Water Resources Management Plan 2024

Technical Appendix I –

Deployable Output

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Background and Introduction

This section of our Water Resources Management Plan 2024 (WRMP24) describes the amount of water which is currently available for water supply, known as Deployable Output (DO).

In this section, we describe our existing supply systems and how we have calculated DO, including the changes that we have made to our assessment between WRMP19 and WRMP24.

Our DO calculation has involved use of datasets and models developed through the Water Resources South East (WRSE) Regional Group, and our DO calculation method is aligned with methods developed through WRSE.

I.1 DO is one of the key metrics used in water resources planning. When allowances for outage, network constraints, treatment losses, and climate change are taken away from DO, we are left with Water Available for Use (WAFU), which is a key component in defining the supply-demand balance.

I.2 DO is also used as a metric when considering other components of WAFU. For example, the impact of climate change on supply capability is determined as the reduction or increase in DO that climate change impacts may result in. Additionally, the benefit that new sources of water would bring to a Water Resource Zone (WRZ) are measured in terms of DO benefit.

I.3 DO is a measure of the supply capability of a water resource system under specified (generally drought) conditions. The constraints considered in the calculation of DO are:

- Hydrological Yield
- Licensed Quantities
- Level of Service
- Treatment Constraints
- Water Quality
- The Environment, via Licence Constraints
- Pumping Assets and Raw Water Mains
- Abstraction Well, Borehole, Spring and Aquifer Characteristics

I.4 The water that we supply to our customers comes from a variety of different sources, including boreholes, wells, springs, ‘run-of-river’ (RoR) surface water abstractions, pumped surface water abstraction from rivers into reservoirs, and a desalination plant. DO can be calculated at the level of individual sources, leading to the calculation of Source Deployable Output (SDO) values, or at the WRZ level. In some cases, groundwater and surface water sources operate within the same WRZ and, if operated in combination, can bring about a larger WRZ DO than the sum of individual SDOs; such combined operation is known as conjunctive use.

I.5 In this section we detail:

- Key guidance documents which set out how we should calculate DO, along with relevant methodology documents
- Salient changes that have occurred between the publication of our WRMP19 and rdWRMP24
- The characteristics of our different WRZs, and how this has shaped our DO calculation methodologies for different zones, including a description of the Lower Thames Operating Agreement (LTOA)
- The methods that we have applied in calculating WRZ DO and our approach to water resources system modelling, including a brief introduction to stochastic weather datasets
- How we have assessed the yield/SDO of groundwater sources
- Our approach to hydrological modelling
- The results of our DO assessment for each of our WRZs
- Details of our Aquator model (known as WARMS2) and Pywr model, including calibration and validation of these models

I.6 Several abbreviations are used in this document. While our WRMP contains a more comprehensive glossary and list of abbreviations, those of specific application in this appendix are included here.

Abbreviation	Meaning
DO	Deployable Output
SDO	Source Deployable Output
WRZ	Water Resource Zone
GW	Groundwater
SW	Surface Water
RoR	Run of River
WAFU	Water Available for Use
WRSE	Water Resources South East
PET	Potential Evapotranspiration

Table I-1: Commonly Used Abbreviations in this Appendix

Key Guidance and Methodology Documents

I.7 DO is calculated subject to prescribed methodologies, both at the source level, and at the WRZ level.

I.8 The primary guidance documents referred to in the development of our DO figures are:

- Environment Agency, April 2022, Water Resources Planning Guideline: This document sets out the key requirements for the development of our supply forecast, including key inclusions, exclusions, and methodological stipulations
- Environment Agency, March 2021, Water Resources Planning Guideline supplementary guidance – 1 in 500: One of the key changes to guidance around DO is that water companies should determine a '1 in 500-year' DO for WRMP24. This document sets out supplementary guidance on how we should assess a '1 in 500-year' DO
- Environment Agency, March 2021, Water Resources Planning Guideline supplementary guidance – Stochastics: With key historical weather records being generally a hundred years or less in length, the determination of a '1 in 500-year' DO involves consideration of drought events which have not occurred during the historical record. This supplementary guidance note sets out how 'stochastic' datasets can be used to help define a '1 in 500-year' DO

I.9 In addition to the Environment Agency (EA) guidance documents, other important method documents include:

- UKWIR, 2014, Handbook of source yield methodologies: This sets out methods that can be applied when calculating yields and/or DO for individual sources and conjunctive use systems
- UKWIR, 2016, WRMP19 methods – risk-based planning: This sets out methods that can be applied to link risk-based/probabilistic methods of assessment to the derivation of deterministic water resource plan inputs. It includes guidance on the generation of stochastic datasets

I.10 An important change between WRMP19 and WRMP24 has been the focus on regional groups in water resource planning. Thames Water is part of the Water Resources South East (WRSE) regional group. WRSE has developed datasets, methods and models which have been applied in the calculation of DO across all WRSE companies. These include:

- WRSE, 2021, Method Statement: Calculation of DO
- WRSE, 2021, Method Statement: Stochastic Datasets
- WRSE, 2021, Method Statement: Groundwater Framework
- WRSE, 2021, Method Statement: Hydrological Modelling
- WRSE, 2021, Method Statement: Regional System Simulation Model

Key Changes Between WRMP19 and WRMP24

I.11 There have been a number of changes that have taken place between the publication of our WRMP19 and WRMP24 which have influenced the calculation of DO. These include changes in guidance, new methods, and changes in our understanding/operation of existing sources.

Requirement to Determine a '1 in 500-year' Deployable Output

I.12 The Water Resource Planning Guideline (WRPG) sets out the requirement that our baseline sources should be available such that our supply system has a 0.2% annual chance of failure caused by drought. In this circumstance, 'failure' is defined as a need for emergency drought orders.

I.13 Water companies have historically assessed the capability of their sources subject to a 'worst historical' drought condition, i.e. the SDO/DO of a source/group of sources would have been calculated such that the yield of the source/group of sources is that which would have been feasible during the 'worst' drought on record. The benefit of a 'worst historical' assessment is that this involves the use of a measured record (i.e. a weather/flow/groundwater level record in which we can be fully confidence), but the downside is that it limits assessment of supply capability to a small number of events, meaning that potential system vulnerabilities may be omitted from consideration). EA guidance accepts that the determination of a '1 in 500-year' (sometimes written 1:500) DO figure involves a large amount of uncertainty, particularly considering the non-stationary climate that now exists due to the influence of greenhouse gas emissions, but that the aim of the '1 in 500-year' standard is to ensure that droughts that are significantly more severe than those experienced historically are considered.

I.14 Companies' WRMP19 plans have not included a requirement to deliver 1:500 resilience as no such requirement was included in the WRMP19 WRPG, and so this is a marked shift in the level of resilience required. As such, most water companies do not currently offer their customers a 1:500 level of resilience to drought risk. The EA sets out in supplementary guidance that 1:500-year resilience should be achieved before the 2040s, although the EA and Ofwat have also set out that different timescales, both later and earlier, for achievement of 1:500 resilience should be considered. For example, if delivery of 1:500 resilience by the early 2040s results in a materially cheaper plan, then this may be acceptable, but if delivery of 1:500 resilience by the mid-2030s is not significantly more costly than delivery by 2039 then quicker delivery would be the 'best value' option.

I.15 Our current Level of Service regarding emergency restrictions is that we would not impose such restrictions more often than once every 100 years. Our anticipated pathway towards greater resilience involves a move to a '1 in 200-year' resilience by the early 2030s and '1 in 500-year' resilience before the 2040s.

I.16 The concept of a '1 in 500-year' DO can be somewhat confusing. The '1 in 500' DO for a WRZ will be less than or equal to the '1 in 200' DO, which will in turn be less than the '1 in 100' DO. This is because the drought event being considered in the '1 in 500' condition will be more severe than that considered in the '1 in 200' condition, and so on.

Emphasis on 'System Response' in the Calculation of Deployable Output

I.17 This is not an explicit change to requirements set out in the WRPG but is a significant change in emphasis. The WRPG supplementary guidance on 1 in 500 states:

> *You should define your '1 in 500' supply deployable output using your system response. Your system should be defined at the water resources zone level*

I.18 The 'system response' approach is specified to contrast against other approaches to determining extreme drought events, such as defining drought based on rainfall or similar. Using system response metrics is intended to better reflect the influence of drought events on outcomes (supply capability), rather than focussing on inputs (rainfall). In addition, the use of the word 'system' alongside response highlights a preference towards consideration of water resource systems, rather than a focus on individual sources. This is reflected in the approaches that we have applied.

Changes and Clarifications Regarding Inclusions/Exclusions in the Calculation of Deployable Output

I.19 The EA have clarified how specific factors should be included or excluded within the assessment of DO. Compared to WRMP19, the most significant clarification/change to reporting of DO is that the Baseline DO figure presented should not include contributions from any demand or supply drought measures. This means that our reported Baseline DO figure will exclude benefits associated with the imposition of Temporary Use Bans (TUBs), Non-Essential Use Bans (NEUBs), and Media Campaigns. Benefits from demand restrictions associated with our stated Levels of Service will be included as options (i.e. they will be excluded from the Baseline supply-demand balance but will be included within our Final supply-demand balance).

I.20 Throughout this document, it is important to ensure that 'like-for-like' comparisons between WRMP19 and WRMP24 DO figures are made. We have not historically included supply-side drought permits or orders within baseline DO, reflecting the uncertainty in these permits and orders being granted, and so this aspect does not reflect a change for us.

I.21 In addition to the changes highlighted as being necessary by the EA, we have also decided to make one change to the presentation, but importantly not the calculation, of DO. We have an export from our London WRZ to Essex & Suffolk (E&S) Water; water is transferred from our Lee Valley Reservoirs to supply E&S Water's customers in Essex. Under normal (non-drought) conditions, this transfer is up to an annual average of 91 Ml/d, with higher peak transfers, but we currently have an agreement with E&S that, during drought periods, we would reduce the transfer to either 55 Ml/d (Jan-Mar) or 70 Ml/d (Apr-Dec); this agreement will change prior to 2025 (60 Ml/d Jan-Mar and 75 Ml/d Apr-Dec), and will revert to the original agreement (91 Ml/d average) from 2036 onwards.

I.22 A transfer as large as this has important 'system response' consequences, and so it is important that we include this transfer within our DO modelling. However, to facilitate transparency and understanding, we wish to explicitly highlight the volume of the transfer to E&S in our supply forecast, including the changes that will be made to this agreement over the course of the planning period. Using our Aquator model we have determined that the DO reduction of making the transfer to E&S under the current agreement is 62 Ml/d, that the DO reduction of the intermediate agreement is 67 Ml/d, and that the DO reduction of the original agreement is 90 Ml/d. In our DO modelling, we have included the intermediate agreement transfer (i.e. 60 Ml/d in Jan-Mar and 75 Ml/d in Apr-Dec) to capture system response impacts associated with the agreement at the beginning of the planning period, but will report a DO that is adjusted upwards so that the supply capability of assets within the London WRZ is recognised. This is summarised in Table I-2.

	DO Calculated	DO Reported	Export Reported
WRMP19	2000	2000	0
WRMP24	2000	2067	67

Table I-2: Comparison of Reporting of Essex & Suffolk Transfer (AR22-AR34 period, i.e., inclusive of agreement to amend bulk supply agreement terms in a drought) in WRMP19 and WRMP24

Updates to Source DO/yield Values Between WRMP19 and WRMP24

I.23 Understanding of our sources, changes to licences, and other changes have been made between the publication of our WRMP19 and WRMP24. These result in changes in WRZ DO but are not due to changes in methodology. In addition, some sources may have been represented using a single 'SDO' figure in WRMP19 but may now be represented using 'Yield Timeseries' (see Section on Groundwater Framework and Hydrogeological Modelling) in our WRZ DO modelling. As a result, the SDO changes listed below, which are 'Worst Historical DO' figures following WRMP19 methods, may not be reflected in our WRZ DO assessments. Table I-3 and Table I-4 show material (>1 Ml/d) changes to SDO values between WRMP19 and WRMP24.

WRZ	Source	WRMP19 DYAA DO	WRMP24 DYAA DO	Reason for Change
London	Langley Vale	4.49	2.52	Update to treatment capability assumption
London	Honor Oak	1.73	0.00	Long term Outage
London	Nonsuch	1.00	0.00	Long-term outage
London	North Orpington	8.75	0.00	Sustainability Reduction
London	Hoddesdon Transfer Scheme	12.5	0.00	Long-term outage
London	Barrow Hill	1.72	0.00	Long-term outage
London	Gateway Desalination Plant	150	100*	Reassessment of consistent source capability during long drought periods
SWOX	Woods Farm	4.99	2.59	Water quality issues at higher outputs
SWOX	Childrey Warren	3.72	0.00	Sustainability Reduction
Henley	Sheeplands	15.3	11.2	Pump capacity/water quality – DO reassessed considering long-term outages
SWA	Datchet	16.5	15.3	Review of Source Performance
SWA	Medmenham	44.9	52.3	Licence transfer from Pann Mill
SWA	Pann Mill	16.8	9.50	Sustainability Reduction
SWA	Hawridge	6.78	0.00	Sustainability Reduction

Table I-3: Material (>1 Ml/d) changes to DYAA SDO values between WRMP19 and WRMP24

* Further discussion of the Deployable Output from the Gateway Desalination Plant is given in this section.

WRZ	Source	WRMP19 DYCP DO	WRMP24 DYCP DO	Reason for Change
London	Waddon	15.1	13.6	Update to treatment capability assumption
London	Langley Vale	4.60	2.52	Update to treatment capability assumption
London	Honor Oak	1.73	0.00	Long-term Outage
London	Nonsuch	1.00	0.00	Long-term Outage
London	Streatham	9.00	7.03	Update to treatment capability assumption
SWOX	Leckhampstead	3.00	1.99	Update to treatment capability assumption
SWOX	Woods Farm	5.50	2.59	Water quality issues at higher outputs
SWOX	Childrey Warren	3.72	0.00	Sustainability Reduction
Kennet Valley	Bishops Green	15.4	10.4	Water quality issues limiting output
Henley	Sheeplands	15.3	11.2	Transfer Pumps – not all BHs available following long-term outages
SWA	Datchet	16.5	15.3	Review of Source Performance
SWA	Taplow	49.3	44.0	Pump capacity reassessment
SWA	Pann Mill	16.8	15.5	Sustainability Reduction
SWA	Hampden	4.78	2.00	Water Quality Issues
SWA	Hawridge	6.90	0.00	Sustainability Reduction
Guildford	Ladymead	9.00	13.5	AMP7 Scheme

Table I-4: Material (>1 Ml/d) changes to DYCP SDO values between WRMP19 and WRMP24

I.24 In addition, other major amendments to DO figures between WRMP19 and WRMP24 are:

- Amendment to our Level of Service (LoS) – our stated LoS for TUBs has changed from not more often than once every 20 years to not more often than once every 10 years, to align with other companies across WRSE
- We have included factors on Potential Evapotranspiration (PET) from our reservoirs to ensure that the evaporation from them is reflective of open water, rather than grass for which PET timeseries are generally supplied
- We have updated the 'demand factor profile' used in our DO runs to reflect longer dry periods such as 2018 that had not been experienced until recently

I.25 All of these changes have either been incorporated into the modelling of DO for different WRZs or have been added as amendments to DO in our supply forecast.

I.26 Considering the many changes that have been made between WRMP19 and WRMP24, it is important when reviewing DO figures to compare like-for-like DO figures.

Characteristics of Thames Water's Water Resource Zones

I.27 More detail on this topic can be found in Appendix A, Water Resource Zone (WRZ) Integrity. It is, however, useful to give some brief background on the nature of the supply systems in each of our WRZs, in order to explain why different methods have been used in the assessment of DO.

I.28 Our supply area is split into two main regions: London (London WRZ only) and the Thames Valley (all other WRZs). We have a total of six WRZs.

London

I.29 The London WRZ is a large, conjunctive use zone, involving both surface water and groundwater abstraction. The zone is supplied mainly by surface water resources, whereby water from the River Thames and River Lee is abstracted into large reservoirs in west London and north East London respectively, before treatment at water treatment works (WTW) and subsequent distribution. Abstractions in West London from the Thames range from c.600 Ml/d during drought, when water is limited, to c.1600 Ml/d during normal periods, when reservoirs are full, and between 3000 Ml/d to 5000 Ml/d abstraction possible during periods of reservoir refill. There is around 165,000 Ml of storage in west London spread across 10 reservoirs, with the largest reservoir having a capacity of around 38,000 Ml and the smallest a capacity of around 2,000 Ml. Some of the water abstracted from the River Thames in west London is transferred to north east London via the 'Thames-Lee Tunnel' which can transfer up to 400 Ml/d from the Thames at Hampton to the Lee Valley Reservoirs. Abstraction from the River Lee ranges from less than 100 Ml/d during dry periods to around 300Ml/d during normal periods, with additional abstraction feasible during refill periods. There is approximately 37,000 Ml of storage in the Lee Valley Reservoirs, spread across nine raw water reservoirs, the largest having a capacity of around 16,500 Ml and the smallest around 600 Ml. In addition to abstraction from the River Lee, raw water in the Lee Valley is also sourced from the Northern New River Wells, a series of abstraction boreholes along the New River which augment flow in the New River, which are either transferred to the Lee Valley Reservoirs, or are treated directly at either Coppermills WTW or Hornsey WTW.

I.30 Supply in south east London is dominated by groundwater sources. There are around 30 sources across this area, which together supply up to around 300 Ml/d, and which individually supply from less than 1 Ml/d to over 30 Ml/d.

I.31 West London, north east London and south east London were historically considered as three separate WRZs. However, the Thames Water Ring Main allows us to distribute water across London, making London a single WRZ. In general, water is transferred eastwards from west London, with more water being produced than is needed for supply in west London and less water being produced than is needed for supply in south east London.

I.32 In addition to these baseload sources, we also have several 'Drought' sources which are operated according to the Lower Thames Operating Agreement (LTOA), detailed in the next section. The function of these drought sources is either to increase flows in the River Thames, i.e. the EA's West Berkshire Groundwater Scheme (WBGWS) or the New River, i.e. North London Artificial Recharge Scheme (NLARS), or to supplement supplies directly, e.g. Thames Gateway Desalination Plant, such that we do not draw down our surface water storage reservoirs as quickly.

Lower Thames Operating Agreement (LTOA)

I.33 The amount of water that we can abstract from the Lower Thames is governed by the LTOA. The LTOA is an agreement made between the EA and Thames Water under Section 20 of the Water Resources Act 1991. The LTOA contains a control diagram on which the total storage volume in the Thames Water London reservoirs is plotted on a daily basis. Explicit in the LTOA is the need to maintain a prescribed flow over Teddington Weir. When storage is relatively healthy for the time of year, a minimum flow of 800 Ml/d must be maintained over Teddington Weir, the point at which the Thames becomes tidally influenced. As London reservoir levels fall, the minimum flow over Teddington Weir, the Teddington Target Flow (TTF) may be reduced in defined bands down to a minimum flow of 300 Ml/d. In conjunction with the changing flow constraint, as storage declines we 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. As storage declines, we may/should also trigger the aforementioned drought sources as defined control curves are crossed.

I.34 Between WRMP14 and WRMP19 the Lower Thames Control Diagram (LTCD) shown in Figure I-1, the control diagram governing the LTOA, was optimised to maximise the supply capability of London while reducing the environmental impacts of abstraction in the Lower Thames compared to the previous LTCD. This optimisation exercise was done in close collaboration with the EA, and a six-week public consultation was undertaken. The LTCD has not been re-optimised between WRMP19 and WRMP24.

I.35 The paragraphs below describe how the LTCD is used to trigger various actions. In practice the drought management actions are taken considering forecasts of many factors, such as groundwater levels, rivers flows and reservoir storage, but in our water resources modelling these actions are assumed to be triggered by the LTCD and, in some case, by flow at Teddington on a given day. The operational protocol governing our drought response can be read in more detail in our Drought Plan.

I.36 When storage is in the LTCD blue band (see Figure I-1) no demand restrictions are required and only 'base' sources should be used. The Gateway Desalination Plant, East London Groundwater Sources (known as ELReD) and an abstraction near Stratford are all triggered when London storage moves from the blue band into the green band. At the same time less water needs to be left to go over Teddington Weir, either 600 Ml/d or 700 Ml/d depending on the time of year.

I.37 If storage reduces further and storage moves into the yellow band, we should trigger an enhanced media campaign (Level 1 demand restrictions) and the TTF reduces to either 300 Ml/d or 400 Ml/d, again depending on the time of year. In addition, at this point NLARS can be triggered. Within the yellow band is a line which triggers 'Level 2' demand restrictions, i.e. TUBs. At this point, WBGWS is also triggered.

I.38 If storage declines into the orange band, Non-essential Use Bans (Level 3 demand restrictions) are triggered with the TTF reduced to 300 Ml/d. The horizontal dotted line at approximately 25% of London's storage is our 'Level 4' trigger; this is the point at which we assume that we would impose emergency drought orders. As such, the definition of '1 in 500' failure for us involves determining the highest level of demand at which we would not cross the 'Level 4' line on the LTCD more often than once every 500 years.

I.39 While the description of the LTCD has been included in the 'London' section of this document, some actions also influence other WRZs. Most notably, the WBGWS is a key element of Kennet Valley WRZ's supply capability. In addition, the actions highlighted are assumed to apply to all WRZs, and demand savings actions in other WRZs are assumed to be triggered by London's storage (though a change from WRMP19 to WRMP24 is that demand savings actions during drought events are considered as options, rather than part of the baseline), although full protocols for other WRZs are set out in our Drought Plan. Work carried out as part of the development of the WRMP24 and Drought Plan have shown that use of London storage as a trigger for demand savings across our whole supply area may not be the optimal approach if trying to maximise drought resilience benefit while minimising customer disruption, and so we will review this in the future.

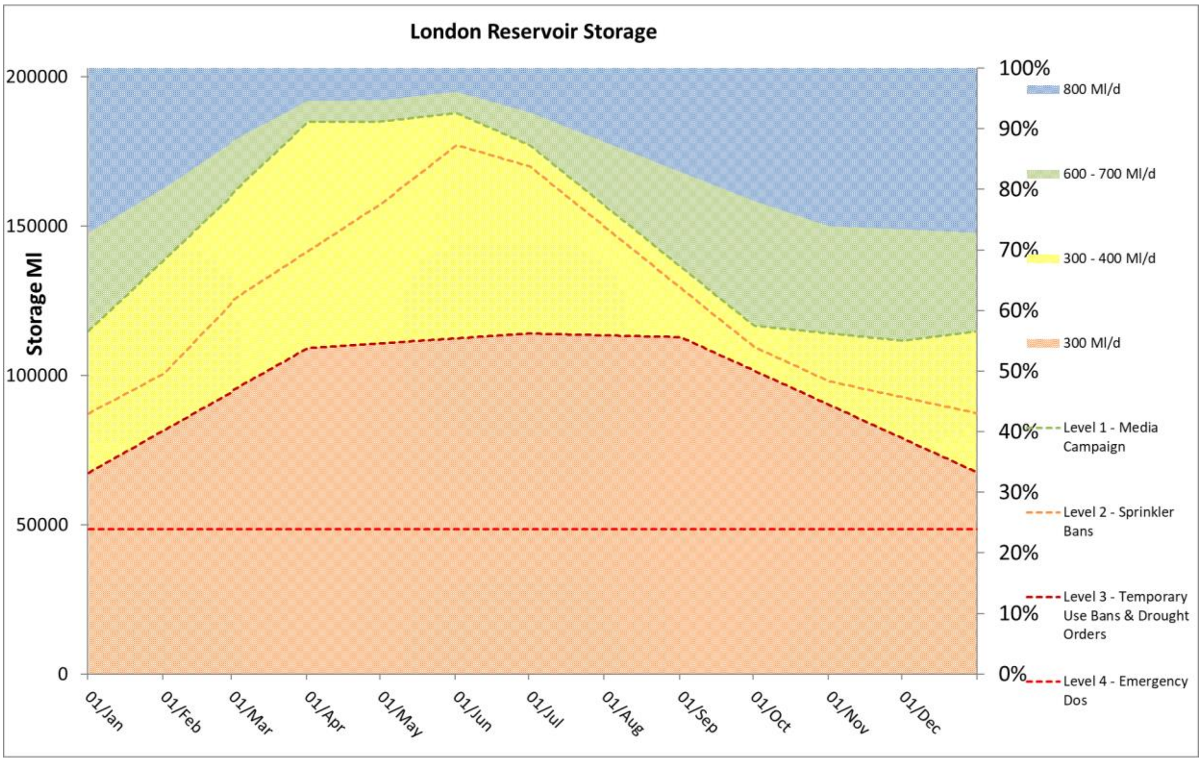


Figure I-1: Lower Thames Control Diagram

I.40 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 (for example, the Drought Direction 2011[1]).

I.41 While the LTOA sets out the requirement that Thames Water introduce demand saving measures as storage in London declines, the EA guidance has required that benefits associated with demand restrictions are not included in baseline DO modelling. As a

1 Defra, 2011, The Drought Direction 2011, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/182606/droughtdirection2011.pdf

result, demand restrictions have been disabled in our baseline DO modelling while the supply-side triggers such as drought schemes and TTF changes have been included in our DO modelling.

I.42 The emergency storage volume in London is calculated as 30 days of emergency storage.

Swindon and Oxfordshire (SWOX)

I.43 The SWOX WRZ is a conjunctive use zone, with approximately 60% of its supplies coming from groundwater sources and around 40% from surface water.

I.44 The zone can be split into three 'sub-zones' which have major transfers between them:

- South Oxfordshire (area stretching from Goring to Chinnor): groundwater only from mainly Chalk aquifer sources; produces more water than is needed for local demand
- North Oxfordshire (Oxford, Banbury, Witney, Farringdon): surface water only – abstraction from the River Thames into Farmoor Reservoir, treated at Farmoor and Swinford WTWs; can produce more water than is needed for local demand, but during drought output is managed to conserve reservoir storage
- Swindon & Cotswolds: groundwater only, mainly from Cotswolds Oolitic Limestone sources and Chalk sources; produces less water than is needed for local demand

I.45 In general, water is transferred Northwards and Westwards from South Oxfordshire, and Westwards from Farmoor. The large transfers that are feasible between these sub-zones allow the zone to be considered a single WRZ.

I.46 Our WRMP19 DO assessment for the SWOX WRZ involved conjunctive use modelling of the North Oxfordshire and Swindon & Cotswolds sub-zones, with the aggregate of the South Oxfordshire SDOs being added on. The WRMP19 DO assessment including conjunctive use modelling assumed 'static' groundwater SDOs, but with many drought-sensitive sources in the zone the conjunctive use modelling approach has been changed to include time-variant groundwater yields and a whole-WRZ conjunctive use modelling approach for WRMP24.

I.47 Level 1, 2, and 3 demand savings actions, although not triggered in baseline DO model runs, are assumed to be triggered by London storage. Level 4 emergency drought order restrictions are assumed, however, to be triggered by storage at Farmoor falling into the 'emergency storage' bracket of 4,500 Ml. The Farmoor reservoir constructed in two stages has a total volume of around 14,000 Ml.

Slough, Wycombe and Aylesbury (SWA)

I.48 The water resources of the Slough, Wycombe and Aylesbury zone are derived from twelve groundwater sources. There are no surface water sources in the SWA zone. The bulk of the abstraction in the WRZ is from sources located near to the River Thames, with significant reductions in abstraction licence having been made elsewhere in the Chilterns for the benefit of rivers such as the Wye and Chess. Water is transferred Northwards from sources near the Thames around Slough and Marlow, through the zone, to Wycombe and to Aylesbury.

I.49 With the vast majority of the abstraction being from riparian groundwater sources, and a lack of surface water abstraction, the SWA zone is not considered conjunctive and indeed involves almost no sources whose yield has been determined to be responsive to drought conditions. The lack of drought-sensitive sources has meant that detailed modelling of source yield in SWA has not been undertaken for WRMP24.

I.50 In our WRMP19, demand savings benefits were not included in DO calculations for the SWA zone and so the requirement to exclude them from baseline DO calculation is not a change in assumption for this zone. However, benefits from demand savings were excluded from our water resources planning entirely in the SWA zone; for WRMP24 we have included demand savings benefits as options for the SWA zone.

Kennet Valley

I.51 The resources of the Kennet Valley WRZ are predominantly groundwater derived from confined and unconfined chalk aquifers; some of the groundwater sources in the zone have yields which are dependent on antecedent weather conditions. There is also a significant RoR surface water abstraction from the River Kennet in Reading, called Fobney, which is potentially highly vulnerable to drought conditions.

I.52 Our previous assessments of the WRZ DO for Kennet Valley have involved aggregating SDO values for the different sources across the zone. There is, however, the potential that the minimum yield of the surface water abstraction could come at a point when groundwater sources' yields are not at their minimum, and so a conjunctive-use assessment was carried out for WRMP24.

I.53 The SDO of the Fobney RoR surface water source is determined by examination of flow records (modelled or observed) of the River Kennet, and consideration of treatment and licence constraints. Per the UKWIR (2014) methodology, the DO of a RoR surface water abstraction with no storage is governed by the minimum flow that can be abstracted.

I.54 EA 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, an investigation of the flows in this area was undertaken in 2003-04. This included a series of flow gaugings and low flow modelling of the flows in the Kennet with and without augmentation from the WBGWS. It showed that flow decreased between Theale and the Labyrinth weir, upstream of the Fobney abstraction point, due to the flow down the Holy Brook, a distributary of the Kennet, and leakage from the river into the adjacent gravels.

I.55 Flow volumes at Theale 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 into the Holy Brook and reaching the Fobney abstraction point. 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 EA 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-5. Figure I-2 shows the impact that the flow control structure has on flows at Fobney.

I.56 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:

$$\text{Flow in Kennet @ Labyrinth Weir} = 0.782 * \text{flow @ Theale GS} - 40.68\ (\text{Ml/d})$$

Band	Daily mean flow at Theale (Ml/d)	Flow Structure State
Band 1	>195	Fully open
Band 2	<195	First opening closed
Band 3	<173	Second opening closed; third opening remains open for environmental protection of Holy Brook

Table I-5: Operation of Holy Brook Flow Structure

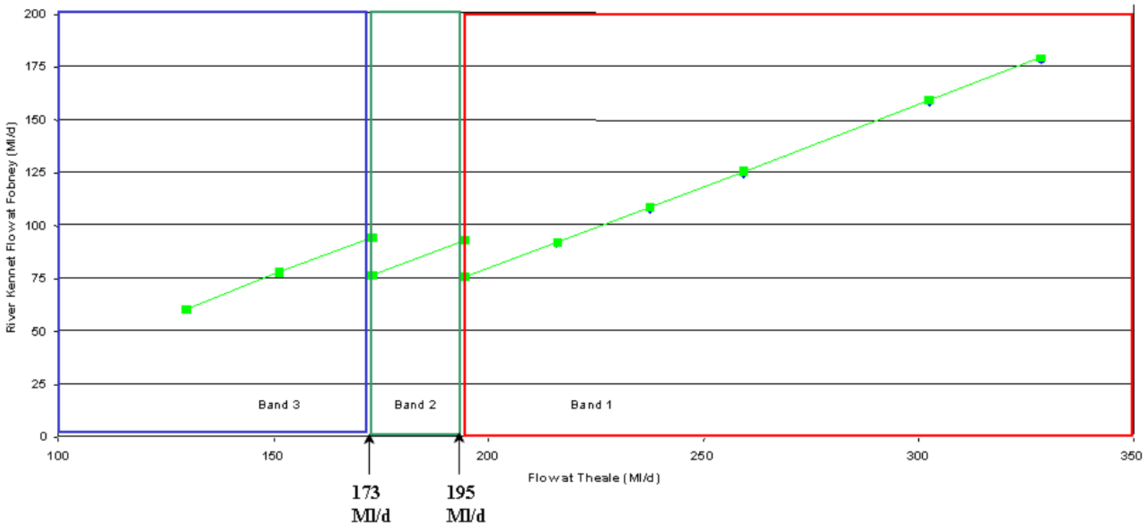


Figure I-2: Impact of flow control structure on flow in the River Kennet at Fobney

I.57 During a drought, operation of the WBGWS abstracts groundwater from the Chalk aquifer, which will also contribute to flows in the Kennet. The DO assessment carried out for the zone (detailed in a later section) will show that the DO of the zone is heavily dependent on this flow augmentation from WBGWS.

I.58 Some testing of the WBGWS has been undertaken by the EA however further joint investigations by the EA and Thames Water are planned to confirm its yields. As a result, there is some uncertainty about the WBGWS contribution and a risk to the supply demand balance in the Kennet Valley. The Fobney source 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 EA.

I.59 The calculation of a ‘1 in 500’ DO for the Kennet Valley WRZ has involved fairly significant change from the ‘worst historical’ DO assessment that was carried out previously. The ‘worst historical’ assessment relied primarily on measured flow and groundwater level data, but the assessment of a ‘1 in 500’ DO in a zone with sources vulnerable to drought has required significant modelling effort.

I.60 In our WRMP19, demand savings benefits were not included in DO calculations for the Kennet Valley zone and so the requirement to exclude them from baseline DO calculation is not a change in assumption for this zone. However, benefits from demand savings were excluded from our water resources planning entirely in the Kennet Valley zone; for WRMP24 we have included demand savings benefits as options for the Kennet Valley zone.

Guildford

I.61 The Guildford WRZ is supplied by groundwater from the Chalk and Lower Greensand aquifers and one surface water source which abstracts from both the River Wey and River Tillingbourne. The vast majority of the groundwater sources in the WRZ are assessed not to be drought sensitive. The abstraction licence for the surface water source at Shalford is far exceeded by available flow in the River Wey and Tillingbourne, and so while hydrological modelling and conjunctive use analysis is undertaken, the zone is shown not to be drought sensitive and the WRZ DO is effectively an aggregate of source DOs.

I.62 In our WRMP19, demand savings benefits were not included in DO calculations for the Guildford zone and so the requirement to exclude them from baseline DO calculation is not a change in assumption for this zone. However, benefits from demand savings were excluded from our water resources planning entirely in the Guildford zone; for WRMP24 we have included demand savings benefits as options for the Guildford zone.

Henley

I.63 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. There is nitrate contamination of groundwater at the Sheeplands source which is managed by treatment as well as blending with groundwater from the Harpsden source under an aggregate abstraction licence.

I.64 There are no surface water sources in the Henley WRZ, and the yields of the groundwater sources in the zone are not deemed to be drought sensitive. As such, while a model of the Henley WRZ exists, the DO assessment of the zone effectively relies on an aggregate of the SDOs.

I.65 In our WRMP19, demand savings benefits were not included in DO calculations for the Henley zone and so the requirement to exclude them from baseline DO calculation is not a change in assumption for this zone. However, benefits from demand savings were excluded from our water resources planning entirely in the Henley zone; for WRMP24 we have included demand savings benefits as options for the Henley zone.

Methods Used in Calculation of WRZ DO

I.66 As has been highlighted previously, the requirement to conduct analysis to determine a ‘1 in 500-year’ DO, the focus on ‘system response’ in the determination of this DO, and the increased focus on the WRSE Regional Group all necessitated significant change from our previous ‘worst historical’ DO analyses. While analyses using ‘stochastic’ datasets were undertaken for WRMP19, this was only conducted for the London WRZ, and modelling for London involved use of heavily simplified hydrological (catchmod) and water resource (IRAS) models, the results from which required amendment to bring them in line with existing model (WARMS2) results. Other zones relied on Extreme Value Analysis for determination of '1 in 200-year' DO calculation.

I.67 Thames Water's vulnerability assessment has highlighted that the London and SWOX zones are high risk and require the application of complex methods. Consequently, in order to ensure that we have applied appropriate methods in determining a '1 in 500-year' DO for these complex zones, and to align with WRSE methods of DO assessment, our DO assessment is based on hydrological, hydrogeological and water resources modelling using 'stochastic' datasets.

I.68 Figure I-3 shows the modelling processes that we have followed when calculating DO. WRSE commissioned Atkins to produce 'Stochastic' weather datasets (explained further in Section on Stochastic Weather Datasets). These weather datasets were used as inputs to hydrological and hydrogeological models; these models produced river flows and timeseries of groundwater yields respectively. Timeseries of river flow and groundwater source yield were used as inputs to 'Pywr'[2] models developed for the different WRZs as part of the WRSE Regional Simulation Modelling project, along with non-weather dependent inputs, such as WTW capabilities and yields for GW sources deemed not to be drought sensitive. The WRSE Groundwater Framework (see Section on Groundwater Framework and Hydrogeological Modelling for details) was applied to determine which groundwater sources should be subject to modelling and which could reasonably be assumed to be represented as 'static' yields. Further details on the hydrological modelling and water resources modelling carried out can be found in Sections within this document. This section includes descriptions of the generation of stochastic weather datasets and how water resource model outputs were converted into DO.

I.69 The stochastic weather datasets were produced on behalf of WRSE; the hydrological and hydrogeological modelling was carried out by/on behalf of Thames Water; the water resources modelling was undertaken as part of a WRSE-led project.

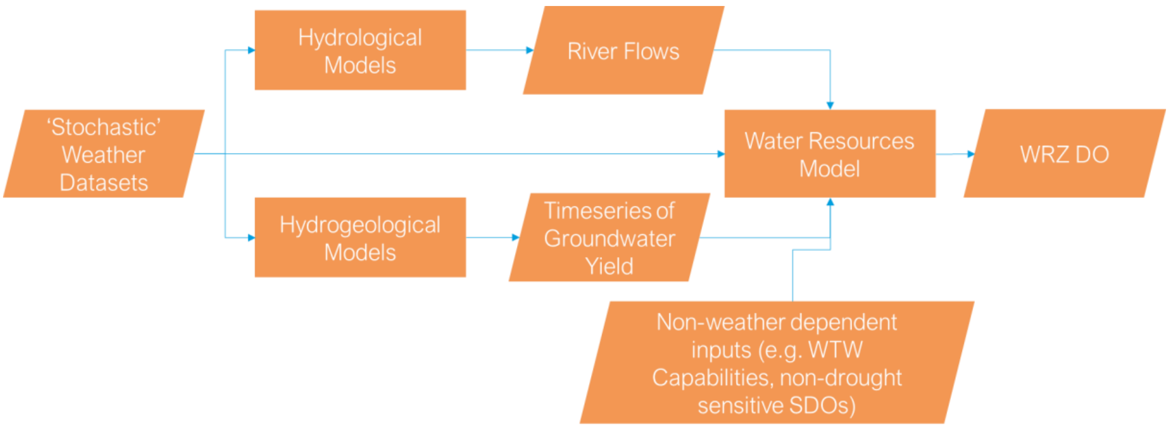


Figure I-3: High-level Flow Chart of DO Calculation Process

[2] Tomlinson, J.E., Arnott, J.H. and Harou, J.J., 2020. A water resource simulator in Python. Environmental Modelling & Software. https://doi.org/10.1016/j.envsoft.2020.104635

Stochastic Weather Datasets

I.70 For more detail on stochastic weather datasets, please see the Atkins report for WRSE on the generation of stochastic weather datasets[3] and the WRSE method statement on stochastic datasets[4].

I.71 The weather datasets used as inputs to hydrological, hydrogeological and water resources models are key in determining DO. With reliable, granular datasets for rainfall and potential evapotranspiration (PET) needed for water resources modelling generally only available for no more than 100 years, the consideration of '1 in 500-year' drought events requires the application of statistical and/or modelling techniques.

I.72 The need to consider droughts more severe than those which have occurred historically has driven the UK water industry to broadly adopt a 'stochastic' weather generation process in drought risk assessment. WRSE commissioned Atkins to undertake production of stochastic weather datasets which are spatially and temporally coherent across the WRSE region; other Regional Groups and water companies across the UK have also adopted stochastic datasets produced using the same methods, also produced by Atkins. While different regional groups have used the same stochastic weather generation methodology, a national stochastic dataset does not, however, exist, because the links between climate and weather are different in different parts of the UK.

I.73 The use of the term 'stochastic' references the partially random nature of rainfall. Rainfall volumes cannot be predicted solely based on climate variables, but rainfall volumes are influenced by climate variables. The stochastic datasets that have been generated are intended to represent different versions of what historical weather timeseries 'could' have been, given the underlying climate drivers. A statistical model has been trained which links climate drivers to monthly rainfall volumes, considering random and non-random processes.

I.74 Compared to datasets generated for WRMP19, there are a few salient differences:

- The datasets generated have required a smaller amount of bias correction, due to the improved datasets used in training
- A wider range of climate drivers has been used for model training
- A different baseline period has been used – 1950-97 rather than 1920-97. This shorter period was used because there is a more comprehensive set of climate driver variables available for this period, although it is recognised that this is a shorter baseline period.
- Point-based HadUK data have been used as the rainfall data on which the stochastic datasets have been trained, as opposed to the catchment average datasets that were used in WRMP19

I.75 EA Guidance references evidence that states that monthly precipitation in Central England is stationary until 2010, based on a study of precipitation in Oxford[5], which is within the Thames catchment. As such, the use of a stochastic timeseries with a baseline up until 1997 is considered appropriate. To extend the training set until the present day would result in double counting of the impacts of climate change.

[3] Atkins, 2020, Regional Climate Data Tools, https://www.wrse.org.uk/media/ok1mtsoq/wrse_file_1338_regional-climate-data-tools.pdf
[4] WRSE, 2021, Method Statement: Stochastic Climate Datasets
[5] Sun et al., 2018 assessed stationarity in the Oxford precipitation record from 1767 to 2010.

I.76 The stochastic datasets represent 400 different versions of what rainfall and PET could have been over a baseline period (1950-97). This is a sub-set of 1000 versions which were initially generated before implausible sequences were ruled out and a subsample generated. The 400 'replicates' of 48 years give weather datasets which are deemed to represent a total of 19,200 years but this is not representative of a continuous 19,200-year sequence, rather it is 400 48-year sequences.

Validity of Stochastic Rainfall Datasets

I.77 We have analysed the stochastic rainfall dataset which has been used in our WRMP24 Deployable Output modelling. In this analysis we compare the WRMP24 stochastic dataset with historical rainfall datasets and the WRMP19 stochastic dataset. The analysis focusses on a comparison of extreme event rainfall accumulations over different accumulation periods.

I.78 In this comparison, we have used a Thames catchment areal average for each dataset (calculated by averaging rainfall for the Chilterns East, Cotswolds West, Berkshire Downs and Wey Greensand hydrometric areas). The datasets used are:

- HadUK historical rainfall dataset (considering both 1920-2020 and 1891-2020 assessment periods) – this dataset is included as the HadUK rainfall dataset was used in the training of the WRMP24 stochastic dataset.
- A rainfall dataset labelled as "EQUIS" which is an internal corporate database. This rainfall dataset is provided by the Environment Agency. It is this rainfall dataset which has historically been used for our "worst historical" Deployable Output assessments, and was the dataset used in training the WRMP19 stochastics.
- The WRMP19 stochastic dataset
- The WRMP24 stochastic dataset

I.79 For each dataset analysed, we first calculate the monthly rainfall. For a given accumulation period of N months, we have then identified the minimum rainfall accumulation over the N months ending August, September, October, November or December (recognising the drought events which impact our supply system). We have then ranked these accumulation values and derived a return period for each rainfall accumulation volume according to the length of the dataset. For example, in the 1920-2020 HadUK dataset, for a 1-year accumulation period we have calculated 101 rainfall accumulation values, and the lowest rainfall accumulation is said to have a return period of 101 years. We have then plotted rainfall accumulation as a proportion of the long-term average against the return period. We have undertaken this analysis for values of N of 12 months, 18 months, 24 months, 36 months, and 48 months. The Figures below are the result of this analysis.

I.80 The key points of interpretation from this analysis are:

- Both the WRMP19 and WRMP24 stochastic datasets perform well when compared to the different historical datasets, when considering all accumulation periods. The stochastic data most accurately fits rainfall accumulation totals for droughts lasting up to 24 months, which are important for the water supply system since the zone is more affected by these drought events. This gives confidence in planning and Deployable Output estimates of water supply options. For droughts longer than 24 months, the data fits slightly less well and tends to show the rainfall accumulation in the stochastic datasets is less than may be expected relative to the historical datasets. However, the water supply system is more resilient against these longer droughts, and so despite the potential over-representation of long-duration drought events, Deployable Output estimates are not likely to be impacted.

- The different historical datasets give slightly different results, highlighting that uncertainty also exists in measuring rainfall volumes (e.g., 12-month accumulation for 1934 is 63.9% in the HadUK dataset and 61.4% in the EQUIS dataset).
- The most significant differences between the WRMP24 stochastic dataset and other datasets exist in events with 1 to 10-year return periods, which are not material events when calculating supply capability.
- When looking at all rainfall accumulation durations, for drought events with return periods of c.20 years and more, the WRMP19 and WRMP24 datasets give very similar results.
- When looking at long-duration rainfall accumulation, both the WRMP19 and WRMP24 stochastic datasets appear to possibly over-estimate long-duration droughts. As an example, the most severe 3-year accumulation on the historical record is c.80% of the LTA, whereas a 1 in 100-year 3-year event in both the stochastic datasets would indicate an accumulation of 72-73% of LTA. As the accumulation period considered increases, the WRMP24 stochastic dataset appears to over-estimate long droughts more than the WRMP19 stochastic dataset.

I.81 While the relative performance of the WRMP19 and WRMP24 stochastic datasets is not materially different (i.e., the question may be raised as to why new datasets were produced given that the results are similar), it is important to bear in mind the significant improvements that were made in the production of the WRMP24 datasets, in particular:

- A nationally coherent method was applied, using the same base dataset. In WRMP19, different companies used different rainfall datasets as the training set, meaning that national coherence was compromised. In WRMP24, the HadUK dataset was used.
- Reduced bias correction. In WRMP19, the stochastic datasets were criticised for the bias correction required. Less bias correction is needed in the WRMP24 datasets, and a more sophisticated approach was taken.

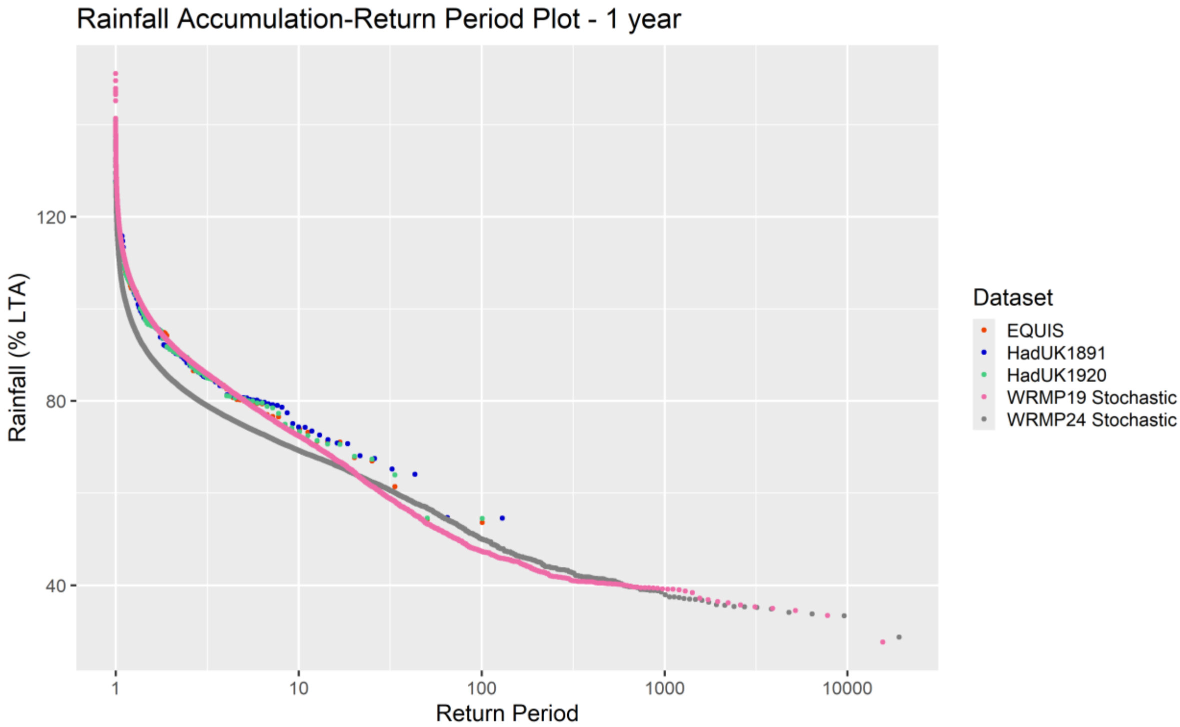


Figure I - 4: Validation plot for 1-year rainfall accumulation

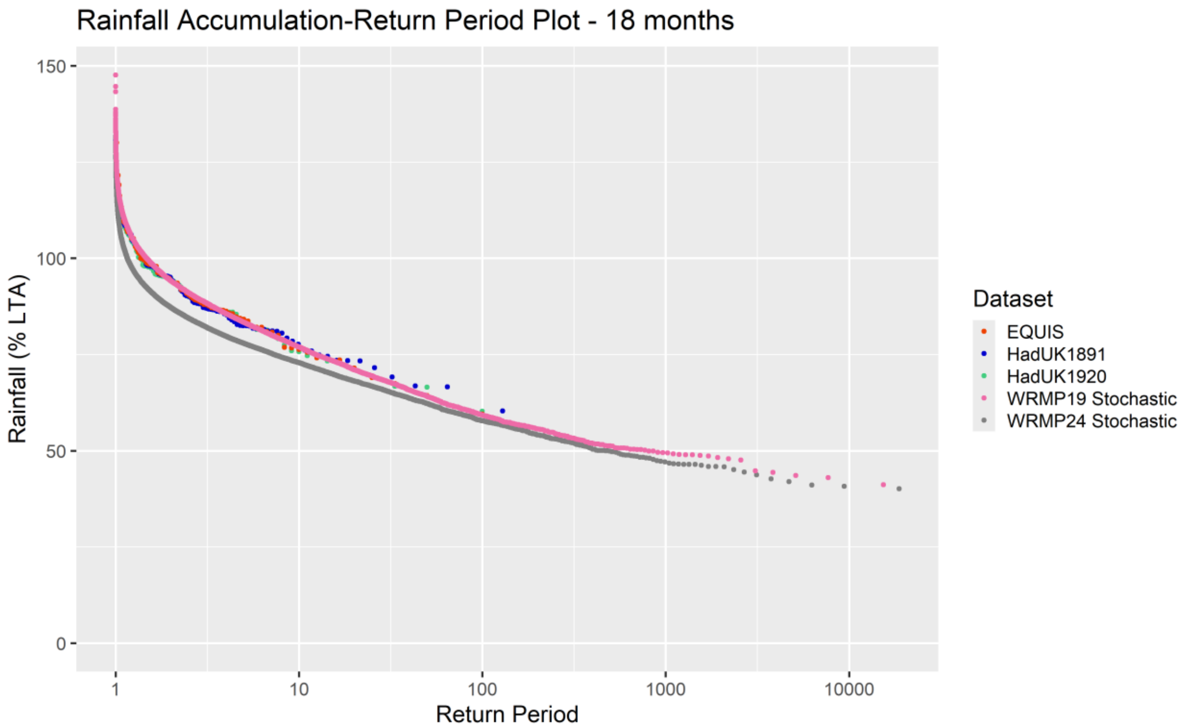


Figure I - 5: : Validation plot for 18-month rainfall accumulation

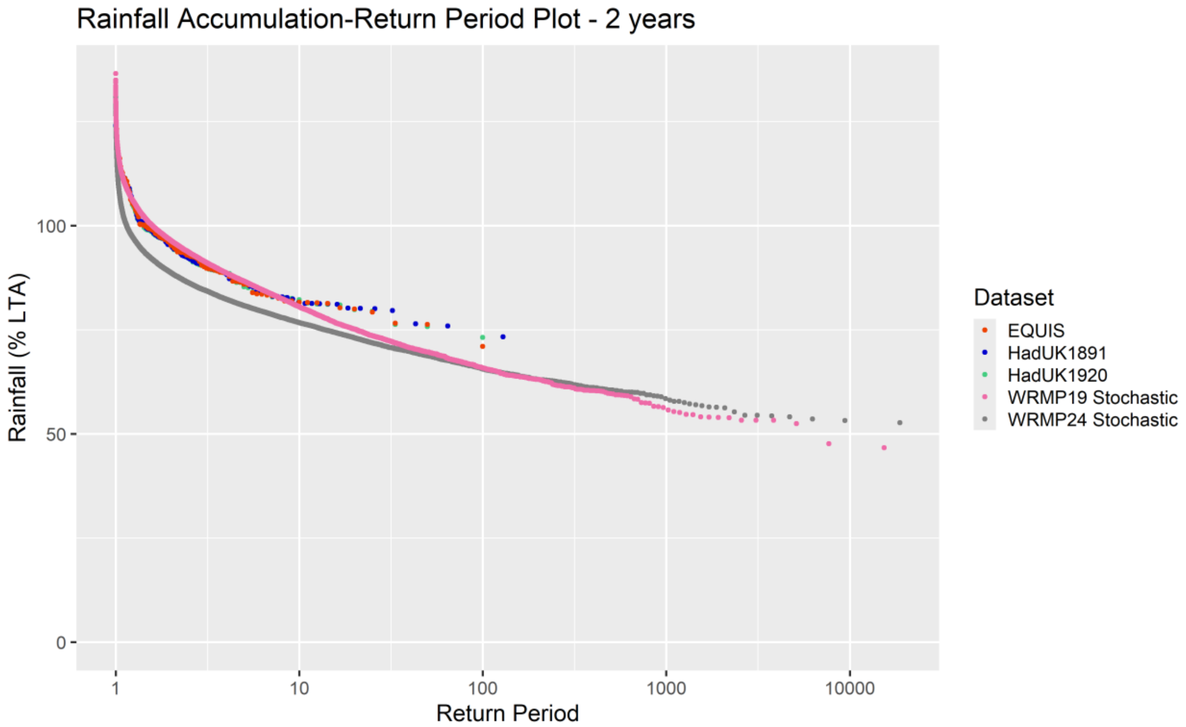


Figure I - 6: : Validation plot for 2-year rainfall accumulation

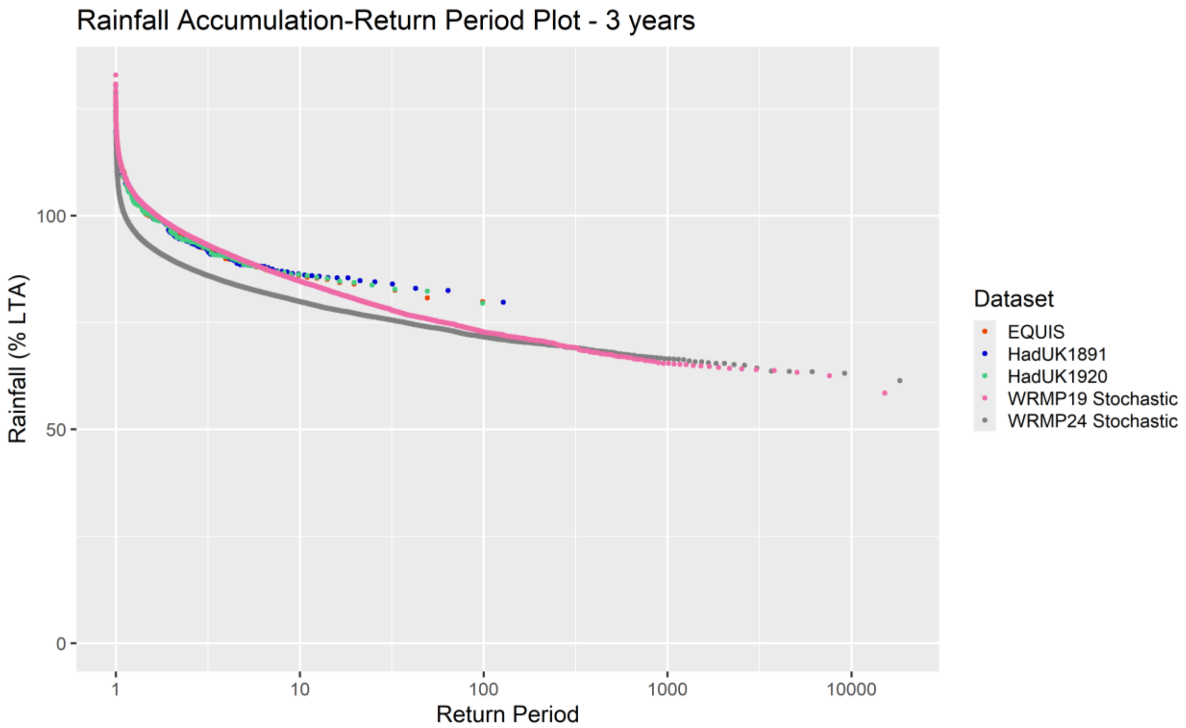


Figure I - 7: Validation plot for 3-year rainfall accumulation

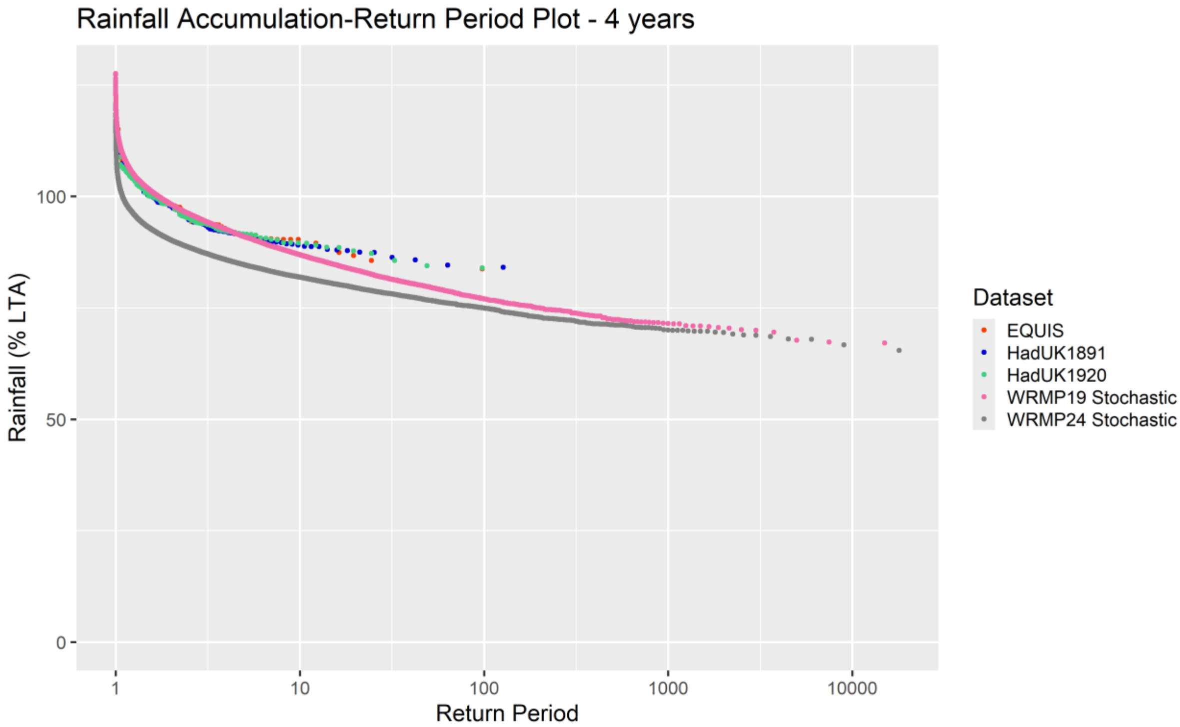


Figure I - 8: : Validation plot for 4-year rainfall accumulation

Conclusion

I.82 This analysis demonstrates that the stochastic datasets are well calibrated for droughts lasting up to 24 months in duration. During the development of our plan, concerns were raised that the datasets could, due to the training dataset used, under-estimate long-duration droughts. This analysis demonstrates that the datasets used do not under-estimate the likelihood of long-duration droughts. One of the key benefits of exploring stochastic datasets is that the impact of more severe long-duration droughts than those historically observed can be explored. As the stochastic datasets contain more severe long-duration droughts than the historical record, we do not consider that modelling of additional long-duration droughts is required.

WRZ DO Calculation

I.83 The stochastic weather datasets were run through hydrological and hydrogeological models. The resultant timeseries of flow and groundwater source yield were then used as inputs to the relevant Pywr models, alongside other inputs such as non time-variant groundwater yields (see later section on groundwater source yields). The Pywr models contain ‘demand’ nodes, which represent demand for water, as well as nodes and links which represent rivers, reservoirs, and other water supply infrastructure. The model can also represent constraints which can either be relatively simple (e.g. pipe capacity) or more complex, e.g. determining the minimum flow that must be left to flow over Teddington Weir, given the state of London storage for the time of year. For each timestep considered, a Pywr model solves a linear algebra equation to determine the ‘most efficient’ (efficient in terms of a modelled view of ‘cost’, where ‘cost’ is a non-economic variable used to guide the relative use of different sources) way to satisfy demands which are present. The model is able to track the 'state' of different model variables (e.g. reservoir storage) from day to day. The models can be used to conduct 'what-if' scenario-based investigations, for example determining minimum reservoir storage when applying different levels of customer demand.

I.84 As previously described, we plan to progressively increase the Level of Service that we offer to customers. Currently, our stated LoS is that we would not impose emergency restrictions more often than once every 100 years; this will increase to not more often than once every 200 years by the early 2030s, and not more often than once every 500 years before the 2040s. As such, it was necessary for us to determine not just the '1 in 500-year' DO for each WRZ, but also the '1 in 100-year' and '1 in 200-year' DO figures. A '1 in 2' DO figure was also determined as representing a normal year DO, although the water resources models are set up to determine drought capabilities and their applicability in normal year circumstances is less robust.

I.85 Our aim was that all WRZs could have their DOs modelled using behavioural water resource modelling, in order that a 'system response' based 1 in 500-year DO could be established. When starting to build the Pywr models we did not know which groundwater sources would be represented as static and which would be represented as time-variant, and so we assumed that all WRZ DOs would involve some sort of time variance, making water resource modelling useful. In the end, our Henley, Guildford and SWA WRZs had few/no sources with time variant yields, but it was nonetheless possible for modelling to be carried out. Our SWA zone had a single source modelled as being time-variant, and our Guildford zone has a RoR surface water abstraction at which river flows are found to always be well in excess of the licensed quantity.

I.86 The use of a water resource modelling approach across all zones meant that we had a consistent approach to the calculation of DO for all zones.

I.87 In calculating DO figures, the key model variables to track are those which determine whether emergency restrictions would be required. For London and SWOX this involves tracking whether reservoir storage falls below the 'Level 4' control curve on the LTCD or Farmoor Storage diagram respectively, as well as tracking whether all demand centres had their demands satisfied. For all other zones, which don't have reservoir storage, it involves tracking whether demands being applied are met (i.e. tracking deficits). Where deficit-tracking was used in calculating DO, deficits of four days or greater were used to determine when emergency storage would be required – this criterion was consistent across WRSE's modelling to reflect the fact that water supply systems have potable storage; water companies, unlike electricity generating companies, do not need to instantaneously balance supply and demand.

I.88 We calculate DO alongside demand, and the supply-demand balance for two different scenarios – Dry Year Annual Average (DYAA, also known as Average or ADO) and Dry Year Critical Period (DYCP, also known as Peak or PDO). The Annual Average DO calculation involved observation and counting of 'Level 4' events at any point during the year. The Critical Period DO calculation involved counting only 'Level 4' events that occurred during a specified period. We considered the 'Peak' period to be July and August.

I.89 For each WRZ individually, many levels of demand were applied in the Pywr models, and outcomes were observed. In DO runs, due to the long timeseries used and requirement for model speed to allow DO runs to be completed in a reasonable timeframe, only those variables which were absolutely necessary for the calculation of DO were stored. Had large numbers of variables been stored a great deal of storage space would have been necessary, and models would have run more slowly. In a given model run, the variable captured was an indication of whether, for the WRZ of interest, in any given year at a given level of demand Level 4 restrictions would have been required; April to March was used to define a year as drought events often span into January. For each LoS of interest, the DO figure was determined as the highest level of demand that could be applied before emergency restrictions would need to be applied more often than the LoS states. In practice, this means that the DO is the highest level of demand that can be applied before the number of 'Level 4' events exceeds the value as prescribed by the Level of Service (Table I-6).

Level of Service (Level 4)	Number of allowed 'Level 4' events across 19,200 years (400 x 48-years)
1 in 100-year	192
1 in 200-year	96
1 in 500-year	38
1 in 2-year	9600

Table I-6: Levels of Service and Number of Allowable Level 4 Events Across Stochastic Record

Assessment of Yield/Source Deployable Output of Groundwater Sources

I.90 As described, groundwater source yields are one of the key inputs in the calculation of DO. In previous WRMPs we have calculated single 'DYAA' and 'DYCP' SDO values for individual sources, based on observation and hindcasting of groundwater levels and application of groundwater level-yield relationships to establish DOs. While the methods applied were advanced and gave robust DO values, they could not necessarily be used in isolation to determine '1 in 500-year' system-response DO values at the WRZ level. Additionally, in our water resources modelling we have historically used 'static' DO values when establishing our WRZ DOs, meaning that we have not previously considered the potentially dynamic response of groundwater source yields when determining DO. A more dynamic consideration of groundwater source yields was deemed a priority in the development of the WRSE DO modelling approach, and so the Groundwater Framework was developed to prioritise those sources for which dynamic modelling of groundwater source yield would be valuable. Hydrogeological modelling was then carried out for these sources in order to provide groundwater yield timeseries for inclusion in Pywr modelling.

Groundwater Framework and Hydrogeological Modelling

I.91 The WRSE Groundwater Framework[6] proposed a standard assessment approach to characterise groundwater sources. It also suggested the most appropriate modelling approach for representation of groundwater source yield or DO in the Regional System Simulator (RSS, referred to in this document as the Pywr model) developed in Pywr, taking into account need, data availability and timescale.

I.92 Following assessment through the Framework, all of our groundwater source yields were calculated outside of the Pywr model and were provided as an input, with the exception of Gatehampton. They are classified as either 'External Profile' or 'External Timeseries' in the Groundwater Assessment Framework, as defined below.

External Profile:

I.93 Sources that are not sensitive to groundwater level fluctuations and have a DO modelling approach of 'External Profile' have been represented by a fixed yield accounting for average and peak conditions. This fixed yield has been determined following the same approach as that used in WRMP19, updated to reflect the AR20 supply position. It is based on the standard UKWIR method for calculating groundwater DO, using an established relationship between the Source and hindcast Catchment Indicator Borehole (CIB, an Observation borehole which is representative of the aquifer being monitored which is minimally affected by abstraction), to shift the drought curve to produce a 12-month average and summer peak constrained yield during the critical drought year defined for the WRZ.

I.94 AR20 Source DOs were included within the Pywr model, along with abstraction licence information. The assumption is that the yield remains the same under all of the planning scenarios being considered.

[6] WRSE, 2021, Method Statement: Groundwater Framework, https://www.wrse.org.uk/media/zbmazk2c/method-statement-groundwater-framework-aug-2021-1.pdf

External Timeseries (Borehole Sources):

I.95 Sources that are sensitive to groundwater level fluctuations and have a DO modelling approach of 'External Timeseries' have been represented by a timeseries of yields. The method is similar to that used in WRMP19, but it has been adapted to account for the WRSE stochastic weather sequences.

I.96 Already available, calibrated CatchMod lumped parameter models for 9 no. key Observation Boreholes (OBH) across the Thames Water Catchment were run using the weather data from the 400 no. 48-year stochastic replicates. These models were run and produced river flow timeseries, which were transformed using existing relationships into daily timeseries of groundwater level at each of the OBHs.

I.97 For each source of interest, relationships were developed between modelled groundwater levels at the 9 OBHs and the observed data within the relevant CIB. Source yield (as a daily timeseries) was assessed using the same procedure as followed in WRMP19; the CatchMod output, adjusted for the CIB, was transformed based on a relationship between the OBH and the associated abstraction borehole source (ABH), revised as necessary for new data sets. The transformed groundwater levels were then used to shift the source drought curve to produce a timeseries of constrained yields. These timeseries were then further amended, where necessary, to account for treatment capability, licence limits and process losses.

I.98 There were 14 sources where this method was followed to generate an External Timeseries:

- Eight in London WRZ
- Four in SWOX WRZ
- One in Kennet Valley WRZ; this source, Pangbourne, required further processing due to a flow constraint on the abstraction licence
- One in Slough, Wycombe & Aylesbury WRZ

I.99 Our spring sources were identified as requiring an 'External Timeseries' DO modelling approach in the Groundwater Framework. There are five spring sources in the Cotswolds in the SWOX WRZ, one in London WRZ and one in Guildford WRZ. Relationships had previously been established for the Cotswolds springs using the 4R recharge model from the EA Cotswolds Groundwater Model. The 4R recharge model allows fast processing of the 400 48-year stochastic replicates, and therefore this approach was used to produce a timeseries of yields.

I.100 For each source a relationship was developed between 4R simulated flows and observed spring discharge. The 4R models were run using the full stochastic dataset and yields were produced, which were then processed to account for treatment capability, process losses, and licence constraints.

I.101 Individual source timeseries were amalgamated where necessary to match the nodes in the Pywr model.

Sources with a Flow Constrained Licence:

I.102 With the exception of the Gatehampton licence, all other flow constraints on Thames Water sources are on rivers that are not represented in the Pywr model. This meant that the yield of several sources with flow constraints needed to be pre-processed and applied to the timeseries of yields, prior to input to the Pywr model.

Outputs

I.103 For those sources where a timeseries of yield had been derived, the yield timeseries was used as an input to the Pywr modelling. For those sources where yield timeseries had not been deemed necessary, the DO values calculated were used as inputs to the Pywr modelling.

Hydrological Modelling

I.104 Flows are a key input when determining DO of a water resources system in which surface water abstractions are present. Generally, flows are modelled considering a 'naturalised' element (flows without any abstractions or discharges present), and a method of considering the influence of abstractions and discharges (denaturalisation). Abstractions and discharges are, however, dependent on the level of demand being considered, and denaturalisation can be considered using methods which vary between being static and dynamic, and between being lumped or more disaggregated. A key requirement of the WRSE hydrology method statement is that flows which eventually determine DO in a given WRZ should be reasonably consistent, with demands elsewhere in the catchment being equal to WRMP19 Final Plan 2025 Distribution Input (DI), i.e. the level of demand anticipated at the beginning of the period for which WRSE is producing a plan. The method of reaching this point is not specified, since different denaturalisation methods may be implemented, and denaturalisation may occur variously inside or outside the WRSE regional simulation model.

I.105 At WRMP19 we used two water resources/hydrological modelling tools. The first of these, our existing water resources model (WARMS2), takes several rainfall timeseries and PET timeseries as well as two observed flow timeseries as inputs, and contains rainfall-runoff models directly within the water resources model. Some of these rainfall-runoff models are modelled as having abstractions and discharges coming from/going into these rainfall-runoff models directly, and so abstractions within the model directly influence flows. As such, we have previously not needed to use any denaturalisation approaches outside water resources models, and instead rely on denaturalisation occurring directly within the water resources model. Were WARMS2 fast enough to be used with stochastic weather datasets, we would use this model. The second model used for WRMP19 was IRAS (a heavily simplified model of the London supply system, not incorporating the rest of the Thames catchment) – this model was used only for London and used semi-naturalised flow inputs (flows in the Thames which have had artificial influences between Windsor and Teddington removed) for the Thames at Teddington as a direct input. The model does not consider the impact of abstractions and discharges dynamically within the water resources model, but due to the simplicity of the model and lack of rainfall-runoff models within it, this model runs very quickly.

I.106 In terms of these respective water resources models, a summary of the advantages and disadvantages is included in Table I -7.

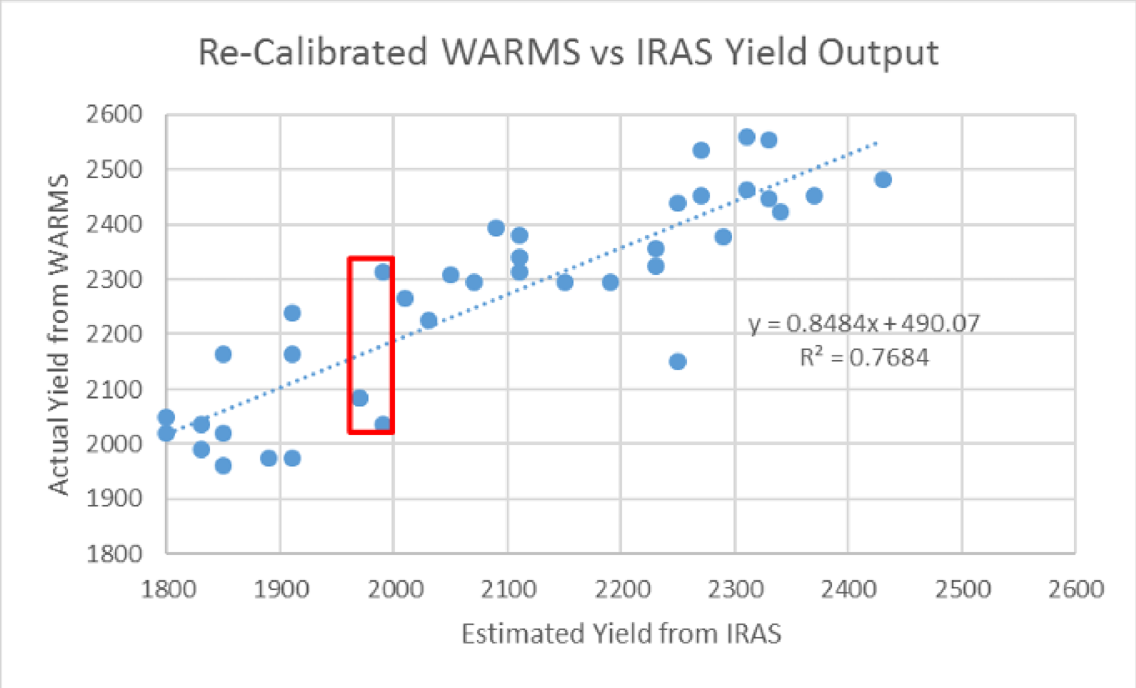
Table I -7: Advantages and Disadvantages of WARMS2 and IRAS/Catchmod

	WARMS2	IRAS/Catchmod
Advantages	Well calibrated, with the semi-distributed modelling approach meaning that complexities of hydrological response around the catchment can be captured, and calibration of different locations within the Thames ensures good overall calibration. The hydrological models being within the water resources model allows for denaturalising influences to be considered dynamically.	Very fast, meaning that the model is suitable for Deployable Output modelling using long, stochastically generated weather datasets.
Disadvantages	Relatively slow to run, as the model is detailed and includes hydrological models within a water resources model. Too slow to run full stochastic weather sequences through the model. Flows are required as an input (at Days Weir and Teddington Weir), meaning that the model cannot be run for non-historical sequences without input flows being provided.[7]	Use of single, lumped parameter rainfall-runoff model rainfall run-off models meant that the model calibration was relatively poor.

I.107 When developing IRAS, checks were undertaken in which a comparison was made between Deployable Output for given stochastic replicate as calculated by IRAS, compared to the Deployable Output as calculated by WARMS2. This comparison was presented in Figure I-17 in WRMP19, reproduced below. Note that the red box on this Figure is referred to in WRMP19, but is not of relevance in this discussion.

[7] The reason that flows are needed as an input to WARMS2 is that there are two components within WARMS2 that produce flows. The first component type is a hydrological model which represents the baseflow contribution of larger catchments. The second component takes flow inputs (from lumped models/observations) and attributes those flows across the catchment; these components represent flow contribution from faster-response and ungauged catchments. This means that lumped rainfall runoff modelling is needed, to provide the flow inputs for the second flow input component type. The combination of model types has resulted in a well calibrated model, as can be seen in the Annex as the end of this Appendix.

Figure I-17: Comparison of IRAS and WARMS2 yields



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

Figure I - 9: - WARMS vs IRAS Yield Output from WRMP19

I.108 As is shown on this graph there was a significant difference between Deployable Outputs calculated using IRAS and WARMS2. This difference was attributed primarily to the hydrological modelling differences. As such, a translation equation was used to take a DO from catchmod/IRAS and convert it into a result which would be found in WARMS2. This equation is included on Figure I - 9. As an example, a Deployable Output figure of 2000 Ml/d as calculated in IRAS would result in a WARMS2-equivalent Deployable Output of 2187 Ml/d. The IRAS model has been superseded in WRMP24 and is no longer in use.

I.109 The WRSE Pywr model does not directly contain rainfall-runoff models due to the model speed penalty that this would entail and the requirement for the model to be used with around 20,000 years' worth of input data. As such, we have needed to develop new approaches to determine input flow timeseries that are consistent with the requirements of WRSE DO modelling, as some elements of denaturalisation currently carried out dynamically in WARMS2 need to be conducted externally and supplied to the WRSE Pywr model as timeseries inputs.

I.110 Table I- 8 details the different sources of denaturalisation in WARMS2, all of which are considered dynamically, how these 'types' are considered within the Pywr model and gives an assessment (RAG) regarding how similar or different this approach is to the approach in WARMS2.

Influence as represented in WARMS2	How is this dealt with in the Pywr model?	Within Pywr. or external?
SW abstractions and GW abstractions represented as SW abstractions	SW abstractions and GW abstractions represented as SW abstraction are both represented as SW abstractions (i.e. dealt with in Pywr)	Pywr
Effluent returns, from TW, AfW & SEW, direct to river	Effluent returns calculated as % of demand, returned to river	Pywr
Effluent returns, from TW, AfW & SEW, to rainfall-runoff model	Effluent returns calculated as % of demand, returned to river	Pywr
Didcot power station	Represented in Pywr model, with ability to model both licence and amendments – improvement on WARMS2 as can link to LTCD	Pywr
Abstractions & demands from non-PWS abstractions represented as SW abs	Denaturalisation nodes included at model coupling stage to mimic abstractions from WARMS2	External, but exactly the same
GW abstractions which do not impact surface water flows	GW abstractions not currently assumed to impact river flows will not impact river flows in Pywr (standard GW node in Pywr)	Pywr
GW abstractions from rainfall-runoff models	New approaches needed and have been developed – cannot replicate within Pywr as rainfall-runoff models will not be included. Will apply a Flow Duration Curve (fdc) adjustment approach developed by Thames Water where this has been determined for each rainfall-runoff model and will be applied on a 'per Ml/d abstraction' basis.	External time series inputs, source of potential change

Table I- 8: Representation of Denaturalising Influences in WRSE Pywr model

I.111 As can be seen in the table, the main source of difference in the consideration of denaturalisation in the Thames catchment is associated with abstractions from catchments which are represented in WARMS2 using rainfall-runoff models. Abstractions represented as surface water abstractions in WARMS2 are continuing to be represented as surface water abstractions in the WRSE Pywr model and, subject to correct representation within the Pywr model, will appropriately represent the level of demand applied in the Pywr model. Effluent returns are also represented in almost the same way as in WARMS2, and so should provide an adequate representation of effluent returns.

I.112 As such, the input flow timeseries required are:

- Naturalised flow timeseries at points across the Thames catchment
- Denaturalisation timeseries associated with abstractions which are represented as coming from rainfall-runoff models in WARMS2. These timeseries have been developed to represent influences from abstractions that would satisfy equal to WRMP19 Final Plan 2024-25 DI

I.113 In WRMP24, stochastic water resources modelling is now expected to be the basis of our Deployable Output assessments, given the requirement to calculate a 1 in 500-year

Deployable Output. However, we want to improve upon the hydrological modelling undertaken for WRMP19 in order that we do not need to rely on corrections such as the regression used in WRMP19. Additionally, in order to ensure a coherent plan for the South East, the WRSE Regional Group developed a regional-scale water resources model meaning that hydrological modelling for WRZs other than London would be necessary. As such, aims for our hydrological modelling in WRMP24 were:

- The hydrological models used should be semi-distributed, in order to provide flows across the Thames catchment and in order to ensure good calibration.
- Hydrological modelling should be done outside the water resources model, in order to ensure speed within the water resources model.
- Given the significant denaturalising influences within the Thames catchment, as many of the denaturalisation processes as possible should be represented dynamically within the water resources model.

I.114 Based on these aims, the following approach was taken to hydrological modelling in our WRMP24:

- WARMS2 was used as the hydrological model for WRMP24. This is because it is acknowledged as a well-calibrated model (see Annex – calibration of WARMS2) which takes a semi-distributed approach, and ensures consistency between our WRMPs.
- Due to the requirement for hydrological modelling to be undertaken outside the water resources model, WARMS2 was to be run for a single scenario, reflective of a naturalised catchment.
- Denaturalising influences were to be considered within the water resources model where possible.
- Recognising that WARMS2 itself requires flow inputs (Thames at Teddington and Thames at Days Weir) in order to produce flow outputs, the calibration of models for the Thames at Teddington and Thames at Days Weir was undertaken.

I.115 The resulting process is demonstrated in the schematic below. Ovals below represent models, while rectangles represent datasets. The existing WARMS2 model is shown in blue, while new models/datasets are shown in green. The result of this process is that we have taken the WARMS2 model, which has been shown to be well calibrated and which has been used as our hydrological model for several iterations of water resources planning, and have calibrated models to provide the inputs that WARMS2 needs in order to run for scenarios other than the historical time series. We have then used flows produced by WARMS2 as the inputs to the pywr model. This process ensures that we are able to utilise the robust and well-calibrated WARMS2 model for hydrological modelling, but are able to ensure the speed required for water resources modelling using stochastic datasets.

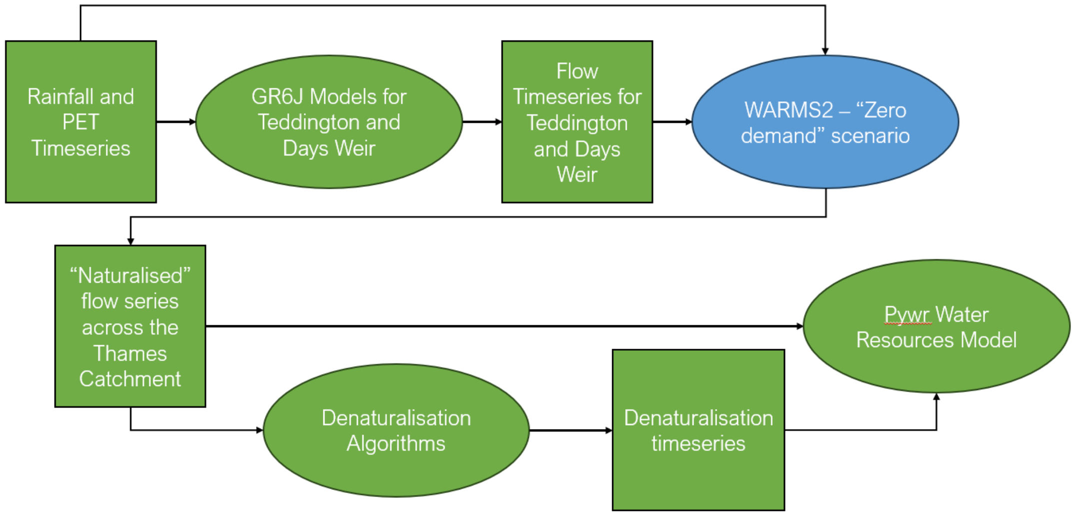


Figure I - 10- Hydrological Modelling Process for WRMP24

Hydrological Modelling to Produce 'Naturalised' (Zero-demand) Flows

I.116 Atkins undertook a project to produce the zero-demand flows that would be used in our DO modelling. The aim was to produce zero-demand, rather than naturalised, flow timeseries for the 15 flow input nodes included in the Pywr model. These flows are consistent with flows generated from 'flow generation' components in WARMS2, i.e. those prefixed TA and TI in Aquator,) when no demands are applied in the Aquator model, to then subsequently be denaturalised.

I.117 This project involved the calibration of new hydrological models to provide the necessary input timeseries to feed Thames Water's Aquator model. GR6J models were calibrated to semi-naturalised flows at Teddington and Days Weir and further modelling was undertaken to split these flows into 'baseflow' and 'surface flow' components, as required by our Aquator model. Thames Water's Aquator model was then used, employing a zero-demand parameter and sequence set, to provide required inputs for the WRSE Pywr model.

I.118 These models were then run using the stochastic weather timeseries in order to produce the flow timeseries needed for water resources modelling.

I.119 In this section, we have first detailed the calibration of the models produced for Teddington and Days Weir, and then the validation of the flows produced by WARMS2 using these new flow inputs as compared to flows produced when WARMS2 is run using historical measures flows.

Calibration of Lumped Parameter Rainfall-Runoff Models for the Thames at Teddington and Thames at Days Weir

I.120 Daily lumped GR6J and Catchmod models were calibrated at both Day's Weir and Teddington Weir to observed naturalised flows. The selection of CATCHMOD and GR6J for Thames Water's WRMP24 hydrological modelling was driven by their respective strengths. GR6J was chosen for its superior performance in simulating low flows and baseflow during droughts, which is critical for accurate water resource assessments, and its computational efficiency. CATCHMOD was tested for comparison due to its historical use, ensuring continuity with previous models and providing a benchmark to assess model discrepancies. Model performance was compared over calibration and validation periods, 1920 to 1966 and 1967 to 2013 respectively, as well as during key historical drought events. The GR6J models fit better to the observed flows in the calibration period and outperformed Catchmod in all error and correlation model fit statistics (as shown in Figure I - 11and Figure I - 12). Comparison with historical drought years shows that during low flow periods, baseflow is better represented by the GR6J models, whilst the Catchmod models show a flashier response than the observed record (as shown in Figure I - 13and Figure I - 14). As a result of this hydrological model comparison work, the GR6J hydrological models were used to provide the inflows required for WARMS2 (zero demand scenario), which was then subsequently used to produce flows used in the water resources model.

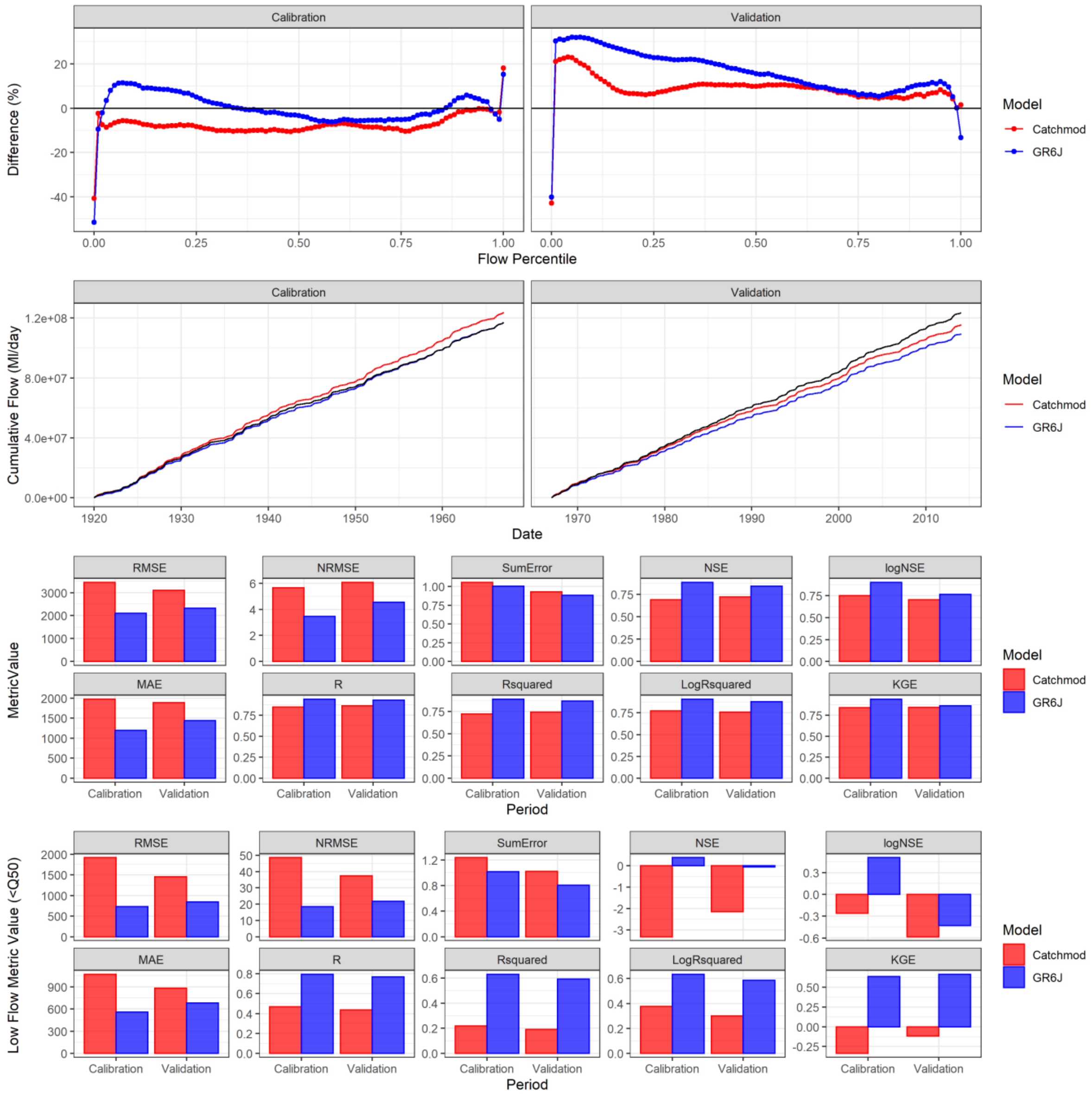


Figure I - 11: Teddington Weir comparison of hydrological model fit statistics for calibration and validation periods

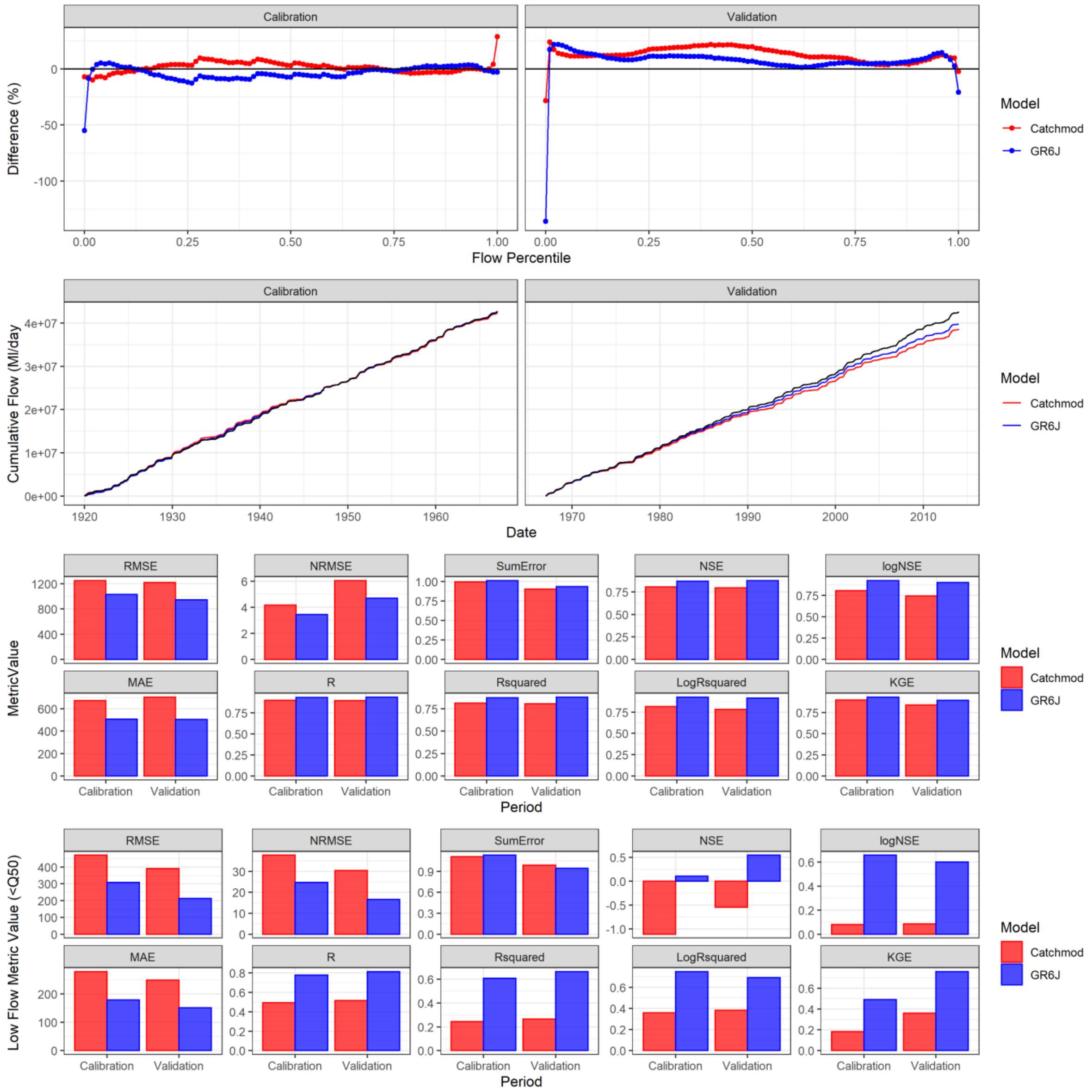


Figure I - 12: Days Weir comparison of hydrological model fit statics for calibration and validation periods

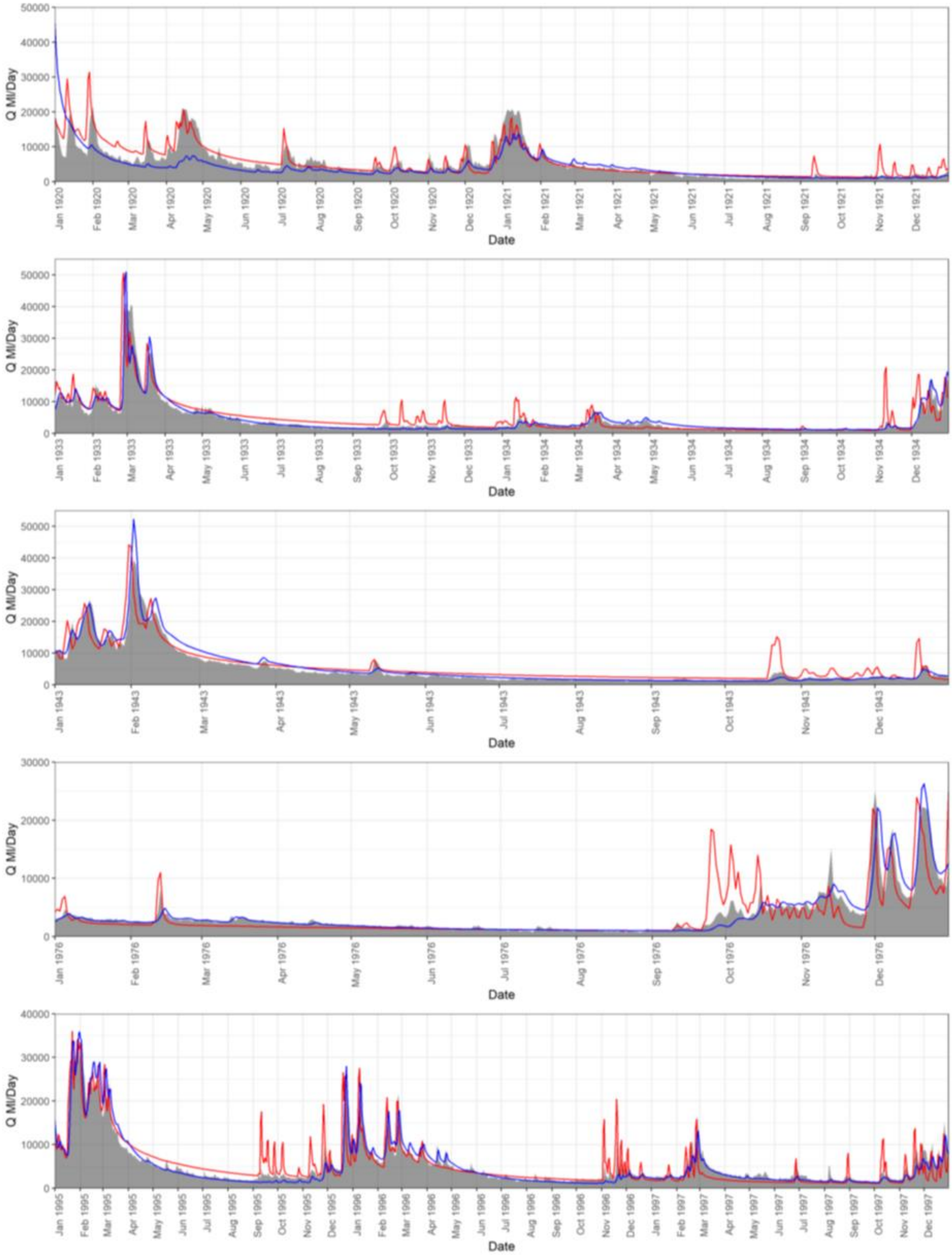


Figure I - 13: Teddington Weir historical drought year hydrographs (Observed flow in grey, GR6J in blue, Catchmod in red)

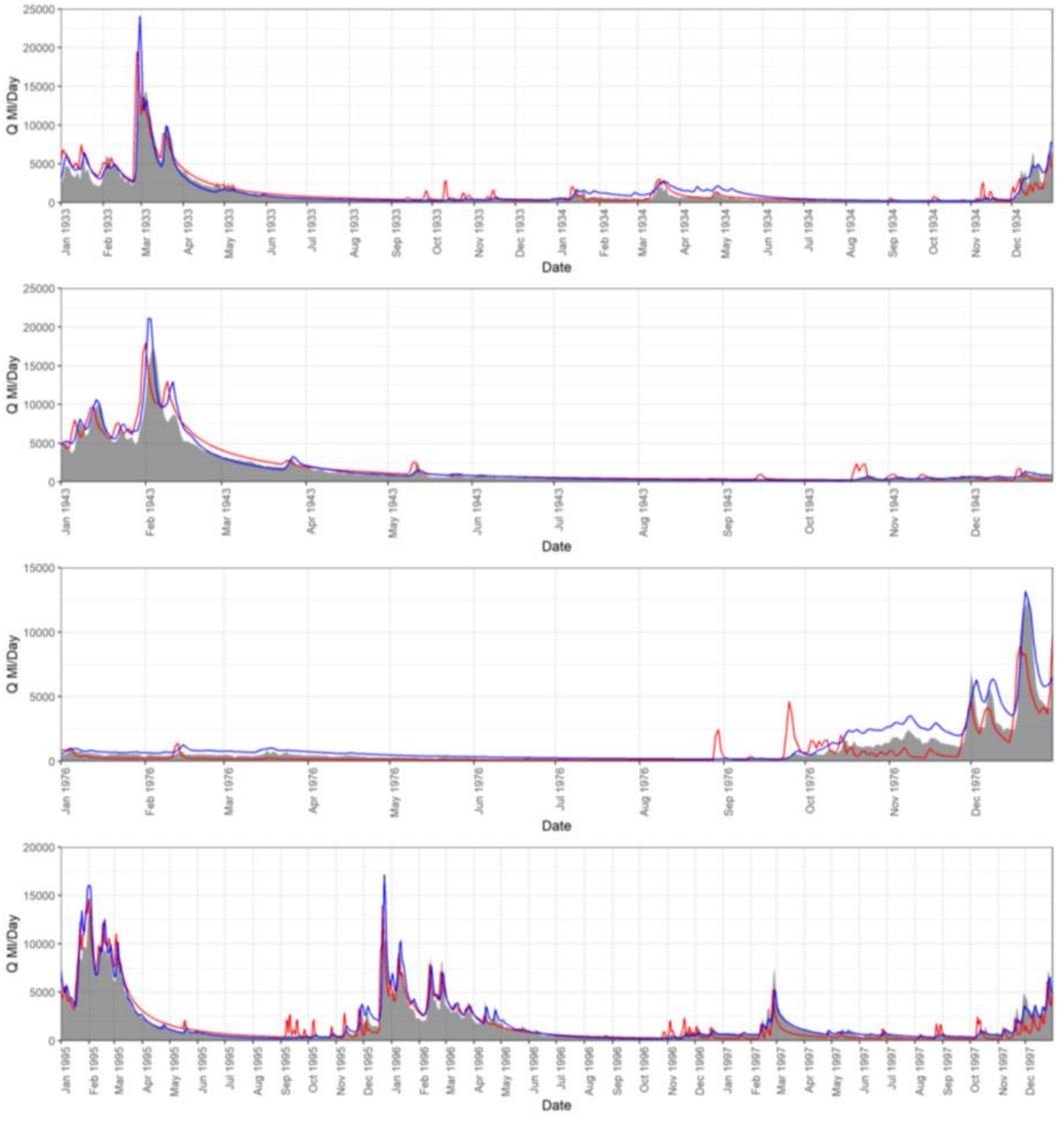


Figure I - 14: Days Weir historical drought year hydrographs (Observed flow in grey, GR6J in blue, Catchmod in red)

I.121 Calibration statistics for the calibrated models are shown in Table I - 9. The key values of Nash-Sutcliffe Efficiency (logNSE) being around 0.9 for both models, logNSE (a metric which is particularly important when considering low flow calibration) also being around 0.9 for both models, and Kling-Gupta Efficiency (KGE) being >0.9 for both models indicate strong model calibration performance.

	Thames at Teddington	Thames at Days Weir
RMSE	2074.89	992.9135
NRMSE	3.3985	3.3002
SumError	0.9385	0.9643
NSE	0.8818	0.8693
logNSE	0.8833	0.9046
KGE	0.9149	0.9201
MAE	1183.863	512.413
R	0.9428	0.9337
Rsquared	0.8888	0.8719
LogRsquared	0.9036	0.9123

Table I - 9: Calibration Statistics for Hydrological Models

Naturalised flows simulated by using GR6J models for Days Weir and Teddington Weir were processed to produce the “baseflow” and “surface flow” components required as inputs to Aquator (WARMS2). The Aquator model (WARMS2) was then run with demands set to very low levels using these inflows and compared to the flows produced from an Aquator model run using the same demand levels, but in which observed flows were used as an input (observed flow inputs have historically been the inputs used in WARMS2).

I.122 Statistics of a comparison between Aquator modelled flows for key locations relative to the WRMP19 methodology (observed flow inputs) are provided in Table I - 10. The statistics show a very good level of correlation between the two sets of flows indicating that the method applied to generate the flows was robust. Comparisons of flow duration curves and hydrographs for key historical years are shown in Figure I - 15 to Figure I - 19.

	Thames at Teddington	Lee at Feildes Weir	Kennet at Theale	Wey at Guildford	Thames at Farmoor
NSE	0.912	0.977	0.985	0.960	0.954
logNSE	0.938	0.999	1.000	0.999	0.999
r^2	0.914	0.939	0.952	0.875	0.913
Mean Absolute Error (Ml/d)	1028.963	37.941	43.946	36.327	46.664
Volume Error	0.981	0.976	0.996	0.973	0.997
RMSE (Ml/d)	1924.046	104.318	131.381	113.452	428.247
RMSE for flows below Q50 (Ml/d)	582.740	39.964	57.057	41.686	123.289

Table I - 10: Summary “zero demand” flow statistics for key locations generated by Aquator using the GR6J simulated flows relative to the WRMP19 method

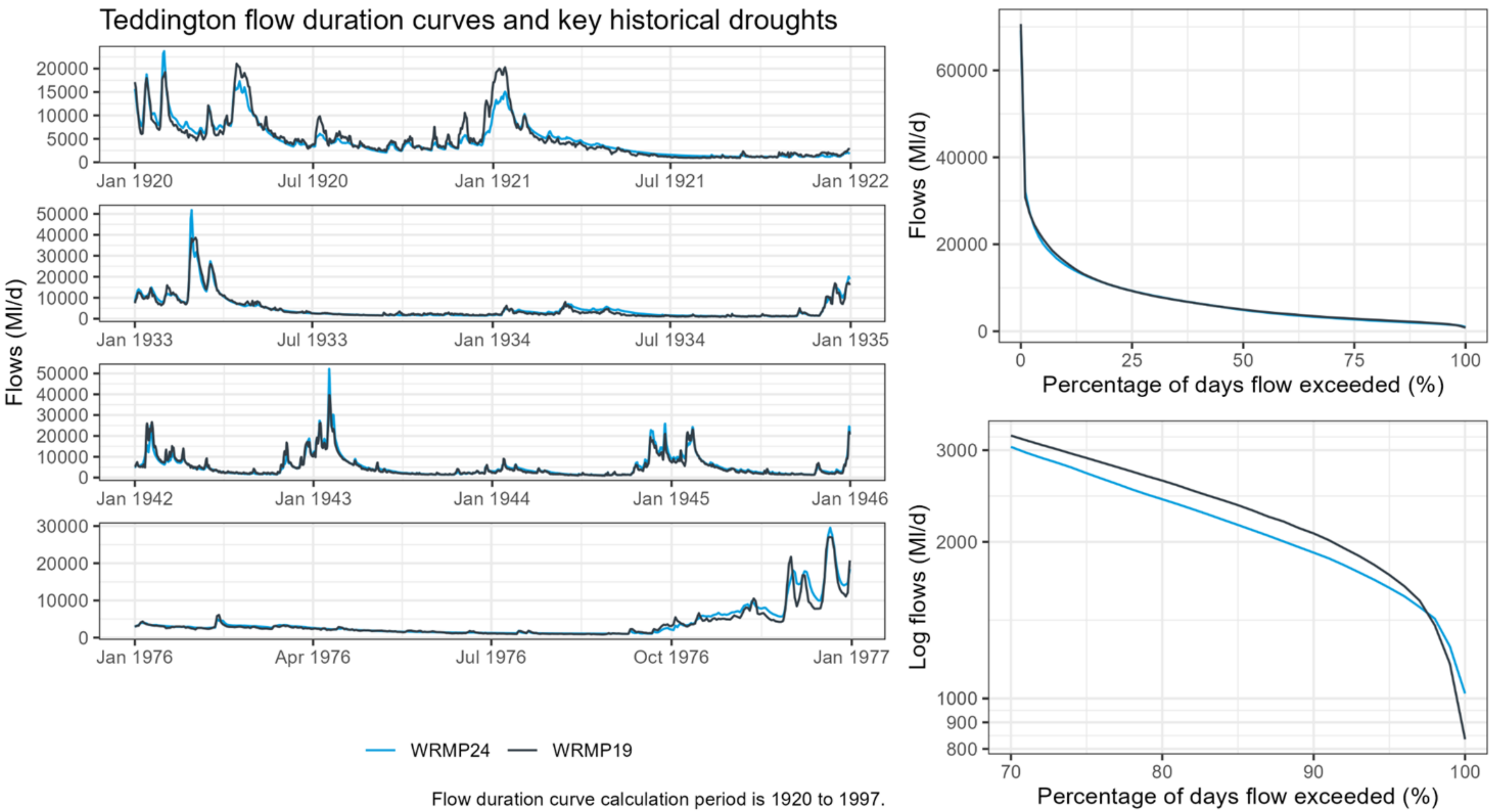


Figure I - 15: Thames at Teddington flow duration curves and key historical droughts for WRMP24 and WRMP19 zero-demand flows. Note: for water resources purposes, the calibration of the model in the flow range above 5000 Ml/d is not significant, and the flow range below 3000 Ml/d is of most significance. This is due to the Teddington Target Flow (300-800 Ml/d), abstractions made by Affinity Water (c.400 Ml/d), the maximum abstraction experienced from our Lower Thames Intakes (c.3000 Ml/d) and the abstraction level needed to maintain levels in our reservoirs (c.1600 Ml/d)

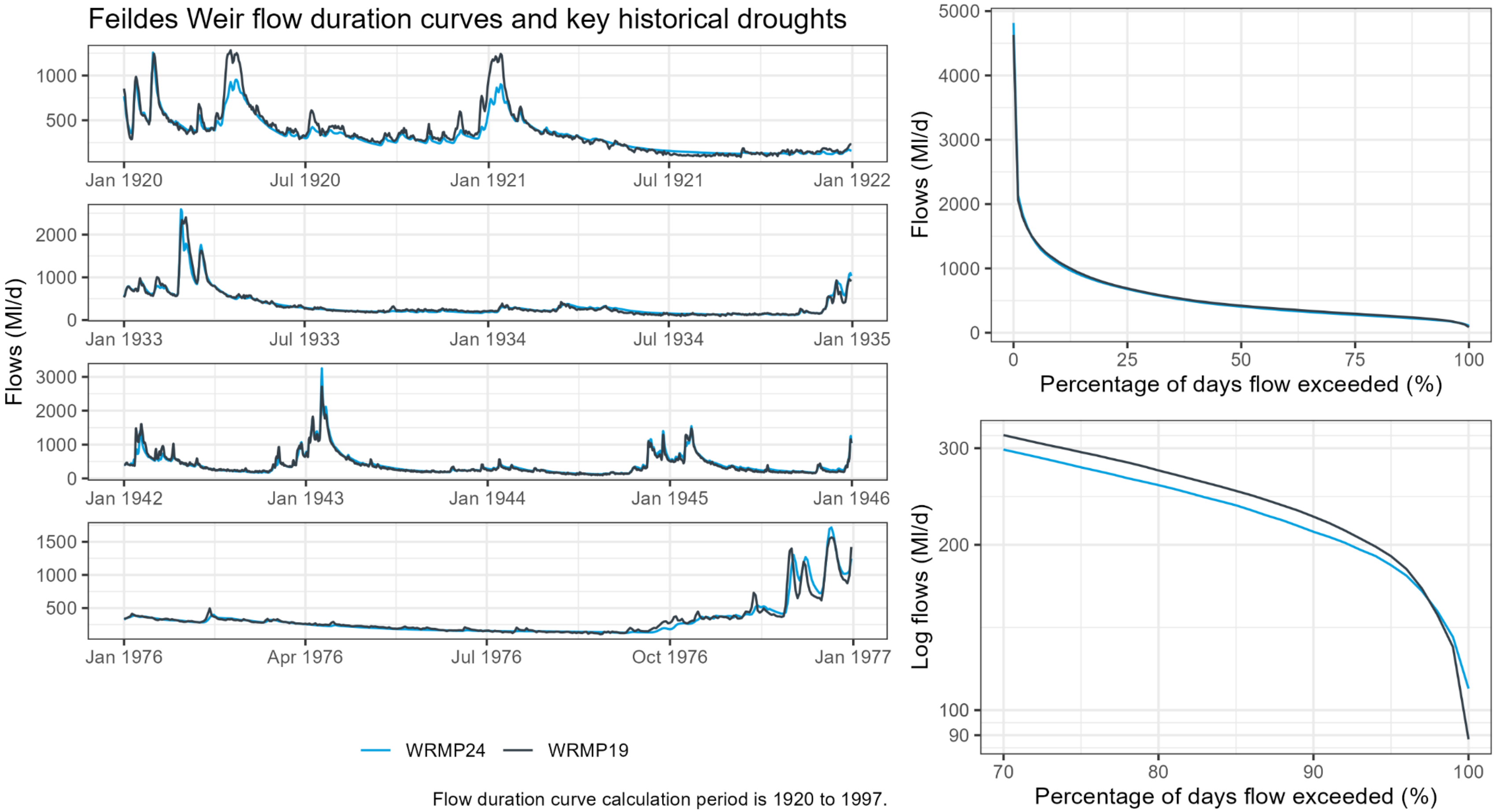


Figure I - 16: Lee at Feildes Weir flow duration curves and key historical droughts for WRMP24 and WRMP19 zero-demand flows. Note: for water resources purposes, calibration of flows above 1000 Ml/d is not significant, and flows below around 300 Ml/d are of most significance. This is because there is no HOF on the River Lee, and so low flows are of most importance.

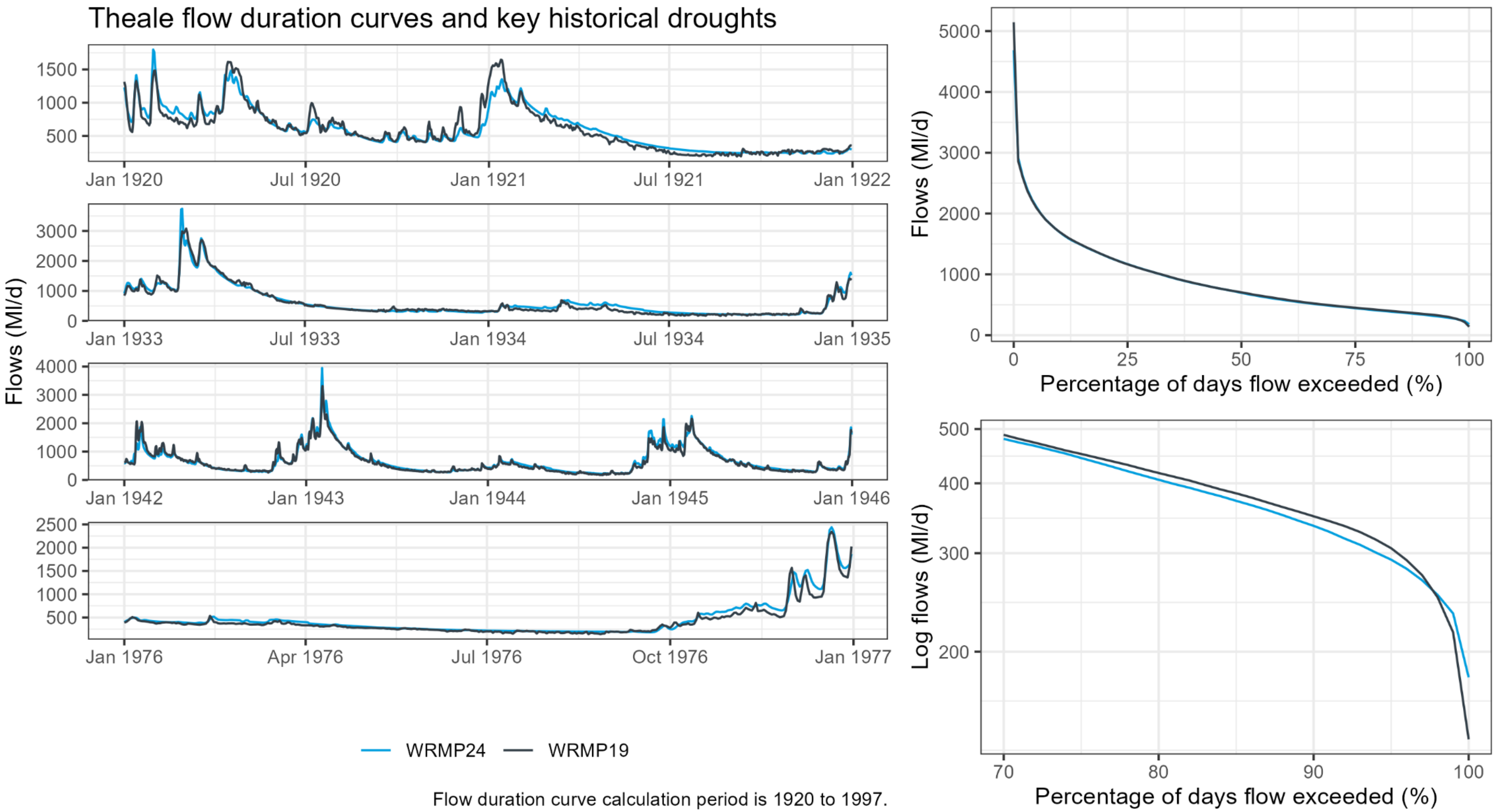


Figure I - 17: Kennet at Theale flow duration curves and key historical droughts for WRMP24 and WRMP19 zero-demand flows. Note: the lowest flows are of most importance for calibration, with flows below 200 Ml/d of most significance. This is because there is no HOF on the Kennet and Fobney is a run of river abstraction with a licence of around 70 Ml/d, with there also being a flow diversion associated with the Holy Brook.

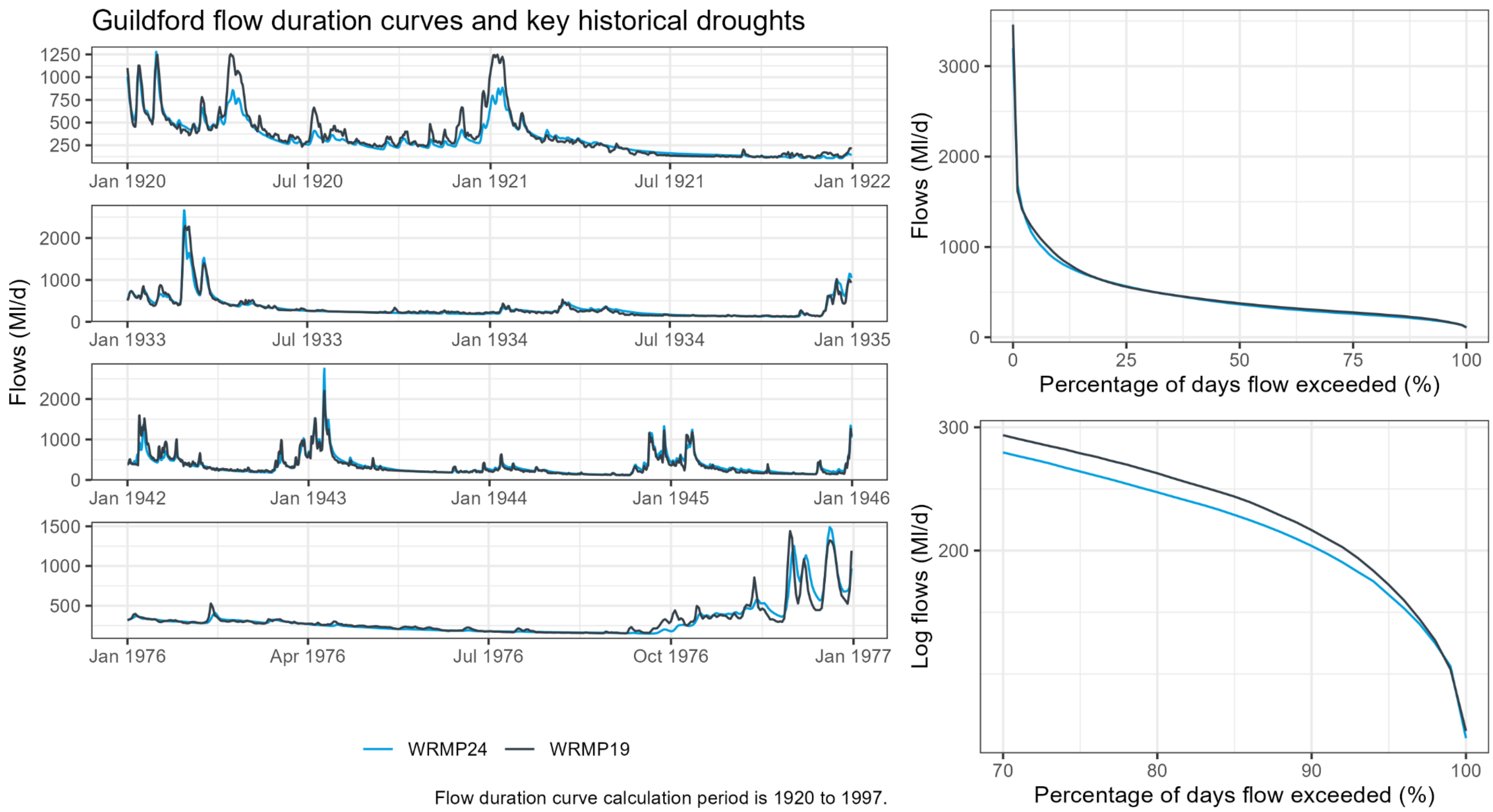


Figure I - 18: Wey at Guildford flow duration curves and key historical droughts for WRMP24 and WRMP19 zero-demand flows. Note: the lowest flows are of most importance for calibration, with flows below 100 Ml/d of most significance. This is because there is no HOF on the Wey and Shalford is a run of river abstraction with a licence of 30 Ml/d.

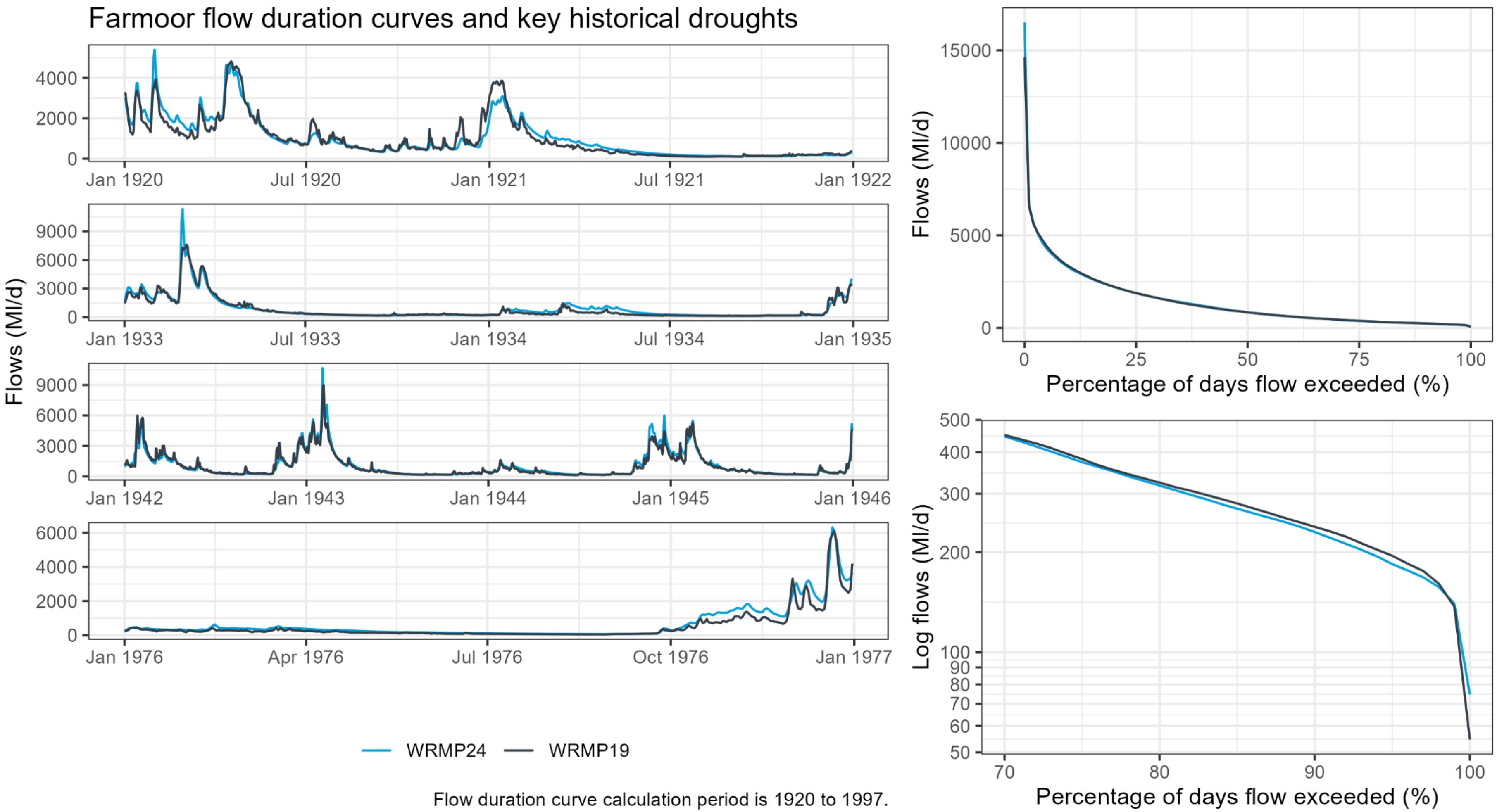


Figure I - 19: Thames at Farmoor flow duration curves and key historical droughts for WRMP24 and WRMP19 zero-demand flows. Note: calibration of low flows (<400 Ml/d) is more significant, with flow controls coming into place at flows of 377 Ml/d, 136 Ml/d, and 77 Ml/d.

I.123 As with all forms of modelling there is uncertainty, whether from the gauged data or the modelling methodology applied. The purpose of using calibration metrics which prioritise periods of low flow is to reduce as far possible the uncertainty associated with DO calculation further down the modelling chain.

I.124 Recognising that the Deployable Output of water resources systems with reservoir storage requires water resources modelling and should involve comparisons of reservoir storage drawdown and Deployable Output as well as comparison of flows, the "Model Validation" section of this Appendix documents a staged validation process in which the water resources model is first validated using flows taken directly from the WRMP19 model, and is then validated using these newly produced flows. As is described later in this Appendix, the cascaded impact on the assessment of DO was found to be less than 1%, and was as such deemed to be immaterial.

Denaturalisation Timeseries

I.125 As stated in the previous sections, while the flow series used in the WRSE Pywr model are named 'naturalised' and 'denaturalisation', the 'naturalised' flows are from a model (WARMS2) which has been calibrated based on producing denaturalised flows, with demand turned off. The aim of this 'denaturalisation' step is to return the 'naturalised' flows to something representative of a denaturalised flow considering abstraction that would be made to meet WRMP19 Year 5 (2024-25) Final Plan demand.

I.126 The approach taken to flow denaturalisation was to compare flow outputs from each individual TA component for Aquator model runs with demands on and demands off (with non-London demands at a demand level of 2014-15 DI) and to determine the impact of abstractions on river flows across the flow-duration curve, calculated as an Ml/d impact per Ml/d of abstraction.

I.127 For each TA component:

- A historical 'zero demand run' was completed, outflows recorded and a flow duration curve (FDC) of outflows for the historical period plotted
- A run with non-London demand at AR15 DI was completed and outflows recorded to produce a FDC for the historical period, with abstractions and discharges from that component only recorded and averaged across the run

I.128 The two FDCs were compared and differences across the FDC calculated (e.g. a difference of X Ml/d at QY). The FDC-difference curve was then normalised by the average net abstraction across the run, to give an Ml/d river flow reduction per Ml/d abstraction, across the FDC. In some cases it was necessary to amend this approach slightly. The result of this stage was a FDC amendment curve with units of Ml/d per Ml/d, as per Figure I-20 for each TA component.

I.129 In order to turn these denaturalisation FDC amendments into a denaturalisation timeseries for each TA component, it was necessary to combine these with modelled stochastic flows as follows:

- Multiply the unit (Ml/d/Ml/d) FDC amendments by the abstraction that should be considered at each aquifer unit; i.e. average abstraction to meet AR15 DI, which was assumed to be approximately equal to abstraction required to meet AR25 DI
- Produce an overall FDC amendment for each TA component, with the FDC determined for the 1950-97 historical naturalised flow series
- For each day of the stochastic time series, the TA component flow was mapped to a quantile of the historical TA component flow, such that each day of the stochastic timeseries was given a Qx value
- A denaturalisation impact was calculated by interpolating the overall FDC amendment curve at the appropriate Qx value for that day
- Where the stochastic flow sat outside the range of historical flows, the denaturalisation impact was deemed to be the same as at Q100 or Q0 as appropriate, rather than extrapolating the FDC-amendment curve

I.130 The resultant denaturalisation timeseries were used in the water resources modelling, conducted in Pywr.

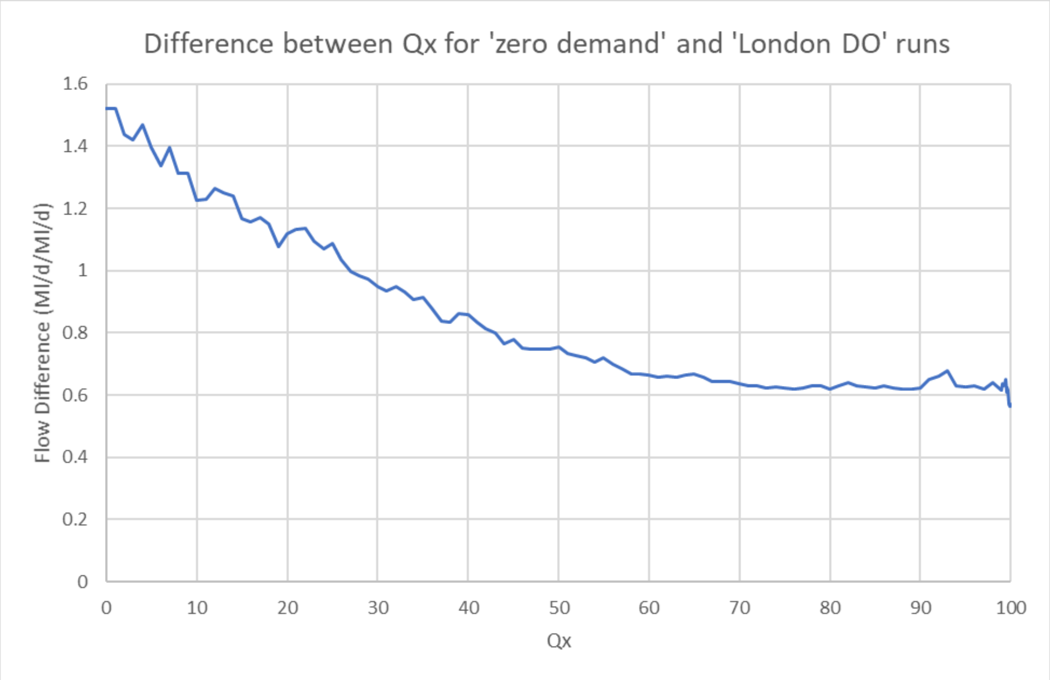


Figure I-20: Example FDC-based Denaturalisation Curve

Water Resources Models

I.131 When producing WRMP19, we made use of two water resources models:

- WARMS2, built in Aquator – a detailed model of the whole Thames catchment incorporating rainfall-runoff models. This model is reliable and detailed, but does not run quickly enough for us to use it to conduct ‘full stochastic’ DO analyses, as is required in the calculation of a ‘1 in 500-year’ DO
- IRAS – a heavily simplified model of the London supply system, not incorporating the rest of the Thames catchment. Rainfall-runoff models were not included (i.e. flows were an input to this model). This model is fast, but is not detailed and the lumped nature of

the hydrological inputs meant that its calibration was not sufficiently good for results from IRAS to be used in isolation

I.132 In producing WRMP24 we have made use of newly developed Pywr models, which were developed as part of the WRSE Regional Simulation Modelling project. For us, the aim of these models is that they would bridge the gap between WARMS2 and IRAS, being sufficiently detailed, sufficiently fast and that they could be used to determine a '1 in 500-year' DO. This section describes the development and validation of these models.

I.133 The 'WRSE Regional Simulation Model' (another name for the WRSE Pywr model) is not a single model, but rather a collection of sub-models which can be coupled and run as larger 'sub-regional' models (Figure I-21). For example, a sub-model exists for the Henley WRZ which can be run on its own, but this can be coupled with other Thames Water models (and Affinity sub-models) to give a model for the Thames catchment as a whole. The ability to consider sub-regional or whole regional solutions was considered important given the increased standing of Regional Groups in the WRMP process, and for us in particular due to the large multi-zonal and multi-company solutions being considered by the company (e.g. Severn-Thames Transfer, South East Strategic Reservoir Option, Thames to Southern Transfer, Thames to Affinity Transfer).

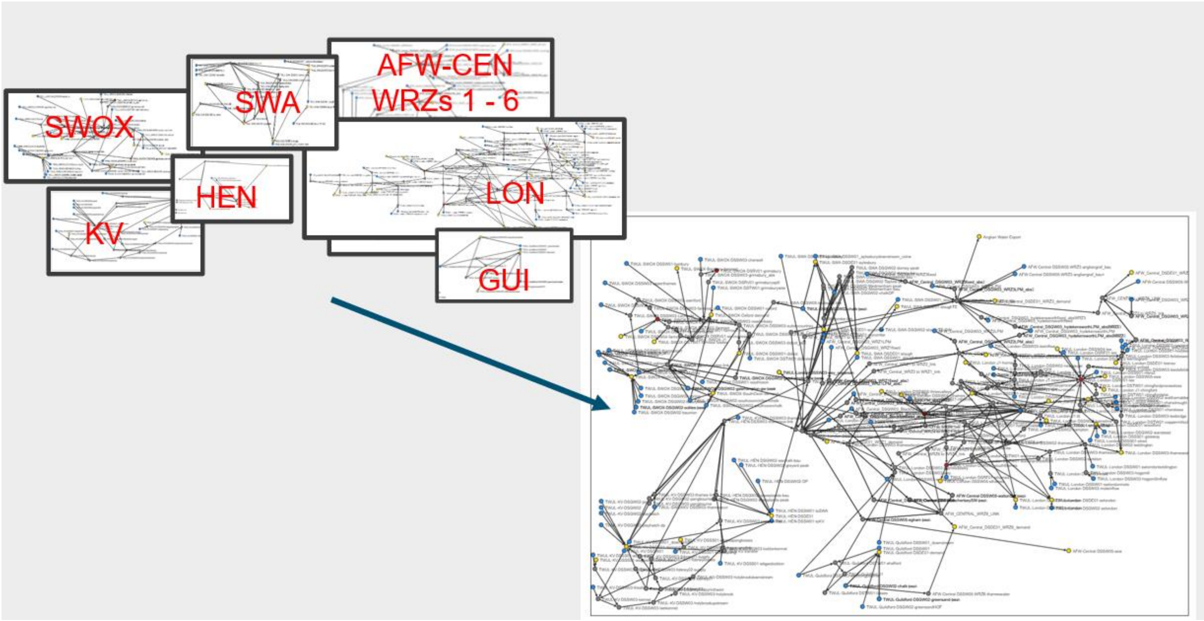


Figure I-21: WRSE North Pywr Model Schematic

I.134 The Thames Water sub-models were built as relatively detailed simplifications of the representation of the Thames Water supply system, providing a moderately simplified version of the WARMS2 model. As an example of the level of simplification included, the SWOX system is represented as having 10 demand centres (Banbury, Oxford, Faringdon, Witney, Wantage, South Oxon, Watlington, Cotswolds, Swindon, Marlborough), but in Pywr these demand centres have been aggregated to four (Marlborough / Swindon / Cotswolds, Oxford/Faringdon/Witney, Banbury, South Oxfordshire/Watlington/Wantage). A fully simplified model, such as that built for the National System Simulation Model Project (Water Resource England and Wales, WREW), would represent SWOX as a single demand centre. Similarly, groundwater sources have been aggregated at fewer nodes than in WARMS2, but not generally aggregated to a single node per WRZ. The approach taken in Pywr was to include significant within-WRZ infrastructure in order to ensure that our future plans would 'work' at a sub-WRZ level.

Model Validation

I.135 As highlighted previously, groundwater timeseries and river flow timeseries are key inputs to water resources modelling, and input timeseries heavily influence the behaviour of the London and SWOX WRZs. WARMS2 has previously been shown to be a reliable and well calibrated model for the Thames catchment, and so the Pywr model was validated relative to results from WARMS2. As such, in order to establish the influence of the different model developments that have been undertaken, a stepped validation process was undertaken for these zones:

- Validation of 'the Pywr model' itself – using historical input flows from our WARMS2 model to establish that simplifications/amendments to model behaviour had not unduly influenced model outputs
- Validation of the model, including changes to hydrological modelling – using historical flows derived from our revised hydrological modelling assessments for the historical time period, the Pywr model was validated by comparing outputs to those from WARMS2
- Validation of model outputs from stochastic DO assessments – using flows generated when hydrological and hydrogeological timeseries for the 'full stochastic' timeseries were used as inputs to the model, we validated the 'DO' output against our previous understanding of DO for different return periods

I.136 The stepped approach to model validation was also taken in terms of model coupling. Where feasible, the London sub-model was validated in isolation, before being coupled with other Thames Water models (e.g. treating Affinity Water as a boundary condition), and then being coupled to form a full 'WRSE North' model. In this section, the fully coupled WRSE model is the focus, as this is the model that was used for London's DO runs.

I.137 The validation of the London model is presented here. Validation of the model has included validating specific aspects of model behaviour (e.g. checking that the Gateway desalination plant and NLARS switched on and off at the right time, according to the Lower Thames Operating Agreement), but the validation plots presented here focus on Total London Storage.

I.138 Model validation was conducted by comparing Thames Water's Aquator model (known as WARMS2) against the Pywr model results. Validation was not undertaking comparing the Pywr model with the IRAS model. This is because the heavily simplified water resources and hydrological modelling used in IRAS necessitated the use of significant alterations to Deployable Output figures produced by IRAS in WRMP19.

Validation of Model Using Historical Datasets, Excluding Hydrological Model Changes

I.139 The first step in validation of the London Pywr model was to use historical flows simulated by WARMS2 to establish whether reservoir drawdown timeseries seen in the Pywr model were close to those seen in WARMS2. The aim of this step is to remove the influence of changes in hydrological modelling, and so to focus only on changes brought about by moving from one water resources model to another.

I.140 The results in Figure I-22 for key drought periods show that the Pywr model provided a very close match to results seen in WARMS2 during this validation step.

I.141 In addition to the plots a comparison with a 'worst historical' DO figure was also generated. The figure from the Pywr model was 2314 Ml/d, compared with a DO of 2302 Ml/d generated by WARMS2 with the same underlying assumptions.

I.142 This demonstrates that the "Water Resources" element of the Pywr model is an extremely good match with our WARMS2 model, a good validation outcome. Alongside the validation of storage outputs, at this point it was also verified that key source outputs and model rules were being followed, for example:

- Teddington Target Flow following the LTOA rules, and abstractions meaning that the Teddington Target Flow is being met
- Strategic schemes switching on and off at the right time, including the Gateway desalination plant, NLARS, WBGWS, and others
- Abstractions from Affinity Water in the Lower Thames being as expected
- Abstractions from TW groundwater sources being as expected, including the South East and South West London wells, Northern New River Wells, etc
- Overall mass balance of demands and output from sources
- Water balance followed through the model, including tracing process loss returns to river from the London LPPs, and effluent returns from sewage treatment works
- While not of relevance for baseline DO, it was checked that demand savings actions (TUBs etc) were being triggered appropriately
- Transfers to Essex and Suffolk

Figure I-22: Step 1 Pywr Model Validation Plots (y-axis is London storage in Ml)

Validation of Model Using Historical Datasets, Including Hydrological Model Changes

I.143 The next step in model validation was to introduce the flows generated through the hydrological modelling project when these models were run using historical input timeseries. The performance of the London supply system is heavily dependent on hydrological inputs and so a greater degree of change was expected. In addition to the change in hydrological model used, an additional change implicit in this step was a change in the rainfall dataset used, with HadUK rainfall being used. This change in rainfall dataset was expected to drive some change, as the HadUK rainfall was, at times, notably different to the rainfall timeseries previously used. This was carried out in two steps, with only denaturalising influences tested first, followed by the full hydrological updates. Figure I-23 shows validation plots for key drought periods for the fully updated hydrological and water resources model (run in the ‘WRSE North’ configuration). These plots show a close agreement between Pywr and WARMS2 outputs for key drought periods, with the revised hydrological modelling/rainfall datasets seeming to suggest greater drawdowns during some moderately dry periods. The DO calculated when the model was run was 2296 Ml/d (a figure comparable with the 2302 Ml/d WARMS2 DO). Considering the degree of change that had been undertaken and results from WRMP19 hydrological modelling, this was considered a good fit. Note that, in these model validation runs, demand savings were turned on to maintain consistency with runs undertaken in WARMS2.

I.144 While we consider that the model outputs shown here provide a sufficiently close match with WARMS2 (itself shown in WRMP19 to be a suitable model when validated against observed data) to be acceptable for use in our Deployable Output assessment, it is notable that the primary source of change between the WRMP19 and WRMP24 DO modelling is in the hydrological modelling, rather than the water resources modelling. Rainfall-runoff models can be very sensitive, and hydrological modelling of extreme drought is challenging and uncertain. Section 6 of our WRMP describes how we have accounted for this uncertainty within Target Headroom.

Figure I-23: Step 2 Pywr Model Validation Plots (y-axis is storage in Ml)

I.145 It is important to note that the validation outputs shown here are a notable improvement on the validation of the IRAS model. In WRMP19 a formula was used to convert IRAS DO figures to something suitable for use in the supply forecast, which involved conversions of several hundred Ml/d in DO. Due to the positive results seen here, we do not consider that the adoption of a conversion approach is necessary.

Validation of Model Considering Stochastic Datasets

I.146 The model was next run with the ‘full stochastic’ input hydrological timeseries. London DYAA DO for different return periods was the metric of interest and so those metrics needed for the calculation of DO were recorded, i.e. whether, in each year, at each level of demand, the different control curves had been breached.

I.147 In order to maintain comparability with modelling carried out for WRMP19, it is important to ensure like-for-like comparisons are carried out. As noted previously, several key changes have occurred between WRMP19 and WRMP24.

I.148 At WRMP19, our ‘worst historical’ DO was estimated to have a return period of around 100-125 years. When adjusted for underlying changes in SDOs and other assumptions (e.g. TUBs moving to Level 2 LoS, +18 Ml/d, inclusion of open water evaporation factors, -10 Ml/d) but not accounting for the required removal of demand savings, nor removing the Essex and Suffolk transfer, the most comparable DO figure for London’s ‘worst historical’ DO was 2297 Ml/d. With demand savings turned on and prior to reaccounting for the Essex and Suffolk transfer, the DO figures calculated from the Pywr model can be seen in Table I-11. In modelling carried out for dWRMP19, the DO impact of moving from 1:100 to 1:200 and 1:100 to 1:500 resilience levels were 140 Ml/d and 250 Ml/d respectively. The results obtained from this modelling were deemed align sufficiently aligned with WRMP19 to be considered acceptable.

Return Period of DO	DO (Ml/d)
1 in 100	2377
1 in 200	2244
1 in 500	2073
Difference between 1:100 DO and 1:200 DO	133
Difference between 1:100 DO and 1:500 DO	303

Table I-11: London DO - With Demand Savings Turned On, and Prior to Re-accounting for E&S Transfer

I.149 The next run undertaken was one in which demand savings were turned off. The DO results can be seen in Table I-12.

Return Period of DO	DO (Ml/d)	DO Reduction from Removal of Demand Savings (Ml/d)
1 in 100	2236	141
1 in 200	2119	125
1 in 500	1970	103
Difference between 1:100 DO and 1:200 DO	117	-
Difference between 1:100 DO and 1:500 DO	266	-

Table I-12: London DO - With Demand Savings Turned Off, Prior to Re-accounting for E&S Transfer

I.150 The benefit of demand savings when considering the historical record as modelled in WARMS2 is 129 Ml/d, and so the DO impact of the removal of demand savings is approximately the same as has been calculated previously, although it is interesting to note the reduced benefit from demand savings in more extreme drought conditions.

I.151 The Essex and Suffolk Transfer was then re-accounted for (+67 Ml/d on London's DO, to be removed when accounting for imports and exports), as were process losses (+7 Ml/d on London's DO, to be removed when calculating WAFU), in order to arrive at a final DO figure.

Scenario	Baseline DO (Ml/d)	WRMP19 Comparator (Ml/d)	Change (Ml/d)
1:100 DO	2310	2242-2277	+33-68
1:200 DO	2193	2102-2137	+56-91
1:500 DO	2044	1992-2027	+17-52

Table I-13: Baseline DO Calculated Using Pywr Model - As of March 2021

I.152 When compared on a like-for-like basis, the values found were considered to be sufficiently close (1-4% change to baseline DO figures) to those used in WRMP19 to be acceptable. It is also worth bearing in mind that the stochastic modelling carried out for WRMP19 needed to be 'anchored' to historical results because the 'raw' results were found to be very different to those that were found in WARMS2. The results presented from the Pywr model are 'raw' results that have not been amended but are deemed sufficiently close that further amendment is not necessary. These results gave us confidence in the modelling chain that had been undertaken, from revised stochastic weather generation through to the development of the Pywr model.

Results of WRZ DO Assessment

I.153 DO modelling was undertaken using the WRSE Pywr model for each of our WRZs. In each of the following sections, the values presented are 1 in 100-year, 1 in 200-year and 1 in 500-year DO, with demand savings benefits turned off. Values presented in the following sections are DO figures for the AR22 "base" year. In some cases, amendments are made in our supply forecast to account for anticipated changes, e.g., known sustainability reductions or planned works which will increase sources' DO contributions.

I.154 For each zone and planning scenario 'WRMP19 DO' and 'Re-accounted WRMP19 DO' values are presented for comparison. The 'WRMP19' value is the value presented in planning tables. The 'Re-accounted WRMP19 DO' values remove, as far as possible, any benefits associated with demand savings and re-accounting (e.g. for transfers, process losses), but does not correct for underlying SDO adjustments or other changes (e.g. TUB LoS change).

I.155 In Section 6 of our WRMP, our WRMP19 and WRMP24 supply-demand balance position is compared for the year 2025, in order to fully document the reasons for change between our WRMP19 and WRMP24.

London WRZ

I.156 Only a DYAA DO run was undertaken for London. We do not undertake a DYCP assessment for London due to the presence of the Thames Water Ring Main and other strategic mains enabling treated water transfer around London.

Scenario	DO (Ml/d)	WRMP19 DO (Ml/d)	Re-accounted WRMP19 DO (Ml/d)
1 in 100 DYAA DO	2335	2302	2247-2282
1 in 200 DYAA DO	2219	2162	2107-2142
1 in 500 DYAA DO	2076	2052	1997-2032

Table I-14: WRMP24 London DYAA DO Figures

I.157 Variance from WRMP19 has been explained in previous sections and so the detail is not repeated here. Broadly, however, variance is due to:

- Amendments to SDO of individual sources
- A change to our stated LoS related to the imposition of TUBs (1 in 10 LoS for WRMP24, compared to 1 in 20 LoS for WRMP19)
- Newly developed stochastic weather datasets, hydrological modelling, and water resources models

I.158 Note that these DO figures do not account for the North Orpington groundwater source sustainability reduction, which is anticipated to be made before the end of AMP8. These DO figures also assume that the Thames Gateway desalination plant has a reliable capability of 100 Ml/d. The capability of our desalination plant is discussed in Section 4 of the WRMP.

I.159 In our supply forecast, we have accounted for the reduced availability of the Gateway desalination plant which is the result of long-term outage at the site. We have included a 100 Ml/d capability in the base year and before (2019/20-2021/22), a reduction of 50 Ml/d in the capability of the site for the period 2022/23 to 2029/30, and a reduction of 25 Ml/d in the capability of the site for the period 2030/31 onwards. This reflects the anticipated outcomes of the investment plans which we have for the site.

Year of planning period	Site Capability (Ml/d)	Line 7.4BL, change in DO from prolonged outage (Ml/d)
2020-2022	100	0
2023-2030	50	-50
2031 onwards	75	-25

Table I-15: WRMP24 SWOX DYAA DO Figures

I.160 There are limited 'system response' consequences of changes in the Gateway capability, i.e., 1 Ml/d capability reduction corresponds broadly to 1 Ml/d in London WRZ DO reduction, and so we have represented it as such in WRMP24 supply forecast.

SWOX WRZ

I.161 DO figures calculated for SWOX are presented in Table I-16 and Table I–17.

Scenario	DO (Ml/d)	WRMP19 DO (Ml/d)	Re-accounted WRMP19 DO (Ml/d)
1 in 100 DYAA DO	321.7	329.2	311.2
1 in 200 DYAA DO	310.6	323.8	305.8
1 in 500 DYAA DO	297.2	306.8	288.8

Table I-16: WRMP24 SWOX DYAA DO Figures

I.162 At WRMP19, our 'worst historical' DO figure was 329.2 Ml/d. River flow modelling rather than water resource modelling was used to estimate DO reductions when moving to 1:200 (-5.4 Ml/d) and 1:500 (-22.4 Ml/d) resilience levels. All figures, however, included the benefit of demand savings which, for the historical record, are approximately 26 Ml/d.

I.163 Multiple changes were made in WRMP24 in producing a SWOX DO, most notably:

- SDO updates, including sustainability reductions totalling around 12 Ml/d at Axford, Ogbourne and Childrey Warren
- New stochastic datasets, including use of a different underlying rainfall dataset
- New hydrological input data and use of WRSE Pywr model
- Inclusion of time-variant groundwater yields, which will likely increase SWOX DO due to conservative SDO figures for sources having been used previously
- Modelling of conjunctive use system for whole of SWOX; in WARMS2, South Oxfordshire considered separately with groundwater assumed to be a fixed import
- Update of demand splits across the SWOX WRZ (from using AR15 data to AR20) and associated changes in effluent returns

I.164 The combined impact of conjunctive use modelling and updated accounting of demand plus effluent returns is likely to be significant for SWOX, with an estimated impact of +10 Ml/d.

Scenario	DO (Ml/d)	WRMP19 DO (Ml/d)	Re-accounted WRMP19 DO (Ml/d)
1 in 100 DYCP DO	345.1	385.4	393.5
1 in 200 DYCP DO	332.6	379.1	387.2
1 in 500 DYCP DO	319.4	359.2	367.3

Table I–17: WRMP24 SWOX DYCP DO Figures

I.165 Our approach to the calculation of SWOX's DYCP DO has changed between WRMP19 and WRMP24. The calculation for WRMP19 involved factoring the calculated DYAA DO figure and ensuring that this did not exceed the treatment capability of the zone. For WRMP24 we have produced a modelled 'system response' DYCP DO which was revised between dWRMP and rdWRMP. In addition, the approach to considering severe and extreme drought has been improved significantly; the river flow impacts found for the DYAA scenario were scaled to produce DYCP impacts for SWOX at WRMP19, whereas a modelled 'system response' DO was found for each DO return period in rdWRMP24. Between dWRMP and rdWRMP we reviewed the modelling that had been undertaken and noted that the SWOX DYCP assessment had omitted EDO implementation due to emergency restrictions being in place during the peak period.

Slough, Wycombe and Aylesbury WRZ

I.166 DO figures calculated for the SWA WRZ are presented in Table I-18 and Table I–19.

Scenario	DO (Ml/d)	WRMP19 DO (Ml/d)	Re-accounted WRMP19 DO (Ml/d)
1 in 100 DYAA DO	183.4	185.1	185.5
1 in 200 DYAA DO	183.2	184.6	185.0
1 in 500 DYAA DO	183.2	184.4	184.8

Table I-18: WRMP24 SWA DYAA DO Figures

I.167 The main change between WRMP19 and WRMP24 for the SWA DYAA DO calculation is a sustainability reduction at Pann Mill, offset by a licence increase at Medmenham. Note that the WRZ DO does not account for the Hawridge sustainability reduction, which is anticipated to be made before the end of AMP7.

Scenario	DO (Ml/d)	WRMP19 DO (Ml/d)	Re-accounted WRMP19 DO (Ml/d)
1 in 100 DYCP DO	199.7	214.4	215.1
1 in 200 DYCP DO	199.7	213.9	214.6
1 in 500 DYCP DO	199.7	213.7	214.4

Table I–19: WRMP24 SWA DYCP DO Figures

I.168 The main changes between WRMP19 and WRMP24 for the SWA DYCP DO are SDO reductions. Again, the WRMP24 WRZ DO does not account for the Hawridge sustainability reduction.

Kennet Valley WRZ

I.169 DO values initially calculated for the Kennet Valley WRZ for the WRMP24 are presented in Table I-20 and Table I-21.

Scenario	DO (Ml/d)	WRMP19 DO (Ml/d)	Re-accounted WRMP19 DO (Ml/d)
1 in 100 DYAA DO	150.6	143.9	144.1
1 in 200 DYAA DO	150.0	141.1	141.3
1 in 500 DYAA DO	150.0	139.8	140.0

Table I-20: WRMP24 Kennet Valley DYAA DO Figures

Scenario	DO (Ml/d)	WRMP19 DO (Ml/d)	Re-accounted WRMP19 DO (Ml/d)
1 in 100 DYCP DO	150.8	155.4	155.6
1 in 200 DYCP DO	150.6	152.0	152.2
1 in 500 DYCP DO	150.1	141.1	141.3

Table I-21: WRMP24 Kennet Valley DYCP DO Figures

I.170 Between WRMP19 and WRMP24 changes had been made to underlying SDOs which should have reduced the DYCP DO by around 5Ml/d and decreased the DYAA DO by around 1Ml/d. The DYAA DO was somewhat higher than anticipated, and it was also noted that there was little difference between 1:100 and 1:500 DO despite a known vulnerability of the River Kennet. As such, additional investigation was undertaken into Kennet Valley's DO.

dWRMP – Additional Modelling Undertaken – Flow in the Kennet

I.171 The river flow available for abstraction at Fobney is calculated using the following approach:

- Determination of flow in the Kennet at Theale, in the absence of the augmentation via the EA's West Berkshire Groundwater Scheme (WBGWS)
- Determination of flow benefits in the Kennet at Theale from WBGWS
- Translation of total flow in the Kennet at Theale into an abstractable rate at Fobney, taking into account the flow control structures which divert flow from the Kennet into the Holy Brook between Theale and Fobney

I.172 The hydrological models used produce a lowest flow in the Kennet at Theale during 1976, excluding augmentation from WBGWS. This modelled lowest flow is around 180 Ml/d, whereas the recorded lowest flow during 1976 was around 80 Ml/d, excluding any flow benefits from WBGWS. As such, it appears that the hydrological model may be significantly overestimating extreme low flows and, as a result, this investigation focusses mainly on the prediction of flows in the Kennet at Theale In absence of augmentation from WBGWS, and is split into several parts:

- Investigation into the validity of the gauged record for the Kennet at Theale during 1976
- Investigation into other hydrological models
- Investigation into statistical amendments to modelled flows

I.173 The conclusions from the investigation into the validity of the gauged record at Theale were:

- The recession in the Kennet at Theale does not appear to be materially different to recessions in flow and groundwater level in other parts of the Kennet catchment, indicating that the flow record during 1976 is likely to be valid
- There is a potential irregularity in the gauged record at Theale, with a step down seen in the gauged record prior to the period of the very lowest flow, which is not seen elsewhere in the catchment
- There is not sufficient evidence to conclude that the gauged record is incorrect, and so it is considered in our analysis as though it is correct

I.174 The conclusion from the investigation into other hydrological models was that it was not possible to materially improve the low flow calibration of the hydrological model for the Kennet at Theale without negatively impacting the overall calibration. This leads to the position that there is reduced confidence in the use of hydrological model outputs to determine a ‘1:500-year’ low flow. As such, it was determined that statistical amendment of the modelled record would be an alternative, potentially better method to apply for deriving a 1:500-year DO.

I.175 Different bias correction methods were considered. The approach used involved comparing empirical observed and modelled cumulative distribution functions (CDFs) of flows for the Kennet at Theale and ‘mapping’ between quantiles of modelled flow and observed flow. An example of this would be that the lowest observed flow (i.e. Q100) was 79.9 Ml/d and the lowest modelled flow was 184.1 Ml/d, such that when the mapping is applied, if a flow of 184.1 Ml/d is fed in, a flow of 79.9 Ml/d will be the output.

I.176 Figure I-24, Figure I-25, and Figure I-26 show the inputs to this process. These are flow-duration curves (FDC); Figure I-24 is the whole FDC, Figure I-25 is the same on a semi-logarithmic plot with Figure I-26 showing only the low flow end of the FDC. On each figure, the red line is the observed flow, and the blue line is the modelled flow. These demonstrate that the modelled flow matches the observed well across a wide range of flows but performs poorly at very extreme low flows (Q99 and below).

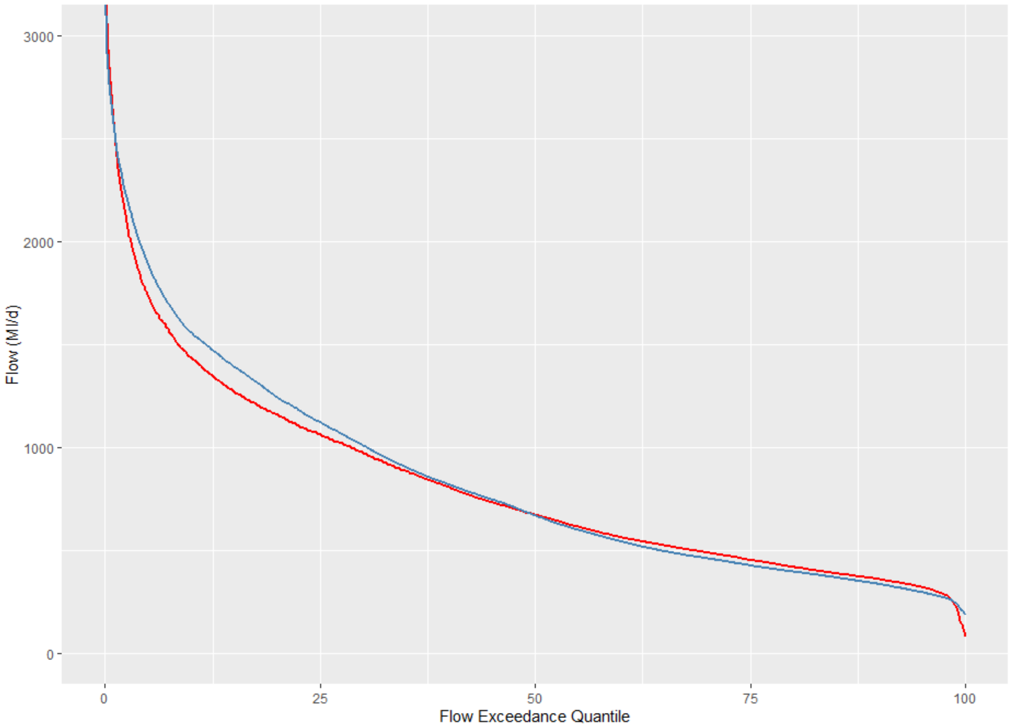


Figure I-24: Flow-Duration Curves for the Historical Observed (red) and Modelled (Blue) Record

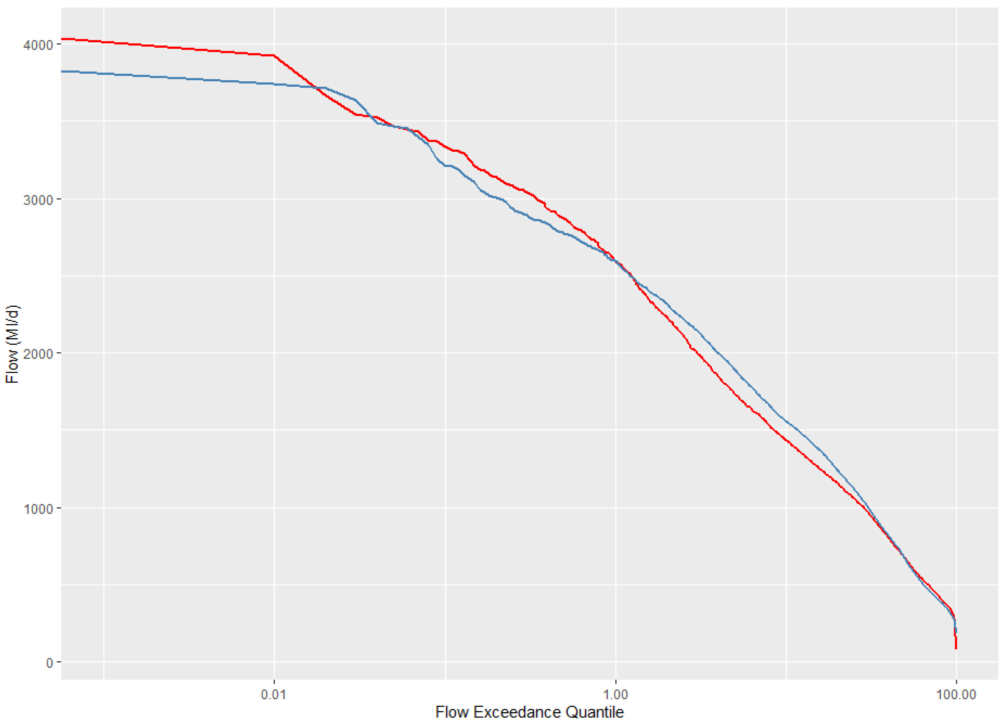


Figure I-25: Flow Duration Curves for the historical observed (red) and modelled (blue) record

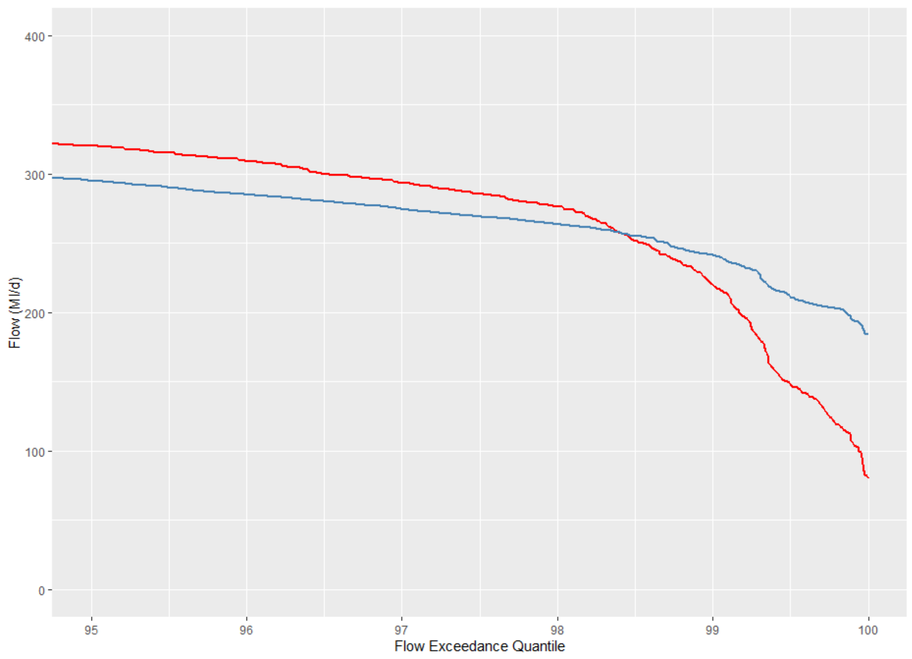


Figure I-26: Flow Duration Curves for the historical observed (red) and modelled (blue) record – low flow focus

I.177 The quantile mapping was determined using a period of common historical observed and modelled records. This period was 1962-1997. Figure I-27 shows that the mapping causes the CDF of the modelled record over the common period to become the same as the CDF of the historical record (i.e. the blue line is used as the input here, and the dotted yellow line is the output; the red line is the historical record).

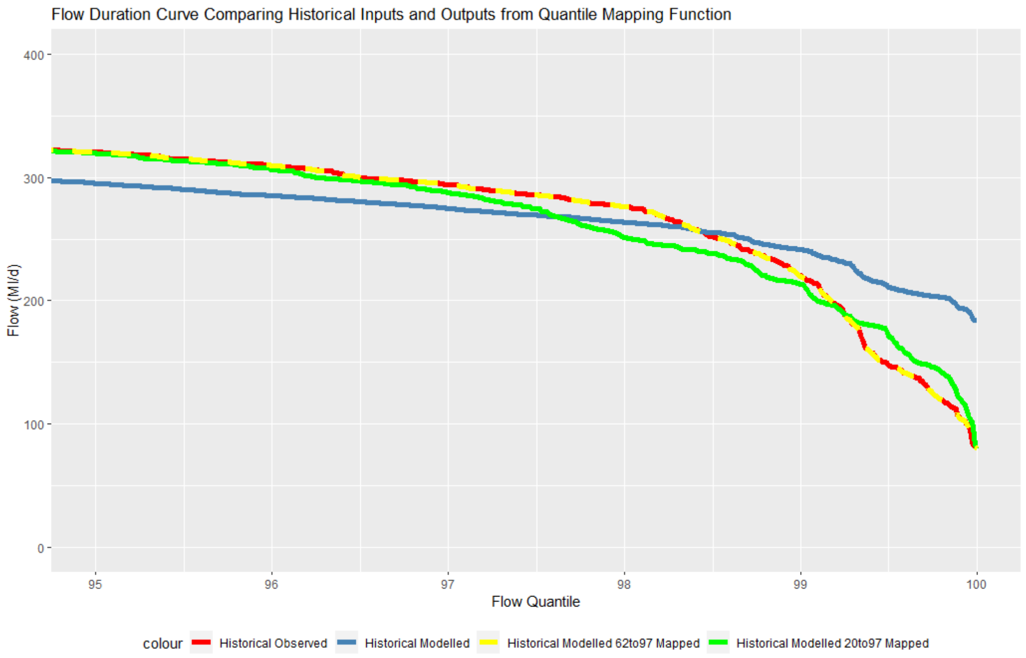


Figure I-27: Flow Duration Curves for the historical observed (red) and historical modelled (blue) record, along with the mapped modelled historical (overlapping reference period, yellow dotted) and mapped modelled historical (non-overlapping reference period, green

I.178 With the focus on extreme low flows, and the goal of establishing a 1:500-year DO, it was important to consider the possibility of flows being input to the quantile mapping algorithm which are lower than the lowest historical modelled flow. It can be seen in Figure I-28 that many of the replicates from the stochastic record contain flows which are lower than the lowest flow in the historical modelled record.

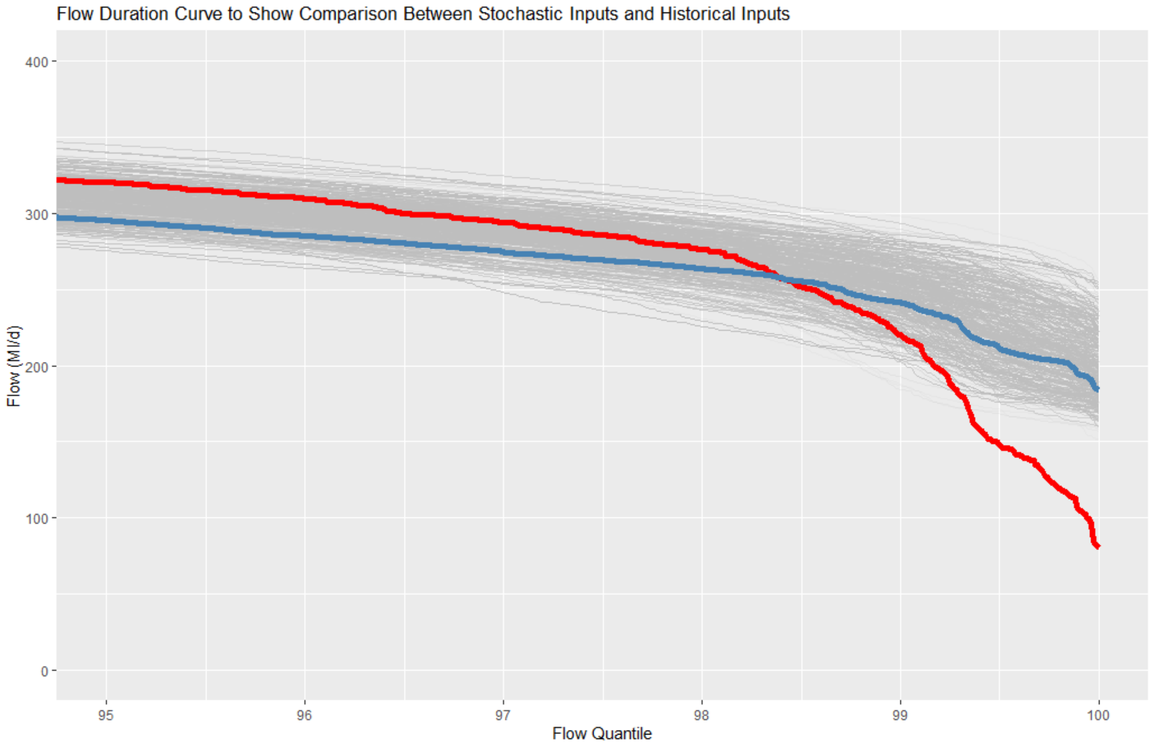


Figure I-28: Flow Duration Curves for the historical observed (red), historical modelled (blue), and stochastic modelled (grey – 400 stochastic replicates)

I.179 Conventional quantile mapping approaches would perhaps assume that flows lower than the lowest modelled historical input would be mapped to the lowest observed historical input, but this would not seem to give a reasonable output. To account for this a simple approach was applied. If the input flow to the mapping was lower than the lowest modelled historical flow, then the input flow was divided by the minimum modelled historical flow and multiplied by the minimum observed historical flow, i.e.

$$If\ Q_{in} < Q_{hist\ min,mod}: \qquad Q_{out} = Q_{hist\ min,obs} \times \frac{Q_{in}}{Q_{hist\ min,mod}}$$

I.180 Figure I-29 shows that, when this mapping is applied, flows lower than the historical observed record are seen in the stochastic outputs, as expected.

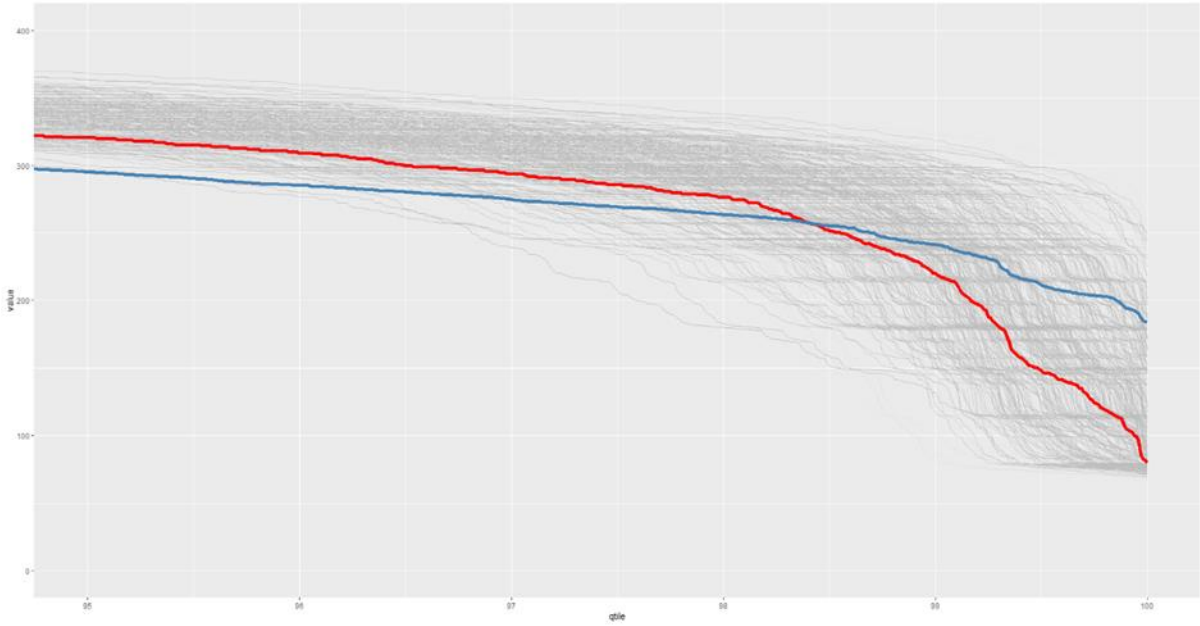


Figure I-29: Flow Duration Curves for the historical observed (red), historical modelled (blue), and mapped stochastic modelled (grey – 400 stochastic replicates) – low flow focus

I.181 These 'mapped stochastic' flows were taken through to determine a 1:500-year DO for Fobney. The amendment to Fobney's DO figures were applied to the Kennet Valley DO figure in the dWRMP.

I.182 As has previously been mentioned, WBGWS is key in the determination of Fobney's DO. WBGWS timeseries were taken from a 'full stochastic' London run with London demand at the 1:500-year DO figure (i.e. WBGWS was assumed to be triggered by London storage, as per our existing drought protocol and the operating agreement in place for WBGWS). WBGWS timeseries were added to the mapped stochastic flows. The relationship between flow at Theale and flow at Fobney, used in existing DO calculations, was then applied to determine the available flow at Fobney. A scenario excluding WBGWS was also used to establish the value of WBGWS to Kennet Valley's DO.

I.183 For each year of the record, the minimum flow arriving at Fobney (4-day rolling minimum, to be consistent with other WRSE methods) was found, while only flows during July and August are considered for the peak DO assessment. Each minimum flow was compared to the licensed maximum and treatment capability to determine a 'yearly yield' figure (i.e. 19,200 years, each with the yearly minimum yield from the source). These are ranked, and the 1:100, 200, 500 DO figures are determined from the ranked yearly yield figures (i.e. the 1:500-year DO figure is the 19,200/500 = 38th lowest yearly yield across the stochastic record). This process was repeated for the 'peak' period (July and August only). The results can be seen in Table I-22 and Table I-23.

	1:100 DO (Ml/d)	1:200 DO (Ml/d)	1:500 DO (Ml/d)
No WBGWS	37.1	18.4	15.6
WBGWS triggered by London Storage	49.0	34.6	18.1

Table I-22: Fobney DYAA DO Values Calculated After the Application of Quantile Mapping Techniques – WRMP24

	1:100 DO (Ml/d)	1:200 DO (Ml/d)	1:500 DO (Ml/d)
No WBGWS	63.1	35.3	18.2
WBGWS triggered by London Storage	63.1	51.6	35.3

Table I-23: Fobney DYCP DO Values Calculated After the Application of Quantile Mapping Techniques – WRMP24

dWRMP24 - Additional Analysis Undertaken – Abstraction from Groundwater Sources

I.184 When the WRSE Pywr model was being used to produce the Kennet Valley WRZ DO, it was noted that the values were somewhat higher than anticipated. On further investigation, it was found that over-aggregation of licence parameters was allowing sources in the Kennet Valley WRZ to effectively over-abstract, inflating the zone's DO. This section includes:

- A description of the issue, including an example
- Methods used to determine the magnitude of the issue
- Amendments made to the Kennet Valley WRZ DO

I.185 The issue is best explained using an example. In the water resource system below, there are two sources, source A and source B. Source A is a source with a time-variant maximum possible yield, a peak daily licence, and an average yearly licence, as follows:

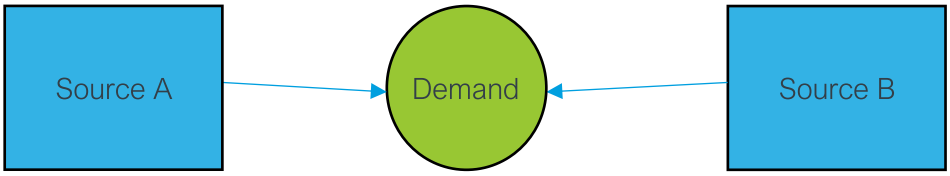


Figure I-30: Example Water Resources System with Two Sources

- Max possible yield during Jan-Jun = 10 Ml/d
- Max possible yield during Jul-Sep = 5 Ml/d
- Max possible yield during Oct-Dec = 10 Ml/d
- Peak licence = 10 Ml/d
- Average licence = 10 Ml/d

I.186 Source B is a source with a yield that is not dependent on weather, a peak daily licence, and an average yearly licence, with details as follows:

- Max possible yield all year round = 25 Ml/d
- Peak licence = 25 Ml/d
- Average licence = 20 Ml/d

I.187 If we aggregate together the average licences and do not apply the average licences to the individual sources, the annual average licence = 30 Ml/d. If this is done and a demand of 30 Ml/d is imposed, a water resources model would be able to do the following:

- Jan – Jun – abstraction at source A of 10 Ml/d, abstraction at source B of 20 Ml/d

- Jul – Sep – abstraction at source A of 5 Ml/d, abstraction at source B of 25 Ml/d
- Oct – Dec – abstraction at source A of 10 Ml/d, abstraction at source B of 20 Ml/d

I.188 In this example, the model would believe that a demand of 30 Ml/d could be satisfied by this water resources system. However, it can be seen that the average abstraction at source B is greater than the annual average licence, which the model has been allowed assume due to the aggregation of licences.

I.189 If the licences were not aggregated in this way and the individual licences were assigned, applying a 30 Ml/d demand would result in the following:

- Jan – Jun – abstraction at source A of 10 Ml/d, abstraction at source B of 20 Ml/d
- Jul – Sep – abstraction at source A of 5 Ml/d, abstraction at source B of 25 Ml/d
- Oct – early-Dec – abstraction at source A of 10 Ml/d, abstraction at source B of 20 Ml/d
- Mid-Dec – end Dec – abstraction at source A of 10 Ml/d, abstraction at source B of 0 Ml/d (run out of licence)

I.190 At some point during early to mid-December, source B would hit its annual licence limit and the model would no longer be able to take water from this source. This would show that a demand of 30 Ml/d could not be supplied throughout the year from these sources. This example shows how over-aggregating licences in a water resource model can over-estimate the supply capability within a WRZ.

I.191 In the example of the Kennet Valley WRZ in the WRSE Pywr model, the Pangbourne source has a time-variant yield; a peak and average licence of 38.6 Ml/d but a daily maximum yield often below 38.6 Ml/d. In addition, there are a number of other sources without time-variant yields in the zone with peak DOs greater than their average annual licence. The annual average licences were aggregated across the zone when the model was built, meaning that during periods of reduced availability of the Pangbourne source other sources in the zone increased their yields above their average licence, without subsequently running out of licence.

I.192 The magnitude of the issue, and so the required correction to dWRMP 24 DO figures generated via the WRSE Pywr model, was calculated using a script which established the over-abstraction that was being allowed by the model. The outputs were:

Scenario	1:100 (Ml/d)	1:200 (Ml/d)	1:500 (Ml/d)
Over-abstraction	2.26	5.01	5.76

Table I-24: Over-abstractions calculated from analysis of Pywr model outputs

rdWRMP4 Kennet Valley DO Assessment

I.193 As described above, in the dWRMP24, post-modelling amendments were made to the Kennet Valley WRZ DO figures for both DYAA and DYCP scenarios. For the rdWRMP24 and final WRMP24, amendments were made to our water resources modelling such that post-modelling amendments were not necessary. These amendments were the inclusion of the ‘quantile mapped’ flows as hydrological inputs used when calculating the Kennet Valley WRZ DO, and amendment to the representation of abstraction licences within the Pywr model to stop the over-abstraction problems noted.

I.194 Revised DO values initially calculated for the Kennet Valley WRZ DO can be found in Table I-25 and Table I-26.

Scenario	DO (Ml/d)	WRMP19 DO (Ml/d)	Re-accounted WRMP19 DO (Ml/d)
1 in 100 DYAA DO	152.7	143.7	153.4
1 in 200 DYAA DO	138.3	140.9	150.8
1 in 500 DYAA DO	116.4	139.6	149.5

Table I-25: WRMP24 Revised Kennet Valley DYAA DO Figures

Scenario	DO (Ml/d)	WRMP19 DO (Ml/d)	Re-accounted WRMP19 DO (Ml/d)
1 in 100 DYCP DO	158.6	155.2	164.8
1 in 200 DYCP DO	156.6	151.8	161.4
1 in 500 DYCP DO	140.4	140.9	150.5

Table I-26: WRMP24 Revised Kennet Valley DYCP DO Figures

I.195 From these results it can be seen that 1:200-year and 1:500-year DO estimates have decreased significantly for Kennet Valley – this is due to the work undertaken to establish what a '1 in 500-year' flow series for the River Kennet at Theale may be.

Guildford WRZ

I.196 DO figures calculated for the Guildford WRZ can be seen in Table I-27 and Table I-28.

Scenario	DO (Ml/d)	WRMP19 DO (Ml/d)	Re-accounted WRMP19 DO (Ml/d)
1 in 100 DYAA DO	68.87	65.82	69.02
1 in 200 DYAA DO	68.87	65.82	69.02
1 in 500 DYAA DO	68.87	65.82	69.02

Table I-27: WRMP24 Guildford DYAA DO Figures

Scenario	DO (Ml/d)	WRMP19 DO (Ml/d)	Re-accounted WRMP19 DO (Ml/d)
1 in 100 DYCP DO	74.28	71.7	74.9
1 in 200 DYCP DO	74.28	71.7	74.9
1 in 500 DYCP DO	74.28	71.7	74.9

Table I-28: WRMP24 Guildford DYCP DO Figures

I.197 There are minimal changes in the Guildford DO calculations or inputs.

Henley WRZ

I.198 DO figures calculated for the Henley WRZ can be seen in Table I-29 and Table I-30.

Scenario	DO (Ml/d)	WRMP19 DO (Ml/d)	Re-accounted WRMP19 DO (Ml/d)
1 in 100 DYAA DO	21.55	25.65	25.65
1 in 200 DYAA DO	21.55	25.65	25.65
1 in 500 DYAA DO	21.55	25.65	25.65

Table I-29: WRMP24 Henley DYAA DO Figures

Scenario	DO (Ml/d)	WRMP19 DO (Ml/d)	Re-accounted WRMP19 DO (Ml/d)
1 in 100 DYCP DO	21.7	25.9	25.9
1 in 200 DYCP DO	21.7	25.9	25.9
1 in 500 DYCP DO	21.7	25.9	25.9

Table I-30: WRMP24 Henley DYCP DO Figures

I.199 The only change in the Henley DO calculation is an amendment to an SDO to account for a long-term outage.

Annex: Calibration of WARMS2

I.200 The following Figures show the hydrological validation summary of the WARMS2 Water Resources Model. The validation exercise was carried out in 2015 and used a period of 2005-2010 to compare WARMS2 modelled flows with observed flows. This period was selected recognising that inclusion of a drought event in the validation period is necessary, but also recognising that the large denaturalising influences in the Thames catchment (which change according to abstractions and discharges) mean relatively recent events should be used.

I.201 The Figures demonstrate that the hydrological models in WARMS2 are well calibrated, with NSE and log-NSE values above 0.9 at the most salient gauging locations, and thus the flows from WARMS2 are suitable as the basis for further modelling.

River Thames at Farmoor - Calibration Report

Model Run Details: With NEFF, AR12 data, v23c, Mole Update, 24/07/2015

Statistics	Calibration (Observed)	Description
NSE	0.93	Nash-Sutcliffe Efficiency
Log NSE	0.96	Log_N Nash-Sutcliffe Efficiency
Correlation	0.97	Pearson's product-moment correlation coefficient (r)
Log Correlation	0.98	Log_N Pearson's product-moment correlation coefficient (r)
Volume Error	1.04	Modelled volume / Observed volume
RMSE	322.35	Root mean square error
RMSE Q50-Q95	122.62	Root mean square error for data between Q50 and Q95
Mean Flow	1446 (1385)	Mean flow
Q50	964 (976)	Flow exceeds this value 50% of the time
Q95	257 (251)	Flow exceeds this value 95% of the time

Contributing Rainfall-Runoff Models

Aquator Aquifer Unit		Time Series Assigned
Component	**Label**	**Rainfall and Evaporation**
TA31	A1 U. Thames	Cotswolds West (6010)
TA32	A2 Churn	Cotswolds West (6010)
TA33	A3 Ampney	Cotswolds West (6010)
TA34	A4 Coln	Cotswolds West (6010)
TA2	A5 Leach	Cotswolds West (6010)
TA3	A6 Windrush	Cotswolds West (6010)

Catchment Area

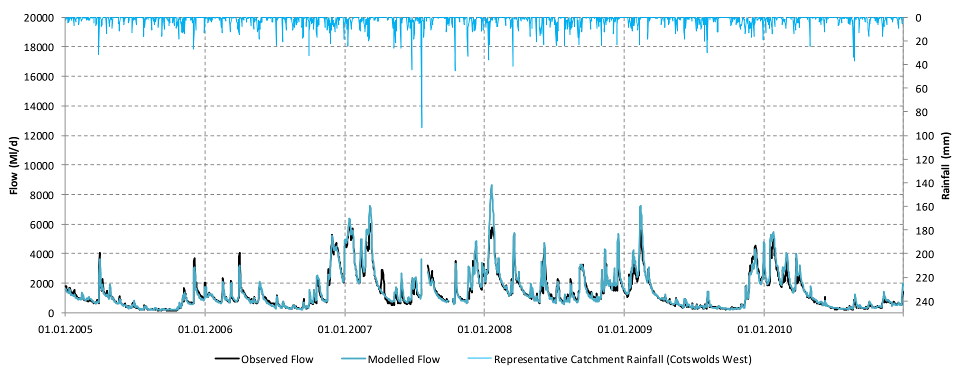
Grid Ref: SP4380006800

Area: 1600 km^2

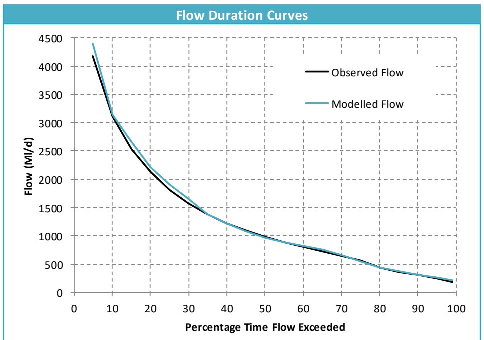
Station Ref No: 39129

Note

Calibration Flow Hydrograph



Flow Duration Curves



Flow Duration Curves Q50 to Q95

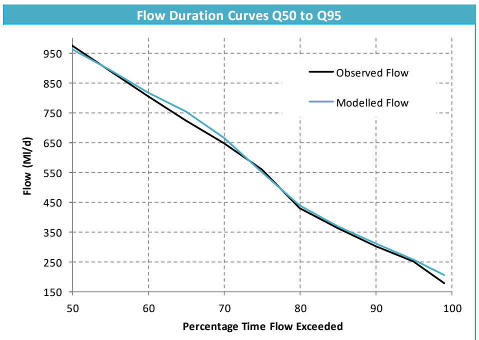


Figure I - 31: WARMS2 Validation Summary – Thames at Farmoor

River Thames at Day's Weir - Calibration Report

Model Run Details: With NEFF, AR12 data, v23c, Mole Update, 24/07/2015

Statistics	Calibration (Observed)	Description
NSE	0.99	Nash-Sutcliffe Efficiency
Log NSE	0.99	Log_N Nash-Sutcliffe Efficiency
Correlation	1.00	Pearson's product-moment correlation coefficient (r)
Log Correlation	1.00	Log_N Pearson's product-moment correlation coefficient (r)
Volume Error	1.01	Modelled volume / Observed volume
RMSE	258.30	Root mean square error
RMSE Q50-Q95	88.99	Root mean square error for data between Q50 and Q95
Mean Flow	2657 (2641)	Mean flow
Q50	1682 (1624)	Flow exceeds this value 50% of the time
Q95	422 (374)	Flow exceeds this value 95% of the time

Contributing Rainfall-Runoff Models

Aquator Aquifer Unit		Time Series Assigned
Component	Label	Rainfall and Evaporation
TA31	A1 U. Thames	Cotswolds West (6010)
TA32	A2 Churn	Cotswolds West (6010)
TA33	A3 Ampney	Cotswolds West (6010)
TA34	A4 Coln	Cotswolds West (6010)
TA2	A5 Leach	Cotswolds West (6010)
TA3	A6 Windrush	Cotswolds West (6010)
TA4	B1 Evenlode	Cotswolds East (6020)
TA6	G3 Ock	Berkshire Downs (6070)
TA7	G4 Ginge	Berkshire Downs (6070)

Catchment Area

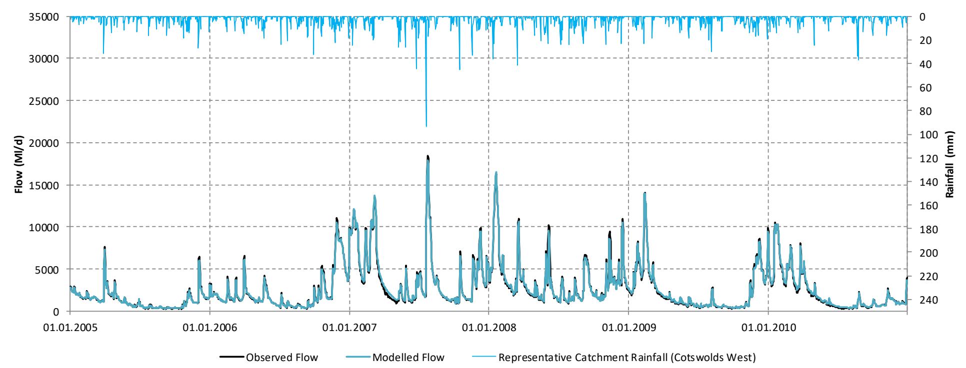
Grid Ref: SU5690093600 Area: 3445 km^2

Station Ref No: 39002

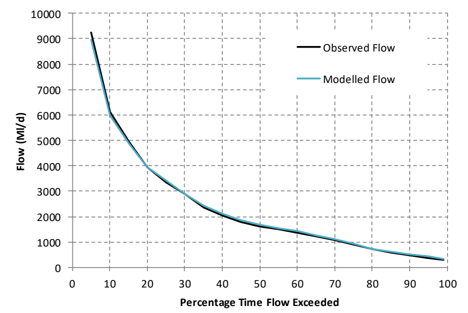
Note

The rainfall-runoff models listed above all contribute to the total flow at Day's Weir. Cotswolds West rainfall has been selected as most representative of the catchment and is used in the graph below.

Calibration Flow Hydrograph



Flow Duration Curves



Flow Duration Curves Q50 to Q95

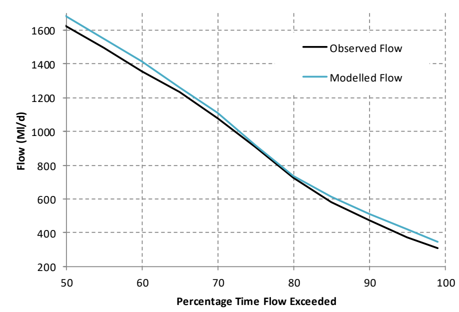


Figure I - 32: WARMS2 Validation Summary – Thames at Days Weir

River Thames at Reading - Calibration Report

Model Run Details: With NEFF, AR12 data, v23c, Mole Update, 24/07/2015

Statistics	Calibration (Observed)	Description
NSE	0.98	Nash-Sutcliffe Efficiency
Log NSE	0.99	Log_N Nash-Sutcliffe Efficiency
Correlation	0.99	Pearson's product-moment correlation coefficient (r)
Log Correlation	0.99	Log_N Pearson's product-moment correlation coefficient (r)
Volume Error	1.01	Modelled volume / Observed volume
RMSE	465.61	Root mean square error
RMSE Q50-Q95	135.43	Root mean square error for data between Q50 and Q95
Mean Flow	3215 (3197)	Mean flow
Q50	2052 (2039)	Flow exceeds this value 50% of the time
Q95	516 (482)	Flow exceeds this value 95% of the time

Contributing Rainfall-Runoff Models

Aquator Aquifer Unit		Time Series Assigned
Component	**Label**	**Rainfall and Evaporation**
TA31	A1 U. Thames	Cotswolds West (6010)
TA32	A2 Churn	Cotswolds West (6010)
TA33	A3 Ampney	Cotswolds West (6010)
TA34	A4 Coln	Cotswolds West (6010)
TA2	A5 Leach	Cotswolds West (6010)
TA3	A6 Windrush	Cotswolds West (6010)
TA4	B1 Evenlode	Cotswolds East (6020)
TA6	G3 Ock	Berkshire Downs (6070)
TA7	G4 Ginge	Berkshire Downs (6070)
TA5	N3 Thame	Chilterns East - Colne (6140)
TA8	G8 Mill	Berkshire Downs (6070)
TA30	G7 Pang	Berkshire Downs (6070)

Catchment Area

Grid Ref: SU7180074100

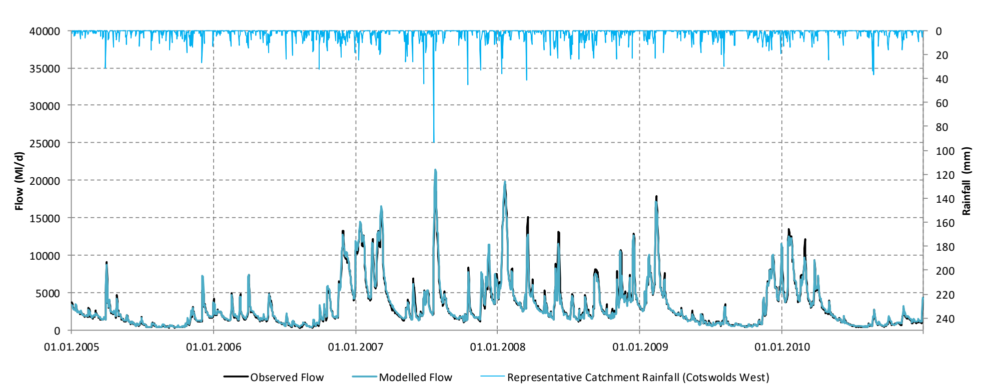
Area: 4640 km^2

Station Ref No: 39130

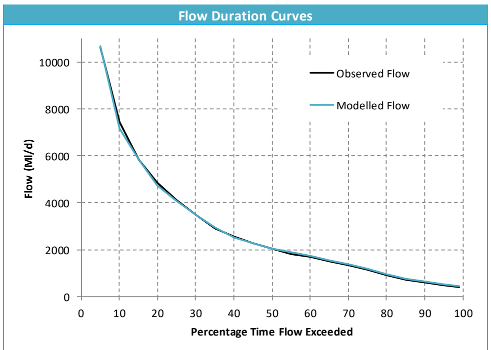
Note

The rainfall-runoff models listed above all contribute to the total flow at Reading. Cotswolds West rainfall has been selected as most representative of the catchment and is used in the graph below.

Calibration Flow Hydrograph



Flow Duration Curves



Flow Duration Curves Q50 to Q95

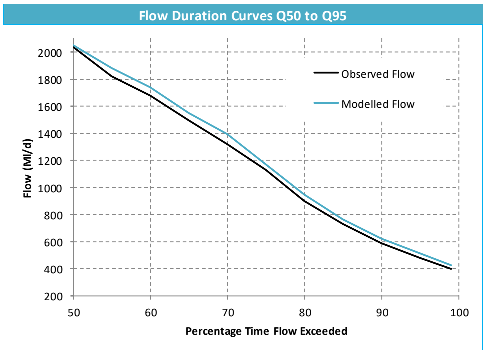


Figure I - 33: WARMS2 Validation Summary – Thames at Reading

River Thames at Windsor - Calibration Report

Model Run Details: With NEFF, AR12 data, v23c, Mole Update, 24/07/2015

Statistics	Calibration (Observed)	Description
NSE	0.98	Nash-Sutcliffe Efficiency
Log NSE	0.98	Log_N Nash-Sutcliffe Efficiency
Correlation	0.99	Pearson's product-moment correlation coefficient (r)
Log Correlation	0.99	Log_N Pearson's product-moment correlation coefficient (r)
Volume Error	1.01	Modelled volume / Observed volume
RMSE	622.72	Root mean square error
RMSE Q50-Q95	241.70	Root mean square error for data between Q50 and Q95
Mean Flow	5184 (5113)	Mean flow
Q50	3542 (3586)	Flow exceeds this value 50% of the time
Q95	1196 (1210)	Flow exceeds this value 95% of the time

Catchment Area

Grid Ref: SU9800077200 Area: 7100 km^2

Station Ref No: 39072

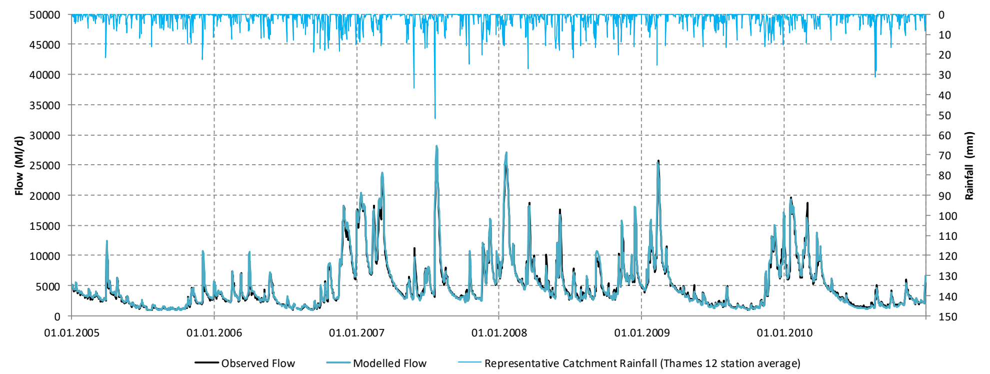
Contributing Rainfall-Runoff Models

Aquator Aquifer Unit		Time Series Assigned
Component	**Label**	**Rainfall and Evaporation**
TA31	A1 U. Thames	Cotswolds West (6010)
TA32	A2 Churn	Cotswolds West (6010)
TA33	A3 Ampney	Cotswolds West (6010)
TA34	A4 Coln	Cotswolds West (6010)
TA2	A5 Leach	Cotswolds West (6010)
TA3	A6 Windrush	Cotswolds West (6010)
TA4	B1 Evenlode	Cotswolds East (6020)
TA6	G3 Ock	Berkshire Downs (6070)
TA7	G4 Ginge	Berkshire Downs (6070)
TA5	N3 Thame	Chilterns East - Colne (6140)
TA8	G8 Mill	Berkshire Downs (6070)
TA30	G7 Pang	Berkshire Downs (6070)
TA1	G1 U. Kennet	Berkshire Downs (6070)
TA12	G5 Knighton	Berkshire Downs (6070)
TA23	G2 Lambourn	Berkshire Downs (6070)
TA29	G6 Enborne	Berkshire Downs (6070)
TA14	P1 Upper Loddon	North Downs - Hampshire (6162)
TA15	P2 Blackwater	North Downs - Hampshire (6162)
TA13	M1 Thames direct (Nth - Henley)	Chilterns West (6130)
TA10	M3 Thames direct (Sth - Henley)	Chilterns West (6130)
TA9	M2 Wye	Chilterns West (6130)

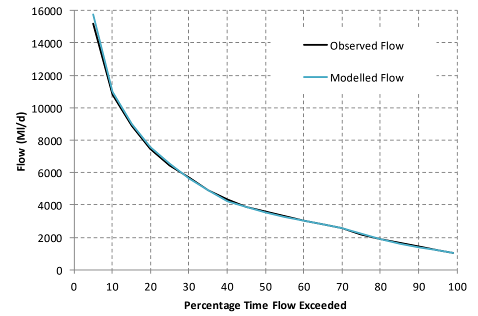
Note

The rainfall-runoff models listed above all contribute to the total flow at Windsor. The rainfall shown on the graph below is the average of 12 stations located across the Thames region.

Calibration Flow Hydrograph



Flow Duration Curves



Flow Duration Curves Q50 to Q95

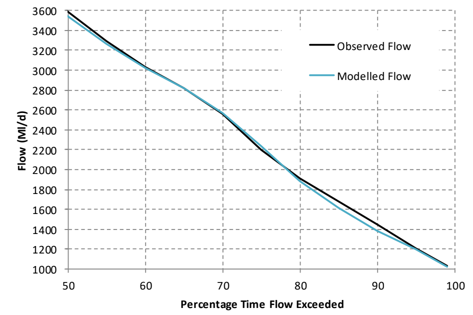


Figure I - 34: WARMS2 Validation Summary – Thames at Windsor

River Colne at Denham - Calibration Report

Model Run Details: With NEFF, AR12 data, v23c, Mole Update, 24/07/2015

Statistics	Calibration (Observed)	Description
NSE	0.69	Nash-Sutcliffe Efficiency
Log NSE	0.81	Log_N Nash-Sutcliffe Efficiency
Correlation	0.85	Pearson's product-moment correlation coefficient (r)
Log Correlation	0.91	Log_N Pearson's product-moment correlation coefficient (r)
Volume Error	1.01	Modelled volume / Observed volume
RMSE	90.40	Root mean square error
RMSE Q50-Q95	44.49	Root mean square error for data between Q50 and Q95
Mean Flow	345 (341)	Mean flow
Q50	300 (316)	Flow exceeds this value 50% of the time
Q95	142 (145)	Flow exceeds this value 95% of the time

Contributing Rainfall-Runoff Models

Aquator Aquifer Unit		Time Series Assigned
Component	Label	Rainfall and Evaporation
TA26	N2 Colne	Chilterns East - Colne (6140)

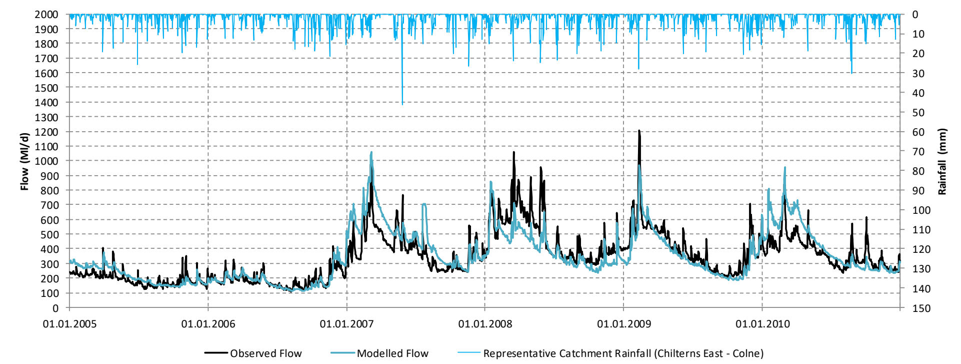
Catchment Area

Grid Ref: TQ0520086300 Area: 743 km^2

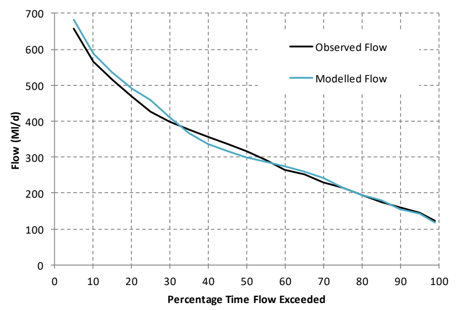
Station Ref No: 39010

Note

Calibration Flow Hydrograph



Flow Duration Curves



Flow Duration Curves Q50 to Q95

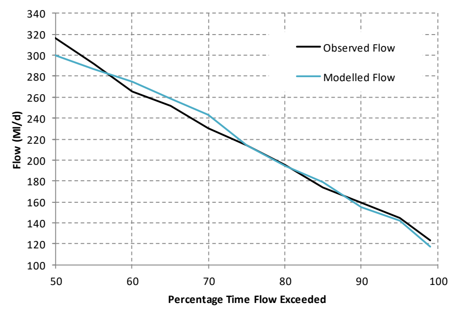


Figure I - 35: WARMS2 Validation Summary – Colne at Denham

River Misbourne at Denham Lodge - Calibration Report

Model Run Details: With NEFF, AR12 data, v23c, Mole Update, 24/07/2015

Statistics	Calibration (Observed)	Description
NSE	-1.81	Nash-Sutcliffe Efficiency
Log NSE	0.26	Log_N Nash-Sutcliffe Efficiency
Correlation	0.68	Pearson's product-moment correlation coefficient (r)
Log Correlation	0.83	Log_N Pearson's product-moment correlation coefficient (r)
Volume Error	1.46	Modelled volume / Observed volume
RMSE	13.95	Root mean square error
RMSE Q50-Q95	8.36	Root mean square error for data between Q50 and Q95
Mean Flow	25 (17)	Mean flow
Q50	21 (16)	Flow exceeds this value 50% of the time
Q95	4 (4)	Flow exceeds this value 95% of the time

Contributing Rainfall-Runoff Models

Aquator Aquifer Unit		Time Series Assigned
Component	Label	Rainfall and Evaporation
TA11	N1 Misbourne & Alderbourne	Chilterns East - Colne (6140)

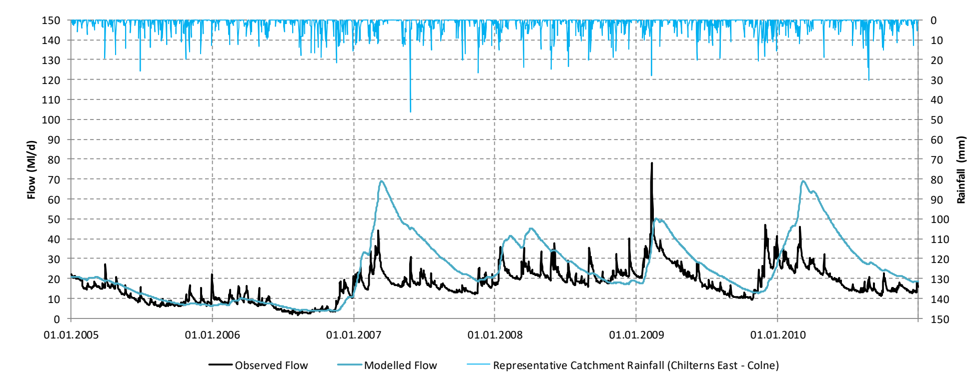
Catchment Area

Grid Ref: TQ0470086400 Area: 95 km^2

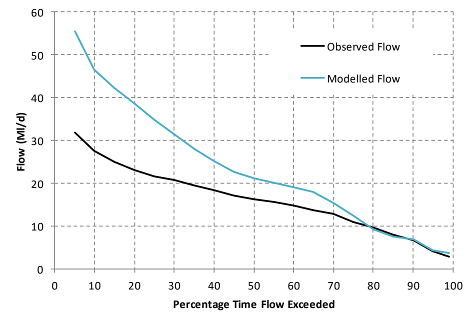
Station Ref No: 39102

Note

Calibration Flow Hydrograph



Flow Duration Curves



Flow Duration Curves Q50 to Q95

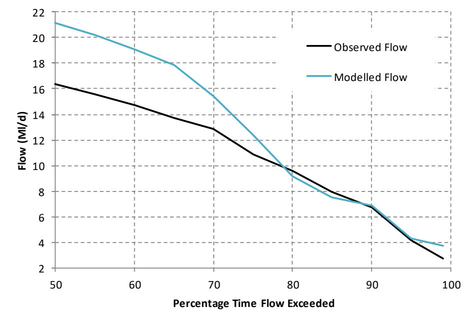


Figure I - 36: WARMS2 Validation Summary – Misbourne at Denham Lodge

River Wey at Tilford - Calibration Report

Model Run Details: With NEFF, AR12 data, v23c, Mole Update, 24/07/2015

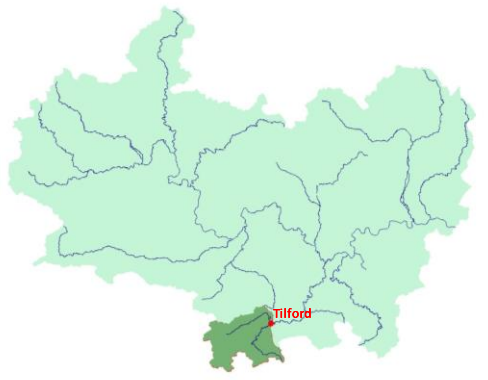
Statistics	Calibration (Observed)	Description
NSE	0.62	Nash-Sutcliffe Efficiency
Log NSE	0.77	Log_N Nash-Sutcliffe Efficiency
Correlation	0.79	Pearson's product-moment correlation coefficient (r)
Log Correlation	0.90	Log_N Pearson's product-moment correlation coefficient (r)
Volume Error	1.03	Modelled volume / Observed volume
RMSE	131.06	Root mean square error
RMSE Q50-Q95	32.48	Root mean square error for data between Q50 and Q95
Mean Flow	265 (257)	Mean flow
Q50	202 (194)	Flow exceeds this value 50% of the time
Q95	107 (112)	Flow exceeds this value 95% of the time

Contributing Rainfall-Runoff Models

Aquator Aquifer Unit		Time Series Assigned
Component	Label	Rainfall and Evaporation
TA16	S1 Wey	Wey Greensand (6190)

Catchment Area

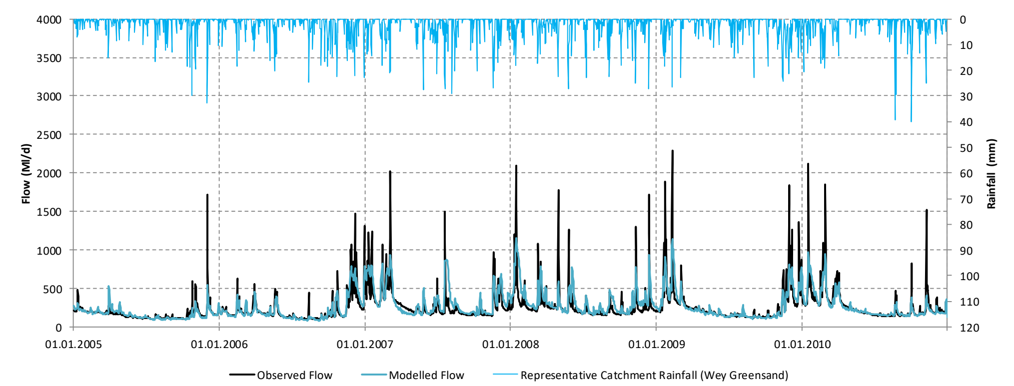
Grid Ref: SU8740043200 Area: 396 km^2



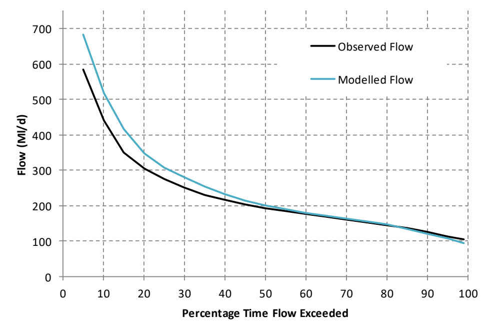
Station Ref No: 39011

Note

Calibration Flow Hydrograph



Flow Duration Curves



Flow Duration Curves Q50 to Q95

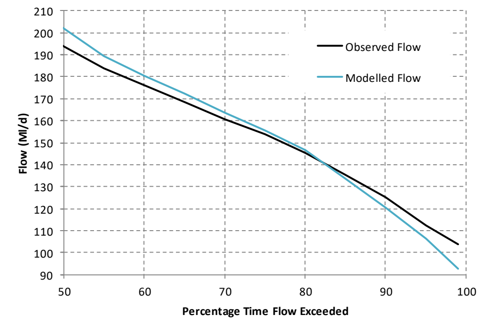


Figure I - 37: WARMS2 Validation Summary – Wey at Tilford

River Tillingbourne at Shalford - Calibration Report

Model Run Details: With NEFF, AR12 data, v23c, Mole Update, 24/07/2015

Statistics	Calibration (Observed)	Description
NSE	0.41	Nash-Sutcliffe Efficiency
Log NSE	0.40	Log_N Nash-Sutcliffe Efficiency
Correlation	0.77	Pearson's product-moment correlation coefficient (r)
Log Correlation	0.82	Log_N Pearson's product-moment correlation coefficient (r)
Volume Error	1.15	Modelled volume / Observed volume
RMSE	12.82	Root mean square error
RMSE Q50-Q95	8.96	Root mean square error for data between Q50 and Q95
Mean Flow	48 (41)	Mean flow
Q50	46 (37)	Flow exceeds this value 50% of the time
Q95	26 (26)	Flow exceeds this value 95% of the time

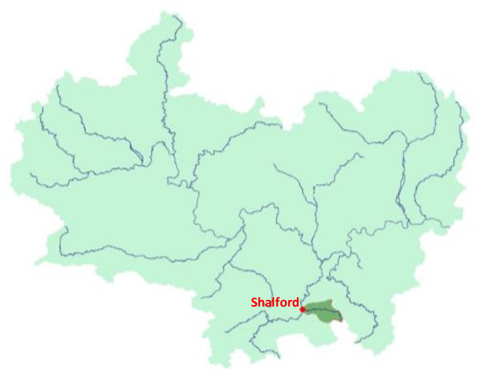
Contributing Rainfall-Runoff Models

Aquator Aquifer Unit		Time Series Assigned
Component	Label	Rainfall and Evaporation
TA17	V1 Tillingbourne	Wey Greensand (6190)

Catchment Area

Grid Ref: TQ0000047700

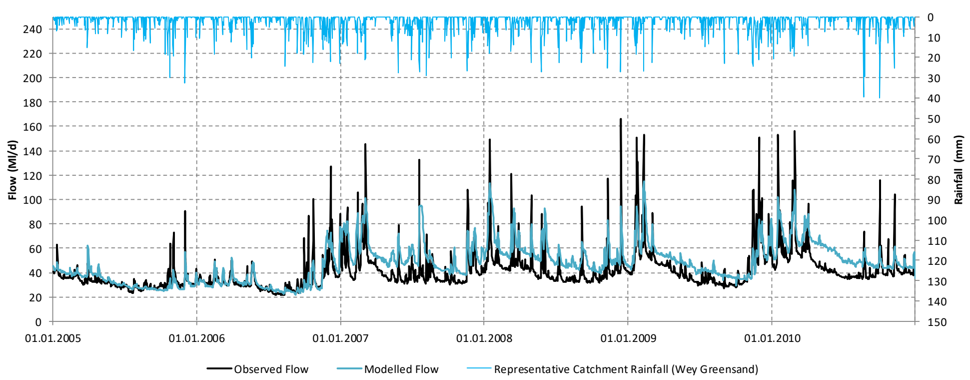
Area: 59 km²



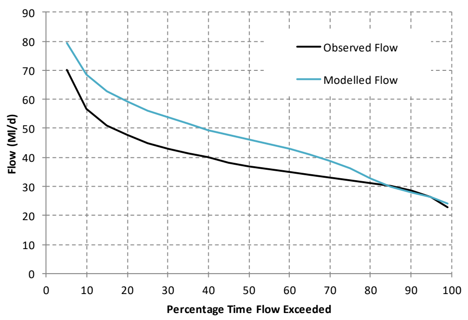
Station Ref No: 39029

Note

Calibration Flow Hydrograph



Flow Duration Curves



Flow Duration Curves Q50 to Q95

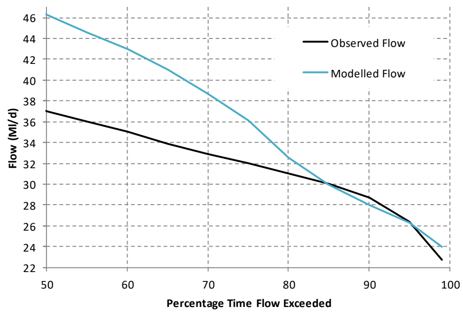


Figure I - 38: WARMS2 Validation Summary – Tillingbourne at Shalford

River Wey at Guildford - Calibration Report

Model Run Details: With NEFF, AR12 data, v23c, Mole Update, 24/07/2015

Statistics	Calibration (Observed)	Description
NSE	0.63	Nash-Sutcliffe Efficiency
Log NSE	0.79	Log_N Nash-Sutcliffe Efficiency
Correlation	0.82	Pearson's product-moment correlation coefficient (r)
Log Correlation	0.89	Log_N Pearson's product-moment correlation coefficient (r)
Volume Error	0.93	Modelled volume / Observed volume
RMSE	276.56	Root mean square error
RMSE Q50-Q95	65.87	Root mean square error for data between Q50 and Q95
Mean Flow	474 (510)	Mean flow
Q50	371 (362)	Flow exceeds this value 50% of the time
Q95	198 (200)	Flow exceeds this value 95% of the time

Contributing Rainfall-Runoff Models

Aquator Aquifer Unit		Time Series Assigned
Component	**Label**	**Rainfall and Evaporation**
TA16	S1 Wey	Wey Greensand (6190)
TA18	S2 Wey Inflow	Wey Greensand (6190)
TA17	V1 Tillingbourne	Wey Greensand (6190)

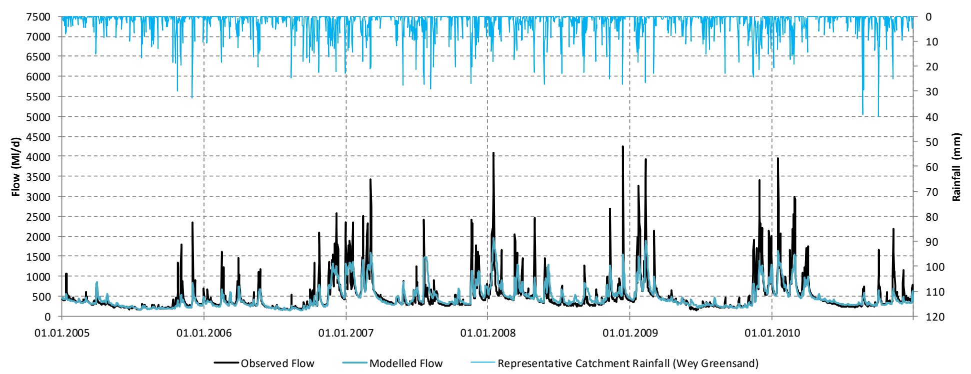
Catchment Area

Grid Ref: SU9940049500 Area: 690 km^2

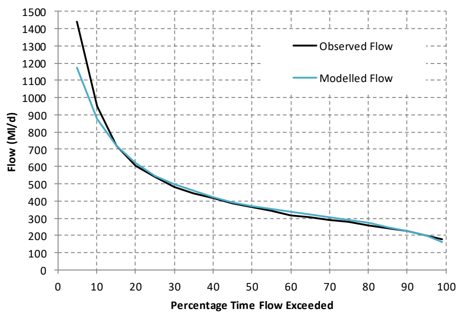
Station Ref No: 39141

Note

Calibration Flow Hydrograph



Flow Duration Curves



Flow Duration Curves Q50 to Q95

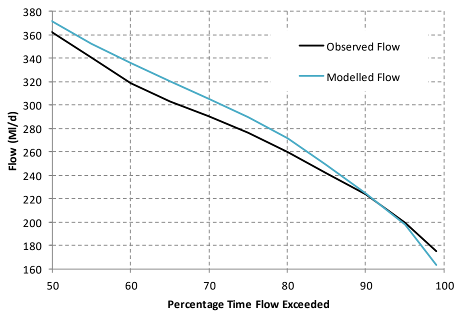


Figure I - 39: WARMS2 Validation Summary – Wey at Guildford

River Mole at Esher - Calibration Report

Model Run Details: With NEFF, AR12 data, v23c, Mole Update, 24/07/2015

Statistics	Calibration (Observed)	Description
NSE	0.49	Nash-Sutcliffe Efficiency
Log NSE	0.69	Log_N Nash-Sutcliffe Efficiency
Correlation	0.71	Pearson's product-moment correlation coefficient (r)
Log Correlation	0.84	Log_N Pearson's product-moment correlation coefficient (r)
Volume Error	0.88	Modelled volume / Observed volume
RMSE	401.29	Root mean square error
RMSE Q50-Q95	119.07	Root mean square error for data between Q50 and Q95
Mean Flow	407 (465)	Mean flow
Q50	257 (284)	Flow exceeds this value 50% of the time
Q95	127 (124)	Flow exceeds this value 95% of the time

Contributing Rainfall-Runoff Models

Component	Aquator Aquifer Unit Label	Time Series Assigned Rainfall and Evaporation
TA22	Y1 Mole LGS	North Downs - South London (6230)
TA21	T2 Mole Chalk	Wey Greensand (6190)
TW1	Mole u/s T2	North Downs - South London (6230)

Catchment Area

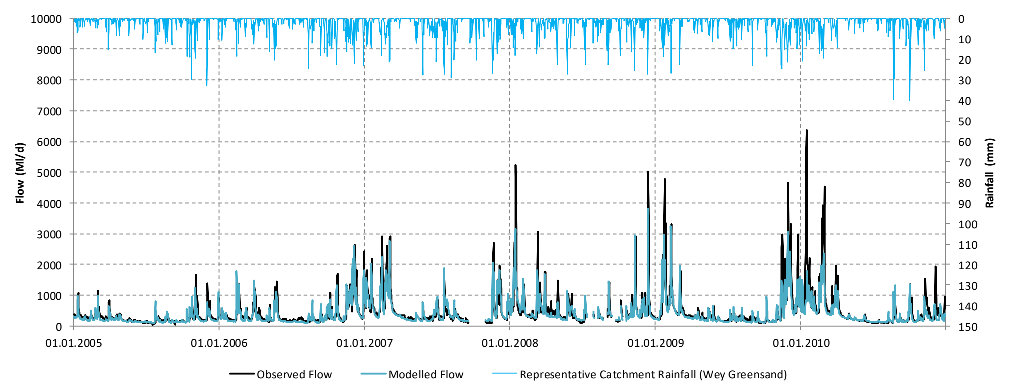
Grid Ref: TQ1300065300 Area: 465 km^2

Station Ref No: 39104

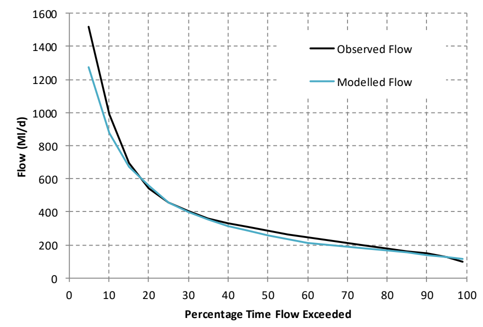
Note

The rainfall-runoff models listed above all contribute to the total flow at Esher. The representative rainfall chosen for presentation on the graph below is for the Wey Greensand rainfall area.

Calibration Flow Hydrograph



Flow Duration Curves



Flow Duration Curves Q50 to Q95

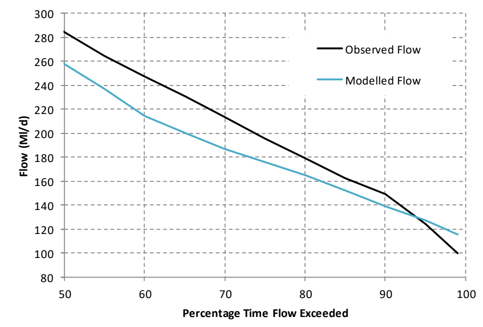


Figure I - 40: WARMS2 Validation Summary – Mole at Esher

River Hogsmill at Kingston - Calibration Report

Model Run Details: With NEFF, AR12 data, v23c, Mole Update, 24/07/2015

Statistics	Calibration (Observed)	Description
NSE	0.58	Nash-Sutcliffe Efficiency
Log NSE	0.54	Log_N Nash-Sutcliffe Efficiency
Correlation	0.77	Pearson's product-moment correlation coefficient (r)
Log Correlation	0.76	Log_N Pearson's product-moment correlation coefficient (r)
Volume Error	0.97	Modelled volume / Observed volume
RMSE	37.16	Root mean square error
RMSE Q50-Q95	14.79	Root mean square error for data between Q50 and Q95
Mean Flow	103 (106)	Mean flow
Q50	90 (89)	Flow exceeds this value 50% of the time
Q95	65 (65)	Flow exceeds this value 95% of the time

Contributing Rainfall-Runoff Models

Aquator Aquifer Unit		Time Series Assigned
Component	**Label**	**Rainfall and Evaporation**
TW2	Hogsmill	North Downs - South London (6230)

Catchment Area

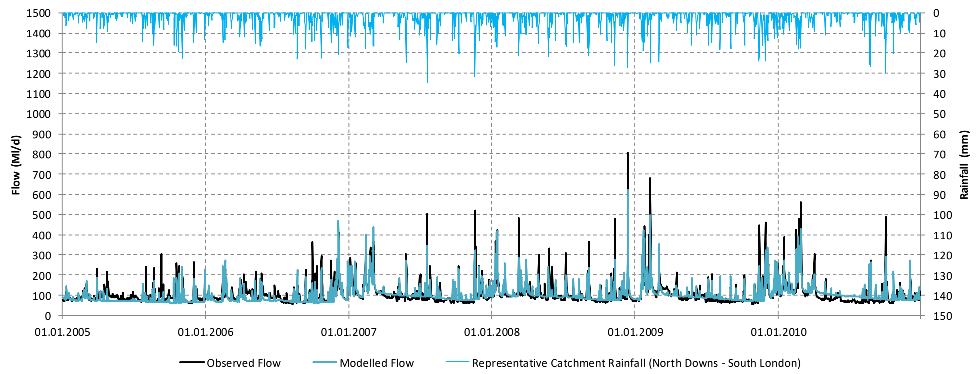
Grid Ref: TQ1820068700

Area: 69 km^2

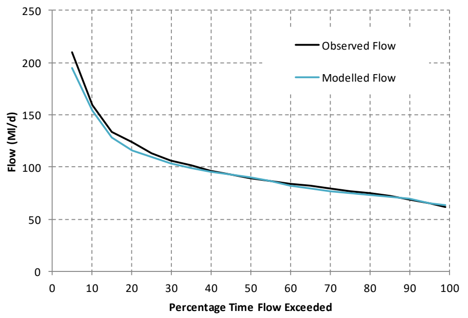
Station Ref No: 39012

Note

Calibration Flow Hydrograph



Flow Duration Curves



Flow Duration Curves Q50 to Q95

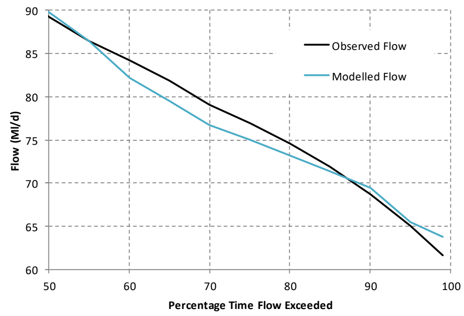


Figure I - 41: WARMS2 Validation Summary – Hogsmill at Kingston

River Thames at Teddington - Calibration Report

Model Run Details: With NEFF, AR12 data, v23c, Mole Update, 24/07/2015

Statistics	Calibration (Observed)	Description
NSE	0.97	Nash-Sutcliffe Efficiency
Log NSE	0.98	Log_N Nash-Sutcliffe Efficiency
Correlation	0.99	Pearson's product-moment correlation coefficient (r)
Log Correlation	0.99	Log_N Pearson's product-moment correlation coefficient (r)
Volume Error	1.03	Modelled volume / Observed volume
RMSE	1009.03	Root mean square error
RMSE Q50-Q95	348.74	Root mean square error for data between Q50 and Q95
Mean Flow	7344 (7097)	Mean flow
Q50	5180 (5061)	Flow exceeds this value 50% of the time
Q95	2064 (2049)	Flow exceeds this value 95% of the time

Catchment Area

Grid Ref: TQ1770069800 Area: 9948 km^2

Station Ref No: 39001

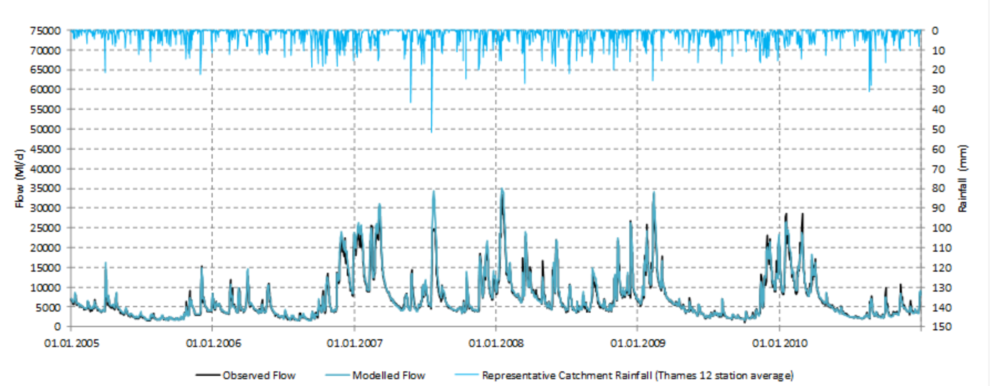
Contributing Rainfall-Runoff Models

Aquator Aquifer Unit		Time Series Assigned
Component	Label	Rainfall and Evaporation
TA31	A1 U. Thames	Cotswolds West (6010)
TA32	A2 Churn	Cotswolds West (6010)
TA33	A3 Ampney	Cotswolds West (6010)
TA34	A4 Coln	Cotswolds West (6010)
TA2	A5 Leach	Cotswolds West (6010)
TA3	A6 Windrush	Cotswolds West (6010)
TA4	B1 Evenlode	Cotswolds East (6020)
TA6	G3 Ock	Berkshire Downs (6070)
TA7	G4 Ginge	Berkshire Downs (6070)
TA5	N3 Thame	Chilterns East - Colne (6140)
TA8	G8 Mill	Berkshire Downs (6070)
TA30	G7 Pang	Berkshire Downs (6070)
TA1	G1 U. Kennet	Berkshire Downs (6070)
TA12	G5 Knighton	Berkshire Downs (6070)
TA23	G2 Lambourn	Berkshire Downs (6070)
TA29	G6 Enborne	Berkshire Downs (6070)
TA14	P1 Upper Loddon	North Downs - Hampshire (6162)
TA15	P2 Blackwater	North Downs - Hampshire (6162)
TA13	M1 Thames direct (Nth - Henley)	Chilterns West (6130)
TA10	M3 Thames direct (Sth - Maidenhea	Chilterns West (6130)
TA9	M2 Wye	Chilterns West (6130)
TA11	N1 Misbourne & Alderbourne	Chilterns East - Colne (6140)
TA26	N2 Colne	Chilterns East - Colne (6140)
TA16	S1 Wey	Wey Greensand (6190)
TA18	S2 Wey Inflow	Wey Greensand (6190)
TA19	T1 Wey Chalk	Wey Greensand (6190)
TA17	V1 Tillingbourne	Wey Greensand (6190)
TA22	Y1 Mole LGS	North Downs - South London (6230)
TA21	T2 Mole Chalk	Wey Greensand (6190)
TW1	Mole u/s T2	North Downs - South London (6230)
TW2	Hogsmill	North Downs - South London (6230)

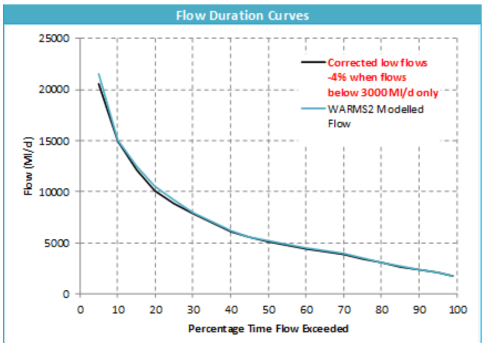
Note

The rainfall-runoff models listed above all contribute to the total flow at Teddington. The rainfall shown on the graph below is the average of 12 stations located across the Thames region.

Calibration Flow Hydrograph



Flow Duration Curves



Flow Duration Curves Q50 to Q95

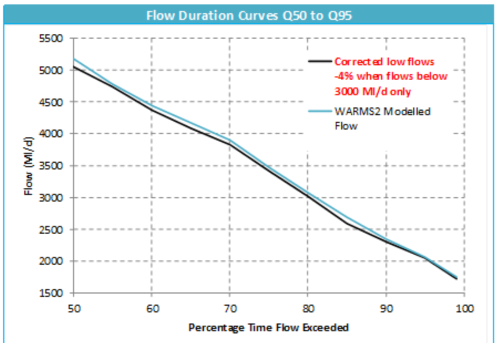


Figure I - 42: WARMS2 Validation – Thames at Teddington

River Lee at Feildes Weir - Calibration Report

Model Run Details: With NEFF, AR12 data, v23c, Mole Update, 24/07/2015

Statistics	Calibration (Observed)	Description
NSE	0.64	Nash-Sutcliffe Efficiency
Log NSE	0.74	Log_N Nash-Sutcliffe Efficiency
Correlation	0.81	Pearson's product-moment correlation coefficient (r)
Log Correlation	0.88	Log_N Pearson's product-moment correlation coefficient (r)
Volume Error	1.04	Modelled volume / Observed volume
RMSE	204.53	Root mean square error
RMSE Q50-Q95	74.95	Root mean square error for data between Q50 and Q95
Mean Flow	425 (410)	Mean flow
Q50	308 (318)	Flow exceeds this value 50% of the time
Q95	153 (159)	Flow exceeds this value 95% of the time

Contributing Rainfall-Runoff Models

Aquator Aquifer Unit		Time Series Assigned
Component	Label	Rainfall and Evaporation
TA28	L1 Upper Lee	Lee Chalk (6600)
TA27	L2 Stort	Rainfall = Lower Lee (6506) Evaporation = Lee Chalk (6600)

Catchment Area

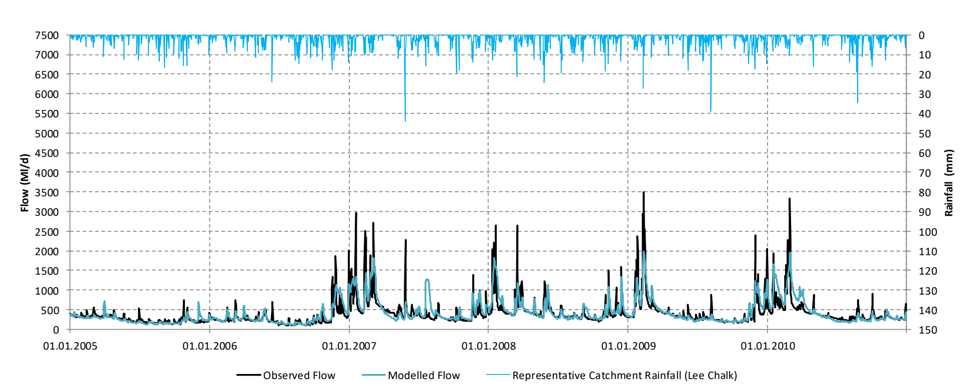
Grid Ref: TL3900009200 Area: 1036 km^2

Station Ref No: 38001

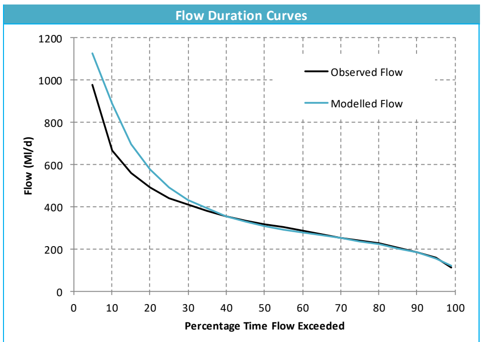
Note

The rainfall-runoff models listed above both contribute to the total flow at Feildes Weir. Lee Chalk rainfall has been selected as most representative of the catchment and is used in the graph below.

Calibration Flow Hydrograph



Flow Duration Curves



Flow Duration Curves Q50 to Q95

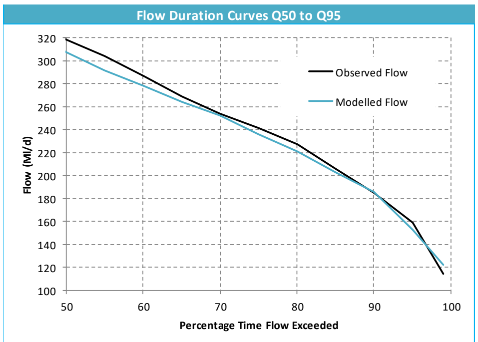


Figure I - 43: WARMS2 Validation – Lee at Feildes Weir

I.202 Alongside the validation of the hydrological models, validation of WARMS2 as a water resources model was also undertaken in 2015.

I.203 To validate the model a period of drawdown of the London reservoir system was used to ensure that the model reflects operational use in a reasonably accurate manner. The validation aimed to ensure that the model reflects the use of operational assets given the water available for abstraction, licences and operating agreements, sources available and constraints on operational use, and to ensure that the water balance was carried out correctly. The London model was also validated against the dry period of 2006, which was a recent event that offered scope for validation. A significant amount of operational data was collated to test the response of the model for 2006. The inputs to the model also included the Environment Agency record of “Natural” river flows at Teddington and Feildes Weir together with the effluent discharge from Rye Meads STW, which are the flows that feed London’s water resource system.

I.204 In the validation exercise, checks were undertaken to ensure that the model’s outputs and calculations were undertaken correctly. The key model output, London’s reservoir storage, is shown in Figure I - 44. The simulated reservoir storage when compared to the observed data demonstrates that the WARMS2 model is well calibrated and thus is suitable as the basis for further modelling.

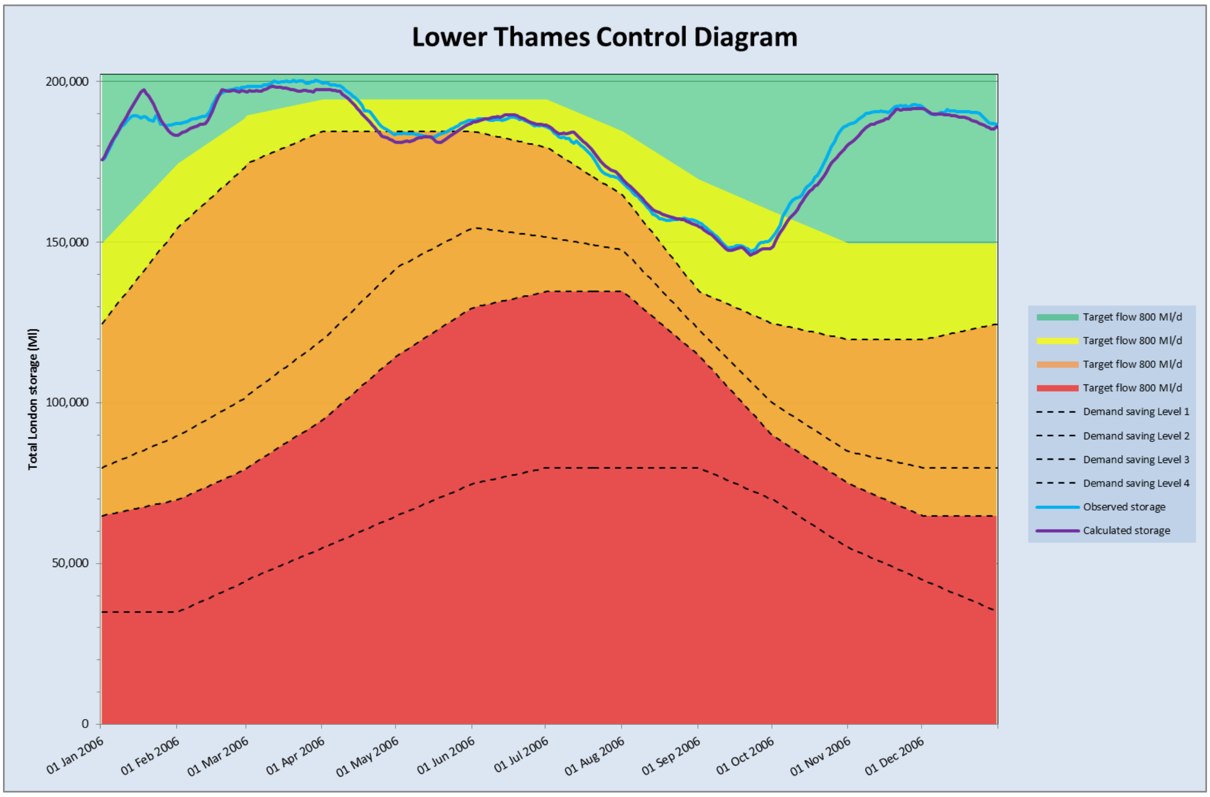


Figure I - 44: WARMS2 Validation – London Reservoir Storage

Annex: Changes Made Between Plan Iterations

I.205 The text in the boxes below summarises the changes made to this Section between dWRMP24 and rdWRMP24, and rdWRMP24 and final WRMP24.

Changes made between dWRMP24 and rdWRMP24:
In order to ensure that our WRMP is based on up-to-date data, we have updated our supply forecast using Source Deployable Output figures consistent with our Annual Review 2022 submission.

We have revised our approach to calculation of our SWOX zone's Peak DO.

In the dWRMP we made amendments to Deployable Output figures in the Kennet Valley WRZ associated with issues that we discovered in our hydrological and water resources modelling. We have made necessary changes to our hydrological and water resources model between dWRMP and rdWRMP such that these amendments are no longer necessary.

We have provided an expanded description of the Deployable Output contribution of the Gateway desalination plant across the planning period.

Additional detail has been provided regarding the validation of our water resources modelling tool.

Changes made between rdWRMP24 and final WRMP24

Additional text has been added in line with additional information requested by the Environment Agency.

Thames Water