Thames Water

Final Water Resources Management Plan 2019

Technical Appendices

Appendix I: Deployable Output

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Appendix I.

Deployable Output

- This section of our Water Resources Management Plan 2019 (WRMP19) describes the amount of water which is currently available for water supply (Deployable Output (DO)) and how this has been assessed. We also present how the baseline supply forecast has been constructed.
- DO is defined and how it is calculated is explained for each of our water resource zones (WRZs). The base year DO is presented and its sensitivity to Levels of Service demonstrated. Potential impacts of possible licence reductions are also highlighted.

A. Report structure

I.1 This appendix is structured as follows:

- Definition of DO
- Explanation of conjunctive and non-conjunctive zones (CUZs)
- Explanation of DO calculation for groundwater sources with reference to confidence grades and historical records
- Exploration of the linking of groundwater SDOs to Levels of Service
- Explanation of the link between the Lower Thames Operating Agreement (LTOA) and the calculation of DO for London and Swindon & Oxfordshire (SWOX)
- Description of the Water Resources Management System (WARMS2) and explanation of how it is used to calculate DO
- Presentation of the calculation of the DO for the non-CUZs
- Demonstration of the base year DO and how recent changes to data and assumptions have impacted the calculation
- Presentation of the sensitivity of DO to changes in Levels of Service and the impacts of potential sustainability reductions
- Review of the DOs as reported in the Annual Review 2017

B. Background to Deployable Output

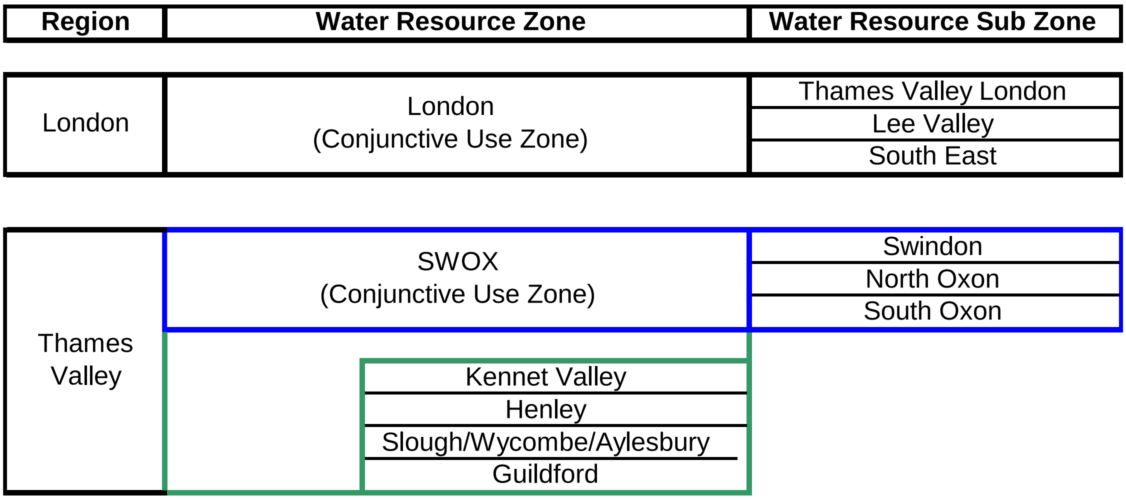
Water resource zone characteristics

I.2 Our supply area is split into two main regions: London and the Thames Valley, which are comprised of six WRZs. These WRZs have a complex supply system where in many areas surface and groundwater are mixed and operated together to increase yields over the year in reaction to antecedent weather and demand patterns. These are known as conjunctive use systems.

I.3 The London WRZ consists of three water resource sub zones (WRSZs), which are combined into a CUZ. In the Thames Valley region the SWOX WRZ consists of three WRSZs of Swindon, North Oxfordshire and South Oxfordshire. The remaining four WRZs of Kennet Valley, Henley, Guildford and Slough, Wycombe & Aylesbury (SWA) are discrete zones. These WRZs derive their raw water supplies predominantly from groundwater sources, although Kennet Valley and Guildford have significant surface water sources at Fobney and Shalford water treatment works (WTWs), respectively.

I.4 The split between the regions, WRZs and WRSZs is shown in Figure I-1.

Figure I-1: Water Resource Zones



Region	Water Resource Zone	Water Resource Sub Zone
London	London (Conjunctive Use Zone)	Thames Valley London Lee Valley South East
Thames Valley	SWOX (Conjunctive Use Zone)	Swindon North Oxon South Oxon
	Kennet Valley Henley Slough/Wycombe/Aylesbury Guildford	

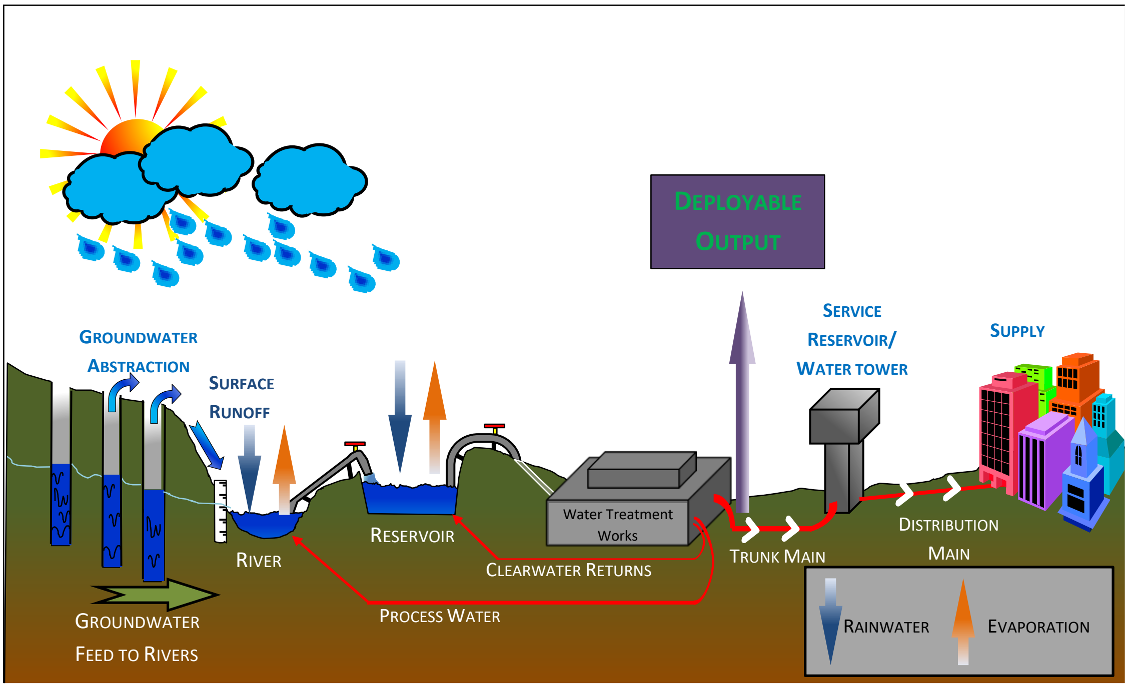
Definition of Deployable Output

I.5 DO is defined as the output of a commissioned water source or group of sources or of a bulk supply for a given Level of Service as constrained by:

- Hydrological yield;
- Licensed quantities;
- Environment (through licence constraints);
- Pumping plant and/or well/aquifer properties;
- Raw water mains and/or aquifers;
- Transfer and/or output main;
- Treatment;
- Water quality.

I.6 This is expressed in Figure I-2 below:

Figure I-2: Definition of Deployable Output



Source: Water Resources Planning Tools 2012 Definitions & Environment Agency Guidelines May 2016

Deployable Output for Thames Water

I.7 DO is calculated with reference to prescribed methodologies for surface and groundwater sources[1]. The assessment of DO also follows the principles for DO derivation as outlined in

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[1] Drayton & Lambert 1995, Environment Agency 1997, Beeson, van Wonderen & Mistear 1995, and UKWIR & Environment Agency 2000

the UKWIR report on Water Resources Planning Tools (2012) (WR27)[2]. In addition, for the purposes of producing our WRMP19, we've also applied the updated guidance, including Section 4.3 of the 2018 Water Resources Planning Guideline (WRPG)[3] and the UKWIR reports Handbook of source yield methodologies (2014)[4] and WRMP19 Methods - Risk based planning (2016)[5].

I.8 London's water comes from many sources, including boreholes, wells and springs, but most is abstracted from the Rivers Thames and Lee and stored in reservoirs before being put into supply. The reservoirs provide a buffer for use in dry periods when abstraction from the Thames is restricted. The quantities that can be abstracted from the river depend on the relationship between the quantities stored in the reservoirs, the need to ensure a residual flow over the Teddington weir, and the time of year. This is governed by the formal operating agreement between Thames Water and the Environment Agency under Section 20 of the Water Resources Act 1991, the LTOA.

I.9 Since our Water Resources Management Plan 2014 (WRMP14) there have been a number of actions that we have taken to improve our method of calculating DO. One key activity is that we have upgraded the WARMS, which is the primary tool by which we calculate DO for London and SWOX. As part of the re-development steps were taken to re-calibrate the model to improve the representation of flows at key sites (particularly looking at effluent returns and the rainfall runoff models that contribute flows to the tributaries). It also allowed for the review of the LTOA. The upgrade of our system simulation model is now called WARMS2. WARMS2 has been independently audited by HR Wallingford in 2017 as part of our WRMP19 quality assurance work, see Section 0: WARMS2 independent review, below.

I.10 There has also been agreement with the Environment Agency on a revised LTOA. The LTOA is fundamental to the calculation of DO because it determines the relationship between the flow in the River Thames, and the amount of abstraction available, for given levels of storage in the London water supply reservoirs. This in turn defines the manner in which the abstractions from the Lower Thames are managed and therefore determines the supply capability for London. Due to the interconnectivity across London it also influences the operation of other strategic sources. The LTOA is discussed further in Section D: London, below.

I.11 Furthermore our methodology for calculating groundwater DO has been reviewed and revised to align it with the current guidance and good practice, with specific changes including the use of a common drought year for all sources within a WRZ and a common peak demand period.

I.12 The SWOX WRZ is the other CUZ within our supply area, which is also modelled using WARMS2. The non-conjunctive zones of Kennet Valley, Henley, Guildford and SWA are not modelled using WARMS2 and the approach to the calculation of DO is described in the following sections.

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[2] UKWIR 12/WR/27/6 Water Resource Planning tools 2012: Summary Report
[3] Environment Agency and Natural Resources Wales produced in collaboration with Defra, the Welsh Government, and Ofwat, Water Resources Planning Guideline: Interim update, July 2018
[4] UKWIR, Handbook of Source Yield Methodologies, 2014
[5] UKWIR, WRMP 2019 Methods - Risk based planning, 2016

C. Groundwater Source Deployable Output

Annual review

I.13 Each year we review the need to update groundwater abstraction SDOs. This annual process considers two main aspects:

1) new information to enhance or update our understanding of the source constraints, such as changes to installed pumps or water treatment processes

   and/or

2) new hydrogeological data to re-assess abstraction performance and so improve the robustness of drought performance curves; this may include data from recent droughts, operational abstraction or test pumping results.

I.14 The Annual Review has been undertaken each year since 2002 and prior to this was done biennially. Over this period, our approach has been to seek continual improvement in the DO assessments, both in terms of the quality of the assessment as well as consistency through the development and adoption of documented procedures for the assessment. Improvements of particular note have included the following:

1) Adoption of an enhanced assessment grading approach, based on the original 1995 UKWIR methodology[6] that documents consistent and objective definitions of the key classifications such as “good” versus “poor” operational data.
2) Inclusion of an audit sheet that documents clearly items such as, the assessment version number, the reason for the assessment review, the assessment grading as well as the factors constraining the DO.

I.15 As a result of improvements such as the above, each of our groundwater sources has an auditable DO assessment that, since 2007, has documented a consistent and objective confidence grading.

I.16 Since WRMP14, a further improvement has been introduced to the groundwater SDO assessment methodology. The approach now defines source DOs for a common drought year for all sources within a WRZ, thereby providing consistency in their assessment. In addition, the groundwater SDOs are characterised by defining a demand driven peak DO reflecting the time of peak summer demand, a 12 month average DO, as well as a minimum DO that accounts for the lowest groundwater levels in the drought year. The calculation of these groundwater SDOs is aligned to good practice and enables a coherent assessment of our DO across the WRZs.

I.17 The procedures that underpin the calculation of DOs are set out in Thames Water’s internal document the ‘Procedure for the Assessment of Groundwater SDOs’, 2017[7].

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[6] A Methodology for the Determination of Outputs of Groundwater Sources, UK Water Industry Research (1995)

[7] Procedure for the Assessment of Groundwater Source Deployable Outputs 2017, Groundwater Resources, Water Strategy, Planning & Assurance.

I.18 To assess groundwater SDO, the important constraints that influence the outputs can be defined. This can include constraints such as:

- Abstraction borehole construction
- Pump capacity
- Depth of pump intake
- Groundwater level
- Natural hydrogeological characteristics of aquifers
- WTWs capability and process losses

I.19 In some cases it is possible to remove these constraints through, for example, the installation of new larger pumps deeper in the abstraction borehole, borehole rehabilitation or the drilling of new boreholes. Such options can provide opportunities to increase SDO within the current abstraction licence limits. Where such opportunities arise they are developed into potential future water resource options as part of the WRMP process.

Confidence grades

I.20 We recognise the importance of understanding groundwater source constraints on our DOs. Apart from spring sources, our groundwater SDOs have consistently assessed abstraction performance using groundwater levels versus abstraction output, considering the Deepest Advisable Pump Water Level (DAPWL) as a key constraint. Where it is possible, we define DAPWLs hydrogeologically at levels below which there would be a significant reduction in abstracted flow, resulting from the natural hydrogeological characteristics of aquifers. We also identify and record other potential constraints such as pump capacity, treatment works and process losses, and of course, abstraction licence limits. We review these annually to account for new information that may enhance or update our understanding of these constraints.

I.21 Since 2013, following the recommendations from the WR27 Deployable Output report[8], we have assigned a confidence grade to our source constraints information. For each of eight constraint categories identified, the availability and consistency of constraints data has been scored using an approach we have defined. An example of scoring and the results of this approach is summarised in Table I-1.

I.22 There has been a marked improvement in our knowledge of the individual source constraints since the grading system was introduced. Those classified as confidence grade “A” have increased from 29% to 40% of the total, with the remaining sources classified as “B”. This improvement has mainly been driven through the availability of Mass Balance & Resilience Models for the WTW, thereby providing a greater clarity and consistency in defining treatment capability and process losses. Further improvement has been achieved through investigations into water quality issues, CCTV surveys and pump replacements.

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[8] UKWIR 12/WR/27/6 Water Resource Planning tools 2012: Summary Report

Table I-1: Confidence grading assessment of source constraints data

Site	Licence	DAPWL	Pump Capacity	Pump Intake	Transfer	Treatment Capability	Process Loss	Water Quality	TOTAL	Score
Addington	1	1	1	1	1	1	1	1	**8**	**A**
Battersea	1	3	1	1	1	1	1	1	**10**	**B**
Brixton	1	3	1	1	1	1	1	1	**10**	**B**
Epsom - East St	1	1	1	1	1	1	1	1	**8**	**A**

Scoring

1 =	*Known*	*<9*	*= A (available and of consistent quality)*
2 =	*Estimated/Uncertain*	*9-14*	*= B (mostly available but of variable quality)*
3 =	*Unknown*	*>14*	*= C (not available)*

I.23 Using this approach, the distribution of confidence grades of our source constraints data is as follows:

A – Constraints available and of consistent quality	40%
B – Constraints mostly available but of variable quality	60%
C – Constraints not available	0%

I.24 Since 2007 we have assessed the quality and confidence in our hydrogeological data sets used to establish abstraction source performance. This is based on an objective, comparative assessment of operational abstraction data and test pumping data as described in our Procedure for the Assessment of Groundwater SDOs, 2017[9]. Using this approach, our current confidence grading for groundwater SDO assessments is summarised in Table I-2, illustrating that confidence can be graded as High, Medium or Low. The distribution of confidence grades for our groundwater SDO assessments, based on the quality of abstraction performance data, have been defined as follows:

High	19%
Medium	58%
Low	23%

I.25 The assessment of confidence in our abstraction performance data is important and complements the assessment of confidence in the constraints data discussed above. Consequently, we continue to use this confidence grading of abstraction performance data, whilst also continuing to use the confidence classification that considers the length of the hydrogeological data set (see Figure I-3). However, we recognise that there is an implication that the longer the data record the greater the confidence, as a wider range of historical droughts can be considered. Broadly, this is sensible, but if large parts of the historical record need to be hindcast by modelling, the impact of the modelling uncertainty will tend to become lost, such that the hindcast record derived from a poorly calibrated model could be taken to represent a high confidence hydrogeological record. With this in mind, a summary view of the distribution of grades using the composite confidence indicator described in Figure I-3 is presented from paragraph I.32 below.

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[9] Procedure for the Assessment of Groundwater Source Deployable Outputs 2017, Groundwater Resources, Water Strategy, Planning & Assurance.

Table I-2: Confidence grading assessment of abstraction performance data (for colour definitions see Figure I-3)

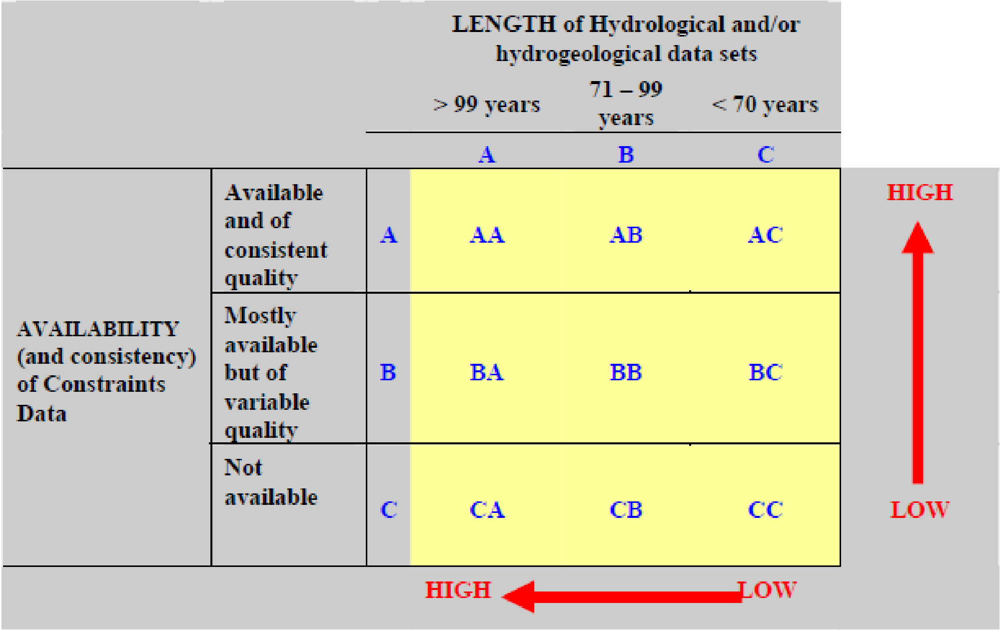
			A	B	C	D
Single Well or Borehole Sources	Good operational data, good test data	**1**	🟥 1A	🟨 1B	🟩 1C	1D
	Poor operational data, good test data	**2**	🟥 2A	🟥 2B	🟨 2C	2D
	Good operational data, poor/no test data	**3**	🟥 3A	🟥 3B	🟨 3C	3D
	Poor/no data	**4**	🟥 4A	🟥 4B	🟥 4C	4D
Multiple Well or Borehole Sources	Good operational data, good test data	**5**	🟥 5A	🟨 5B	🟩 5C	5D
	Poor operational data, good test data	**6**	🟥 6A	🟥 6B	🟨 6C	6D
	Good operational data, poor/no test data	**7**	🟥 7A	🟥 7B	🟨 7C	7D
	Poor/no data	**8**	🟥 8A	🟥 8B	🟥 8C	8D

Assessment Option
A = Abstraction output only, no water level data
B = Water level vs abstraction output
C = Water level vs abstraction output and DAPWL
D = Analytical method

Figure I-3: Confidence grading assessment of hydrogeological data

Confidence

🟥 Low 🟨 Medium 🟩 High



			LENGTH of Hydrological and/or hydrogeological data sets			
			> 99 years	71 – 99 years	< 70 years	
			A	B	C	
AVAILABILITY (and consistency) of Constraints Data	Available and of consistent quality	A	AA	AB	AC	HIGH
	Mostly available but of variable quality	B	BA	BB	BC	
	Not available	C	CA	CB	CC	LOW

Examining historical events

I.26 Since 2013, a hindcasting approach has been adopted to account, as far as is reasonably possible, for hydrological conditions back to 1920. This is in line with WR27 and the WRMP planning guidelines. This has enabled potentially key droughts from the 1940s, 1930s and 1920s to be considered. However, it is recognised that hindcasting of groundwater levels can place significant demands on data and resources and, as a result, the requirements for hindcasting need to be proportional to the source constraints on drought performance, as well as the WRZ supply demand position. Consequently, we have used the hindcasting approach to assess the impact of historical drought events on 79% of our sources, which represents 69% of our London sources and 88% of our Thames Valley sources. The sources that have not been subject to hindcasting are either disused, emergency sources, or do not show a natural recharge response and therefore are not sensitive to drought.

I.27 The hindcasting approach identified a representative observation borehole for each groundwater source, and a long-term hydrograph was constructed for each of these “Catchment Indicator Boreholes”. In order to do this, the groundwater sources were grouped into zones where aquifer behaviour is considered to be similar and an indicator borehole was identified. Selection of the indicator borehole was based on:

- Length of borehole record;
- Data quality of the borehole record;
- The similarity of the hydrograph to the groundwater sources; and
- Whether the borehole shows impact of abstraction.

I.28 The majority of the observation boreholes have records that do not go further back than the 1970s, and many are only a few years long. However, measured groundwater level data is available, for example, for the Chalk aquifer from 1942 for the Chipstead observation borehole (formerly Well House Inn borehole) and from 1933 for the Rockley observation borehole, in the London and SWOX WRZs respectively. Furthermore, lumped parameter groundwater models developed by the British Geological Survey, as part of the Environment Agency/UKWIR Future Flows and Groundwater Levels project[10], have been hindcast to at least 1920. Prior to this, the British Geological Survey models use rainfall and temperature-derived potential evapotranspiration (PET) data to hindcast groundwater level records back to 1888 for Chipstead/Well House Inn and 1907 for Rockley, as well as to 1910 for observation boreholes in the Great and Inferior Oolite aquifers in the Cotswolds of the SWOX WRZ. Nevertheless, in most cases, it was necessary to construct longer hydrographs for the indicator boreholes based on regression relationships with other boreholes, with the record infilled to create a “composite” record (Figure I-4).

I.29 For some groundwater sources, there was insufficient available data to construct an acceptable composite hydrograph, often because of a difference in the amplitude of groundwater level fluctuation. In these cases, an existing composite record has been compared with an observation borehole, often with a short record, closer to the groundwater

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[10] Centre for Ecology and Hydrology Natural Environment Research Council (2012) Future Flows and Groundwater Levels: British projections for the 21st century

source, and a regression relationship developed. The equation for this regression was then used to factor the whole composite record to generate a “reconstructed” record (Figure I-4).

I.30 Within each indicator borehole hydrograph, the groundwater level in the critical drought year, at a specified demand period, can be identified. This level is used to adjust the drought performance curve for the associated groundwater source so that its SDO assessment is representative of the defined critical drought. The detail of how the long term indicator borehole hydrographs have been constructed and applied to the SDOs is contained in our Procedure for the Assessment of Groundwater SDOs, 2017[11]. Further discussion is provided in paragraph I.34 below, describing recent improvements to the assessment methodology around the critical drought year and demand period.

I.31 As discussed in paragraph I.25, model uncertainty needs to be acknowledged as a limitation when assigning a higher confidence in DO assessments due simply to a longer groundwater level record. Notwithstanding this, the analysis of pre-1920 droughts in the Chipstead/Well House Inn observation borehole indicates, for example, that notable low groundwater levels hindcast for the period 1888 to 1920 are not significantly lower than those levels experienced in 2005/06 and 2012, and are above those hindcast for the 1920s. This indicates that droughts prior to 1920 are unlikely to affect groundwater SDOs in London.

I.32 Following the hindcasting of groundwater levels, and the constraints confidence assessment described in paragraph I.20 and following, a composite confidence grading indicator, as presented in Figure I-3, has been assigned to each of our operational sources. The distribution of grades is as follows:

AA – Constraints available, Length of Record >99 years	23%
BA – Constraints mostly available, Length of Record >99 years	21%
AB – Constraints available, Length of Record 71 – 99 years	4%
BB – Constraints mostly available, Length of Record 71 – 99 years	12.5%
AC – Constraints available, Length of Record <70 years	12.5%
BC – Constraints mostly, Length of Record <70 years	27%

I.33 All of the sources have constraints availability scores of A or B. Therefore there are no sources in the categories CA, CB and CC, which have been omitted from the list above. The gradings above also indicate that approximately 60% of all our operational sources have lengths of hydrological record ≥71 years.

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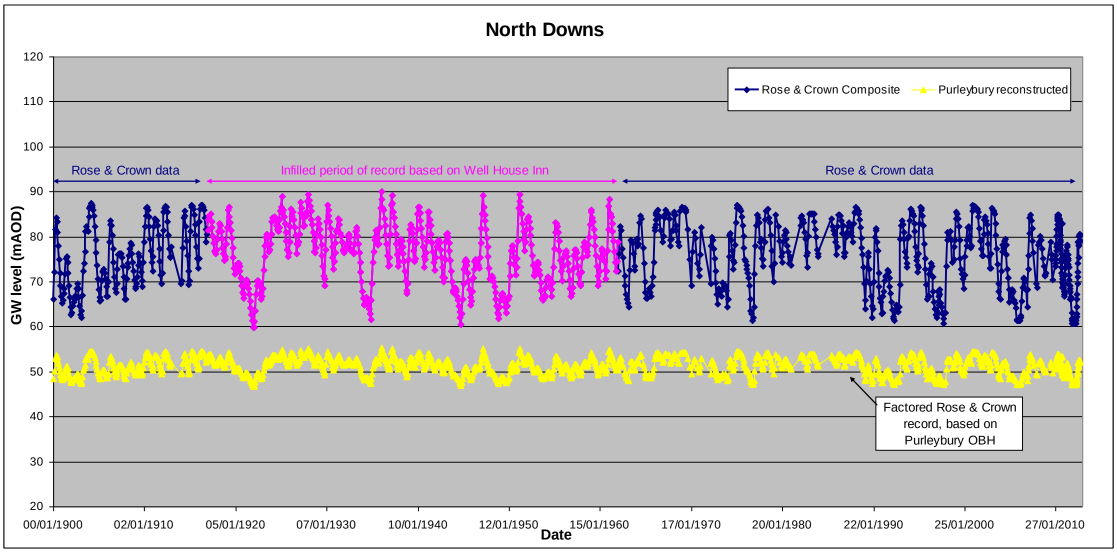
[11] Procedure for the Assessment of Groundwater Source Deployable Outputs 2017, Groundwater Resources, Water Strategy, Planning & Assurance.

Figure I-4: Groundwater hydrographs for the Rose & Crown and Purleybury indicator boreholes, showing the difference between a composite record and a reconstructed record



Realigning groundwater Source Deployable Output assessments

I.34 To ensure a consistent assessment of DO within a WRZ, we have made improvements to the groundwater Source Deployable Output assessment methodology. The approach now defines source DOs for a single drought year for all sources within a WRZ. The critical year for each WRZ is presented in Table I-3 as follows:

Table I-3: Definition of critical drought year for WRZ

WRZ	Critical drought year	Defined by
London	1921	WARMS2
SWOX	1976	WARMS2
Kennet Valley	1976	Fobney WTW
Henley	1976	Groundwater Records
SWA	1976	Groundwater Records
Guildford	1992	Groundwater Records

I.35 The critical years for the CUZs of London and SWOX have been defined by WARMS2. The critical year for Kennet Valley WRZ has been defined by Fobney WTW, with reference to flows in the River Kennet; Fobney WTW is an important surface water source within the zone. Examination of groundwater records suggests varying critical years for different sources within the Kennet Valley, but 1976 represents the critical year for the largest proportion of DO in the zone, and therefore is a sensible drought year to use. The remaining WRZs have used groundwater level and performance records to define the critical year. Henley and SWA are groundwater only zones. Guildford WRZ also has the run of river source that feeds Shalford WTW. This source is robust across all of the drought years examined, and therefore it is reasonable to use groundwater records to define the critical year for this zone. The approach described ensures a coherent, hydrologically consistent, assessment of DO across all sources within each of the WRZs.

I.36 For WRZs outside of London, there is now less reliance on the hindcasting described in paragraph I.26 and following. Nevertheless, the Catchment Indicator Borehole hydrograph that has been compiled for hindcasting is still essential for the assessment of the groundwater SDO. It is used to identify the groundwater level in the defined critical drought year for the WRZ, at the time of the appropriate demand period. This groundwater level is then used to adjust the drought performance curve for the associated groundwater source, so that its SDO may be determined.

I.37 The UKWIR Handbook of source yield methodologies (2014)[12] notes that an approach that is frequently used is to declare Minimum SDOs as the Average SDO. This means that the SDO is assessed at the time of minimum groundwater level, but the report states that this represents a compromise as it compares average demand with a critical period output. The hindcast indicator boreholes described above present the ability to determine the SDO for any given time period. Consequently, in addition to calculating a Minimum SDO for the critical drought year, we now also calculate a 12 month Average SDO for the critical drought year (Dry Year Annual Average (DYAA)), and also a demand driven Peak SDO for the Average Day Peak Week (ADPW) at the time of peak summer demand (Dry Year Critical Period (DYCP)). These changes improve the groundwater SDO assessment methodology by further aligning it with the current guidance and presenting a more consistent approach across the entire WRZ.

Linking groundwater Source Deployable Outputs to Levels of Service

I.38 Following the introduction of a hydrologically consistent drought year for each of the WRZs, we have assessed the sensitivity of SDO to the hindcast groundwater levels in the critical year, at specified demand periods. We have identified that 78% of our London groundwater sources, when considering the 12 month average condition, are not constrained by groundwater levels but by licence or other infrastructure constraints. In addition, considering the peak condition for the Thames Valley shows a figure of 73% of sources that are not constrained by groundwater levels. This means that, considering average conditions for London and peak in other WRZs, current or alternative Levels of Service will have no effect on the DO of around 76% of our groundwater sources.

I.39 The corollary of our current assessment is that there may be 24% of our groundwater sources, where resource availability constrains our DO. Consequently, for this group of sources, there may be a discernible effect on level of service implementation on groundwater availability and, as such, an increase in DO might result. Table I-4 below is an analysis of the distribution of these groundwater level dependent sources by WRZ. At first sight, when considering the proportion of resource constrained SDO in the context of total (groundwater) WRZ SDO, there would appear to be a significant opportunity to increase DO through the

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[12] UKWIR, Handbook of Source Yield Methodologies, 2014

introduction of Levels of Service for certain WRZs. For many sources, even if the resource constraint was removed, perhaps by the introduction of Levels of Service, another secondary infrastructure constraint is sometimes present, which prevents the realisation of the full licensed quantity. This aspect is examined and quantified in more detail in Table I-5. However, when the potential opportunity from Levels of Service is examined further in the context of the planning guidelines, see Paras I.41 to I.46 below, the magnitude of the opportunity diminishes.

I.40 In addition, for the London and SWOX WRZs, Levels of Service are based on the conjunctive use nature of these zones.

Table I-4: Analysis of groundwater level constrained SDOs

WRZ	No. of sources constrained by groundwater level		Groundwater level constrained SDO as percentage of total WRZ SDO		Maximum difference between the licensed output and groundwater level constrained SDO as percentage of total WRZ SDO		Difference between the output limited by secondary constraint and GWL constrained SDO as percentage of WRZ SDO	
	Average	Peak	Average %	Peak %	Average %	Peak %	Average %	Peak %
London	11	10	19	19	4	6	3	4
SWOX	11	12	19	16	7	12	6	9
Kennet Valley	1	1	36	32	12	10	12	10
Henley	0	0	0	0	0	0	0	0
SWA	2	2	5	11	2	2	0	2
Guildford	1	1	5	5	2	2	1	1

Note: In the calculations above, WRZ SDO excludes surface water sources

Table I-5: Analysis of secondary constraints on SDOs

WRZ	No. of sources constrained by groundwater level		Difference between the output limited by secondary constraint and groundwater level constrained SDO (Ml/d)		Difference between the output limited by secondary constraint and groundwater level constrained SDO as percentage of WRZ SDO	
	Average	Peak	Average %	Peak %	Average %	Peak %
London	11	10	14.1	21.1	3	4
SWOX	11	12	11.7	18.7	6	9
Kennet Valley	1	1	9.5	9.5	12	10
Henley	0	0	0.0	0.0	0	0
SWA	2	2	0.7	4.1	0	2
Guildford	1	1	0.3	0.3	1	1

Note: In the calculations above, WRZ SDO excludes surface water sources

I.41 With the above initial analysis providing a framework, all of our groundwater sources have been categorised into one of the following three categories:

1) Current or an alternative level of service will have no effect on DO as the source output is not constrained by resource but by licence or infrastructure constraint;
2) The resource constrains DO but the effect of Levels of Service implementation is mainly increased stream or spring flow. There may be a discernible effect of level of service implementation on DO;
3) The resource constrains DO. There will be a discernible effect of level of service implementation on groundwater availability from which an increase in DO should result.

I.42 The number of sources that fall within category 1 is 84; that is, considering average conditions in London and peak in Thames Valley, there will be no effect on DO through the introduction of Levels of Service. For the remaining sources, it is considered sensible to impose a threshold whereby if the potential DO gain is ≤1 Ml/d, then there will be no discernible effect of level of service implementation on DO. Applying this threshold highlights 15 sources where Levels of Service will not impact on DO. A further three sources are springs, which fall within category 2; it is unlikely that applying Levels of Service will deliver a discernible impact on DO as the main effect of implementing Levels of Service will be to increase spring flow rather than increase DO. The remaining nine sources where there may be a discernible impact from applying Levels of Service based on groundwater levels are split over four WRZs; London, SWOX, SWA and Kennet Valley, and are discussed in more detail below. In the remaining two WRZs, Henley and Guildford, there are no opportunities to deliver a discernible effect on DO from implementing Levels of Service based on groundwater levels.

I.43 Three sources potentially fall within category 3 in the London WRZ; Addington, Deptford and Turnford. However, Levels of Service for the London WRZ are already based upon the conjunctive use of groundwater, surface water and raw water storage and therefore, there is no clear driver to implement alternative Levels of Service based on groundwater levels for these two sources.

I.44 Four sources potentially fall within category 3 in the SWOX WRZ; Ashton Keynes, Latton, Ogbourne and Cleeve. The licence at Ogbourne was revoked on 1 April 2017. It has been included in the analysis as it is declared in our Base Case. However there is no benefit in considering it further within this context. The conjunctive use nature of this resource zone also precludes there being a clear driver to introduce alternative Levels of Service based on groundwater levels as Levels of Service related to conjunctive use are already in place.

I.45 The Kennet Valley WRZ contains one source, Pangbourne, which may potentially fall within category 3. It represents 10% of the potentially available groundwater resource, limited by the secondary constraint. It is worth noting that although the Kennet Valley WRZ operates as a discrete zone, it has Fobney WTW as a significant surface water source, and that the peak DO benefit from this source (65 Ml/d) has not been taken into account in the tables above. Taking this into account indicates that groundwater resource constrained DO is <7% of the total WRZ DO and, as a result, it is considered that there is no clear driver to implement alternative Levels of Service based on groundwater levels at Pangbourne WTW.

I.46 The Slough/Wycombe/Aylesbury WRZ contains the final source, Dorney, which may potentially fall into category 3. It represents only 2% of the potentially available groundwater resource, limited by the secondary constraint. Dorney abstracts from the River Gravels, and therefore a proportion of the water will be from induced leakage from the River Thames. There would therefore be no benefit to DO from implementing Levels of Service based on groundwater levels.

D. London

Lower Thames Operating Agreement

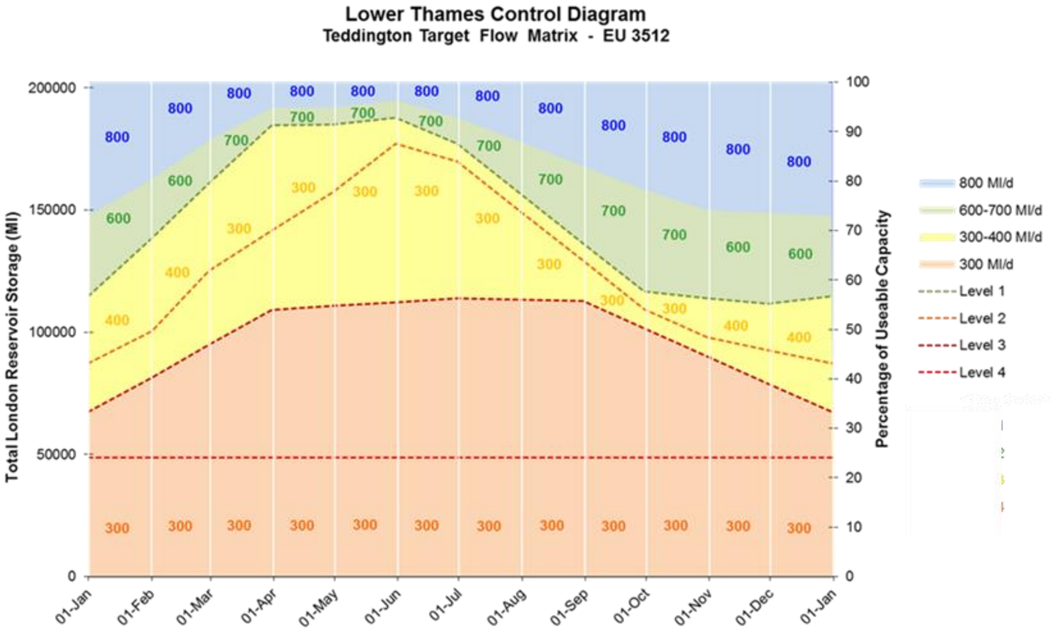
I.47 The abstraction from the Lower Thames, where water is abstracted to the London reservoirs, is constrained not just by the abstraction licence but also by the LTOA. The LTOA contains a control diagram on which the total volume in storage in the Thames Water London reservoirs is plotted on a daily basis against time. Explicit in the LTOA is the need to maintain a prescribed flow over Teddington Weir which is controlled according to total London storage and the imposition of water use restrictions on customers and the time of year. As London reservoir levels fall, the minimum flow over Teddington Weir (the residual river flow to tidal waters) may be reduced by abstraction in defined bands down to a minimum flow of 300 Ml/d. In conjunction with the changing flow constraint, as storage declines the company must apply progressively more intensive demand management measures and restrictions on water use by customers in order to both preserve available storage and mitigate against over abstraction from the River Thames and consequent environmental damage.

I.48 The development of WARMS2 allowed the timely review of the LTOA and the chance to optimise the Lower Thames Control Diagram (LTCD). The optimisation of the LTCD aimed at getting an improved DO for London whilst at the same time reducing the environmental impact of the abstractions. The shape of the LTCD was previously reviewed in 1997 although the assumed savings from restrictions placed on customers was updated in 2012 following the Drought Direction 2011. TW worked closely with Environment Agency colleagues to determine the environmental objectives for the LTCD and to develop the methodological approach. A 6-week public consultation was also undertaken.

I.49 A number of optimisation criteria and constraints relating to management of the lower Thames were agreed between TW and Environment Agency and subsequently used to govern the optimisation process. The criteria included determining the Level 4 restriction line dynamically as DO changes; this line also acts as the level of "Emergency Storage" for the London reservoir system and is a pre-requisite of the methodology for determining DO. Several thousand versions of the LTCD were generated and these were subsequently screened against a variety of different criteria to reduce the long list of potential control curves to a more manageable number for examination of the environmental effects of the new control diagram.

I.50 The Senior Management of both organisations endorsed the revised control diagram, seen in Figure I-5, and a subsequent amendment to Schedule 2 of the existing LTOA (version dated 25 March 2014) to include the updated, optimised LTCD.

Figure I-5: Lower Thames Control Diagram



I.51 For about 85% of the time, the residual flow over Teddington Weir would be at or above 800 Ml/d. As flows recede during drought periods however, the operating strategy provides the framework for continued abstraction through the progressive reduction of the residual flow down to 300 Ml/d. At the same time, as storage declines, progressively more enhanced measures of water use restrictions are applied to manage demand and strategic schemes (additional sources of supply which help to off-set the depletion of surface water resources during drought) are progressively triggered and operated to support yields.

I.52 These measures range in severity and are commensurate with the Company's Levels of Service. The restrictions imposed and the Levels of Service are outlined in Table I-6. The level of service frequency has been determined from analysis of the historical record of rainfall and evaporation from 1920.

Table I-6: Levels of Service

Restriction Level	Frequency of occurrence	Water use restrictions
Level 1	1 year in 5 on average	Intensive media campaign
Level 2	1 year in 10 on average	Sprinkler/unattended hosepipe ban, enhanced media campaign
Level 3	1 year in 20 on average	Temporary Use Ban (TUB) (formerly Hosepipe ban), Drought Direction 2011 (formerly non-essential use bans) requiring the granting of an Ordinary Drought Order
Level 4	Never*	If extreme measures (such as standpipes and rota cuts) were necessary their implementation would require the granting of an Emergency Drought Order

** Based on historical twentieth century droughts.*

I.53 Planned annual risk, expressed as a percentage, of drought measures linked to trigger levels on the LTCD and how the annual risk will change through the 80 planning period following a step up in drought resilience from 1:100 year worst historic drought event to 1:200 year drought event in 2030/31 is presented in Table I-7.

Table I-7: Thames Water's planned levels of service (as agreed with customers) and actual levels of service (as modelled) presented as **annual** average **risk of all restrictions as a percentage and as a level of frequency. Planned levels of service agreed with customers are linked to trigger levels on the Lower Thames Control Diagram (LTCD) with actual levels modelled outputs as provided to customers. A step up in company drought resilience from 1:100 year worst historic drought events to 1:200 year drought events in 2030/31 is shown to maintain planned levels of service and improve actual levels of service through the 80 year planning horizon.**

		PLANNED LEVELS OF SERVICE (AS AGREED WITH CUSTOMERS)		ACTUAL LEVELS OF SERVICE (AS MODELLED)	
	Water Use Restrictions	2016/17 to 2029/30 1 in 100 Drought Resilience Planned Frequency of Occurrence (Planned % Risk)	2030/31 to 2099/100 1 in 200 Drought Resilience Planned Frequency of Occurrence (Planned % Risk)	2016/17 to 2029/30 1 in 100 Drought Resilience Modelled Frequency of Occurrence (Modelled % Risk)	2030/31 to 2099/100 1 in 200 Drought Resilience Modelled Frequency of Occurrence (Modelled % Risk)
Level 1	Intensive water saving media campaign	1 year in 5 on average (20% annual average risk)	1 year in 5 on average (20% annual average risk)	1 year in 5 on average (20% annual average risk)	1 year in 5 on average (20% annual average risk)
Level 2	Sprinkler / unattended hosepipe ban, enhanced media campaign	1 year in 10 on average (10% annual average risk)	1 year in 10 on average (10% annual average risk)	1 year in 13 on average (8% annual average risk)	1 year in 25 on average (4% annual average risk)
Level 3	Temporary Use Ban (formerly hosepipe ban), Drought Direction 2011 (formerly non-essential use bans) requiring the granting of an Ordinary Drought Order. NB. Drought Permits are also part of Level 3 measures but do not impinge directly on customers and so are not strictly relevant to customer service levels.	1 year in 20 on average (5% annual average risk)	1 year in 20 on average (5% annual average risk)	1 year in 25 on average (4% annual average risk)	1 year in 40 on average (2.5% annual average risk)
Level 4	Extreme restrictions such as standpipes and rota cuts in supply. If such measures were necessary their implementation would require the granting of an Emergency Drought Order.	1 year in 100 on average (1% annual average risk)	1 year in 200 on average (0.5% annual average risk)	1 year in 100 on average (1% annual average risk)	1 year in 200 on average (0.5% annual average risk)

I.54 The assumptions used to estimate the planned annual risk of these drought measures through the planning period are as follows:

I.55 Level of Service for demand restrictions (TUBS and NEUs) and drought permits are stated in our 2018 revised draft Drought Plan and WRMP (Table I-6) as a frequency of occurrence which is fixed through every year of the planning horizon as agreed with customers through stakeholder engagement.

I.56 Atkins has analysed IRAS results for Level 2 and Level 3 to assess the difference when the demand on the London reservoirs is reduced from AR17 London Baseline DO of 2305 Ml/d down to 2165 Ml/d (reflecting the 140Ml/d DO improvement to get to 1 in 200 year resilience (Section L 1:200 Table I-26 and Table I-27) under the stochastic data to see which years fail and to determine the return period of failures. We have also completed this analysis within WARMS2 reducing the demand from 2305 Ml/d down to 2165 Ml/d under the historic data, analysing the results for Level 2 and Level 3 to see which years fail and to determine the return period of failures. The results from this analysis provide the frequency of occurrence and annual average risk of restrictions under the historic data plus the change under the stochastic 1 in 200 data.

I.57 This analysis shows that for us planning to a 1 in 100 level of drought resilience, before the step up to 1 in 200 after 2030, the annual risk of Level 2 and Level 3 restrictions is lower than that stated in the Level of Service as agreed with customers, this is lowered further when resilience steps up to 1 in 200 in 2030. The annual risk of Level 4 restrictions is in line with the company's stated level of drought resilience and it is maintaining this level of supply security that is the driver for investment in the WRMP.

I.58 We aim to maintain Levels of Service, in terms of restrictions on customers, through the planning horizon whilst reducing the frequency of occurrence of environmentally damaging drought permits which this analysis supports.

I.59 The LTOA was originally implemented as part of the Teddington Flow Public Inquiry in 1986. At that time, there were more opportunities to reduce demand through pressure management and leakage control. Level 1 demand management measures, therefore, included an intensified leakage control programme. Since the mid-1990s however, leakage control has become a major component of the company’s baseline supply demand strategy and now the LTOA reflects the restrictions imposed by the more recent legislative powers.

I.60 The new legislative powers arose to clarify what, when, and how water companies could impose restrictions on the water use of customers during a drought. These powers came into effect with the passing of Flood and Water Management Act 2010[13] and further prescribed by the Water Use (Temporary Bans) Order 2010 (referred to herein as Temporary Use Ban or ‘TUB’) and the Drought Direction 2011 (DD11). These replaced the historic hosepipe ban and non-essential use ordinary drought order restrictions respectively. As a result of this a review of the demand savings that could be achieved with the implementation of drought measures was undertaken. The assumptions for savings in demand as a result of the implementation of these demand management measures are presented in Table I-8 for the Thames Valley and Table I-9 for London. The cumulative savings achieved up to and including Level 3 are

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[13] http://www.legislation.gov.uk/ukpga/2010/29/contents

greater in the Thames Valley (maximum 19.1 per cent in July) than those seen in London (maximum 14.5 per cent in July).

I.61 The frequency with which these measures are used to restrict demand defines the Levels of Service customers receive. The lower the level of service, the more frequent the imposition of restrictions to supply (such as TUB) occurs, and conversely, the higher the level, the less frequently they occur. As the differing levels of restrictions are imposed there are assumed reductions in demand. These are key factors in establishing the supply capability as presented below.

Table I-8: Revised estimates (%) for the impacts of (Ml/d) demand reduction in Thames Valley during a drought, based on DD11 assumptions

Units of Percent	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Level 1	1.3	1.4	1.4	1.8	1.9	3.6	3.8	3.7	1.6	1.4	1.4	1.4
Level 2	2.4	2.5	2.6	3.9	4.3	10.1	10.5	10.2	3.5	2.8	2.6	2.5
Cumulative Levels 1-2	3.8	3.9	4.0	5.7	6.3	13.7	14.3	13.9	5.1	4.2	4.0	3.9
Level 3a: TUB	0.8	0.8	0.8	1.3	1.4	3.4	3.6	3.4	1.1	0.9	0.8	0.8
Level 3b: DD11	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Cumulative Levels 1-3	5.8	5.9	6.0	8.2	8.9	18.3	19.1	18.6	7.4	6.3	6.1	5.9
Level 4	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Total Savings Levels 1-4	23.8	23.9	24.0	26.2	26.9	36.3	37.1	36.6	25.4	24.3	24.1	23.9

Table I-9: Revised estimates (%) for the impacts of (Ml/d) demand reduction in London during a drought, based on DD11 assumptions

Units of Percent	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Level 1	1.1	1.2	1.2	1.3	1.5	2.2	2.2	2.1	1.3	1.2	1.2	1.2
Level 2	2.2	2.2	2.3	3.2	3.8	7.5	7.9	7.1	3.2	2.6	2.4	2.3
Cumulative Levels 1-2	3.4	3.4	3.4	4.5	5.3	9.7	10.1	9.2	4.5	3.8	3.6	3.5
Level 3a: TUB	0.7	0.7	0.7	1.1	1.4	2.8	3.0	2.7	1.1	0.9	0.8	0.8
Level 3b: DD11	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Cumulative Levels 1-3	5.4	5.5	5.5	7.0	8.0	13.9	14.5	13.2	7.0	6.1	5.8	5.6
Level 4	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Total Savings Levels 1-4	23.4	23.5	23.5	25.0	26.0	31.9	32.5	31.2	25.0	24.1	23.8	23.6

TUB = Temporary Use Ban

DD11 = Drought Direction 2011.

I.62 Demand side benefits are quantified for CUZs, both London and SWOX. The DO benefit of demand restrictions in London included in baseline DO under a worst historic drought is 126 Ml/d and for SWOX 27 Ml/d as set out in Appendix A: Table 10. Table 10 presents the ‘no restrictions imposed’ scenario modelled in WARMS2 for the London WRZ with a decrease in DO of 126 Ml/d.

I.63 For our other zones, which are not CUZs the demand restrictions do not affect DO and so are not included in our supply demand balance. For these zones there is no strategic storage and so no progressive loss of storage during a drought and our WRMP19 shows that we can meet demand with the DO for the zone and so demand reduction does not contribute to the maintenance of DO. However during a drought, demand restrictions will be implemented across all zones in line with our 2018 revised draft Drought Plan and so will help to reduce demand in the groundwater dominated zones thereby providing resilience to droughts greater than those observed in the historic record which may give rise to some marginal reductions in yield as set out in our analysis for Appendix A: Table 10.

I.64 The mechanism by which demand restrictions are triggered in the Thames Valley Water Resource zones is set out in detail in our 2018 revised draft Drought Plan. Drought management decisions must start with a consideration of the impact the drought is having on the supply capability within each WRZ and the approach taken in formulating the drought management protocol is dependent upon the nature of the water resources system within each WRZ. Because of the dominant nature of the London WRZ, it will generally be the case that the water use restrictions introduced in the London WRZ will also be applied to the rest of our supply area. Nonetheless, the Drought Plan recognises that there may be situations in which more local measures may need to be introduced for the other WRZs, consequently, protocols have also been developed for these zones. Table I-10 below presents the protocol for each zone.

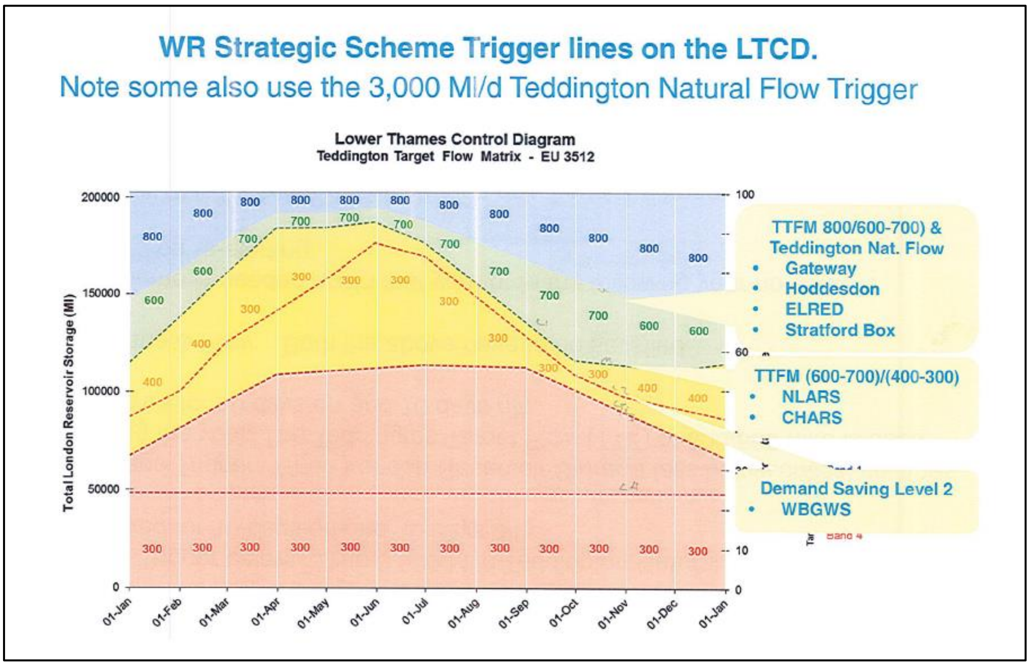
Table I-10: Protocol for triggering demand restrictions in the Thames Valley WRZs

WRZ	Demand Restriction Protocol
SWOX	• In SWOX the protocol is similar to that of London for the introduction of water use restrictions associated with the Levels of Service. However, unlike the London WRZ, there are no supply-side strategic drought schemes built into the zone's DO; the major supply-side augmentation comes mainly in the form of increased abstraction from existing sources introduced through the drought permit mechanism. • The principal and most drought-critical source in the SWOX WRZ is the Farmoor water resources system comprising abstraction from the River Thames transferred to Farmoor reservoir, referred to in the next sub-section. Following the publication of the Drought Plan 2010, the methodology for the zone was reviewed and amended in recognition of the concern expressed by the EA and Defra on the potentially relatively rapid decline in Farmoor reservoir storage compared to London reservoir storage under comparable low flow conditions. • New triggers: The Farmoor licence increasingly constrains abstraction from the river as the River Thames recedes under low flow conditions. This, in turn, governs the quantity of river water that can be transferred to Farmoor reservoir. This river/reservoir dependency has been used to define a set of triggers based on critical low flows at Farmoor, the criteria are as follows: Trigger for determining the submission date for DD11 order and drought permit applications is set at 200 Ml/d (5-day running mean) under DEL3 or DEL4 drought event scenarios;
Kennet Valley and Guildford	• Although groundwater provides a major contribution in these zones, the critical drought elements are the surface water sources on the River Kennet and River Wey for Kennet Valley and Guildford, respectively. The protocol for these zones is therefore based on river flow reaching critical low levels which act as the trigger mechanism for the introduction of drought measures. But as mentioned above, the drought situation in London is the principal factor in determining the drought response in these zones.
Slough/Wycombe/ Aylesbury (SWA) and Henley	• These two zones are entirely supplied by groundwater sources, which historically have remained robust during drought. That is to say, the critical point at which source outputs decline below their DO has never been reached. The approach in these zones, therefore, is to track key regional observation boreholes as well as to track the performance of selected groundwater sources in relation to their DO. However, as mentioned above, the drought situation in London is the principal factor in determining the drought response in these zones. This is because in a severe drought measures are likely to be implemented Company-wide and measures implemented in the SWA and Henley WRZs will have a small but positive benefit for London.

I.65 The London WRZ further relies on the introduction of water resource strategic schemes, including the WBGWS, which increases London's supply capability helping to off-set the depletion of surface water resources during drought. Strategic schemes are operated in the following order as LTCD storage and flow triggers are crossed as shown in Figure I-6.

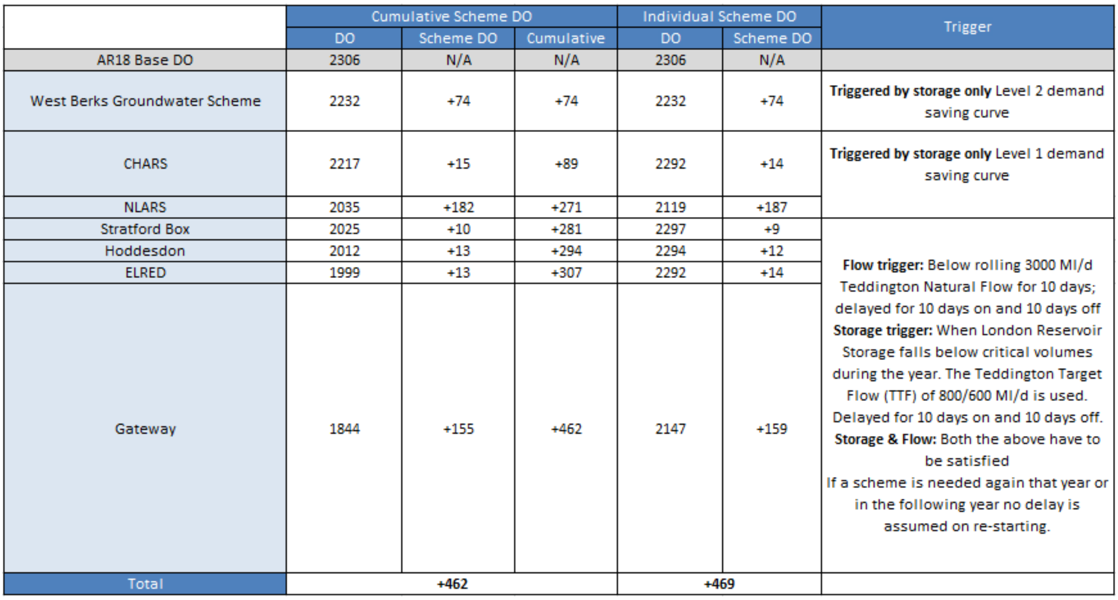
1) **Gateway** the Beckton desalination plant which takes raw water resource from the Thames Tideway), **the Hoddesdon Transfer Scheme** which takes effluent from the Deephams STW catchment to Rye Meads STW catchment via a pipeline and a sewage pumping station increasing the volume of water in the River Lee diversion channel and allowing increased abstraction and the **East London Resource Development Project (ELRED**) **and Stratford Box (and Old Ford),** small groundwater schemes located in confined Chalk which can be operated in conjunction.
2) **North London Aquifer Recharge Scheme (NLARS) and Chingford Artificial Recharge Scheme (CHARS)** which enable beneficial use of the confined Chalk aquifer in North London by a technique known as managed aquifer recharge.
3) **West Berkshire Groundwater Scheme (WBGWS)** a strategic drought river augmentation scheme

Figure I-6: Water Resources Strategic Scheme Trigger lines on the LTCD



I.66 Strategic schemes support yield and provide DO benefit included within the baseline DO for London. The DO benefits in Ml/d and details of the LTCD flow and storage triggers are shown in Table I-11. It is noted that the DO of the schemes varies depending on the order they are switched off as the nature of the system is changed with each switch off. Table I-11 shows both the cumulative DO benefit included within the London WRZ DO (assessed in WARMS2 by switching schemes off in the following order WBGWS → CHARS → NLARS → Hoddesdon → Stratford Box → ELRED → Gateway) versus the individual DO benefit included within the London WRZ (assessed in WARMS2 by switching schemes off one at a time and evaluating each scheme individually). The latter individual approach can cause problems in that in some instances DO are greater than output as impacts of LTCD need to be accounted for. It is noted that Table C of the Drought Plan presents the yields as opposed to the DOs of the strategic schemes as accounted for within the total DO for London.

Table I-11: London WRZ DO benefits of Water Resources Strategic Schemes



	Cumulative Scheme DO			Individual Scheme DO		Trigger
	DO	Scheme DO	Cumulative	DO	Scheme DO	
AR18 Base DO	2306	N/A	N/A	2306	N/A	
West Berks Groundwater Scheme	2232	+74	+74	2232	+74	**Triggered by storage only** Level 2 demand saving curve
CHARS	2217	+15	+89	2292	+14	**Triggered by storage only** Level 1 demand saving curve
NLARS	2035	+182	+271	2119	+187	
Stratford Box	2025	+10	+281	2297	+9	**Flow trigger:** Below rolling 3000 Ml/d Teddington Natural Flow for 10 days; delayed for 10 days on and 10 days off **Storage trigger:** When London Reservoir Storage falls below critical volumes during the year. The Teddington Target Flow (TTF) of 800/600 Ml/d is used. Delayed for 10 days on and 10 days off. **Storage & Flow:** Both the above have to be satisfied If a scheme is needed again that year or in the following year no delay is assumed on re-starting.
Hoddesdon	2012	+13	+294	2294	+12	
ELRED	1999	+13	+307	2292	+14	
Gateway	1844	+155	+462	2147	+159	
Total		+462			+469	

I.67 The WBGWS is triggered by London reservoir storage drawing down to the Level 2 control curve on the LTCD. The yield benefit of the WBGWS is stated as 126 to 67 Ml/d within Table C of the Drought Plan, revised following consultation, and the DO of the scheme has been assessed using WARMS2 for London as +74 Ml/d which is built into the baseline London WRZ DYAA DO figure. During a drought, abstraction from the Chalk aquifer by the WBGWS also contributes to flows in the River Kennet and therefore 43 Ml/d is built into the Fobney WTW DO and therefore the Kennet Valley WRZ DYAA and DYCP DO figures (see Section G: Kennet Valley Deployable Output).

E. Water resources management system

Modelling the Thames catchment

I.68 To calculate DO for the conjunctive use systems, a mathematical simulation model has been developed. The model is operated under a single piece of software known as the WARMS2, which allows "what if" behavioural analysis of the Thames Water system where the "Deployable Output" mode utilises the hydrometric records from 1920 to date. Data inputs and component parameters of WARMS2 include:

- Rainfall, evaporation and flow records obtained from the Environment Agency
- Abstraction licences and operating agreements, e.g. LTOA
- Water resources infrastructure data such as reservoir capacities and transfer capabilities
- DOs of groundwater sources abstracting from the confined and unconfined Chalk of the London Basin
- Details of water treatment capability, constraints, process water use and clear water returns
- Characteristics of strategic schemes such as the London Gateway desalination plant, the North London Artificial Recharge Scheme (NLARS) and the West Berkshire Groundwater Scheme
- Demand distribution and capacities of principal network links
- Seasonal demand distribution and effluent returns
- Assumed demand savings arising from restrictions on customers
- Bulk supply agreements
- Details of other abstractors and water use within the Thames catchment

Key parameters – water treatment works

I.69 One of the key components of the model is the operational capability of our WTWs and the amount of process water lost in the process. Process losses are included in WARMS2 and therefore included in the calculation of DO.

I.70 Table I-12 lists the assumed values within the models at AR17 compared to the updated AR17+; further details are given in Appendix K: Process losses. It is noted that AR18 values are consistent with AR17+; the only change was the groundwater versus surface water split of the Chingford capability in WARMS2. This has consequences for SWOX capability through the associated change in the timing of water use restrictions which is driven by the LTCD. It has resulted in +1 Ml/d DYAA and +1.19 Ml/d DYCP in base year DO in SWOX (See Section H: Reporting Deployable Output).

Table I-12: Water treatment works capability and process water losses

Water Treatment Works	**WARMS2 treatment capability Ml/d**		**WARMS2 process water losses percentage**	
	AR17	**AR17+**	**AR17**	**AR17+**
Ashford Common	700	685.0	4.9	2.3
Hampton	600	567.0	7.2	3.4
Kempton Park	160	179.0	7.8	1.1
Walton	80	125.0	14.0	6.7
Chingford	58	58.0	1.1	0.7
Coppermills	500	539.0	7.0	7.4
Hornsey	40	39.0	2.2	4.6
Farmoor	98	106.7	8.4	6.9
Swinford	90	72.9	3.3	5.7
Fobney	55	63.1	5.9	5.9
Shalford	30	26.8	5.3	5.3

I.71 It is evident that our supplies and WTW outputs are vulnerable to seasonal raw water quality deterioration and that climate change is exacerbating this impact. Therefore as well as raw water resource availability, the water quality challenge and how this may change in the future is important when assessing DO. We are working with subject matter experts to develop decision support tools to predict raw water quality (algal) behaviours in the future.

I.72 Algae can in some cases significantly affect the ability of surface WTWs to produce drinking water and increase the cost of this treatment. The UKWIR study (UKWIR 11/CL/08/02. Climate Change Implications for Water Treatment, 2011) predicts algae will be more problematic for public water supply as a result of climate change.

I.73 In partnership with Imperial College London, a study has been conducted to investigate the frequency and severity of algal events in raw water reservoirs. Using 30 years of data from the early 1980s onwards we have looked for patterns of reservoir algal behaviour correlated to climate.

I.74 By reviewing the resilience of our raw water storage and network we have found that algal bloom severity and longevity appear to be changing, depending on the reservoirs physical structure and management. For example, deeper reservoirs have better control measures to manage the raw water quality and therefore are more resilient to the impacts of climate change.

I.75 This work is at an early stage but the initial results indicate that as we further develop our understanding of the way we operate our reservoir network we may be in a position to make better, more informed decisions and be able to better target investment to improve system resilience.

I.76 The primary aim of this modelling is to better inform our evaluation of system resilience and to be able to form an objective judgement on fact based empirical modelling.

Key hydrological data

I.77 The model simulates the hydrology and water resource system of the Thames and Lee catchments and, to simplify the system, a number of individual components have been amalgamated. For example aquifers have been amalgamated into appropriate units, generally on the basis of the river network they support. The rainfall and evaporation are required to simulate the performance of the aquifers and the flow data are used to estimate surface runoff from impermeable areas and base flows from un-modelled portions of aquifers. These data are collected and distributed to us by the Environment Agency. Details of the historic data sets needed to run the model are listed in Table I-13. Data input to the model in many cases goes back to 1920. However some of the data has had to be hindcast as the flow record at locations such as Day’s Weir does not go back as far as this.

Table I-13: Hydrological data input to WARMS2

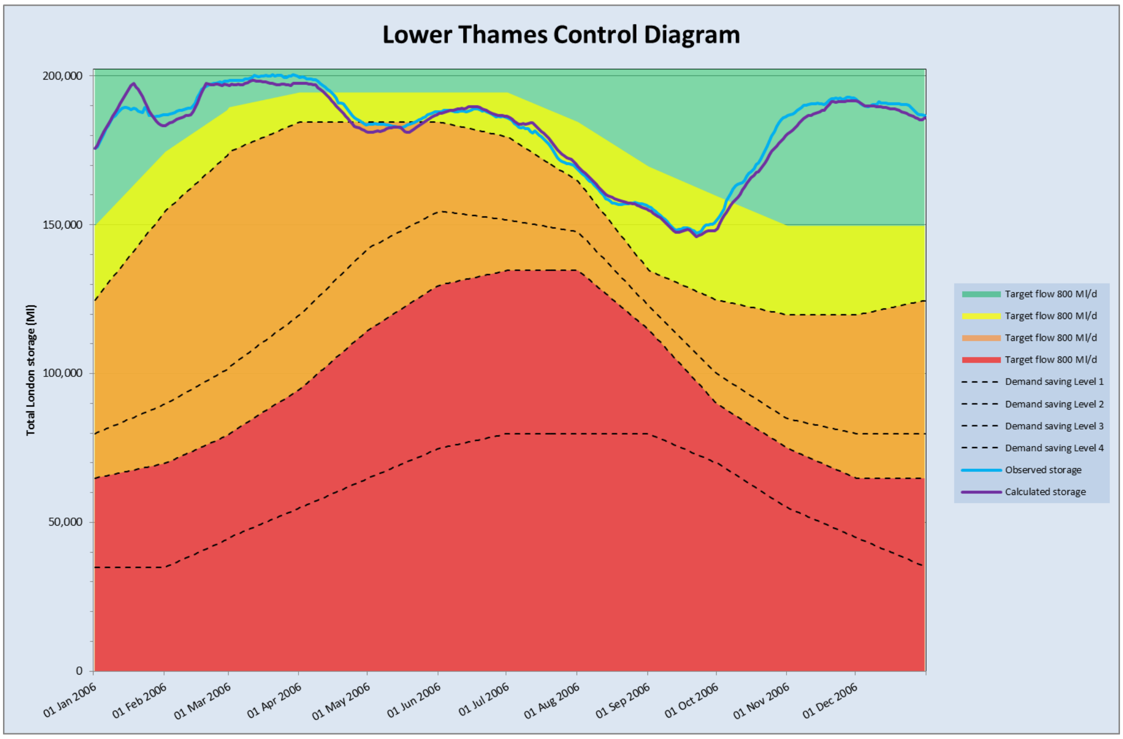
Data Type	Dataset Name	Recording Point Name
Rainfall (mm)	Teddington Historic	North Downs - South London (W)
	Lee Historic	Lee - Chalk
	Eynsham Historic	Cotswolds - West (A)
River Flow (Natural Flows - Ml/d)	Teddington Historic	Thames at Kingston (Teddington) (G&N)
	Lee Historic	River Lee at Feildes Weir (G&N)
	Eynsham Historic	Thames at Eynsham (G&N)
Areal Evaporation (Potential - mm)	Teddington Historic	North Downs - South London (W)
	Lee Historic	Lee - Chalk
	Eynsham Historic	Cotswolds - West (A)
Reservoir Storage (Ml)	Lower Thames Historic	Combined Thames Valley Storage
	Lee at Feildes Weir Historic	Combined Lee Valley Storage
	Thames at Eynsham Historic	Farmoor Storage
Rainfall (mm)	Areal Rainfall	Cotswolds - West (A)
		Cotswolds - East (B)
		Berkshire Downs (G)
		Chilterns - West (M)
		Chilterns - East - Colne (N)
		North Downs - Hampshire (P)
		Wey Greensand (S)
		North Downs - South London (W)
		North Downs - Darent = RAINW x 0.93
		Lee - Chalk
		Lower Lee
River Flow (Natural Flows - Ml/d)	Days Weir (simulated base flows)	-
	Days Weir (simulated surface flows)	-
	Teddington (simulated base flows)	-
	Teddington (simulated surface flows)	-
Areal Evaporation (Potential - mm)	Areal Evaporation (potential)	Cotswolds - West (A)
		Cotswolds - East (B)
		Berkshire Downs (G)
		Chilterns - West (M)
		Chilterns - East - Colne (N)
		North Downs - Hampshire (P)
		Wey Greensand (S)
		North Downs - South London (W)
		North Downs - Darent = PEW
		Lee Chalk

Note: Rainfall, evaporation and flow data originate from the Environment Agency

Validation

I.78 Details of our assets have been collated to provide the essential inputs of the water resource system and, for London, the model has been validated using selected historic hydrological and operational data for the year 2006. The validation of the model shows the timing of the draw down and the bottoming out of the storage volumes giving an excellent fit, as can be seen in Figure I-7. Note the data is plotted against the pre-optimised LTCD that was in force during 2006.

Figure I-7: WARMS2 model validation 2006

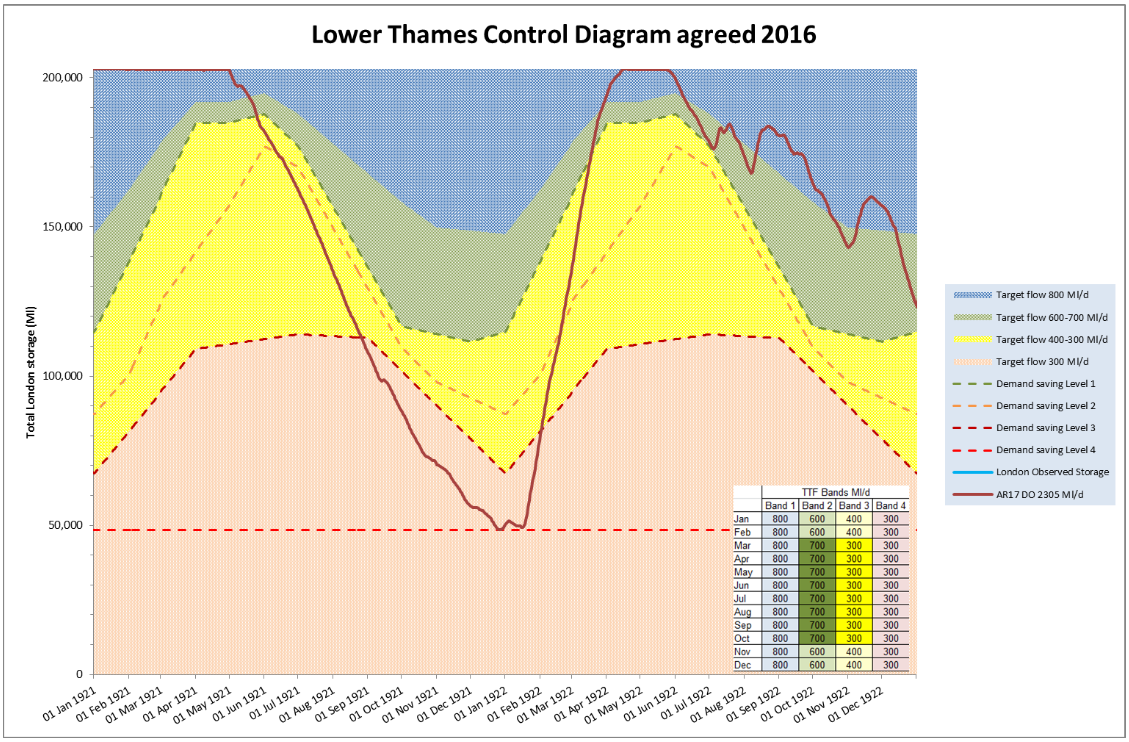


F. London’s Deployable Output

I.79 To determine the DO for London the WARMS2 model is run and the total London reservoir storage for each day over the period 1920 to date is calculated. The strategy for abstraction is defined by the LTCD which is applied to the defined scenario. Demands are met according to the location and the availability of water from the WTWs outputs to those areas. The model is run iteratively and changes demand values for the WRZ until it finds a level of demand that meets the level of service criteria. The number of times the level of storage drops below each of the restriction levels on the LTCD is counted and compared against that number permitted to meet the level of service. This is dependent upon many aspects of the water resource system. The output from each run includes details of the dates and duration of restrictions occurring during the given period. These are then compared against maximum frequencies of occurrence specified for the target Levels of Service (TLOS) being evaluated. For example, during a run of 91 years, if the permissible number of occurrences of restrictions is, on average, one year in twenty (e.g. a TUB), then four incidents are allowed, to meet the TLOS. If the model output shows that restrictions have occurred more than four times for this duration, the TLOS has been exceeded.

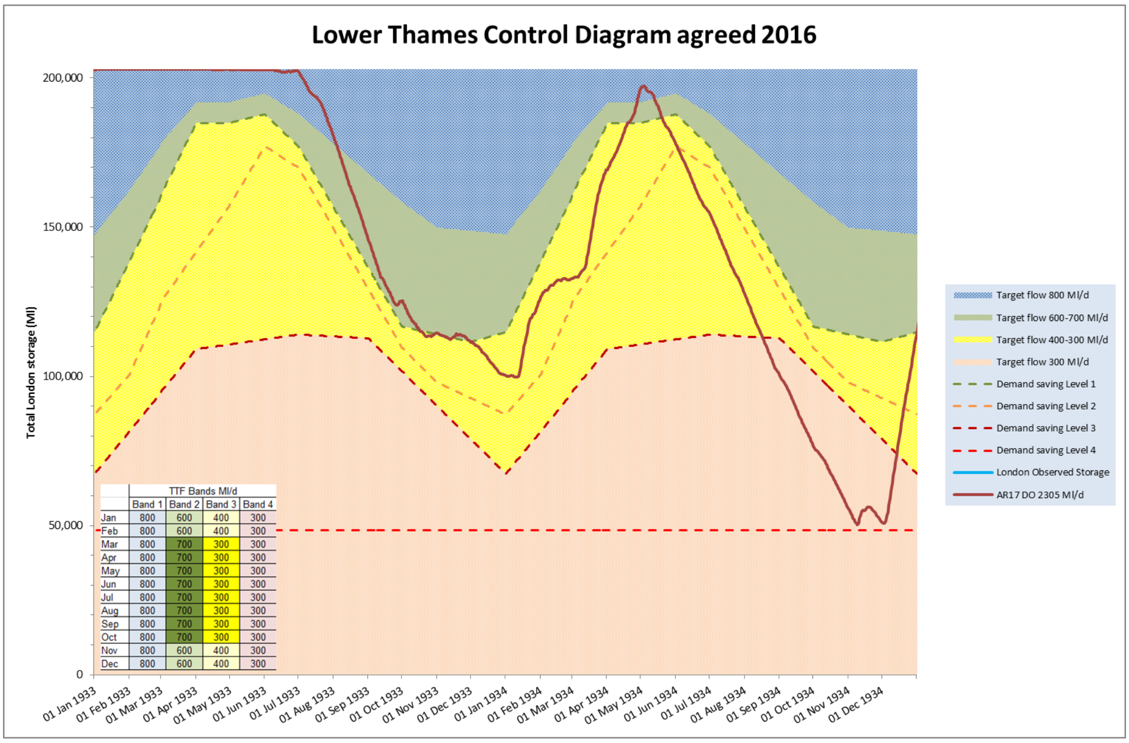
I.80 If the system fails to meet the TLOS based on the given demand, the model is automatically run again with a reduction in demand apportioned across the demand zones by the model, and the output is compared against the TLOS as before. Alternatively, demands are increased to maximize output until restrictions are imposed to the prescribed level of service. This process is repeated until the TLOS is met with restrictions being applied for the prescribed period. Therefore the demand placed on the system at which the TLOS is satisfied, is the DO for the conjunctive use system and is done automatically within WARMS2. The critical drought within the DO analysis is 1921 which sees the lowest storage level and does not recover until 1922 as seen in Figure I-8. Another of the crucial drought events within the Thames catchment is that of 1933/34, as shown in Figure I-9. The hydrology during this period produces one of the lowest storage volumes over the hydrological period examined with draw down starting in 1933 and not fully recovering until 1935. For the Annual Review 2017 the average DO for London was 2,305 Ml/d. The AR17+ average DO for London is 2,302 Ml/d.

Figure I-8: London reservoir storage 1921/22



	TTF Bands Ml/d			
	Band 1	Band 2	Band 3	Band 4
Jan	800	600	400	300
Feb	800	600	400	300
Mar	800	700	300	300
Apr	800	700	300	300
May	800	700	300	300
Jun	800	700	300	300
Jul	800	700	300	300
Aug	800	700	300	300
Sep	800	700	300	300
Oct	800	700	300	300
Nov	800	600	400	300
Dec	800	600	400	300

Figure I-9: London reservoir storage 1933/34



	TTF Bands Ml/d			
	Band 1	Band 2	Band 3	Band 4
Jan	800	600	400	300
Feb	800	600	400	300
Mar	800	700	300	300
Apr	800	700	300	300
May	800	700	300	300
Jun	800	700	300	300
Jul	800	700	300	300
Aug	800	700	300	300
Sep	800	700	300	300
Oct	800	700	300	300
Nov	800	600	400	300
Dec	800	600	400	300

G. Thames Valley

SWOX Deployable Output

I.81 SWOX is made up of the three water resource sub zones (WRSZ) of Swindon, North Oxfordshire (NOX) and South Oxfordshire (SOX). The water resources of the Swindon WRSZ are mainly groundwater derived from the Cotswolds Oolitic Limestone aquifer, together with groundwater from the Chalk aquifer. Significant transfers are made into Swindon, from the Farmoor reservoir complex in NOX, and from the chalk groundwater sources at Gatehampton and Cleeve in SOX. Whilst much of the NOX WRSZ is supplied from surface water sources there is also a significant transfer into the NOX WRSZ from Gatehampton and Cleeve in SOX. The water resources of the SOX WRSZ are derived from the Chalk aquifer and Upper Greensand aquifer groundwater sources.

I.82 WARMS2 is used to calculate the DO for the Upper Thames (UT) part of SWOX, namely Swindon and NOX and data and parameters are input to the model in the same manner as for London. The period over which the model is run is the same 1920 to date. The DO for the UT is calculated by reference to the storage derived for Farmoor reservoir. When calculating the UT DO using WARMS2 the London demand figure (equivalent to the London DO) is held as a constant value and the demand restrictions throughout our supply area are introduced in line with the TLOS. The model runs iteratively and changes demand values for the WRZ until it finds a level of demand that shows Farmoor storage staying just above the emergency storage volume of 4,500 Ml, which equates to the volume of water needed for 30 days of

Water into Supply. During the iteration process if a particular demand falls below the Farmoor emergency storage volume of 4,500 Ml, the model is run again with a reduced demand and the output is compared as before. Alternatively, the demand is increased to maximise the output until Farmoor storage is at or above 4,500 Ml. Thus the demand, at which Farmoor is held marginally above the Emergency Storage level of 4,500 Ml, is the DO of the UT. The groundwater SDOs, less the transfer to NOX, are then added to the UT DO strategic reservoir / groundwater source conjunctive use system, to give the total DO for SWOX.

Kennet Valley Deployable Output

I.83 The resources of the Kennet Valley WRZ are predominantly groundwater derived from unconfined and confined chalk aquifers, with the SDOs of these sources calculated as described in Section C: Groundwater Source Deployable Output, above. The Fobney WTW however is situated on the River Kennet. The DO of this source is calculated by examination of the flow records on the River Kennet and the treatment processes at the Lower Kennet WTW, Fobney. The Kennet Valley WRZ has not been assessed as a CUZ because it does not have any strategic reservoir storage; rather the WRZ is served by a combination of run of river sources and groundwater sources. As a result there is not the potential to use groundwater sources while resting reservoir storage to prolong its contribution to the overall system yield. However we have reviewed and revised our approach to the calculation of groundwater SDO, such that a time variant yield can be calculated. This enables calculation of peak DO at the time of peak customer demand as well as average DOs for 12 month periods, and is informative especially where the source yield is constrained hydrogeologically. This approach can also be implemented for surface water sources such as Fobney, and will form an important component of exploring the need and benefit from producing a conjunctive water resources analysis for the Kennet WRZ in preparation for WRMP24.

I.84 The DO calculation for Fobney run-of-river surface water source with no raw water storage follows the approach outlined in the UKWIR 2014 guidance[14]. This relies on flow data provided by the Environment Agency, rather than model outputs.

I.85 Environment Agency flow data are available for the period October 1961 to date from the gauging station on the River Kennet at Theale, which includes the major drought of 1976. As there is a complex system of channels in the Kennet and Holy Brook system, we engaged Halcrow to carry out investigations of the flows in this area, which were undertaken in 2003/04. At the same time a series of flow gaugings were undertaken in support of this study. The investigation included low flow modelling of the flows in the Kennet with and without augmentation from the Environment Agency's West Berkshire Groundwater Scheme (WBGWS). It showed that the water decreased between Theale and the Labyrinth weir (upstream of the abstraction point at Fobney), due to the flow of water down the Holy Brook and leakage from the river to the adjacent gravels.

I.86 Flow volumes experienced here have to be apportioned between different water courses to calculate how much flows past Fobney. This is due to a percentage of the flow at Theale branching from the Kennet to travel down the Holy Brook and thus not flowing down the River

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[14] UKWIR, 2014, Handbook of Source Yield Methodologies

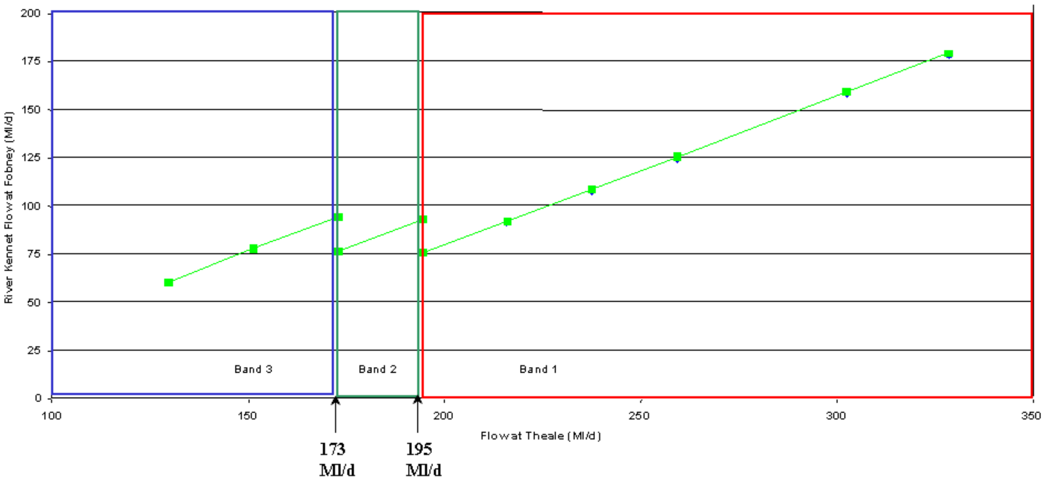
Kennet past Fobney WTW. A flow control structure has been constructed in the Holy Brook to divert flow into the River Kennet during periods of low flow (i.e. when river flow at Theale is less than 195 Ml/d). The operation of the structure is by agreement with the Environment Agency and ensures that water reaches Fobney for abstraction whilst maintaining adequate flows in the Holy Brook to meet environmental needs. The structure consists of three openings and the gates are closed depending on the flows at the Theale gauging station as shown in Table I-14 and Figure I-10.

Table I-14: Strategy for the operation of the flow split structure

Critical period	Daily mean flow at Theale (Ml/d)	New flow split structure state
Band 1	>195	Fully open
Band 2	<195	First opening closed
Band 3	<173	Second opening closed; third opening retains flows in Holy Brook for environmental protection

Note: Below 195 Ml/d, also ensure Burghfield Mill Sluices are closed.

Figure I-10: Impact of the flow control structure on the flow in the River Kennet at Fobney



I.87 The flow upstream of the Fobney abstraction is governed by the operation of the Holy Brook structure during low flows. During a drought, abstraction from the chalk aquifer by the WBGWS will also contribute to flows in the Kennet. From Table I-15 it can be seen that the average DO is dependent on the operation of the WBGWS. The estimate of the flows reaching the Labyrinth Weir, just upstream of the Fobney intake with the gates of the Holy Brook structure closed, is calculated by using the following formula:

*Flow in Kennet @ Labyrinth Weir = 0.782 * flow @ Theale GS - 40.68 (Ml/d)*

Table I-15: Fobney WTW average DO

Critical Year 1975/76	Theale Flow (Ml/d)	West Berks Groundwater Scheme (Ml/d)	Total Flow (Ml/d)	Labyrinth Weir (Ml/d)	Potential Abstraction (Ml/d)	Process Water Losses 7% (Ml/d)	DYAA DO (Ml/d)
Fobney (no WBGWS)	79.9	0.0	79.9	21.8	21.8	1.4	20.4
Fobney (with WBGWS)	79.9	66.4	146.3	73.7	72.7	3.7	63.1

I.88 By analysing the data to find the minimum flow experienced at Theale, this is translated into the reliable raw water available to be abstracted at Fobney WTW. Taking into account the treatment capacity of the works and process water losses, a value for DO is calculated; as shown for the average position in Table I-15 and for peak in Table I-16.

Table I-16: Fobney WTW peak DO

Critical Year 1975/76	Theale Flow (Ml/d)	West Berks Groundwater Scheme (Ml/d)	Total Flow (Ml/d)	Labyrinth Weir (Ml/d)	Potential Abstraction (Ml/d)	Process Water Losses 7% (Ml/d)	DYCP DO (Ml/d)
Fobney (no WBGWS)	79.9	0.0	79.9	21.8	21.8	1.4	20.4
Fobney (with WBGWS)	79.9	66.4	146.3	73.7	72.7	3.7	63.1

I.89 Note the availability of output from the WBGWS is critical to the Fobney DO. Some testing of the scheme has been undertaken by the Environment Agency however the investigations are on-going and thus there remains a risk to the supply demand balance in the Kennet Valley. The DO also assumes that the fish pass at the Labyrinth weir is closed or else much of the water would not be available for abstraction. If the fish pass cannot be closed then the contingency option of pumping from the River Kennet below Labyrinth weir into the Kennet and Avon canal upstream of the Fobney intake would be used. The contingency arrangement would be implemented through the use of a transfer licence from the Environment Agency.

I.90 The DO calculation method for the Fobney run-of-river surface water source with no raw water storage currently produces a conservative surface water DO, reflecting the hydrological yield being the minimum raw water availability across the historical record, although the DO for this source is not limited by hydrological yield and instead constrained by treatment capability. For WRMP24 we plan to update this run-of-river DO assessment and reporting templates, which will improve transparency; for Fobney this will include the methodology for calculating the WBGWS contribution, on which its DO relies heavily.

I.91 The groundwater sources of the Kennet WRZ abstract from both the confined and unconfined chalk aquifer in the Hungerford, Newbury and Reading area. Their SDOs have been calculated as described in Section C: Groundwater Source Deployable Output, above. The groundwater sources range widely in their capabilities from, for example, Bradfield (2.27 Ml/d), Bishops Green (15.4 Ml/d) in the confined chalk, through to Pangbourne (29.1Ml/d) in the unconfined chalk of the lower reaches of the River Pang catchment.

I.92 About 44% of all the Kennet WRZ groundwater sources have their peak (DYCP) SDOs constrained by their abstraction licence limits. Only one Kennet WRZ source has its SDO constrained by hydrogeological factors, reflecting groundwater response to hydrological conditions during drought.

Henley Deployable Output

I.93 The water resources of the Henley WRZ are derived from three groundwater sources abstracting from the unconfined Chalk of the south west Chilterns and the lower River Loddon catchment. Their SDOs have been calculated as described in Section C: Groundwater Source Deployable Output, above. There is nitrate contamination of groundwater at the Sheeplands source and this is managed by treatment as well as blending with groundwater from the Harpsden source under an aggregate abstraction licence.

I.94 For the Henley WRZ sources, the peak (DYCP) SDOs for the base year (see Section 4: Current & future water supply) are constrained by abstraction licence limits and pumping plant capacity. This means that the outputs of the Henley WRZ sources are not constrained by groundwater responses to hydrological conditions during drought.

Slough Wycombe and Aylesbury Deployable Output

I.95 The water resources of the Slough Wycombe and Aylesbury WRZ (SWA) are derived from twelve groundwater sources abstracting from the unconfined chalk of the south west Chilterns. Their SDOs have been calculated as described in Section C: Groundwater Source Deployable Output, above. The groundwater sources range widely in their capabilities from, for example, Dancers End (1.64 Ml/d) on the scarp slope of the Chilterns near Tring, Pann Mill (16.8 Ml/d) on the banks of the River Wye in High Wycombe, through to Medmenham (55.0 Ml/d) located on the banks of the River Thames.

I.96 Approximately 25% of the SWA WRZ groundwater sources have their peak (DYCP) SDOs constrained by their abstraction licence limits, with 50% having their SDO constrained by factors such as treatment works and pump capabilities. Two of the SWA WRZ sources have their peak SDOs constrained by groundwater responses to hydrological conditions during drought. This drought constraint equates to approximately 11% of the peak groundwater abstraction capability of the SWA WRZ.

Guildford Deployable Output

I.97 The resources of the Guildford WRZ are predominantly groundwater derived and the SDOs of these sources have been calculated as described in Section C: Groundwater Source Deployable Output, above. The groundwater sources abstract from both the chalk aquifer within Guildford and the Lower Greensand elsewhere in the WRZ, comprising abstractions from boreholes and one spring source located in Haslemere. The peak (DYCP) SDOs for the base year of the Guildford groundwater sources are largely constrained by abstraction licence limits, with minor pump capacity and treatment works constraints at the Mousehill & Rodborough, Ladymead and Dapdune sources. Only the spring source in Haslemere has an SDO constrained by hydrological conditions. This equates to around 5% of the peak groundwater abstraction capability and around 3% of the total peak WRZ DO.

I.98 The DO calculation for the Shalford WTW run-of-river surface water source with no raw water storage follows the approach outlined in the Handbook of Source Yield Methodologies (2014)[15]. This relies on flow data provided by the Environment Agency, rather than model outputs.

I.99 The surface water works in the Guildford Resource WRZ is at Shalford WTW located between the River Wey and the Tillingbourne Stream. It has two abstraction points, one from each of the water courses so these have to be assessed separately. The DO of this source is calculated by examination of the flow records on the Tillingbourne and Wey, and the treatment processes at Shalford. The treatment capability of Shalford is 26.8 Ml/d average and peak.

I.100 The gauging station on the Tillingbourne Stream is at Shalford itself, just upstream of the point of abstraction; the period of record from May 1968 to date was used as the basis for the DO calculation. The most appropriate gauge for the Wey is at Tilford, some way upstream of Shalford with the record available from October 1954 to date. The River Wey and Tillingbourne flows were combined and analysed for minimum flow years. The years with the lowest flows were 1992 and 1956 for the Tillingbourne and Wey respectively. Note some of the data for the Wey at Tilford is unreliable for 1956 and the Tillingbourne data pre-May 1968 is estimated by regression with the Wey data, therefore the low flows for 1976 are also considered. The record when combined shows flows well above the abstraction licence at Shalford throughout the record, thus it is the licence that becomes the constraining factor to available water. Therefore the DO for the works as a whole is limited by the abstraction licence and the treatment process. Taking into account the treatment capacity of the works and process water losses, a value for DO of 26.8 Ml/d is calculated; as shown for the average and peak position in Table I-17.

Table I-17: Shalford WTW average and peak DO

Critical Years 1956 & 1992	Tillingbourne @ Shalford (Ml/d)	Wey @ Tilford (Ml/d)	Total Flow (Ml/d)	Potential Abstraction (Ml/d)	Process Water Losses 12% (Ml/d)	Average & Peak DO (Ml/d)
Shalford 1956	13.5*	49.7	65.2	30.0	3.2	26.8
Shalford 1992	18.7	84.7	103.4	30.0	3.2	26.8
Shalford 1976	26.5	81.2	107.7	30.0	3.2	26.8

**Statistically fitted value*

I.101 The Guildford WRZ has not been assessed as a CUZ because it does not have any strategic reservoir storage; rather the WRZ is served by a combination of run of river sources and

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[15] UKWIR, 2014, Handbook of Source Yield Methodologies

groundwater sources. As a result there is not the potential to use groundwater sources while resting reservoir storage to prolong its contribution to the overall system yield. However we have reviewed and revised our approach to the calculation of groundwater SDO, such that a time variant yield can be calculated. This enables calculation of peak DO at the time of peak customer demand as well as average DOs for 12 month periods, and is informative especially where the source yield is constrained hydrogeologically. This approach can also be implemented for surface water sources such as Shalford, and will form an important component of exploring the need and benefit from producing a conjunctive water resources analysis for the Guildford WRZ in preparation for WRMP24.

I.102 The DO calculation method for the Shalford run-of-river surface water source with no raw water storage currently produces a conservative surface water DO, reflecting the hydrological yield being the minimum raw water availability across the historical record, although the DO for this source is not limited by hydrological yield and instead constrained by licence limits and process losses. For WRMP24 we plan to update this run-of-river DO assessment and reporting templates, which will improve transparency.

H. Reporting Deployable Output

Base Year Deployable Output

I.103 Each year we review the DOs and examine any changes to the information on which the DOs are assessed, the operating regime and assumptions in the derivation of the conjunctive use DOs. These are reported as part of the Annual Review regulatory process and subject to audit. The DO for each WRZ as reported in the Annual Review 2017 to the Environment Agency and Ofwat is shown in Table I-18 for the DYAA and the DYCP. The AR17+ figures are also shown in Table I-18. These figures reflect the best available information available at the time of producing the WRMP19 between AR17 and AR18.

Table I-18: DYAA and DYCP DO

WRZ	Deployable Output (Ml/d)			
	DYAA AR17	DYAA AR17+**	DYCP AR17	DYCP AR17+**
London*	2305	2302	--	--
SWOX	329.2	329.2	385.4	385.4
Kennet Valley	135.8	143.9	157.8	155.4
Henley	25.7	25.7	25.9	25.9
SWA	183.3	185.1	213.3	214.4
Guildford	65.4	65.8	71.3	71.7

**The DO for our London WRZ is assessed for DYAA only due to both London's reservoirs and ring main providing a buffer during peak periods.*

***Note A17+ figures have been used in the WRMP19. These are AR17 figures including the impact of updates to SDOs (following internal review of constraints) and revised treatment works capabilities and treatment works loss figures (using our WTW Process model) between the draft and final WRMP19.*

I.104 AR18 DOs are consistent with the AR17+ DOs with the exception of SWOX which is +1 Ml/d DYAA and +1.19 Ml/d DYCP due to a refinement to how the Chingford WTW capability split between groundwater and surface water was represented in WARMS2.

I. Deployable Output sensitivity analysis to Levels of Service

Impact on Deployable Output of changes to Levels of Service

I.105 One of the key assumptions within the WARMS2 modelling is the savings that can be made by placing restrictions on our customers during a drought, for example TUB and sprinkler bans. The LTOA reflects the timing of when these restrictions would be in place and the reduction in demand as a result. The level at which savings are assumed from the restrictions has a direct impact on the DO for London and SWOX. The current Levels of Service for Thames Water are shown in Table I-6.

I.106 A sensitivity analysis of alternative Levels of Service has been undertaken to demonstrate the impact on the DO for London and SWOX. Four scenarios of Levels of Service have been assessed to compare with the current position:

1) Introducing TUBs at Level 2 rather than Level 3. The amended savings for the scenarios are shown in Table I-19 and Table I-20
2) Introducing sprinkler bans and TUBs at Level 1 rather than Level 2 and Level 3 respectively. This applies the cumulative savings Level 1 to 3a all at Level 1 from Table I-19 and Table I-20
3) Having no restrictions on customers - the constant rate of supply that can be maintained from the resource zone throughout the entire period of assessment, with no customer restrictions or other drought actions applied.
4) Customer use restrictions of 1 in 10 years and non-essential use restrictions of 1 in 40 years.

I.107 WARMS2 simulates reservoir storage over the historic period from 1920 to 2013 (94 years). Within this data there are four major events 1921-22, 1933-34, 1943-44 & 1976 that drive the DO calculation, all of which produce a drawdown of a similar nature, see Figure I-11. As the LTCD is now optimised it is the Level 4 restriction level that is critical in determining the DO for the current Levels of Service with the storage allowed to fall below the Level 3 curve four times in the 91 years to achieve a frequency of 1 year in 20. To achieve a frequency of 1 year in 40, only two events can occur where storage can fall below the Level 3 curve. Given the shape of the control curves demand has to be reduced to raise storage above the Level 3 control curve to allow only two events where storage falls below the Level 3 curve. The impact on storage can be seen in Figure I-12, and to achieve this demand has to be reduced more than if there were no restrictions on customer use. From Table I-21 this amounts to a reduction of 157 Ml/d as opposed to 126 Ml/d for the scenario with no restrictions. The reason being that to achieve a more rational answer the LTCD would have to be re-optimised to a new level of service so as to achieve a maximum DO for this criterion and to maximise use of the available storage.

Table I-19: Revised estimates (%) for the impacts of (Ml/d) demand reduction in London when introducing TUB at Level 2 during a drought

Units of Percent	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Level 1	1.1	1.2	1.2	1.3	1.5	2.2	2.2	2.1	1.3	1.2	1.2	1.2
Level 2 + Level 3a: TUB	2.9	3.0	3.0	4.3	5.2	10.4	10.9	9.8	4.3	3.5	3.2	3.1
Cumulative Levels 1-3a	4.1	4.1	4.2	5.6	6.6	12.5	13.1	11.9	5.7	4.7	4.4	4.2
Level 3b: DD11 ban	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Cumulative Levels 1-3	5.4	5.5	5.5	7.0	8.0	13.9	14.5	13.2	7.0	6.1	5.8	5.6
Level 4	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Total Savings Levels 1-4	23.4	23.5	23.5	25.0	26.0	31.9	32.5	31.2	25.0	24.1	23.8	23.6

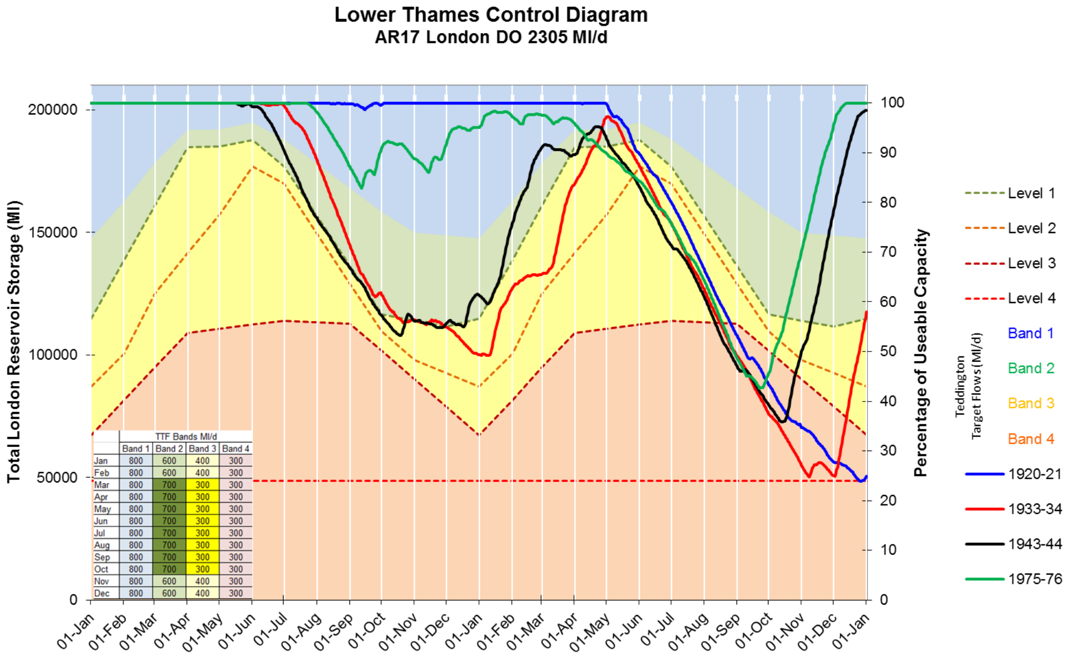
Table I-20: Revised estimates (%) for the impacts of (Ml/d) demand reduction in Thames Valley when Introducing TUB at Level 2 during a drought

Units of Percent	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Level 1	1.3	1.4	1.4	1.8	1.9	3.6	3.8	3.7	1.6	1.4	1.4	1.4
Level 2 + Level 3a: TUB	3.2	3.3	3.4	5.2	5.8	13.5	14.1	13.7	4.6	3.7	3.4	3.3
Cumulative Levels 1-3a	4.5	4.7	4.8	6.9	7.7	17.1	17.9	17.3	6.2	5.1	4.8	4.6
Level 3b: DD11 ban	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Cumulative Levels 1-3	5.8	5.9	6.0	8.2	8.9	18.3	19.1	18.6	7.4	6.3	6.1	5.9
Level 4	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Total Savings Levels 1-4	23.8	23.9	24.0	26.2	26.9	36.3	37.1	36.6	25.4	24.3	24.1	23.9

TUB = Temporary Use Ban

DD11 = Drought Direction 2011.

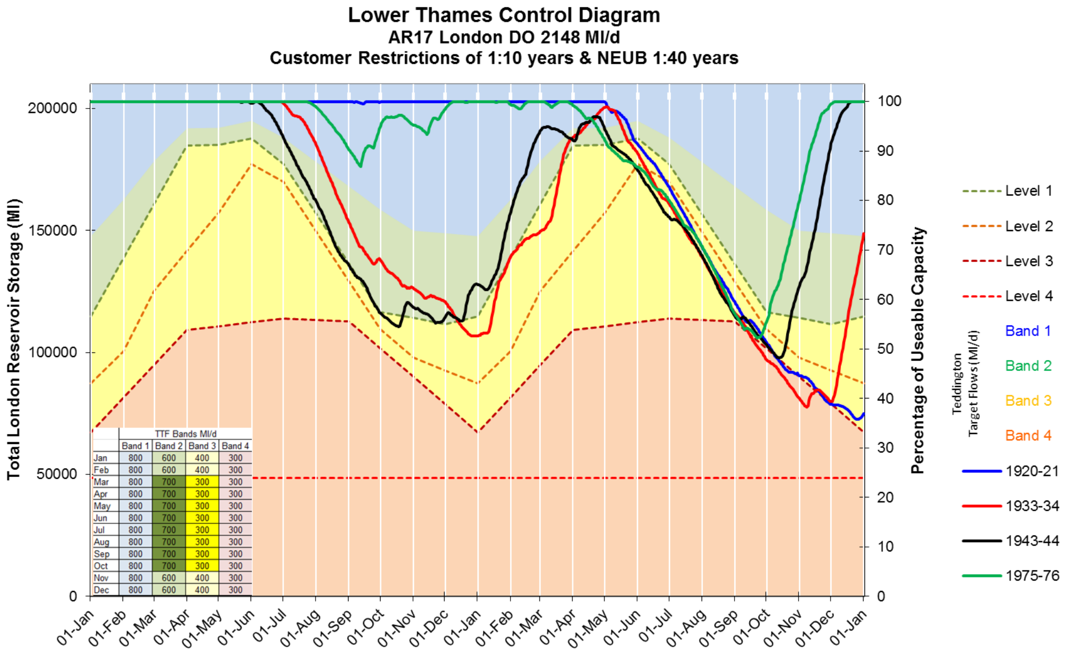
Figure I-11: London reservoir storage used in deriving London DO



Lower Thames Control Diagram
AR17 London DO 2305 Ml/d

	TTF Bands Ml/d			
	Band 1	Band 2	Band 3	Band 4
Jan	800	600	400	300
Feb	800	600	400	300
Mar	800	700	300	300
Apr	800	700	300	300
May	800	700	300	300
Jun	800	700	300	300
Jul	800	700	300	300
Aug	800	700	300	300
Sep	800	700	300	300
Oct	800	700	300	300
Nov	800	600	400	300
Dec	800	600	400	300

Figure I-12: London reservoir storage derived from Scenario 4: NEU restriction 1:40



Lower Thames Control Diagram
AR17 London DO 2148 Ml/d
Customer Restrictions of 1:10 years & NEUB 1:40 years

	TTF Bands Ml/d			
	Band 1	Band 2	Band 3	Band 4
Jan	800	600	400	300
Feb	800	600	400	300
Mar	800	700	300	300
Apr	800	700	300	300
May	800	700	300	300
Jun	800	700	300	300
Jul	800	700	300	300
Aug	800	700	300	300
Sep	800	700	300	300
Oct	800	700	300	300
Nov	800	600	400	300
Dec	800	600	400	300

I.108 As expected and as can be seen in Table I-21 and Table I-22, with an increased frequency of restrictions, DO in both London and SWOX increases, and with no restrictions imposed there is a significant decrease in DO. This potential change ranges over 188 Ml/d in London (2336 – 2148 from Table I-21) and 31 Ml/d in SWOX (331.2 – 300.2 from Table I-22).

Table I-21: Potential impact of level of service changes in London[16]

London		
Scenario	**DO (Ml/d)**	**Change in DO (Ml/d)**
Average DO - Annual Review 2017	2305	--
Enhanced media campaign, sprinkler and TUB all at Level 1	2336	+31
Sprinkler and TUB at Level 2	2314	+9
No restrictions	2179	-126
Customer use restrictions of 1 in 10 years and non-essential use restrictions of 1 in 40 years	2148	-157

Table I-22: Potential impact of Level of Service changes in SWOX

SWOX		
Scenario	**DO (Ml/d)**	**Change in DO (Ml/d)**
Average DO - Annual Review 2017	329.2	--
Enhanced media campaign, sprinkler and TUB all at Level 1*	331.2	+2
Sprinkler and TUB at Level 2*	331.2	+2
No restrictions	302.2	-27
Customer use restrictions of 1 in 10 years and non-essential use restrictions of 1 in 40 years	300.2	-29

*Note: * DO restricted by Farmoor annual licence limit.*

J. Sustainability reductions

Loss of Deployable Output from sustainability reductions

I.109 Reductions in abstraction licences are proposed at various stages over the planning period and details are given in the WRMP19 Section 4: Current and future water supply, subsection C: Sustainability reductions. The sustainability reductions would impact on our DO and are summarised in Table I-23. These potential impacts have been modelled using WARMS2 and those already agreed with the Environment Agency for Axford, Ogbourne, Pann Mill and Childrey Warren have been included in the Headroom modelling as part of the baseline

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[16] Note – in our scenario testing we assessed the impact of changes in Deployable Output of +/-50Ml/d and +/-100Ml/d. The results simulate the impact of changing levels of service.

supply / demand balance. The only other sustainability reductions that are included in our baseline are Hawridge and Bexley, which is in line with the Environment Agency's WINEP 3.

Table I-23: Sustainability reductions impact on DO, including WINEP 3 and AMP6 reductions

		Loss of DO (Ml/d)		
WRZ	**Source**	**DYAA**	**DYCP**	**Year**
London**	Bexley***	9.0	--	2024/25
SWOX	Axford*	5.0	6.0	2017/18
	Ogbourne*	4.0	4.7	2017/18
	Childrey Warren	3.7	3.7	2019/20
SWA	Hawridge***	6.8	6.9	2024/25
	Pann Mill	0.0	7.3	2019/20

Notes:

** The impact on SWOX shown in the table of the Axford and Ogbourne source DO reductions are from the results modelled in WARMS2.*

***The DO for our London WRZ is assessed for DYAA only due to both London's reservoirs and ring main providing a buffer during peak periods.*

**** WINEP 3 (all other reductions in the table are AMP6 reductions)*

K. Strategic schemes uncertainty

Yield of strategic water resource drought schemes

I.110 The risk of a yield reduction from a number of the strategic drought schemes needs to be considered as part of the planning process, using improved information on the performance of these schemes when available. These schemes are:

1) NLARS
2) NNRWS
3) WBGWS

NLARS

I.111 NLARS was originally designed for short-term operation over 6-7 months during an average 1 in 8 year drought, i.e. it was designed to meet demand during peak periods, not necessarily annual average demand over a longer and more extreme drought. With improved information on borehole performance, together with better information about the aquifer state of storage allowed an updated view of NLARS output in the Annual Review 2016; named NLARS

Scenario 3. There remains however a risk around what the scheme may actually be capable of delivering during a drought thus two further scenarios of the output from NLARS have been evaluated (named 1 and 2) to aid the evaluation of the risk around NLARS:

- **NLARS Scenario 1** Is the original view of the NLARS output used prior to the Annual Review 2016.
- **NLARS Scenario 2** Following a review of the NLARS sources and with improved information on borehole performance an updated view of the schemes output was produced.

I.112 The impact of the modified output from NLARS for the two alternative scenarios was evaluated by inputting this data into WARMS2 and comparing with the value of DO before the change; here the AR17 Baseline London DO of 2,305 Ml/d derived using the optimised LTCD is used as the base run. The impact on DO and thus the level of risk is shown in Table I-24.

Table I-24: Estimated risk around the NLARS

NLARS		
Scenario	**London DO (Ml/d)**	**DO Difference**
NLARS Sc3 (base)	2,305	--
2013/14 profile Sc1	2,288	-17
NLARS Sc2	2,290	-15

Northern New River Wells (NNRW)

I.113 The output from the NNRW is at risk from bromate pollution within the chalk, with mitigation currently provided by the scavenging remediation scheme operated at Affinity Water’s Hatfield groundwater abstraction. The source of the bromate pollution is a former bromine chemicals factory at Sandridge. In 2005, a remediation scheme was implemented in conjunction with Affinity Water from one of Affinity Water’s groundwater sources at Hatfield between Sandridge and the NNRW. There is however a risk that the NNRW would not be able to deliver their SDOs should there be a problem, for whatever reason, with the scavenging remediation scheme. At WRMP14 the maximum risk to these sources was -23 Ml/d when using WARMS. This equated to around -13 Ml/d in the first year of the plan when applied in the Target Headroom model. The current evaluation of risk using WARMS2 is based on the scenario described as Hatfield Off 1.

- **Hatfield Off 1** Assumes a predicted bromate concentration during a drought year based on information prior to the start of the Hatfield remediation scheme.

I.114 The impact of the reduced output from the NNRW was evaluated by inputting this data into WARMS2 and comparing with the value of DO before the change; here the London DO of 2,305 Ml/d derived using the optimised LTCD is used as the base run. The WARMS2 analysis shows there is likely to be a 12 Ml/d reduction in DO. This perceived risk of -12 Ml/d is applied as the most likely impact in the Target Headroom analysis and is similar to the value used in WRMP14.

I.115 In summary therefore it can be seen from Table I-25 that there is potentially a risk of reduction that could be expected from reviewing these two schemes of around 28 Ml/d.

Table I-25: Risks to yield of drought schemes (Ml/d)

Scheme	Risk of DO Reduction
NLARS	-15 - 17
NNRW	-12
Total	~-28

I.116 The level of risk around the NNRW and NLARS and the variance in DO presented in Table I-24 and Table I-25 has been input to the Target Headroom model and the output compared with the updated base DO position of 2,305 Ml/d using the optimised LTCD in WARMS2.

WBGWS

I.117 With regard to the longevity of the WBGWS, we await the EA's national review of their environmental augmentation schemes, to be completed by March 2019, which will consider their longer term availability, including the WBGWS. This will be followed up by discussion of the scheme ownership and operation beyond 2031. To assess the potential future water supply impact for the London and Kennet Valley WRZs, the WBGWS has been included within the EBSD model as a 'what-if' scenario within Section 10: Programme appraisal and scenario testing as part of programme appraisal; the DO benefit included within the London (+74 Ml/d DYAA DO) and Kennet Valley (+43 Ml/d DYAA and DYCP DO) WRZs will be reduced in the EBSD baseline from 2031 onwards in the scenarios tested.

L. Drought and risk

Background to stochastic modelling

I.118 In our WRMP14, we discussed whether the risk to water supplies from climate change is underestimated using traditional approaches (see Section 5: Allowing for Risk and uncertainty, Section 10: Programme appraisal and scenario testing, and Appendix U: Climate change).

I.119 These approaches primarily use analysis of historic, recorded data for rainfall, evaporation, flow and groundwater levels to calculate DO and the climate impacts on them. There are some limitations to this, particularly with respect to understanding the resilience of the current or future system to different types of droughts that might occur under climate change. The historic record does not contain sufficient representation of extended severe droughts which are likely to become a real and more frequent occurrence under climate change.

I.120 The most recent drought in our supply area (2010-2012) exposed potential weaknesses in the existing processes for assessing the impact of climate change on supplies; in that simply perturbing the historic record of rainfall and evaporation may not adequately reflect how the system might respond to multi-year droughts likely to occur under climate change.

I.121 We are reliant on groundwater sources and groundwater dependent river flows for a substantial proportion of the area's supplies. These sources respond slowly to variability in rainfall with the result that rainfall deficits of up to two years can often be buffered by groundwater storage. However, prolonged droughts beyond this period can pose a serious problem as once groundwater stores become depleted; recharge also takes a considerable time to restore groundwater levels.

I.122 The publication of the Future Flows and Groundwater Levels report[17] and datasets by CEH-NERC in 2012[18], together with encouragement within the Environment Agency's 2018 WRPG to examine risks to future schemes, provided us an excellent opportunity to examine whether flows like those anticipated in the dataset would highlight future challenges for the Thames Basin. We appointed HR Wallingford to do this work, the detail of which is set out in WRMP14 Section 10: Programme appraisal and scenario testing, and Appendix U: Climate change.

I.123 The analysis undertaken confirmed that prolonged periods of drought, more severe than those seen in the historical record, are predicted to occur in the Future Flows dataset. This demonstrated that simply perturbing the historic record of available data is unlikely to give a robust forecast of the potential future impacts of climate change on river flows.

I.124 Further climate change evidence for WRMP19 is the MaRIUS project data. We commissioned CEH to complete the Severn Thames Transfer Study (CEH, June 2018) using simulations from the NERC-funded project MaRIUS. The results showed that the number of droughts of moderate severity or greater in the Thames catchment is projected to increase into the future.

Applications for WRMP19

I.125 The stochastic data has been used in our WRMP19 to help understand that the risks associated with drought are quite varied and has also been used to help us understand aspects of system and strategic resource resilience within our overall programme appraisal process to inform the development of a best value investment programme. For example:

- Understanding resilience: The stochastic weather data set has enabled us to understand the recurrence intervals of the historic 20th century droughts we have previously used for planning (1 in 100 year recurrence) so that we have been able to determine what resilience level we should be planning to (1 in 200 or 500 year, depending on customer support) including the ability to set out, and present as a scenario, a reference level of service that would mean resilience to a 1 in 200 year drought event in line with the 2018 WRPG.
- Better understanding the yield of potential new water resource schemes: this is particularly useful for those that depend on surface water abstraction. We have used the stochastic weather data set and associated 'drought libraries' to determine a more robust DO figure for the Severn Thames Transfer[19] and the South East Strategic

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[17] HR Wallingford (2012) *Thames Water Three Dry Winters Scenarios. Investigation of the potential for a three dry winter scenario for water resources planning. Technical Note MAM6468-11*

[18] Centre for Ecology and Hydrology Natural Environment Research Council (2012) *Future Flows and Groundwater Levels: British projections for the 21st century*

[19] Thames Water WRMP19 Stochastic Methods Options Appraisal Unsupported Severn Thames Transfer, Atkins, 2017.

Reservoir Option[20] than would simply be obtained from analysing the historic data from the 20th century.

- Programme appraisal: Testing the resilience of our potential water supply strategy. Seeing how well the plan performs against more severe droughts than we have seen in the historic record and detailed in Appendix W: Programme appraisal methods.

Stochastic modelling for WRMP19

I.126 For the WRMP19, we have noted the Environment Agency's updated guidance, including Section 3.4 of the 2018 WRPG on drought risk assessment and the UKWIR WRMP19 Methods report on Risk Based Planning (2016). Water companies are encouraged to consider resilience of the supply system to more extreme drought events than might be present in the historical record.

I.127 Sensitivity testing of WRMP14 showed vulnerability of the preferred plan to severe droughts not present in the historic record 1920-2013. We know of a prolonged period of drought in the late 19th century (1890-1910) and Kew Gardens records show intense drought in mid-18th century.

I.128 We commissioned Atkins, along with HR Wallingford and the University of Manchester to take this work forward for the WRMP19. The first phase was to conduct a project scoping exercise that defined how the project would be taken forward and objectives of the work including how the outputs were to be used. The outcome was reported in August 2015[21] and followed up with details of the process to be adopted in delivering a stochastically based approach to our water resources planning[22].

Models used in the stochastic analysis

I.129 The following models are being used in a process described in Figure I-13 below:

- A stochastic weather generator
- Catchmod & Kestral rainfall-runoff models
- WARMS2 simulation model
- Interactive River Aquifer Simulation (IRAS) model (a simplified version of WARMS, that is able to be run multiple times, quickly)
- Groundwater models

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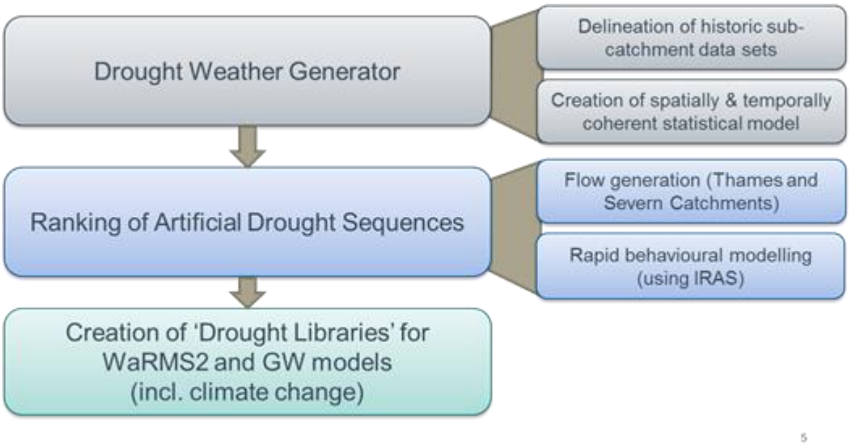
[20] Stochastic Water Resources: Stage 4 Options Appraisal Upper Thames Reservoir, Atkins, 2017

[21] Thames Water Stochastic Drought Generation, Atkins, August 2015

[22] Thames Water Stochastic Drought Generation, Atkins November 2015

Figure I-13: Process for creating stochastic drought libraries



I.130 The 'core' of the method is a statistically based weather generator, which is used to generate spatially and temporally coherent artificial drought data that models current climate. The weather and flow generator has been developed based on the rainfall and potential evapotranspiration (PET) in the 20th century, and specifically for the known droughts in that period. It uses a multi-site analysis process to evaluate the influences of random variability, regional climatic factors (such as the North Atlantic Oscillation and Mean Sea Surface Temperature) and observable drought anomalies to produce an emulation of the 20th century climate. The model can be run multiple times in order to produce 'what if' analyses of drought conditions that could have occurred within the 20th century.

I.131 The historic PET record that was used for re-sampling and generation was limited to the period 1920 – 1959 and 1973-1997 inclusive. This was because there is a clear inconsistency within the PET record for the north western half of the catchment, where PET for the period 1950 to 1972 is not consistent with the rest of the record.

I.132 This information is set out in Figure 2.6 of Atkins' Thames Water Stochastic Resource Modelling Stage 2&3 Report' (July 2018)[23]. The report states: 'The historic PET record that was used for re-sampling and generation was limited to the period 1920 – 1959 and 1973-1997 inclusive. This was because there is a clear inconsistency within the PET record for the north western half of the catchment, where PET for the period 1950 to 1972 is not consistent with the rest of the record. The exact reason for this is not known, but a comparison of the PET for that half of the sub-catchment in comparison to the PET for the south-eastern half of the sub-catchment, and the Central England Temperature (CET) record is provided in Figure I-14.

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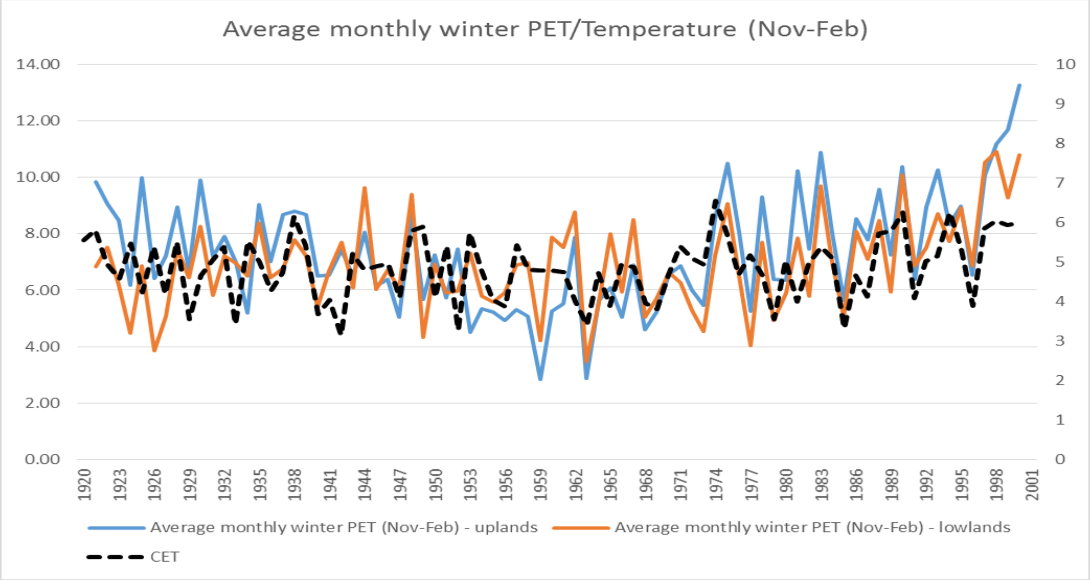
[23] Thames Water Stochastic Resource Modelling 2 & 3 Report, Atkins, July 2018.

Figure I-14: Comparison of Winter Average PET against Central England Winter Temperature: Comparison of the PET record for the northwest half of the Thames catchment against the southwest PET and the CET record. This shows that the northwest (in blue) switches from being above the southeast temperature to being below the southeast in the 50s and 60s, and has a trend that is not evident within the CET.



I.133 The rainfall and PET are then run through a Catchmod based rainfall/runoff model to generate multiple 100 year time series of River Thames and River Severn river flows. The River Thames flows are then run through the Integrated River Aquifer System (IRAS) model, which is a highly simplified, but much faster, version of our WARMS2 water resources model. This carries out a mass-balance analysis of the Thames reservoirs, which can produce yield, resilience and 'DO' metrics in a similar way to WARMS2. The main point of using IRAS is not to replace WARMS2, but to allow the full stochastically generated weather and flow dataset to be analysed within reasonable timescales. The IRAS outputs are then used to rank both individual droughts and each 100 year time series according to water resource severity. This allows specific 100 year sequences, with known relative risk profiles, to be selected for full testing of resilience and key water resource options within the WARMS2 model.

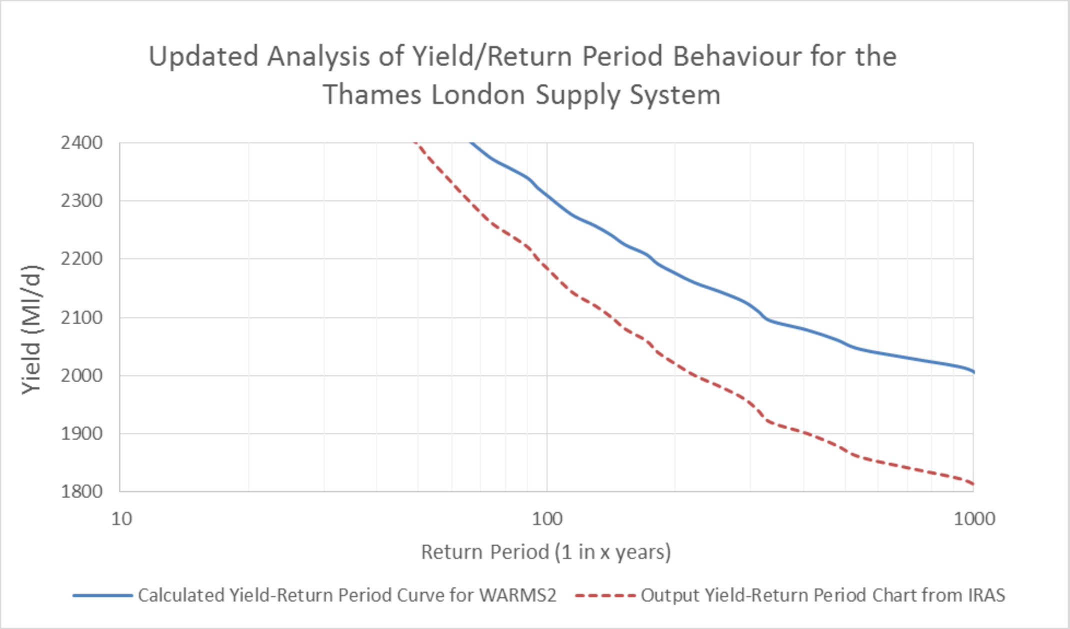
Results of the London stochastic analysis

I.134 A full weather data set equivalent to 200 'what if' iterations has been run and the IRAS behavioural analysis tool has been used to analyse the relative return period of all droughts contained within this data set according to system yield. This has allowed a number of 'drought libraries' with known return period events in them to be extracted and run using a more detailed analysis in the WARMS2 behavioural analysis model. Each drought within each 'drought library' is therefore temporally and spatially coherent, and generates time-series that can be run through the existing rainfall-runoff and behavioural models (WARMS2), or used to examine the probability of meteorological conditions associated with events that have been tested in the Drought Plan.

I.135 We have not used the stochastic dataset as a basis for DO calculation for the entire system. Although WARMS2 does not directly facilitate the derivation of a stochastically derived DO estimate we have used IRAS as a 'pre-screening tool' in accordance with the UKWIR (2016) WRMP19 Methods-Risk Based Planning Methods report. This pre-screening has been done according to system yield, so we have preserved our understanding of risk within each of the droughts contained in the libraries that are run through WARMS2. Based on this we consider that our methodology follows the principles of a 'Risk Composition 3 – Fully Risk Based Plan'.

I.136 Analysis of the results of this work for the Thames catchment, and presented in Figure I-15, illustrate that a 1:200 year event reduces DO by approximately 130-150 Ml/d and a 1:500 year event reduces it by around 250 Ml/d. Details of this analysis were published by Atkins in December 2016[24]. This report also shows that the current return period of the historic 20th century drought events in the Thames catchment is 1:100 years.

Figure I-15: London supply system yield / return period



Source: Figure 5.4 Analysis of WARMS2 Yield/Return Period Curve after Catchmod Re-Calibration, Thames Water Stochastic Resource Modelling Stage 2 and 3 report, July 2018.

I.137 Additional modelling between the draft and final WRMP19 of 1 in 200 droughts in WARMS2 and a comparison of DOs generated to those from IRAS has justified the appropriateness of using IRAS as a screening tool for WARMS2.

I.138 Atkins 'Thames Water Stochastic Resource Modelling Stage 2&3 Report' (July 2018) describes the analysis carried out to derive 1 in 200 yields in the London Water Resource Zone for use within Thames Water's WRMP19; these yields are equivalent to Deployable Output (DO) due to Level 4 events being the critical constraint. The analysis involved using stochastic weather data to calculate drought event yields in IRAS and then developing a

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[24] Thames Water Stochastic Resource Modelling 2 & 3 Report, Atkins, July 2018.

regression equation to convert the IRAS calculation of yield to a WARMS2 equivalent (See Section 5 of the report). The conclusion of the Atkins report states that 'By far the biggest challenge for the stochastic water resource analysis was caused by the differences in the lumped Catchmod hydrological model used for generating flow data for IRAS, and the more granular, distributed hydrological modelling contained within WARMS2. Although they both used the same weather generator outputs, the generated flows were sufficiently different to cause notable differences in estimated yields for the same droughts. However, this issue was addressed through the use of 'Drought Libraries' which provided a practicable method for using the weather generator outputs for more detailed analysis within WARMS2. This meant that IRAS and WARMS2 outputs could be directly compared, providing the necessary conversion factors and allowing for future detailed analysis of new water resource options and climate change within WARMS2.'

I.139 Between the draft and final WRMP19 we have completed modelling work testing the validity of this IRAS-WARMS2 regression, focussing on yields of around a 1 in 200 year return period.

I.140 In order to test the IRAS-WARMS2 regression for droughts close to a 1 in 200 year return period, the production of a 'drought library' for such droughts was necessary. The data sets required for the production of a drought library are rainfall, PET, River Thames flows at Teddington and at Days Weir, which were available for the whole of the stochastic record; the stochastic record consists of 200 78 year records. As such, the production of a drought library essentially involved appropriate filtering of drought events. This drought library was to be a sample of 10 droughts with a return period of around 1 in 200 years, and so the yearly yield results were filtered to include only those with a return period of around 1 in 200 years. A 10 year period around this drought, up to 6 years before and 3 years after, was then extracted to allow for a period of 'warmup' to maximise the accuracy of the modelling analysis of the selected drought. Droughts too close to the beginning or end of the stochastic record that they are contained within to allow for these warmup periods were excluded. The corresponding sequences of rainfall, PET and river flow were then extracted and put into a drought library template. Where IRAS yields for years preceding or following the '1 in 200' year were found to be less than the '1 in 200' year itself, particular care was taken when analysing results to ensure it was the yield for the correct drought event that was being found, rather than the yield for a more severe event. In practice, only one such drought event was included in the sample.

I.141 The drought library was then run in WARMS2 at many levels of demand. For each drought a Level 4 yield value was found, as the level of demand just before the emergency reservoir storage was crossed on the LTCD.

I.142 The WARMS2 yields found for all drought events within the library were collated, alongside the corresponding yields found in IRAS. The regression equation to translate between IRAS and WARMS2 yields was used to provide the WARMS2 yield estimate that would be generated from IRAS yields, and this was compared with the WARMS2 yield found directly from WARMS2. The results can be seen on Figure I-16.

I.143 The root mean squared error (RMSE) and the mean absolute error (MAE), based on the difference between the WARMS2 yield found from the regression and the WARMS2 yield found from WARMS2 for each drought, were then calculated. The RMSE was found to be 94Ml/d and the MAE was found to be 77Ml/d. In comparison, an RMSE of 87Ml/d and MAE of

72Ml/d were found when considering the droughts that the regression was 'trained on', which contain IRAS yield values of between 1800Ml/d and 2430Ml/d. Although there is a spread of values for the WARMS2 yield found for droughts which, using IRAS, give 1:200 return period yields, the regression used to find WARMS2 yields holds almost equally as well for droughts focussed around the 1 in 200 year return period as it does for a sample containing a much wider range of yield return periods.

I.144 The mean error (not absolute error) of WARMS2 yields compared with those expected from the regression is -0.11, showing no bias regarding whether yields for 1:200 droughts are higher or lower than the IRAS-WARMS regression would predict. This is also the case the original full set of yields from IRAS (mean error of +0.8Ml/d). The consequence of this is that, in terms of yield return periods, WARMS2 yields may 'reorganise' themselves, with some droughts that are relatively more severe when modelled in IRAS being less severe in WARMS2 and vice versa. This means that based on the full set of yields from IRAS it is possible to accurately predict return periods of different WARMS2 yields.

I.145 Atkins' 2016 Stage 2&3 Report (July 2018) presents a graph (Figure I-167 below) which shows relative yields of each of the droughts calculated in IRAS versus WARMS2 and the regression equation from this trend analysis used to convert the IRAS calculation of yield to a WARMS2 equivalent. Mapping Figure I-156 on to Figure I-167 demonstrates that additional analysis completed between the draft and final WRMP19 verifies the analysis completed by Atkins and the robustness of the regression equation used within our WRMP19.

Figure I-16: IRAS and WARMS2 level 4 yields for London WRZ found for droughts in the 1:200 year return period drought library

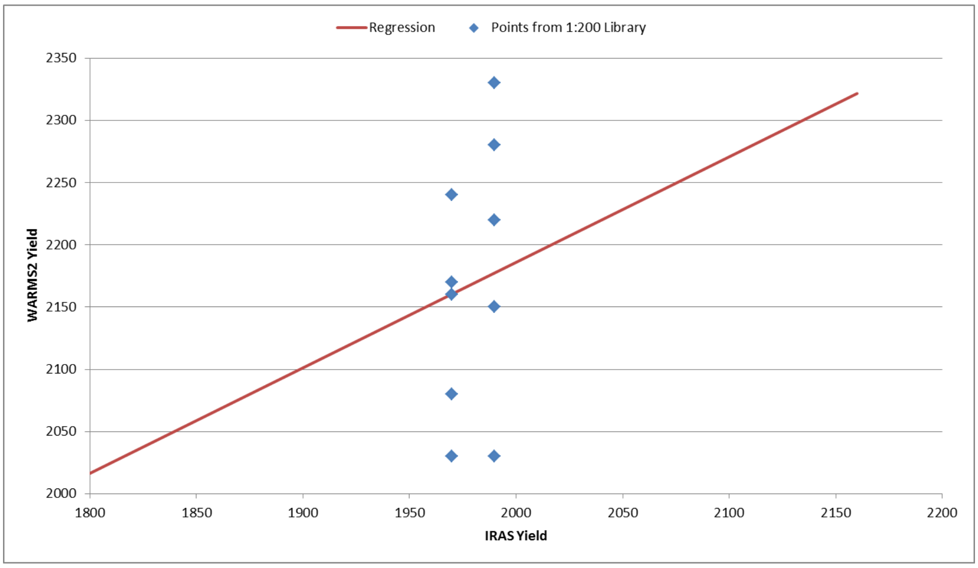
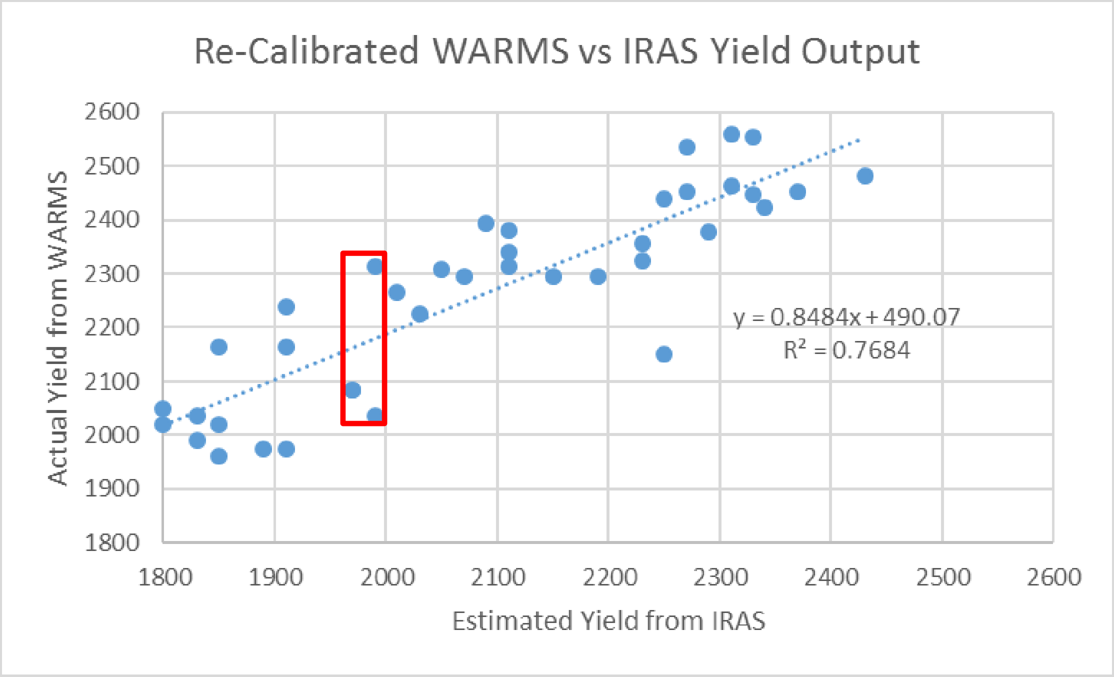


Figure I-17: Comparison of IRAS and WARMS2 yields



Source: Figure 5-2 Atkins' 2016 Stage 2&3 Report (July 2018).

I.146 This analysis demonstrates that it is appropriate to use IRAS as a screening tool for WARMS2 and there are no risks to the WRMP19 preferred programme as a result. We have considered specific drought events that are close to a 1 in 200 year drought DO and compared the IRAS and WARMS2 simulations, providing confidence that the 1 in 200 year drought DO produced by Atkins for the draft WRMP19 and carried forward for the final WRMP19 is clear and appropriate.

Results of the stochastic analysis

I.147 We also commissioned Atkins to analyse more severe droughts for the other Thames Valley Water Resource Zones; SWOX, Kennet Valley, Henley, SWA and Guildford. These zones were assessed using a simpler Extreme Value Analysis (EVA) methodology.

I.148 The following text is taken from the 'Thames Water Table 10 Extreme Value Analysis' (November 2017) report[25], although the report itself contains a lot more detail:

> *'This report contains an evaluation of the potential risks faced by Thames Water in Water Resource Zones (WRZs) outside of London during severe (1 in 200) and extreme (1 in 500) droughts, and is written to act as a support to Thames Water's Table 10 of the WRMP19 submission. The form of assessment is relatively simple and follows the Extreme Value Analysis (EVA) principles outlined in the UKWIR 'WRMP19 Methods: Risk Based Planning'*

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[25] Atkins, Thames Water Table 10 Extreme Value Analysis, November 2017

> *guidance. In order to provide inputs to Table 10 of the Water Resources Management Plan (WRMP) the impact of the two drought severities has been calculated in relation to the 'baseline' Deployable Output (DO), which has been calculated separately by Thames Water and in all cases is equal to the calculated DO for the overall worst historic drought on record for each WRZ.'*

I.149 For the Guildford, Kennet and SWA WRZs the primary analysis was carried out for the summer Dry Year Critical Period (DYCP) as this generates the greatest stress in the supply/demand balance, however Dry Annual Average (DYAA) conditions were also assessed to allow completion of Appendix A: Table 10. For SWOX only the DYAA was analysed as the WRZ incorporates the Farmoor storage reservoir. For the Henley WRZ there are no sources vulnerable to drought DO impacts, so no analysis was required for Appendix A: Table 10.

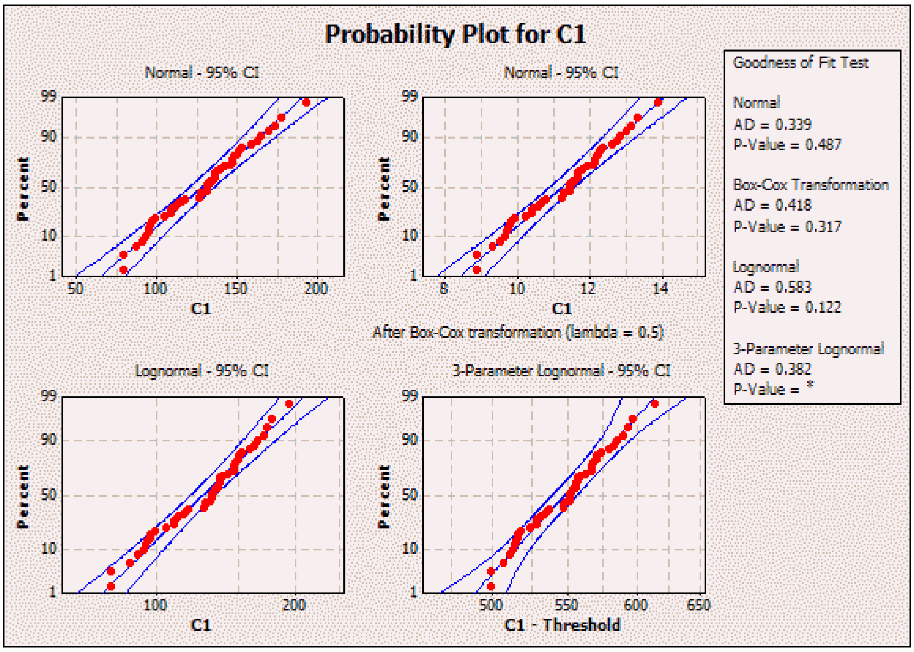
I.150 Atkins completed the EVA analysis based on the primary system stress metric for sources that were identified as potentially at risk during a severe drought i.e. sources that are at potential risk from the hydrology associated with more severe events; the potentially vulnerable sources were identified through discussion with us.

I.151 The metrics that were used were as follows:

- Kennet and Guildford (Fobney and Shalford WTWs) run of river works: annual summer minimum flow (with comparisons against the absolute annual minimum for the DYAA analysis).
- Kennet and SWA groundwater sources: annual summer minimum levels in the indicator observation borehole (OBH) that is used for each source in the hindcasting DO analysis (with comparisons against the absolute annual minimum for the DYAA analysis)
- SWOX: annual calculated Farmoor reservoir storage minima for the DO demand condition run in WARMS2.

I.152 The estimated return period of the worst historic event used for DO hindcasting was estimated from the resulting EVA curve fit. The estimated indictor level for the 1 in 200 drought scenario was then calculated based on the EVA curve. An example of the EVA curve fit is shown in Figure I-18 below. As shown, the selection of the best curve fit was based on the P statistic and the Anderson-Darling goodness of fit test, although in some cases some manual interpretation was also used based on the nature of the fit around the lower annual minima values.

Figure I-18: Example EVA analysis output (combined Wey and Tillingbourne flow for Shalford)[26]



I.153 The system stress metric was converted into a DO impact using one of the following methods:

- For the two run of river sources, the potentially available abstraction was calculated based on the minimum flow, adjusted to account for any other factors. This was then compared against licence and other DO constraints to determine if the DO is affected by the increased drought severity.
- For the groundwater sources, the Thames Water SDO spreadsheets were used. The OBH groundwater levels calculated for the drought events were entered as dummy values into the ‘1) Adjust OBH Input’ worksheet and the resulting source rest water levels were then pasted into the ‘Input’ worksheet. The macro was then run and the potential yield generated based on the same method as the Annual Review 2017 groundwater DO assessment. This was then compared against other DO constraints to estimate the DO impact from the drought scenarios.
- For Farmoor DYAA the change in storage from worst historic to the two drought scenarios was taken from the EVA and divided by a drought recession period to determine the impact on DO. The recession period in both 1976 and 1921 (the second worst drought in the calculated record) was found to be approximately five months, so there was a reasonable amount of certainty in this method. The analysis was carried out on modelled reservoir storage minima that included the impact of TUBs, so the calculated difference is directly compatible with the ‘with restrictions’ analysis of yield for Farmoor. The DYCP was not evaluated using a curve fitting approach, as there was no reasonable way of doing this given the method that is used. A simple proportional impact was therefore assigned to the DYCP based on the percentage impact that was observed for the DYAA.

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[26] Atkins Table 10 Extreme Value Analysis Thames Water, November 2017

I.154 Analysis of the results indicates that there is a reduction in DO for a 1:200 year event for SWOX, Kennet Valley and SWA WRZs, but that Henley and Guildford WRZs are resilient[27], as shown in Table I-26 and Table I-27.

I.155 The stochastic analysis has not been updated between the draft and final WRMP19 however the baseline DOs have been updated to align them with AR17+ figures.

Table I-26: Risk to DYAA DO of increased 1:200 drought severity

WRZ	Annual Review 2017+ DYAA DO (Ml/d)	Critical Year (Ml/d)	DO of 1:200 drought (Ml/d)	Impact on DO of 1:200 drought (Ml/d)
London	2302.00	1921	2162.00	140.00
SWOX	329.17	1976	323.29	5.88
Kennet Valley	143.87	1976	141.07	2.80
Henley	25.65	1976	25.65	0.00
SWA	185.05	1976	183.19	1.86
Guildford	65.82	1992	65.82	0.00

Table I-27: Risk to DYCP DO of increased 1:200 drought severity

WRZ	Annual Review 2017+ DYCP DO (Ml/d)	Critical Year (Ml/d)	DO of 1:200 drought (Ml/d)	Impact on DO of 1:200 drought (Ml/d)
London*	N/A	N/A	N/A	N/A
SWOX	385.38	1976	378.51	6.87
Kennet Valley	155.40	1976	152.04	3.36
Henley	25.9	1976	25.9	0.00
SWA	214.40	1976	211.14	3.26
Guildford	71.70	1992	71.70	0.00

**Note: Impact on London based on DYAA*

I.156 Analysis of the results indicates that there is a greater reduction in DO for a 1:500 year event compared to a 1:200 year event for London, SWOX, Kennet Valley and SWA WRZs, but that Henley and Guildford WRZs remained resilient[27], as shown in Table I-28 and Table I-29.

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[27] Thames Water Table 10 Extreme Value Analysis, Thames Water, Atkins, November 2017

Table I-28: Risk to DYAA DO of increased 1:500 drought severity

WRZ	Annual Review 2017+ DYAA DO (Ml/d)	Critical Year (Ml/d)	DO of 1 : 500 drought (Ml/d)	Impact on DO of 1:500 drought (Ml/d)
London	2302.00	1921	2052.00	250.00
SWOX	329.17	1976	306.77	22.4
Kennet Valley	143.87	1976	139.77	4.1
Henley	25.65	1976	25.65	0.00
SWA	185.05	1976	181.55	3.5
Guildford	65.82	1992	65.82	0.00

Table I-29: Risk to DYCP DO of increased 1:500 drought severity

WRZ	Annual Review 2017+ DYCP DO (Ml/d)	Critical Year (Ml/d)	DO of 1 : 500 drought (Ml/d)	Impact on DO of 1:500 drought (Ml/d)
London*	N/A	N/A	N/A	N/A
SWOX	385.38	1976	359.18	26.2
Kennet Valley	155.40	1976	141.1	14.3
Henley	25.9	1976	25.9	0
SWA	214.40	1976	209.9	4.5
Guildford	71.70	1992	71.70	0

**Note: Impact on London based on DYAA*

I.157 We have assessed the impact of more severe droughts in our WRMP19 and 2018 revised draft Drought Plan. We have assessed the impacts of a 1:200 year drought for our WRMP19 and included the assessment results in Appendix A: Table 10. This demonstrates that we can manage a 1:200 year drought but would require the use of Drought Permits for an extended period. We have assessed the potential impact of 1:300 and 1:500 droughts in our Drought Plan and this also shows that it is possible to maintain supplies through these droughts with the use of Drought Permits over an extended period and with Drought Orders to ban non-essential use. This means that we do not plan for reaching Level 4 and our Levels of Service reflect this. However the environmental and economic impact of this prolonged use of Drought Permits and DOs would be severe, particularly on the environment, and in our view it is not acceptable to plan for water management on this basis. Therefore we plan to develop an increased resource base so that we are resilient to 1:200 year drought without the requirement for prolonged use of drought permits; Section 11: Preferred plan describes how the preferred plan will increase the company’s level of drought resilience from 1 in 100 to 1 in 200 by 2030.

I.158 It should be noted that the resilience described in our 2018 revised draft Drought Plan is for the duration of the current plan only and so relates to the next 6 years after which we will develop our next edition of the plan. Therefore the plan does not include the impacts of future growth in population or of climate change and so without new resource development or improved supply demand balance we are not likely to be resilient to more severe droughts for the period of our next Drought Plan.

I.159 For the London WRZ, 'drought severity' has been calculated using WARMS2 that quantifies the combined duration and intensity of a drought, as stated according to the amount of stress it places on the London water resource system. All drought severities (return periods) have been defined according to the relative London system yield as calculated in IRAS, with the return period of each drought calculated based on a simple ranked return period analysis. The 'severity' of each drought therefore takes into account all of the meteorological drought attributes (timing, duration and intensity) and expresses them in terms of the impact that they have on the London system yield. This represents the best practice for drought analysis as described in the UKWIR 2016 'WRMP19 Risk Based Methods' Guidance and the Environment Agency 2017 'Drought Vulnerability Framework' Guidance (Environment Agency, 2017[28]).

I.160 The Environment Agency issued guidance in 2017 on the production of 'Drought Vulnerability Surfaces' (DVS) (Environment Agency, 2017[28]). The essence of a DVS is a chart with an x-axis of drought length, a y-axis of rainfall, and a z-axis (represented using colours) showing a system drought performance metric. The idea is that a water resource system should be tested against droughts of various durations and intensities, in order to identify tipping points where system performance quickly degrades and to highlight areas of relative vulnerabilities of water resource systems. These DVSs were initially to be produced for inclusion in the WRMP19, although the Environment Agency later withdrew this requirement, suggesting that DVSs should be included as part of the Annual Review process.

I.161 We have decided to include DVSs for the London WRZ, our most vulnerable and complex WRZ, within the WRMP19 as these are useful illustrations of the impact that droughts, across a range of varying intensities and durations as well as severities, have on the supply system. We have followed a slightly different methodology than initial EA guidance suggested regarding the production of DVSs, where it was suggested that DVSs should present days of emergency restrictions at a level of demand equal to Distribution Input (DI) plus Target Headroom. We have instead decided to present yield-based metrics on our DVSs in order to align with Appendix A: Table 10. This has also allowed us to produce a more meaningful system metric for our planning, particularly relating to draft WRMP19 stakeholder consultation responses regarding the consideration of contrasting extreme and severe drought profiles and our drought resilience across a range of 'types' of droughts. In addition, data was also readily available for the production of a DVS using a yield-based metric, where further modelling would have been necessary to produce a DVS using days of emergency restrictions. A final point is that 2017 Environment Agency guidance on the production of DVSs was withdrawn so the production of a yield-based DVS, presented here, is going beyond the requirements within the current Environment Agency guidelines for the WRMP19.

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[28] Using the Drought Vulnerability Framework in Water Resources Management Plans, 2017, Environment Agency

I.162 DVSs for London are presented in Figure I-19 and Figure I-20 under worst historic (1 in 100 year) company drought resilience using a yield-based metric to align with Appendix A: Table 10. These surfaces present the resilience / sensitivity to droughts of different durations, intensities and severities and the range of drought 'types' of varying duration and intensity which the drought severities presented in Appendix A: Table 10 (1 in 100, 1 in 200 and 1 in 500) account for. The DVSs also include points relating to the historical record to indicate how the worst historical events relate to more extreme events.

Figure I-19: DVS for London WRZ with SDB as the metric and historic droughts shown - 'calendar' year end point under worst historic (1 in 100 year) drought company resilience

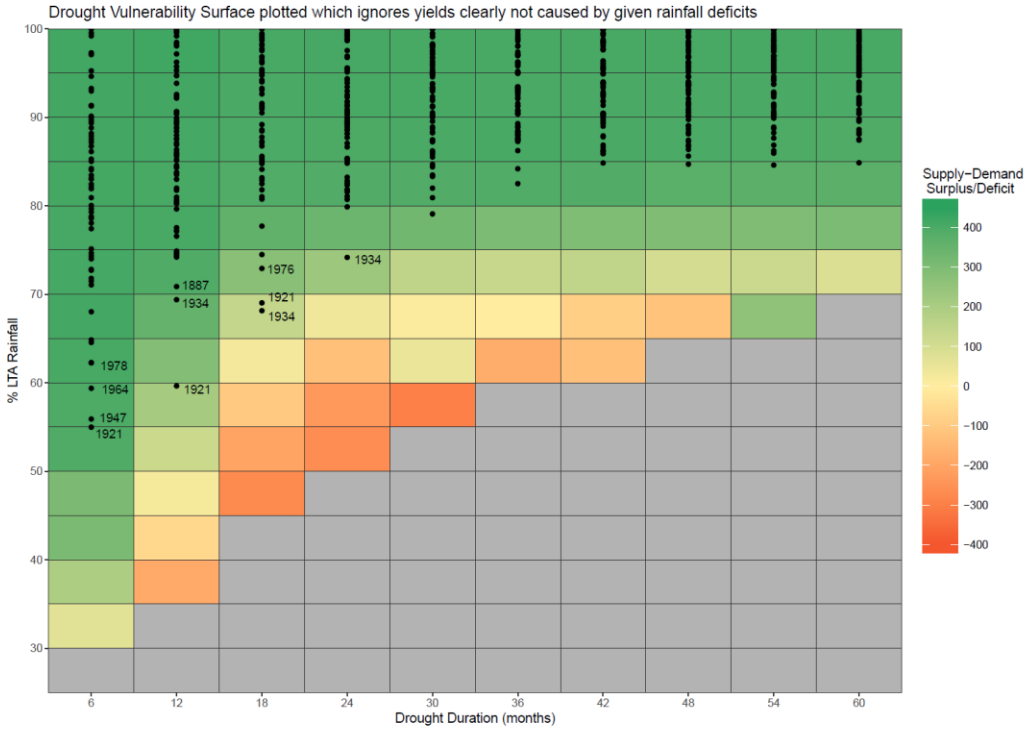
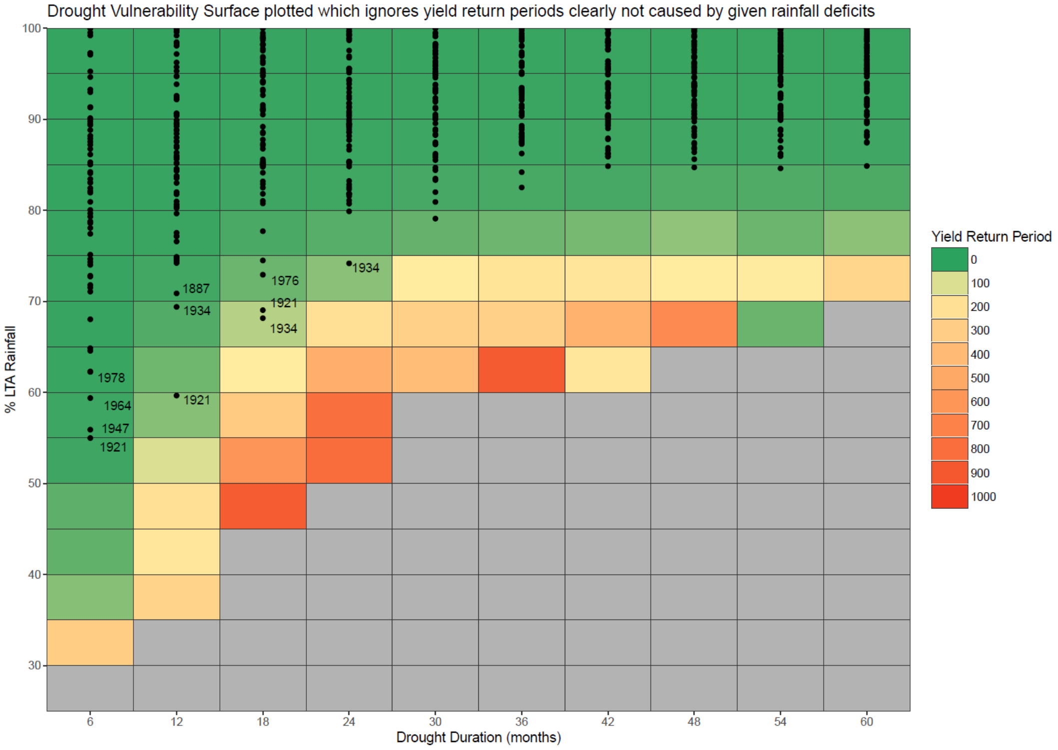


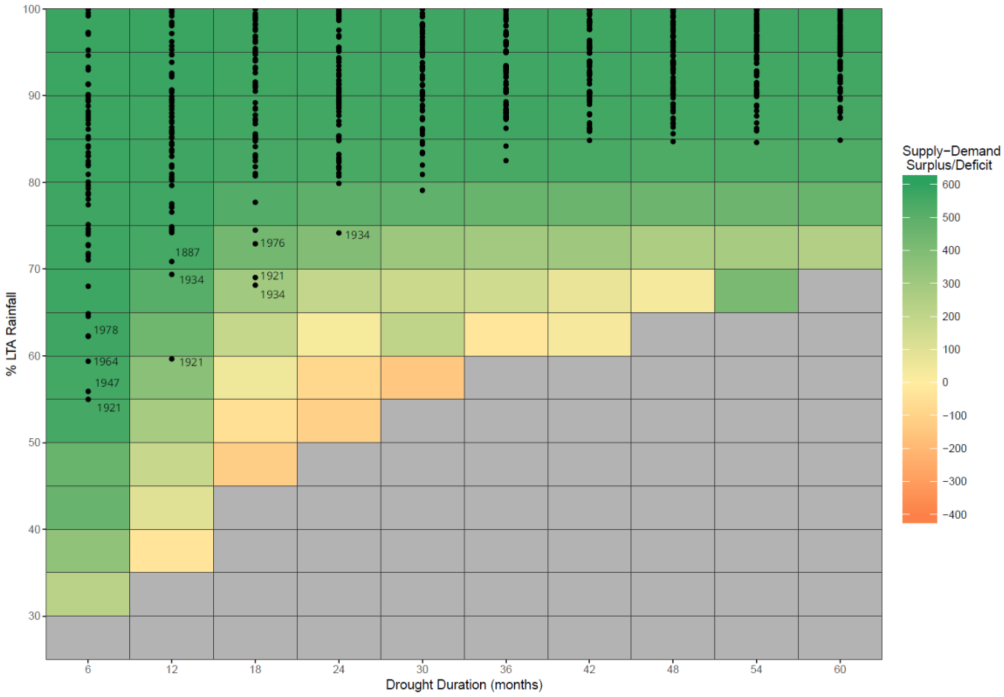
Figure I-20: DVS for London WRZ with return period of average yield as the metric and historic droughts shown - 'calendar' year end point



I.163 The DVSs presented here are for the base year of the WRMP19 to align with Appendix A: Table 10 for the London WRZ under worst historic (1 in 100 year) company drought resilience.

I.164 The DVS presented in Figure I-21 is an illustration of how company resilience will improve in 2030 following the step up in company drought resilience from resilience to a worst historic (1 in 100 year) to a 1 in 200 year drought. This aligns with the 2030 drought resilience scenario presented in Appendix A: Table 10 for the London WRZ. See Section 11: Preferred plan for the suite of demand and supply options selected in 2030 which result in this increased 1 in 200 resilience.

Figure I-21: DVS for London WRZ with SDB as the metric and historic droughts shown - 'calendar' year end point under 1 in 200 year drought company resilience.



I.165 The key point from Figure I-19, as expected, is that the London WRZ is most vulnerable to droughts of 18-24 months. This is where cells change colour relatively quickly from green (surplus) to orange (deficit) as %LTA rainfall decreases, and also where historical events plot closest to the green-yellow-orange tipping point. For events longer than 24 months, while severe impacts do occur, they are well beyond events that have historically occurred, and are well outside the scope of consideration within planning (e.g. the 30 month, 55-60% LTA cell shows a very severe impact, but this has a yield return period of over 1000 years).

I.166 When Figure I-20 with return period of average yield as a metric is viewed in conjunction with the DVS with SDB as the metric (Figure I-19), the worst historic critical drought event experienced in the London WRZ, the 1921 drought, is shown to have a 1 in 100 years yield impact (Figure I-20) and is not shown to result in a deficit (Figure I-19). This demonstrates that for the base year of the WRMP19 the London WRZ the baseline DO is resilient to a worst historic 1 in 100 drought event and this level of resilience is maintained for the first 10 years of the plan.

I.167 The 'severity' of each drought under which the preferred programme has been tested takes into account all of the meteorological drought attributes (timing, duration and intensity) and expresses them in terms of the impact that they have on the London system yield. For the critical 1 in 100 drought event Figure I-20 demonstrates that this covers a range of percentage long term average rainfall deficits and durations.

I.168 When considering the impact of more severe droughts under worst historic (1 in 100 year) company drought resilience, the droughts which do result in a deficit in Figure I-19 and which have a return period of greater than 1 in 100 in Figure I-20, for the first 10 years of the WRMP19 the 2017 Drought Plan shows that:

I.169 1 in 200 year droughts in Figure I-20 can be managed but would require the use of Drought Permits for extended periods of time, i.e. greater than 12 months.

I.170 It is possible to maintain supplies through 1 in 300 and 1 in 500 droughts in Figure I-20 with the use of Drought Permits over an extended period and with Drought Orders to ban non-essential use.

I.171 This means that we are robust against Level 4 severe drought restrictions and our Levels of Service reflect this. However, as noted above, the environmental and economic impact of this prolonged, extended use of DPs and DOs would be severe, particularly on the environment, and in our view it is not acceptable to plan on this basis.

I.172 Therefore we plan to develop an increased water resource base so that we are resilient to the 1 in 200 year droughts identified in Figure I-20 from 2030 onwards without the requirement for prolonged use of drought permits. Figure I-21 presents a DVS for 2030 and the step change to 1 in 200 drought resilience in the London WRZ.

I.173 It should be noted that the resilience described in our 2018 revised draft Drought Plan is for the duration of the current plan only and so relates to the next 6 years after which we will develop our next edition of the plan. Therefore the plan does not include the impacts of future growth in population or climate change and so without new resource development or improved supply demand balance we are not likely to be resilient to more severe droughts for the period of our next Drought Plan.

I.174 For the Thames Valley WRZs, the drought resilience has been assessed as detailed within the 2018 revised draft Drought Plan. Where potential vulnerabilities to drought were identified for sources then these were estimated using similar methods to those detailed in the EA draft 'Drought Vulnerability Framework' with the estimates based on groundwater levels, minimum river levels or reservoir storage as appropriate. As for the London WRZ, the drought severity risks therefore inherently account for both duration and intensity of droughts.

I.175 The impact on DO of a 1:500 year drought on all WRZs is presented in Table I-28 and Table I-29 and will be included as a ‘what-if’ scenario as part of programme appraisal in Section 10: Programme appraisal and scenario testing. An additional scenario exploring the timing of delivering 1 in 200 drought resilience will also be included as part of programme appraisal in Section 10: Programme appraisal and scenario testing.

I.176 With regard to the resilience during drought of strategic schemes that support London during a drought (described in Section D: London), and which are included within the London DO, the assumed benefit of schemes from WARMS2 is essentially fixed according to a monthly based profile of yield, which is triggered when the relevant Lower Thames Operating Agreement control curve is triggered (Table I-11 presents DO benefit of strategic schemes and LTOA control curve trigger levels). Currently this does not vary under more extreme drought scenarios, as it is not possible to model the performance of such schemes outside of the historic record, however a comment on drought resilience of each strategic scheme is provided below:

I.177 **Gateway (the Beckton desalination plant)** is resilient to more extreme events because the raw water resource is from the Thames Tideway and so is effectively unlimited during drought. The operating protocol for the Beckton desalination plant is set out in our 2018 revised draft Drought Plan. The scheme provides a beneficial yield of 150 M/d with a fixed profile assumed during drought. We will consider the potential impact of raw water quality on abstraction and therefore yield during extreme droughts for our WRMP24.

I.178 **Hoddesdon Transfer Scheme** is resilient to more extreme events because this is an effluent transfer scheme taking effluent from the Deephams Sewage Treatment Works (STW) catchment to Rye Meads STW catchment via a pipeline and a sewage pumping station. The transfer increases the volume of water in the River Lee diversion channel and allows increased abstraction during periods of drought and so is effectively unlimited during drought. We will consider nitrate challenges which may constrain abstraction during drought in the River Lee catchment as part of the AMP7 NEP.

I.179 **The East London Resource Development Scheme (ELRED) and Stratford Box (and Old Ford),** small groundwater schemes which can be operated in conjunction, are located in confined Chalk and are therefore considered to be drought resilient with a fixed profile assumed during drought.

I.180 **The North London Artificial Recharge Scheme (NLARS) and the Chingford Artificial Recharge Scheme (CHARS)**, which enable beneficial use of the confined Chalk aquifer in North London by a technique known as managed aquifer recharge, and the **West Berkshire Groundwater Scheme (WBGWS)**, a strategic drought river augmentation scheme, have been assessed through modelling to provide a yield that can be expected in the worst droughts in the historical record; the yields diminish during drought. The NLARS and CHARS schemes have a yield based on 16 months of use with the WBGWS based on 240 days of use. These durations arise from the duration for which they are required in the most severe drought in the historical record and the difference arises because the NLARS and CHARS are triggered at Level 1 and WBGWS is triggered at Level 2. The yield available from the NLARS, CHARS and WBGWS schemes have not been assessed for more severe droughts, this would entail significant work to establish what a longer term sustainable abstraction rate might be during more extreme droughts, i.e. those longer than the current historical drought duration modelled, and we will consider this for our WRMP24.

M. WARMS2 independent review

HR Wallingford review of WARMS2

I.181 We have an on-going programme of work to improve the assessment of DOs , which includes reassessing the yields of drought schemes and enhancing the WARMS2 system. HR Wallingford Limited previously reviewed the WARMS system in July 2014 (HR Wallingford, 2014)[29].

I.182 We requested HR Wallingford Limited to undertake an updated review to focus on updates to WARMS (now known as WARMS2), primarily verifying the performance of WARMS2 for selected design runs, the assessment of supply-side options and estimating system DO using stochastically generated weather sequences and climate change scenarios.

I.183 The latest review[30] has demonstrated that the overall mass balance across the system is maintained throughout a range of historical, stochastic and climate change simulations. WARMS2 implements the triggering of strategic schemes and demand savings in accordance with the document rules and the updated LTCD. This includes ensuring minimum flow requirements are complied with on both the River Thames and River Lee. This performance is also maintained under a selected climate change scenario and a stochastically generated drought library. The climate change impacts on flows for the selected scenario were consistent with the climate change impacts assessment undertaken for the WRMP 2019, and the monthly changes in flows projected for Teddington (HR Wallingford, 2017).

I.184 The review also included an assessment of WARMS2 performance when considering selected Upper Thames Reservoir and Unsupported Severn Thames Transfer option variants. For both option variants the LTCD control curves for the current system (AR16 Design Simulation) are used and these schemes are implemented within WARMS2 in accordance with the published rules and assumptions associated with each option. With regards to the unsupported Severn Thames Transfer, this review confirms that the WARMS2 simulations comply with the Hands-Off Flow conditions and other operational constraints (e.g. dealing with spate flows) applicable to the River Severn at Deerhurst. For the South East Strategic Reservoir Option, the triggering of releases and reservoir refill is as set-out in the published reporting associated with this option.

I.185 It should be noted that the review has not considered hydrological model calibration / validation, derivation of effluent returns, estimation of groundwater DOs or the assumptions regarding operational practices of other water users on the River Thames, River Lee and River Severn, as these were addressed in the 2014 audit.

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[29] Independent Review of WARMS2, HR Wallingford, July 2014
[30] WRMP19, WARMS2 Independent Review, HR Wallingford, August 2017