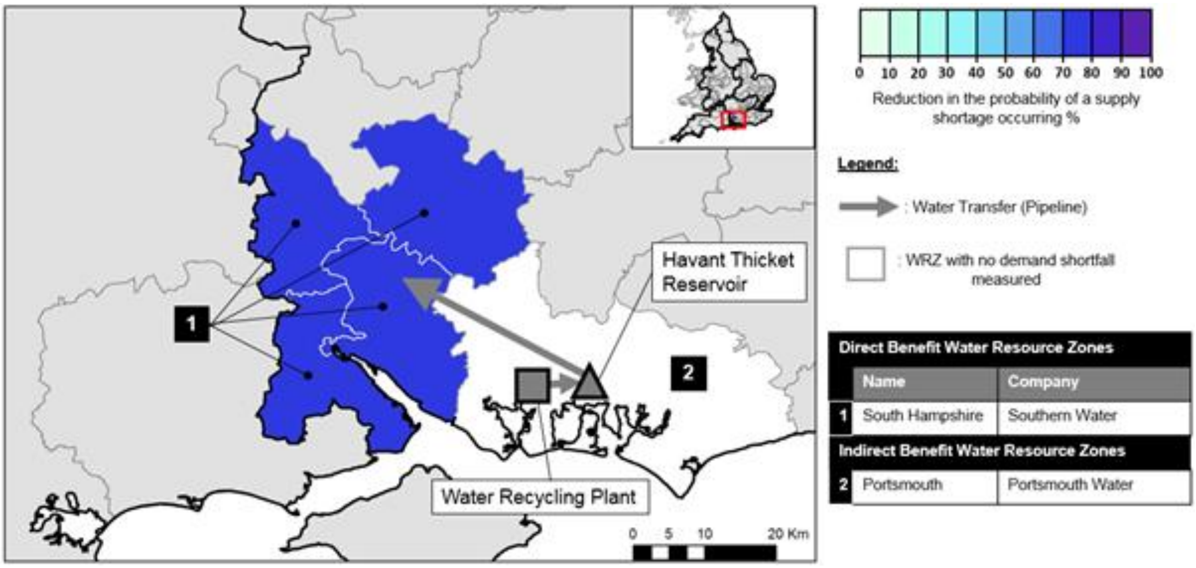


Figure 53 Spatial reduction in the relative probability of a supply shortfall under Scenario 11: Southern Water – Water Recycling solution and Havant Thicket

The Southern Water – Water Recycling and Havant Thicket solution provides a reduction of 77% in the relative probability of a supply shortfall for the Southern Water South Hampshire aggregated demand node (Hampshire Southampton West, Hampshire Southampton East, Hampshire Rural and Hampshire Winchester WRZs), see Figure 52 and Figure 53. While the solution doesn't supply water to the Portsmouth Water, the Portsmouth WRZ and South Hampshire demand centre both abstract water from the River Itchen. It is possible that the Southern Water – Water Recycling and Havant Thicket solution would reduce the amount of water that the South Hampshire demand centre abstracts from the River Itchen, increasing the amount of water available for Portsmouth Water and the associated drought resilience benefit. However, the Portsmouth WRZ does not experience any supply shortfalls in the baseline scenario, which limits the ability to measure a drought resilience benefit.

5.3.1.12 Southern Water – Water Recycling solution

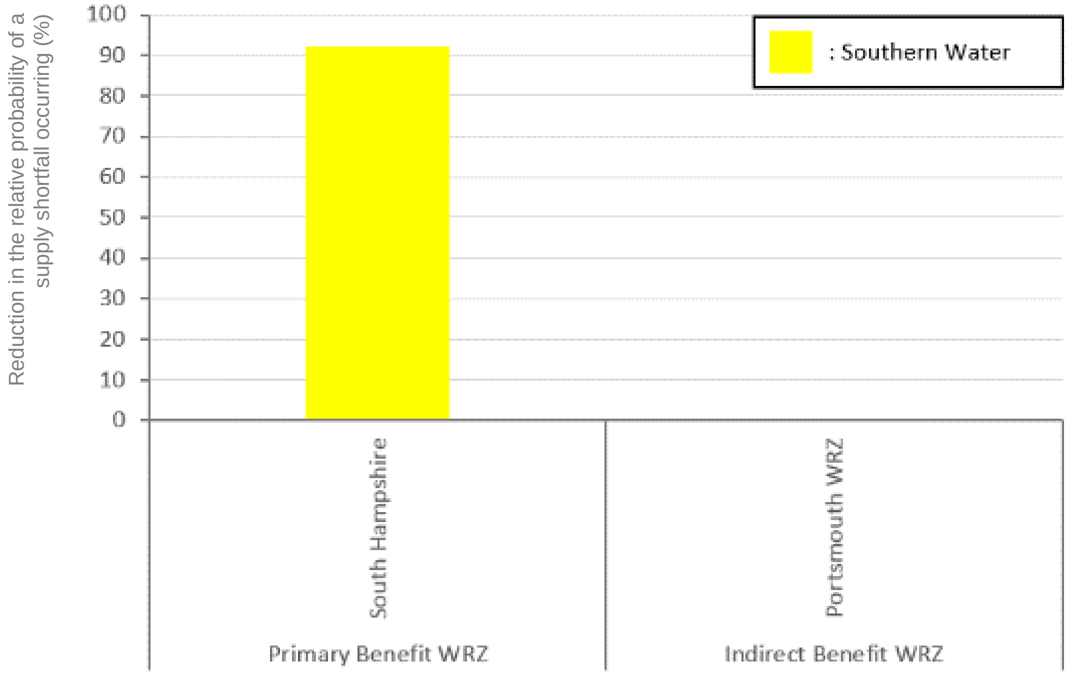


Figure 54 Reduction in the relative probability of a supply shortfall for Scenario 12: Southern Water's Water Recycling solution

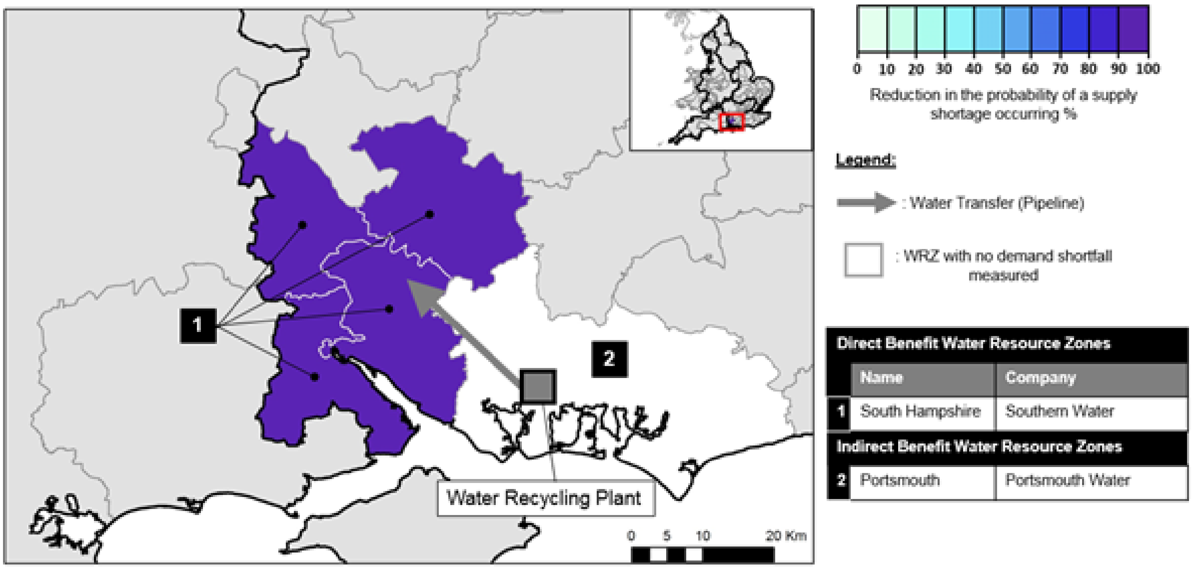


Figure 55 Spatial reduction in the relative probability of a supply shortfall under Scenario 12: Southern Water – Water Recycling Solution

The Southern Water – Water Recycling Only solution almost completely reduces (92%) the relative probability of a supply shortfall in comparison to the baseline for the Southern Water South Hampshire aggregated demand node (Hampshire Southampton West, Hampshire Southampton East, Hampshire Rural and Hampshire Winchester WRZs), see Figure 54 and Figure 55. This observed benefit is ~15% greater than when the solution configuration involves utilisation of water storage in Havant Thicket reservoir (compare Figure 52 and Figure 54). This marked difference in performance can be explained by the Southern Water – Water Recycling Only solution having a larger yield of 75 Ml/d compared to the 61 Ml/d that the solution can provide when linked to Havant Thicket reservoir storage.

While the solution doesn't supply water to the Portsmouth Water, the Portsmouth WRZ and South Hampshire demand centre both abstract water from the River Itchen. It is possible that the Southern

Water – Water Recycling and Havant Thicket solution would reduce the amount of water that the South Hampshire demand centre abstracts from the River Itchen, increasing the amount of water available for Portsmouth Water and the associated drought resilience benefit. However, the Portsmouth WRZ does not experience any supply shortfalls in the baseline scenario, which limits the ability to measure a drought resilience benefit.

5.3.1.13 West Country Sources & West Country to Southern Water Transfer

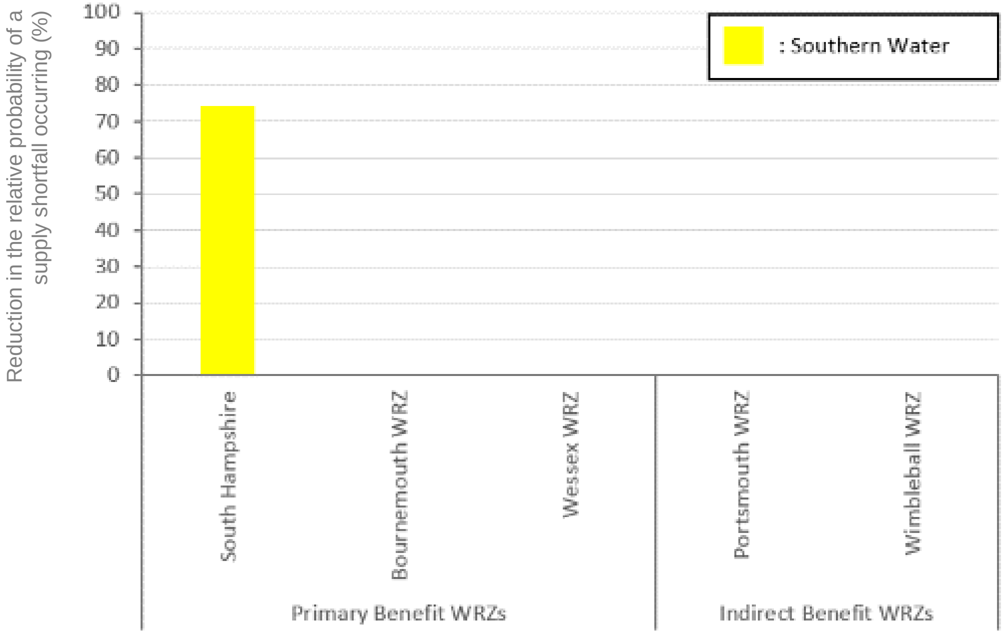


Figure 56 Reduction in the relative probability of a supply shortfall under Scenario 13: West Country South Sources and West Country to Southern Transfer

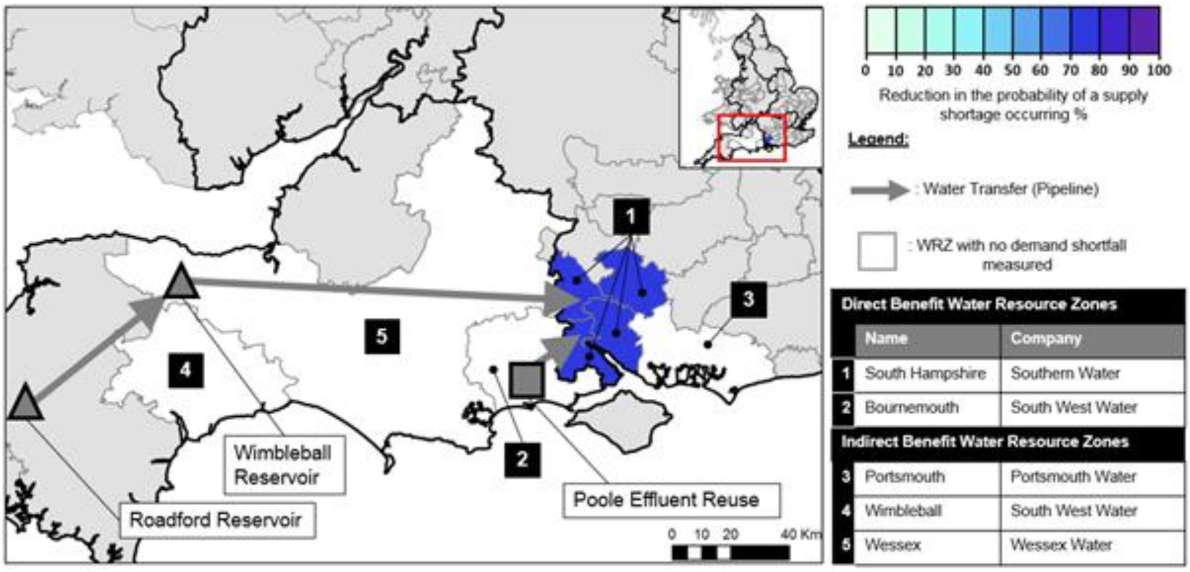


Figure 57 Spatial reduction in the relative probability of a supply shortfall under Scenario 13: West Country South Sources and West Country to Southern Transfer

The West County South Sources and West Country Transfer solution reduces the relative probability of a supply shortfall by 74% for the Southern Water South Hampshire aggregated demand node (Hampshire Southampton West, Hampshire Southampton East, Hampshire Rural and Hampshire Winchester WRZs), see Figure 56 and Figure 57. The water reuse part of the solution can also supply up to 30 Ml/d to South West Water's Bournemouth WRZ, while the Roadford Reservoir transfer component of the solution can supply up to 20 Ml/d to Wessex Water's Wessex WRZ. However, neither WRZ experiences a supply shortfall in the baseline scenario and therefore a drought resilience benefit cannot be measured.

By supplying water to Southern Water's South Hampshire demand centre there is a possibility the solution might offset abstraction on the River Itchen and indirectly benefit Portsmouth Water who also abstract from the river. Similarly, the Roadford Reservoir transfer component of the solution is routed via Wimbleball Reservoir and has the potential to indirectly benefit the South West Water Wimbleball WRZ. Neither the Wimbleball WRZ nor the Portsmouth WRZ experience a supply shortfall in the baseline scenario which limits the ability to measure a drought resilience benefit.

5.3.1.14 West Country North Sources & Transfer

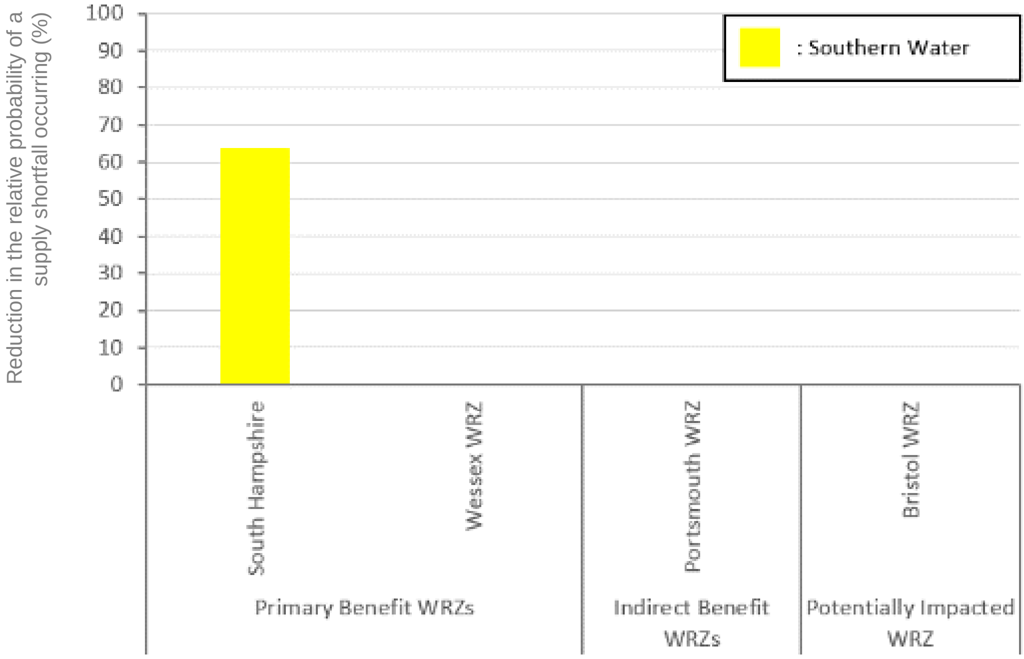


Figure 58 Reduction in the relative probability of a supply shortfall under Scenario 14: West Country North Sources

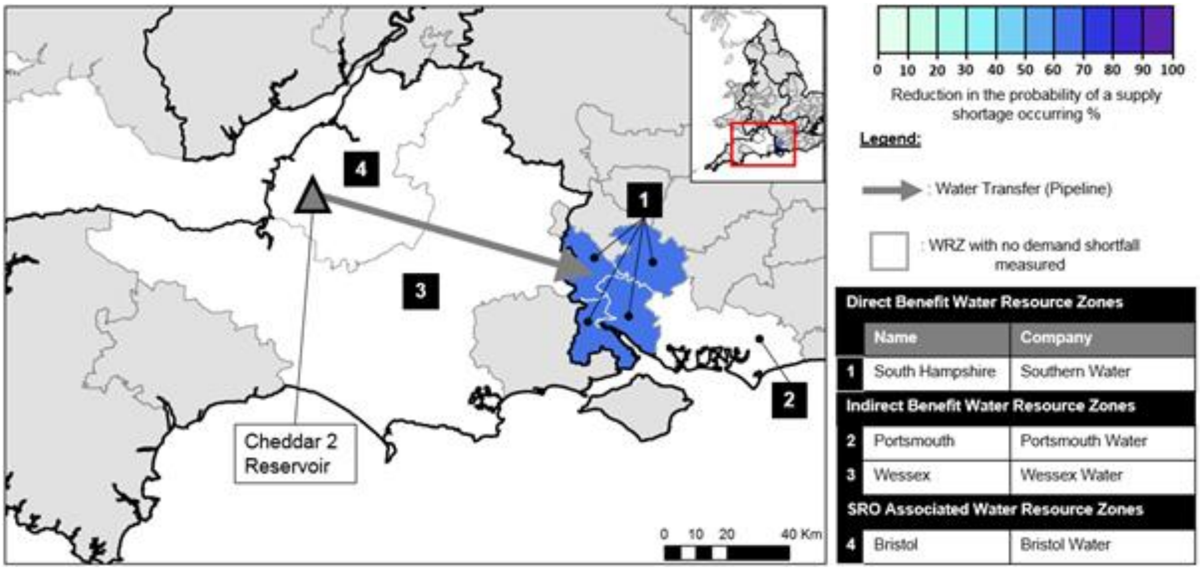


Figure 59 Spatial reduction in the relative probability of a supply shortfall under Scenario 14: West Country North Sources and Transfer

While the West Country North Sources and Transfer solution has a comparatively small yield (40 Ml/d) relative to the other solutions that supply Southern Water, it generates a reduction in the relative probability of a supply shortfall, in comparison to the baseline, of 63% for the Southern Water South Hampshire aggregated demand centre (Hampshire Southampton West, Hampshire Southampton East, Hampshire Rural and Hampshire Winchester WRZs), see Figure 58 and Figure 59).

In the same way as the West Country South solution, the West County North solution can supply up 20 Ml/d to Wessex Water's Wessex WRZ. However, the Wessex WRZ does not experience a supply shortfall in the baseline scenario and therefore a drought resilience benefit cannot be measured. By supplying water to Southern Water's South Hampshire demand centre there is a possibility the solution might offset abstraction on the River Itchen and indirectly benefit Portsmouth Water who also abstract from the river. Similarly, the Cheddar 2 Reservoir fills via Cheddar Reservoir, which supplies Bristol Water's Bristol WRZ. It is possible that filling relationship between the two reservoirs could impact upon the reservoir levels in

Cheddar reduce supply to the Bristol WRZ. Neither the Portsmouth WRZ nor Bristol WRZ experience a supply shortfall in the baseline scenario which limits the ability to measure a drought resilience benefit.

5.3.2 Combined solution Outputs

5.3.2.1 STT and SESRO

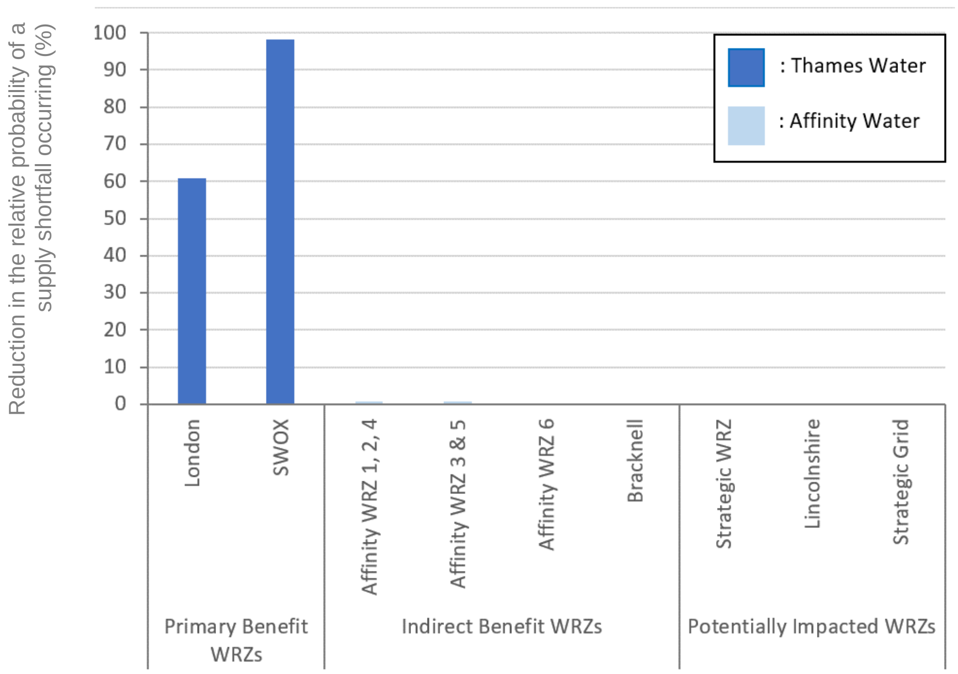


Figure 60 Reduction in the relative probability of a supply shortfall under Scenario 15: combined use of STT and SESRO

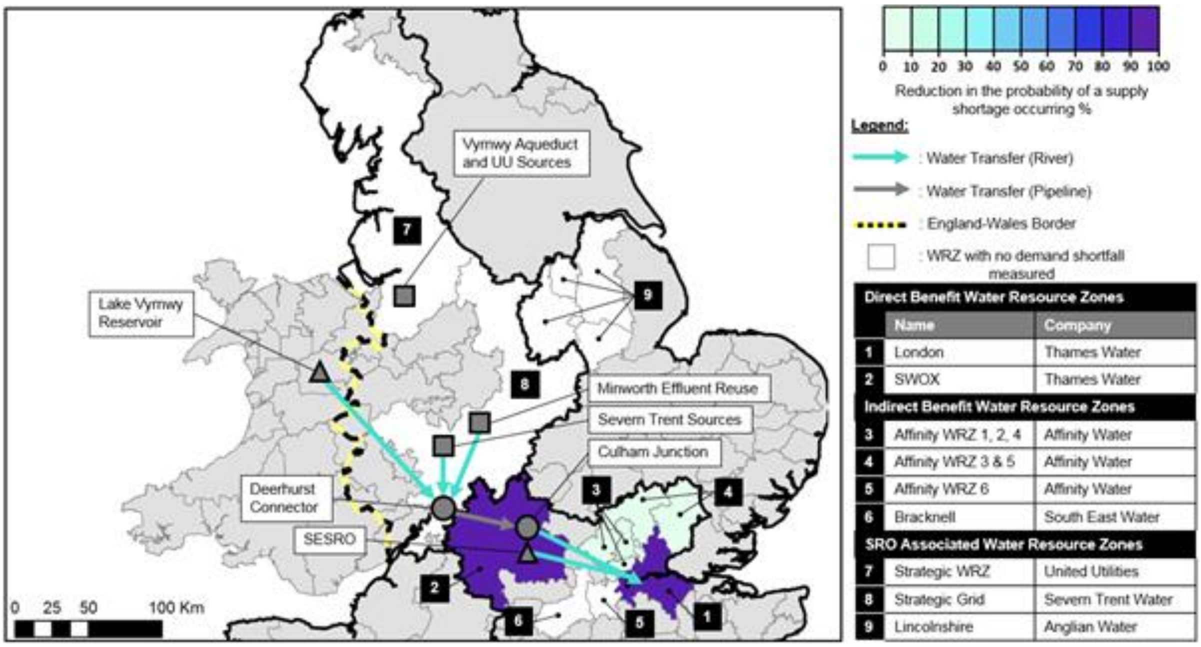


Figure 61 Spatial reduction in the relative probability of a supply shortfall under Scenario 15: combined use of STT and SESRO

The combination of SESRO and STT results in a 91% reduction in the relative probability of a supply shortfall in comparison to the baseline, for the Thames Water London WRZ and a 99% reduction for the Thames Water SWOX WRZ, see

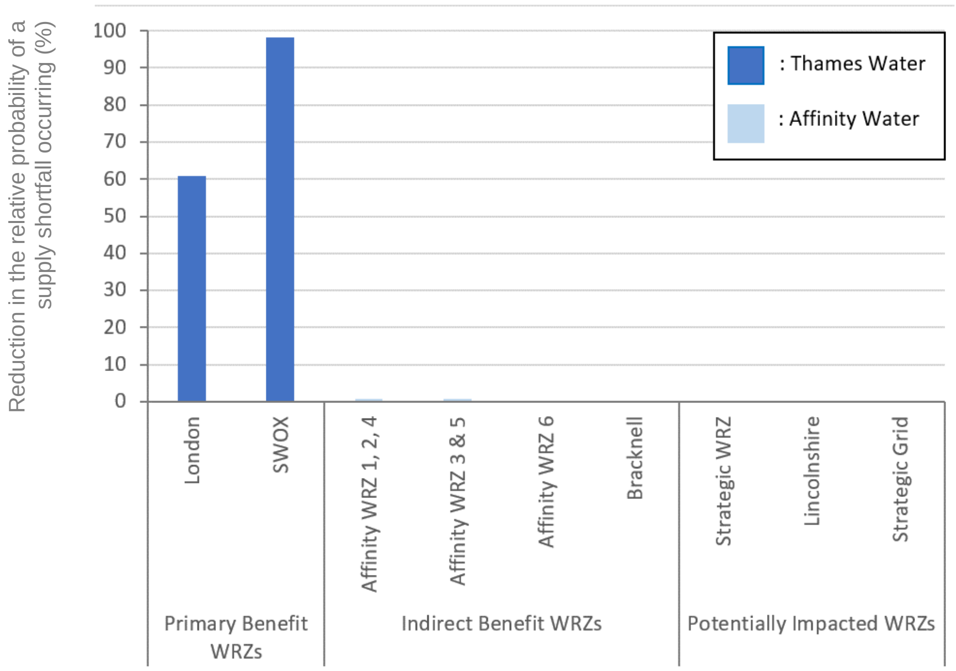


Figure 60 and Figure 61. Figure 61 In combination, the two solutions can therefore significantly reduce the relative probability of a supply shortfall for the WRZs they supply.

Drought resilience benefits under this combined scenario are much greater than those observed when the solutions are implemented independently (see Figure 32 and Figure 34), which is to be expected as the combined yield of the solutions is up to 821 Ml/d. Both solutions combined do not completely remove the relative probability of a supply shortfall in the London WRZ, even though the largest supply shortfalls experienced by the zone are ~700 Ml/d. This interesting result can be explained by the coincidence of drought events for the Thames and Severn catchments. For example, when drought conditions in the Thames Catchment reduce river flows, the amount of water available for abstraction in the London WRZ is significantly reduced. If at the same time drought conditions in the Severn Catchment are also acting to reduce river flows, the hydrological constraints on the unsupported flow component of the STT will reduce the transfer yield during severe and widespread drought events. Similarly, if drought conditions in the Thames Catchment coincide with those in the Trent Catchment, when flow levels on the River Trent are very low and/or the minimum required flow level is breached, the support that Minworth Effluent Reuse provides to STT is reduced, as is transfer yield. The coincidence of droughts events between discrete hydrological areas explains why supply shortfalls are still observed when STT is combined with SESRO.

As observed for other scenarios involving STT, there is a very negligible (~1%) indirect benefit for Affinity Water's WRZ 1, 2, 4 and WRZ 3 & 5 associated with STT (see Figure 60 – indirect benefit). This result is likely a function of the STT being configured as a virtual transfer in WREW, which means other abstractors cannot directly benefit from the transfer. An indirect benefit could be observed if supply from STT and SESRO were to offset the amount of water abstracted from the River Thames by the London and SWOX WRZs, thereby leaving more water available for abstraction by other WRZs. However, hydrological conditions when STT and SESRO are activated, and more importantly when supply shortfalls are measured, prevent this situation from occurring. The solutions are only triggered when London Storage drops below the control curve when the Teddington Target Flow transitions from 800 Ml/d to 600/700 Ml/d, which coincides with low flow levels on the River Thames. Furthermore, the supply shortfall events used to assess performance only occur during the more severe drought events when flow levels on the River Thames are extremely low. The high demands in the London and SWOX WRZs mean that these WRZs still abstract what little water is available from the River Thames, even when they receive additional supply from STT and SESRO, and therefore no additional water is freed up for abstraction by other WRZs. The very small benefit observed for Affinity WRZ 1, 2, 4 can be discounted as a minor difference in total water (mass) balance solution found by the model's Network Flow Program between the baseline and STT and SESRO scenarios (i.e., this is an immaterial result and within the model tolerance).

Other abstractors on the River Thames (Affinity Water WRZ 6 and South East Water Bracknell WRZ) do not experience any reduction in the relative probability of a supply shortfall. Similarly, none of the WRZs which supply water to STT, or share a supply source with the STT, show any change in the relative probability of a supply shortfall occurring. However, the Affinity and STT supply or donor WRZs do not experience supply shortfalls in the baseline scenario, limiting the ability to measure relative benefits, as described in Section 5.2.1. However, a change in the probability of a shortfall in donor WRZs is considered unlikely since the majority of the supply sources for the transfer solution operate on a 'put and take basis' and the STT unsupported flow component is subject to hydrological constraints.

5.3.2.2 STT and GUC

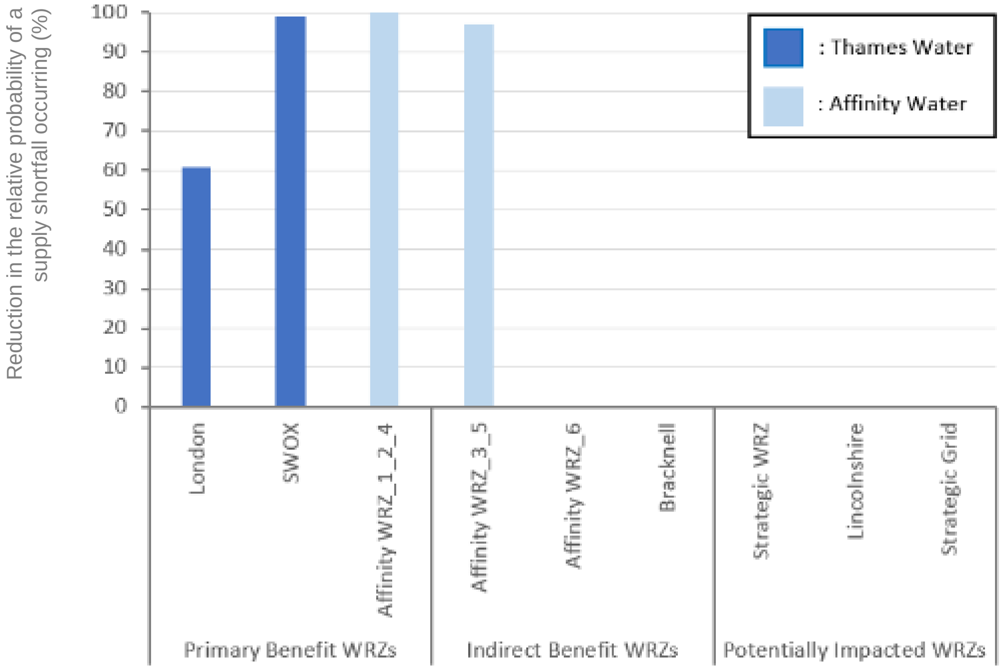


Figure 62 Reduction in the relative probability of a supply shortfall under Scenario 16: combined use of STT and GUC

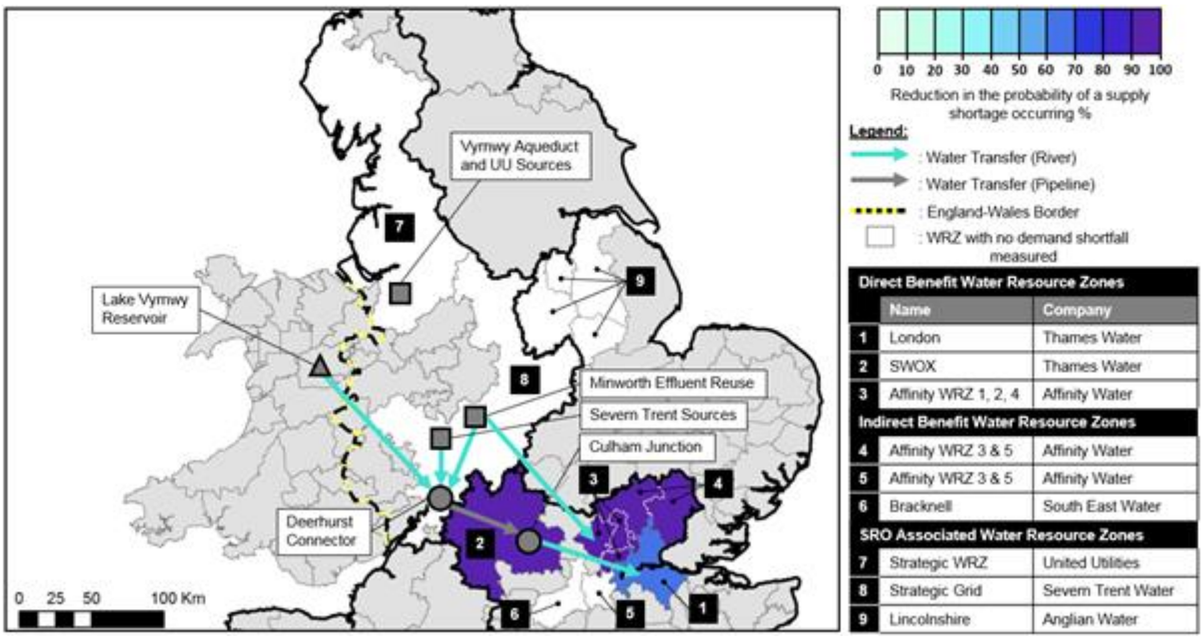


Figure 63 Spatial reduction in the relative probability of a supply shortfall **under Scenario 16: combined use of STT and GUC**

The in-combination benefit of STT and GUC results in a reduction in the relative probability of a supply shortfall of 60% and 99% for the Thames Water London and SWOX WRZs, respectively, and a 100% and 97% reduction for the Affinity Water WRZ 1, 2, 4 and WRZ 3 & 5 WRZs, respectively, see Figure 62 and Figure 63.

Although the GUC only supplies Affinity WRZ 1, 2, 4, a transfer with Affinity WRZ 3 & 5 explains why the drought resilience benefit is shared. These benefits found for running the GUC and STT solutions in combination, are the same as those observed for the individual GUC and STT scenarios (compare Figure 32, Figure 46, and Figure 62). Although the same drought resilience benefit is observed for the primary demand centres that the two solutions supply, the individual GUC scenario shows a small (~5%) indirect benefit for Thames Water SWOX and London WRZs, which does not accumulate with the benefit from STT in the combined scenario (compare Figure 32 and Figure 46). It is likely that the small indirect benefit GUC provides to London and SWOX WRZs occurs for some less severe drought events, where the extra water which GUC supplies to Affinity WRZ 1, 2, 4 acts to offset the amount of water abstracted from the River Thames by this WRZ, so that more water is available for abstraction by the SWOX and London WRZs. When STT and GUC are run in-combination the extra water supplied by STT cancels out the indirect benefit from GUC to London and SWOX WRZs.

Other abstractors on the River Thames (Affinity Water WRZ 6 and South East Water Bracknell WRZ) do not experience any reduction in the relative probability of a supply shortfall. Similarly, none of the WRZs which supply water to STT, or share a supply source with the STT, show any change in the relative probability of a supply shortfall occurring. However, the Affinity and STT supply WRZs do not experience supply shortfalls in the baseline scenario, limiting the ability to measure relative benefits, as described in Section 5.2.1. However, change in probability of a shortfall in supplying WRZs is considered unlikely since the majority of the supply sources for the transfer solution operate on a ‘put and take basis’ and the STT unsupported flow component is subject to hydrological constraints.

5.3.3 Outputs Summary

5.3.3.1 Solutions that primarily supply Thames Water

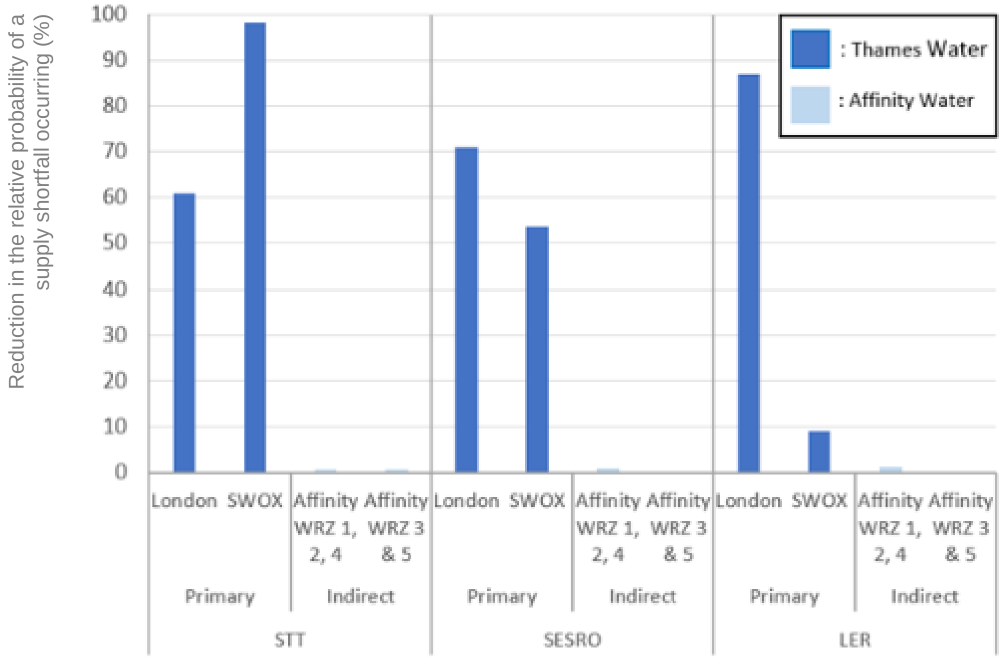


Figure 64 Reduction in the relative probability of a supply shortfall for solutions that primarily supply Thames Water (model scenarios 1-3)

Key themes:

- Drought resilience benefit to the London WRZ decreases as theoretical yield of solutions increases from LER to SESRO to STT. This trend is partly caused by connectivity with SWOX WRZ increasing from STT to SESRO to LER, making less water available for London WRZ. The result is mainly a function of solution type where finite storage in SESRO and hydrological constraints on elements of the STT act to reduce yield during certain drought events.
- No material drought resilience benefit is observed for Affinity Water or other abstractors from the River Thames.

For the three solutions that primarily supply Thames Water, a trade-off exists in the drought resilience benefit between the London and SWOX WRZs (Figure 64).

For example, STT provides a greater benefit to SWOX WRZ over London WRZ, whereas the opposite is observed for SESRO, albeit with a smaller difference between the benefit to the two WRZs. This is in part due to the different capacities of the solutions to supply SWOX, relative to the size of the SWOX supply shortfalls. SESRO supplies 100 Ml/d to SWOX, and STT 20 Ml/d, relative to SWOX supply shortfalls that range from 10 up to ~150 Ml/d. However, a greater supply capacity to SWOX WRZ will act to reduce benefit to London WRZ where supply shortfalls are observed up to ~700 Ml/d. For the LER scenario, there is no connectivity between the effluent reuse plant and SWOX WRZ. Therefore, the drought resilience benefit observed for SWOX WRZ is generated indirectly as a result of demand saving measures linked to the different levels of water use restrictions, which are triggered by reservoir storage levels in the London WRZ, but are also applied to the SWOX WRZ. LER supplying water to the London WRZ thus acts to slow progression through the levels of water use restriction and consequently increase the duration over which demand savings are in place for both London and SWOX WRZs.

The differing drought resilience benefit to London WRZ, from LER, SESRO and STT can also be explained by the nature of these solutions. Effluent reuse is not linked to the hydrological system, meaning it can consistently supply 300 Ml/d to the London WRZ. In contrast, SESRO storage volume is finite and can become depleted during extreme events. SESRO release is also subject to the abstraction rules for the Lower Thames Abstraction, which do not follow a 1:1 relationship with river flow levels. The STT benefit is constrained due to a combination of hydrological constraints on transfer capacity and the same Lower Thames Abstraction rules mentioned above.

The supply shortfall events used to assess solution performance only occur during more extreme drought events when flow levels on the River Thames will be low, therefore concerning the aforementioned Lower Thames Abstraction hydrological constraints. Some drought events for the River Thames Catchment also coincide with events affecting the River Severn Catchment. During these times the hydrological constraints on the River Severn at Deerhurst act to reduce or remove the unsupported flow component of the STT, resulting in a lower transfer yield. The same behaviour is observed for coincident drought events between the River Thames and River Trent Catchments, where hydrological constraints on the River Trent act to reduce support from Minworth Effluent reuse to STT, which lowers the transfer yield. These constraints can, under some simulated drought events, limit the consistency of supply from STT and therefore reduce the drought resilience benefit to London WRZ when compared to SESRO and LER. This behaviour is compounded by the frequency at which the model uses the 100 Ml/d connection to SWOX WRZ under the STT scenario, which allows the majority of supply shortfall events experienced by the WRZ to be satisfied, but also reduces the transfer capacity available to the London WRZ.

No material indirect drought resilience benefit is observed for the Affinity Water WRZs. This is a result of STT, SESRO and LER only being triggered when London Storage drops below the control curve when the Teddington Target Flow transitions from 800 Ml/d to 600/700 Ml/d. At these times flow levels on the River Thames will be low and therefore extra water supplied by the solutions will not offset abstraction from the River Thames and more water will not be available for abstraction by other WRZs (e.g., Affinity WRZ 1, 2, 4 and Affinity WRZ 3 & 5). In the same way, the supply shortfall events used to measure change in drought resilience naturally coincide with more severe droughts, when River Thames flows will be low and the opportunity for indirect benefit will be very small.

5.3.3.2 Solutions that primarily supply Affinity Water

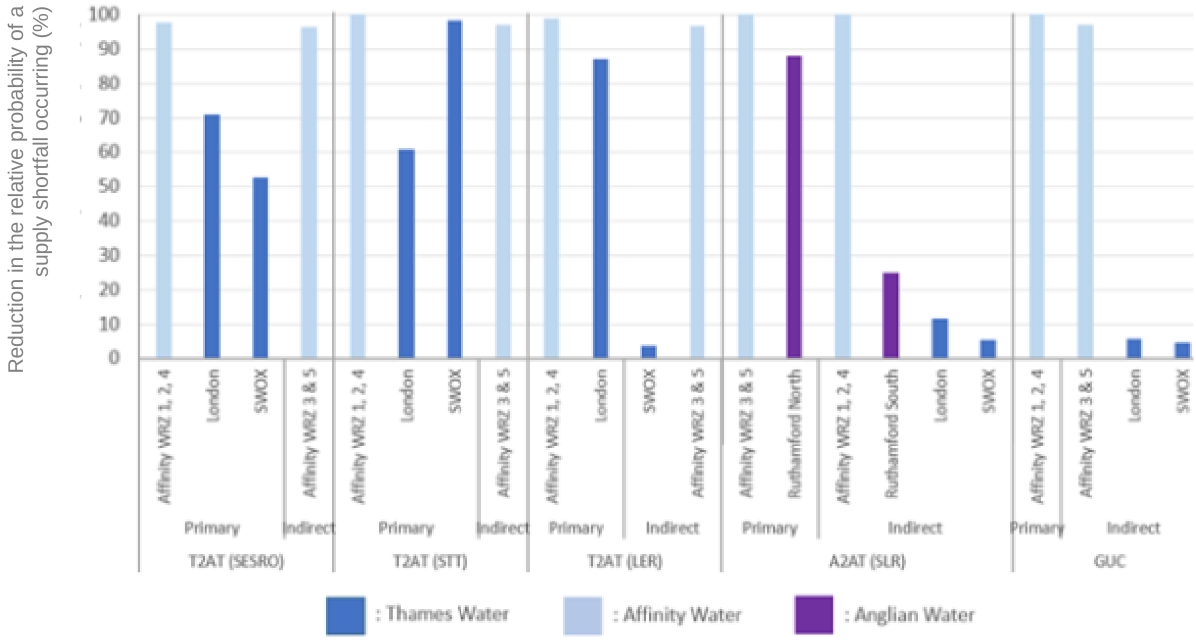


Figure 65 Reduction in the relative probability of a supply shortfall for solutions that primarily supply Affinity Water (model scenarios 4-8)

Key themes:

- Under all T2AT scenarios, the drought resilience benefit to Affinity Water's WRZs 1-5 is greater than for Thames Water's SWOX and London WRZs due to different scales of supply shortfalls. The comparatively small-scale supply shortfalls experienced by Affinity WRZs in the model is driven by the extent to which this part of the system relies on groundwater supply and the simplified way in which groundwater is represented in WREW.
- Under all T2AT scenarios, the drought resilience benefit is the same for London and SWOX WRZs as when the solutions that supply the transfer operate on a standalone basis. One would expect to see a disbenefit since the same amount of water is being shared more widely. The trend is a result of reservoir storage offsetting the timing at which supply shortfalls are experienced by the Affinity WRZs and the Thames WRZ. This behaviour is likely controlled by model setup and may not translate into real world operation.
- Although A2AT and GUC do not supply London and SWOX WRZs an indirect benefit is observed for these WRZs. This pattern demonstrates how solutions can have a wider indirect benefit by alleviating water stress on key supply sources.

The drought resilience benefit to Affinity Water's WRZ 1, 2, 4 and WRZ 3 & 5 is similar under all of the T2AT scenarios (4, 5, 6) with the relative probability of a supply shortfall almost completely removed (Figure 65).

T2AT's supporting solutions (STT, SESRO, and LER) also supply Thames Water. The benefit observed to Thames' WRZs is less than that to Affinity's WRZs, but is the same observed benefit to the Thames WRZs as when the STT, SESRO and LER solutions operate without T2AT (compare Figure 32, Figure

34, Figure 36 and Figure 65

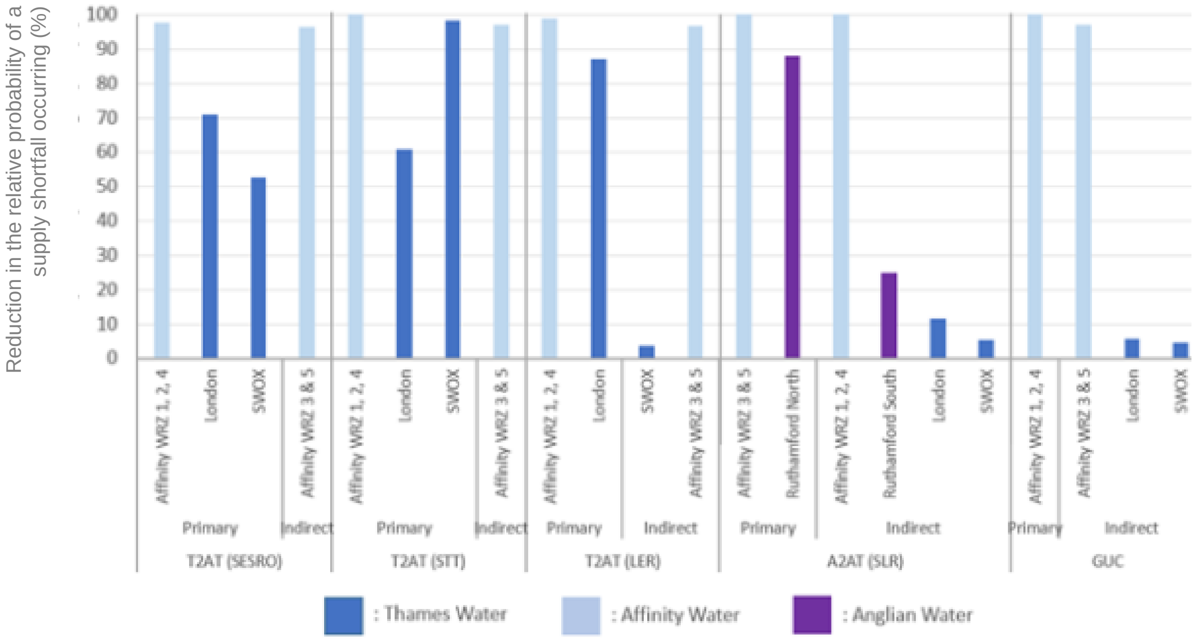


Figure 65). Maintaining the benefit to Thames' WRZs, whilst also supporting T2AT solution is possible due to the range of Affinity's WRZ supply shortfalls (at ~10-50Ml/d) being comparatively smaller than those for Thames' WRZs (at up to 600 Ml/d). The amount of water required from T2AT to satisfy supply shortfall events in Affinity Water is therefore comparatively small enough to not negatively impact upon the drought resilience benefit that SESRO and STT provide to Thames Water. Phase 2 of this project will investigate whether the small-scale supply shortfall events experienced by Affinity Water are realistic, and not as a result of poor calibration of the model's representation of Affinity's groundwater supply.

This behaviour can also be explained by the way in which T2AT and supporting solutions are configured in WREW, as well as the timing of supply shortfall events between Affinity Water and Thames Water. The T2AT supply to Affinity Water is available all of the time (as the lowest priority source). In contrast, the supply to Thames Water is only triggered when London Storage and drops below its control curve and when the lower Teddington Target Flow is reached. As a result, there will be times during drought events when the supporting solution is not supplying Thames Water but the transfer to Affinity Water is active. London and SWOX WRZs are also linked to reservoir storage, which acts to delay the timing of supply shortfall events relative to Affinity WRZ 1, 2, 4 and therefore reduces the occasions where T2AT supplies Affinity Water coincides with SESRO or STT supplying Thames Water.

A2AT and GUC are observed to present similar benefits in drought resilience to Affinity WRZs as T2AT, reflecting the same 100 Ml/d capacities that the solutions provide. Both GUC and A2AT also allow for a small indirect benefit to the Thames Water's London and SWOX WRZs. This is a result of the model using GUC and A2AT to satisfy more demand in the Affinity WRZs than just the supply shortfalls themselves. This offsets abstraction from the River Thames which is instead is used to benefit the London and SWOX WRZs. Although the A2AT and GUC solutions are configured in WREW to be used as the last supply sources for Affinity WRZs, the model's primary optimisation objective to remove supply shortfalls means it overrules some supply priorities to find a more efficient solution for the high supply shortfalls in London and SWOX.

A water transfer from Affinity WRZ 1, 2, 4 to Affinity WRZ 3 & 5 explains why drought resilience benefit is shared between the two demand centres for the T2AT and GUC scenarios, which only supply Affinity WRZ 1, 2, 4. Similarly, a water transfer from Affinity WRZ 3 & 5 to Affinity WRZ 1, 2, 4 allows resilience benefit to be shared for the A2AT, which only supplies Affinity WRZ 3 & 5. Finally, although A2AT only supplies water to Ruthamford North, a transfer from this WRZ to the Ruthamford South demand centre allows for the resilience benefit to be shared.

5.3.3.3 Solutions that primarily supply Southern Water

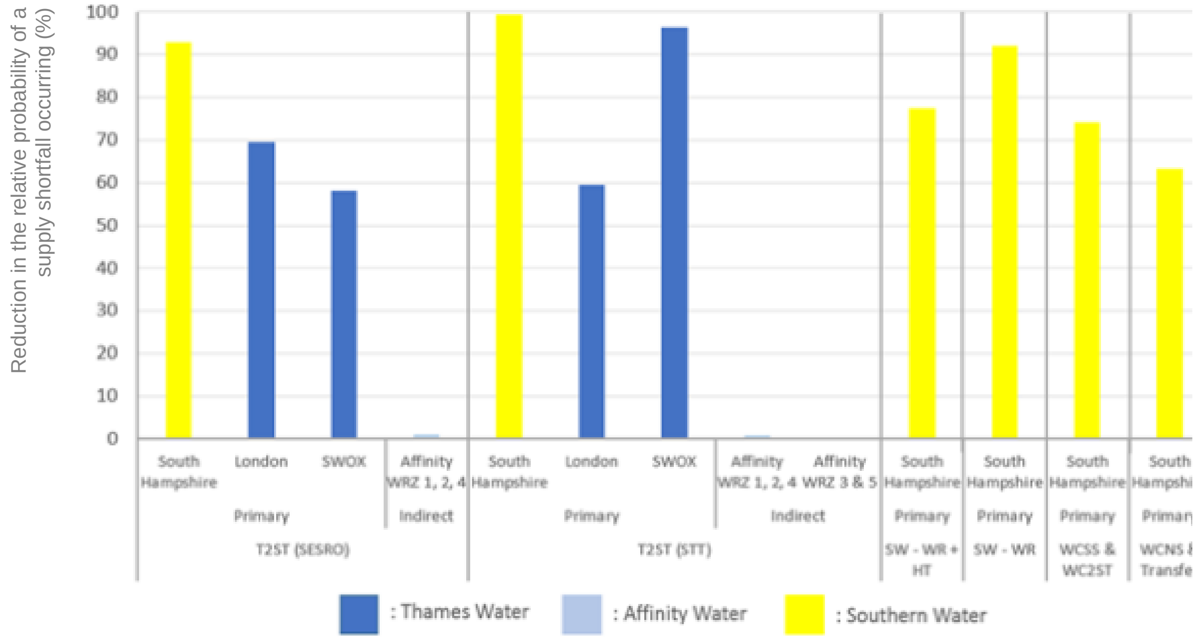


Figure 66 Reduction in the relative probability of a supply shortfall for solutions that primarily supply Southern Water (model scenarios 9-14)

Key themes:

- Both T2ST solution configurations and the Southern Water – Water Recycling solution provide a considerable drought resilience benefit to Southern Water's Hampshire WRZs.
- The benefit from T2ST to Southern Water is much greater than to Thames Water due to different scales of supply shortfalls. The Southern Water Hampshire WRZs experience supply shortfalls of ~10-60 Ml/d compared to 370-600 Ml/d events for the London WRZ.
- Under both T2ST solution scenarios, the drought resilience benefit is the same for London and SWOX WRZs as when the solutions that supply the transfer operate on a standalone basis. One would expect to see a disbenefit since the same amount of water is being shared more widely. The trend is a result of reservoir storage offsetting the timing at which supply shortfalls are experienced by the Affinity WRZs and the Southern Water Hampshire WRZs. This behaviour is likely controlled by model setup and may not translate into real world operation.
- Benefit from T2TST supplied by SESRO is the same as from the Southern Water – Water Recycling solution, although the latter can theoretically supply 25 Ml/d less water. This trend is predominantly caused by demand on SESRO from London and SWOX WRZs, and/or drawdown of SESRO, acting to reduce the amount of water available for transfer to Southern Water's Hampshire WRZs at times when both recipients encounter drought.
- The Southern Water – Water Recycling solutions, WCSS & WC2ST and WCNS all follow a clear pattern of drought resilience benefit associated with solution yield.

Of all the solutions that primarily supply Southern Water, the T2ST solution supported by STT gives the greatest drought resilience benefit, almost completely removing the relative probability of a supply shortfall for the South Hampshire demand centre (Hampshire Southampton West, Hampshire Southampton East, Hampshire Rural, and Hampshire Winchester WRZs), see Figure **66**. The T2ST solution supported by SESRO is observed to provide a similar drought resilience benefit to South Hampshire, suggesting both supporting SESRO and STT solutions are largely able to support the 100 Ml/d T2ST capacity transfer. The benefit to Southern Water when T2ST is supported by SESRO is marginally lower due to SESRO's total operating capacity (321 Ml/d), being lower than that of STT (500 Ml/d), and having to reduce and offset support to Southern Water via T2ST on coinciding occasions of also needing to support London and SWOX WRZs. The same situation occurs if demand to support other WRZs supply shortfalls earlier in the drought event has depleted SESRO's storage levels.

For the above reasons, the Southern Water – Water Recycling solution, which has a lower yield of 75 Ml/d, than T2ST's 100 Ml/d transfer, is also observed to provide a similar level of drought resilience to T2ST when supported by SESRO.

The SESRO and STT solutions that support T2ST also supply Thames Water, and the benefit to these Thames WRZs is not diminished as a result of also supplying T2ST (compare Figure 32, Figure 34, and Figure 66). This is due to the way in which T2ST and supporting solutions are configured in WREW, as well as the timing of supply shortfall events between Southern Water and Thames Water. The T2ST supply to Southern Water is available all of the time (as the lowest priority source). In contrast, the supply to Thames Water is only triggered when London Storage and drops below its control curve and when the lower Teddington Target Flow is reached. As a result, there will be times during drought events when the supporting solution is not supplying Thames Water but the transfer to Southern Water is active. London and SWOX WRZs are also linked to reservoir storage, which acts to delay the timing of supply shortfall events relative to Affinity WRZ 1, 2, 4 and therefore reduces the occasions where T2ST supplies Southern Water coincides with SESRO or STT supplying Thames Water.

The drought resilience benefits observed for the two configurations of the Southern Water – Water Recycling solution, the West Country South Sources and West Country – Southern Transfer (WCSS & WC2ST) and the West Country North Sources and transfer (WCNS & Transfer) follow a clear pattern associated with solution yield. The Southern Water – Water Recycling solution has the largest yield (75 Ml/d) and benefit, followed by the Sothern Water – Water Recycling and Havant Thicket Transfer solution with a yield of 62 Ml/d and then the WCSS & WC2ST with a yield of 60 Ml/d and finally the WCNS & Transfer with a yield of 40 Ml/d (see Figure 66). Increase in drought resilience benefit does not scale linearly with solution yield, which is to be expected since drought severity is not linear.

5.3.3.4 Solution Combinations

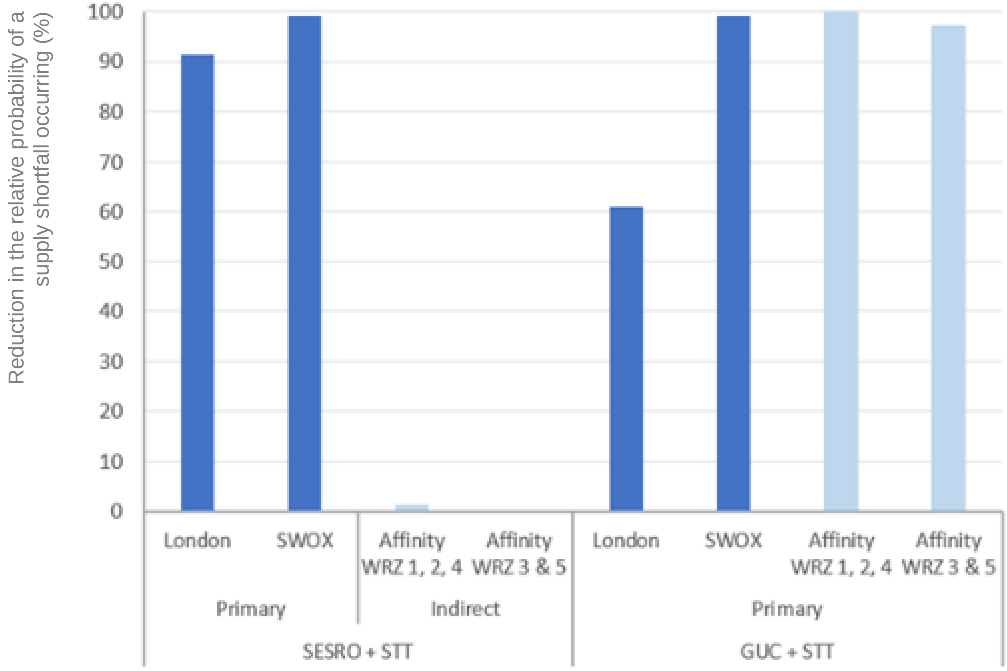


Figure 67 Reduction in the relative probability of a supply shortfall for solutions combinations (model scenarios 15 & 16)

Key themes:

- The combined benefit for STT and SESRO is considerable and almost entirely removes the possibility of a supply shortfall occurring for London and SWOX WRZs, under current levels of demand and without any sustainability reductions in place. Any residual risk is caused by hydrological constraints on elements of the STT limiting transfer capacity.
- No additional in-combination benefit is observed under the STT and GUC scenario, this is a result of the solutions sharing Minworth Effluent Reuse as a supply source and the supply from STT cancelling out the in-direct benefit observed for London and SWOX WRZs under the GUC scenario.
- There are periods of time in the modelling results where sensitivities are observed between flow levels on the River Trent and the level of support that Minworth can provide to the STT and GUC solutions.

Only when STT and SESRO are combined does the relative probability of a supply shortfall become almost entirely (~90%) reduced for the Thames Water London WRZ (Figure 67), which is a ~30% increase in resilience compared to when the supporting solutions are configured individually (compare

Figure 32, Figure 34, and Figure 67). Even though the combined yield of the two solutions is theoretically 821 Ml/d, not all of the relative probability of a supply shortfall occurring is removed, especially when considering the maximum supply shortfall experienced by the London WRZ under severe droughts is ~700 Ml/d. This result is a function of the hydrological controls on the unsupported flow component of the STT and the amount of water released from Lake Vyrnwy reservoir, which reduce the transfer yield during severe inter-regional drought events and explains why supply shortfalls are still observed when STT is combined with SESRO.

Results for combining GUC and STT do not show any additional drought resilience benefit over when these solutions are configured individually demonstrating that there is no benefit from combining the solutions. When configured as an individual solution scenario, GUC shows a small (~5%) indirect benefit for Thames Water SWOX and London WRZs, which does not accumulate with the benefit from STT in the combined scenario (compare Figure 46 and Figure 67). It is likely that the small indirect benefit GUC provides to London and SWOX WRZs occurs for some less severe drought events when flow levels are sufficient on the River Thames that the extra water GUC supplies to Affinity WRZ 1, 2, 4 offsets the amount of water abstracted by this WRZ and therefore more water is available for abstraction by the SWOX and London WRZs. When STT and GUC are run in combination the extra water supplied by STT cancels out the indirect benefit from GUC to London and SWOX WRZs.

The STT and GUC solutions are both supplied by the Minworth Effluent Reuse solution, which also supports flow on the River Tame; a tributary of the River Trent from which other WRZs such as the Anglian Water Lincolnshire demand centre (Central Lincolnshire, South Lincolnshire and Anglian Nottinghamshire WRZs) have abstractions on. One of the reasons for testing the STT and GUC solution configuration was to assess whether the extra support required from Minworth Effluent Reuse would impact on water availability on the River Trent. However, supply shortfall events are not observed in the baseline scenario for the Lincolnshire demand centre and therefore the ability to measure impact of the solutions is limited. The lack of sensitivity in this area may be due to the model using incomplete water demand data for the Trent Catchment and/or overestimated river flows. Whilst it is not possible to observe an impact at the Lincolnshire demand node in WREW associated with Minworth Effluent Reuse supporting STT or GUC. It is worth noting that an impact can be observed in the modelling results in the opposite direction. For example, when flow levels are very low on the River Trent, and/or the minimum required flow level is breached, the support from Minworth to STT and GUC is substantially reduced. This suggests there is a sensitivity between Minworth supporting flow on the River Trent and supplying water to STT and GUC solutions.

5.3.4 Key Conclusions

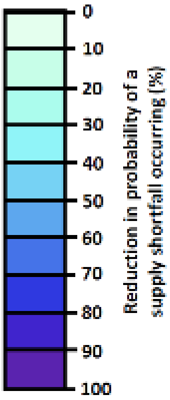
5.3.4.1 Reduced relative probability of a supply shortfall

The solutions act to significantly reduce the relative probability of a supply shortfall occurring. It is however important to note that the benefits associated with solutions are not unique, groups of other supply options could provide a similar benefit. Individual solutions that primarily supply Southern Water and Affinity Water are capable of completely removing the chance of a supply shortage occurring, whereas the larger deficits for the Thames Water London WRZ mean that solutions must be combined in order for the same level of benefit to be realised. These trends are observed under current levels of demand and without sustainability reductions in place. The scale of resilience benefit is proportional to the baseline configuration of the model, which is undergoing further validation in Phase 2. This is particularly true for the Affinity Water supply system where the drought resilience performance of solutions may be overestimated as a result of understating baseline supply shortfalls.

Table 2 The reduction in relative probability of a supply shortfall for each of the solution model scenarios tested in WREW

Where a cell contains a dash not a percentage value, this indicates that a supply shortfall was not observed for this zone.

Scenario number	SRO	WREW Demand Centre/WRZ						
		Thames Water		Affinity Water		Anglian Water		Southern Water
		London	SWOX	Affinity WRZ 1, 2, 4	Affinity WRZ 3 & 5	Ruthamford North	Ruthamford South	South Hampshire
1	STT	60-70%	90-100%	0-10%	0-10%	-	-	-
2	SESRO	70-80%	50-60%	0-10%	0-10%	-	-	-
3	LER	80-90%	0-10%	0-10%	0-10%	-	-	-
4	T2AT (SESRO)	70-80%	50-60%	90-100%	90-100%	-	-	-
5	T2AT (STT)	60-70%	90-100%	90-100%	90-100%	-	-	-
6	T2AT (LER)	80-90%	0-10%	90-100%	90-100%	-	-	-
7	A2AT (SLR)	10-20%	0-10%	90-100%	90-100%	80-90%	20-30%	-
8	GUC	0-10%	0-10%	90-100%	90-100%	-	-	-
9	T2ST (SESRO)	60-70%	50-60%	0-10%	-	-	-	90-100%
10	T2ST (STT)	50-60%	90-100%	0-10%	0-10%	-	-	90-100%
11	SW - WR + HT	-	-	-	-	-	-	70-80%
12	SW - WR	-	-	-	-	-	-	90-100%
13	WCSS & WC2ST	-	-	-	-	-	-	70-80%
14	WCNS & Transfer	-	-	-	-	-	-	60-70%
15	SESRO + STT	90-100%	90-100%	0-10%	0-10%	-	-	-
16	GUC + STT	60-70%	90-100%	90-100%	90-100%	-	-	-



5.3.4.2 Interaction v standalone

Solutions that involve interaction with the hydrological (river) network offer less drought resilience benefit than those that are standalone. For example, the STT has a transfer capacity of up to 500 Ml/d, however flow level constraints on the River Severn can act to remove the unsupported flow component of the transfer and similarly, hydrological constraints on the River Trent can limit the amount of water that Minworth Effluent Reuse can provide to support the transfer. This means that the yield of the STT is lower than the 500 Ml/d capacity.

The yield of the solution being lower than the capacity reflects the hydrological constraints arising from severe and widespread (inter-regional) drought events. Any assessment of the drought resilience of the solution should take account of these factors.

5.3.4.3 Notable in-combination drought resilience benefit

The drought resilience benefit associated with the combination of SESRO and STT has been noted in the results, with the relative probability of a supply shortfall being reduced to 91% and 99% for the Thames Water London WRZ and SWOX WRZ, respectively. This will be investigated further in Phase 2.

Despite the reduction in relative probability of a supply shortfall, the solutions do not remove the risk entirely, however.

Any residual risk is likely a function of coincident droughts between the Thames and Severn Catchments that mean the STT yield is lower than its capacity as mentioned above and also demonstrate the scale of water need (deficit) for the London WRZ.

5.3.4.4 Supporting multiple areas

When the SESRO and STT are configured to also support the T2AT and T2ST they significantly reduce the relative probability of a supply shortfall for Southern Water and Thames Water while maintaining the same performance benefit for the Thames Water WRZs. Lack of a negative trade-off for sharing water supplied by supporting solutions indicates that the transfer configurations allow for an overall more efficient setup.

It should be noted that this result is largely driven by the timing of when the solutions are active in WREW inadvertently optimising the utilisation of the STT and SESRO solutions when configured to support T2AT and T2ST. The result may therefore be a function of the simplified way in which solutions are configured in WREW, rather than representing real world behaviour.

5.3.4.5 Benefit of supporting SROs

Some of the solutions are supplied water by supporting solutions, which are in turn connected with other areas of the hydrological and supply system network. The supporting solutions have been shown to be utilised during droughts events in enabling the receiving solutions (such as STT) to deliver its benefits to the receiving WRZs. The supporting solutions are designed to cause no change to resilience in the supplying WRZs, but the lack of supply shortfalls observed in these WRZs means we were limited in our ability to measure and conclude this. This circumstance has also limited the ability to conclude resilience benefits to WRZs or demand centres that are indirectly connected with the same areas of the supply system as the supporting or receiving solutions. It is important to note that the use of a level of restriction metric, rather than a supply shortfall metric, could increase the sensitivity of the model in key areas where an indirect benefit or impact might be expected. Exploring the use of level of restriction metrics is a consideration for future work and is covered in section 6.1.6.

The high-level results presented in this report demonstrate solution performance simulated over 2,500 years of near future climate projections, which include many different spatial and temporal patterns of drought.

More detailed work is required on understanding how the solutions behave under different drought events, especially those that are geographically widespread, but that also align with the 1:500 planning requirements for severity.

6 Next Steps

The Phase 1 results presented in this report demonstrate solution performance simulated over 2,500 years of near future climate projections, which include many different spatial and temporal patterns of drought. It is clear that the WREW model is an extremely useful tool with which to explore the behaviour and drought resilience benefits of each solution and in-combination.

Nevertheless, as with all models, there can be continuous development and improvement of different aspects. Below are a number of areas where further development of the model would be useful to improve confidence and enable a greater understanding how the solutions behave under different drought events, especially those that are geographically widespread, and more severe.

6.1 Further development

6.1.1 Improve model behaviour and supply system calibration for United Utilities' network

A comparison of the simulated reservoir storage for the historic period from WREW with the outputs from the United Utilities Aquator models shows an imperfect calibration of Haweswater Reservoir, which is the company's key indicator of resource position.

Further investigation is required to assess and resolve why this discrepancy occurs. It might be brought about by operational constraints or configuration of the supply system, differences in hydrological input, or a combination of all these factors.

Improving the calibration of this reservoir, and consequently the behaviour and drought resilience characteristics of the United Utilities system in WREW, is important for understanding wider resilience impacts on STT. The United Utilities Sources and Vyrnwy Aqueduct solutions allow Lake Vyrnwy to support the STT; without a fully calibrated supply system in WREW it is difficult to assess 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.

6.1.2 Extend the geographic coverage of model validation

The spatial coverage of model validation carried out for Phase 1 is limited by the availability of simulated reservoir storage level outputs from water company modelling. In Phase 2 of the project more data will be requested from the water companies in order to extend the coverage of model validation.

6.1.3 Update representation of solutions in WREW

The representation of the RAPID solutions in WREW is based on the information available at the time of Phase 1 and is consequently a snapshot of scheme design. Since then, solutions have been further developed as part of the of the RAPID and regional planning process, which has brought about changes in scheme design. In Phase 2 of the project, important changes to solution design will be taken into account by updating the representation in WREW.

These updates will include the United Utilities Sources solution; a diffuse set of small supply options, which have been represented in WREW using an aggregated supply source that also includes the Vyrnwy Aqueduct solution.

This representation is an over-simplification as the two solutions have fundamentally different purpose and should be activated at different times. Furthermore, water from the various supply solutions that make up the United Utilities Sources solution enters the United Utilities supply system at various locations rather than one. Both solutions have implications for the resilience of the STT and therefore it is important that they are represented in a more realistic way.

Important updates to solutions in the East and West Country have been brought about by sustainability reductions increasing water needs in these regions and consequently reducing the availability of water for transfer to the South East. New configurations for water transfer pathways, such as a cascade transfer for the West Country North Sources & Transfer solution and the possibility for STT to supply the West and West Country, will also be considered in Phase 2.

6.1.4 Improve the representation of Affinity Water's groundwater abstraction

Large parts of Affinity Water'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 current representation of groundwater in WREW.

In WREW, an empirical model based on the relationship between observed antecedent ground water abstractions and rainfall is used to predict the maximum available groundwater abstraction rate from boreholes, under the weather@home2 climate scenarios. While this approach is basic, it does allow for time-variant groundwater times inputs, without the need for separate and more sophisticated groundwater modelling.

Furthermore, the GUC, Thames to Affinity Transfer, and Anglian to Affinity Transfer solutions all supply water to this area of the model, which means that groundwater representation has implications for reliability of the findings around drought resilience benefits for these solutions. The groundwater abstraction vs rainfall relationship should be explored and revised for the Affinity Water central region, to incorporate more robust groundwater level information.

6.1.5 Greater scenario testing

In Phase 1, solutions have been tested individually, in order to assess their relative performance. The pressures on national water resources are such that a set of solutions will likely be required to meet future water needs. Phase 2 of this project should investigate the in-combination benefits of the solutions and explore the associated synergies and trade-offs.

The scenario configurations tested in Phase 1 involve holding steady all of the parameters and varying only the supply system configurations for each solution. While this approach is useful for isolating the drought resilience benefits of the solutions and providing a first pass result on relative performance, it does not allow for testing uncertainty in potable demand or exploring the water needs of the environment. Investigating the uncertainty around different levels ambition for environmental destination is critical since sustainability reductions are expected to drive the largest changes in future water needs.

The next phase of the project should involve a more robust stress test of the solutions through comprehensive scenario testing and sensitivity analysis.

6.1.6 Inter-regional drought correlation

Initial findings on the drought resilience benefits of the STT show that there are times when drought conditions in the Severn Catchment impose hydrological constrains on the unsupported component of the transfer, reducing the capacity of the solution.

If similar drought conditions cover the Thames catchment at the same time and thus reduce flow on the River Thames, less water is available for the main abstractors such as Thames Water, Affinity Water and the energy sector, which leads to increased risk of water shortages. It would be useful to look in more detail at how inter-regional drought events play out in the hydrological system and supply system behaviour: this is a key benefit of using a national scale water resource model such as WREW.

6.1.7 Drought resilience metrics

A supply shortfall metric has been used in this report to measure the drought resilience performance benefit associated with the solutions. This approach is suitable because supply shortfalls incur a cost penalty within the model, and the software's Network Flow Program centres on minimising cost (i.e., the model will avoid a supply shortfall wherever possible).

An alternative metric could be used: level of service and associated water use restrictions. For example, level 4 restrictions would be a useful means of comparing with water company and regional group modelling for 1:500 level of resilience. This metric can be calculated by the model but are not part of its objective function. In real-world terms, a supply shortfall can be considered an extreme event, whereas water use restrictions are commonly imposed during drought conditions. Furthermore, whilst supply shortfall is a binary situation, there are different levels of water use restrictions, which could improve the resolution at which the drought resilience is measured in WREW.

More work is required on making sure that level of service is robustly calculated within WREW for all water companies, and is representative of real-world behaviour, before the metric can be used to reliably measure performance for the key demand centres in WREW (i.e., those that the solutions target).

Additionally, there are some demand centres that are part of the same hydrological system as those which solutions target and therefore could indirectly benefit from a solution supply offsetting use of the shared hydrological resource. Similarly, many of the solutions involve transfer of water from areas of supply, which could be affected by the solution. However, the majority of the indirect benefit and potentially impacted demand centres do not experience a supply shortfall event in the baseline scenario and therefore a benefit or dis-benefit cannot be measured. Reporting on a level of service metric for these areas should increase sensitivity of the model and generate outputs that allow investigation of how the solutions promote drought resilience.

6.1.8 Comparison of climatological input data

The modelling approach used in this study is different to the approach taken by the regional groups in that it takes a national-scale approach and spatially consistent datasets. It is however hoped that insights from the national modelling can be used to help sense check the findings of regional models and aid reconciliation between them.

For this process to work with confidence, there needs to be an understanding of whether any differences observed are a function of the input data and modelling approach or realistic behaviour that only a national model can capture. The most robust way of investigating this would be to perform an end-to-end comparison of the national and regional modelling approaches in order to explore how differences propagate through the climatological, hydrological and WR systems modelling steps in the process.

Unfortunately, the time and resources required to carry out such an analysis mean that it is not feasible as part of Phase 1. For Phase 2 therefore it is recommended that the weather@home2 climatological inputs used in WREW be compared with the stochastic datasets used by the regional groups, as well as transient UKCP18. This should help identify any discrepancies in the scale, pattern and spatial correlation of drought events, which might propagate through the hydrological modelling and affect the outputs from the water resources modelling.

6.1.9 Improve model behaviour linked to reservoir storage

Reservoir storage is an important component of supply system infrastructure since storage levels give a reliable indication of the resource position for a WRZ. For this reason, control curves set at different reservoir storage levels allow operational rules or constraints to be imposed that reduce stress on the supply system and improve performance during drought.

The majority of reservoirs in WREW include control curve information and associated strategic measures such as demand reduction. However, some reservoir control curves and operational rules and/or demand saving measures are missing from the model. Additionally, water companies change reservoir control curves as part of the drought planning statutory process, which means that some of the existing control curves in WREW also need to be updated.

Improving the representation of control curves in WREW will help improve model behaviour during drought events.

6.1.10 Test against more extreme droughts

Some of the WRZs examined in Phase 1 did not show any demand deficit against the simulated droughts, limiting the examination of additional indirect benefits of the solutions to associated areas.

It would be useful to assess the performance of the solutions against more challenging droughts in order to stress test existing and proposed infrastructure, and ascertain the direct and indirect benefits of new solutions on a nationally coherent scale.

The scenarios performed in Phase 1 have used the 'near future' drought event set outputs from the MaRIUS project which represent possible conditions in the period 2020 to 2049. A further drought event set is available which spans the 'far future', projecting changes in drought characteristics over the years 2070 to 2099 which will be more severe than the 'near future' set. It would be useful therefore to run scenarios with the far future' event set.

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