Water resources long term planning framework

(2015-2065)

Annexes

WATER UK

Table of contents

Appendix A. Glossary

Acronym or Term	Explanation
ADO	Annual average DO – see more explanation under '*DO*'
AFIXL	Future Flows climate change scenario for a 'median' condition
AFIXJ	Future Flows climate change scenario for a 'dry' condition – one with worse summer conditions, but wetter winters
AFIXO	Future Flows climate change scenario for a 'dry' condition – one with less winter rainfall, but also lower PET and higher rainfall (in relative terms) over the summer
AISC	Average Incremental Social Cost – The Average Incremental Cost (AIC) is calculated by dividing the net present value of all the costs by the net present value of the volume of water provided by an option or scheme. The Average Incremental Social Cost (AISC) extends this calculation to include any external costs arising from "externalities" – wider cost impacts for society and environment (UKWIR 2012, WR27 definition)
AMP	Asset Management Plan period – 5 yearly review period. The previous AMP was known as "AMP5" (because it was the 5th AMP period since water industry privatisation), and covered the time period from April 2010 to March 2015.
Aridity Index	A metric that compares the accumulated rainfall and evaporation deficit that occurs for a given drought event against the long term average for that period (e.g. 12 months), modified according to the natural variability that is seen for that area.
CC	Climate change
CCRA	Climate Change Risk Assessment – sets out the main priorities for adaptation in the UK. The CCRA was published on 25 January 2012, and was the first assessment of its kind for the UK and the first in a 5 year cycle.
Conditional probability analysis	A measure of the probability of an event given that another event has occurred. In this case it is used to estimate the drought severity in a given *supply* region given that a drought of a given severity is occurring in the *deficit* region and that this severity is maintained once the deficit region has become joined by the proposed transfer.
DI	Distribution input – The amount of water entering a water supply distribution system at the point of production. (UKWIR 2012, WR27 definition) i.e. the sum of: household and non-household water delivered, both measured and unmeasured, including USPL; distribution losses and water taken unbilled. Calculated at a specified year and spatial scale – WRZ, supply area or region

Acronym or Term	Explanation
DO	Deployable output – the output of a commissioned source or group of sources or of bulk supply as constrained by: • licence, if applicable • pumping plant and/or well/aquifer properties • raw water mains and/or aqueducts • transfer and/or output main • treatment • water quality for specified conditions and appropriate demand profiles to capture variations in demand over the year. (UKWIR 2012, WR27 definition)
Drought coherence	The spatial coherence of drought severity across multiple regions or sub-regions, as defined by probability.
Drought Configurations	A system of defining droughts within different regions and sub-regions that is reflective of the expected drought coherence, put together in such a way that it can be used to both analyse the resource capability under given levels of drought severity and provide timeseries analysis for the resilience testing of resource systems on a national scale.
Drought Deficit Regions	Those Regions that are most likely to experience deficit under median growth and climate change by the 2040 and 2065 time horizons.
Drought resilience	The ability of a given resource system to continue to supply water during a drought of a given severity, based on the volumetric availability of water (i.e. not accounting for other resilience risks).
EA	Environment Agency
EBSD	Economics of Balancing Supply and Demand - A methodology developed for the water industry to assess the Economics of Balancing Supply and Demand. (UKWIR 2012, WR27 definition)
EDO	Emergency Drought Order - most severe type of restrictions on household water use and imply the use of standpipes and/or rota cuts. See also '*Level 4 (L4) restrictions / failures*'.
Extreme Drought	Very rare events of a type only observed a few times in even the longest reconstructed records (using tree ring analysis or similar).
GVA	Gross Value Added – a measure of non-household economic activity
HER	Hydrologically effective rainfall – the amount of rainfall that is not re-evaporated back into the atmosphere (i.e. that percolates past the root zone).
HILL	High Impact, Low Likelihood
Historic Drought	See '*worst historic drought*'

Acronym or Term	Explanation
HoF	Hands off Flow – A condition included in an abstraction licence that requires the licence holder to stop or cut back their abstraction when the river flow falls below the predetermined flow rate stated in the licence. (UKWIR 2012, WR27 definition)
Investment portfolio	See '*portfolio*'
Level 1 (L1) restrictions / failures	Activities such as media campaigns to reduce water use as water resource situation becomes stressed. 'Level 1' restrictions on demand have not been considered in this Project
Level 2 (L2) restrictions / failures	Restrictions on demand related to the introduction of Temporary Use Bans on 'discretionary' uses such as hosepipes.
Level 3 (L3) restrictions / failures	Restrictions on demand related to the introduction of Drought Order to ban on non-essential use of water.
Level 4 (L4) restrictions / failures	Restrictions on demand related to the introduction of emergency drought actions such as standpipes/emergency drought orders.
LoS	Levels of Service – The planned average frequency of drought-driven customer demand restrictions. For example, a water company may plan to offer a level of service of one temporary use restriction (e.g. hose pipe ban) in 10 years on average, and further restricts demand by way of rota cuts or standpipes with a longer frequency of one in 100 years on average. (UKWIR 2012, WR27 definition)
MDO	Minimum DO – where water resource availability tends to be at its lowest. See more explanation under '*DO*'
NRW	Natural Resources Wales
NEP	National Environment Programme – this is a programme of investigations and actions for environmental improvement schemes that ensures that water companies meet European Directives, national targets and their statutory environmental obligations. The Environment Agency provides a list of investigations and solutions for the NEP after consultation with the water industry and a number of other organisations. The NEP Phase 5 (NEP 5) forms part of the final Asset Management Plan that determines the overall level of investment that water companies need to make from 2015 to 2020, based on the new price set by Ofwat. Companies incorporate these requirements into their proposed business plans, which inform Ofwat's decision on price limits.
NEUBs	Non-essential use bans
Non-PWS	Non-public water supplies – i.e. private abstractions
NPV	Net present value - The difference between the discounted sum of all of the benefits arising from a supply-demand balance option (or scheme) and the discounted sum of all the costs arising from the option or scheme. (UKWIR 2012, WR27 definition)
Ofwat	The economic regulator of the water sector in England and Wales

Acronym or Term	Explanation
ONS	Office for National Statistics
NUTS2	Nomenclature of Territorial Units for Statistics (NUTS), created by the European Office for Statistics (Eurostat) as a single hierarchical classification of spatial units used for statistical production across the European Union (EU).
PET	Potential evapotranspiration – a measure of the ability of the atmosphere to remove water from the surface through the processes of evaporation and transpiration assuming no control on water supply
Portfolio	In the context of this project: A group of supply side options to increase WAFU, and transfer options to redistribute WAFU, in order to maintain the supply demand balance in surplus throughout a given planning period. Each portfolio is determine for a specified level of distribution input savings resulting from demand management.
PR14	Price Review 2014 – Each water company submits a Business Plan for the period of the review which is assessed by Ofwat. The price limits for the current period (2015 to 2020) were set at the end of 2014 and is referred to as Price Review 14 (PR14).
PWS	Public water supplies
Restrictions	Enforceable restrictions on water demand – for example temporary water use restrictions. (UKWIR 2012, WR27 definition)
RET	Resilience Evaluation Tool – developed for this project to assess yield, understand consequences of possible failures and to test the resilience of future strategic investment portfolios
SDB	Supply demand balance – The difference between total water available for use (as supply) and forecast distribution input (as water demand) at any given point in time over the Water Resource Management Plan's planning period/horizon. (UKWIR 2012, WR27 definition)
SIC / SIC07	Standard Industry Classification 2007
Scenario 0	A *drought configuration* that is run without climate change influences in order to check the validation of water resource system modelling for historic droughts, and estimate the risks from droughts more severe than those seen in the historic record.
SEEL	South East excluding London – one of the Drought sub-Regions defined and used in this project
SEPI	Standardised Evaporation and Precipitation Index – a method which looks at the difference between monthly rainfall and monthly actual evapotranspiration (i.e. PET adjusted to account for the fact that plants tend to stop taking water from the ground after they wilt during longer, hotter dry periods) to generate a 'hydrologically effective' rainfall (HER) total for that month.

Acronym or Term	Explanation
Severe Drought	Rare events beyond those seen in the 20th Century – might only be expected to occur once every couple of centuries
Severity 2 (S2)	Relates to level of restriction/failure – see explanation under '*Level 2 (L2) restrictions / failures*'
Severity 3 (S3)	Relates to level of restriction/failure – see explanation under '*Level 3 (L3) restrictions / failures*'
Severity 4 (S4)	Relates to level of restriction/failure – see explanation under '*Level 4 (L4) restrictions / failures*'
SP	Stated preference – for the purposes of this project, these are a measure of the "willingness to pay" of consumers for changes in service levels
SR	Sustainability reduction – see below
SSSI	Site of Special Scientific Interest
Stochastic	A stochastic process is a process incorporating an element of randomness, the evolution of which can only be predicted within a range of values of the uncertain variables. (UKWIR 2012, WR27 definition)
Supply area	A group of one or more geographically adjacent water resource zones, sharing similar water resource characteristics, used for supply demand balance calculations and portfolio development at a national level.
Sustainability Reduction	Reductions in deployable output required by the Environment Agency to meet statutory and/or environmental requirements. (UKWIR 2012, WR27 definition)
SWOX	Thames Water's Swindon and Oxford WRZ
Tier 1 analysis	A simple estimate of the capability of water company sources during droughts more severe than those seen in the historic record, both prior to and accounting for climate change. Based on an analysis of aridity indices compared with WRMP14 evidence of the variability of source capability with different historic droughts and climate change.
Tier 2 analysis	An analysis designed to support Tier 3, whereby the smaller resource systems within an integrated zone are analysed using the historic record and flows/capability are derived for the Tier 3 timeseries based on regression analysis.
Tier 3 analysis	An estimate of the capability of water company sources during droughts more severe than those seen in the historic record, both prior to and accounting for climate change, based on weather generation and associated rainfall-runoff modelling.
TUBs	Temporary Use Bans

Acronym or Term	Explanation
USPL	Underground Supply Pipe Losses – leakage from pipes occurring between the distribution network and household properties, both measured and unmeasured.
WAFU	Water Available for Use – the sum of: deployable output, including any changes due to climate change or sustainability reductions; imported and exported water; outage allowance, raw water losses and treatment losses. Calculated at a specified year and spatial scale – WRZ, supply area or region.
Wathnet	Water resource simulation and optimisation modelling software developed by the University of Newcastle, Australia
WFD	Water Framework Directive – A European Union directive which commits European Union member states to achieve good qualitative and quantitative status of all water bodies.
Worst Historic Drought	The rainfall deficit pattern from the worst drought (in terms of yield) seen in the 20th Century. This can be perturbed for climate change, so it becomes representative of the type of drought that would be planned for under the current ‘standard’ planning assumptions used by most water companies.
WRE	Water Resources East (formerly referred to as Water Resources East Anglia, or WREA)
WRMP	Water Resource Management Plan – The statutory 25 year plans that the Water Companies in England & Wales are required to produce at five year intervals to show how they intend to provide security of supply at least all-in cost to customers, society and the environment, whilst meeting environmental obligations
WRMP14	The most recent previous set of Water Resource Management Plans that were published by water companies in 2014
WRSE	Water Resources South East
WRZ	Water Resource Zones - The largest possible zone in which all resources, including external transfers, can be shared and hence the zone in which all customers experience the same risk of supply failure from a resource shortfall. (UKWIR 2012, WR27 definition)
WTP	Willingness to pay – Willingness to pay (WTP) is the maximum amount of money a person or group would be willing to pay, sacrifice or exchange in order to receive a good or improvement. (UKWIR 2012, WR27 definition)

Appendix B. Drought Planning Scenarios and Resource Evaluations

B.1. Weather Generation, Aridity Indices and Drought Coherence Analysis

Purpose and Core Concepts

The analysis of meteorological drought risks, as evaluated through the use of historic data, the stochastic weather generator and associated aridity indices, underpinned all of the resource evaluations that were carried out for this study. There were four primary objectives from the analysis

A. **Generation, identification and selection of drought events more severe than the historic record.** This was done according to a variety of duration metrics to allow the creation of Drought Configurations for the resource evaluation and resilience testing.

B. **Analysis of drought coherence across the country.** This was required to allow the evaluation of transfer capability and hence define the Drought Configurations that were used in the resource evaluation and resilience testing.

C. **Creation of aridity index outputs from the historic record and the stochastic weather generator for the selected Drought Configurations.** These were required (with and without climate change impacts) as inputs for the 'Tier 1' resource evaluation

D. **Creation of rainfall and PET timeseries to allow the generation of Tier 2 and 3 flows for all Drought Configurations.**

Methodology

An overview of the generation and drought sequence selection process is provided in Figure App-1. This incorporates the following calculation notes:

1. **The Aridity Index** was calculated based on a standard SEPI analysis for a variety of durations. Two versions of each index were produced:
    a. An index for *x* months ending in the August to October period ('hydrological year'): this type of index is important across the whole country, but particularly so in the north and west, as the large proportional differences in seasonal rainfall between the summer and winter mean that the critical period of all drought events only tends to last until the end of October (at the latest).
    b. An index for *x* months ending in the October to December period ('calendar year'): this type of index is important across the south and east of the country, where critical drought periods can persist beyond October.

The SEPI Aridity index calculation was based on the following equation:

$$SEPI(n,e) = \frac{\left(\sum_{0}^{m=-n}(Rain_m - AET_m)\right) - \mu\left({}_{1}^{t}Y\ \sum_{0}^{m=-n}(Rain_m - AET_m)\right)}{\sigma\left({}_{1}^{t}Y\sum_{0}^{m=-n}(Rain_m - AET_m)\right)} \quad (1)$$

Where:

n = number of months in the index (6, 12, 18, 24 or 36 months)

e= month ending period (Aug to Oct or Oct to Dec)

$Rain_m$ = total rainfall in month m

AET_m = actual evaporation in month m (calculated using a Catchmod soil storage module, with a drying constant of 100mm and a slope of 0.3)

μ, σ (${}_1^tY$)= mean and standard deviation of the SEPI (n.e) for all years in the historic record

Figure App-1 Weather Generation, Drought Coherence Analysis and Drought Selection Process

1. Generate historic data series (1900 to 2000) for 22 sites (sites 1 to 22) across England & Wales, as shown in Figure App-2, based on the CEH GEAR rainfall data set and Oudin calculations based on the HRW gridded temperature records

S2. Input the monthly rainfall along with NAO and SST records for the 20th Century into the stochastic weather generator

H2. Generate 6, 12, 18, 24 and 36 month hydrological and calendar year SEPI values (**see note 1**) for each year in the historic record at different spatial scales

S3. Carry out 8 stage weather generation process (**see note 2** overleaf).

S5. Generate 6, 12, 24 and 36 month hydrological and calendar year SEPIs for all years at different spatial scales

V5. Rank historic and stochastic SEPI values to carry out validation analysis of historic to stochastic SEPI/probability curves at various spatial scales

S8. Use ranked catchment average SEPI values to examine the joint probability between Hydrological Areas (see **note 3**); evaluate from two loci, the Thames (sites 4&10) and the Yorkshire Water east (sites 12&13). Determine drought coherence based on the joint probability charts (**see note 4**)

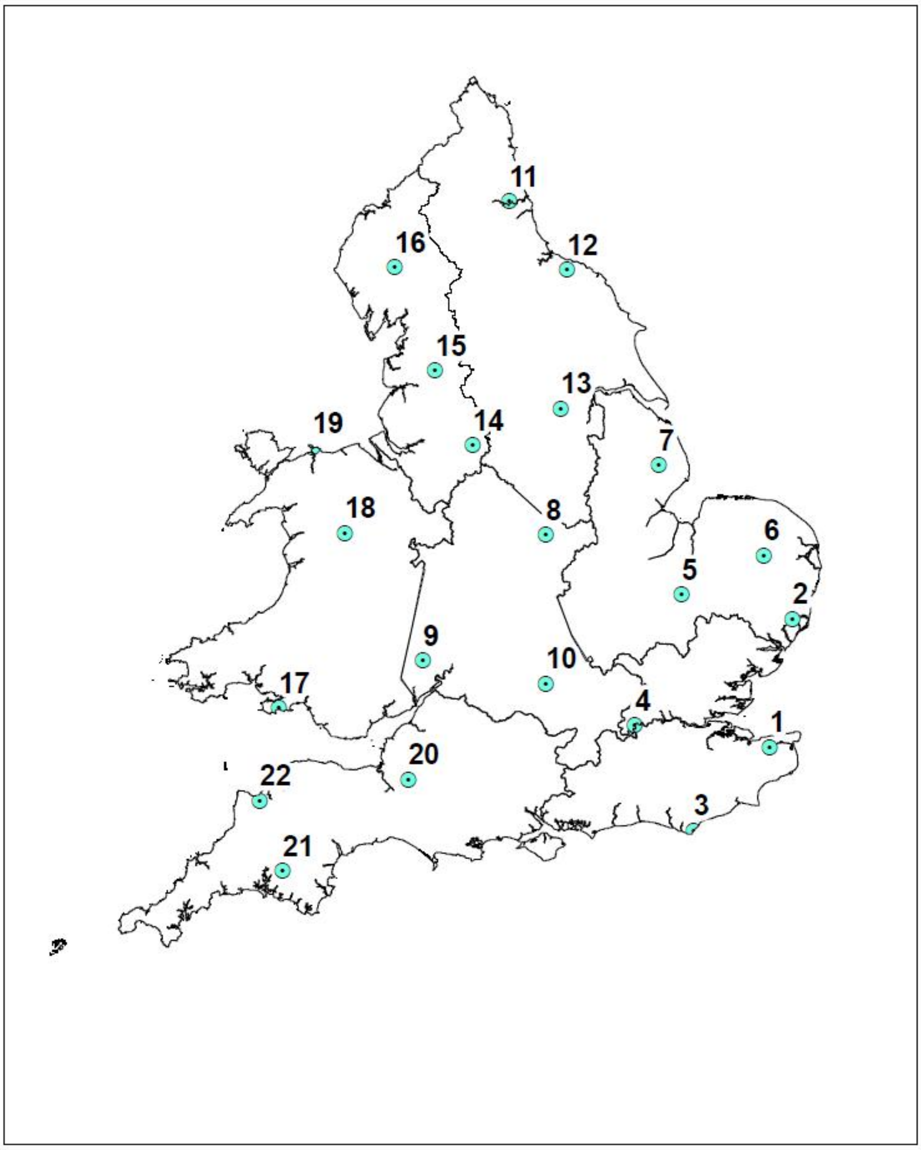
V6. Sense check against the coherence shown in 1 in 10 and 1 in 20 year events in the historic record

8. Develop the Drought Configuration tables (incorporating historic and stochastic droughts), as per Section 6 of the Technical Report (see **note 5**)

S8. Where required (i.e. where Drought Configurations require droughts with severities beyond the historic record), rank and manually identify representative drought events based on the relevant SEPI aridity indices (see **note 5**).

9. Output SEPI values for each required Drought Configuration for Tier 1 resource assessment (historic and stochastic) and rainfall and PET timeseries for the Tier 3 resource assessment plus resilience testing (8 year sequences for each drought).

Figure App-2 Location of the 22 Rainfall and PET Sites used in the National Modelling



2. **The weather generator** is an entirely stochastically based 'rainfall led' model (i.e. it simulates rainfall and then re-samples PET from the historic record, allowing for observed persistence bias). It uses a number of steps of analysis to generate plausible 'what-if' scenarios of the 20th Century weather, based on natural variability in rainfall and PET, accounting for regional influences such as NAO, SST and the major anomalies that can be seen across the central, south and east of the country. **The analysis of natural temporal and spatial variability and the influence of NAO and SST on that variability are managed through a monthly based stochastic model, which is a fully parametric version of the model first developed by Kilsby & Serinaldi (2012). This manages spatial coherence through a system of deconstruction and then copula analysis that ensures the correlation in the 'random error' between sites is reflected in the generated weather.** This has been demonstrated to work on a country wide basis as shown in Figure App-3, taken from the original paper.

   However, in order to incorporate other observed anomalies in rainfall persistence between months, allow for correlated persistence between rainfall and PET, and generate daily rainfall from the monthly totals, an 8 stage calculation process was required. This is summarised in Figure App-4. Two points are noted in relation to the process:

a. The persistence anomalies in rainfall were evaluated and fitted on a Hydrological Area basis (typically 3 or 4 sites – see Note 3 below)
b. The PET persistence anomalies were then fitted on a larger, Regional basis, which is more reflective of the observable temperature anomalies that are seen in typical Met Office seasonal summaries.

This approach, of rainfall anomaly curve fitting at the sub-Regional level combined with PET persistence fitting at the Regional level, was found to provide a good match between historically observed and generated SEPI on a variety of scales (local to sub-Regional to Regional to National – see 'validation' section below).

Figure App-3 Extract from Kilsby and Serinaldi (2012) Demonstrating Spatial Validation on a National Basis.

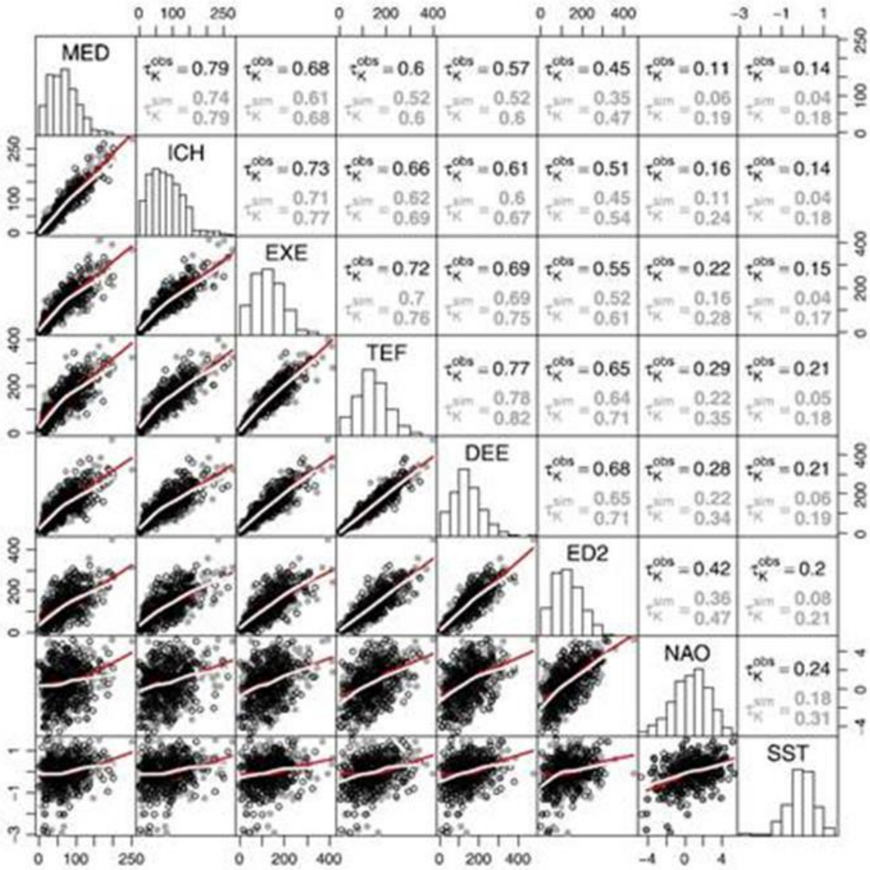


Figure App-4 Flow Diagram for the 8 Stage Stochastic Weather Generation Process

Step 1: Analyse rainfall time-variant behaviour. The R model analyses the 'natural' statistical behaviour of each site for each month, including the influence of NAO and SST

↓

Step 2: Generate spatial 'scatter' between sub-catchments. The R model uses the analysis of behaviour at each sub-catchment to 'deconstruct' the rainfall, effectively turning it into a random (Gaussian) scatter. In simple terms this 'scatter' is representative of the natural rainfall variability that occurs in each site for each month.

↓

Step 3: Analyse spatial coherence in monthly rainfall. The R model examines the nature of these random scatters to determine how well the 'natural' variability is correlated across each site

↓

Step 4: Generate 'basic' monthly rainfall for each month. The R model takes the historic record of NAO and SST and re-samples it to generate *n* (in this case 200) statistically valid 'what if' runs of potential NAO and SST sequences. The model then uses the statistical relationships between NAO, SST and all other sub-catchments to generate a 'basic' output of monthly rainfall.

↓

Step 5: Perform Multi-Metric Curve Fitting. The R model then uses a number of sub-modules to account for climatic factors other than NAO and SST, which are causing observable persistence in the rainfall beyond that 'explained' by the NAO and SST. This is done through a multi-metric step-wise 'curve fitting' process.

↓

Step 6: Generate Non-Persistent PET. Monthly PET is then initially generated by matching stochastic rainfall in each month against the nearest historic record for that month (e.g. January to January match). This is done based on rainfall averages for each Region, which means that the matching of PET across Regions is spatially coherent.

↓

Step 7: Incorporate PET Persistence Effects. Observable marginal persistence effects for the spring, summer and autumn PET are then accounted for based on an annual percentile curve fitting process.

↓

Step 8: Scale monthly to daily rainfall. The monthly rainfall record is turned into a daily rainfall record by taking the daily pattern for each of the months that were matched for PET, and then scaling that daily rainfall to match the total for that stochastic month

3. **'Hydrological Areas'** were used as the main basis for the drought coherence analysis and the selection of drought events for input to the Drought Configurations. These groups of rainfall/PET sites are approximately representative of the way that the major catchments and resource systems are separated (physically or hydrologically) across the country. The Hydrological Areas used in the analysis incorporated the following groupings of rainfall/PET sites:

   - Kent, Sussex & Surrey: sites 1 and 3
   - Essex & Suffolk: sites 2 and 6
   - Thames: sites 4 and 10
   - Ruthamford and lower Trent: sites 5, 7, 8
   - Severn and upper Trent: sites 8, 9, and 18
   - Northumbria: site 11
   - East Yorkshire: sites 12 and 13
   - Dee Valley: sites 14, 18, 19
   - Western Pennines: sites 14 & 15
   - Cumbria: site 16
   - Bristol & Wessex: sites 9 and 20
   - South west: sites 21 & 22

4. The 'patchy' nature of droughts meant that the **conditional probability distribution** between Hydrological Areas was highly non-linear. The point of the analysis was to examine the ***on average*** difference between sub-Regions on a relative basis. Conventional plots such as correlation analyses were not therefore a great deal of use, as they would not have allowed quantification of this 'on average' difference. Such plots do show how correlation reduces with distance, but what was required here was an analysis of how the conditional probability surface varies with distance and drought severity.

   In order to evaluate the drought coherence base on a 2 dimensional plot of conditional probability, the following procedure was therefore adopted:

   a. For each Hydrological Area the average SEPI across the relevant sites was calculated on a weighted basis (i.e. the average rainfall and AET were calculated for each month as a catchment system average, allowing for relative contribution to the Area, and then the SEPI was calculated for the Hydrological area in accordance with equation 1 described previously).

   b. The *conjunctive* SEPI for the two regions was then calculated for each year. Because a large scale transfer would involve the two Areas becoming joined, it was important to ensure that the conjunctive capability of the joined system should also be evaluated at the design severity (e.g. 1 in 200).

   c. The Area average and conjunctive SEPIs were then ranked according to the drought locus (Thames or east Yorkshire) and the 100 or 50 values around the required rank (100 for a severe event, 50 for an extreme event) were taken for graphical analysis.

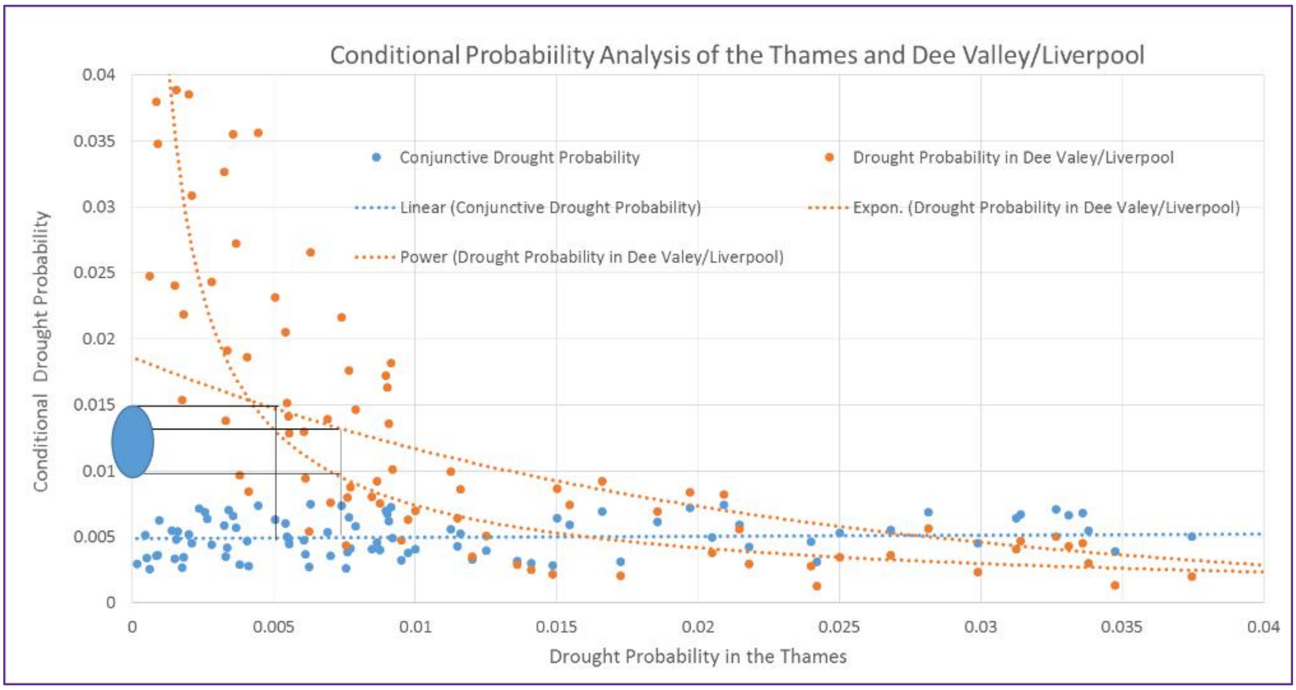
   d. A chart was plotted that compared:
      i. The ranking of years according to SEPI for the locus Area
      ii. The associated ranking of years for the Area for which the conditional probability was being evaluated
      iii. The associated ranking of years for the conjunctive SEPI between the two Areas.

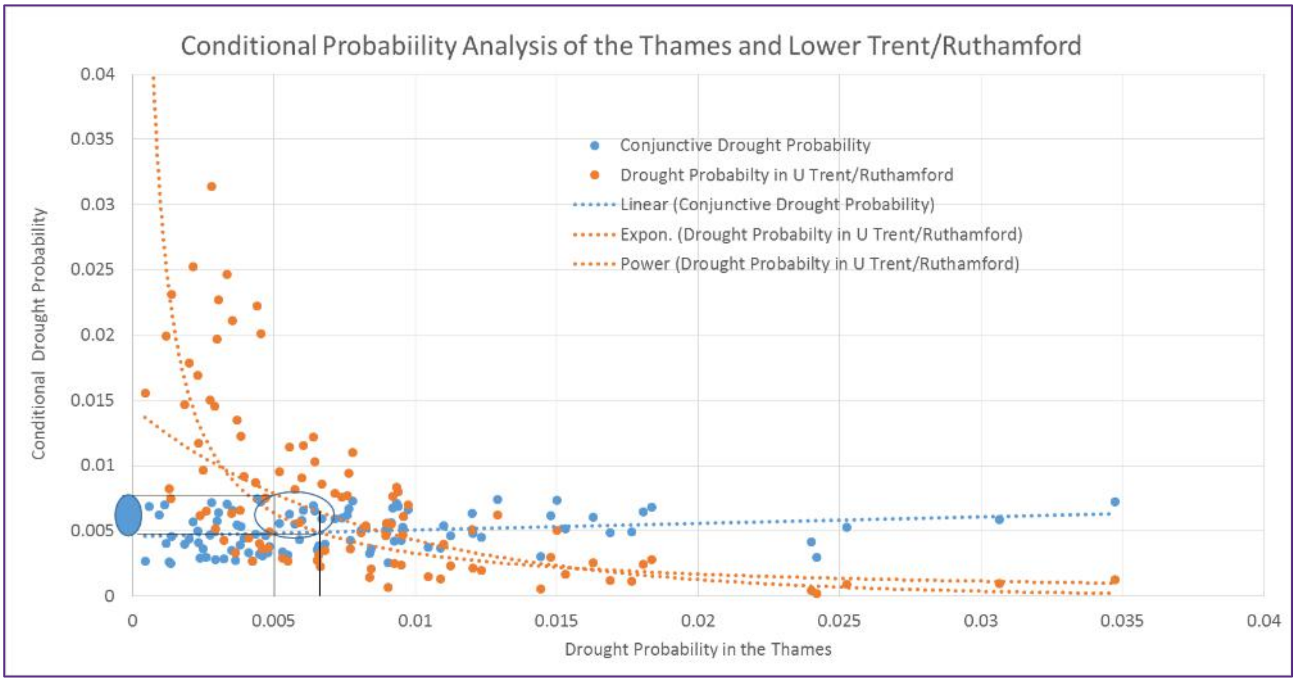
This was done for all sub-Regions based on the conditional probability of the drought in that region compared with a drought that was focused either on the Thames basin, or on east/central Yorkshire.

An example of the above analysis, as plotted for the Thames Region acting conjunctively with the Lower Trent/Ruthamford Region for a 1 in 200, 24 month drought, is provided in Figure App-5. In this figure, all risks are shown as probabilities rather than return periods, which reduces the level of non-linearity of the plots (return periods can easily be calculated based in 1/probability). This shows the tradeoff between the two Regions; the conjunctive drought probability is set to be near the 0.005 (1 in

200) level. This means that the level of risk that is planned for in the Upper Trent/Ruthamford will decrease as the level of risk in the Thames increases. We are interested in the point at which a 0.005 probability event (1 in 200 RP) occurs in both Thames and conjunctively across the joint Region, and need to understand the probability that should be planned for in the Upper Trent/Ruthamford Region. Because the conditional relationship between the Thames and Upper Trent/Ruthamford Regions is highly non-linear, this requires some interpretation (exponential and power trend plots are shown), but overall the equivalent level of risk that satisfies this condition is something like 0.06. In other words the expected drought risk that should be planned for is approximately 1 in 166. The same plot, shown for Thames compared with the Dee Valley/Liverpool region is also shown in Figure App-5. This shows that the droughts are much less correlated across those Regions, (and the level of uncertainty about the 'expected' drought is larger); during a 0.005 probability (1 in 200 return period) event across the Thames you would only 'expect' a 0.0125 (1 in 80) event across the Dee Valley/Liverpool Region.

Figure App-5 Example Conditional Probability Analysis Charts

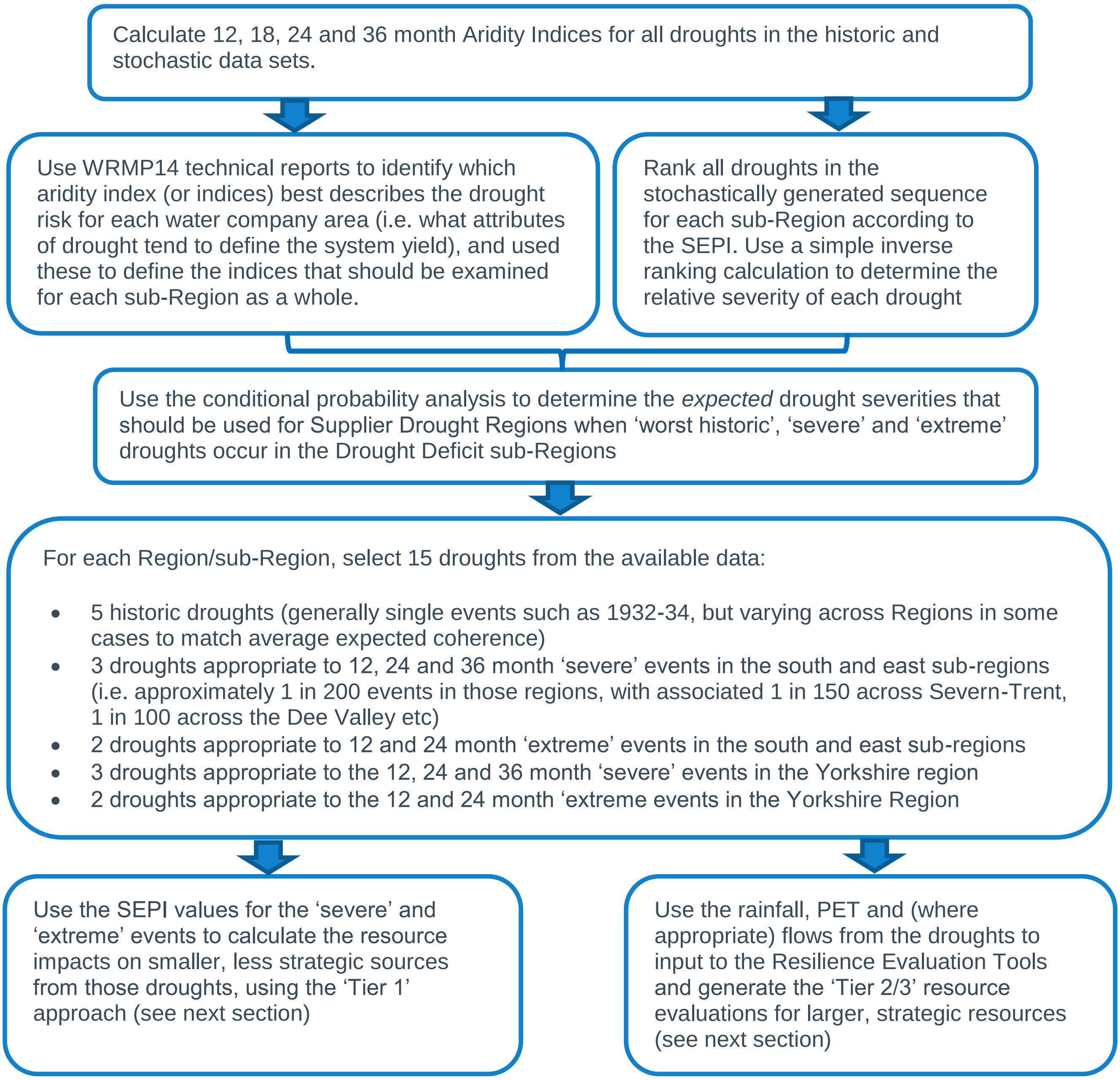




N.B. this method produces similar results to a simple comparison of the mathematical means of the two Areas within the defined joint probability space. However, plotting the trendlines reduces the sensitivity of the estimate to the size of the joint probability space that is used (e.g. a sample space covering 100 droughts around the chosen conjunctive resilience would give a different answer to a sample space covering 50 droughts). Because this is a 2D representation of the conditional probability surface, it is not possible to create a chart where the 0.005 conjunctive conditional probability intersects the probability in the Thames at exactly 0.005, so the general zone of intersection has been shown, and a mean estimate taken.

5. **Drought Configurations** were developed to provide a reasonable overview of the drought risk within each of the different sub-Regions, given the expected coherence between the different Regions and sub-Regions. Each one contained 15 droughts of different severities and durations that were spatially coherent in the expected sense. The general procedure that was used to generate these Drought Configurations and apply them to the resource evaluation for the Portfolio analysis and resilience testing is described in Figure App-6.

Figure App-6 Procedure used to develop and apply Drought Configurations



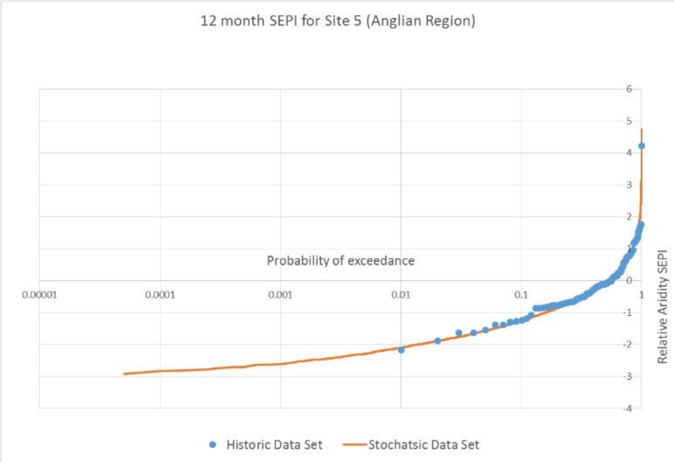
6. Because the scale and complexity of the project meant that it was necessary to limit the number of Drought Configurations that actually contained droughts with severities beyond those seen in the historic record, it was important to ensure that each of those droughts were reflective of the average *expected* drought coherence. Therefore, whilst the drought was initially selected based on the ranking of the SEPI calculated as an average across the Hydrological Area, the selected drought also contained a reasonably consistent and close approximation of the SEPI ranking for the *individual* sites in that sub-Region. For example, for the Ruthamford sub-Region (covering sites 5, 7 and 8) the 'severe' 24 month drought was selected by:

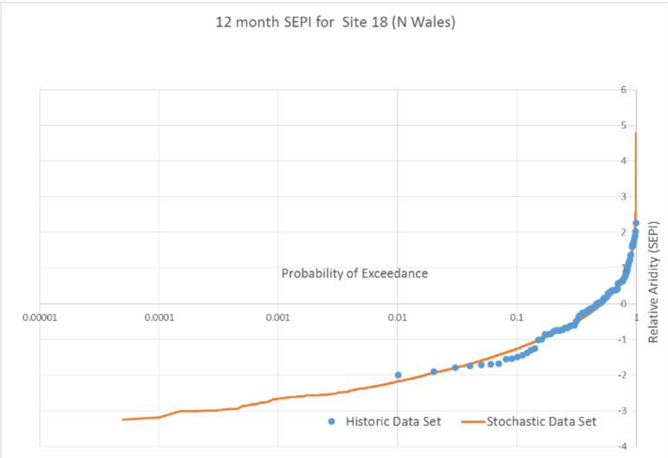
    a. Taking a weighted mean of the 24 month calendar year SEPI for sites 5,7,8 for all years, and ranking all of the SEPI outputs according to that mean.
    b. Droughts around the 100th rank (20,000 years' worth of data had been generated, so this was roughly approximate to the 1 in 200 event) were then identified.
    c. Of that shortlist of potential droughts, the selected drought was the event that was both close to the 100th rank across the sub-Region, *and* contained individual site rankings that were close to the 100th rank.

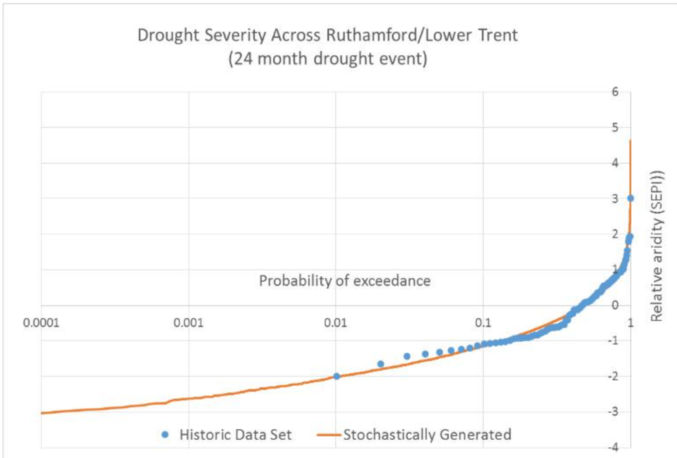
The above process was slightly more complex for Hydrological Areas such as the Severn/Upper Trent, as there tended to be less coherence between the rankings of the individual sites. The selection process was therefore essentially the same, but care was taken to ensure that the sites that were closest to the Deficit Region to the south and east were closest to the desired ranking, and the more distant sites (e.g. site 18 in N Wales) were at a higher rank (less severe return period).

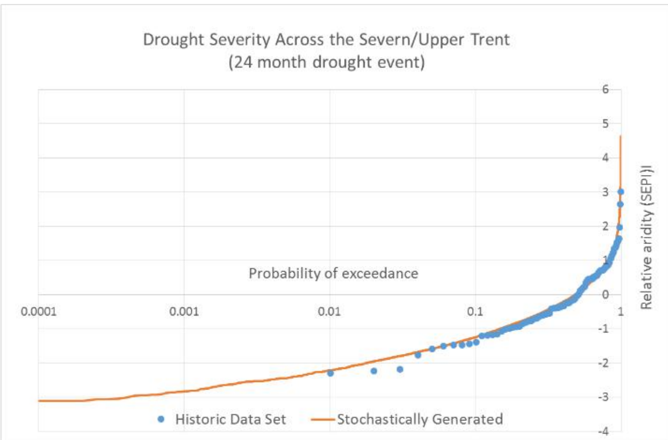
Validation

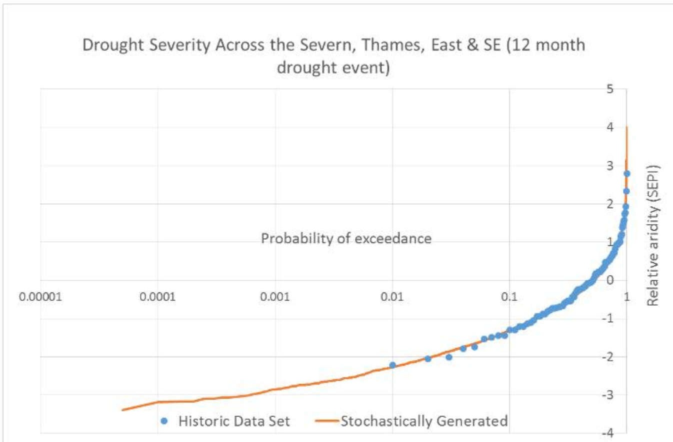
The key validation of the weather generator was provided through the comparison of historic versus stochastic SEPI plots for various durations and scales. Example outputs are provided below.











Key Uncertainties and Assumptions

There were two main uncertainties behind this analysis:

1. Anomaly fitting for rainfall was based on the core assumption that the 20th Century is an average representation of the typical weather that could be expected for any given century (i.e. worst historic events are generally expected to have a probability of occurrence of around 0.01 per annum, although because the fitting was regionally based there would be localised areas of drought that were more severe than this). This only affected the central, south and east of England, and the uncertainty was addressed by work carried out by Atkins in separate studies for Anglian and Thames Water, which indicated that the 20th Century does indeed appear to be 'typical' within a longer term context.

2. Only a very limited number of droughts could be selected for the resource assessment and resilience testing, and these were selected according to aridity rather than flow or relative yield. This meant that there is a high degree of uncertainty about the relative ranking of those droughts in relation to system yield. This was addressed in two ways:
    1. A variety of durations and indices were incorporated into the analysis when the 'Tier 1' evaluation was being carried out.
    2. The resilience testing relied on general interpretation of the results, rather than absolute calculations, and was done by comparing the results of all of the severe and extreme Drought Configurations against historic drought outputs.

Outputs

A total of 7 aridity index databases containing the SEPI calculations for all sites and Hydrological Areas for the historic data set and all 20,000 years' worth of stochastically generated data were produced. These were:

1. 6 month SEPI ending August to October
2. 12 month 'hydrological year' SEPI (year ending August to October)
3. 12 month 'calendar year' SEPI (year ending October to December)
4. 18 month hydrological year SEPI
5. 24 month hydrological year SEPI
6. 24 month calendar year SEPI
7. 36 month hydrological year SEPI

All databases were conditionally formatted to allow rapid checking and identification of the nature and extent of specific drought periods. An example screenshot from the 12 month hydrological year, stochastically generated database, is provided below (this contains a localised south-east drought, shown in red, around year 19 and more widespread, but patchy, events around years 36 and 47).

	SEPI																						1,3,4	4,10	5, 7, 8,10	8,9, 18	12,13	14,15	9, 20	15, 16	14, 18, 19	2,5,6
Year	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10	Site 11	Site 12	Site 13	Site 14	Site 15	Site 16	Site 17	Site 18	Site 19	Site 20	Site 21	Site 22	SE	TH	TR	SV	ECY	CP	BW	Cum	DVL	ESN
0	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23										
1	0.178073	-0.81948	-0.28403	-1.06326	-0.58489	-0.70572	-0.47716	-0.35936	-1.22192	-0.32171	-1.20804	-0.57573	-0.65471	-0.20078	-0.15841	0.649535	0.488645	0.508714	-0.85051	-0.09106	-0.7853	0.211903	-0.40601	-0.74906	-0.49866	-0.44696	-0.69876	-0.21578	-0.75304	0.383315	-0.06185	-0.72447406
2	0.461352	0.117702	0.181805	-0.3851	-0.37901	-0.05605	-0.76854	-0.67894	0.646739	-0.30077	-0.6504	-0.19844	-1.46326	-0.3576	-0.10743	-0.03384	0.771675	0.240291	0.262028	-0.21415	0.410874	-0.07571	-0.10185	-0.59257	-0.75116	0.025176	-0.75233	-0.15275	0.229442	-0.0556	0.09685	-0.0345463
3	-0.01355	0.201598	0.161903	-0.02048	0.556853	1.097965	-0.31178	0.111337	-0.02266	0.024531	-0.39315	-0.99555	-0.00737	1.217506	1.771428	1.571139	0.885451	1.489756	0.491373	0.287606	0.922779	1.660944	0.041699	0.03999	0.140238	0.680516	-0.61985	1.633972	0.129994	1.874202	1.303294	0.78714081
4	-0.7872	-1.03918	-1.40217	-0.2341	-0.80984	-0.91446	-1.00066	-0.70734	-0.89837	-0.53765	-0.68643	-0.86345	-1.02616	-0.40064	0.062701	0.129325	-0.8132	-0.18198	-1.18424	-0.97592	-0.55561	-0.83268	-0.99203	-0.63531	-1.02483	-0.80953	-0.97528	-0.06452	-0.99197	0.1322	-0.51613	-0.98242345
5	1.927252	0.767467	1.396583	1.147688	0.901612	0.947694	-0.28541	0.148546	1.094358	1.168727	-0.58901	-0.39597	-0.44612	0.397531	0.571444	1.028069	1.350956	1.17771	1.951127	1.444345	1.190849	1.199709	1.596137	1.362948	0.257292	0.997553	-0.43799	0.566536	1.326081	0.994694	1.261596	1.0447094
6	0.145808	-0.20556	-0.42544	-0.02074	0.632438	0.344857	0.743561	0.650028	0.50186	0.424503	-0.29172	0.298621	-0.18894	0.699738	0.523406	1.596696	2.277277	1.656882	-0.26901	0.303947	1.628099	1.330944	0.025055	0.25718	0.805987	1.15495	0.100988	0.656551	0.419471	1.391875	1.065298	0.32793472
7	-1.21666	-0.81462	-1.09704	-1.32208	-0.9587	-1.25701	-1.39447	-0.79889	-1.11599	-0.96563	-0.7983	-1.02522	-1.29477	-0.20602	0.215244	0.861375	-0.22644	-0.43503	-1.43317	-0.88876	-0.54798	0.201837	-1.35108	-1.35596	-1.2074	-0.98493	-1.19033	0.10698	-1.06354	0.729602	-0.66833	-1.09114396
8	0.971128	0.69415	1.427741	0.668449	0.862586	0.663387	0.823865	1.204885	1.093169	1.074312	-0.9065	0.546577	1.331883	1.021542	1.174789	1.941479	2.468568	2.143612	1.789848	1.58412	1.878925	1.947754	1.007498	0.70442	1.013326	1.687889	0.906297	1.187129	1.397654	1.90591	1.94506	0.88124783
9	1.675851	1.596228	1.882164	1.40679	1.925091	1.745226	1.370364	1.024629	0.515833	1.361218	1.007732	1.055381	1.902525	1.208861	1.223381	1.289742	0.643061	1.170292	1.257851	1.660688	0.704026	1.206473	1.800849	1.482849	1.501369	1.031158	1.465059	1.291418	1.127874	1.448079	1.309854	2.02357475
10	0.476237	0.298067	-0.57315	-0.25281	0.792554	0.966122	-0.12871	-0.24793	-0.49406	-0.18499	0.479805	0.490592	-0.23303	0.099454	0.282228	-0.55741	-0.74442	-0.98884	-0.7339	0.220185	-0.50888	-0.47563	-0.36963	-0.02406	0.169697	-0.63194	0.200555	0.269465	-0.15741	-0.28264	-0.72485	0.83954942
11	-1.39774	-1.30394	-1.17906	-1.51764	-0.64911	-0.984	-0.27684	-0.5995	-0.60247	-0.95257	0.168396	-0.0002	0.01271	0.320298	0.922601	0.476772	0.310846	1.005225	0.046383	-0.11743	-0.40647	0.210708	-1.45289	-1.21494	-0.50542	-0.03505	0.003056	0.753228	-0.38992	0.731898	0.667207	-1.06424944
12	0.028924	0.215415	-0.28352	-0.20359	0.48713	0.081718	-0.20359	0.492012	0.374125	0.158359	-0.78075	0.084926	0.373316	-0.02927	-0.61839	-0.23943	0.584164	0.417733	0.239982	0.066844	-0.13565	-0.29444	-0.27872	0.064095	0.351308	0.55892	0.210255	-0.33883	0.228539	-0.41132	0.283625	0.32988635
13	-1.96479	-1.47148	-1.83411	-1.39819	-1.35529	-1.47978	-0.98839	-1.33481	-1.19041	-0.64321	-1.41584	-0.0334	-0.83468	0.230961	0.830275	0.312506	-0.48859	-0.00928	-0.77938	-1.02289	-0.98608	-0.89012	-1.95271	-1.24414	-1.34046	-1.00205	-0.38088	0.6607	-1.17271	0.574522	-0.14148	-1.56139347
14	0.935594	0.561583	1.96959	0.793026	1.358206	1.451485	1.36266	1.714319	2.233174	1.136855	0.934297	0.652983	1.047642	1.022599	0.832797	1.106426	2.767327	2.045237	1.612944	1.408374	1.762579	2.176292	1.311786	1.223787	1.730791	2.418941	0.850055	0.975926	1.917673	1.157009	1.845211	1.32550723
15	-0.94008	-1.09781	-0.59258	-0.92881	-0.5962	-0.55161	-1.06696	-0.18542	-0.73823	-1.06783	-0.31272	-0.57444	-1.0179	-1.03041	-1.13199	-0.85057	-1.33686	-0.47794	-0.29715	-0.52535	-1.29233	-1.01992	-0.86213	-1.15002	-0.7053	-0.61348	-0.79337	-1.05333	-0.6734	-1.06512	-0.63857	-0.78145236
16	-0.31438	1.261014	-0.24213	0.111952	1.046149	0.73556	1.750505	0.739228	1.380945	0.725128	2.19072	2.117054	1.262887	1.213184	0.799582	0.784603	0.686703	0.014917	2.044128	1.551849	-0.41359	0.150274	0.036834	0.675904	1.35273	0.842896	1.845942	1.030887	1.535172	0.907968	0.848611	1.18598893
17	1.755862	1.71087	1.600122	0.419929	1.933883	1.850087	1.953217	0.794344	1.826284	1.385885	1.742768	2.560956	2.051189	1.398101	0.912759	0.060375	1.124814	1.076176	1.99736	2.212182	1.208644	1.670536	1.087868	0.921796	1.651786	1.429774	2.458003	1.174188	2.114924	0.422974	1.493045	2.11563493
18	-1.55176	-0.74815	-1.37972	-1.61125	-0.39166	-0.62631	0.179808	-0.72117	-0.80631	-1.36742	0.052163	0.259767	-0.29427	0.366503	0.431142	0.44926	-0.71738	0.338077	0.14024	-0.65896	-1.0365	-0.66225	-1.63807	-1.54569	-0.34477	-0.47645	0.031831	0.467423	-0.7789	0.514441	0.323255	-0.61703878
19	-1.0518	-1.16639	-0.35069	-0.96651	-1.27955	-1.14633	-0.90049	-0.81797	-0.23661	-1.16705	-0.53531	-0.11376	-1.15602	-0.50803	-0.30771	-0.28262	0.106847	-0.19428	-0.29255	0.724916	0.078233	0.128707	-0.73011	-1.18096	-1.07776	-0.52007	-0.5683	-0.33628	0.241282	-0.31822	-0.33075	-1.27664475
20	-1.61899	-2.05814	-1.28383	-1.23978	-2.35316	-2.0292	-0.07749	-0.35787	0.057908	-1.41659	-1.91704	-1.40255	-1.04509	-0.54828	-0.29221	-0.1396	-0.4545	0.264272	0.285252	-0.84858	-0.39753	-0.09002	-1.31699	-1.41032	-0.87164	-0.05382	-1.31611	-0.34264	-0.41381	-0.20725	0.063364	-2.33209999
21	-1.67679	-1.21096	-1.38723	-1.05565	-0.85488	-1.0214	-0.61259	-0.85192	-1.31577	-0.71025	-0.21794	0.392222	-0.93658	-0.6552	-0.2633	-0.14169	-0.72829	-0.33661	-1.07958	-1.61662	-0.89372	-1.43114	-1.3975	-0.97352	-0.79498	-0.95914	-0.16191	-0.36711	-1.54661	-0.19718	-0.64884	-1.10842309
22	-0.15641	-0.9218	-0.36078	-0.55314	-1.50861	-0.88561	-0.36441	-0.07621	0.733944	0.02989	0.477166	-0.01751	0.583098	-0.22052	-0.01726	0.765216	0.07374	0.272743	0.327525	0.277431	0.09052	-0.05348	-0.39209	-0.27182	-0.54182	0.400212	0.237013	-0.04264	0.530123	0.56583	0.169721	-1.14064892
23	0.501155	0.410594	0.27304	0.888215	0.653725	0.570043	1.032763	0.737266	0.120735	0.347975	0.144186	0.296413	1.404055	0.63019	0.372708	-0.00982	-0.60118	0.33438	0.318749	-0.05669	1.155258	0.610677	0.644276	0.594955	0.859481	0.395412	0.78286	0.535744	0.028952	0.154746	0.438839	0.6678529
24	1.680449	0.343501	0.983745	1.358908	1.184206	0.342773	0.038625	0.709026	0.55894	1.117859	0.682439	0.378977	0.781444	0.0642	-0.09993	-0.0371	0.396753	0.072763	0.117872	1.052873	0.375665	0.458318	1.310981	1.330332	0.654442	0.497345	0.566778	0.01902	0.836963	-0.05498	0.082566	0.70726646
25	0.53853	0.465114	0.534787	-0.03226	-0.17848	-0.32116	-0.25937	0.547296	-0.03584	0.581623	-0.31077	-0.36463	0.251081	1.370915	1.329915	1.614599	0.897312	1.701577	1.299054	0.08524	-0.5035	1.052063	0.264081	0.447905	0.16718	0.953903	-0.11962	1.42155	0.018386	1.728778	1.667861	0.04513764
26	0.630348	0.382711	0.466126	-0.09934	1.00234	0.745981	1.447521	1.035906	1.124087	1.400469	-0.05512	-0.74963	0.541548	0.199261	0.12298	-0.43795	0.164614	-0.35165	0.580413	0.850302	0.017984	0.023918	0.358535	0.784189	1.341624	0.699569	-0.23265	0.21047	1.035116	-0.25908	-0.00652	0.84112025
27	-0.35898	0.058326	0.019968	-0.57336	-0.01358	0.67633	1.237755	1.105825	1.119033	0.964365	0.815425	0.292881	0.619565	0.732783	0.544934	1.029181	1.713454	0.889065	1.182723	0.315252	0.708687	1.282764	-0.36908	0.124294	0.891023	1.140144	0.444213	0.682966	0.755992	0.984866	0.998705	0.373346
28	0.916887	0.186786	0.373334	0.247769	0.208547	-0.09016	0.262607	1.101692	0.788645	0.470567	0.217506	0.48238	-0.26073	0.122316	-0.1404	-0.64824	0.218038	0.352773	-0.2247	-0.3494	0.015018	0.42727	0.563357	0.461262	0.673011	0.885896	0.183606	0.017003	0.235601	-0.51884	0.172895	0.15838023
29	3.0356	1.133551	2.547658	1.108365	0.686119	0.467048	2.098958	1.831591	2.047369	1.929188	1.745981	1.764458	1.394906	1.698867	1.174789	0.891888	2.089058	2.364794	1.575487	2.517323	2.358968	2.310243	2.588091	1.711532	1.803895	2.449874	1.684956	1.455501	2.391021	1.137179	2.205725	0.90961798
30	-0.5175	0.335908	0.121809	-0.13708	-0.13452	0.112431	-0.26761	-0.47089	-0.0399	-0.10912	-0.57479	-0.82345	-0.47483	0.747577	0.98085	0.754022	0.538	0.691926	-0.69762	0.086679	0.298977	0.740304	-0.05217	-0.09669	-0.28936	0.116074	-0.71413	0.95857	0.016953	0.958344	0.421897	0.19746059
31	-0.15118	-1.03047	0.830153	-0.04022	-0.73287	-1.37744	-0.7108	-1.17099	-0.5989	-0.05044	-0.55907	0.515847	-0.3822	-0.54867	-0.0549	0.17083	-0.67143	0.348982	0.505927	0.031489	-0.20945	-0.48051	0.174638	0.023589	-0.96956	-0.54533	0.152161	-0.19595	-0.31107	0.115383	0.166521	-1.15626202
32	1.670148	1.224418	2.418464	1.45484	0.835591	1.643108	1.971882	0.842432	0.954632	1.00723	1.892965	1.885434	0.877123	2.279939	2.718056	3.177252	2.470312	2.77449	2.749926	1.475178	1.729361	2.588681	1.837614	1.183033	1.303748	1.75131	1.537541	2.6407	1.267144	3.430579	2.893176	1.50086903
33	0.234447	0.412212	1.357857	0.333753	0.328865	1.475397	0.725547	0.848338	-0.10243	-0.26143	0.6222	0.274249	0.715498	2.6857	2.622778	2.20469	1.886898	2.379911	1.100103	0.675584	1.295204	1.173651	0.932505	0.248918	0.849893	1.340414	0.473859	2.742515	0.287688	2.680013	2.369847	0.96112218
34	1.290035	1.204751	0.768805	1.438009	0.839139	0.927951	0.715347	0.214426	-0.05467	0.630055	0.216588	1.423607	0.694406	1.645938	1.85139	1.532028	1.044664	1.23909	1.46761	0.341357	1.495907	1.072855	1.196626	1.173838	0.676265	0.605087	1.174152	1.853207	0.140613	1.87766	1.522674	1.18408489
35	-0.87497	-0.87587	-1.55502	-0.90639	-0.68304	-1.03127	-0.82084	-1.24611	-1.14463	-0.93018	-0.28426	-1.13004	-1.1761	-0.5649	-0.43085	-1.6006	-1.05698	-1.14378	-0.96635	-2.10655	-2.56946	-1.48808	-1.16879	-0.9683	-1.02796	-1.40455	-1.20412	-0.43502	-1.70802	-1.33296	-1.05551	-0.93153807
36	-1.37185	-1.79649	-1.3678	-1.48114	-1.22479	-2.05267	-1.77743	-0.50931	-0.73843	-0.33607	-0.6434	-0.59943	-1.04814	-0.35117	-0.24484	-0.84855	-1.22889	-0.73643	0.125471	-0.60356	-1.39833	-1.40381	-1.43526	-0.69135	-1.13121	-0.68959	-0.82176	-0.23523	-0.71391	-0.70748	-0.49197	-1.89402871
37	-0.12163	0.101271	0.819785	0.316324	0.053212	0.397726	-0.73739	-0.03505	-0.38456	0.072282	-0.23733	-1.0073	-1.40722	0.232114	0.454331	0.112366	-0.00475	1.290805	0.436792	-0.43295	-1.04116	-0.21438	0.479658	0.416407	-0.22203	0.410801	-1.2275	0.428525	-0.43617	0.277007	0.90275	0.28947317
38	0.283399	0.384703	1.765893	0.356054	0.06509	0.12669	0.592829	0.972293	1.999406	0.655795	0.799361	0.789588	0.641547	1.121734	1.011174	0.825265	2.323473	0.279483	0.813717	1.872611	2.36617	1.887875	0.810541	0.457286	0.701992	1.274117	0.760189	1.125584	2.032254	1.022697	0.667368	0.28390386
39	0.33694	-0.55957	1.349792	0.476262	0.308658	-0.16793	0.620936	1.344575	0.556462	0.370551	0.360244	0.048016	0.441422	1.181003	1.008714	0.672226	1.132757	0.648555	0.065754	0.559756	0.608272	0.992683	0.659641	0.32471	0.875577	0.945547	0.216686	1.147545	0.580882	0.909623	0.707745	-0.12989095
40	0.009619	-0.12851	0.49329	0.366181	-0.32425	-0.27696	0.02365	0.317693	-0.062	-0.30039	0.663277	0.42772	0.204322	-1.13435	-1.30883	-1.8124	-0.78013	-0.9918	-0.58257	-0.25125	-0.51862	-0.57082	0.146799	0.013649	0.08106	-0.31634	0.349333	-1.20394	-0.16947	-1.84057	-1.03136	-0.20767085
41	-1.05388	-0.49148	-1.07736	-0.01504	-1.10293	-1.02535	-0.53804	0.092548	-0.48455	-0.73489	0.254108	-0.74654	-0.79109	0.385523	0.461896	1.120553	-0.43552	0.217612	0.024658	-0.77468	-0.85262	-0.09645	-0.74031	-0.46385	-0.49098	-0.09499	-0.80231	0.49399	-0.66628	1.01845	0.231087	-0.91154568
42	0.698281	0.03729	0.275425	0.474	0.716507	0.580244	0.121425	-0.13668	-0.45908	0.071115	0.73109	-0.34847	-0.64332	0.239991	0.168005	-0.67221	-0.55196	-0.62747	-0.60901	-0.12463	-0.91829	-0.23173	0.422114	0.243699	0.182018	-0.52757	-0.49325	0.254469	-0.31681	-0.41258	-0.44879	0.5488982
43	-1.5948	-1.06432	-1.59656	-0.78238	-0.48298	-0.56423	-0.39762	-0.00054	-0.38922	-0.07522	0.196508	-0.16321	-0.29211	-0.15905	0.038098	-0.62521	-0.54806	-0.24736	-1.53805	-0.83604	-1.18267	-0.62849	-1.47605	-0.60313	-0.28858	-0.27583	-0.22829	0.015975	-0.6469	-0.43031	-0.57448	-0.73918275
44	0.699802	-0.17868	1.581655	-0.38954	-0.90486	-0.5492	-0.03387	0.829403	1.045008	-0.24199	0.441826	-0.81586	0.012456	0.697241	0.972731	1.998018	2.216042	1.520392	-0.53506	0.745882	1.517092	1.498106	0.479182	-0.51994	0.002489	1.257263	-0.50045	0.933601	0.938801	1.866199	0.920527	-0.52416938
45	-0.86212	-0.44904	-1.13047	0.152927	-0.51815	-0.23012	-0.60022	-0.24305	-0.27932	-0.22267	-0.64111	-0.9114	-0.33316	-0.18402	0.114431	-0.30096	0.007448	-0.26814	-0.32401	-0.16039	-0.5215	-0.60065	-0.87643	-0.29667	-0.51267	-0.36067	-0.70765	0.053314	-0.23897	-0.16218	-0.29072	-0.36975199
46	-0.30838	-0.47356	-1.21586	-0.51921	-0.27118	0.508399	-0.44179	-0.92645	-0.30102	-0.24849	-1.06691	-0.61726	-0.98016	-1.5208	-1.23576	-0.8732	-1.39652	-1.49577	-1.76472	-1.18476	-1.67416	-1.07043	-0.73962	-0.41377	-0.58031	-1.0584	-0.80362	-1.31184	-0.7798	-1.12335	-1.72043	0.01757671
47	-1.47941	-1.52053	-1.14695	-2.08504	-1.4446	-1.32863	-1.41932	-2.50752	-1.70353	-2.70281	-1.15205	-1.30179	-1.50811	-1.72945	-1.16539	-0.34018	-1.69432	-1.02772	-1.80004	-2.25239	-1.21106	-1.72205	-1.72546	-2.62108	-2.02187	-2.05963	-1.45252	-1.35097	-2.08282	-0.70471	-1.52044	-1.54211509
48	-0.17002	-1.19639	-0.5382	-0.61138	-1.29158	-0.9806	-0.34	-0.26813	-0.20301	0.208997	-0.03298	0.35072	-0.36263	-0.51217	-0.6668	-1.32564	0.073815	0.279342	-0.54865	-0.84395	-0.54489	-0.71625	-0.60031	-0.0896	-0.57089	-0.05394	0.058643	-0.56012	-0.55122	-1.2263	-0.12583	-1.21990445
49	0.369871	-0.34087	0.711371	-0.42725	-0.25005	-0.29615	0.19207	0.30436	0.814311	-0.16736	-0.09528	0.533155	0.748789	1.925475	2.123261	2.965109	2.586552	2.771073	3.133272	1.553596	1.323041	2.068343	0.35912	-0.16173	0.245057	1.657441	0.647924	2.132198	1.232473	3.03641	2.888348	-0.27431214
50	-0.92837	-1.33058	-0.82242	-1.70345	-1.96166	-1.22597	-1.70331	-0.5002	-1.29169	-1.63823	-0.65281	-0.50106	-0.71295	0.527021	0.916142	0.424333	0.807134	0.280419	0.031828	-0.21373	-0.28051	-0.32898	-1.53246	-1.85763	-1.41994	-0.5839	-0.61729	0.83114	-0.80895	0.690899	0.307947	-1.58447991
51	-0.25057	-0.63289	0.030787	0.006695	0.284131	-0.308	-0.26935	0.601017	1.216346	0.491792	-0.5959	-1.03927	0.094793	-0.12139	-0.0367	-1.13656	-0.28077	-0.67514	0.519091	-0.04446	-0.05587	0.400435	-0.14542	0.373914	0.243495	0.41359	-0.60301	-0.01539	0.622297	-0.83485	-0.29516	-0.22628281
52	-0.06311	-0.18378	0.102125	-0.88008	-1.11295	-0.75574	-0.26067	-0.32131	0.15086	-0.79022	0.828735	0.364672	0.441549	0.436051	0.665677	0.545908	-0.45777	-0.14116	0.742442	-0.52432	-0.1026	-0.15123	-0.39311	-0.70365	-0.49067	-0.0913	0.412168	0.640109	-0.19649	0.679386	0.219539	-0.6799672
53	-0.53896	-0.24938	0.025273	-1.0587	-0.86584	0.212904	0.973838	0.508649	0.117663	-0.33733	0.579975	0.33562	0.05731	0.666117	0.533862	-0.48927	0.207017	-0.17233	-0.04491	0.008467	0.401934	0.972502	-0.58941	-0.74366	0.427883	0.201166	0.229438	0.6497	0.060969	-0.13171	0.069445	-0.20843247
54	-0.47218	-0.30377	-0.44879	-0.30387	-0.79087	0.105301	-0.23907	-0.35451	0.043539	-0.34267	-0.34186	-0.50388	-0.25298	0.111846	0.900457	1.392813	0.528685	1.409913	-0.70212	-1.03008	-0.34461	-0.67506	-0.52093	-0.38153	-0.46746	0.442492	-0.42175	0.656932	-0.51528	1.393925	0.65342	-0.25279653
55	0.325298	-0.91321	0.395897	0.303815	0.861815	-0.56818	-0.61042	0.167932	0.303568	0.527036	-1.29273	-1.27671	-1.09122	-0.15347	-0.50583	-0.68398	0.669666	0.307797	0.027654	0.887301	1.173901	0.342164	0.093755	0.248731	0.038673	0.256873	-1.25823	-0.3184	0.614598	-0.69172	0.133584	-0.26812402
56	-1.07959	-0.54115	-1.48406	-0.97877	-0.38256	-0.33136	-0.06045	-0.25491	-0.29091	-0.39616	0.989832	0.431959	-0.01156	0.368905	0.774978	0.184755	-0.65298	0.446141	-0.26034	-0.82453	-0.83652	-1.14561	-1.36506	-0.71129	-0.19201	-0.0089	0.259357	0.681139	-0.58829	0.458756	0.285678	-0.40707111
57	0.388706	-0.56978	-0.43106	-0.49257	-0.52324	-0.86411	-0.40977	0.471283	-0.96368	-0.92045	-1.73632	0.154686	-0.60317	0.023374	-0.28852	0.047934	-1.19127	-0.6	-0.5357	-0.88568	-0.77381	-1.21763	-0.29083	-0.75099	-0.09738	-0.46176	-0.1655	-0.11385	-0.98034	-0.06842	-0.47501	-0.69262904
58	0.237896	-0.73844	0.445178	0.702684	1.10893	0.113089	0.641337	0.366096	-0.31678	-0.32687	0.25101	0.261533	0.176495	0.154305	-0.29774	-1.12256	-0.57341	-0.24096	0.190753	-0.28578	-0.39783	-0.128	0.361791	0.188842	0.791366	-0.05054	0.234834	-0.06768	-0.32382	-0.9294	-0.05303	0.17061367
59	-0.70145	-0.88806	-1.0025	-0.46109	-0.91304	-0.27301	0.461413	0.278669	-0.69047	-0.20444	0.435744	0.646536	0.643707	-0.54233	-0.72954	-0.28016	-0.5632	-0.32818	-1.69055	-0.34816	-0.22174	-0.86878	-1.03853	-0.5689	-0.02957	-0.39481	0.67283	-0.6109	-0.55627	-0.48577	-0.76495	-0.67811076
60	0.608408	0.072392	-0.14612	0.068942	0.411391	0.693221	0.302325	-0.6546	-0.48356	-1.15355	1.074282	1.265455	1.006855	0.443928	0.714084	-0.27861	-0.581	-0.28807	0.942355	-0.35186	-1.43791	-0.71537	0.042102	-0.55567	0.007696	-0.54032	1.210556	0.673184	-0.44732	0.094936	0.187829	0.51719598
61	-1.10882	-1.14511	-0.88745	-0.67717	-1.07963	-0.3975	-0.57342	-1.09921	-1.64744	-1.3721	-2.13573	-1.757	-0.32083	0.776587	1.311954	2.910353	1.243348	1.152648	-0.21228	-0.99236	0.81461	0.996342	-0.78509	-1.26247	-1.03195	-0.64058	-1.22423	1.17495	-1.40182	2.67059	0.813434	-0.88184271
62	-2.34234	-1.51891	-2.10392	-2.35019	-1.30176	-0.82089	-1.66175	-1.98667	-1.43706	-1.79233	-0.34932	-0.60737	-1.03226	-1.32244	-0.83841	-0.47599	-1.4952	-0.73362	-0.36425	-1.12936	-1.06489	-1.36832	-2.34808	-1.98399	-1.74325	-1.53263	-0.81986	-0.98737	-1.35987	-0.6729	-0.88206	-1.27707316
63	-0.89313	-0.21154	-0.2931	-0.30186	-0.0577	-0.22255	-0.46783	-0.20626	0.098339	0.450497	-0.15506	-0.06077	0.70851	-0.17557	-0.20302	0.507859	-0.35611	-0.50841	-0.07744	-0.35351	-0.11794	-0.33763	-0.53823	0.142	-0.25678	-0.24653	0.264099	-0.13977	-0.13639	0.302763	-0.36385	-0.13355622

Because the outputs from the conditional probability analysis provided outputs within *approximate* regions on each chart, the drought coherence maps shown in Section 6 of the main report were manually interpreted from those results, rather than automatically drawn in GIS or similar.

B.2. Climate Change Hydrology and Resource Assessments

Purpose and Core Concepts

These analysis were carried out with the following key objectives in mind:

A. **Perturb selected Drought Configurations for climate change** to provide:

- Climate change adjusted SEPI aridity index values for 'Tier 1' analysis of resource capability
- Climate change adjusted rainfall and PET inputs for hydrological models

B. **Estimate 'Tier 1' resource capability** for severe and extreme events under median and dry climate based on WRMP14 values.

C. **Generate baseline and climate perturbed flows for use in the Aquator and Wathnet RETs** to support:

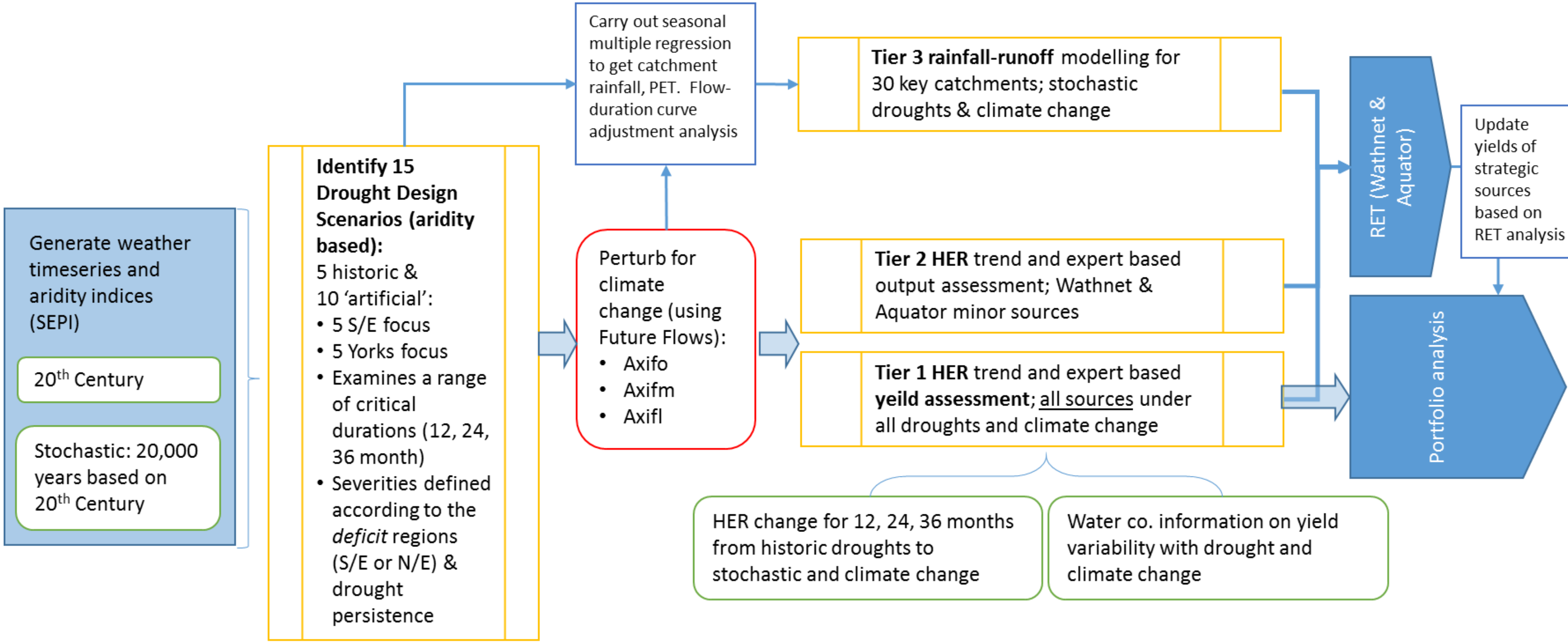
- 'Tier 3' evaluation of resource capability for strategic resources under more severe droughts
- Evaluation of the duration of Level 3 and Level 4 failures used for the consequence analysis
- Resilience testing of the 12 detailed selected Portfolios within the Wathnet RET

Most of the concepts used (climate change perturbation and hydrological modelling) are familiar to practitioners. The 'Tier 1' and 'Tier 3' resource evaluations are less familiar, and were developed to provide an understanding of the impact on source yields that would be expected when droughts that are more severe than the worst historic are experienced within each resource system.

Methodology

A summary of the process that was used to provide the relevant aridity indices, flows and resource evaluations is provided in Figure App-7 below.

Figure App-7 Approach to climate change, hydrology and resource evaluation



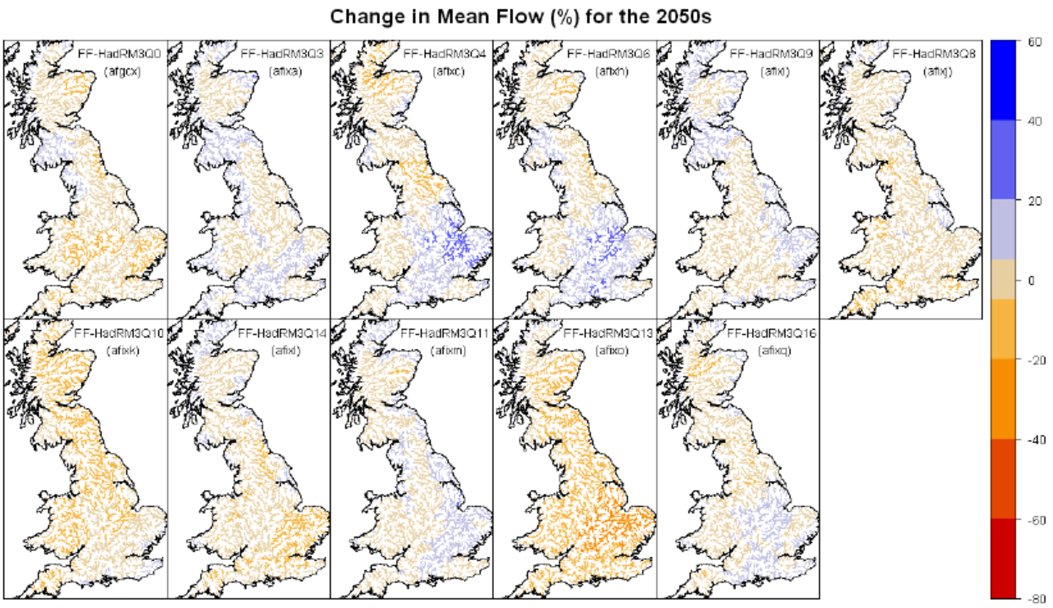
The following explanatory notes support Figure App-7.

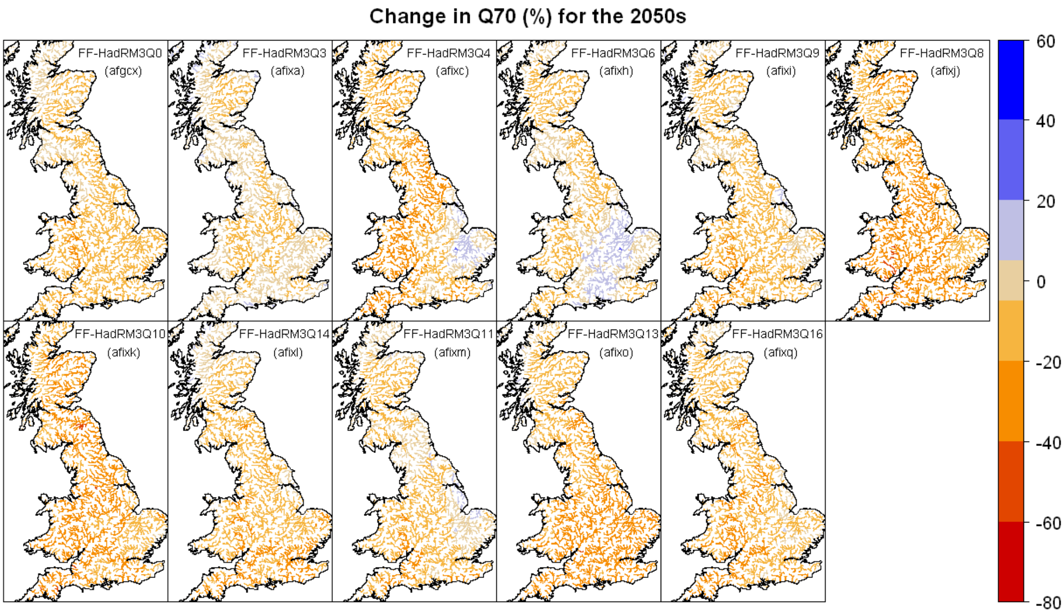
1. Climate Change Perturbation

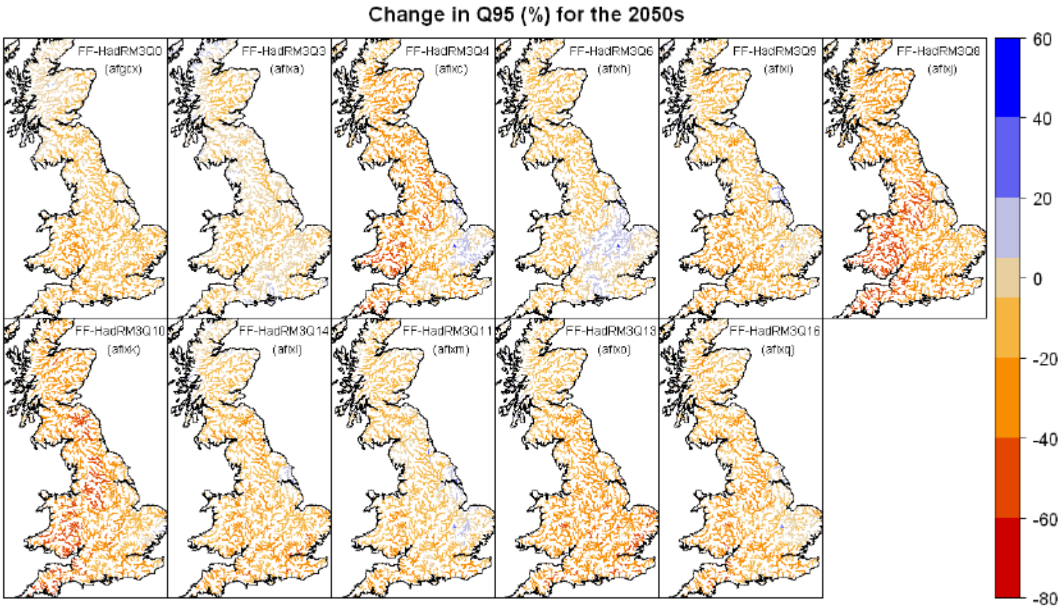
Because this report required the use of spatially coherent, reasonably high probability climate futures, it was decided that the *Future Flows* scenarios should be used for the analysis. For the sake of simplicity this was limited to the use of the following three scenarios:

1. FF-HadRM3Q14 (afixl) – this represented an **average** climate change scenario
2. FF-HadRM3Q13 (afixo) – this represented a **dry** climate change scenario, which incorporates a drier winter and hence affects Q50 flows and systems with larger storage attributes, as encountered in catchments in the eastern half of England.
3. FF-HadRM3Q8 (afixj) – this represented a **dry** climate change scenario, which incorporates wetter winters but much drier summers and autumns, so creates significant stress on 'flashier' systems, as encountered in the west of England and Wales

This decision was made based on an analysis of the Q50, Q70 and Q95 plots of river flows for the 2050s (See **Figure 3** below), and a supporting analysis of the perturbation factors for seasonal rainfall that underlie those plots.







Two sets of perturbation data were derived, both at the 2065 time slice:

1. Monthly rainfall and PET factors, which were applied to:
    a. the analysis of the impacts of climate change on the aridity indices for each of the Drought Configurations
    b. the rainfall and PET entered into the 'Tier 3' rainfall-runoff models
2. Flow factors. These were applied where:
    a. Historic flow data were used for a particular Drought Configuration, without associated hydrological modelling. This was confined to the United Utilities WRZ, where the Drought Configurations meant that data for the Pennines and Cumbria did not exceed the worst historic drought severity, and hence there was no requirement for rainfall-runoff modelling, as the existing historic sequences in the UU Aquator model could be used within Wathnet.
    b. There were any particular concerns about the response of the hydrological models to the rainfall and PET based perturbations. This was only applied in one case, the River Thames. Previous experience of the whole catchment lumped CatchMOD model that was used in the Thames basin indicated that it tended to over-respond to hot, dry spring and summer events. Although the Scenario 0 analysis did not indicate that this was a problem for the baseline, an analysis of the flows under the climate change scenarios demonstrated a much larger impact that suggested by the Future Flows flow factors. Because of the known hydrological modelling risk a decision was therefore taken to limit the impacts of climate change to those represented by the flow factors for the Thames catchment.

For the 2040 horizon a simple assumption was made whereby climate change effects were 60% of the impacts shown at 2065. This was in line with Water Company analyses carried out for WRMP14.

Hydrological Modelling

A total of 30 gauge locations were modelled using existing rainfall-runoff models, gathered from a number of sources:

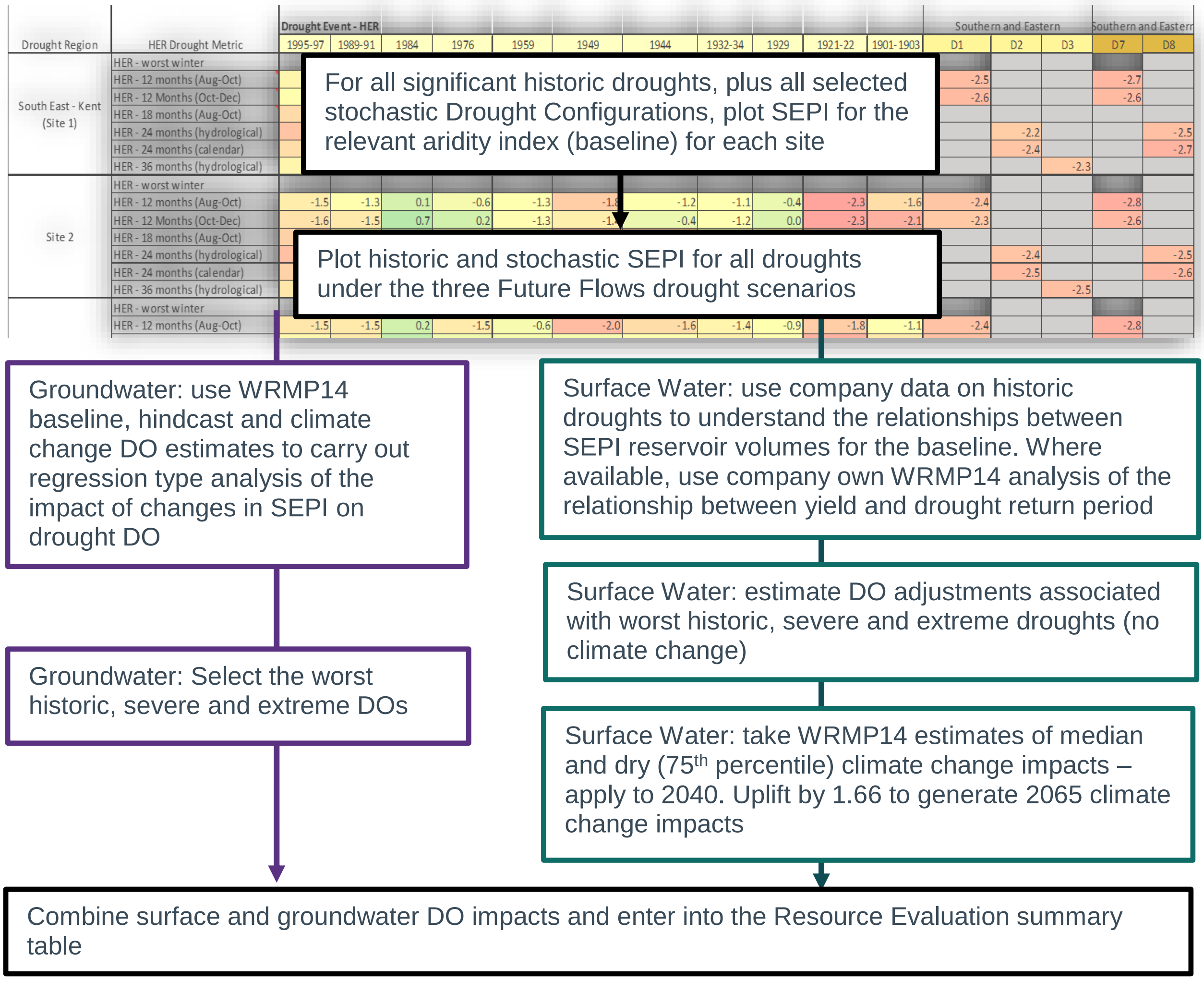
1. Water company own models
2. Models developed for WREA
3. Models developed for the CCRA project

Because the rainfall and PET inputs were based on only a few sites, and a number of the models were not exactly the same as water companies' own data sets (primarily where companies either used naturalised historic flow data, or model set ups were too complex to apply for this project), the following staged process was used to make sure flow responses were as close as possible to water companies own resource model data sets.

1. The historic rainfall and PET data sets from the 22 sites were analysed and seasonally based multiple linear regression analyses were used to derive algorithms that could translate the site data into catchment averages.
2. The generated catchment rainfall and PET data sets were then run through the rainfall-runoff models and compared against the flow data used by the water companies in their own water resource models. A flow-duration curve adjustment algorithm was developed based on this comparison, and applied to all of the project generated flow data.
3. Finally, those Drought Configurations that included an historic data set were checked against the water company historic data sets. This was carried out both for validation purposes (as shown below) and to determine if any further adjustments were required to ensure that there was a good match for low flows under the most significant historic droughts (the FDC adjustment in the previous analysis covered all historic years, and was not necessarily the best fit for significant droughts in a few of the models).

Resource Evaluation

The availability of the Wathnet and Aquator models and associated 'Tier 3' flow data meant that 'Tier 1' resource evaluations only had to be relied on for groundwater sources and a few surface water systems. The following general procedure was used for the 'Tier 1' assessments (an example output of the SEPI analysis sheets used to guide the evaluation is shown in the background):



The Tier 3 evaluation was based on the Scenario 0 outputs that were generated from Aquator and Wathnet. For Aquator, this took the form of a matrix of the number of days of failure against Level 3 and Level 4 compared against increasing levels of demand run through the model. An example of this from the South East Water Barcombe model under climate change scenario A is provided below (the 'failure years' shown relate to the relevant years from the Drought Configuration – in this case the first significant drought occurs in '1917' and relates to the second of the historic events [1932/33] that was incorporated into the Drought Configuration)

Demand (Ml/d) ->	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Failure years ->	11	11	12	13	17	18	20	23	27	31	35	41	41	42
01/01/1900	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1901	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1902	0	0	0	0	0	0	0	0	0	24	52	81	99	114
01/01/1903	0	0	0	0	0	0	0	0	0	0	1	25	31	36
01/01/1904	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1905	0	0	0	0	0	0	0	0	0	13	30	45	63	76
01/01/1906	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1907	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1908	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1909	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1910	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1911	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1912	0	0	0	0	0	0	0	10	36	44	67	90	104	120
01/01/1913	0	0	0	0	0	0	0	12	12	12	17	26	34	47
01/01/1914	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1915	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1916	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1917	0	0	0	0	6	41	67	88	114	125	137	146	152	162
01/01/1918	0	0	0	0	4	4	4	4	4	4	4	4	4	12
01/01/1919	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1920	0	0	0	0	0	0	0	0	0	21	40	47	56	65
01/01/1921	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1922	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1923	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1924	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1925	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/01/1926	0	0	0	0	0	0	0	0	34	50	65	81	90	99

For Wathnet, only a single demand level was run through the Scenario 0 droughts, so the Tier 3 analysis was based on the amount of extra demand that would have to be placed on the worst historic drought (given the length of observed recession) in order to match the reservoir volumes observed for the severe and extreme droughts.

Validation

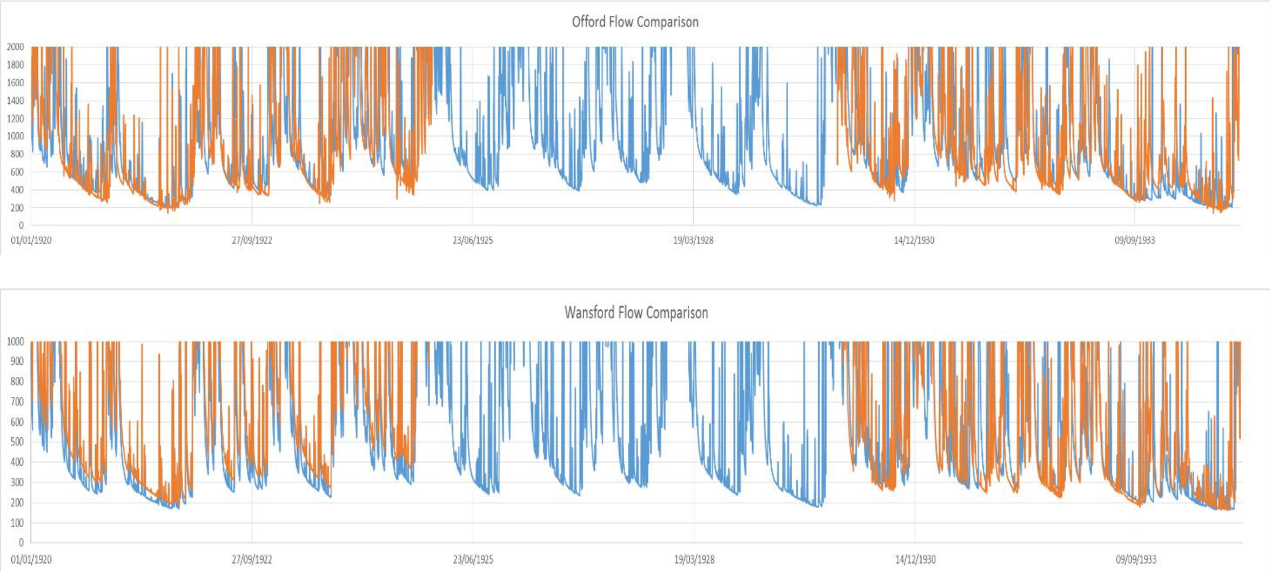
Three types of validation were carried out for this analysis:

1. Sense checking with companies where Tier 1 assessments had been made, and incorporating more detailed company WRMP14 analysis where this was available (Portsmouth Water, South East Water and Sutton & East Surrey Water).

2. For the rainfall-runoff models, the Scenario 0 analyses, which incorporated both stochastically generated and historically based droughts prior to any climate change adjustment, were compared against the flow records for the relevant historic droughts that were used in water companies' own water resource models. Examples of these checks are provided in Figure App-8

3. For the Tier 3 resource evaluation (which was based on running Scenario 0 through the relevant Aquator and Wathnet tools), the general storage behaviour of the historic droughts contained in Scenario 0 was cross compared against the storage behaviour demonstrated in water company WRMP14 water resource models for those drought events. The results of the Scenario 0 analysis are provided in Section 6 of the main technical report.

Figure App-8 Example 'Scenario 0' Flow Checks



Key Uncertainties and Assumptions

The Tier 1 assessments are inherently uncertain, but in most cases only related to the loss of a few percent of yield for the severe and extreme events, and only related to smaller or less drought vulnerable sources (e.g. groundwater).

The main uncertainties within Tier 3 analysis generally related to the translation of the individual site PET and rainfall to into catchment average values, as this could produce different results to the more detailed catchment rainfall analyses that are typically used by water companies in their own rainfall-runoff modelling. In some cases the use of different hydrological models also resulted in differences when compared with water companies' WRMP14 data for historic droughts. However, both of these issues were addressed through the FDC adjustment algorithms, plus the checks on drought flows and storage behaviour that was examined through the Scenario 0 analysis.

Outputs

The outputs generated from the analysis were:

1. Tier 1 resource evaluations (yield of resource systems under severe and extreme droughts, with climate change allowances).

2. Daily rainfall and PET outputs for all of the Drought Configurations that were chosen for analysis within the Wathnet and Aquator tools – this covered 15 droughts of 8 years each at each location under the baseline climate (Scenario 0), and under each of the climate change futures at 2065.

3. Flow records for the 30 sites for all Drought Configurations and climate change scenarios (including Scenario 0).

4. Tier 3 resource evaluation based on the Aquator and Wathnet outputs described in Appendix G

Appendix C. Scenarios and generating supply demand balances

Purpose and core concepts

- Define a suitable range of likely uncertainty associated with key variables in the supply demand balance.
- Specify a number of discrete scenarios for each key variable.
- Combine the component scenarios to develop a range of scenarios for supply demand balance across all water resource zones in England and Wales for 2040 and 2065.

Methodology

We start by determining the following key variables for each water resource zone

Variable reference	Variable description	Calculation methodology
WAFU40, WAFU65	Water Available For Use (2040 and 2065)	Determined from WRMP14 final preferred values, corrected for non-committed resource and for any change in DO in order to correct for different starting levels of service between WRZs. WAFU includes values for outage and treatment works losses as defined at WRMP14.
DI40B, DI40U, DI40L, DI65B, DI65U, DI65L	Distribution Input 2040 and 2065 under base, upper and lower growth scenarios	Calculated from bottom-up as sum of water delivered to households and non-households, distribution losses, underground supply pipe losses and water taken unbilled. Household water delivered is calculated as PCC x population for each scenario. PCC, rate of metering and leakage vary under each demand management strategy as defined in the body of the report and Appendix D.2.
TH	Target Headroom	Fixed at 2016 values for every WRZ
DOBC200b, DOBC500b, DOEC100b, DOEC200b, DOEC500b DOBC100c, DOBC200c, DOBC500c, DOEC100c, DOEC200c, DOEC500c	Correction factors to account for loss in DO due to climate change and drought under different drought scenarios	BC and EC refer to base and extended climate change; 100, 200 and 500 refer to historic, severe and extreme drought; b and c refer to 2040 and 2065. These perturbation factors are calculated using Wathnet results for relevant supply areas and then interpolated between water resource zones according to total DO. This approach recognises the inter-connected impacts of climate change and drought return period. Allowances are also made for additional SDB benefits as a result of drought orders and permits under severe and extreme drought.
SCB, SCE	Base and extended abstraction licence changes	All DO and WAFU values include the confirmed/likely sustainability reductions defined at WRMP14. DO correction factors are applied here to allow for any changes in light of NEP5, and the inclusion of unconfirmed and “non deterioration” impacts on DO – 25% for baseline and 75% for extended scenarios.
SO40DO, SO65DO	New Supply Option DO in 2040 and 2065	These values are calculated by applying a threshold on AISC and summing all new supply options identified as below that threshold for each WRZ.

Forecasting Demand

The medium scenario is based on population forecasts made by all companies at WRMP14 for each Water Resource Zone (WRZ). For London, an updated demand forecast has been input based on the latest forecasts from the Greater London Authority. Upper and Lower scenarios were derived by adjusting all WRMP forecasts up or down by the same % correction, in order to generate national population in 2040 in line with the ONS forecasts for high and low population growth respectively. In this way, the variation between zones was maintained in line with WRMP14, whilst capturing a range of uncertainty in line with ONS.

All population variation was assumed to impact the number of measured households, i.e. all new population is housed in metered properties, such that unmeasured population was consistent between scenarios. Any uncertainty in rate of metering was captured by varying unmeasured household population over time, as described further in Appendix D. A full description of all components of the demand forecast is shown below.

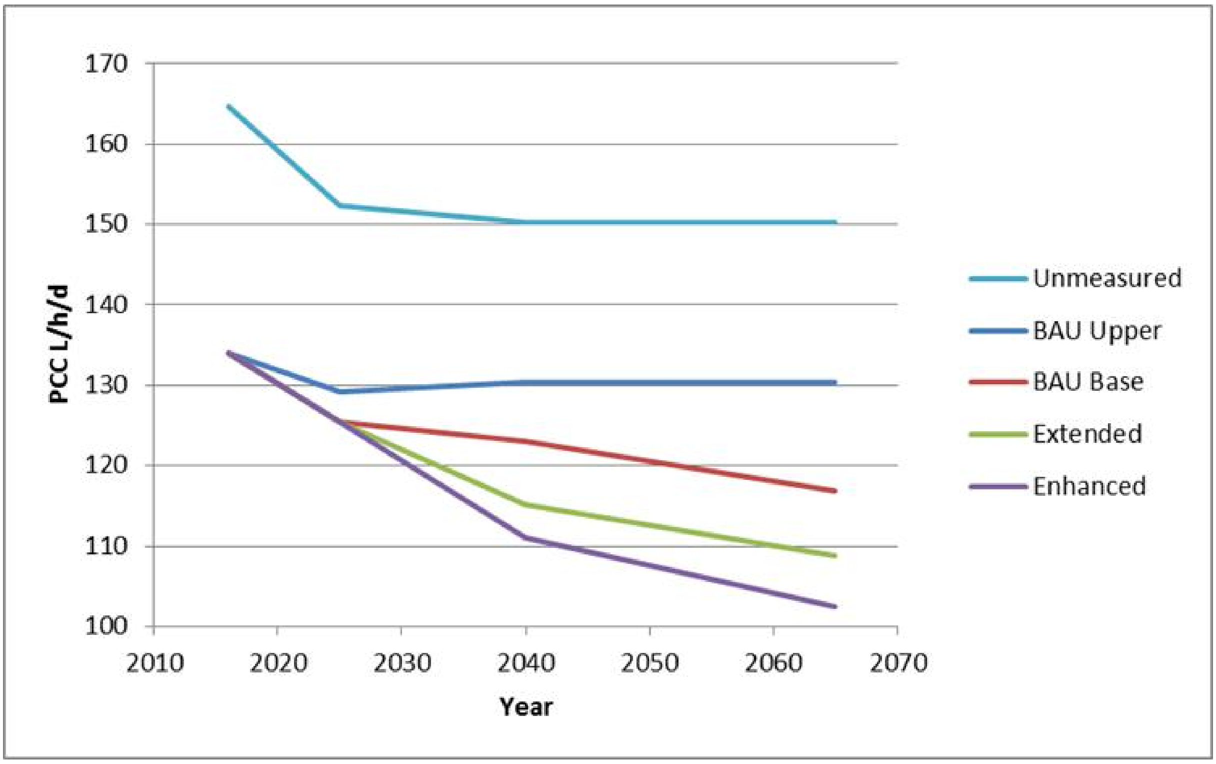
Table App-1 Components of the demand forecast under each growth scenario

Demand Variable	Lower Scenario	Medium Scenario	Upper Scenario
Measured Household Population	Shifted downwards in line with ONS low scenario overall population growth of 20% from 2010 to 2050	WRMP FP values extrapolated to 2065 in proportion to 2025 to 2040 changes in population *(= ONS population forecast)*	Shifted upwards in line with ONS high scenario overall 45% population growth from 2010 to 2050
Existing Measured Household PCC	As per WRMP14 for BAU base strategy, 5% higher for BAU Upper. Savings tailored to water resource zone for extended and enhanced strategies using linear regression analysis (see Section 8.1.1)		
New build properties	110,000 new houses per year	180,000 new houses per year	290,000 new houses per year
Metering	As per WRMP14 to 2040; then slow trickle of optants. Varied between strategies by changing number of unmeasured properties (uniform across scenarios)		
Unmeasured Household PCC	Varies as specified in WRMP14 for each WRZ to 2040 and then decreases slowly until 2065 due to background efficiency improvements		
Non-Household Demand	As per medium scenario but adjusted downward 20%	WRMP FP values, extrapolated forward at 2025-40 rate of change	As per medium scenario but adjusted upward 20%
Distribution Losses	Increase from 2016 at a fixed % of the population growth rate (30% for BAU Base and 50% for BAU Upper) in response to increase in number of properties and length of pipes in the network. Savings tailored to water resource zone under extended and enhanced strategies using linear regression approach		
USPL	Increase from 2016 at a fixed % of the population growth rate (50% for BAU Base and 70% for BAU Upper) in response to increase in number of properties. Savings tailored to water resource zone under extended and enhanced strategies using linear regression approach		

It is likely that a change in occupancy will continue to occur over time and this may impact PCC. We have not attempted to quantify the magnitude of that impact here. This would be a useful part of further work – through further national, regional or local studies. The number of new build properties is provided to illustrate the scale of the demand growth scenarios, assuming no change in occupancy.

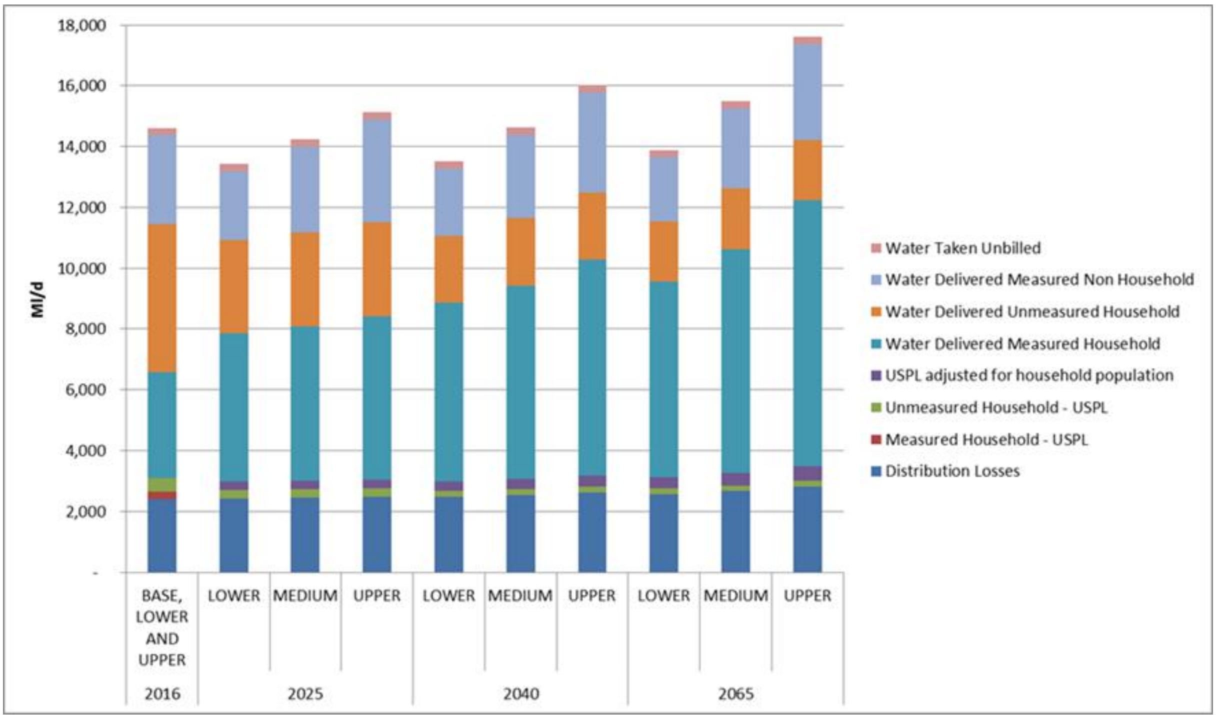
The trends in mean PCC for England and Wales are shown in Figure App-9 below. There is considerable variation between water resource zones, both in absolute values and rates and directions of changes over time. A full description of the different demand management strategies is provided in Appendix D.

Figure App-9 Unmeasured and measured PCC changes between 2016 and 2065 for the BAU Base, BAU Upper, Extended and Enhanced demand management strategies



Under the "Business as Usual – base" demand management strategy, the breakdown of demand for England and Wales under each scenario by year is set out in the figure below.

Figure App-10 Breakdown of demand for England and Wales under each scenario by year



Scenario Calculation

The supply demand balance for every water resource zone under every scenario is calculated by summing the elements in each row as shown in Figure App-11 and Figure App-12 below for 2040 and 2065 respectively.

A macro is run to adjust PCC, leakage and rate of metering under each demand management strategy and re-calculate distribution input and the SDB for each one, with results output automatically to separate tables. A demand management strategy therefore features in all futures, as the ‘first track’ of the solution, with residual deficits being addressed by supply-side options.

All calculations are performed in units of Ml/d or l/h/d (PCC).

Figure App-11 Combination of supply/demand variables for each scenario 2040

Scenario	WAFU40	DI40B	DI40U	DI40L	TH	DOBC100b	DOBC200b	DOBC500b	DOEC100b	DOEC200b	DOEC500b	SCB	SCE	SO40DO
SDB 1	WAFU40	DI40B			TH							SCB		SO40DO
SDB 2	WAFU40	DI40B			TH		DOBC200b					SCB		SO40DO
SDB 3	WAFU40	DI40B			TH			DOBC500b				SCB		SO40DO
SDB 4	WAFU40	DI40B			TH				DOEC100b			SCB		SO40DO
SDB 5	WAFU40	DI40B			TH					DOEC200b		SCB		SO40DO
SDB 6	WAFU40	DI40B			TH						DOEC500b	SCB		SO40DO
SDB 7	WAFU40	DI40B			TH								SCE	SO40DO
SDB 8	WAFU40	DI40B			TH		DOBC200b						SCE	SO40DO
SDB 9	WAFU40	DI40B			TH			DOBC500b					SCE	SO40DO
SDB 10	WAFU40	DI40B			TH				DOEC100b				SCE	SO40DO
SDB 11	WAFU40	DI40B			TH					DOEC200b			SCE	SO40DO
SDB 12	WAFU40	DI40B			TH						DOEC500b		SCE	SO40DO
SDB 13	WAFU40		DI40U		TH							SCB		SO40DO
SDB 14	WAFU40		DI40U		TH		DOBC200b					SCB		SO40DO
SDB 15	WAFU40		DI40U		TH			DOBC500b				SCB		SO40DO
SDB 16	WAFU40		DI40U		TH				DOEC100b			SCB		SO40DO
SDB 17	WAFU40		DI40U		TH					DOEC200b		SCB		SO40DO
SDB 18	WAFU40		DI40U		TH						DOEC500b	SCB		SO40DO
SDB 19	WAFU40		DI40U		TH								SCE	SO40DO
SDB 20	WAFU40		DI40U		TH		DOBC200b						SCE	SO40DO
SDB 21	WAFU40		DI40U		TH			DOBC500b					SCE	SO40DO
SDB 22	WAFU40		DI40U		TH				DOEC100b				SCE	SO40DO
SDB 23	WAFU40		DI40U		TH					DOEC200b			SCE	SO40DO
SDB 24	WAFU40		DI40U		TH						DOEC500b		SCE	SO40DO
SDB 25	WAFU40			DI40L	TH							SCB		SO40DO
SDB 26	WAFU40			DI40L	TH		DOBC200b					SCB		SO40DO
SDB 27	WAFU40			DI40L	TH			DOBC500b				SCB		SO40DO
SDB 28	WAFU40			DI40L	TH				DOEC100b			SCB		SO40DO
SDB 29	WAFU40			DI40L	TH					DOEC200b		SCB		SO40DO
SDB 30	WAFU40			DI40L	TH						DOEC500b	SCB		SO40DO
SDB 31	WAFU40			DI40L	TH								SCE	SO40DO
SDB 32	WAFU40			DI40L	TH		DOBC200b						SCE	SO40DO
SDB 33	WAFU40			DI40L	TH			DOBC500b					SCE	SO40DO
SDB 34	WAFU40			DI40L	TH				DOEC100b				SCE	SO40DO
SDB 35	WAFU40			DI40L	TH					DOEC200b			SCE	SO40DO
SDB 36	WAFU40			DI40L	TH						DOEC500b		SCE	SO40DO

Figure App-12 Combination of supply/demand variables for each scenario 2065

Scenario	WAFU65	DI65B	DI65U	DI65L	TH	DOBC100c	DOBC200c	DOBC500c	DOEC100c	DOEC200c	DOEC500c	SCB	SCE	SO65DO
SDB 1	WAFU65	DI65B			TH							SCB		SO65DO
SDB 2	WAFU65	DI65B			TH		DOBC200c					SCB		SO65DO
SDB 3	WAFU65	DI65B			TH			DOBC500c				SCB		SO65DO
SDB 4	WAFU65	DI65B			TH				DOEC100c			SCB		SO65DO
SDB 5	WAFU65	DI65B			TH					DOEC200c		SCB		SO65DO
SDB 6	WAFU65	DI65B			TH						DOEC500c	SCB		SO65DO
SDB 7	WAFU65	DI65B			TH								SCE	SO65DO
SDB 8	WAFU65	DI65B			TH		DOBC200c						SCE	SO65DO
SDB 9	WAFU65	DI65B			TH			DOBC500c					SCE	SO65DO
SDB 10	WAFU65	DI65B			TH				DOEC100c				SCE	SO65DO
SDB 11	WAFU65	DI65B			TH					DOEC200c			SCE	SO65DO
SDB 12	WAFU65	DI65B			TH						DOEC500c		SCE	SO65DO
SDB 13	WAFU65		DI65U		TH							SCB		SO65DO
SDB 14	WAFU65		DI65U		TH		DOBC200c					SCB		SO65DO
SDB 15	WAFU65		DI65U		TH			DOBC500c				SCB		SO65DO
SDB 16	WAFU65		DI65U		TH				DOEC100c			SCB		SO65DO
SDB 17	WAFU65		DI65U		TH					DOEC200c		SCB		SO65DO
SDB 18	WAFU65		DI65U		TH						DOEC500c	SCB		SO65DO
SDB 19	WAFU65		DI65U		TH								SCE	SO65DO
SDB 20	WAFU65		DI65U		TH		DOBC200c						SCE	SO65DO
SDB 21	WAFU65		DI65U		TH			DOBC500c					SCE	SO65DO
SDB 22	WAFU65		DI65U		TH				DOEC100c				SCE	SO65DO
SDB 23	WAFU65		DI65U		TH					DOEC200c			SCE	SO65DO
SDB 24	WAFU65		DI65U		TH						DOEC500c		SCE	SO65DO
SDB 25	WAFU65			DI65L	TH							SCB		SO65DO
SDB 26	WAFU65			DI65L	TH		DOBC200c					SCB		SO65DO
SDB 27	WAFU65			DI65L	TH			DOBC500c				SCB		SO65DO
SDB 28	WAFU65			DI65L	TH				DOEC100c			SCB		SO65DO
SDB 29	WAFU65			DI65L	TH					DOEC200c		SCB		SO65DO
SDB 30	WAFU65			DI65L	TH						DOEC500c	SCB		SO65DO
SDB 31	WAFU65			DI65L	TH								SCE	SO65DO
SDB 32	WAFU65			DI65L	TH		DOBC200c						SCE	SO65DO
SDB 33	WAFU65			DI65L	TH			DOBC500c					SCE	SO65DO
SDB 34	WAFU65			DI65L	TH				DOEC100c				SCE	SO65DO
SDB 35	WAFU65			DI65L	TH					DOEC200c			SCE	SO65DO
SDB 36	WAFU65			DI65L	TH						DOEC500c		SCE	SO65DO

Validation

Validation was carried out in a number of ways:

- Comparing the bottom-up approach of PCC x Population with a simpler top-down approach where water delivered is scaled according to perturbation factors for growth.
- Cross-check of SDB values and key components against those calculated at WRMP14.
- Calculation of impacts of uncertainty at various scales – from WRZ through to national level to check all variation is as expected.
- Wathnet analysis used to verify climate and drought impacts are as defined in scenario SDBs, with adjustment where necessary.

Key uncertainties and assumptions

The following assumptions are made for scenario calculation:

- ONS high and low population forecasts provide a suitable range of uncertainty for water resource planning.

- WRMP14 forecasts of growth are broadly correct for the medium scenario across all regions, with the exception of London (updated in line with GLA forecast). Any variation in growth is specified about these baseline trends for each WRZ. Growth is extrapolated linearly from 2040 under the medium scenario, adjusted as necessary to fit the respective national population forecast.

- WRMP14 values for WAFU, DO, PCC, Leakage, etc. are accurate enough for use as baseline values here. Unmeasured PCC and USPL are especially uncertain, which may in turn impact the accuracy of distribution loss values.

- “Committed” WRMP14 supply and demand options planned for AMP 6 and 7 are delivered as planned (see Appendix D).

- Distribution losses increase as a % of population growth (dependent on demand management strategy).

- Allowance is made for drought orders and permits that would be granted under severe and extreme drought. These are estimated only, as described previously, and carry considerable uncertainty.

- Allowance for outage and water treatment works losses remain constant over time and across scenarios.

Outputs

- 36 SDB scenarios comprising 3 population growth (upper, medium, lower), 2 climate change (baseline, extended), 2 abstraction licence change (baseline, extended), 3 drought (historic, severe, extreme) scenarios, for both 2040 and 2065.

- Tables of SDB for every WRZ by year and by scenario.

Relative contribution to deficits in 2040

In section 8 of the Technical report, we identify a sub-set of scenarios for the development of portfolios of supply options. The selection of these scenarios is described in more detail there, but here it is useful to use the sub-set to show how the supply/demand balance is built up from a range of different components. The first four of these, demand growth, abstraction changes, climate change and change in drought level of service are described in detail in Section 4 and above. Also of importance for the SDB in every scenario are the following components:

- Starting SDB at 2016: some WRZs are approximately in balance whilst others have a notable surplus due to historic development of water resources, expansion of supply zones, etc.

- New deployable output committed over the next 10 years (AMP 6 and 7), which for the purposes of this study is assumed to be delivered as planned by 2025.

- Drought orders and permits, enabling an increase in abstraction above normal environmental limits, which are considered likely to come into force under severe or extreme drought scenarios. There is considerable uncertainty regarding these and further work is required before they are accurately quantified.

- The demand management savings proposed through reducing consumption by metering, new house building and water efficiency, and reducing leakage by network investment. A number of such strategies are defined and calculated for every WRZ as described in section 8.1.

- A “Level of Service” (LoS) correction, calculated during the preliminary drought analysis to account for different starting levels of service between WRZs.

A full breakdown of these components for each of the 13 sub-sampled scenarios under BAU base demand management is shown below for 2040. The scenarios were selected in order to vary a number of these components methodically, to evaluate the impact of each in turn.

Figure App-13 Deficit contribution components by portfolio, 2040

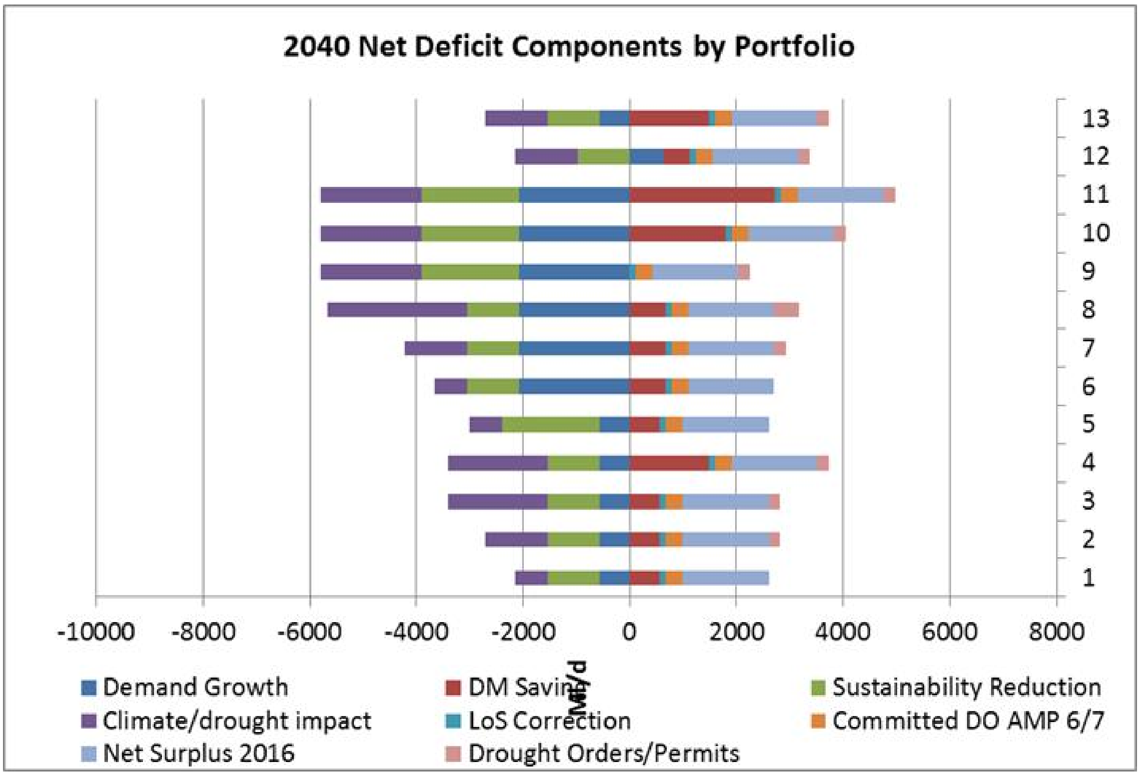
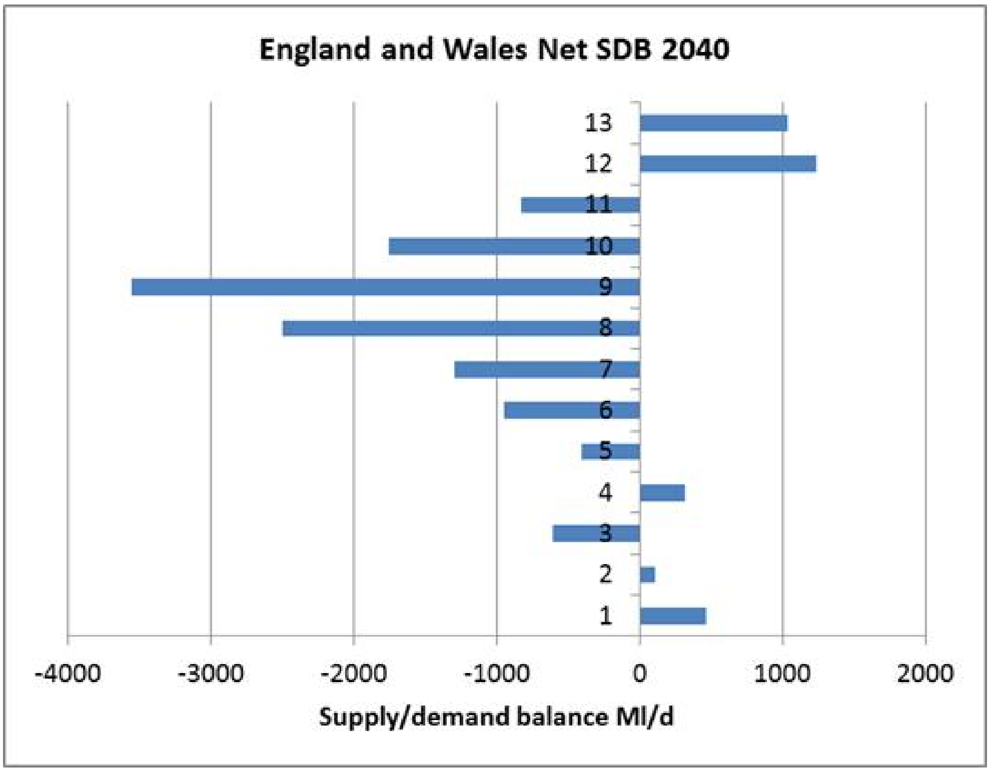


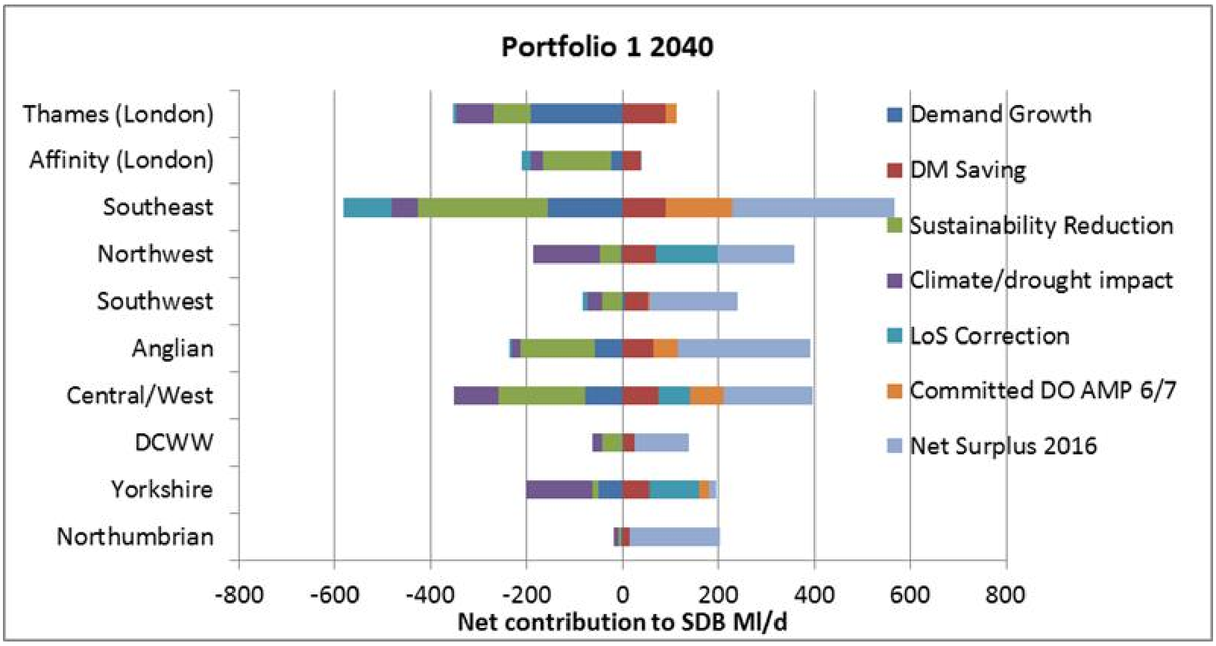
Figure App-14 Net supply/demand balance by portfolio for England and Wales, 2040



Portfolios 1 and 8 are selected for a regional comparison of SDB. The deficit components vary significantly between regions, as shown below. It is important to note that SDB at the supply area scale may mask notable impacts for individual WRZs, which may require significant local investment as mitigation.

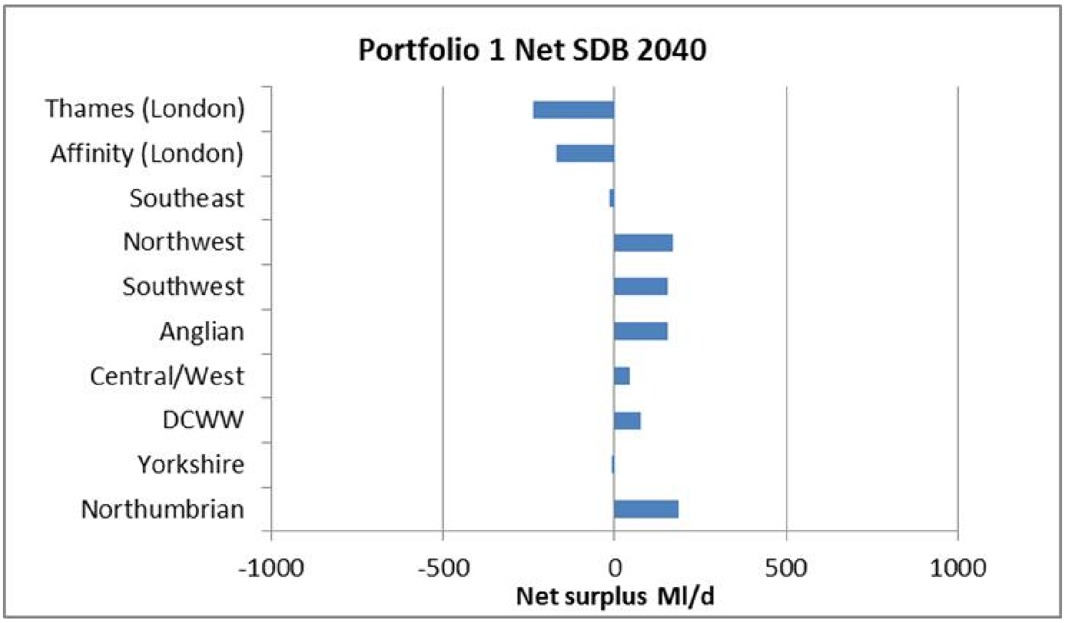
The contribution to deficits by region under portfolio 1 (medium growth, base climate, historic drought, base abstraction licence changes, base demand management) in 2040, is shown in Figure App-15.

Figure App-15 Net deficit components for portfolio 1, 2040



The cumulative effect of all these SDB components is shown in Figure App-16.

Figure App-16 Portfolio 1 Net SBD, 2040

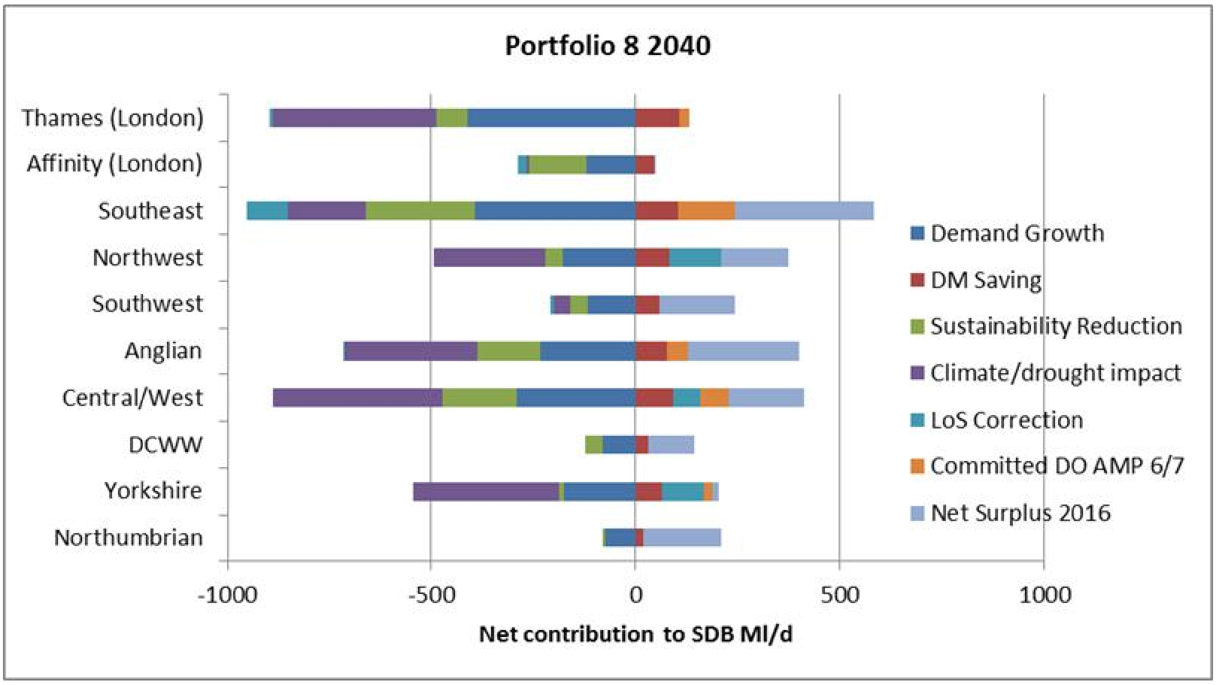


Under portfolio 1, there is sufficient surplus in 2040 for transfers to make a major contribution to mitigating deficits in the southeast, although notable resource development is required locally. The optimum portfolio of resource, demand management and transfers is discussed further in section 8.

For portfolio 8, the magnitude of all deficit components is notably larger, but the impacts on SDB still vary considerably due to differences in starting position.

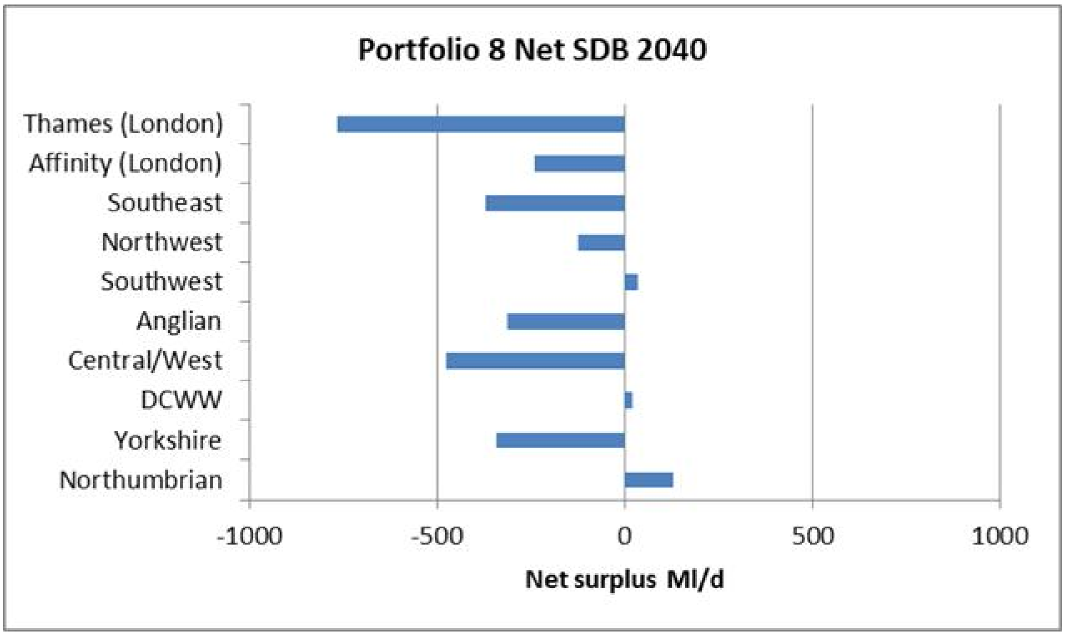
Contribution to deficits by region, portfolio 8 (upper demand, extended climate change, extreme drought, base abstraction licence changes, base demand management) in 2040.

Figure App-17 Net deficit components for portfolio 8, 2040



Net SDB values under portfolio 8 are shown in Figure App-18. There is a notable move from surplus to deficit. From this comparison, it can be envisaged how gradually increasing impacts of a particular component can initially have no impact on resource requirements, but once the SDB balance threshold is crossed, investment required increases rapidly.

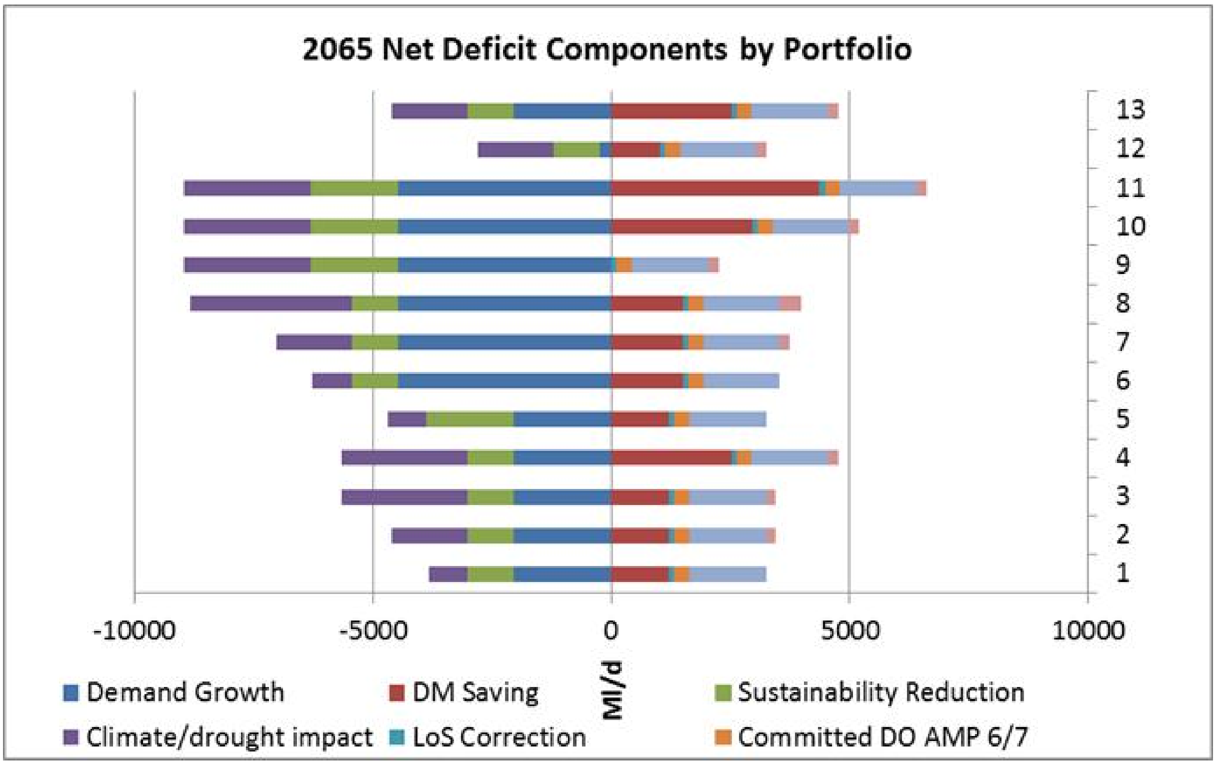
Figure App-18 Portfolio 8 Net SBD, 2040



Relative contribution to deficits in 2065

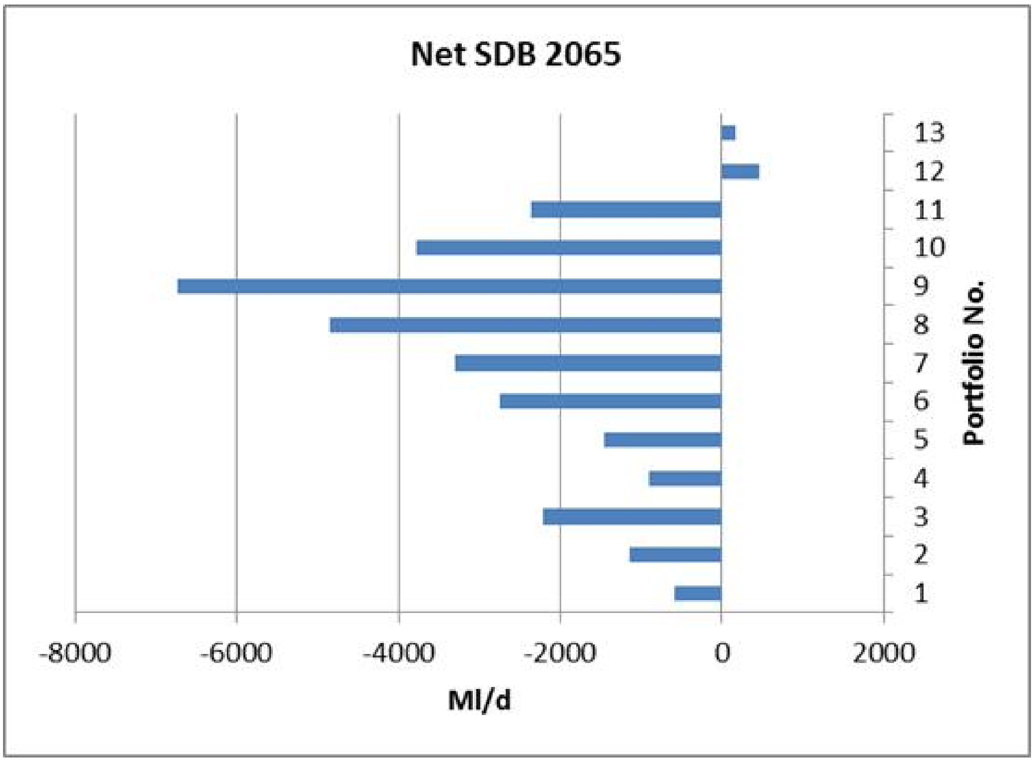
As for 2040, a full breakdown of components for each of the 13 sub-sampled scenarios under BAU base demand management, for England and Wales as a whole, is shown in Figure App-19 for 2065.

Figure App-19 Net deficit components by portfolio, 2065



By 2065, there is a net deficit under most scenarios. Note that this includes surplus volumes, so total deficits across all supply areas and WRZs will be higher.

Figure App-20 Net SDB, 2065



The breakdown by region for portfolios 1 and 8 is shown in Figure App-21 and Figure App-22 (for portfolio 1) and Figure App-23 and Figure App-24 (for portfolio 8).

Contribution to deficits by region, portfolio 1 (medium growth, base climate, historic drought, base abstraction licence changes, base demand management) in 2065:

Figure App-21 Net deficit components for portfolio 1, 2065

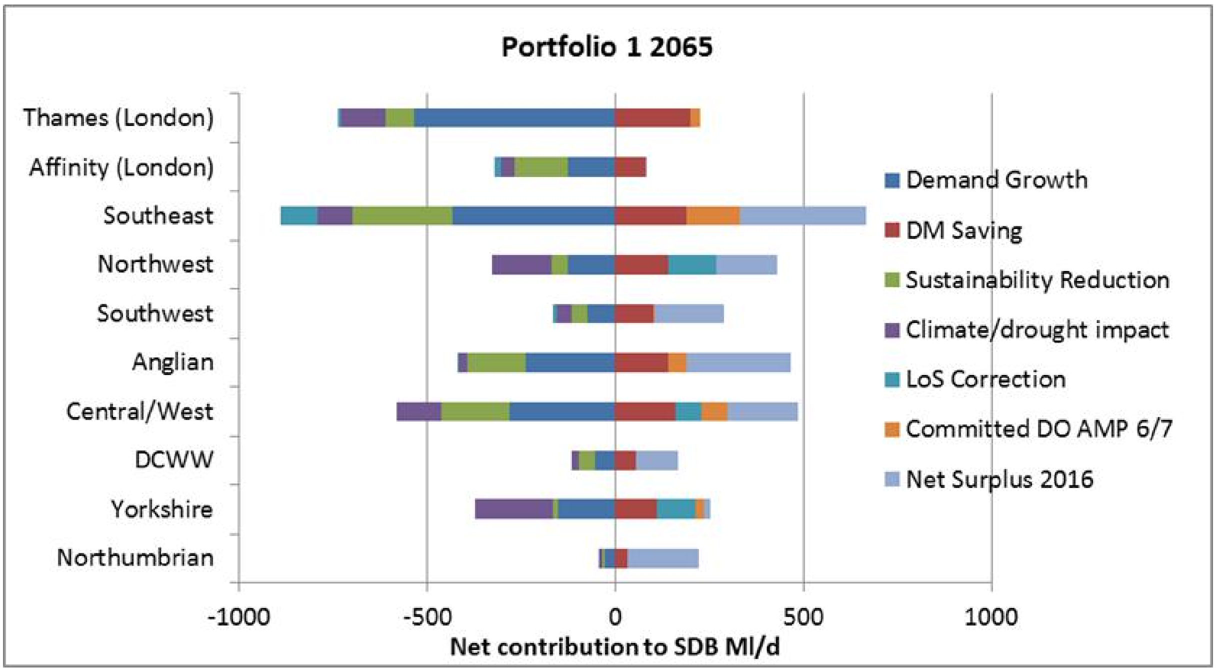
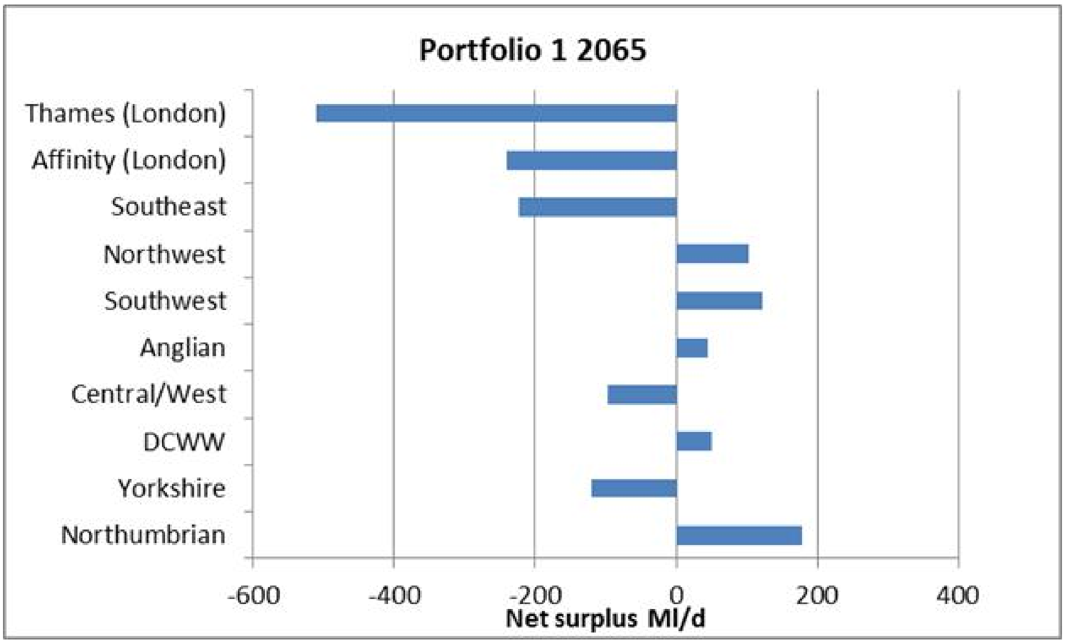


Figure App-22 Net deficit for portfolio 1, 2065



By 2065, the deficit in London far exceeds any surplus in the northwest, even under this relatively optimistic scenario. Note that these do not include development of any supply options, or demand management beyond BAU base.

Contribution to deficits by region for portfolio 8 (upper demand, extended climate change, extreme drought, base abstraction licence changes, base demand management) in 2065 is shown in Figure App-23, with net SDB in Figure App-24.

Figure App-23 Net deficit components for portfolio 8, 2065

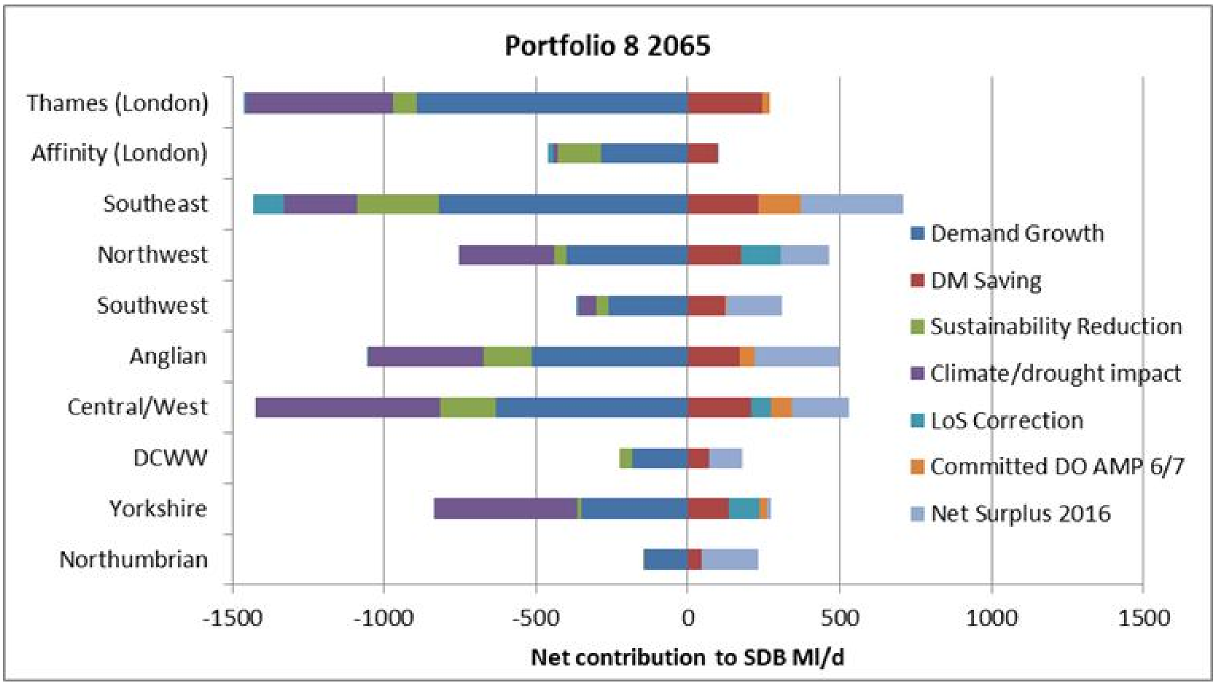
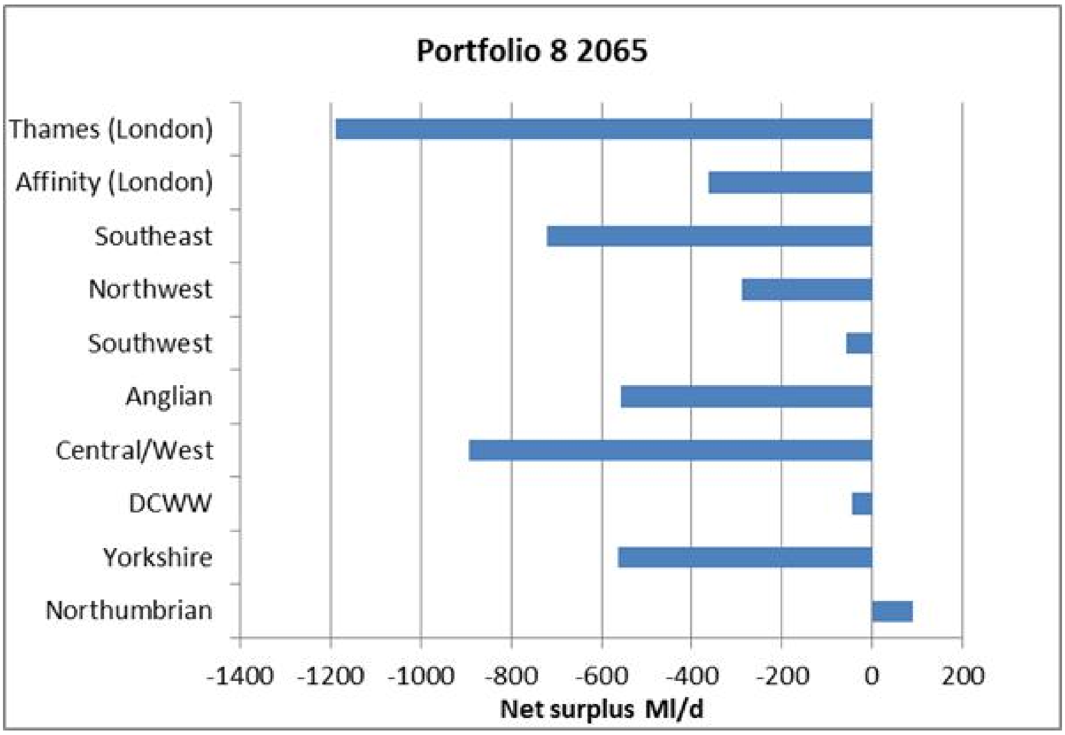


Figure App-24 Net deficit for portfolio 8, 2065



Appendix D. AISC Analysis of Options

D.1. "Committed" options (for AMP6 & 7)

Purpose and core concepts

- Specify options committed for delivery in AMP 6 and 7 to be added to the supply demand balance for every WRZ.
- Update SDB values as necessary to ensure only these options are included across all WRZs in the baseline SDB for all scenarios.

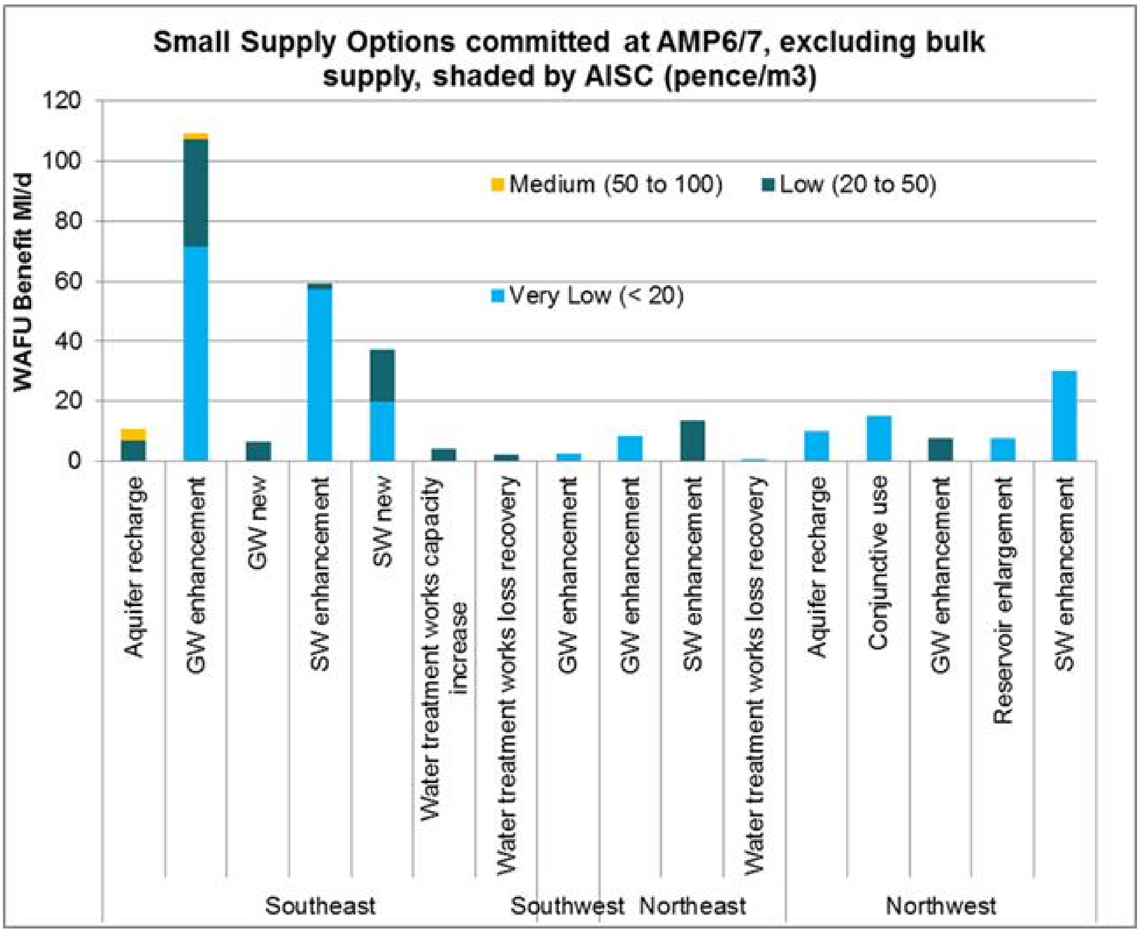
Methodology

For the purposes of this study, 79 schemes were identified as "committed" in company final preferred WRMPs, for delivery in AMP 6 and AMP 7. They include the following:

- Development of 317 Ml/d of new resource (new deployable output) across England and Wales, primarily groundwater enhancement (128 Ml/d) and surface water enhancement (103 Ml/d). The total NPV of committed new deployable output options is £330 million.
- A further 218 Ml/d of small bulk supply transfers are identified as "committed", at a cost of £512 million. 138 Ml/d of these are potable imports.

This committed resource was reviewed in conjunction with water resource managers and an appropriate volume included across all scenarios and portfolios, with the assumption that all will be delivered by 2025. The distribution of WAFU benefit by supply type is shown in the figure below. 70% of committed resource development occurs in the southeast.

Figure App-25 WAFU benefit of WRMP "Committed" supply options resulting in new deployable output (excluding bulk transfers) separated by region, coloured by AISC cost category



Validation

All supply/demand options were checked with company water resource managers for any changes to delivery since WRMP14. A final table of options was compiled and checked.

Key uncertainties and assumptions

Some options are still to be finalised and contain a number of uncertainties over WAFU benefit, timing and feasibility. Primary among these are any hydrogeological uncertainties for groundwater schemes, and any environmental uncertainties regarding abstraction licences, particularly in light of the Water Framework Directive.

We have assumed these issues will be overcome for the majority of schemes, in light of more recent option screening in preparation for PR19.

Outputs

The list of all committed options assumed to be completed by 2025 is presented in the following table, ordered by company and region.

Table App-2 List of committed supply options to be completed by 2025 by company

Supply Option by Company	WAFU On Full Implementation MLD
Southeast	
Anglian Water	**110**
Amendment to Ardleigh Agreement	2.6
Fenland RZ Transfer	1.5
Newmarket RZ Transfer	5
Norwich intake to existing bankside storage	46
Reduce Ruthamford North RZ raw water export	8
River Lark flow augmentation	4.5
Ruthamford North RZ Transfer 1	36
West Suffolk RZ transfer	6
South East Water	**73**
Barcombe WTW- Recovery of Process losses	2
Kippings to Pembury SEW Medway (RZ7 to RZ1)	4
Maytham Farm Option 2 Increase ADO and PDO: Refurbish treatment works	4.3
Portsmouth Water (Clanfield) to SEW RZ5 (Tilmore Reservoir) Transfer	10
RZ1 (Blackhurst) to RZ6 (Aylesford) via East Peckham	4
SESW Bough Beech to SEW Riverhill	5
SESW Outwood to SEW Whitely Hill	5
SEW Blackhurst (RZ1) to Best Beech (RZ2)	10
SEW RZ5 (Tilmore Reservoir) to Portsmouth Water (Clanfield)	10
SEW RZ6 (Aylesford) to SEW Medway RZ1 (Blackhurst) via East Peckham	4
Transfer from Matt's Hill (SWS KME) to Detling SR (SEW RZ6)	5
TWU Windsor to Surrey Hills - 10Ml/d	10
Southern Water	**77**
Additional 5Ml/d PWCo transfer to HS by releasing water from the existing PWC-SN transfer	5
Cross Solent Main to 20 Ml/d	8
Hardham Winter transfer stage 1	2
Implement a licence variation at Danaway combined with an increase in pump capacity	1.6
Lewes Road asset enhancement	1.6
Licence amendment for the River Medway Scheme	5
Pro-active operation of Candover augmentation scheme (SWS owned; MDO)	20
PWCo transfer to Moorhill SR - 10Ml/d transfer but 30Ml/d capacity pipework to accommodate future increases	10
Re-configure Hardham well field	4
Release 'locked in DO' from Kent Medway	4.7
Shoreham to Brighton pipeline (stage 3 of the Hardham Winter Transfer-Brighton scheme)	4
Shoreham to Brighton pipeline (stage 3 of the Hardham Winter Transfer-Brighton scheme) - transfer component only (SW to SB). (Costs included under N8c)	7
Sussex Coast - 8 Ml/d (Lower Greensand) ASR (MDO)	4
Sutton and East Surrey Water	**13**
Existing Transfer - The Avenue (ES to ST)	7.5
New borehole (Lower Greensand) - mains connection at Source 39	3.4
UV treatment for Source 6	2.1
Thames Water	**41**
AR Kidbrooke	5
BT ESW Chingford reduction	17
BT RWE Didcot	17
GW ELRED	1.0
GW Honor Oak	1.5

Supply Option by Company	WAFU On Full Implementation MLD
Southwest	
Bristol Water	**9**
Bulk transfer reduction	4
Honeyhurst Transfer	2.4
Hutspill Axbridge Transfer	3
Northeast	
Yorkshire Water	**22**
East Yorkshire Groundwater Option 1	6.6
North Yorkshire Groundwater Option 1	2
Reduction in WTW process losses Option 3	0.4
Vale of York Phase 2	13.4
Northwest	
United Utilities	**80**
Thirlmere	80
Central/west	
Severn Trent Water	**75**
Lower Worfe Augmentation Scheme	10
Ogston to Mansfield Pipeline Enhancement	5
Raise Dam at Draycote (6%)	7.5
Trimpley-Worcs. Groundwater Conjunctive Use	15
Uckington Expand Bh Output	6.2
Upper Worfe Groundwater Augmentation	20
Weston Jones	1.4
Whitacre ASR Phase 2 - now referred to as Phase 4	10
Grand Total	**501**

D.2. Demand management strategies

Purpose and core concepts

- Determine a range of potentially feasible demand management savings, across PCC, USPL and distribution losses, and compile into a number of strategies for application to scenarios.
- The range should include a "feasible worst case", in which savings specified at WRMP14 are not delivered, and a highly ambitious strategy that approaches what might be technically possible under a scenario of significant changes in policy and customer behaviour.
- Define SDB benefits and high level costs (including any opex savings) associated with each strategy.
- Quantify the savings in such a way that they can be superimposed on SDB scenarios to allow for supply-side portfolio development, cost estimation and analysis in Wathnet.

Methodology

Our starting point for demand management strategies was a high level review of options presented at WRMP14.

After screening for exclusivity, 580 independent or lowest cost demand management options were identified at WRMP14, across 19 option categories.

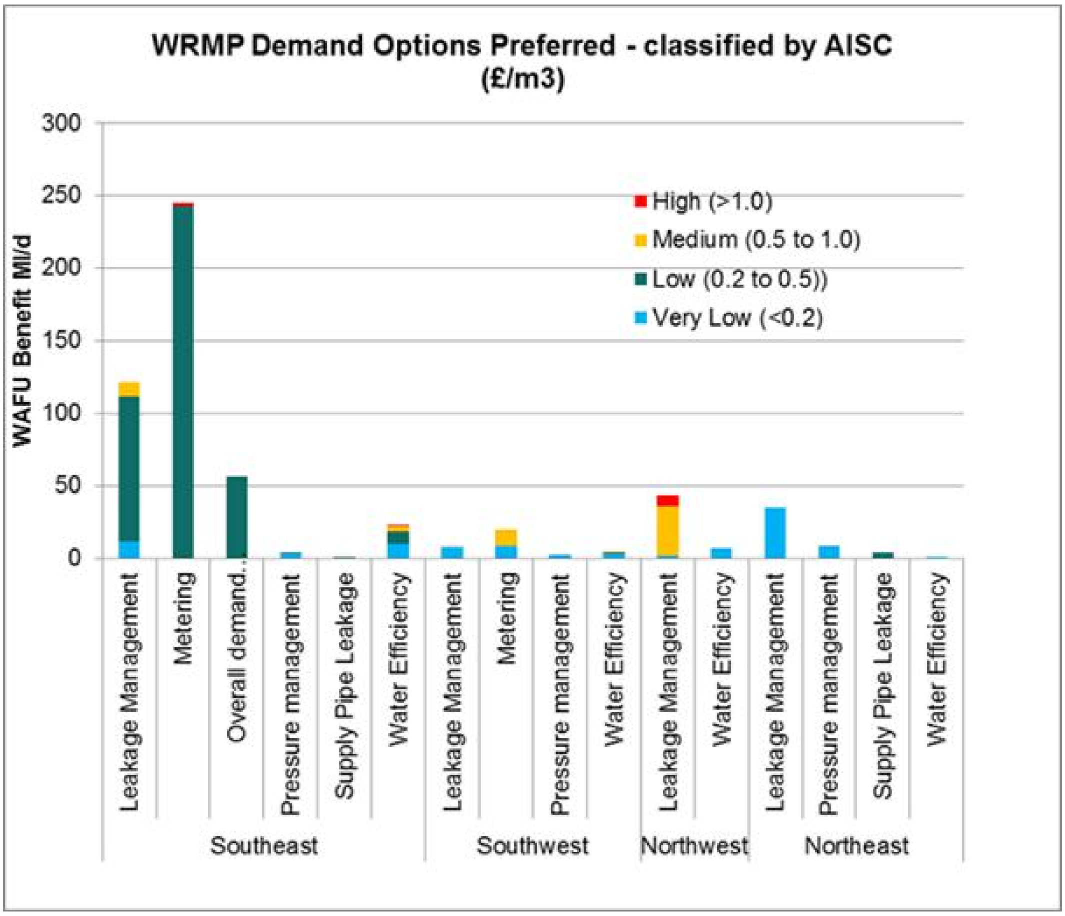
WRMP14 - Preferred Demand Options (those included in final company plans)

Non-leakage preferred demand management totals 364 Ml/d, with leakage reduction of 254 Ml/d. Excluding Thames Water (no cost breakdown available for demand management), total preferred leakage reduction of 132 Ml/d has an associated NPV of £341 million. Remaining demand management of 133 Ml/d is costed at £196 million. For Thames Water, final preferred overall demand management of 289 Ml/d has an associated NPV of £712 million.

Preferred demand management options are shown in Figure App-26, separated by region and shaded by cost category.

The cost breakdown demonstrates the significant increase in costs associated with demand management beyond companies preferred plans. It also highlights the spatial variability in quantified options for demand management, which makes defining options at a national level difficult.

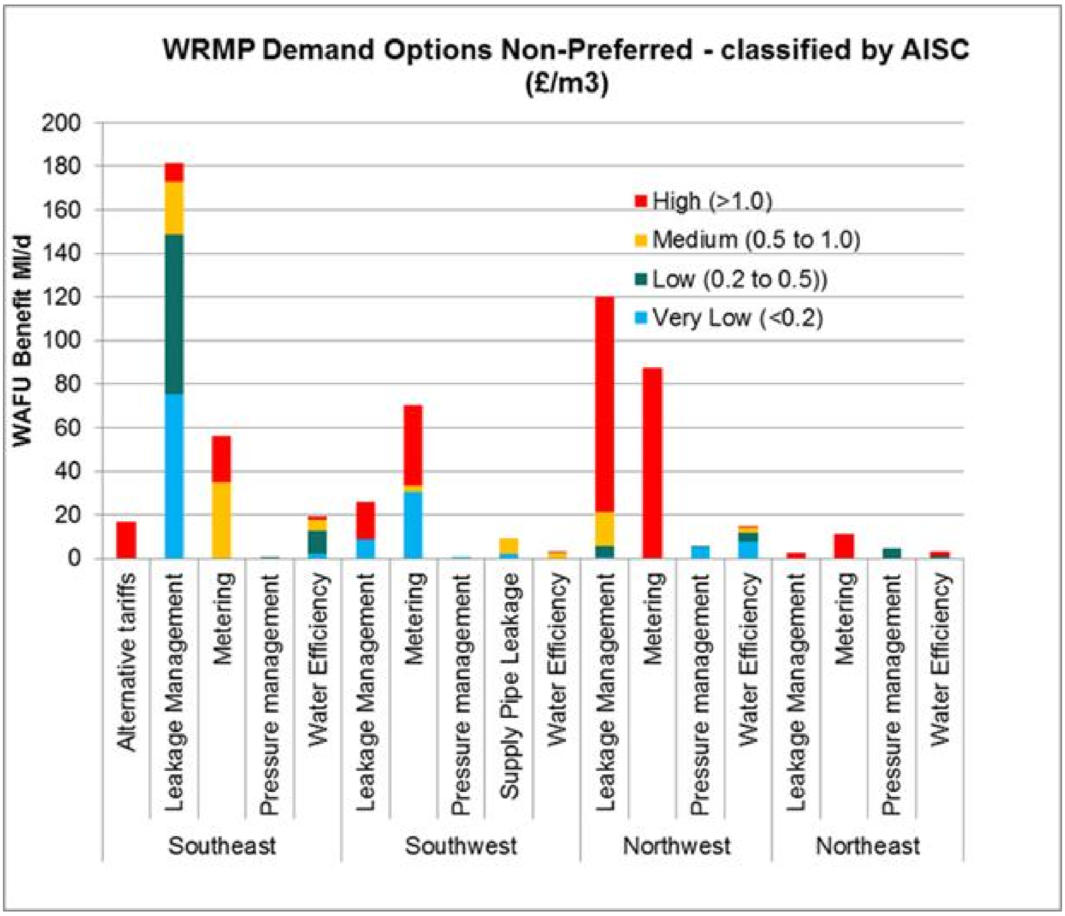
Figure App-26 WAFU benefit of WRMP preferred demand options, separated by region, coloured by AISC cost category



WRMP14 - Non-Preferred Demand Options (options not included in company plans)

Demand management options not included in final preferred plans add up to a total 684 Ml/d of WAFU savings, with a combined NPV of £7 billion. The primary focus is on leakage and metering.

Figure App-27 WAFU benefit of WRMP non-preferred demand options, separated by region, coloured by AISC cost category



Alternative Approach for Demand Management Evaluation at National Level

The delivery team was tasked here with quantifying the potential for highly ambitious demand management to mitigate future imbalances in the supply demand balance. The starting point for this was a review of options presented at WRMP14 across all water companies, the Waterwise evidence base paper for large-scale demand management and a UKWIR research paper on the potential for large-scale leakage published in 2011.

The difficulty with using WRMP14 demand options as a basis for the national study is that they are highly company-specific, vary substantially in size and cost and therefore difficult to compare consistently at a regional or national level. They are also too small in total to form the basis for the more highly ambitious demand management strategies. Furthermore, a large part of demand management at WRMP14 was un-costed – through, for example, fixing leakage at 2015 values (requiring considerable reductions in leakage per property) and with declines in PCC that were not all specified as options.

Therefore for this study, it was decided to use an alternative top-down approach of reviewing PCC and leakage per property for every WRZ, both in 2016 and by 2040, and using a statistical approach to fully quantify the demand management proposed at WRMP14 (both volume and cost) and identify where cost effective savings beyond WRMP14 were likely to be feasible.

This was achieved through a linear regression process by plotting PCC in 2016 v PCC 2040 for each WRZ and identifying straight-line targets on each plot, which are consistent across all WRZs, but allow for differences in starting consumption for whatever reason. The premise is that the required rate of change in PCC at a regional level is as important as absolute PCC target, and will impact both cost and feasibility. Limited metered data for large parts of the country mean that many PCC values carry an element of uncertainty and some variation could be caused by unknown leakage. We make no attempt to identify what causes the variation for specific WRZs, just the assumption that the potential efficiency savings available to a given WRZ are a simple linear function of starting PCC. In all cases, the coefficient for target threshold is less than 1, such that greater savings are targeted at WRZs with higher starting PCC.

It was originally intended to vary PCC and leakage within the various scenarios of future growth to reduce the number of scenarios. However, this would have risked confusing changes in SDB due to growth with changes due to demand management. Therefore instead it was agreed to define four demand management strategies, each of which could be applied to any scenario (growth, climate change, environmental mitigation) as necessary. The scenarios are largely outside the control of companies and policy makers, whilst the strategies are dependent on policy decisions and/or investment.

Using this approach we are also better able to identify the full volume of demand management included in WRMP14 (even where not explicitly identified and costed in company WRMPs), make estimates of the cost of achieving this “BAU Base” scenario; and derive a worse scenario, “BAU Upper”, where these implicit savings in PCC and leakage are not achieved.

The methodology is as follows:

Two BAU PCC scenarios were specified: baseline and upper (conservative), where baseline was roughly in line with WRMP demand management and upper reflected what could happen if WRMP planned measures do not deliver.

Two further strategies were defined as “Extended” and “Enhanced”. A full summary of these is as follows.

- **Business as Usual (BAU) Upper**: the likely trend in consumption if WRMP measures to reduce PCC are largely ineffective or impossible to implement. Slight downward trend is due to background improvements in device efficiency.

- **Business as Usual (BAU) Base**: the trend in PCC planned at WRMP14 through water efficiency schemes and more sustainable new homes.

- **Extended**: more ambitious savings that are cost effective but culturally challenging. For example, under a medium growth scenario, with new-build households achieving a mean PCC of 120 l/h/d, extended demand management equates to 5.9 million existing households saving 40 l/property/day by 2040.

- **Enhanced**: these are considered to be the most ambitious savings that are feasible technically and economically over the time period, but would come at considerable expense and/or require a significant change in legislation or regulation to enable their development. For example, under a medium growth scenario, with new-build households achieving a mean PCC of 120 l/h/d, enhanced demand management equates to 8 million existing households saving 50 l/property/day by 2040.

For each strategy, target PCC was calculated for every WRZ in 2040 and 2065 using the linear regression functions. These PCC values were then incorporated into the SDB tool and applied to all three growth scenarios to calculate total household consumption in each.

Target leakage per property was defined in a similar manner and leakage savings calculated explicitly under extended and enhanced strategies and all three scenarios, based on forecast population in each zone. These savings were subtracted directly from the SDB results.

Water efficiency options

For the water efficiency options, the target PCCs defined for 2040 and 2065 extended and enhanced scenarios were used to calculate the target savings within each strategy. This is illustrated at WRZ level in the figures below.

Three target functions were defined: “low cost”, extended and enhanced. Low cost was used to help calculate BAU base costs of efficiency savings. The latter two were used as described above. It is noted that the gradient and position of these lines is not empirically defined. A process of iteration was applied to find positions which resulted in total costs and levels of ambition (savings per property) that are considered achievable in the time available. Further adjustments could be made but are not considered material to the overall results in terms of setting a framework for long term planning.

Figure App-28 Water efficiency WRMP14 PCC by WRZ and targets, medium growth scenario for 2040

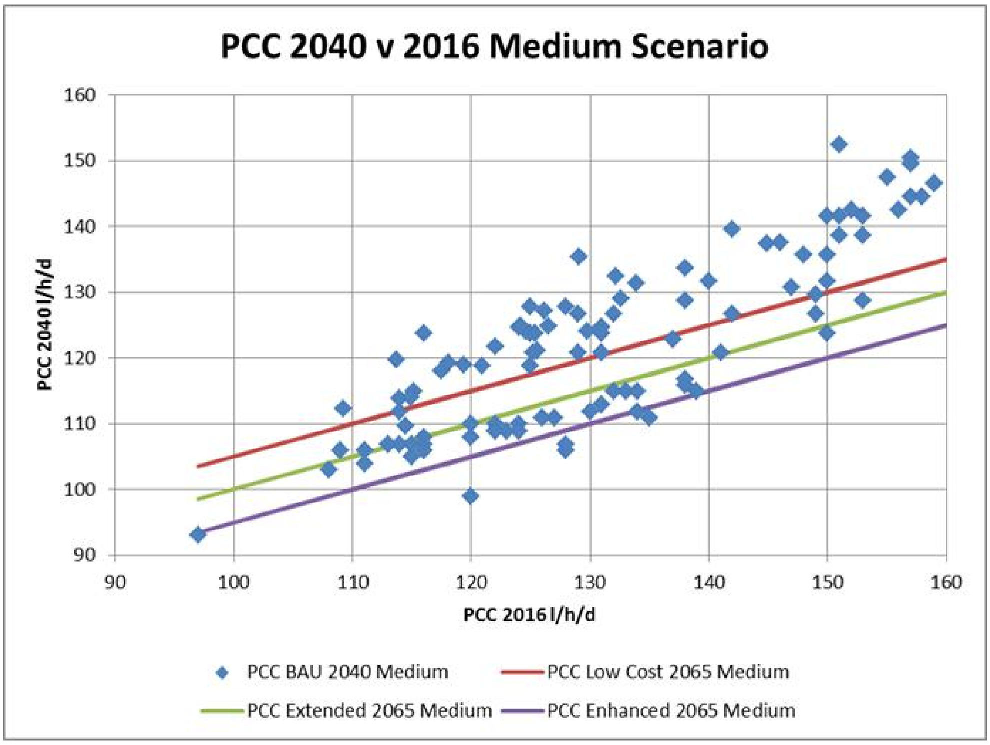


Figure App-29 Water efficiency WRMP14 PCC by WRZ and targets, upper growth scenario for 2040

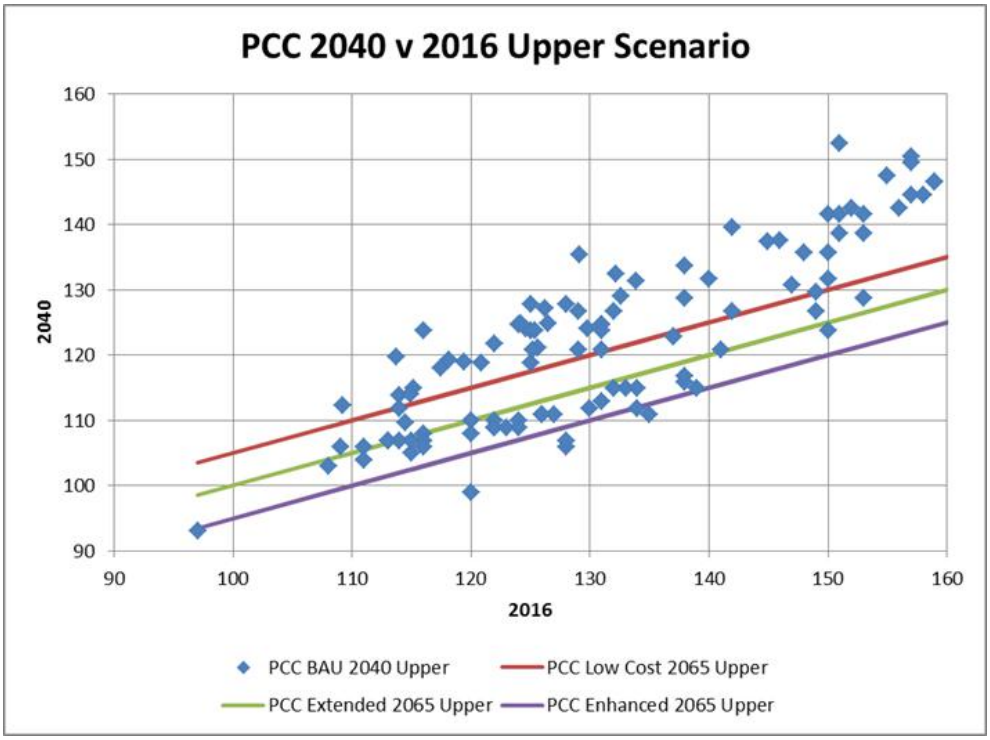


Figure App-30 Water efficiency WRMP14 PCC by WRZ and targets, medium growth scenario for 2065

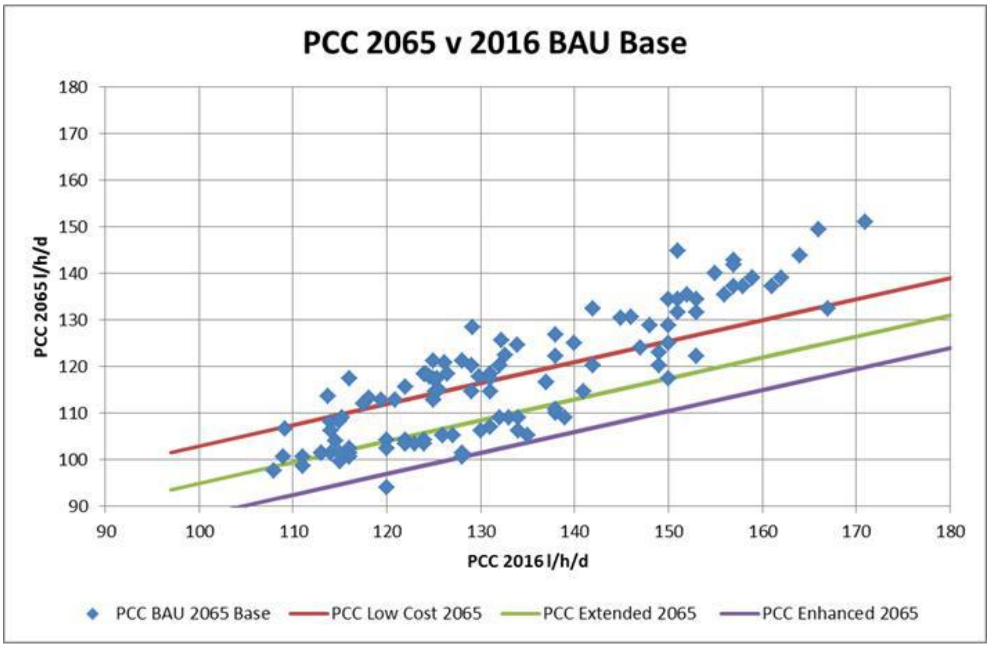
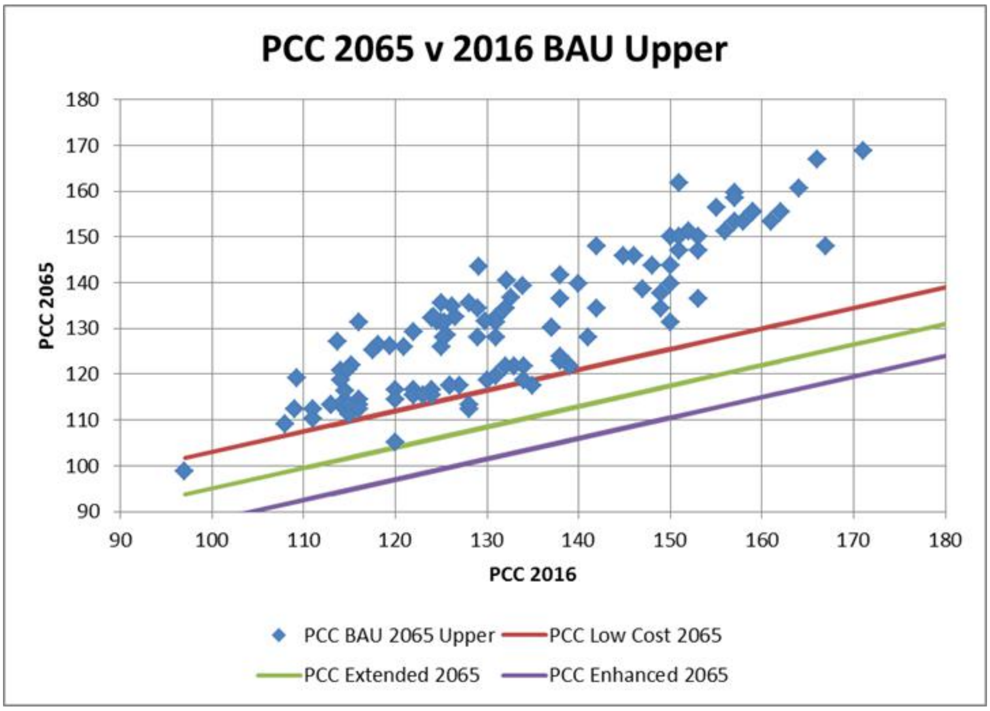
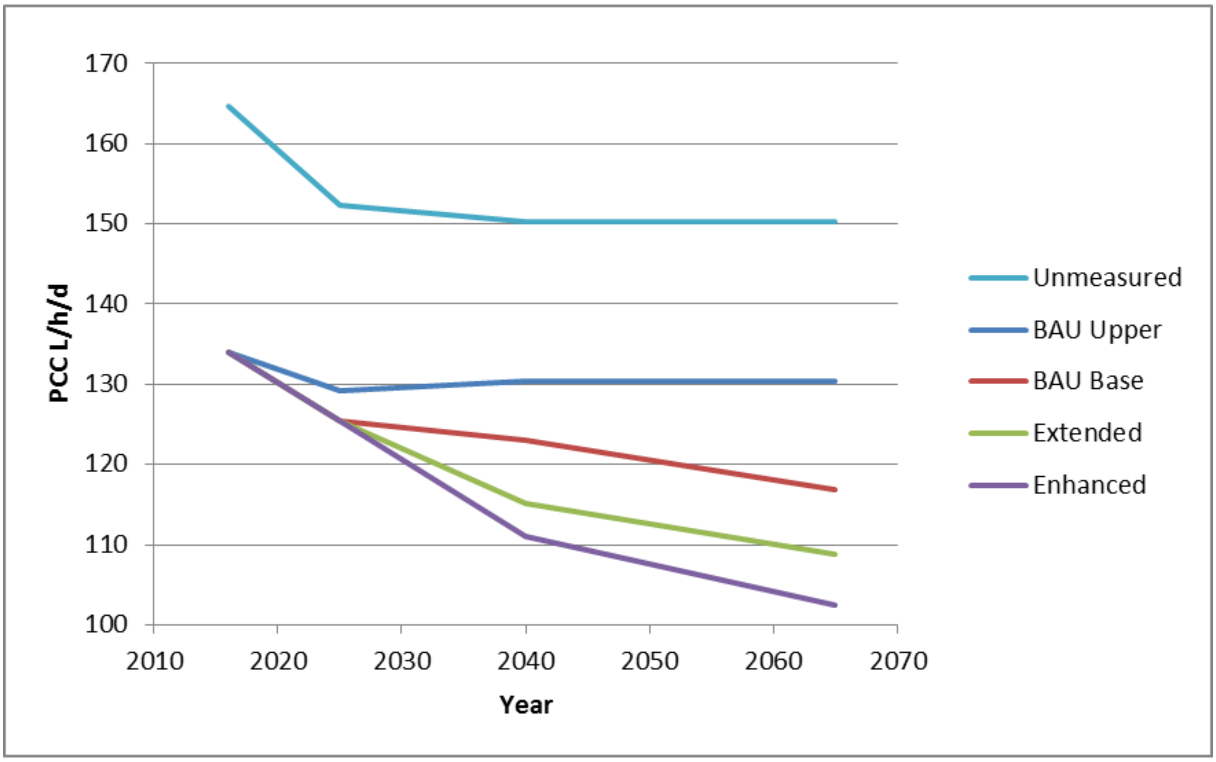


Figure App-31 Water efficiency WRMP14 PCC by WRZ and targets, medium growth scenario for 2065



The resulting mean changes in PCC between 2016 and 2065 for the 4 strategies are illustrated in Figure App-32. Unmeasured PCC is uniform between strategies for simplicity (assumed to be largely outside of company and policy control).

Figure App-32 PCC changes between 2016 and 2065 for the BAU Base, BAU Upper, Extended and Enhanced strategies



NPV costs were calculated by assuming a fixed annual incrementalised cost (AIC) for savings achieved between one linear regression function and the next. BAU and Extended strategy costs were based on the Waterwise Evidence Base for large-scale efficiency. Enhanced costs were determined by calculating costs associated with achieving highly ambitious PCC levels as detailed below, involving greywater reuse and rainwater harvesting.

The implications of each strategy were then determined by estimating the number of existing properties requiring retrofitting assuming that new build properties can achieve a pre-defined PCC level. This analysis was carried out at the regional level. In all scenarios the PCC 2016 WRZ values were used as a starting point. Savings to be achieved by each scenario calculated previously were used as target savings.

It was assumed that water consumption in new builds will be as follows:

- No changes to current policy
  - BAU: 120 l/h/d.
  - Extended: 120 l/h/d.
  - Enhanced: 120 l/h/d.
- Requiring changes to current policy
  - BAU: 120 l/h/d.
  - Extended: 100 l/h/d.
  - Enhanced: 80 l/h/d.

It was also assumed that retrofitting of properties will achieve the following water use savings on average:

- BAU: 20 l/property/d.
- Extended: 40 l l/property/d.
- Enhanced: 50 l/property/d.

The assumptions for extended and enhanced scenarios require higher values (40 and 50 l/property/d) to avoid situations where there are not enough properties within a zone to achieve the total target savings. This applies to some individual WRZs and it is possible that the assumed savings could be lower if the analysis was done at regional level rather than WRZ level.

Leakage reduction options

For leakage reduction options, the WRMP 2016 values were used as a starting point and some growth was allowed under all scenarios at a fixed % of population growth. This % was higher for “BAU Upper” than “BAU Base”. For extended and enhanced strategies, savings were calculated using the UKWIR study (2011) into large-scale leakage as a basis, which provides cost curves associated with achieving a particular leakage reduction for a “type WRZ”, with starting leakage per property of 137 l/p/d. This defined one point on the target functions for both USPL and distribution losses. The gradient of the functions was then specified based on WRMP14 distribution plots and expert judgement. Ml/d savings were estimated for each WRZ accordingly by multiplying target l/p/d saving by forecast number of properties under each growth scenario.

Figure App-33 and Table App-3 show projections of the lowest level of leakage that might be achieved over 25 years under current conditions and optimistic projected future conditions along with the net present cost (against their respective baselines and excluding externalities) of achieving the reductions (UKWIR 2011).

Figure App-33 Cost curves for leakage (UKWIR, 2011)

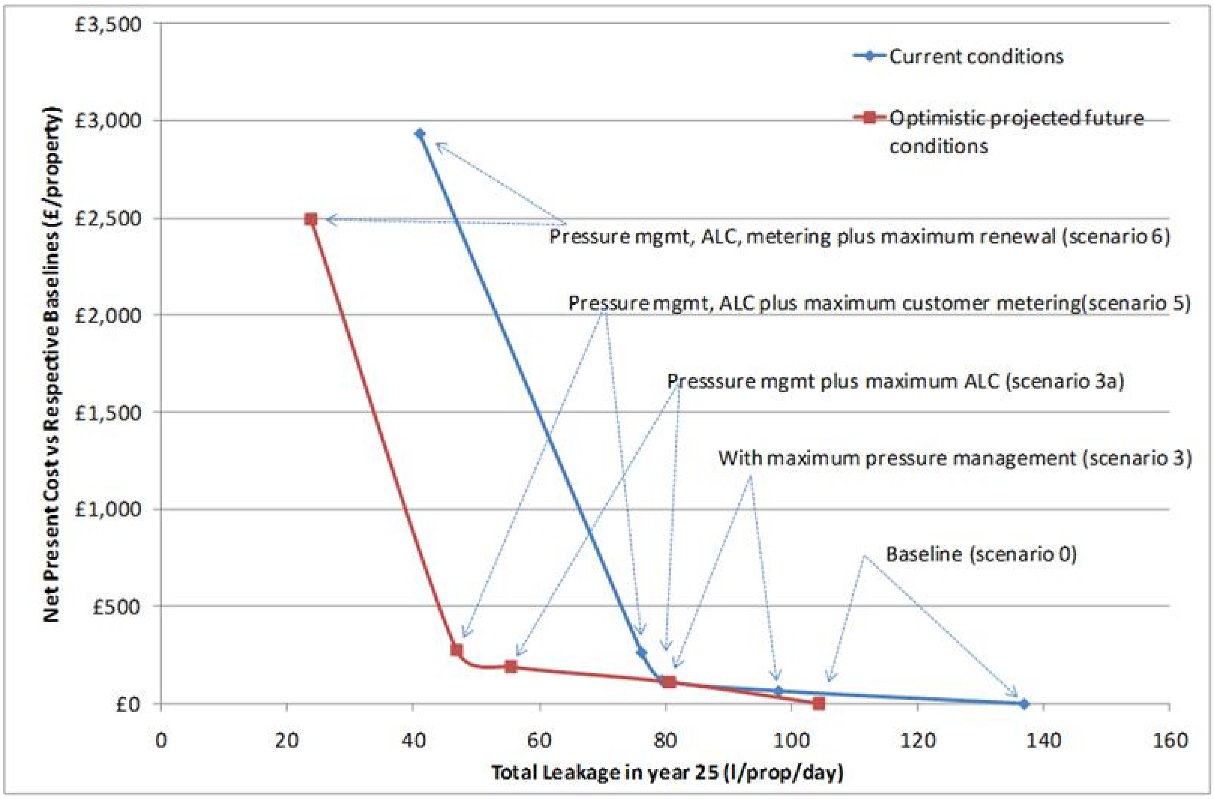


Table App-3 Leakage and NPV projections under current and future conditions (UKWIR, 2011)

Scenario	Current conditions		Optimistic projected future conditions	
	Total leakage (l/p/d)	Net present cost (£/property)	Total leakage (l/p/d)	Net present cost (£/property)
Baseline	137	£0	104	£0
Maximum pressure management	98	£65	81	£111
Pressure management and maximum Active Leakage Control	79	£122	55	£190
Pressure management, ALC and maximum customer metering	76	£265	47	£278
Pressure management, ALC, customer metering and maximum renewal	41	£2,933	24	£2,496

The "current conditions" curve was used in order to maintain consistency with supply-side options. Optimistic projected future conditions are highly uncertain and only applicable to certain WRZ conditions. They are not considered appropriate to major cities, where the most significant deficits will occur.

Leakage savings for underground supply pipe losses (USPL) and distribution losses within each strategy were calculated and are illustrated at WRZ level in the figures below.

Figure App-34 Measured underground supply pipe losses and targets for 2040 vs 2016

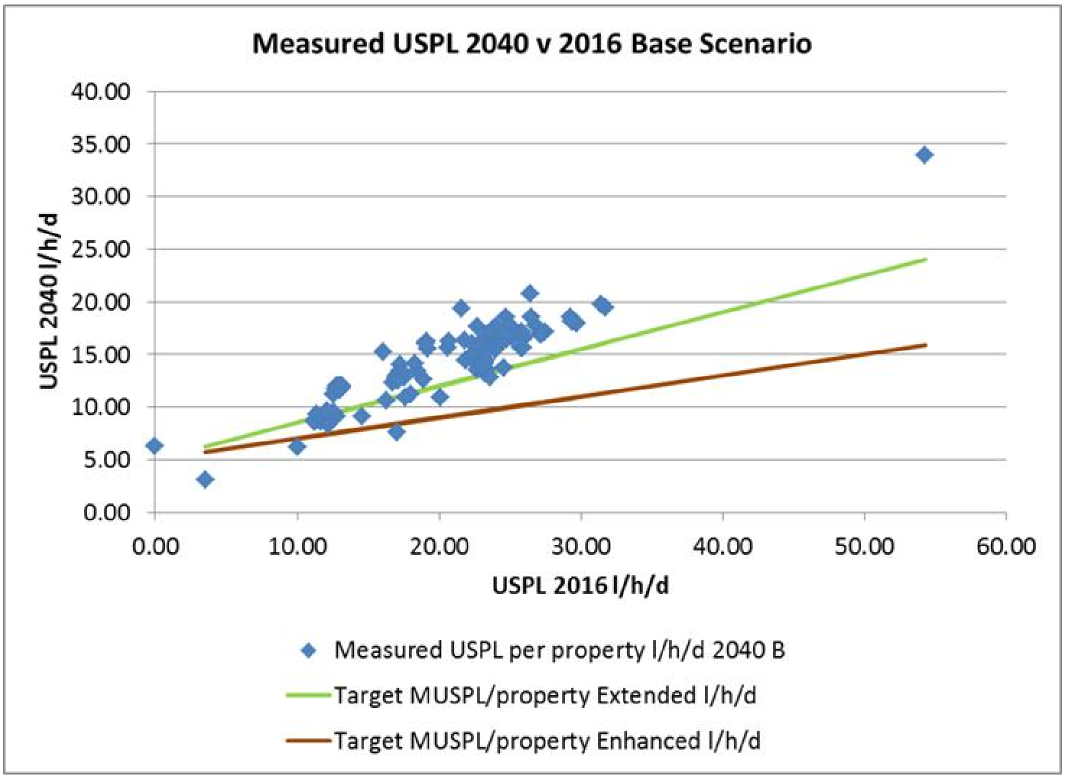


Figure App-35 Measured underground supply pipe losses and targets for 2065 vs 2016

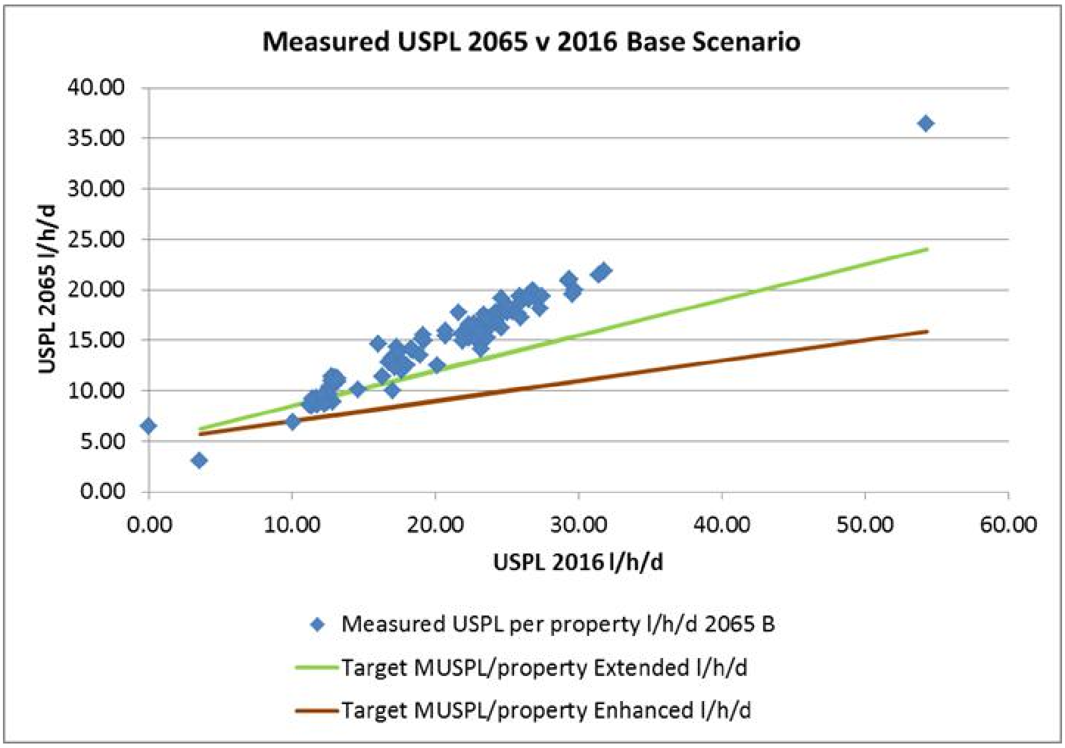


Figure App-36 Distribution losses and targets (l/property/d) for 2040 vs 2016

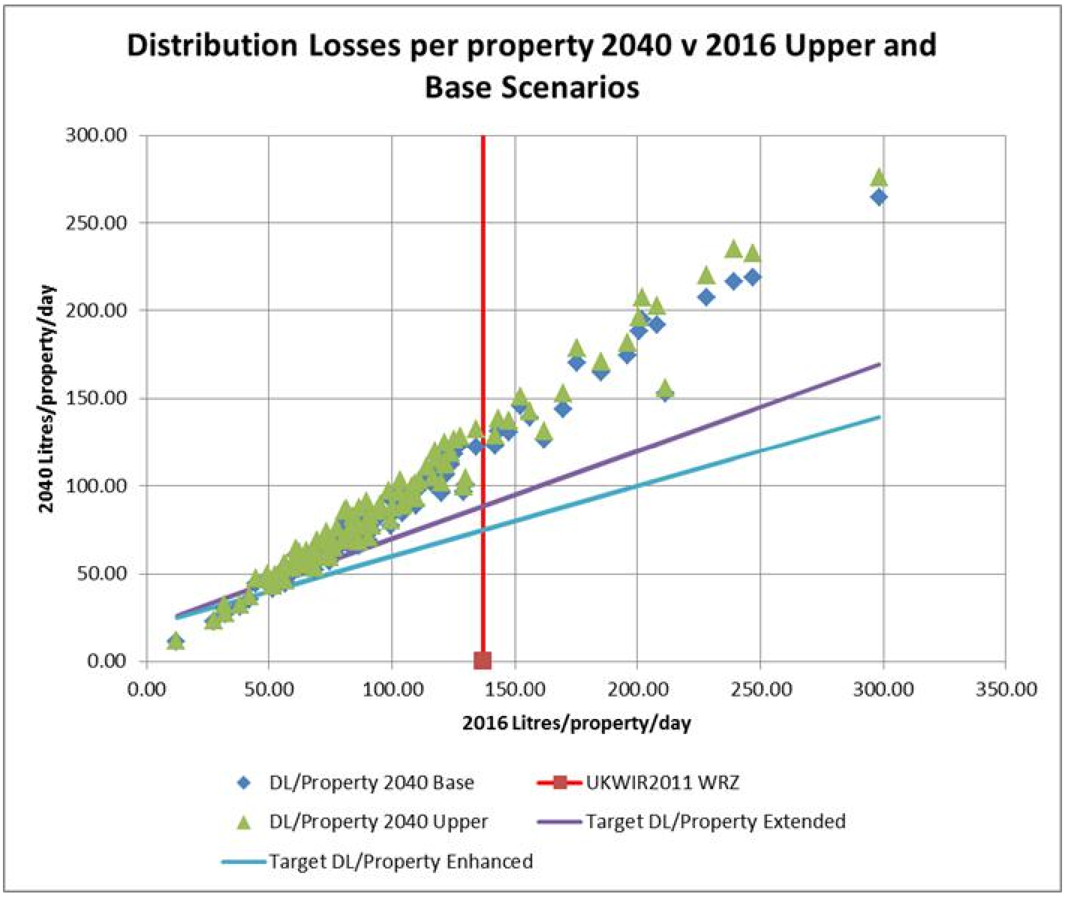
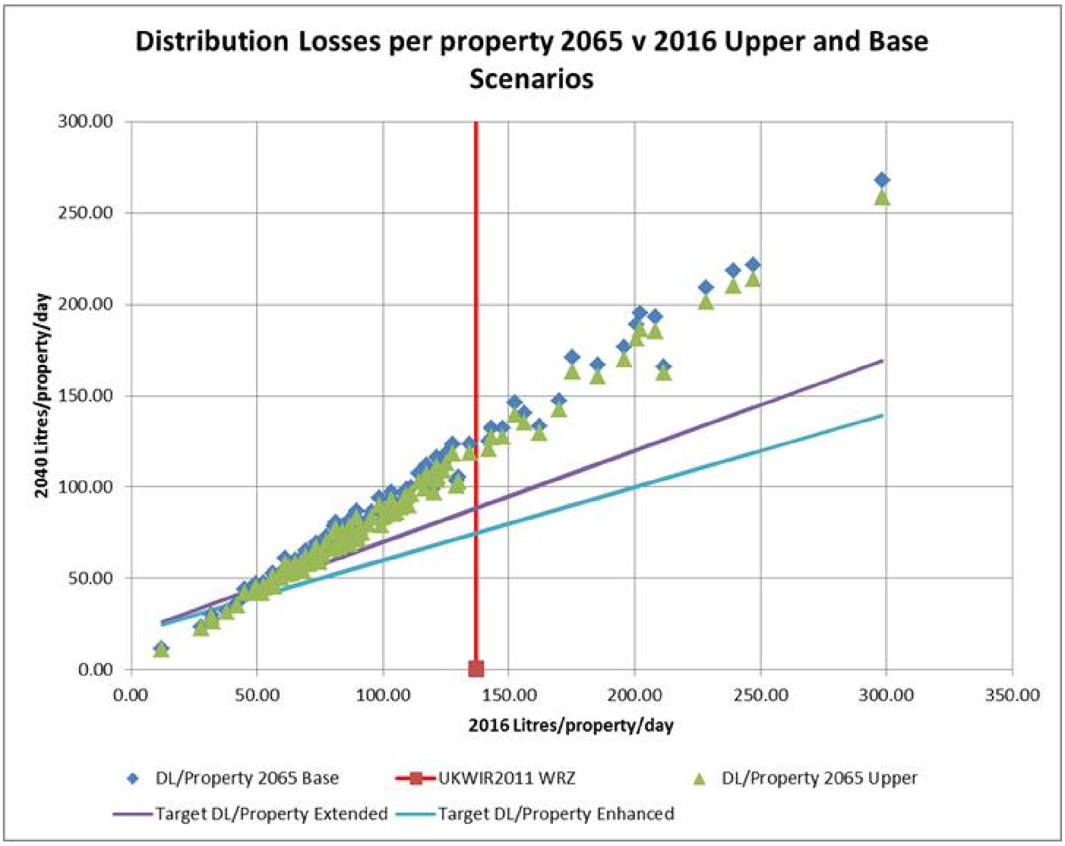


Figure App-37 Distribution losses and targets (l/property/d) for 2065 vs 2016



Metering options

For metering, correction factors were applied to WRMP unmeasured population in each year to calculate different levels of metering under each strategy and scenario. The SDB tool was then re-run to calculate total change in SDB as a result of metering combined with efficiency savings.

Validation

Validation of the results is not straightforward as there is no known historical precedent for demand management savings on this scale. The methodology itself is designed to be self-validating by comparing water resource zones against one another – both present values and planned future values across all water companies in England and Wales. The following further validation was applied:

- Check that no WRZs are designated planned savings below practical limits of basic human consumption.
- Benchmark national PCC values with European and international comparisons to check for scale of ambition and practicality, being aware of notable differences in water supply systems internationally.

Key uncertainties and assumptions

The following assumptions are made:

- The high level cost and difficulty of achieving reductions in PCC and leakage per property is a simple linear function of starting PCC or leakage per property, with linear coefficient always < 1, i.e. savings become more expensive and difficult as starting PCC and leakage per property decreases. Therefore, for example, WRZs with a higher starting PCC can achieve greater savings in PCC at lower cost than those with lower starting PCC, but are unlikely to achieve the same final PCC.

- Linear savings functions are uniform for all of England and Wales, with any local or regional differences captured in variation of starting PCC and leakage per property of each WRZ.
- All population growth is housed in metered properties.
- Occupancy rates remain constant over time.
- Costs of meters are uniform everywhere, increasing step-wise as meter penetration increases.

There are major uncertainties in the long-term costs of achieving and maintaining ambitious, large-scale savings in both PCC and leakage. These uncertainties are ~ 100% of cost, and depend heavily on both cost of installation of various devices and the cost of maintaining these over time. We recommend that major large-scale trials of smart meters are implemented as soon as possible to better understand the significant variations in household demand that occur nationally and refine demand forecast uncertainty.

Outputs

The output comprised the following:

- Target PCC values and NPV costs for every water resource zone under medium, lower and upper growth scenario for BAU base, extended and enhanced strategies in 2040 and 2065. These are input directly into the SDB calculation tool to produce SDB values across all strategies.
- Absolute savings in distribution losses and measured USPL (Ml/d) and associated NPV costs for every water resource zone under medium, lower and upper growth scenario for BAU base, extended and enhanced strategies in 2040 and 2065. These adjustments are input directly into the SDB calculation tool to derive updated leakage and SDB values across all strategies.
- Costs and savings compiled for every region to inform the cost calculations across all scenarios, broken down into leakage (distribution losses and USPL) and efficiency (PCC savings and metering savings).
- A breakdown of the possible compositions of each strategy, in terms of new house "PCC target" and corresponding savings required by existing properties.

The total results are shown in the following tables.

Water efficiency

Table App-4 Water efficiency target savings for England and Wales (Ml/d)

Scenario	Water efficiency target savings (Ml/d)	
	2040	2065
Medium growth		
BAU Base	509	948
Extended	890	1,424
Enhanced	1,120	1,836
Upper growth		
BAU Base	565	1,025
Extended	990	1,590
Enhanced	1,247	2,081

Table App-5 Water efficiency NPV cost for England and Wales (£M)

Scenario	Water efficiency NPVcost (£M)	
	2040	2065
Medium growth		
BAU Base	260	485
Extended	1,895	3,015
Enhanced	4,910	8,828
Upper growth		
BAU Base	289	524
Extended	2,130	3,566
Enhanced	5,537	10,567

Table App-6 Water efficiency unit NPV cost for England and Wales (£M/Ml/d)

Population Growth	Scenario	Water efficiency unit NPVcost (£M/Ml/d)	
		2040	2065
Medium growth	BAU Base	0.51	0.51
	Extended	2.13	2.12
	Enhanced	4.38	4.81
Upper growth	BAU Base	0.51	0.51
	Extended	2.15	2.24
	Enhanced	4.44	5.08

Table App-7 Properties requiring retrofitting for medium growth scenario for 2040

Efficiency Medium 2040	Number of properties requiring retrofitting to achieve calculated savings				
Scenario	BAU	Extended	Enhanced	Extended	Enhanced
New build water efficiency policy (l/h/d)	120	120	120	100	80
Water efficiency achieved from retrofitting existing properties (l/prop/d)	20	40	50	40	50
Cumulative existing properties requiring retrofit from BAU	**2,675,455**	**5,941,945**	**7,948,916**	**4,790,048**	**4,985,093**

Table App-8 Properties requiring retrofitting for upper growth scenario for 2040

Efficiency Upper 2040	Number of properties requiring retrofitting to achieve calculated savings				
Scenario	BAU	Extended	Enhanced	Extended	Enhanced
New build water efficiency policy (l/h/d)	120	120	120	100	80
Water efficiency achieved from retrofitting existing properties (l/prop/d)	20	40	50	40	50
Cumulative existing properties requiring retrofit from BAU	**4,300,186**	**7,604,925**	**9,879,640**	**5,810,374**	**5,611,972**

Table App-9 Properties requiring retrofitting for medium growth scenario for 2065

Efficiency Medium 2065	Number of properties requiring retrofitting to achieve calculated savings				
Scenario	BAU	Extended	Enhanced	Extended	Enhanced
New build water efficiency policy (l/h/d)	120	120	120	100	80
Water efficiency achieved from retrofitting existing properties (l/prop/d)	20	40	50	40	50
Cumulative existing properties requiring retrofit from BAU	**7,061,247**	**8,628,325**	**11,128,645**	**7,671,574**	**7,836,127**

Table App-10 Properties requiring retrofitting for upper growth scenario for 2065

Efficiency Upper 2065	Number of properties requiring retrofitting to achieve calculated savings				
Scenario	BAU	Extended	Enhanced	Extended	Enhanced
New build water efficiency policy (l/h/d)	120	120	120	100	80
Water efficiency achieved from retrofitting existing properties (l/prop/d)	20	40	50	40	50
Cumulative existing properties requiring retrofit from BAU	**11,572,004**	**13,472,222**	**16,733,826**	**12,006,942**	**11,973,852**

Leakage

Table App-11 Leakage savings for England and Wales (Ml/d)

Population Growth	Scenario	Leakage savings (Ml/d)			
		2040	2040	2065	2065
		Measured USPL	Distribution losses	Measured USPL	Distribution losses
Medium	BAU Base	161	439	180	440
	Extended	201	835	244	961
	Enhanced	272	1114	333	1,286
Upper	BAU Base	190	349	149	613
	Extended	227	909	292	1,116
	Enhanced	305	1216	398	1,489

Table App-12 Leakage reduction NPV cost for England and Wales (£M)

Population Growth	Scenario	Leakage reduction NPV cost (£M)			
		2040	2040	2065	2065
		Measured USPL	Distribution losses	Measured USPL	Distribution losses
Medium	BAU Base	330	808	369	899
	Extended	455	2,064	572	2,551
	Enhanced	2,030	11,166	2,706	13,866
Upper	BAU Base	389	715	305	1,254
	Extended	504	2,487	757	2,845
	Enhanced	2,145	13,992	4,123	14,682

Table App-13 Leakage reduction unit NPV cost for England and Wales (£M/Ml/d)

Population Growth	Scenario	Leakage reduction unit NPV cost (£M/Ml/d)			
		2040	2040	2065	2065
		Measured USPL	Distribution losses	Measured USPL	Distribution losses
Medium	BAU Base	2.05	1.84	2.05	2.04
	Extended	2.26	2.47	2.34	2.65
	Enhanced	7.46	10.02	8.13	10.78
Upper	BAU Base	2.05	2.05	2.05	2.05
	Extended	2.22	2.74	2.59	2.55
	Enhanced	7.03	11.51	10.36	9.86

Metering

The table below shows the reduction in unmetered properties for all the scenarios considered.

Table App-14 Percentage metered properties England and Wales

Scenario	Year		
	2016	2040	2065
Medium growth			
BAU Base	46%	78%	83%
Extended		83%	90%
Enhanced		87%	94%
Upper growth			
BAU Base	46%	81%	86%
Extended		85%	91%
Enhanced		88%	95%

The total results are shown in the following tables. Costs were calculated assuming unit costs of meter installation of £200, £300 and £400 under BAU base/upper, extended and enhanced scenarios respectively. The increase in costs reflects the challenge of installing meters in certain properties.

Table App-15 Metering savings for England and Wales (Ml/d)

Scenario	Metering savings (Ml/d)	
	2040	2065
BAU Base	78	143
Extended	200	379
Enhanced	337	615

Table App-16 Metering NPV cost for England and Wales (£M)

Scenario	Metering NPVcost (£M)	
	2040	2065
BAU Base	401	471
Extended	801	970
Enhanced	1,202	1,413

Table App-17 Metering unit NPV cost for England and Wales (£M/Ml/d)

Scenario	Metering unit NPV cost (£M/Ml/d)	
	2040	2065
BAU Upper	4.68	3.84
BAU Base	2.72	0.78
Extended	3.60	1.70
Enhanced	4.74	2.72

The decline in unit costs from 2040 to 2065 is due to the high up-front costs and then ongoing opex savings achieved through reduced water distribution, treatment and wastewater treatment. Similarly the decline in NP costs from BAU Upper to BAU Base is because the savings in opex more than outweigh the additional upfront cost of meter installation when installation costs are fixed at £200 per meter.

D.3. Strategic supply options

Purpose and core concepts

- Compile a list of feasible supply options > 30 Ml/d in size across England and Wales, specified by WRZ.
- Define the WAFU benefit, NPV capex, NPV opex (as function of utilisation), AISC, lead time and any key constraints, risks or issues associated with each option.
- Define engineering specification in sufficient detail for inclusion in Wathnet model.
- Provide a means of option selection based on AISC and addition to the supply/demand balance for each WRZ, such that SDB values can be updated for each WRZ on the basis of AISC.

Methodology

The starting point for all options was WRMP14, which included feasible options totalling 2600 Ml/d of new resource across a number of companies.

WRMP14 Strategic Supply Options

Strategic options were defined here as being greater than 30 Ml/d in size, excluding any intra-company transfers. Again screening for exclusivity, the total WAFU comes to 2600 Ml/d of new resource (new DO), with a combined NPV of £12 billion. These are predominantly new reservoirs, desalination, effluent reuse and enhanced/new surface water (river abstraction). There is a further 450 Ml/d of strategic new bulk transfers, with a combined NPV of £2 billion. A map showing the approximate location and nature of all of these options is provided in Figure App-38.

Only 300 Ml/d of this strategic resource is included in final preferred plans, with a total NPV of £940 million. Most of the non-preferred resource is relatively expensive.

Figure App-38 Summary Overview of all Strategic Options

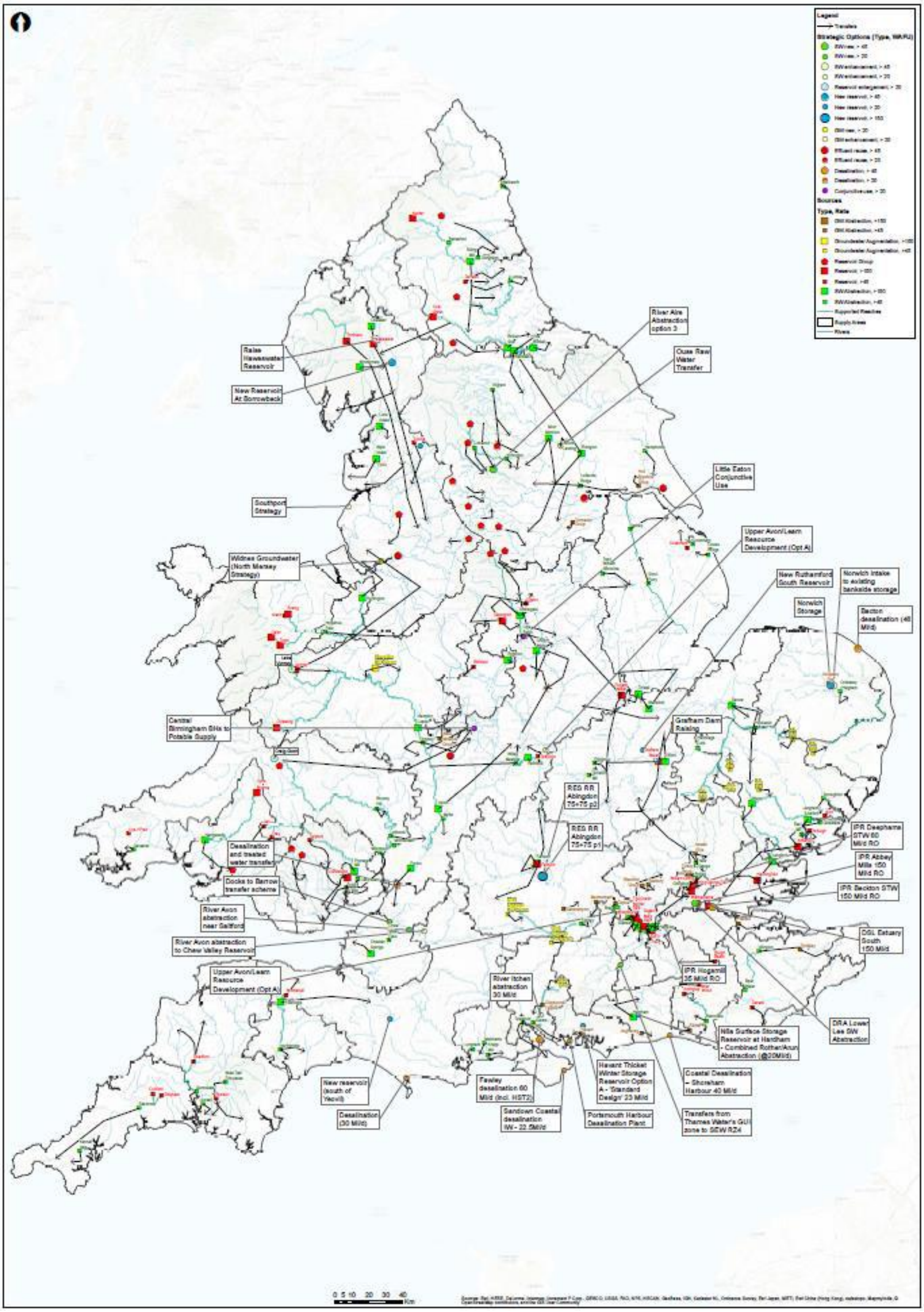
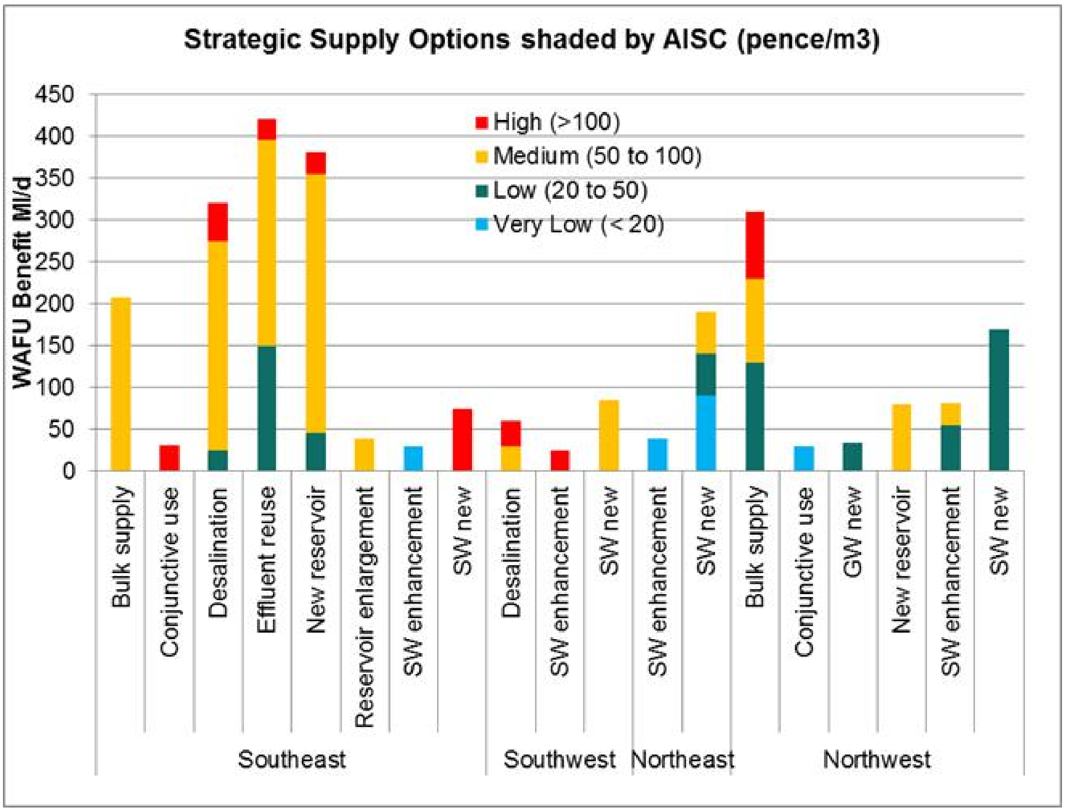


Figure App-39 WAFU benefit of WRMP Strategic supply options separated by region, coloured by AISC cost category



For the purposes of this study, the aim of looking further ahead to 2065, exploring low probability but high impact scenarios, and aiming to exploit bulk transfers of water as much as possible in order to reduce costs and environmental impacts, meant that it was necessary to look beyond WRMP14 for other potential options.

Our initial step was to invite company water resource managers to provide suggestion for unconstrained options not included in WRMP14 through a questionnaire issued to all companies and follow-up telephone calls where appropriate. We also carried out an extensive review of national and regional studies into water resource options over the last 40 years, many of which have not yet been implemented due to a lack of need or various delivery risks. Deployable outputs and costs for all of these were compiled and updated as far as possible to allow derivation of NPV values over an 80 year time period from 2020 to 2100, such that they could be compared on an equal basis with WRMP14 options.

A high-level screening process was carried out to exclude options that relied on the same source water, duplicate options, or those that are likely to remain unfeasible on technical or cost grounds. Some additional “high level” options were specified where necessary to fill supply/demand deficits under the most extreme scenarios. These were primarily effluent reuse, desalination and tankering from abroad, where costs were specified using cost curves as described below. Tankering costs were based on information provided in confidence by Albion Water and Thames Water.

The full set of potentially feasible strategic options is shown in Table App-18. Most of these are defined at a high level and require considerable refinement of costs, yield and engineering scope before definition as feasible. Various issues and risks are associated with each, as specified in the “Comment” column.

Table App-18 List of potentially feasible strategic supply options, beyond WRMP14 options

Company	New Options & Reservoirs	WAFU Ml/d	Description	Comment
Anglian	Norwich storage	10	The reservoir would be filled from the existing intake at Heigham WTW and would require a twin pipeline between Heigham and the new reservoir. Assume 2 Mm3 in size.	10 Ml/d estimated benefit for use as river regulation reservoir. WRMP14 option is for environmental mitigation (with higher DO).
Anglian	Pitsford Dam Raising	11	This option involves increasing Pitsford Reservoir capacity by 50%, giving a 13.8 Ml/d rise in yield. This would be achievable within the current Duston annual refill licence.	
Anglian	Rutland Dam Raising	16	This option involves a 10% increase in volume at Rutland Water by raising the dam, resulting in a 20 Ml/d rise in hydrological yield. Initial assessment shows that 10% increase in volume would require the dam to be raised by 1m.	
Anglian	Grafham Dam Raising	40	Raise dam 3m to increase volume 50%.	
Anglian	South Lincs reservoir	113	River Trent source, with yield of 113 Ml/d.	Storage and pump refill TBC. Yield and costs estimate only.
Anglian	Trent to Rutland	200	600 Ml/d intake and pump station at Shardlow. 1x1800mm diameter pipeline 43km long to Rutland Water. 200Ml/d treatment plant including metaldehyde treatment.	WAFU benefit and costs are uncertain. Potentially greater DO benefit.
Anglian - Essex, Suffolk, Ely	Additional Anglian Effluent Reuse	50	Proposed to meet forecast deficits under extreme scenarios	Costs highly uncertain – based on national cost curve
DCWW	Raise Llyn Brianne dam	127	Would supply River Towy to Camarthen and Swansea, with transfer to Wye or Severn	Potential environmental risks
DCWW	Craig Goch enlargement 1	150	190 million m3. Refill from immediate catchment only.	High environmental risk of breaching the Habitats Directive
DCWW	Craig Goch enlargement 2	200	250 Mm3. Immediate Catchment and Yystwyth, Diluw and Diluw Fechan Gravity Diversions.	High environmental risk of breaching the Habitats Directive
DCWW	Craig Goch enlargement 3	280	360 Mm^3. Immediate catchment, above gravity diversions, pumped segmentation from the River Wye and diversion from the River Dulas.	High environmental risk of breaching the Habitats Directive
Essex & Suffolk	E&S Eff Reuse	40	Proposed to meet forecast deficits under extreme scenarios	Costs highly uncertain – based on national cost curve
South East Water - Kent	Additional SEW Effluent Reuse	46	Proposed to meet forecast deficits under extreme scenarios	Costs highly uncertain – based on national cost curve
Southern Water - Central	Additional Desalination	75	Proposed to meet forecast deficits under extreme scenarios	Costs highly uncertain – based on national cost curve

Company	New Options & Reservoirs	WAFU Ml/d	Description	Comment
Southern Water - East	Additional SW Effluent Reuse	76	Proposed to meet forecast deficits under extreme scenarios	Costs highly uncertain – based on national cost curve
Southern Water - West	Additional SW Eff Reuse	32	Proposed to meet forecast deficits under extreme scenarios - details require refinement	Costs highly uncertain – based on national cost curve
Thames Water - London	London Tankering from abroad	150	Proposed to meet forecast deficits under extreme scenarios	Costs highly uncertain – based on national cost curve
Thames Water - London	Additional Desalination	300	Proposed to meet forecast deficits under extreme scenarios	Costs highly uncertain – based on national cost curve
Thames Water - London	Additional London Effluent Reuse	300	Proposed to meet forecast deficits under extreme scenarios	Costs highly uncertain – based on national cost curve
UU	Larger Manchester ship canal option		Increase size of option	
UU	Longdendale Compensation Flow Reduction	25	Permanent reduction in compensation flow from current 45.5 Ml/d	
UU	New reservoir in Cumbria / North Lancashire	43	New dam across Borrow Beck valley, North East of Kendal, to form a 33,000 Ml storage IR between Shooter Howe and Belt Howe. The majority of the source raw water will be pumped from the River Lune into the new reservoir to be stored and then pumped to Watchgate WTW for treatment when required.	This option may fall within a national park and therefore carries significant environmental risks
UU	Vyrnwy transfer support	100	River regulation of the Severn to support downstream abstraction/transfers	DO benefit estimated only – lower than the current yield of the scheme on the R Dee.
Yorkshire - the Grid	Yorkshire Tankering from abroad	55	Proposed to meet forecast deficits under extreme scenarios	Costs highly uncertain – based on national cost curve

Cost normalisation

In order to select options for portfolios, once screening was carried out, the basis for selection was primarily AISC. WRMP14 costs were taken as a starting point for this process, but refinement of costs was necessary for a number of reasons:

- To account for differences in utilisation between companies and options, necessary to normalise opex between options. Most costs presented in WRMP14 are generated from EBSD models which calculate utilisation required to fill very specific deficits under a single scenario for a single WRZ. This results in notable variation in opex for apparently very similar option types in different WRZs, and correspondingly different AISCs.

- For un-costed options (large-scale effluent reuse, desalination etc.), a means of estimating the high level capex and opex was required.

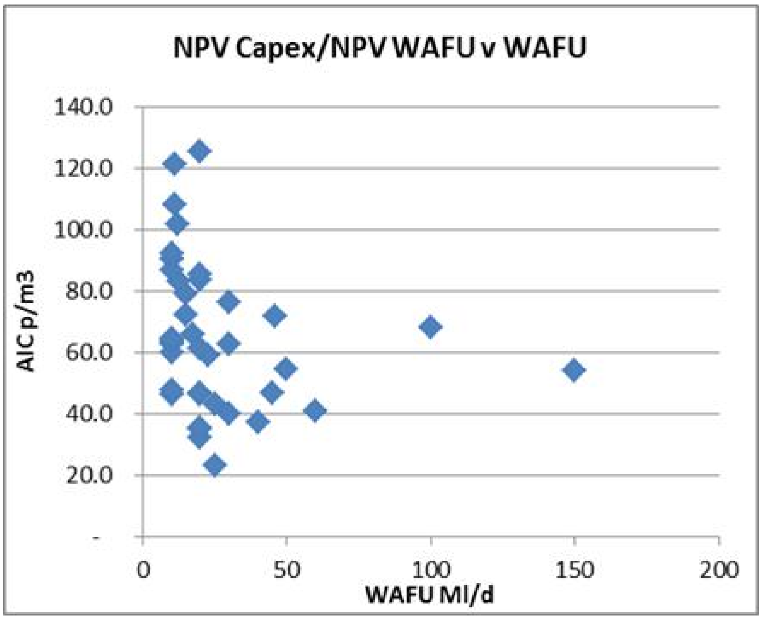
Cost normalisation is most critical for options involving high variable opex costs, where the assumption around utilisation has a major impact on total AISC. At a strategic level, this applies mainly to desalination, effluent reuse and large-scale transfers. Our approach for all of these is to use the costs presented at WRMP14. Unfortunately the variable/fixed breakdown for opex is mostly unavailable, so we separate into opex and capex instead, and start by plotting [NPV of (opex or capex)/NPV of WAFU] v. WAFU on completion (Ml/d). We then aim to use this to define either cost curves of AISC varying with WAFU, or a fixed AISC to normalise existing options and derive costs of new options.

Initially a pragmatic approach was taken to define AISC values sufficiently accurate to enable ranking and option selection to inform Wathnet modelling. Refinement of costs was then carried out as necessary, once options utilisation was better understood, to calculate total portfolio costs.

For all other option types, the options are generally too site-specific to warrant any form of normalisation. Where costing is unavailable for new options (e.g. reservoirs), we used representative values for AISC from WRMP14 for AISC ranking, with further refinement for full costing as necessary.

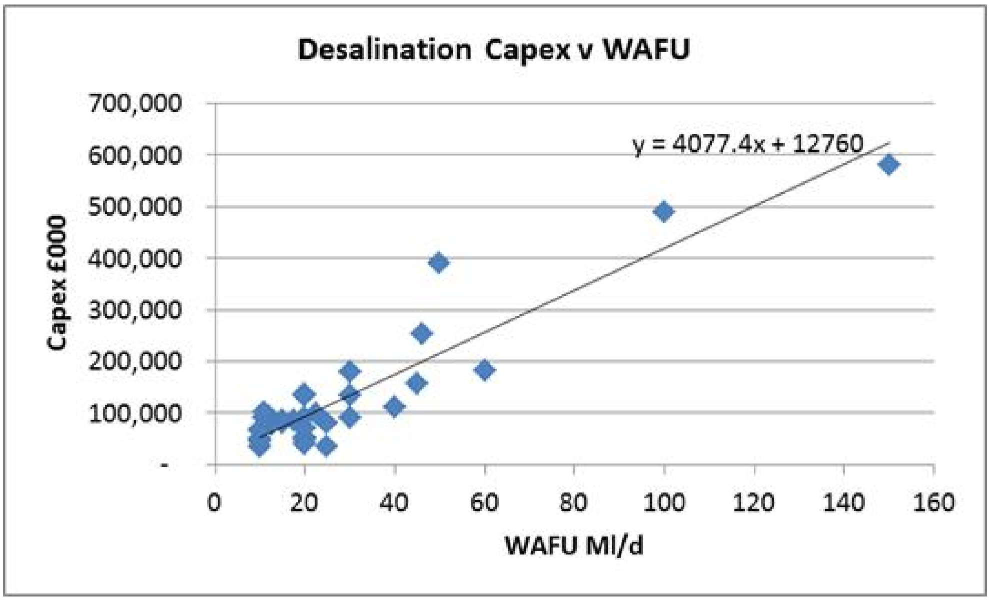
Desalination

- Desalination costs “AIC capex” v WAFU for all WRMP options are presented as follows:



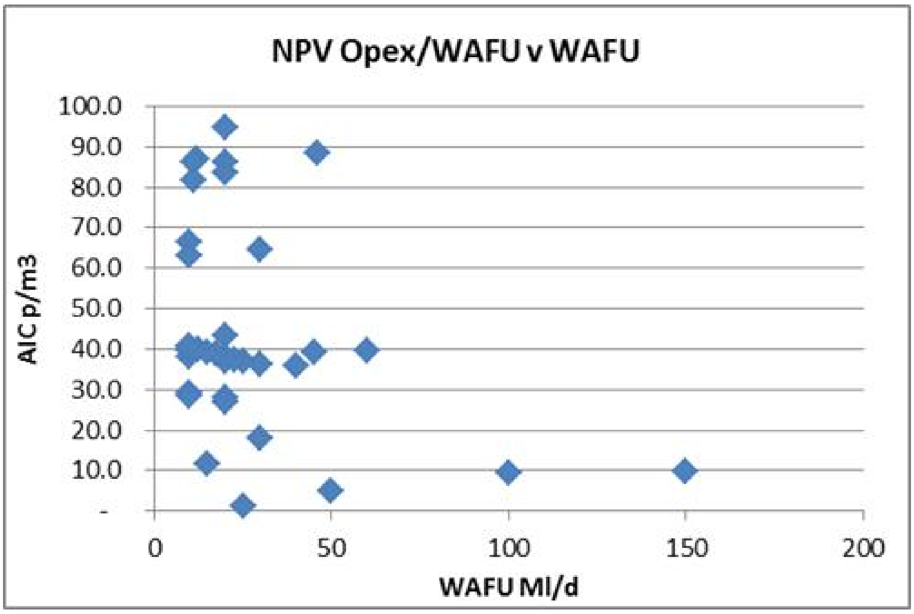
- Capex variation is partly due to economies of scale, but there are abnormally low AIC values for some small options. These are excluded in defining the cost curve.

- The capex v WAFU plot for options selected to be representative for costing is shown below:

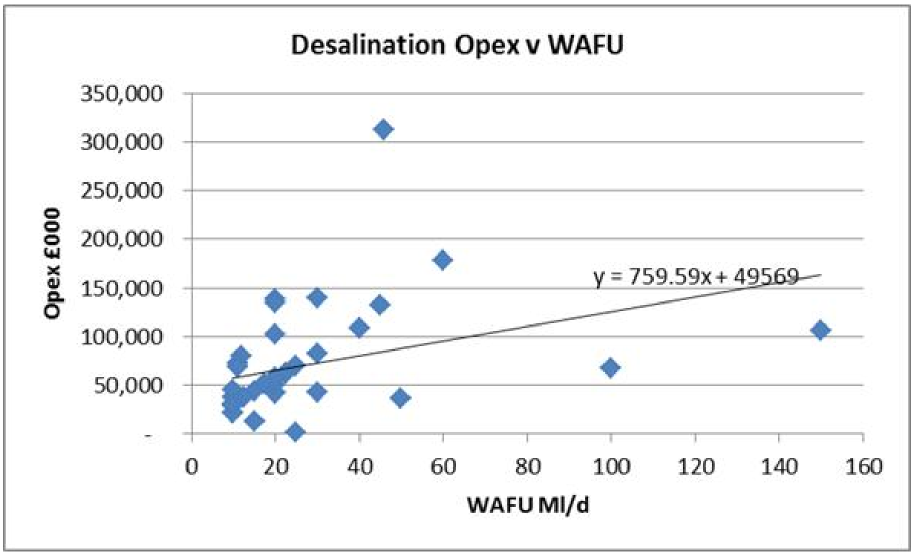


It is recognised that there are few large scale fully costed options, but the regression fit is reasonable and considered good enough for strategic option evaluation. Desalination costs are likely to change considerably over the coming years and decades, in response to major demand worldwide, and so these costs are indicative only.

- For desalination opex, the cost curve is uncertain, with variation most likely due to variation in utilisation assumptions. “AIC opex” v WAFU plots as follows:

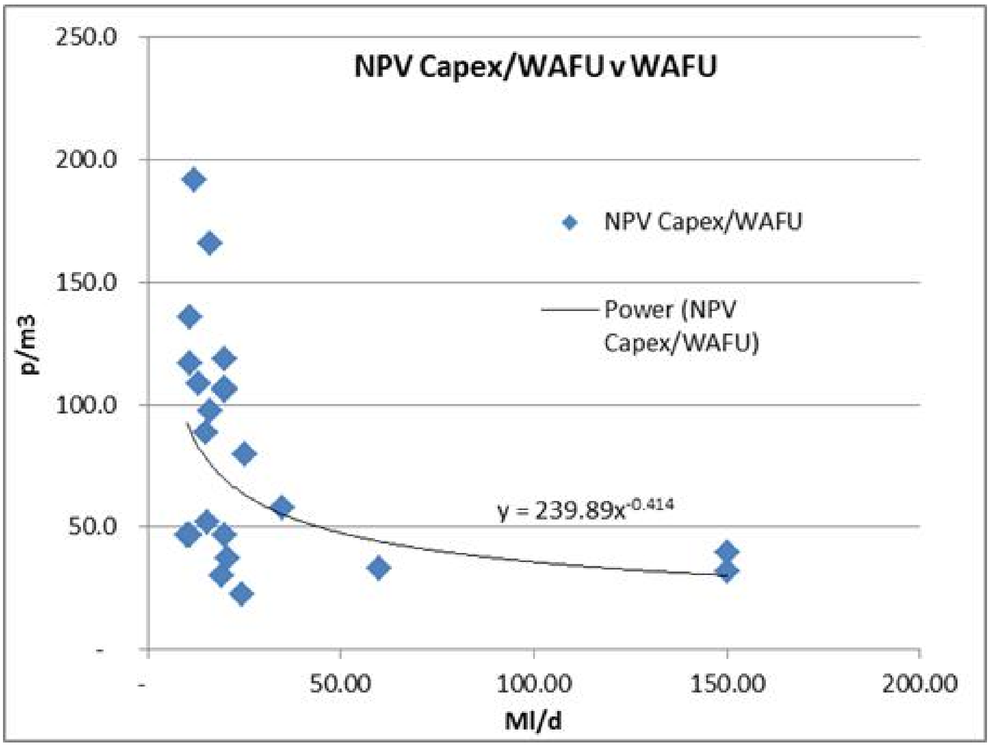


Opex was normalised using the following linear cost curve. This is sufficient for AISC ranking, as desalination is considerably more expensive than most options. Costs are also likely to change significantly over the next 50 years due to technological innovation.



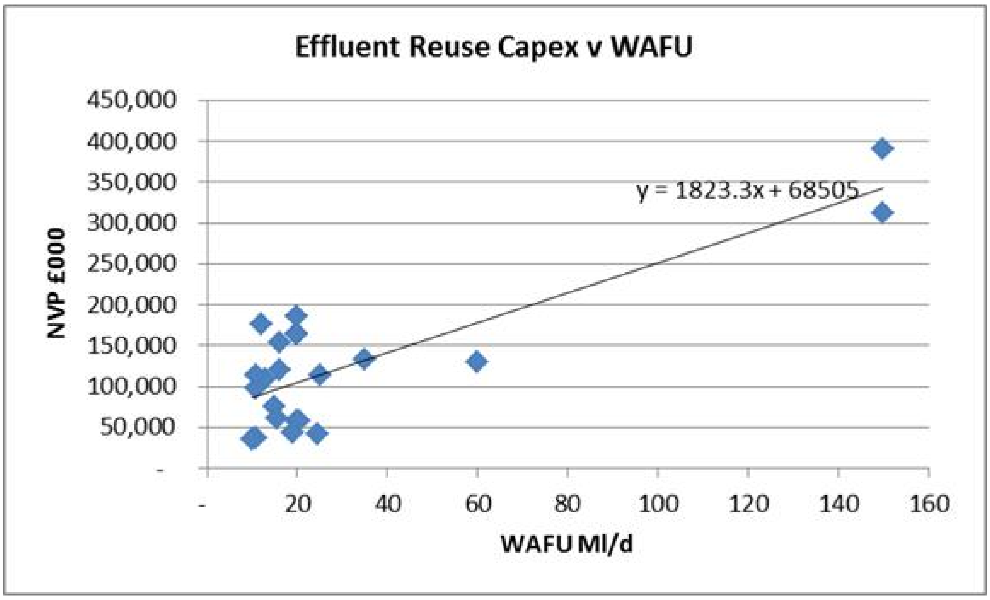
Effluent Reuse

- “AIC Capex” v WAFU plot for every option specified at WRMP14 is as follows:



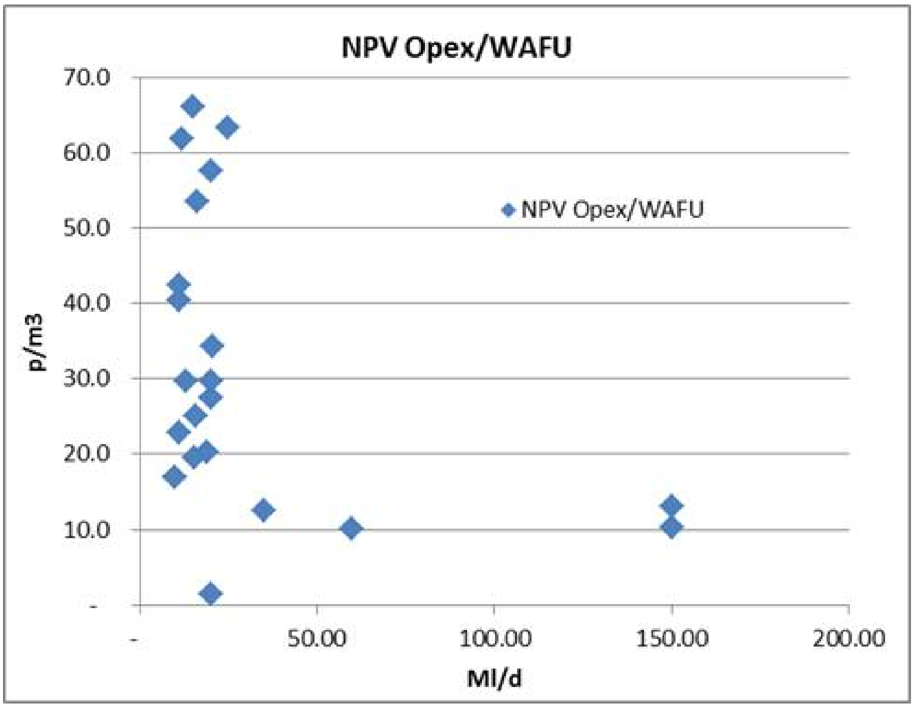
This assumes reverse osmosis treatment is required for all effluent reuse.

- Excluding anomalously low costs, we define a cost curve for normalisation of strategic options and new options, as per desalination.

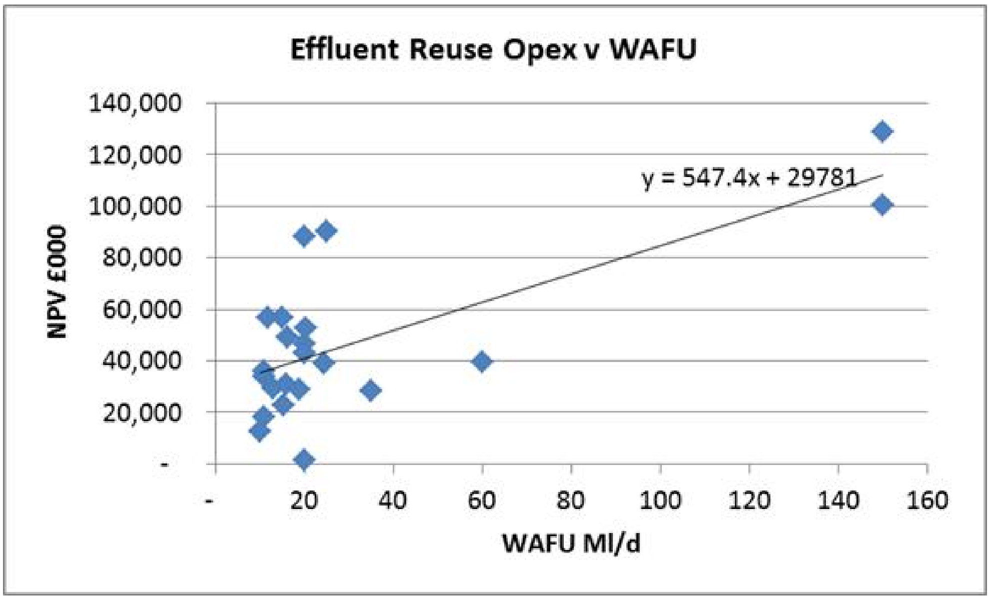


As for desalination, there are only two options >100 Ml/d with detailed costs defined. For all other options of this size, we are therefore reliant on these points to inform costs. However, once again accepting the long timescale, over which technology is likely to change markedly, and the purpose of this project, in defining a planning framework only, these cost curves are considered acceptable.

- For opex, the "AIC Opex" v WAFU plot of all options is as follows:



As for desalination, there is considerable uncertainty in operational cost due to high variable opex and differing utilisation. However, we have assumed the following cost curve for normalisation of options.



The principal uncertainty over indirect potable reuse is the extent to which reverse osmosis is required as part of treatment, prior to release back into a raw water reservoir. At present, considerable volumes of IPR occur naturally through the supply system by release of final effluent into rivers upstream of reservoir or direct surface water abstraction points downstream. The precise volumes are yet to be determined, but a key policy question is the extent to which IPR without reverse osmosis is acceptable for supply. This has a major bearing on the cost effectiveness of IPR and selection of strategic options.

Validation

- The cost normalisation provided a means of validation for all effluent reuse and desalination options.
- AISC checks were performed across all strategic options and costs updated where significantly different from the mean for a given option type, unless a good reason for the discrepancy could be identified.
- Analysis in Wathnet provided a means of validating WAFU benefit for hydrologically-dependent options.

Key uncertainties and assumptions

A number of the largest strategic options are yet to be fully designed, costed and evaluated for WAFU benefit. For all of these, accuracy of costs and WAFU benefit is no better than 50%. This is sufficient for high-level ranking of options, but not for any detailed planning at a regional or local level. Option refinement is urgently required for the highest priority options.

We assume the following:

- For strategic options (> 30 Ml/d), cost curves are appropriate for specifying costs at a high level for effluent reuse, desalination and some reservoir options.
- WRMP14 values for WAFU benefit, capex and opex are used as a basis for all WRMP options and for costing new options. National normalisation of costs is made where considered appropriate.
- Costs defined in historic studies are appropriate for costing potentially feasible options where no more detailed costs are available, adjusted for price inflation over time.
- Utilisation of all options on average is 1 in 10 years for historic drought, 1 in 20 years for severe drought and 1 in 50 years for extreme drought.

There remain considerable uncertainties associated with environmental impacts and risks, water quality impacts and risks and other planning constraints for most strategic supply options. These require refinement at regional or local level before a best “pathway” of strategic options is determined.

Outputs

The output comprised the following:

- Table of strategic supply options, with associated WAFU benefit, WRZ, capex, opex (based on historic drought utilisation), and AISC.
- Updated SDB tool able to recalculate the SDB for every WRZ under every scenario and strategy on the basis of a specified AISC threshold in 2040 and 2065.

Following portfolio generation (described in section 8 of the main report), strategic options were grouped and categorised by likelihood of implementation under the assumption of given volume of transfers. The key strategic options utilised in the portfolios are listed in the table below, grouped by frequency of utilisation across all 13 portfolios. **It should be noted that this reflects the simple AISC process only – the more comprehensive analysis of potential future developments, which incorporates this analysis alongside resilience testing of portfolios and qualitative constraints analysis is described within the main technical report.**

Table App-19 List of key strategic options utilised in the AISC derived Portfolios

	Water Supply Area	Option Name	WAFU Ml/d
Key Strategic Options utilised under most scenarios by 2040	Anglian – Ruthamford & Fenland	River Trent to Rutland transfer	**200**
	Portsmouth	River Itchen abstraction 30 Ml/d	**30**
	Severn Trent - Nottinghamshire	Little Eaton Conjunctive Use	**30**
	Severn Trent - Strategic Grid	Lower Derwent to Melbourne (no Carsington Raise)	**30**
	Thames Water - London	Indirect Potable Reuse Beckton STW 150 Ml/d RO	**150**
	United Utilities	Vyrnwy Transfer support	**100**
	Yorkshire - the Grid	Ouse Raw Water Transfer	**40**
	Yorkshire - the Grid	Tees to Swale River Transfer Option 2 Phase 1	**50**
Strategic options utilised under most scenarios by 2065, or by 2040 under more severe scenarios	DCWW - SEWCUS	River Wye Regulation Release through new small option replacement	**130**
	Severn Trent - Strategic Grid	River Severn Augmentation (Barnhurst)	**25**
	Severn Trent - Strategic Grid	Middle Severn to Draycote Opt A (6% +80 Avon)	**169**
	South East Water - Guildford & West	Bray WTW extension	**29**
	Thames Water - London	IPR Mogden	**200**
	United Utilities	Longdondale Compensation Flow Reduction	**25**
	United Utilities	Reservoir Wave Walls	**30**
	Yorkshire - the Grid	Tees to Swale River Transfer Option 2 Phase 2	**30**
	Yorkshire - the Grid	Tees to Swale River Transfer Option 2 Phase 3	**60**
Strategic Options utilised by 2065 under more severe scenarios or by 2040 under most extreme scenarios	Anglian - Lincolnshire	South Lincs Reservoir	**113**
	Anglian - Norfolk	Norwich Storage	**10**
	Anglian – Ruthamford & Fenland	Grafham Dam Raising	**40**
	DCWW - SEWCUS	Craig Goch Enlargement 1	**150**
	DCWW - SEWCUS	Brianne Dam Raising	**50**
	Northumbrian	Kielder Maximise Yield	**200**
	Portsmouth	Portsmouth Harbour Desalination Plant	**25**
	Severn Trent - Strategic Grid	Birmingham Resilience/Conjunctive Use	**50**
	Severn Trent - Strategic Grid	Middle Severn to Draycote Opt B (50% expansion)	**155**
	South East Water - Kent	Effluent reuse to River Ouse: source – Peacehaven	**25**
	Southern Water - Central	Coastal Desalination – Shoreham Harbour 40 Ml/d	**40**
	Southern Water - West	Fawley desalination 60 Ml/d (incl. HST2)	**60**
	Thames Water - London	IPR Deephams STW 60 Ml/d RO	**60**
	Thames Water - London	IPR Abbey Mills 150 Ml/d RO	**150**
	Thames Water - London	IPR Hogsmill 35 Ml/d RO	**35**
	Thames Water - London	150 Mm3 Upper Thames Reservoir	**283**
	United Utilities	Additional Groundwater	**55**
	United Utilities	WIDNES GROUNDWATER (NORTH MERSEY STRATEGY)	**34.5**
	United Utilities	Additional Groundwater	**20**
	United Utilities	River Mersey Effluent Reuse	**100**
	Yorkshire - the Grid	River Aire Abstraction option 3	**50**
Options required by 2065 under most extreme scenarios only	Anglian - Essex, Suffolk, Ely	Additional Anglian Effluent Reuse	**50**
	Anglian - Norfolk	Bacton desalination (46 Ml/d)	**46**
	Bristol Water	Docks to Barrow transfer scheme	**30**
	Bristol Water	Artificial pumped re-charge Chew reservoir	**25**
	Bristol Water	Desalination and treated water transfer	**30**
	DCWW - SEWCUS	Craig Goch Enlargement 2	**280**

	Water Supply Area	Option Name	WAFU Ml/d
	DCWW - SEWCUS	Craig Goch Enlargement 3	**200**
	Essex & Suffolk	E&S Eff Reuse	**40**
	Severn Trent - Strategic Grid	Upper Avon/Leam Resource Development (Opt A)	**27**
	South East Water - Kent	Additional Effluent Reuse	**46**
	Southern Water - Central	Additional Desalination	**75**
	Southern Water - East	Additional Effluent Reuse	**76**
	Southern Water - West	SW West Ext Eff Reuse	**32**
	Thames Water - London	Reservoir Raising	**50**
	Thames Water - London	Additional Desalination	**300**
	Thames Water - London	Additional London Effluent Reuse	**300**
	Thames Water - London	London Tankering	**150**
	Thames Water - London	DSL Estuary South 150 Ml/d	**150**
	United Utilities	Manchester Ship Canal Upscaled	**40**
	United Utilities	NEW RESERVOIR AT BORROWBECK	**80**
	United Utilities	Non-PWS Reservoirs	**30**
	Wessex	River Avon abstraction near Saltford	**30**
	Wessex	Desalination (30 Ml/d)	**30**
	Yorkshire - the Grid	Hull Effluent Reuse	**100**
	Yorkshire - the Grid	Humber Desalination	**50**
	Yorkshire - the Grid	Yorkshire Tankering	**55**

D.4. Regional and intra-regional transfers

Purpose and core concepts

- Determine the potential nature of key regional and intra-regional transfers forming part of least-cost portfolios of supply-side options under specified scenarios.
- Specify a range of values for magnitude of each transfer, as well as potential capex and opex.
- Set up the transfers for testing in Wathnet for resilience against drought.

Methodology

The approach to defining transfers is described in the main report. In short, transfers were used to match areas of surplus to areas of deficit using existing infrastructure and water bodies where possible. This involved an iterative approach where AISC cost of new supply options was increased incrementally and transfers introduced when clearly lower cost than the next cheapest local supply option. The AISC cost of a transfer was based on a review of WRMP14 costed raw water transfers.

NPV cost plots for WRMP14 raw water transfers are shown below. Note a number of these include costing new resource in the donor area to support the transfer. For our purposes, these costs are excluded from transfer costs, as transfers are only specified to connect a supply area in surplus with one in deficit. There is no new deployable output associated with the transfers themselves. The large variation reflects the site-specific nature of all transfers amongst other aspects. Nonetheless it provides a starting point for costing transfers on a large scale.

Figure App-40 WRMP14 Raw Water Transfers: capex NPV v WAFU benefit

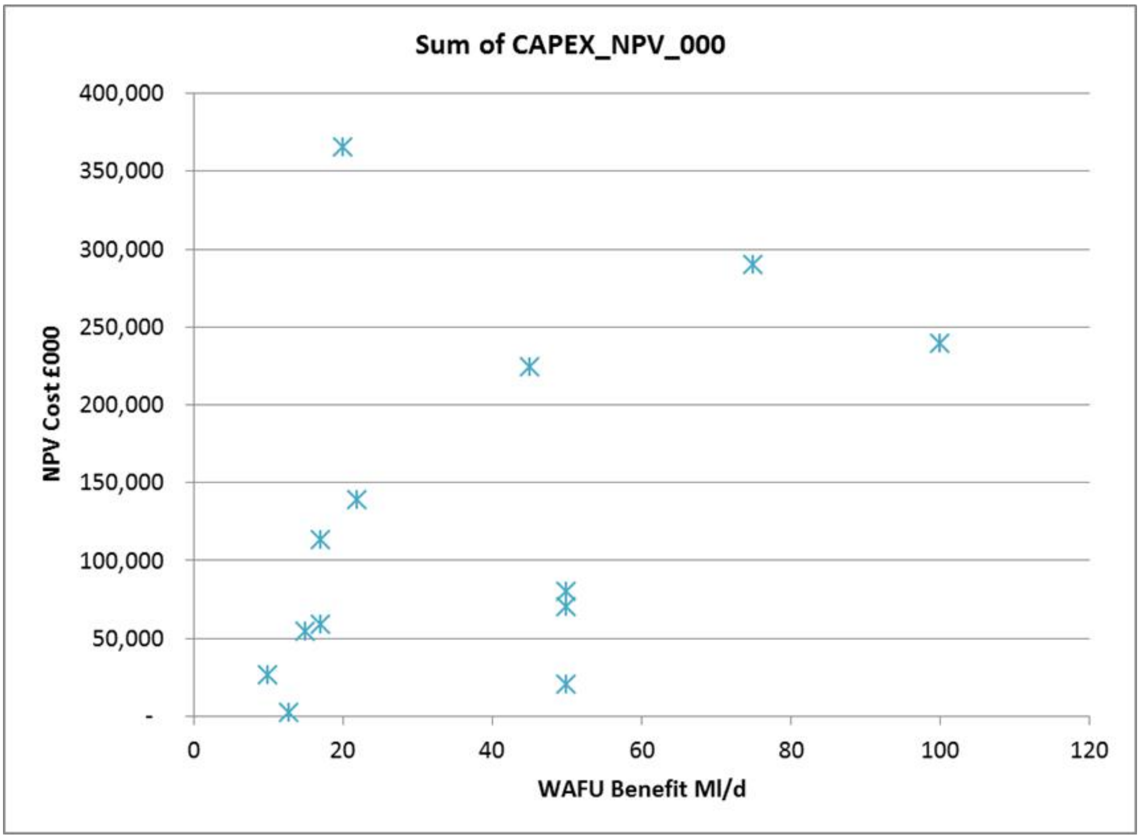
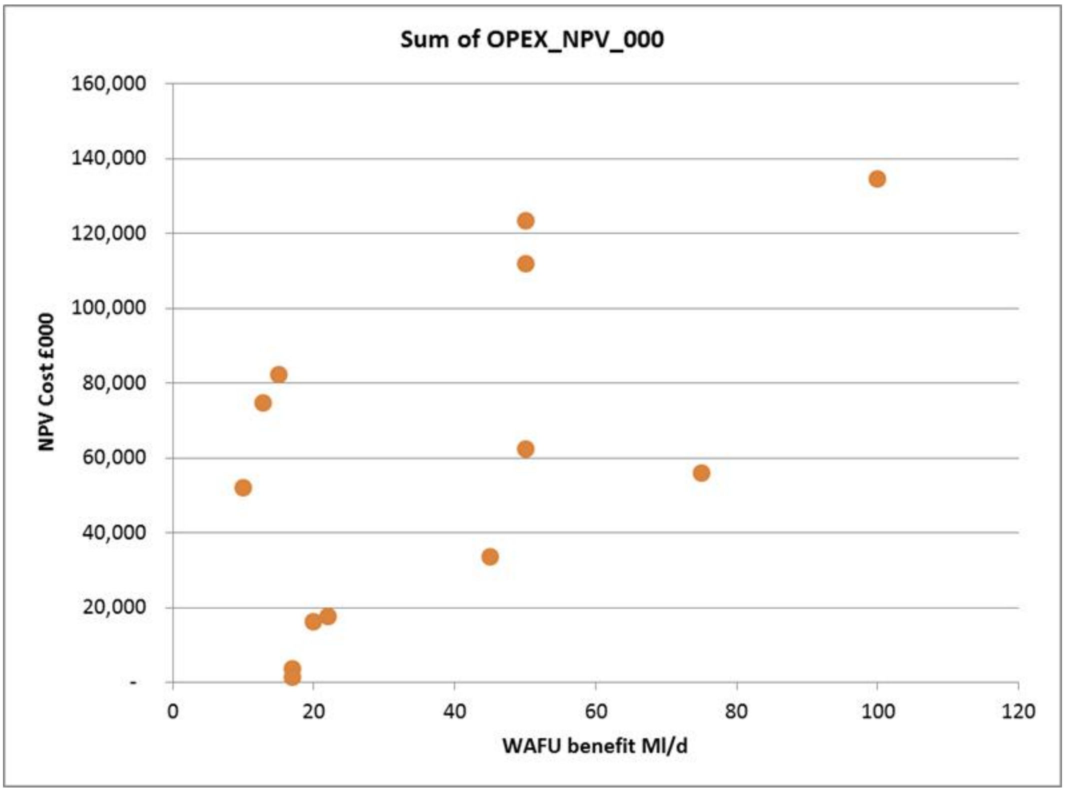


Figure App-41 WRMP14 Raw Water Transfers: opex NPV v WAFU benefit



All transfers move water from an area of surplus to one of deficit, and therefore are fully supported under the scenario in question. Their ability to perform well under more severe scenarios was then tested by running the full portfolio of transfers and supply options through Wathnet under different drought scenarios.

In practical terms, transfers were specified as follows. Firstly, supply options were introduced incrementally in order of AISC, adding WAFU benefits irrespective of SDB in a given supply area. This process continued until a significant surplus is obtained nationally (typically 1000 Ml/d at national level), subject to a minimum AISC of 25 p/m^3 (the base cut-off for unsupported transfers). All remaining deficits were filled initially by transferring water from adjacent supply areas where possible, or with small-scale “cascades” of water. Regional transfers were then applied to fill the remaining deficits up to a prescribed limit and taking account of geographical and hydrological constraints. Where transfers were incapable of filling all deficits, additional supply options were introduced as necessary to complete the portfolio. Lastly, any unnecessary options were removed in reverse order of total NPV. In this way, it was attempted to derive a “least cost” portfolio, irrespective of supply area and company boundaries.

The benefit of transfers was estimated in two ways. Firstly, 2 portfolios were compared where the total WAFU generated under the first from both supply side options and transfers is approximately equal to the WAFU benefit generated solely by supply options in the second. The cost difference between [supply side options plus transfers] in portfolio A and [supply side options only] in portfolio B gives an idea of the cost benefit of transfers. Secondly, transfer benefit is estimated by looking at the regional cost resulting from “switching off” a particular regional transfer and replacing the required WAFU with local supply-side options. The value of transfers varies significantly depending on the scenario in question, as the marginal cost of supply-options varies, and between different transfers, locally and regionally. Therefore it is impossible to specify precisely, but typical cost benefits on the order of 30% to 50% are apparent using these methods. We recommend regional studies attempt to quantify these cost benefits further where necessary. A number of the benefits do not relate solely to cost, for example in terms of improving resilience to drought and other factors. Certain regions will be entirely dependent on transfers under certain scenarios, irrespective of cost.

Validation

Final portfolios of transfers and supply options were run through Wathnet to test against drought. This also acted as a process of validation and changes were made where transferred volumes were considered too large.

Key uncertainties and assumptions

The detail around a number of the proposed transfers is uncertain, as significant time is required to fully evaluate the engineering requirements of each. Costs are correspondingly uncertain. Some of the assumptions are as follows:

- Unit cost of transfers is uniform across all regions and supply areas, and independent of size. This is a notable simplification, but taken pragmatically given the time available.
- All water quality and environmental issues associated with transfers can be overcome at reasonable cost.

Outputs

The full set of transferred water volumes is shown in the following tables for 2040 and 2065 respectively. Positive numbers indicate imports and negative numbers exports. The specific source and donor supply areas for each import/export are not defined explicitly, as this level of detail is not considered appropriate here.

Transfers on this scale are highly ambitious and subject to a number of risks, as described previously. The aim here is to provide a framework for regional and local planning and therefore to set a scale of ambition for transfers. Significant further investigation is required to properly evaluate each transfer in turn.

Strategic regional transfers were calculated by taking the net import and export from the respective source and recipient regions, summing all intra-regional imports and exports. These were input to Wathnet to test under drought.

Table App-20 Supply area transfer specified under each portfolio 2040

Supply Area	1	2	3	4	5	6	7	8	9	10	11	12	13
Affinity Water - South East	1	1	2		1	5	4	3	6				
Affinity Water - Dour	2	3	3		2	8	8	7	9	4	2	1	1
Affinity Water - London N	26	27	27	2	55	52	53	49	90	53	36	5	2
Affinity Water - London S	100	101	96	23	215	150	142	137	287	172	155	51	15
Anglian - Essex, Suffolk, Ely			4		7	13	14	25	35	33	31		
Anglian - Lincolnshire			-1		-6	3	6	2	-71	14	1		
Anglian - Norfolk			0		-4	2		1	20	20	21		
Anglian – Ruthamford & Fenland	-229	-193	-115	-151	-254	-227	-231	-175	-146	-190	-120		
Bournemouth			-40					-40	-34	-42	-50		
Bristol Water	4	20	32	11	8	8	17	37	47	25	8	1	1
Cambridge	3	3	3		18	12	14	12	31	23	19		1
DCWW - Central Wales						-4	-8				-11		
DCWW - North Wales													
DCWW - Pembrokeshire						4	4	2	4				
DCWW - SEWCUS							24	-250	-290	-135			
DCWW - Tywi CUS							-20		0				
Dee Valley									2		-5		
Essex & Suffolk	-20	-13	-9	-34	-54	-20	21	57	40		-25	-35	-35

Supply Area	1	2	3	4	5	6	7	8	9	10	11	12	13
Essex & Suffolk - Blyth													
Essex & Suffolk - Hartismere								-2	-1				
Essex & Suffolk - Northern & Central					-8					-5	-5		
Northumbrian			-21				-131	-107	-78				
Portsmouth	18	29	24	12	18	6	14	-4	3	-1	-10	14	12
Severn Trent				-34	52	17	17	17	102	67	40	-8	-8
Severn Trent - Nottinghamshire	13	22	27	9	85	34	34	47	122	101	85	8	8
Severn Trent - Strategic Grid	-132	-22		151	-116	-68	-30	16	16		-10		
South East Water - Guildford & West	-31	-25	-25	-45	-53	-50	-44	-40	-57	-87	-55		
South East Water - Kent	4	30	2		-25	18	32	62	-8	-25	-5	17	23
South Staffs				-17	-5	10	17	36	55	20			
South West & Roadford									-3				
South West Water - Colliford									3	-10			
Southern Water - Central	49	22	25	13	64	8	19	29	87	64	71	6	12
Southern Water - East		65	10	33	125	20	25	-40	24	62	76	50	50
Southern Water - West	10	39	23	0	42	35	38	40	71	73	68	25	25
South-West - Wimbleball													
Sutton & East Surrey	8	10	18		8	19	18	18	32	6	3		
Thames Water - Guildford					-7		-8	-5	1	-3	-5	-15	-15
Thames Water - London	220	186	277	331	204	240	162	283	-70	105	135	202	170
Thames Water - Provinces	-28	-65	-80	-85	2	-45	-56	-65	56	-6	-8	-70	-61
United Utilities		-220	-273	-175	-328	-242	-231	-230	-442	-310	-374	-254	-201
United Utilities - Carlisle									1				
United Utilities - North Eden													
Wessex	-18	-20	-30	-44	-46	-8	-24	-29	-24	-29	-69	0	0
Yorkshire					1				2	1	1		
Yorkshire - the Grid			21		-1		100	107	78			2	

Table App-21 Supply area transfer specified under each portfolio 2065

Supply Area	1	2	3	4	5	6	7	8	9	10	11	12	13
Affinity Water - South East	2	2	2		2	9	6	6	11	3	1		1
Affinity Water - Dour	5	5	7	2	5	13	12	8	13	3	5	2	3
Affinity Water - London N	52	51	48	18	80	87	87	86	148	81	58	21	25
Affinity Water - London S	145	137	125	34	241	226	221	219	411	237	183	65	48
Anglian - Essex, Suffolk, Ely	15	14	31	26	29	55	47	-16	24	54	41		12
Anglian - Lincolnshire	-15		-15	-22	6	27	28	-81	-28	49	26		
Anglian - Norfolk			22	19	7	22	11	19	11	39	29		
Anglian – Ruthamford & Fenland	-202	-228	-165	-175	-262	-200	-200	-105	-133	-165	-184	-119	-200
Bournemouth			-55		-55	-25	-32	-33	-19	-37	-45		-62
Bristol Water	35	35	41	12	8	52	5	-44	-15	-55	-45	15	31
Cambridge	15	12	11	8	26	29	25	25	49	37	29	1	9
DCWW - Central Wales								-6		-13			
DCWW - North Wales						1			5	-10			
DCWW - Pembrokeshire						7	6	6	8	2			
DCWW - SEWCUS	7	-120	-121		7	-150	-220	-270	-676	-310	-150		-35
DCWW - Tywi CUS	-7				-7	4			13	-12	-12		
Dee Valley						9	7	7	12	3			
Essex & Suffolk	-43	8	15	-22	-43	11	61	100	61	-11	-1		-26
Essex & Suffolk - Blyth						1		0	1		-1		
Essex & Suffolk - Hartismere					-2		-1	-1			-2		
Essex & Suffolk - Northern & Central		-4	-8		-8	2		0	3		-4	-10	-10
Northumbrian		-72	-132				-145	-136	-240	-180	-4		
Portsmouth	21	2	-14	-2	-7	9	8	11	29	-13	-26	12	12
Severn Trent	-9			-26	61	46	46	46	149	94	54	-40	-40
Severn Trent - Nottinghamshire	45	45	53	40	117	79	79	95	183	147	121	20	50
Severn Trent - Strategic Grid	-202	-60	-57	136	-156	-302	-152	116	271	250	113	-45	
South East Water - Guildford & West	-52	-43	-50	-65	-40	-18	-19	-3	-6	-60	-80	-13	-12
South East Water - Kent	47	43	48	11		88	97	37	-20	-12	7	23	74
South Staffs	2	9	26		16	51	58	82	118	61	28		
South West & Roadford								-4	12				
South West Water - Colliford						10	4	4	19				
Southern Water - Central	32	40	28	13	35	41	53	25	78	59	81	20	31
Southern Water - East	75	50	12		70	-4	-19	-20	9	24	12	2	65
Southern Water - West	30	37	44	8	73	44	53	-39	20	59	43	26	14
South-West - Wimbleball						2			7				
Sutton & East Surrey	30	27	22		22	48	45	50	73	20	2	7	12
Thames Water - Guildford	-7		-5		-4	-3			11	2		-10	-10
Thames Water - London	341	455	370	376	228	178	135	176	-470	-10	189	360	343
Thames Water - Provinces	-26	-45	-46	-72	5	9	10	6	158	58	5	-55	-54
United Utilities	-273	-369	-315	-247	-385	-380	-428	-365	-335	-473	-348	-267	-236
United Utilities - Carlisle						1		0	2				
United Utilities - North Eden								-3	-3				
Wessex	-63	-53	-54	-72	-69	-39	-33	-133	-99	-103	-129	-15	-55
Yorkshire					2			-1	4	2	1		
Yorkshire - the Grid		22	132		-2	-40	145	136	131	180	3		10

D.5. Non-strategic supply options

Purpose and core concepts

- Compile a list of feasible supply options < 30 Ml/d in size across England and Wales, specified by WRZ.
- Define the WAFU benefit, NPV capex, NPV opex (as function of utilisation), and AISC for each option.
- Provide a means of option selection based on AISC and addition to the supply/demand balance for each WRZ, such that SDB values can be updated for each WRZ on the basis of AISC.

Methodology

The approach for non-strategic options was largely in line with that for strategic options, with the following key differences:

- The focus for small options was WRMP14. Water resource managers were invited to put forward other small options, but generally these were only included where grouped together by WRZ, their total WAFU benefit exceeded 30 Ml/d.
- No specific option details were compiled as small options were not modelled explicitly in Wathnet. Their inclusion simply results in a change in overall DO and WAFU for each supply area.
- No risks and issues were compiled.
- No cost normalisation was applied. Costs were taken at face value or, where absent, estimated using high level cost curves.

Non-committed Options

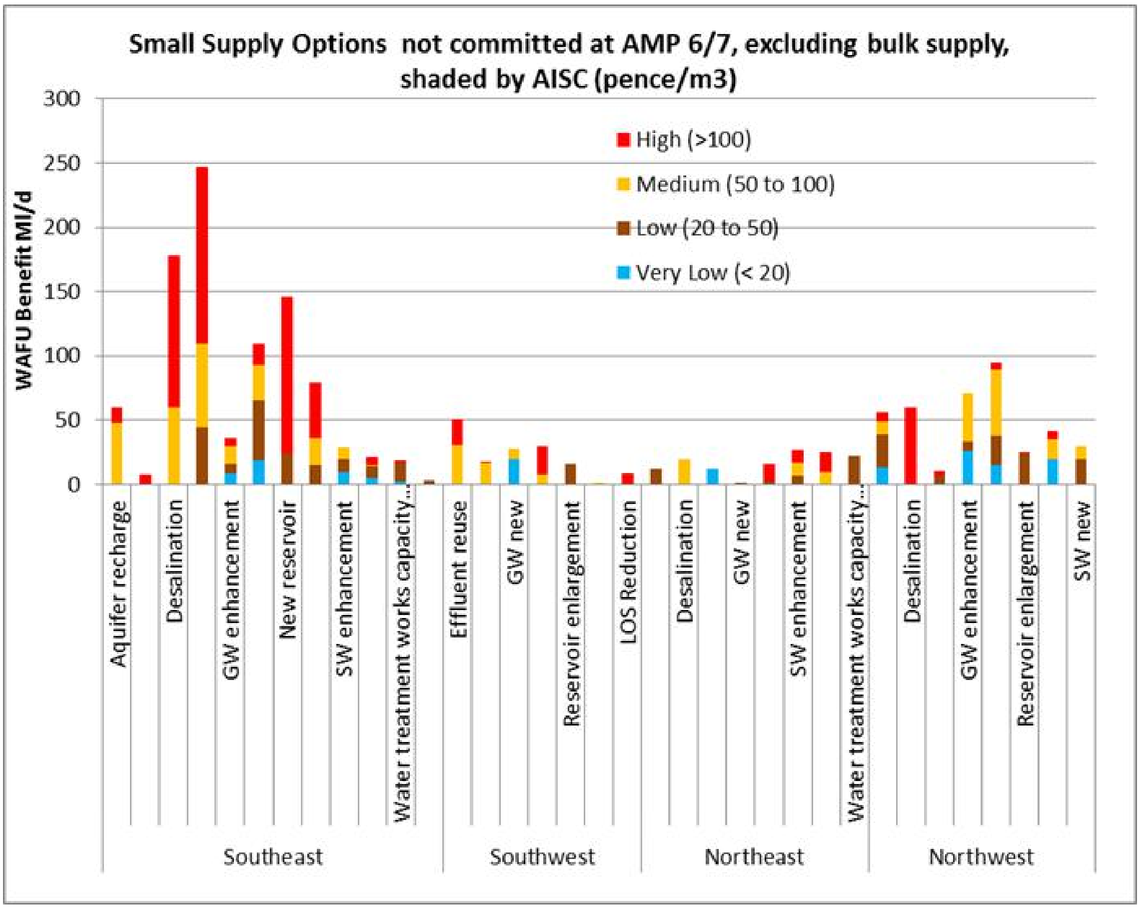
Final WRMPs include a total 177 Ml/d of preferred small options beyond AMP 7, with a total NPV of £1.1 billion. These comprise significant effluent reuse, new reservoirs and desalination (schemes < 30 Ml/d).

The remaining feasible small options, not selected in company preferred plans, comprise the following:

- Options providing new deployable output totalling 1,437 Ml/d of new WAFU in England and Wales, with total NPV £9.6 billion.
- A further 1000 Ml/d of small bulk transfers within and between companies, with total NPV £3.6 billion.

58% of non-committed options occur in the southeast. The full distribution is shown below, shaded by cost. It is apparent that there are relatively few low-cost options, and most of these are included in final preferred plans, as one might expect.

Figure App-42 WAFU benefit of WRMP non-committed supply options resulting in new deployable output (excluding bulk transfers) separated by region, coloured by AISC cost category



Validation

- No significant validation was carried out. A process of company review through steering group discussion and company telephone calls identified any significant issues.

Key uncertainties and assumptions

A number of the non-strategic options may not be feasible on a number of technical, environmental or planning grounds. Option refinement will be required for a number of them. We assume the following:

- For un-costed options, strategic option cost curves are appropriate for specifying costs at a high level for small options.
- WRMP14 values for WAFU benefit, capex and opex are used as a basis for all WRMP options and for costing new options.
- Utilisation of all options on average is 1 in 10 years for historic drought, 1 in 20 years for severe drought and 1 in 50 years for extreme drought.

Outputs

The output comprised the following:

- Table of small supply options, with associated WAFU benefit, WRZ, capex, opex (based on historic drought utilisation), and AISC.
- Updated SDB tool able to recalculate the SDB for every WRZ under every scenario and strategy on the basis of a specified AISC threshold in 2040 and 2065.

D.6. Generation of Portfolio Cost curves and Total Costs

Purpose and core concepts

- Define national and regional cost curves for total NPV cost v total sum of supply area deficits for England and Wales using portfolio outputs.

- Apply cost curves to all 144 SDB futures to estimate supply-side costs required to mitigate drought under each scenario for every demand management strategy and for each region in turn. In this way supply-side costs are allocated to the region in deficit, even where new supply resources or demand management are required elsewhere.

- Attempt to reallocate demand-side costs where these are utilised to fill a deficit in a different region from where the savings are made.

- Use the results to take forward for consequence analysis.

A summary of the key steps is shown below, placing the cost analysis in the broader picture of the overall analysis.

Figure App-43 Summary of key steps in option portfolio selection

Key steps	*Explanation and objectives*
Develop a wide range of possible futures each with a different potential deficit or surplus in 2040 and 2065	•Take account of future uncertainties and growth scenarios relating to environmentally-driven abstraction changes, growth in demand, climate change and drought resilience. •Assess against a range of potential future demand management strategies. This shows the amount of demand remaining that needs to be satisfied by supply-side options
Select sample of futures for which solutions will be identified	•To cover a broad range of potential future deficits to allow understanding of how strategic solutions may change. •Incorporate estimated demand savings due to various demand management strategies.
Generate 13 investment portfolios based on least cost approach for selecting the supply side options	•Solve the deficit remaining using supply side options, having already applied a specific demand management strategy. •Selection of options on a least cost basis initially. •Ultimate aim is to provide understanding of relative balance between supply-side options for given alternative demand-side strategies that could be applied. •Project is not providing a single plan or solution.
Develop cost curves for all remaining futures	•Use the cost estimates for the 13 investment portfolios to develop cost curves that can be applied to provide an indication of the cost of each of the 144 future scenarios (i.e. covering plausible futures under each of the 4 levels of demand management). •Can see how much the cost of portfolios (per Ml/d benefit delivered) changes according to the different size of the SDB and the key scenario issues
Develop a coherent drought resilience library to improve understanding of resilience	•Aridity index plus conditional probability analysis to determine the coherence of droughts. •Drought resilience analysis based on stochastic emulator of the 20th Century Climate; perturbed for climate change. •To answer question: If you have a drought of severity x in a recipient Drought Zone, what should we plan for in the potential donor Drought Zones?
Test the 13 investment portfolios for resilience against a wider range of drought events	•Test each of the portfolios against a wider range of scenarios in the Resilience Evaluation Tool to understand how each portfolio performs in terms of resilience and failure metrics. •This includes testing against a “drought library” covering 15 different drought events, which are derived from a mixture of historic and stochastically generated drought. Allows us to test the reliability of regional transfers under drought conditions.
Evaluate the results in terms of the costs of potential portfolios of options to meet deficits, and the relative consequences of failure	•To understand the relative resilience and costs of the portfolios to address the range of plausible futures. •To inform the trade-offs between cost and resilience, and the environment and public water supplies. •To help inform discussion around what is the appropriate level of drought resilience to plan for
Draw conclusions: appropriate mixes of options for regions which may be susceptible to certain futures	•To understand themes around strategic options / option types, transfers and demand management strategies under various plausible futures. •To inform identification of enabling actions or policies that will be needed to support future options. •Water companies and regional modelling groups to investigate detailed options further as part of forthcoming and future WRMPs.

Methodology

- Cost curves were developed by plotting total NPV cost (sum of local DO capex and opex, transfer capex and transfer opex) v. total sum of supply area deficits for each portfolio. Curves were plotted by region as well as nationally.
- Apply cost curves to all 144 SDB futures to estimate supply-side costs required to mitigate drought under each scenario for every demand management strategy and for each region in turn.
- Annualise costs by converting back to cost per annum, assuming costs are averaged over 8 years, both capex and opex. In reality opex would be charged when the expense was incurred, but for the purposes of simplification we annualise opex across the full time horizon.
- Costs per household are then calculated for each region by dividing regional annualised costs by regional number of households in 2040. This provides a simple metric of the economic impacts on different regions, which is of most use for policy makers. It is not equivalent to a bill impact, or even represents in any way a forecast change in the price of water, which depends on a multitude of factors.

Validation

Validation was carried out by checking portfolio costs against those estimated by cost curves.

Key uncertainties and assumptions

- For the purposes of this study, national cost curves are considered most appropriate for all supply-side costing.
- A discount factor of 4.5% is used throughout.

Outputs

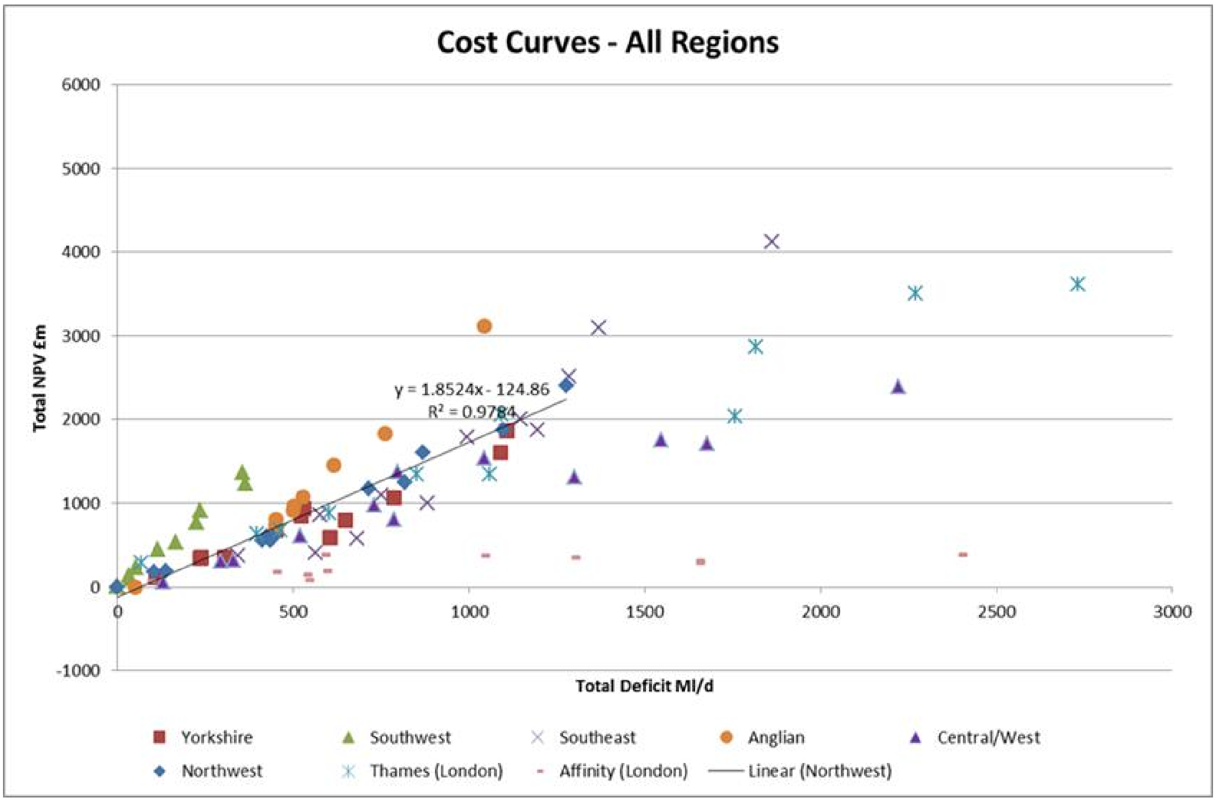
- Regional and national cost curves.
- NPV costs.
- Annualised costs by region for all 36 scenarios across 4 demand management strategies, both absolute values and values per household.

The regional and national cost curves are as shown in Figure App-44 and Figure App-45.

Costs over the 2065 time period are relatively diminished relative to 2040 due to the standard use of discounting.

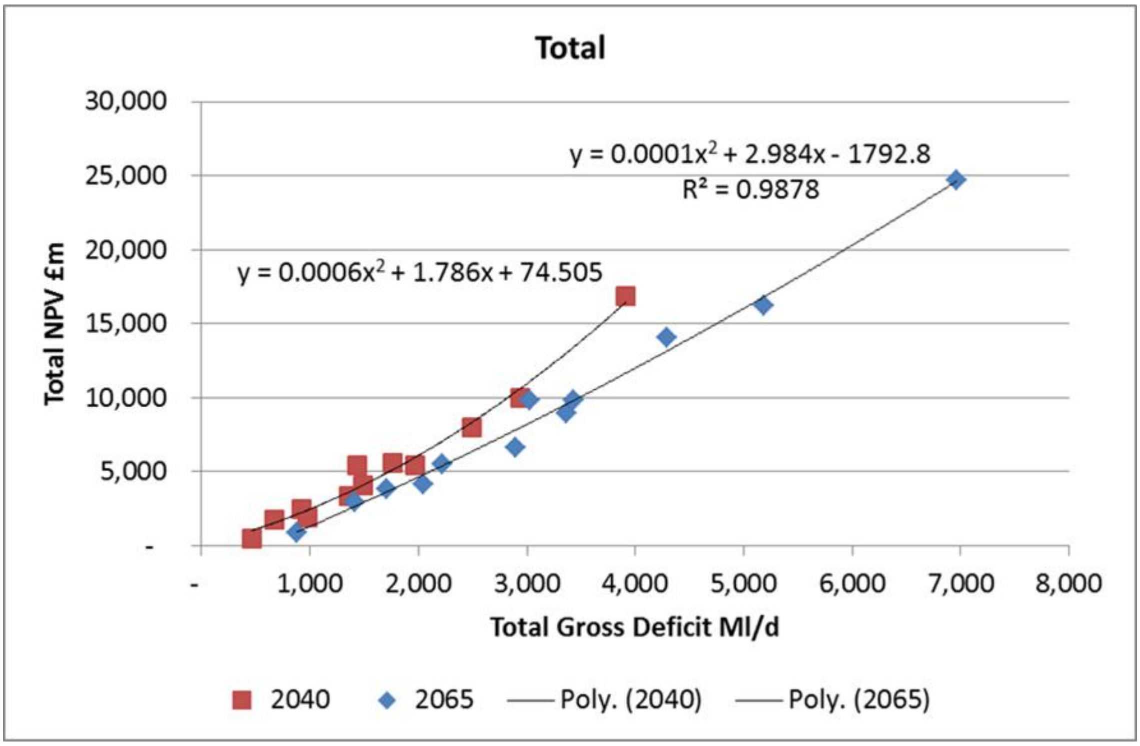
Demand management costs were primarily defined for a given population growth scenario for each region and applied equally to all relevant scenarios. The exception was for lower population growth scenarios, where cost curves were used to estimate the costs of demand management.

Figure App-44 Cost Curves derived from portfolio costs v sum of supply area deficits, broken down by region



There was no clear, significant trend in costs between regions, and the regional costs are distorted because a significant proportion of costs for a region subject to high levels of imported bulk transfers are incurred by other regions. Therefore for the purposes of this study it was decided to use the national curves at 2040 and 2065 to estimate NPV costs of each scenario and demand management strategy.

Figure App-45 National Cost Curves derived from portfolio costs v sum of supply area deficits for England and Wales



Appendix E. Drought Permits and Orders

Purpose and Core Concepts

The purpose of the Drought Permits and Orders analysis was to provide a reasonable allowance for the impact of supply side operational interventions on supply/demand balances and system resilience under severe and extreme drought events. Because of the democratic process of investigation, review, potential objection and environmental control that occurs each time a Permit or Order is applied for, it is not possible to accurately predict the outcome that they would have for any given drought. This means that supply side interventions are not *reliable* in an investment planning sense. However, it was not considered to be reasonable to ignore their potential benefits, particularly when droughts that are more severe than the worst historic were being considered, so a series of assumptions were agreed with the Steering Group to quantify their benefit. This Appendix details those assumptions and shows how the benefits were translated into the resource evaluations and RETs.

There were two objectives from the analysis

A. Create benefits for the severe and extreme Drought Configurations in the resource evaluation

B. Evaluate and configure the benefits Drought Orders and Permits for input to Wathnet

Methodology

The methodology for incorporating Permits and Orders was straightforward:

1. All water company Drought Plans were reviewed and the referenced Permit and Orders were classified into High, Medium and Low reliability. This classification depended primarily on the evaluation of environmental risk contained within the Drought Plans, although some allowance was also made where water companies have actual experience of applying for the Permits and Orders. A summary of the number and magnitude of the Permits and Orders in each category for each company is provided in Table App-23 below.

2. A high level conceptual assumption was defined for incorporating the benefits, based on discussion with the project Steering Group. These are detailed in Table App-24.

3. For the resource evaluation these were translated into a more detailed set of assumptions, based on the following procedure:

    a. All companies were classified according to the duration of their critical drought type (based on the analysis of historic droughts and the Scenario 0 evaluation).

    b. The benefit of each Permit and Order was assigned to the ‘Severe’ and ‘Extreme’ drought configurations according to the company classification and the allocation algorithms described in Table App-24.

4. For the resilience evaluation tool, all Permits and Orders were attributed either a ‘simple’ or a ‘modelled’ classification. Simple Permits and Orders were only added as benefits under the relevant drought configurations, in accordance with the general principles used for the resource evaluations. A number of larger Permits and Orders that had less certain benefits were classed as ‘modelled’, and these were coded into Wathnet in accordance with the general parameterisation described in Table App-25.

Table App-22 Summary of Drought Permit/Order Classifications and Benefits

Company	Area	Drought Permit/Order Group name	Description/no. of permits	Modelled in Wathnet/ Aquator/ other	DO benefit (Ml/d)	Reliability	*Estimate for DO benefit (including modelled permits)*
Affinity Water	Affinity Water - Central	Affinity Water - Central: small permits	3 permits	No	11.64	M	11.64
		Affinity Water - Central: unlikely/excluded permits	7 permits	N/A	N/A	L	N/A
	Affinity Water - South East	SLYE	Increased abstraction. Priority for implementation: 1	No	2.5	M	2.5
		Affinity Water - South East: unlikely/excluded permits	3 permits	N/A	N/A	L	N/A
South East Water	South East Water - West	River Ouse (Ardingly Reservoir)	Maintain the MRF of 20 Ml/d but allow abstraction of everything above this up to the licensable limit	Yes	N/A	H	Variable (depending upon permit application)
		River Ouse (Ardingly Reservoir)	Reduce augmentation to 2 from 4 Ml/d (winter only)	Yes	N/A	M	2
		River Ouse (Ardingly Reservoir): unlikely/excluded permits	5 permits	N/A	N/A	L	N/A
	South East Water - Mid Kent	South East Water - Mid Kent: small permits	2 permits	No	8.6	H	8.6
		South East Water - Mid Kent: unlikely/excluded permits	6 permits	N/A	N/A	L	N/A
Southern Water	Southern Water - West	Permit - Isle of Wight - U433	Concerned with borehole abstraction from Lower Chalk in Lukely Brook Valley	No	7.3	H	7.3
		Southern Water - West: unlikely/excluded permits	6 permits	N/A	N/A	L	N/A
	Southern Water - Central	Permit - R648 – reduce MRF (winter)	Application to allow a reduction in the MRF at Hardham Weir, which effectively allows greater abstraction from the R648 surface water intake once abstraction in the River Rother becomes constrained by the existing licensed MRF.	No	5	H	5
		Permit - R648 – reduce MRF (summer)	As above	No	10	M	10
		Permit - E282 – reduction in compensation flow	Reduce the compensation flow from E282 reservoir to maintain water levels and E282 WSW.	No	3.6	M	3.6

Company	Area	Drought Permit/Order Group name	Description/no. of permits	Modelled in Wathnet/ Aquator/ other	DO benefit (Ml/d)	Reliability	*Estimate for DO benefit (including modelled permits)*
		Southern Water - Central: unlikely/excluded permits	4 permits	N/A	N/A	L	N/A
	Southern Water - East	Permit - P562 (winter)	P562 is a pumped storage reservoir with abstractions from the River Teise at Smallbridge and the River Medway at Yalding. The Permit may take the form of winter authorisations to allow increased re-filling and conservation of existing storage	Yes	N/A	H	Variable – dependent upon need and availability of water
		Permit - P562 (summer)	The Permit may take the form of summer authorisations, principally to reduce the requirements of releases to support downstream abstraction at Springfield.	Yes	N/A	H	Variable – dependent upon need and availability of water
		Order - River Medway scheme – further changes to MRF & release factors	Reduce the MRF for abstraction at Springfield, Yalding or Smallbridge and reduce the release factor from P562	Yes	N/A	M	Variable – dependent upon need and availability of water
		Southern Water - East: small permits	2 permits	No	2.5	M	2.5
		Southern Water - East: unlikely/excluded permits	3 permits	N/A	N/A	L	N/A
Portsmouth	Portsmouth	Eastergate Group (Slindon)	Under extreme conditions, it may be acceptable to abstract additional quantities, up to 8.5 Ml/d, at Slindon following a Drought Permit to increase the licensed capacity.	No	8.5	M	8.5
Sutton & East Surrey	Sutton & East Surrey	River Eden drought permit - 1	A drought permit to enable the winter abstraction from the River Eden to continue for an additional period of time; historically this has been into May, so this permit is often termed the May drought permit	No	+5% DO	H	+5% DO
		River Eden drought permit - 2	A drought permit to enable summer abstraction from the River Eden (after any May drought permit has ceased)	No	+10% DO	M	+10% DO
		Sutton & East Surrey: small permits	2 permits	No	7.08	M	7.08
		Sutton & East Surrey: unlikely/excluded permits	1 permit	N/A	N/A	L	N/A

Company	Area	Drought Permit/Order Group name	Description/no. of permits	Modelled in Wathnet/ Aquator/ other	DO benefit (Ml/d)	Reliability	*Estimate for DO benefit (including modelled permits)*
Anglian Water	Anglian - Essex, Suffolk, Ely	Anglian - Essex, Suffolk, Ely: small permits	2 permits	No	10.5	H	10.5
		Anglian - Essex, Suffolk, Ely: unlikely/excluded permits	1 permit: Alton Water	N/A	N/A	L	N/A
	Anglian - Norfolk	River Wensum intake	Increase the annual abstraction quantity for the 24 Norwich boreholes and other boreholes. Subject to ongoing investigations.	No	24	M	24
	Anglian – Ruthamford & Fenland	Grafham Water	50% MRF reduction at intake on River Great Ouse - winter	Yes	N/A	H	34
		Pitsford	50% MRF reduction at intake on River Nene - winter	Yes	N/A	H	8.5
		Rutland Water	50% MRF reduction at intake on River Nene - winter	Yes	N/A	H	31
		River Wissey intake	Increased abstraction licence for the supporting groundwater source	No	10	M	10
		Anglian – Ruthamford & Fenland: unlikely/excluded permits	3 permits	N/A	N/A	L	N/A
Severn Trent	Severn Trent	Drought permit: The Derwent Valley Reservoirs	Reduce the aggregate quantity of compensation water from Ladybower Reservoir to the River Derwent and to Jaggers Clough from 74 Ml/d (or 92 Ml/d when flow at Derby is <340 Ml/d) to 51 Ml/d - reduce compensation water from Ladybower Reservoir from 54 Ml/d to 34 Ml/d	Yes	N/A	M	23

Company	Area	Drought Permit/Order Group name	Description/no. of permits	Modelled in Wathnet/ Aquator/ other	DO benefit (Ml/d)	Reliability	*Estimate for DO benefit (including modelled permits)*
		Drought permit: The Tittesworth Reservoir and River Churnet Conjunctive Use Area	Variation to the compensation requirements from Tittesworth Reservoir and Deep Haye Valley. Would also ask for a variation to the Leek Groundwater Unit abstraction licences.	Yes	N/A	M	16
		Drought permit: The River Leam at Leamington and the River Avon at Stareton	Authorise abstraction at Eathorpe on the River Leam to Draycote Reservoir at any time of year when the lower storage condition at Draycote Reservoir would normally prohibit such abstraction - Relax the prescribed flow in the River Leam at Princes Drive Weir in Leamington from 18 Ml/d to 12 Ml/d - Reduce the hand -off flow in the River Avon at Stareton of 45 Ml/d to 35 Ml/d	Yes	N/A	M	18
		Severn Trent: unlikely/excluded permits	3 permits	N/A	N/A	L	N/A
Wessex	Wessex	Wessex: unlikely/excluded permits	5 permits	N/A	N/A	L	N/A
Essex & Suffolk	Essex WRZ	Essex & Suffolk: small permits	1 permit	No	0.91	M	0.9
South Staffs	South Staffs	South Staffs: unlikely/excluded permits	1 permit	N/A	N/A	L	N/A
Dwr Cymru Welsh Water	SEWCUS	SEWCUS: Small permits	2 permits	No	4.4	M	4.4
		Reduce compensation water releases from Llwynon Reservoir	Tier 1 - more likely to be implemented	Yes	N/A	M	9.1
		Compensation Water Reduction of 50% at Pontsticill Reservoir	Tier 1 - more likely to be implemented	Yes	N/A	M	9.5

Company	Area	Drought Permit/Order Group name	Description/no. of permits	Modelled in Wathnet/ Aquator/ other	DO benefit (Ml/d)	Reliability	*Estimate for DO benefit (including modelled permits)*
		SEWCUS: unlikely/excluded permits	8 permits	N/A	N/A	L	N/A
Yorkshire	Yorkshire	Re-commission Gorpley Reservoir and Water Treatment Works	Use existing infrastructure that is currently mothballed. Gorpley Water Treatment Works will be reinstated to treat supply taken from Gorpley reservoir under the existing licence.	No	4.9	H	4.9
		Silsden Reservoir abstraction	Water abstracted from Silsden Reservoir will be transferred through an existing pipeline to the Nidd Aqueduct. The abstraction will only be made when the reservoir stocks are above 55Ml.	No	10	H	10
		Yorkshire: Small permits	8 permits	No	39.04	M	39.04
		Damflask Reservoir	Compensation releases / maintained flows will be reduced by 50% to 67% of the licensed requirement. Reductions will be considered on a selective basis as some releases are more critical than others.	No	10.5	M	10.5
		River Wharfe at Lobwood increased abstraction	Increase abstraction	Yes	N/A	M	22.7
		River Hull at Hempholme increased abstraction	Increase abstraction	Yes	N/A	M	20.45
		Yorkshire: unlikely/excluded permits	37 permits	N/A	N/A	L	N/A
United Utilities	United Utilities	United Utilities: small permits	4 permits	No	15.9	H	15.9
		Jumbles Reservoir drought permit/order: reduce compensation flow from 19.9 to 12.0 or 6.0 Ml/d	Reduce the compensation flow requirement from 19.9 Ml/d to between 12 Ml/d and 6 Ml/d. The benefit to deployable output of the associated supply reservoirs of Wayoh and Entwistle would be between c.8 Ml/d to 14 Ml/d depending the compensation flow reduction applied for	No	11	H	8
		Longdendale Reservoirs drought permit/order: reduce compensation flow from 45.5 to 22.5 or 15 Ml/d	Reduce the compensation flow requirement from 45.5 Ml/d to 22.5 Ml/d or 15 Ml/d. The benefit to deployable output of the source would be between c.23 Ml/d to 30 Ml/d depending on the compensation flow reduction applied for	No	23	H	23

Company	Area	Drought Permit/Order Group name	Description/no. of permits	Modelled in Wathnet/ Aquator/ other	DO benefit (Ml/d)	Reliability	*Estimate for DO benefit (including modelled permits)*
		River Lune LCUS drought permit/order: reduce prescribed flow from 365.0 to a minimum of 200 Ml/d	Reduce the prescribed flow requirement at Skerton Weir from 365 Ml/d to a minimum of 200 Ml/d. Under dry winter conditions, the benefit could be 50 Ml/d for the period January to March inclusive.	Yes	N/A	H	50
		Ullswater drought permit/order: reduce hands-off flow conditions; construct temporary outlet weir to raise lake level by up to 0.15m and/or relax 12-month rolling abstraction licence limit	Drought powers could cover a number of aspects. Under dry summer weather conditions, the benefit could be 50-60 Ml/d. Under dry winter conditions, the benefit has been estimated as 70-100 Ml/d, if the hands-off flow is reduced to 95 Ml/d	Yes	N/A	H	50
		Lake Vyrnwy drought permit/order: reduce compensation flow from 45.0 to 25.0 Ml/d	Reducing the compensation flow from 45 Ml/d to 25 Ml/d would result in a temporary reduction in flow from Lake Vyrnwy to the Afon Vyrnwy. The benefit to deployable output of the reservoir would be c.20 Ml/d	Yes	N/A	H	20
		Lake Windermere	Scenario 1 reduction in HoF for Lake Windermere	No	N/A	H	?
		United Utilities: unlikely/excluded permits	3 permits	N/A	N/A	L	N/A
Thames Water	Thames Water - Provinces	River Thames @ Farmoor	Category 1, priority 1	Yes	N/A	H	10
		Meysey Hampton	Category 1, priority 2	Yes	N/A	M	11.37
		Thames Water - Provinces: small possible permits	6 permits	No	23.25	M	23.25
		Thames Water - Provinces: small likely permits	2 permits	No	8.5	H	8.5
		Thames Water - Provinces: unlikely/excluded permits	10 permits	N/A	N/A	L	N/A
	Thames Water - London	Lower Thames	Category 2, priority 1	Yes	N/A	M	100
		Thames Water - London: unlikely/excluded permits	9 permits	N/A	N/A	L	N/A

Company	Area	Drought Permit/Order Group name	Description/no. of permits	Modelled in Wathnet/ Aquator/ other	DO benefit (Ml/d)	Reliability	*Estimate for DO benefit (including modelled permits)*
	Thames Water - Guildford	Shalford	Category 2, priority 1	No	2.5	M	2.5
		Thames Water - Guildford: unlikely/excluded permits	1 permit	N/A	N/A	L	N/A

Table App-23 Conceptual Assumptions for Incorporating Permits and Orders into the Resource Evaluation

Planning Reliability (and approximate volume across E&W)	Drought timeline and approach to inclusion in portfolio assessment		
	<12 months	12-24 months	25+ months
High (~400Ml/d)	50% of Permit/Order value	100% of Permit/Order value	100% of Permit/Order value
Medium (~350Ml/d)	None	50% of Permit/Order value	100% of Permit/Order value
Low (108 No.)	None	None	None

Table App-24 Area Classifications and Algorithms used for Calculating Benefits under Severe and Extreme Droughts

Area Drought Permit/Order Category	Description	Assumed benefit	
		Severe	Extreme
0	Almost certainly vulnerable to 12 months or less drought	0	1* high
1	Mixed; 12 to 24 month generally with some sources vulnerable to shorter droughts	0.75*high & 0.25 * med	1* high + 0.75* med
2	Certainly at least 18 month + droughts	1* high & 0.5* med	1* high & 1*med

Table App-25 Summary of Fully Modelled Drought Permits in Wathnet

Resource	Breach Level	Action
Anglian - Ruthamford	DS3	Reduce MRF by 25% - winter only
Anglian - Grafham	DS3	Reduce MRF by 25% - winter only
Derwent Valley Reservoirs	DS2	Reduce compensation to 51Mld
Vyrnwy	DT4	Reduce Compensation to 25Ml/d

Validation

No quantitative validation was possible, but the assumptions and summary list were issued to the water companies in the Steering Group for check and review.

Key Uncertainties and Assumptions

The quantification and attribution of the *reliable* benefits from supply side Drought Permits and Orders is very uncertain. The uncertainties over the reliability of Permits and Orders when evaluating resilience has been highlighted as one of the key messages within the Technical and Summary Reports.

Outputs

The outputs from this analysis are shown within the resource evaluation in Section 6 of the Technical Report, and were incorporated directly into the Wathnet modelling.

Appendix F. Economic valuation

F.1. Drought Consequences: Overview

1. Introduction

The project forms qualitative, quantitative and monetised estimates of the consequences of modelled drought events. The estimates are based on a review of existing evidence on the consequences of and economic valuation of drought events. This sub-Appendix is one of a five on the identification and evaluation of consequences of drought events, and follows the NERA methodology paper shared with the Steering Group and Review Panel in January 2016 then interim drafts dated February and May 2016:

- **Drought Consequences Overview**
- Household and Wider Societal Effects
- Non-Households and PWS Companies
- Environmental Consequences and Valuation
- Scaling to Regions and Years and Multiplier Effects

The scope of work is to use existing literature to identify the consequences of drought events and where possible to place a value on prospective drought events, to aid the evaluation of the appropriate levels of service for, and investments in, water resources infrastructure and demand management interventions.

This sub-Appendix summarises our approach to identifying and valuing drought consequences including water use restrictions across a range of affected stakeholders.

The remainder of this report is structured as follows:

- Section 2 sets out the drought severity situations we define for use in the consortium's wider drought modelling exercises;
- Section 3 summarises existing policy on the application of restrictions under drought conditions;
- Section 4 sets out the indicators that we adopt to measure the economic and social consequences of drought, developed in the consequences sub-Appendices that accompany this overview;
- Section 5 presents case studies of extreme weather events that have had implications for water supply and use restrictions in recent decades;
- Annex A provides a bibliography of the sources reviewed for this study.

2. Defining Drought Consequence Situations (Severities)

This project requires a simple and tractable representation of the consequences of drought for different affected parties, one that captures the most important effects and can be used to scale and – where possible - value the effects emerging from the drought simulations.

The literature on drought consequences suggests that the "size" of the consequences for a given water user depend mostly on the severity of the restrictions placed on water use, and on the duration of those restrictions. In the current and foreseeable UK drought-management frameworks, the severity of the restrictions applied to a given user at any time will fall into one of a few discrete levels (farming and environment aside, arguably), with the severity of restrictions becoming more severe as the drought worsens and continues.

Accordingly for modelling simplicity we adopt three severity levels or steps to represent the degree of restrictions applied to each affected water using group at any point in time in a drought. Prior research suggests that the consequences and costs of early calls for voluntary restraints in water use during droughts are low. Accordingly the three situations we model all represent relatively severe degrees of drought and of associated water use restrictions. We number these as Severity 2, Severity 3, and Severity 4, to remind ourselves that there may be a lesser drought Severity 1 which we do not model.

We also represent the aggregated "total consequence of the drought event" and its implications for aggregated costs or monetary values as varying with the duration of application of each restriction severity step, and varying with the numbers or sizes of affected entities in the impacted group (numbers of households, amount of GVA, number of water bodies).

Also, to allow the modelling to be tractable the consequences and value effects are necessarily aggregated or averaged across fairly large groups of users so we do not claim that they represent the consequences that every affected water user will experience. Rather, we consider that the severity steps and affected groups we define – and show in Table 0.1 below – are a sensible approximate structure to use in "sizing" and in valuing the consequences of the droughts that have the largest effects when considered nationally – including the droughts that are modelled in supply-demand terms in the wider project's Resilience Evaluation Tool (RET).

Table 0.1
Water use restrictions classified over three degrees of drought severity

Severity:	Households	Non-households				Environment
	(PWS supplies)	(PWS supplies)	(private abstraction)	(spray irrigation)	(rain-fed agriculture)	
S4	Emergency Drought Order	Emergency Drought Order	Ordinary Drought Order (demand-side) *	Full S57 restriction	Fourth	Fourth
S3	Temporary Use Bans	Ordinary Drought Order (demand-side)	Ordinary Drought Order (demand-side)	Full S57 restriction	Third	Third
S2	Temporary Use Bans	TUB (for the few affected activities)	Hands off Flow limits apply	Partial S57 restriction	Second	Second

Source: NERA
** At the point where Emergency Drought Orders are applied to PWS customers, we presume the EA/ NRW imposes a more severe level of demand-side Drought Order restrictions on non-household non-PWS abstractors. We note that as for EDOs this step would be regarded as "system failure", has not been experienced since 1976 in the UK, and is not set out in any detail in drought management guidance; VIVID (2013) does not model any further restriction scenario than the first imposition of ordinary drought orders on private abstractors; AECOM (2016) does make some assumptions about what might be done at this step.*

For household water users we assume all are connected to PWS systems, and we model two different severities of water use restriction, resulting from two envisaged levels of restriction on supplies households can take from PWS systems:

- *For Severity 2 and Severity 3, we assume that affected households face the water use restrictions applying under Temporary Use Bans (TUBs).* TUBs prohibit the non-essential use of water for particular purposes by households (and also in some businesses such as sports grounds and landscaping see below). These restrictions include a ban on watering parks, lawns and gardens, washing of private vehicles, and cleaning the exterior of domestic buildings.[1] They thus include the older restrictions

[1] Water Use (Temporary Bans) Order 2010

commonly known as “hosepipe bans”.

- TUB restrictions are the most relevant starting point for identifying and valuing the consequences of drought on household users, as many stated preference studies have shown the impacts of lesser restrictions to be relatively negligible, while the impacts of TUBs are notable for a sub-set of households though much smaller than the impacts of more severe household water use restrictions (see below).[2] TUBs applied to all households with no concessions are estimated to reduce households’ water use by a noticeable amount

- *For our Severity 4, we assume affected household face restrictions applying under Emergency Drought Orders*. These restrictions would consist of rota cuts in supply – for example supply every second day - and/or the cessation of supply to all properties whether household or non-household, with consequent use of some mix of rota-cuts, standpipes, bowsers, and bottled water supplies.

  Before Emergency Drought Order (EDO) restrictions were applied, the lesser step of Ordinary Drought Order demand-side restrictions would be implemented by PWS companies for PWS supplies to non-households, but these are not expected to restrict households much more where a TUB restriction is already in place.[3]

  The EDO restrictions are expected to reduce household water use more substantially. In one recent study AECOM (2016) estimates that emergency drought orders would reduce household water usage by 25% compared with no restriction

For non-household business and public sector water users, we distinguish between drought restrictions to supplies from PWS systems, and drought restrictions applying to private abstraction of water by non-household users.

For the restrictions on non-households’ use of PWS supplies, as shown in Table 0.1 we read-across from the two severity levels used for households. So at Severity 2 TUBs are assumed to restrict the few relevant business and public activities, and the extreme Severity 4 EDO restrictions apply to PWS supplies to all non-households as well as households. As well we introduce an intermediate level of restriction, Severity 3, that applies to all PWS supplies to non-households as implemented by the PWS company through a different instrument, the demand-side Ordinary Drought Order.

- *Severity 3: Non-household restrictions applying under demand-side Ordinary Drought Orders. Ordinary drought orders apply to PWS supplies to ALL non-households and restrict much the same kind of usage as TUBs do for households and a subset of businesses, but as well they restrict non-household use of water for a defined set of “non-essential” purposes. This includes restricted usage of water for commercial car washing, cleaning services on non-domestic premises, and filling of non-public non-domestic swimming pools*.[4]

The water supplies that non-household users obtain by their own abstractions are subject to a different restrictions regime that depends in part on the sector concerned. In a drought, a Hands Off Flow condition in a water abstraction licence will act to limit the allowable abstraction when river flows fall below a specified point. The Environment Agency (EA) and Natural Resources Wales (NRW) can also apply water law provisions (known as Section 57) to restrict abstraction of water for spray irrigation, and can apply Ordinary Drought Orders to limit any abstraction. Accordingly, we apply the following three severity steps in considering the consequences of drought for non-household non-PWS water users:

[2] For example, NERA (2006) estimated that households would be willing to pay, on average, only £1.85 to avoid an expected day of a TUB, in contrast to £53.33 to avoid an expected day of an emergency drought order.

[3] E.g. NERA (2012) estimates the upper bound of the incremental costs for households to be equivalent to 5% of the welfare costs of a hosepipe ban. These incremental costs would result from the likely end of some specific exemptions to the TUB that are relevant to households – such as the use of trickle irrigation watering systems − as well as some possible indirect behavioural effects from increased awareness.

[4] Drought Direction 2011

- *Severity 2 or greater: Limits on water use apply, following from prevailing Hands off Flow (HOF) conditions*. HOF conditions are typically the first restrictions to apply5 before any specific intervention such as S57 restrictions are implemented. We assume that HOF conditions would be applying under the same drought conditions that would result in TUBs being implemented in PWS.

- *Severity 2 or greater: partial or full restrictions on spray irrigation under Section 57.* Under Section 57 of the Water Resources Act 1991, the EA and NRW can reduce or stop spray irrigation under certain conditions. If an irrigator's licence includes HOF conditions, then it is likely that these will already be operating before the EA or NRW introduce a Section 57 restriction. A partial Section 57 restriction is assumed by us to apply whenever a TUB is in place in the same area, so is applied at our Severity 2. Imposition of a full S57 restriction usually coincides with application of an Ordinary Drought Order limiting other business uses of water,[5] so this degree of restriction forms part of our Severity 3 or greater.

- *Restrictions on non-household use applied by the EA/ NRW under a demand side Ordinary Drought Order*. Under an ordinary drought order, the EA and NRW can prohibit or limit the abstraction by any license holder (including PWS companies) of water from a source specified in the order.[6] We model these restrictions on abstraction and use in two stages: the first stage applies at our Severity 3, when full Section 57 restrictions are also applied, and the second stage applies at our Severity 4, when EDOs are simultaneously being applied to PWS customers.

We also notionally consider a linked set of consequences, having three severity levels, for rain-fed agriculture. The consequences of drought for rain-fed crops will be dependent on hydrologically effective rainfall, which depends on seasonal timing as well as total precipitation. For simplicity and completeness we consider three severity situations, read across from the three severities of restrictions applying to supplies from PWS systems and from private abstraction licences.

For drought effects on environmental goods and services, we again consider three severities, linked to the restrictions applying to PWS and to private abstractors. This correspondence between the rain-fed, environmental, PWS and non PWS abstraction severity situations is surely a very broad approximation, but it seems reasonable for present purposes given that the triggering of water use restrictions will be directly or indirectly calibrated to river flow and groundwater levels.

[5] EA (2012) *"Section 57 spray irrigation restrictions - Working together to make water last longer"*

[6] Water Resources Act 1991, Section 74(1)(c)

3. Existing Policy on Drought Restrictions

3.1 Policy Guidance on Implementation of Usage Restrictions

Table 0.2 summarises the most recent guidance on the order in which PWS companies are able to apply restrictions. This is consistent with the set of severity situations in Table 0.1, and provides some details of the activities that would be restricted under each of our severity situations.

Table 0.2
Phased Approach to PWS Water Use Restrictions

The Restrictions		**Notes**	**Summary of exceptions**
No restrictions	No restrictions implemented	• Period of routine monitoring of water resources and environmental baseline by water companies. • Usual company water efficiency and leakage activities	None required
Before restrictions	Voluntary restraint requested	• Awareness raising of water resource situation to promote efficient use of water • Enhanced water efficiency campaigns with customers • Enhanced leakage detection and repair activity	None required
Temporary Use Bans	Section 76(2) of the WIA 1991, as amended by section 36 of the FWMA 2010, states the following 11 uses of water can be restricted: 1. Watering a garden using a hosepipe; 2. Cleaning a private motor-vehicle using a hosepipe; 3. Watering plants on domestic or other non-commercial premises using a hosepipe; 4. Cleaning a private leisure boat using a hosepipe; 5. Filling or maintaining a domestic swimming or paddling pool; 6. Drawing water, using a hosepipe, for domestic recreational use; 7. Filling or maintaining a domestic pond using a hosepipe; 8. Filling or maintaining an ornamental fountain; 9. Cleaning walls, or windows, of domestic premises using a hosepipe; 10. Cleaning paths or patios using a hosepipe; and 11. Cleaning other artificial outdoor surfaces using a hosepipe.	• Restrictions apply to domestic customers i.e. a domestic customer could not undertake these activities unless subject to an exception • Enhanced water efficiency campaigns with customers • Enhanced leakage detection and repair activity	**Statutory Exceptions** are common to all water companies. **Discretionary Universal Exceptions** are common to all water companies and relate to: • Blue Badge Holders (*NB not for all uses*) • Customers using an approved drip or trickle irrigation system fitted with a PRV and timer systems • Commercial customers that use hosepipes as part of their business for some TUB categories, e.g. hand car washing, window cleaning, graffiti removal). **Discretionary Concessional Exceptions** can be granted by individual water companies.
Drought Order Restrictions	The Drought Direction 2011 defines the range of 10 water use activities that may be prohibited with the successful application of a Drought Order. 1. Watering outdoor plants on commercial premises; 2. Filling or maintaining a non-domestic swimming or paddling pool; 3. Filling or maintaining a pond; 4. Operating a mechanical vehicle-washer; 5. Cleaning any vehicle, boat, aircraft or railway rolling stock; 6. Cleaning non-domestic premises; 7. Cleaning a window of a non-domestic building; 8. Cleaning industrial plant; 9. Suppressing dust; and 10. Operating a cistern in any building that is unoccupied and closed.	• Restrictions apply to all customers (domestic and commercial) • Enhanced water efficiency campaigns with customers • Enhanced leakage detection and repair activity	**Statutory Exceptions** are common to all water companies. **Discretionary Universal Exceptions** relate to: • Blue Badge Holders (*NB not for all activities*) The Discretionary Concessional Exceptions in Phase 3 may be rescinded.
Emergency Drought Order	Implement Emergency Drought Order permissions. These are the same as ordinary drought orders but with additional powers.	• Period of increased restrictions as a water company sees fit • Enhanced water efficiency campaigns with customers • Enhanced leakage detection and repair activity	Major restrictions on customers.
Lifting restrictions	All restrictions are lifted	• Period of awareness raising of water resources and lifting of restrictions • Usual company water efficiency and leakage activities	None required

Source: UKWIR (2013) "Managing Through Drought" p.16

In parallel to restrictions applied by PWS companies on their users, the EA and NRW have the authority to impose restrictions on non-PWS abstraction. In the case of spray irrigation, the vehicle for imposing abstraction restriction is Section 57 of the WRA 1991. S57s apply to spray irrigation only and would likely be applied after hands-off flow conditions if these are present in the associated abstraction licence.[7] We discuss the implementation of restrictions on non-PWS supplies in Section 3.3.

3.2 Broader Options available to PWS companies to respond to drought events

Water use restrictions are not the only option available for PWS companies to manage a drought. Our review of Drought Management Plans (DMP) and case studies of previous droughts has highlighted a number of management options for PWS companies:

- **Drought permits and drought orders on the supply-side.** The Water Resources Act 1991 as amended by the Environment Act 1995 and the Water Act 2003 allows for three legislative ways for dealing with drought situations, in ascending order of severity:

[7] EA (12 April 2012) *"Section 57 spray irrigation restrictions. Working together to make water last longer"*.

drought permits, ordinary drought orders and emergency drought orders.

Table 0.3 summarizes the key differences between these actions. Note that drought orders include both supply side measures and water use restrictions – the latter being described in more detail in Table 0.2 above.

Table 0.3
Drought Permits and Drought Orders

	Drought Permit	Ordinary Drought Order	Emergency Drought Order
Legislation	WRA 1991 Section 79a	WRA 1991 Section 74	WRA 1991 Section 75
Applicant	Water company	Water company, EA or NRW	Water company, EA or NRW
Authorised by:	EA or NRW	Secretary of State	Secretary of State
Powers	To modify or suspend conditions on an abstraction in order to increase water supply during a drought	Can increase both supply and restrict non-essential use of water	To set up and supply by means of standpipes or water tanks
Duration	Up to 6 months	Up to 6 months	Up to 3 months
Extensions	For a further 6 months	For a further 6 months	For a further 2 months
Period for powers to be granted	Normally within 12 days from date of application	Normally made within 28 calendar days from date of application	Normally made within 28 days from date of application

Source: Anglian Water Drought Plan 2014.

- **Leakage reduction.** During a drought which coincides with a mild winter, there is potential for increased leakage reduction activity to make additional supplies available for customers.
  There is also evidence suggesting that leakage may increase during a drought as a result of soils drying out, resulting in ground movement and hence the differential movement of pipework that tends to exacerbate leakage from joints. Therefore, without additional leakage detection and repair resources, leakage might ordinarily be expected to increase during drought years.

- **Pressure reduction.** Pressure reduction reduces demand by restricting flow rates from open-tap devices such as garden taps, and from leaks. Further pressure reduction during periods of drought could be implemented where appropriate, but not to such an extent that pressures fail to meet Ofwat's DG2 pressure/flow requirement.
  Affinity Water used pressure management in response to a burst water main in Egham (2015) which affected about 50,000 people for several days. Maintaining some pressure in the grid helps avoid issues of contamination, with no major problems of major discolouration or quality encountered, but did help substantially reduce usage.

- There is an equity issue, in that customers at higher ground experience a greater reduction in water pressure. Overall though the customer response was not large.

- Tanker supplies were mobilised in case needed. Tankers were also provided to critical infrastructure such as hospitals where needed (engage with customers to identify requirements).

- Vulnerable customers were identified and protected. In this case of emergency situation under Gold Command, could share safeguard registers with Local Authorities. This might not be possible under ordinary drought conditions (although companies will maintain their own lists of vulnerable customers).

- **Maximising outputs from all sources in the Resource Zone (RZ).** Many RZs have both surface water and groundwater sources that can be managed conjunctively. In the event of a drought, typical operational responses would include:
  - *Maximising abstraction from run-of-river sources* in order to rest groundwater or reservoir sources during the early stages of drought. This maximises their availability at later stages of the drought when river flows are reduced to such a level that abstraction is constrained by residual flow conditions in the licence.
  - *Maximising pumping from groundwater sources* where this will have little impact on availability later in the drought, in order to rest more vulnerable groundwater sources or surface water reservoirs that can then be used in later stages of a drought.

- **Bulk imports/ provision of alternative supplies**. In the event of a drought, PWS companies would consider the potential for short-term bulk supply imports from neighbouring companies where possible. The tankering of water from adjacent RZs and other companies into RZs that are most affected by drought would also be considered in a severe drought. The feasibility of these options depends on the availability of water in neighbouring RZs, as well as practical issues such as tanker capacity and road access.

  Water Direct is an alternative drinking water supplier that provides help and advice regarding the provision of alternative and emergency water supplies, such as bottled water, bulk water using tankers, and water bowsers.[8] They provide access to the Nationwide Bottled Water Bank, which is a stockpile of quality monitored emergency bottled water, supplied and replenished from multiple approved production sources. At any one time the volume of bank stock can range from 700,000 to 800,000 litres of bottled water, ready for deployment.[9]

  During the floods of 2007, Water Direct accommodated Severn Trent Water's request for emergency assistance.[10] The response, on the biggest scale for many years in the UK water industry, mobilised around 1,500 bowsers (some of them on loan from other companies), more than 150 tankers were operating at any single point in time, and in 48 hours the provision of bottled water escalated to 3 million litres a day.[11]

- **"Insurance" based solutions**. Simple sea-tanker-based bulk supply is used in other countries (e.g. Greece), but is a relatively expensive solution. However some parties are considering a more complex arrangement, whereby water companies would share the costs of providing a back-up service that could be called upon by any individual or group of subscribers.[12]

  In such an arrangement, some supplies could be made on a regular basis, with further volumes being made available at relatively short notice to cope with emergencies, extreme drought conditions, and perhaps for planned peak-lopping. The approach could expand beyond the UK borders and include other countries e.g. in Scandinavia and Northern Europe, with the possibility of establishing an international market for the bulk transportation of water by tanker.

- **Additional output/ (re-)commissioning of sources**. Some PWS companies have a limited number of sources that, for a variety of reasons, were never commissioned or have since been decommissioned. It may be feasible to re-commission these unused sources during a drought. PWS companies might also consider further investment in currently used sources to improve their yield, or fast-tracking any supply scheme

8 http://www.water-direct.co.uk/about-us/about-water-direct

9 http://www.water-direct.co.uk/emergency-water/emergency-bottled-water-bank

10 http://www.water-direct.co.uk/emergency-water

11 Kane, M. (no date) *"Gloucester Flooding Response"*, presentation on behalf of Severn Trent PLC

12 Albion Water has been working on developing a set an "insurance" option of a standby fleet for tankering supplies from abroad. Albion Water (November 2015) *"WATER RESOURCES LONG TERM PLANNING FRAMEWORK (2015-2065): A Contribution by Albion Water"*

available to improve infrastructure and connectivity to secure supplies.
A new possibility is that following the programme of "sustainability reductions" (in the abstraction licence available to some companies) there may be further dormant facilities and resources that could be called upon in the case of emergency shortages. However, this would require that after sustainability reductions companies were able cover the cost of maintaining the assets required to recommence operations, and were able to gain the emergency permission to do so in time to be useful. The trade-off between maintaining the assets and network functionality so that old resources could be used only under specific drought conditions against alternative ways of achieving emergency supplies would also need to be considered.

- **Suspension of planned maintenance programmes**, including mains flushing. Other options include minimising the test pumping of boreholes, minimising treatment losses and reviewing blend options.

- **Emergency desalination**. Currently, desalination plant operation is high in energy consumption and can result in high carbon emissions and higher costs. The plants may also currently be quite difficult to operate compared with other sources of water that require little intervention to provide a continuous supply, but they could be expected to be fully operated in drought.[13]

- **Wastewater recycling**. AECOM (2016) considers that, at the moment, there is effectively a "presumption against" direct effluent reuse in the UK in respect of potable supplies. They further state that in the future, however, direct reuse might be possible on a larger scale and for both potable and non-potable supply.

- **Dewatering discharges**. In the event of a drought, potential options to use dewatering discharges as a replacement for non-potable use would be explored. For example quarry or excavation dewatering discharges could potentially be used to provide irrigation water for high value recreational uses where restrictions on use would have significant economic impact.

- **Targeted metering programmes**. In the event of a prolonged drought, companies might be able to target/ fast-track the delivery of their meter installation programmes to the areas that are most at risk of impacts of the drought.

- **Innovative tariffs, such as seasonal tariffs, or emergency tariffs**. To date in the UK there has only been limited trialling of "conservation" or efficiency tariffs and the results of these trials have not been conclusive. Penetration of regular meters has increased in recent years, through for example the roll out of universal metering by Southern Water, with associated reduction in consumption of the order of around 15%.[14] A trial by Wessex Water of seasonal tariffs – where summer consumption is more expensive than winter consumption (where supply is more readily available) – is reported to have met many customer objections and to have reduced consumption by an additional 6%.[15]

  Affinity Water has also trialled seasonal tariffs but could not robustly identify any incremental reduction in consumption above the effect of standard meters. This may be because expected average bills were required to remain unchanged (so consumers would be no worse off if they continued the same consumption pattern), and the differential between winter and summer tariffs was not large so as to limit incidence effects.

  Innovative or not, having both metered and unmeasured tariffs may raise equity considerations on whether drought restrictions should be applied on an equal basis for unmeasured and measured customers (who have already reduced consumption).

[13] AECOM (2015) *"Strategic Water Infrastructure and Resilience"*, Final Summary Report, pp. 16-17.

[14] Ornaghi and Tonin (2015) *"The Effect of Metering on Water Consumption – Policy Note"*

[15] Wessex Water (2012): *"Towards sustainable water charging"*

Metering may lead to demand reductions which then reduce the ability to respond to drought events through demand-side reductions.
So-called "drought tariffs" have not been trialled or implemented in the UK, but have been introduced in some locations in the USA and in Australia. An advantage over the tools currently available to companies to respond to droughts, such as informational campaigns, is that drought tariffs would be relatively easy to apply and administer (in contrast to requested usage restrictions, which can be violated),[16] reducing the economic cost of achieving the targeted reductions in usage.

Smart meters offer a further potential for affecting behavioural change, through tariffs that better reflect the marginal cost of supply at specific times and locations, such as time of use tariffs, or water-scarcity-level tariffs.

3.3 Implementation of non-PWS restrictions

Alongside working with PWS companies to monitor and take appropriate actions in response to drought events, the EA regional drought plans also include provisions for working with private abstractors. We have reviewed versions of 14 regional EA drought plans to identify how and when non-PWS interventions might occur.

The broad role of the EA regional drought teams includes to:[17]

- Ensure abstractors do not take too much water from rivers and groundwater;
- Check water companies are following their drought plans and taking action to protect water supplies;
- Manage drought permit and drought order applications;
- Mitigate the impact of drought on the environment.

In terms of when restrictions are likely to be felt first, the EA's Devon & Cornwall Area Drought Plan notes that: [18]

> *"Water companies have water resource management plans and drought plans in place, to manage supplies during 'normal' situations as well as during dry spells. Public water supply (PWS) is unlikely to be affected initially by a dry period, whereas the environment and private abstractions will usually be affected much earlier".*

Similarly, the Kent and South London area plan notes that high-value water dependent crops can be reliant on irrigation from sensitive single sources which means that agricultural drought effects are likely to "hit before a water company drought".[19]

The EA drought response teams would identify abstraction licences with HOFs in areas with low flows and *"carry out abstraction license compliance inspections focused on abstractions within the affected area with an increased focus on large consumptive abstractions with HoFs e.g. Spray irrigation"*.[20] During a drought more HOF restrictions would be in place, increasing the need for monitoring and enforcement activities.

For some older licences there may not be HOF restrictions specified, in which case the EA can either use Section 57 of the WRA 1991 to impose restrictions or seek to work with abstractors to introduce voluntary restrictions".[21]

Restrictions may be introduced in phases on irrigators. For example, the spectrum of possible

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[16] Over half of customers breached usage restrictions during a severe drought in California. For more information see: Dixon et al. (1996): *"Drought Management Policies and Economic Effects in Urban Areas of California"*.

[17] EA (May 2015) *"Kent & South London Drought Plan"*

[18] EA (5th October 2015) *"Devon & Cornwall Area Drought Plan 2015"*

[19] EA (May 2015) *"Kent & South London Drought Plan"*

[20] EA (01/07/2015) *"Cumbria and Lancashire Drought Plan"*

[21] EA (5th October 2015) *"Devon & Cornwall Area Drought Plan 2015"*

restrictions extends from a voluntary phase of restrictions, through formal restrictions on quantity and/or the number of days per week on which irrigation is allowed (with night-time irrigation encouraged), continuing up to a 100% targeted reduction with no abstraction allowed.[22,23]

Other options open to the Environment Agency include applying for drought orders itself. The EA would *"generally only apply for a drought order to reduce compensation flow at reservoirs not associated with public or other water supply"*.[24] This may happen to prevent reservoirs drawing down at a rate that will put the downstream river environment at risk, or in response to those interested in the river environment (e.g. angling clubs, environmental groups etc.).[25]

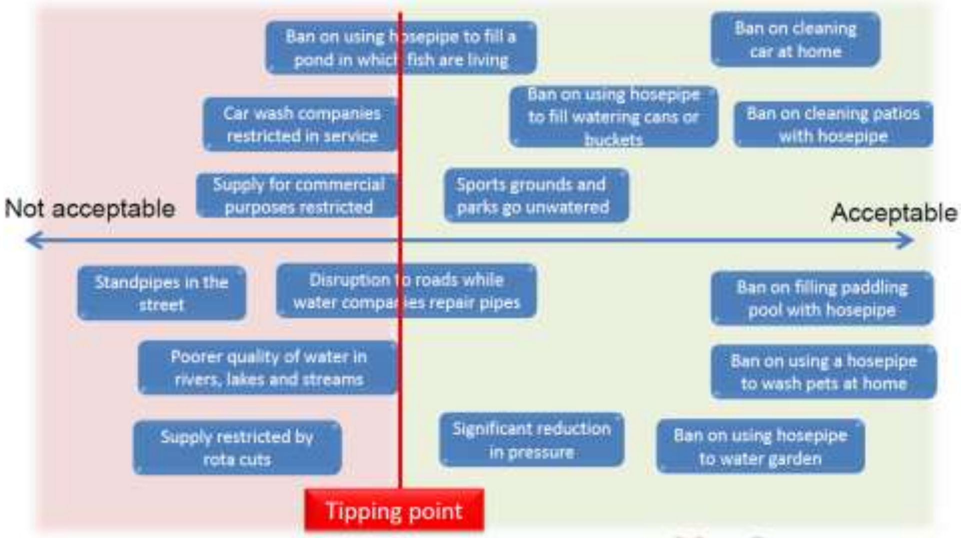
All the plans we have reviewed refer to protection of Sites of Special Scientific Interest (SSSIs) and Special Areas of Conservation (SACs). The Greater Manchester, Merseyside and Cheshire Drought Plan sets out its role in working with other organisations, including Natural England, to protect the environment and in particular sites:[26]

> *"particularly sensitive to the environmental conditions that may be experienced during prolonged drought […] to ensure that the site's interest features are protected, the site condition is maintained and any requirements of the relevant legislation met".*

3.4 Factors affecting drought consequences

Customer research on what customers perceive as likely to occur in a drought, and of what is acceptable, provide a useful reference point to understand the general implications of the different severity situations described in Section 2, before we move on to providing a more granular description of the consequences and valuation techniques in the sub-Appendices that accompany this paper. For example, research by YouGov suggests that while hosepipe bans and pressure reductions may be perceived as acceptable consequences of drought, disruption to businesses and rota cuts are not viewed as acceptable.

Figure 0.1
Acceptability of Different Types of Usage Restrictions



Source: YouGov (2013) prepared for the Consumer Council for Water "Understanding drought and resilience"

There are various dimensions of drought events that might affect both the raw consequences of drought, and how these are valued.

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22 EA (8 April 2015) *"Cambridgeshire & Bedfordshire Area Drought Plan 2015"*

23 EA (4 January 2016) *"Lincolnshire and Northamptonshire Drought Action Plan"*

24 EA (10/07/2015) *"Yorkshire Area Drought Plan"*

25 It is at the EA's discretion whether or not to exercise these rights in consideration of its duties under Sections 6 and 7 of the Environment Act 1995

26 EA (May 2015) *"Greater Manchester, Merseyside and Cheshire Drought Plan"*

- **Duration.** As the duration of the drought event and associated restrictions extends, the impact on different stakeholders may change. For example, household willingness to pay to avoid a further day of restriction may be different for the first week of drought, compared to much longer durations. Similarly, environmental consequences may reach a tipping point beyond certain durations of low flows. Some businesses may be able to withstand restrictions only for short durations, whereas others may have more possibility to adapt to longer duration droughts. The public health consequences and risk of civil unrest in the case of severe restrictions are likely to be increasing in durations.

- **Severity.** As already discussed we consider severity as defined by the level of restriction to be a prime factor, and we model this as summarised in Table 0.1.

- **Frequency.** In previous studies, various stakeholders have said that the frequency of droughts could affect the consequences. For example, in places where drought is more common (e.g. California and parts of Australia), households may be more resilient to, or able/willing to adapt to droughts as they are more used to experiencing them and have adopted different technologies and behaviours to deal with them. Were UK drought events to become more frequent, consumer perceptions of what is and is not acceptable may change and ability to adapt to and thereby mitigate welfare losses may increase.

- **Geographical extent.** The geographical extent of drought events will affect the feasible approaches and costs of responding to the drought. For droughts affecting a relatively narrow area, there may be more scope to substitute alternative sources and draw support from other areas to mitigate the consequences. Consumers may be able to avoid the full welfare losses of restrictions if there are nearby areas where water is plentiful, and business may have more ability to avoid economic losses by switching production locations.

4. Summary of Socioeconomic Impact Indicators

In each of the consequences sub-Appendices accompanying this overview, we discuss monetised and non-monetised indicators to reflect the economic and social consequences of drought events. The principal candidates are summarised in Table 0.4.

Table 0.4
Indicators of Economic Consequences (for each severity level)

	Raw indicators (per area)	Monetised evaluation	Non-monetised assessment
PWS companies	Population affected Duration of restrictions	Communication campaign cost Emergency measures to maintain supply (tankers, bottled water supplies)	Reputational damage
PWS customers			
Households	Number of households affected Duration of restrictions	Welfare loss, based on willingness-to-pay to avoid restrictions	
Business	Affected business extent measured as GVA by sector Duration of restrictions	Economic loss, based on proportional GVA lost, cross-checked by willingness-to-pay to avoid restrictions	
Public sector	Acute hospitals in area Schools in area	GVA losses include loss to public sector	Count of acute hospitals affected
Non-PWS abstractors	Affected user extent measured by GVA by sector Duration of drought or restriction situation	Economic loss, based on proportion of production hence GVA lost	
Environment	HOF (at or below) and duration Area of affected water bodies		(Surface area affected) * (days at HOF level) (Number of SSSIs heavily dependent on water affected)
Wider societal	Density of urban conurbations Days of restriction at urban centres	Knock-on economic effects based on Input : Output tables and income multiplier	Number of days urban centres with population / greater than 150,000 face restrictions

Source: NERA

5. Selected Case Studies of Extreme UK Weather Events

In the following boxes, we present a summary of evidence from five extreme weather events that have led to different severity and duration of restrictions on water use over the past few decades. Our focus in these case studies is to provide a qualitative description of the events that occurred, to supplement these sub-Appendices

These case studies are not intended to represent an exhaustive description of the possible impacts of the droughts modelled in the RET. Rather, they should be viewed as additional descriptive evidence of the consequences of extreme events, from situation that actually occurred.

The events which we characterise in the case studies are:

- The supply shortages in Bradford in 1995-96, as a result of an unusual pattern of dry conditions, and that almost resulted in rota cuts;
- The nationwide drought that impacted on water supplies in 1975-76, and represents the last occasion that emergency drought orders were implemented in the UK;
- Two dry winters across England culminating in usage restrictions for several regions in 2011-12;
- Flooding in Mythe 2007, which resulted in closure of a water treatment plant in Severn Trent's supply area and required a rapid response to supply PWS customers, including provision for acute public services.
- The freeze/thaw in Northern Ireland in 2010-11, during which Northern Ireland Water introduced rota cuts for a limited time, while maintaining supply to critical infrastructure.

Box 1 – Drought Consequences: Bradford 1995-96

In 1996 there was a major supply shortfall centred on Bradford, Yorkshire. Yorkshire Water considered a range of responses, including exploiting sources not previously licenced to them. Hosepipe bans were applied across England and Wales and supplies maintained only through mass tankering in West Yorkshire. The use of rota cuts was narrowly avoided

Supply shortages were accompanied by an unexplained increase in demand, which may have been due to an increase in unmetered outdoor use in the drier conditions, or failure to control leakage following winter pipe bursts.[27]

Households and businesses were extremely concerned about how they would have been able to manage, had rota cuts been implemented. Large businesses spent or made plans to spend many thousands of pounds on on-site tanks and road tankers to bring in water supplies to maintain continuous operations. [28]

Had rota cuts been implemented, the cost of the tanker and administrative expenses for large businesses would have been around £600 a day. A mill that was interviewed after the drought estimates that it would have incurred £10,000-12,000 in fixed costs, plus variable costs of around £2,000-3,000 per week. A restaurant expected to lose over 50% in turnover; a hairdresser, around 30%.[28]

Yorkshire Water suffered severe reputational damage, and was fined more than £40m by Ofwat. [29] The company was criticised for the high levels of reported leakage, and for not having brought water into the area earlier and in greater volumes. Households were entitled to a compensation of £10/day for loss of supply due to distribution failures.[28]

The drought crisis entailed broader political implications. The event inspired several academic papers exploring the links between the crisis and the (at that time, recent) privatization of the industry.[30] The events were raised as an example of failure of competitive markets to adequately take into account public interest.

The water environment was affected in a number of areas. Low flows, high temperatures and low dissolved oxygen threatened fish and wildlife. The National Rivers Authority (NRA) was active in managing fish rescues and other alleviation measures.[31]

River Wharfe in September 1995

[27] Uff Report (May 1996) *"Water supply in Yorkshire Independent Commission of Enquiry"*

[28] Research by Design (1996), *"The Drought of 1995: The Customers' Perspective in Bradford"*

[29] AECOM (2015) "Strategic Water Infrastructure and Resilience", Annex C.

[30] Haughton, G. (1998), *"Private Profits – Public Drought: The Creation of a Crisis in Water Management for West Yorkshire"*
Bakker, K.J. (2000), *"Privatizing Water, Producing Scarcity: The Yorkshire Drought of 1995"*

[31] Environment Agency (1996) *"Interim Report on the Environmental Impacts of the Drought on Yorkshire's Rivers – April 1995 to April 1996"*

Box 2: Drought Consequences – England and Wales 1975-76

1975/76 saw a drought which affected each of the 10 main water supply authorities to different degrees. It was the last time that emergency drought orders were implemented. The consequences on various stakeholders have been studied:

Rota cuts were implemented in Wales, initially lasting 13 hours (7 pm to 8 am), later extended to 17 hours. Town centres were not cut off due to the fire risk to large buildings. Renal dialysis machines, continuous process industries, bakeries and dairies were also kept on. [32]

2,400 standpipes were erected and 21,000 properties were cut off in the SW of England. All industry, all agriculture, and other priority consumers were exempted. This high degree of selectivity led to public controversy. [32]

Standpipes in 1975-76 Drought

Source: The Institution of Civil Engineers (1977)

There were water quality and health hazard concerns, based on the risk of bacterial problems due to insufficient water to flush mains. Additional chlorinators were purchased, and great care was given to disinfecting standpipes.[32]

Households spent an average of £20 to £30 on e.g. buckets and water-butts, replacing plants and shrubs lost during the drought, loss of garden produce and the cost of replacing it with fresh food, etc.[33,34]

Industry supplies were prioritised and there was no apparent effect on total UK volume of production. However, there was anecdotal evidence of substantial water savings (and costs) from changes in production processes to adapt to the drought.[34]

The index of agricultural net product fell, with yields estimated to be about 80% of "normal" levels for many crop types. Reported fish catches (leisure and commercial) of salmon and migratory trout in 1976 were about 50% of those in 1975.[34]

PWS companies incurred additional capital and operating expenditure of around £25m in 1976/77 (c. £135m in 2015 prices) and of around £21m in 1977/78 (c. £105m in 2015 prices).[34]

There is no single reliable estimate of the economic impact of the 1975/76 drought. Some studies do not include estimates for all costs, some may double- count.

32 The Institution of Civil Engineers (1977) "*Proceedings of the One-Day Seminar on the Operational Aspects of the Drought of 1975-76*"

33 Median hourly earnings were c. £0.89, or just over £33 per week for a 27.5 hour week

34 CEH (2011) *"The 1975-76 Drought – a contemporary and retrospective review"*

Box 3: Drought Consequences – England 2011-12

The 2011/12 drought was characterised by two previous dry winters, and affected mainly the south east of England, and to some extent central England. Temporary use bans were introduced across the country and substantial economic business losses incurred.

Among other management actions, 7 PWS companies had to implement Temporary Use Bans (TUBs) for 3-4 months, affecting a total of 20 million customers; [35] 5 companies applied for drought permits/orders to refill reservoirs.[36]

The consequences on various stakeholders have been reported by several studies.

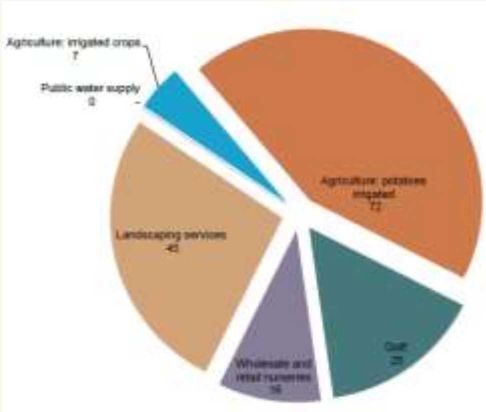
PWS companies incurred an aggregated total cost of around £19m, with Anglian Water and Southern Water spending more than £5m each.[36]

About £165 million in revenue and £96 million in profit were forgone by some firms and sites, including PWS companies, in the second quarter of 2012, of which £72 million was attributed to irrigated potatoes.[36]

The Figure below shows the distribution across sectors of the estimated "first-round" turnover reduction.[37]

The most affected sectors were: irrigated crops, landscaping services, wholesale and retail nurseries, and golf.

Estimated Turnover Reduction, in £ m



Source: Vivid Economics et al. (2013)

The SE of England observed a reduction of 15% reduction in peak week demand and up to 7% on monthly demand and a associated with the coordinated communications programme and TUB restrictions.[38] In a survey by Ipsos MORI, most domestic respondents (70%) agreed the ban had little if any direct impact on them, whereas 14% disagreed (indicating it had a greater impact on them).[35]

There were no reported impacts on employment perhaps because the restrictions were transient. No impacts on recreation or tourism are reported here, due to lack of evidence from the time.[36]

35 UKWIR (2013) *"Understanding the Impacts of Drought Restrictions"*

36 Vivid Economics et al. (2013) *"The impacts of drought in England"*

37 Before consideration of offsetting effects across sectors or regions.

38 Affinity Water (2012) *"Drought Management Plan"*

Box 4: Flooding Consequences – Mythe 2007

Flooding in 2007 affected much of the UK. In July 2007 there was major disruption to transportation and utilities infrastructure, including Severn Trent Water (SVT)'s water treatment works (WTW) at Mythe, Tewkesbury.

As a consequence of river flooding, the Mythe WTW was shut down. The closure left c. 140,000 properties in Gloucestershire without piped water supply for up to 16 days.[39]

Customers were provided with alternative water supplies through use of bottles, bowsers and tankers. At the peak of the incident, SVT deployed over 1,400 bowsers to over 1,100 locations, with up to three fills per day. This represented the largest number of bowsers that have ever been used in a single incident in the UK.

Around 20 Patients at Tewkesbury hospital were transferred to the other hospital facilities within the locality. Disruption to the transport system delayed provision of water tankers and bottled water suppliers' vehicles to the hospital sites. Despite the difficulties, large amounts of bottled water, for example 13 tonnes at Cheltenham hospital site, were delivered by SVT.[40]

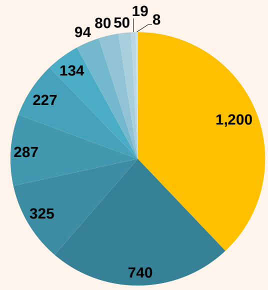
Transport disruption added difficulty to provision of alternative water supplies

Source: Kane, M. (undated) "Gloucester Flooding Response"

Overall costs of c. £30m to Severn Trent Water as a result of flooding at Mythe.

EA estimates nationwide costs of the 2007 floods at about £3.2 bn of which £186 million of which correspond to PWS companies and customers.[39] Of this c. 65% were borne by the utilities from damage and extra operating costs, while c. 35% was borne by users from disruptions to supply.
Schools were seriously affected, losing 400,000 pupil days of education. Some 42,000 hectares of farmland were flooded.

Estimated economic impact of 2007 floods (£3,162m)*



- Household (builings and contents)
- Businesses (buildings, contents and disruption)
- Utilities (electricity, gas, water)
- Public health and fatalities (incl. distress, impact on education and fatalities)
- Communications (roads (including LGA), rail, telecom)
- Local Govt - infrastructure (excl roads) and non-emergency services
- Temporay accommodation
- Vehicles (motors)
- Agriculture
- Environment Agency (23% of costs for emergency)
- Emergency services, (LGA, police, fire and rescue)

Source: NERA analysis of EA (2010)
** Unquantified costs; tourism, nature conservation, community services, military services.*

[39] EA (2010) *"The costs of the summer 2007 floods in England"*

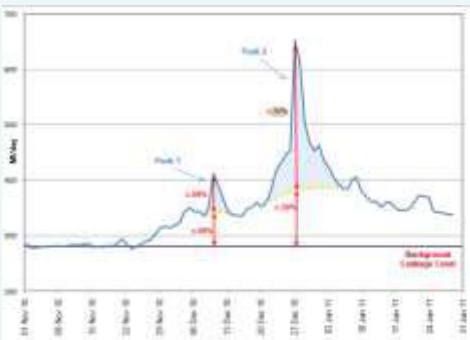
[40] Department of Health (2008) *"Report on the lessons learned from the Summer 2007 flooding experiences from an Estates & Facilities perspective"*

Box 5: Extreme Weather Consequences−Northern Ireland Freeze 2010-11

The freeze-thaw incident over the period December 2010-January 2011 resulted in around 215,000 properties across Northern Ireland having their water supply interrupted at some time – from a short overnight interruption to long periods causing severe difficulties..

A large increase in demand was observed; of which usage or burst pipes on customer properties accounted for at least 80%.[42] Water demand peaked at 70% above average demand and 20% above the capacity of the water treatment works.[41]

NIW minimum night flow



Source: Report to Norther Ireland Executive (2011)

Rotational water supply was introduced for the first time in Northern Ireland. At the peak, 95,000 properties were subject to rotation of supplies. A total of 180,000 properties were subject to rotation of supplies at some time. The focus was on securing supplies to essential services such as hospitals.[42]

Businesses, particularly those in the hospitality trade, claimed the water crisis added to their economic woes following the recession and the big freeze. A hotel had to take seawater to help flush its toilets. A pub hired 20 Portaloos for the New Year's Eve weekend. *"The last thing we can't afford to do is take any chances with our toilets"*, a bar's manager said. [43]

The estimated cost of this incident to NI Water was of the order of £7.5 million. Extra needs included deploying leakage staff, tankering water to WTW and service reservoirs, and balancing water supplies within the network. On 28 December 2010, NI Water received substantially more call attempts in one day than it did in the whole of 2009/10. [44]

During the incident, there was much criticism of the way NI Water dealt with the situation with the result that the Executive Committee of the NI Assembly asked the UR to carry out an investigation.[44,42] A number of failures were identified, mostly regarding communication with customers, leadership and preparation for a crisis of this magnitude.

41 Report to Northern Ireland Executive *"Report of the investigations into the Freeze/Thaw incident 2010/11"*

42 UREGNI *"Utility Regulator's report of the investigation into the Freeze/Thaw incident 2010/11"*

43 McDonald, H. (2010*) "Northern Ireland water crisis to run into next week"*, The Guardian, Thursday 30 December.

44 Northern Ireland Water (2011) *"Annual Report and Accounts"*

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UNEP et al. (2011) *The UK National Ecosystem Assessment*, Chapter 9

Utility Regulator (2011) *Utility Regulator's report of the investigation into the Freeze/Thaw incident 2010/11*

Vivid Economics for Defra (2013) *Economic Impacts of Drought in England*

WHO (2011) *How much water is needed in emergencies*

F.2. Household and Wider Societal Effects

1. Introduction

The project forms qualitative, quantitative and monetised estimates of the consequences of modelled drought events. The estimates are based on a review of existing evidence on the consequences of and economic valuation of drought events. This sub-Appendix is one of a five on the identification and evaluation of consequences of drought events, and follows the NERA methodology paper shared with the Steering Group and Review Panel in January 2016 then interim drafts dated February and May 2016:

- Drought Consequences Overview
- **Household and Wider Societal Effects**
- Non-Households and PWS Company Effects
- Environmental Consequences and Valuation
- Scaling to Regions and Years and Multiplier Effects

The scope of work is to use existing literature to identify the consequences of drought events and where possible to place a value on prospective drought events, to aid the evaluation of the appropriate levels of service for, and investments in, water resources infrastructure and demand management interventions.

This sub-Appendix summarises our review of available literature and studies on the consequences of drought events on household customers and provides a proposed valuation framework to incorporate into the main resilience evaluation tool (RET).

The remainder of this report is structured as follows:

- Section 2 describes how droughts affect household water users and sets out the link between the RET and our valuation framework;
- Section 3 presents evidence from previous studies of the welfare consequences of usage restrictions on households, on public health on wider societal effects and concludes with modelling ranges;
- Section 4 concludes with a summary of the main results to be linked into the RET to allow cost benefit comparisons of solution portfolios to be made.

2. Consequences of Drought for Household Water Users

2.1 Raw consequences of drought for household users

Households use water supplies for a range of purposes; in England and Wales only a small proportion is used for drinking (4%), with the largest usage shares falling to toilet flushing (30%) and personal washing (33%).[45] Outdoor usage only accounts for 7% of domestic water usage.

Households will value different types of usage to different degrees. For example, while outdoor usage accounts for 7% of total domestic usage, this 7% will be concentrated among those with access to garden premises, or for vehicle washing. Similarly some households with health conditions may be much more sensitive to water use restrictions than others.

We have reviewed many sources that give an indication of the importance of, and sometimes the value placed on, reliability of water service for households. Reliability of supply is consistently cited as one of the priority areas for households: For example, MORI (2002) found that a "reliable and continuous supply" was the most highly rated aspect of water service, although noting that customers perceived little need for improvement in this area.[46]

As part of customer research undertaken for Thames, the NERA consortium in 2006 found that:[47]

> *"Customers did not relish the idea of being without water for longer than two to three hours. This was particularly the case where no warning was given. If plenty of notice was given alternative arrangements could be made and it was felt that a maximum of two days was manageable. Any longer than that was seen as too long, especially for those with children. The greatest inconvenience was not being able to flush the toilet".*

In general, leakage reduction has often been seen as the preferred option by customers to address resource shortages, perhaps reflecting a view that leakage is "wasteful" and should be managed by the company. While rota cuts are rarely experienced in developed countries, it is noted that access to running water on alternate days (if at all) is not uncommon in developing countries, and that "you don't spill or waste a drop".[48]

In terms of the types of restrictions being considered in the severity situations for this study, most said of a "Level 3" situation (TUBs and ordinary drought orders where most households were most focussed on the hosepipe ban element)that they "could live with it" as long as it was not any longer than a period of three months. For "Level 4" severity – where rota cuts or standpipes could be imposed, the reaction was that this would be totally unacceptable and would have very serious consequences, both socially and economically. There was disbelief that this could ever happen, especially if the previous levels of restrictions were effectively managed.

We have now also reviewed a number of customer preference studies undertaken by companies for PR14. Where households were asked to rank their priorities for water service, avoiding interruptions consistently ranks highly, typically just below drinking water quality.[49] A recent survey by YouGov for CCW after the 2011/12 drought found that:[50]

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45 Waterwise (2012) *"Water factsheet".* Available from http://www.waterwise.org.uk/data/resources/25/Water_factsheet_2012.pdf

46 MORI (2002), "Joint National Research into Customers' Views on Water and Sewerage Services", research commissioned by DEFRA, Welsh Assembly Government, Office of Water Services, WaterVoice, Water UK, Environment Agency, Drinking Water Inspectorate, English Nature, Wildlife and Countryside Link.

47 NERA (2006) *"The Cost of Water Use Restrictions A Report for Thames Water"*, Annexes p.A22

48 NERA (2006) Op. Cit. p.A23

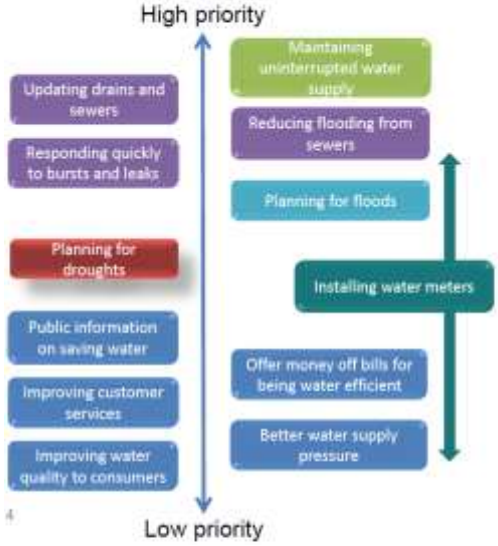
49 NERA review of various materials provided by companies under confidentiality agreement.

50 YouGov (2013) prepared for the Consumer Council for Water *"Understanding drought and resilience"*

> *"Customers accept moderate drought restrictions but identify the tipping point as when drought causes severe service disruptions i.e. rota cuts or impacts on the environment and businesses".*

The same survey also ranked maintaining an uninterrupted water supply top of all customer priorities, as set out in Figure 0.1.

Figure 0.1
Customer Ranking of Priorities for Water Services



Source: YouGov (2013) prepared for the Consumer Council for Water "Understanding drought and resilience"

The Drinking Water Inspectorate (DWI) and the Health Protection Agency (HPA) identify a set of vulnerable groups who may be particularly sensitive to water supply restrictions, both in terms of quantity and quality impacts:[51]

- *Customers with Infants* who rely on water to make up bottle feeds are especially vulnerable if the supply is interrupted for long periods of time.
- *The elderly* are more likely to suffer from chronic diseases for which they may take medication. Medication toxicity is an increased risk when dehydrated. Furthermore, a number of elderly persons live alone and during an extreme event may not be able to access supplies or carry heavy bottles and containers home.
- *Those with chronic diseases* (such as renal failure or cystic fibrosis) at home or in care are more vulnerable when essential supplies such as water are cut off. For example clean water may be needed to sterilise medical equipment.
- *Those with language or communication difficulties* may suffer a delayed response or misinformation due to communication barriers.

The study also noted that *"[d]espite the number of published reports and reflective reviews following extreme events, these do not contain rigorous scientific evidence on the health outcomes of these same episodes".*[52] We discuss broader public health implications and other potential knock-on effects such as civil unrest in Section 2.2.

Water availability can also be restricted in response to other events, and the consequences read across to equivalent circumstances for drought. For example, in 2007 flooding in Gloucestershire

[51] Health Protection Agency and Drinking Water Inspectorate (2012) *"Health impacts from extreme events water shortages"*

[52] HPA and DWI (March 2012) *"Health impacts from extreme events water shortages"*, p.5

forced Severn Trent's water treatment works at Mythe, Tewkesbury to shut down. Following the first news broadcasts warning of imminent loss of supplies, usage of water more than doubled, resulting in a rapid depletion of supplies. By Tuesday 24 July, there were approximately 140,000 properties in Gloucestershire without a piped water supply. Severn Trent's first priority was to ensure that customers were provided with alternative water supplies through use of bottles, bowsers and tankers, which was largely achieved up to 10 litres per person within the first 24 hours, and at over 20 litres per person after 48 hours.[53]

Severn Trent exceeded the minimum of 10 litres per person per day required by the Security and Emergency Measures Direction (SEMD) 1998, stating that *"the provision of alternative supplies to a level of ten litres per day does not meet the expectations of [their] customers who each normally use an average of 138 litres per day", and that "[their] experience of delivering alternative water supplies to such a large population over a prolonged period of time highlighted that this is not an acceptable solution for an incident of this magnitude"*.

A more recent example of water use restrictions is the response to a cryptosporidium outbreak in near Preston (United Utilities) in August 2015. As a result, 300,000 households in Lancashire were required to boil their water for drinking, food preparation and for brushing teeth, to avoid risk of vomiting or diarrhoea.[54] United Utilities sent a compensation of up to £60 to each affected customer. The incident was reported to have cost United Utilities a total of £25m in compensation and clean-up costs.[55] An investigation into cause of the contamination was launched by the Drinking Water Inspectorate last August and is still continuing.[56]

2.2 Public health and social effects

In the event of a severe drought, there may also be concerns for public health, including the health of vulnerable customers and the risk of contagion for infectious diseases. HPA and DWI (2012) include an extensive literature review on the health impacts from extreme water shortage events.[57] Their findings are structured in 4 main points:

- **Dehydration**. The elderly, children, infants and those with pre-existing illnesses are particularly at risk from dehydration. Severe dehydration can present with extreme thirst, confusion, little or no urine output, low blood pressure, rapid heartbeat, delirium or unconsciousness.
- **Infectious disease**. Due to a lack of clean water and sanitation, there can also be an increased risk of faecal-oral disease transmission.
- **Mental health**. Water shortages have been documented to cause panic, despair, feelings of exposure, distress and helplessness among affected populations. This may be exacerbated in the elderly, persons with disabilities, parents with small children, those without money or cars who could not get to water provision.
- **Vulnerable groups**. Vulnerable groups can be described as those who are likely to have additional needs and experience poorer outcomes if these needs are not met:
  - *Infants* who rely on water to make up bottle feeds are especially vulnerable if the supply is interrupted for long periods of time.
  - *The elderly* are more likely to suffer from chronic diseases which they may take medication for. Medication toxicity is an increased risk when dehydrated. Furthermore, a number of elderly persons live alone and during an extreme event may not be able to access supplies or carry heavy bottles and containers home.

53 Severn Trent Water (2007) *"The Impact of the July Floods on the Water Infrastructure and Customer Service"*

54 The Sunday Times (22 November 2015) *"Parasite will not muddy the water at United"*

Lancashire Telegraph (13 August 2015) *"Hundreds of thousands of Lancashire residents to get water compensation"*

55 The Daily Telegraph (24 September 2015) *"Business Insight United Utilities"*

56 Lancashire Telegraph (10 February 2016) *"Cryptosporidium scare reviewed"*

57 Health Protection Agency and Drinking Water Inspectorate (2012) *"Health impacts from extreme events water shortages"*

- *Those with chronic diseases* (such as renal failure or cystic fibrosis) at home or in care are more vulnerable when essential supplies such as water are cut off. For example clean water may be needed to sterilise medical equipment.
- *Those with language or communication difficulties* may suffer a delayed response or misinformation due to communication barriers.

Notwithstanding that PWS companies and the authorities would be expected to make strenuous efforts to protect vulnerable water users and guard against public health effects in droughts, these are serious potential impacts.

A third additional set of possible effects is that severe water restrictions, especially in densely populated conurbations, could result in civil unrest and have knock-on political impacts. We understand from previous severe events, such as the Mythe floods, that a high degree of social solidarity has often been exhibited. However, there have also been examples of civil unrest in the UK in recent years, and severe water restrictions in major cities could have important knock-on effects of this sort.

There may also be political implications of long and/or widespread drought events. In Australia, for example, severe drought and climate change prompted many of Australia's major cities to construct large-scale desalination plants on a rushed-basis to provide a rainfall-independent source of drinking water. In many cities, this decision became a political issue. The CEO of the Australian Water Association, Tom Mollenkopf, mentioned in an interview with Bloomberg that *"unless you can get bipartisan political support it can always degenerate into a political bunfight". He added that, in the state of Victoria, "[i]t was used in the last state election as a weapon by the new government to attack the former government"*.[58]

We describe our proposed approach to allowing for these consequences, drawing on existing research, and note any caveats and areas that could be explored further in future projects of this type, in Section 3.

2.3 Defining severity situations for drought consequences

In the event of water shortages, UK water law allows for a series of restrictions on water use to be applied by water companies, the Environment Agency (EA) or Natural Resources Wales (NRW), in some cases after applying for and being granted the requisite powers.

For example, the Water Resources Act 1991 empowers public water suppliers to apply for powers to *"prohibit or limit the use of water for any purpose specified in the order".*[59] Under an emergency drought order, the water undertaker may prohibit or limit the use of water for such purposes as it thinks fit, and is authorised to supply its area by means of standpipes or water tanks, or by rota cuts. A full discussion appears in the UKWIR *Code of Practice and Guidance for Water Companies on Water Use Restrictions.*[60]

We consider the impact of drought events on household welfare through restrictions to usage applied by public water supply companies.

We consider two types of restriction:

- For Severity 2 and Severity 3, we assume that affected households face the water use restrictions applying under Temporary Use Bans (TUBs). TUBs allow water companies to prohibit specified uses of water. This would include the ban on watering parks, lawns and gardens, washing private vehicles and cleaning the exterior of domestic buildings; an earlier

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[58] Bloomberg BNA (2013) "Drought Prompts Australia to Turn to Desalination Despite Cost"

[59] Water Resources Act (1991), p.58

[60] UKWIR (2014) *"Managing Through Drought: Code of Practice and Guidance for Water Companies on Water Use Restrictions - 2013 [incorporating lessons from the 2011-12 drought]"*, ref. 14/WR/33/6

version of this restriction was known as the “hosepipe ban”.[61]

TUB restrictions are the most relevant starting point for identifying and valuing the consequences of drought on household users. Many stated preference studies have shown the impacts of lesser restrictions to be relatively negligible, whereas the impacts of TUBs are notable for a sub-set of households though much smaller than the impacts of more severe household water use restrictions (see below).[62] TUBs applied to all households with no concessions are estimated to reduce households’ water use by a noticeable amount. For our Severity 4, we assume affected household face restrictions applying under Emergency Drought Orders. These restrictions would consist of rota cuts in supply – for example supply every second day - and/or the cessation of supply to all properties whether household or non-household, with consequent use of some mix of standpipes, bowsers, and bottled water supplies.

Before Emergency Drought Order (EDO) restrictions were applied, the lesser step of Ordinary Drought Order (ODO) demand-side restrictions would be implemented by PWS companies, but these are expected to restrict households further in only minor ways where a TUB restriction is already in place.[63]

The EDO restrictions are expected to reduce household water use substantially. In one recent study AECOM (2016) estimates that emergency drought orders would reduce household water usage by 25% compared with no restriction

How the household restrictions would be applied, and the restrictions we would expect to be applying to other stakeholders at the same time, are set out in Table 0.1.

[61] Water Use (Temporary Bans) Order 2010

[62] For example, NERA (2006) estimates that households would be willing to pay, on average, only £1.85 to avoid an expected day of a TUB, in contrast to £53.33 to avoid an expected day of rota cuts or standpipe restrictions under an Emergency Drought Order.

[63] NERA (2012) estimates the upper bound of the ODO incremental costs for households to be equivalent to 5% of the welfare costs of a hosepipe ban. These costs would result from the end of some specific exemptions to the TUB that are relevant to households – such as the use of trickle irrigation watering systems − as well as some possible indirect behavioural effects from increased awareness.

Table 0.1
NERA Ladder of Restrictions

Severity:	Households	Non-households				Environment
	(PWS supplies)	(PWS supplies)	(private abstraction)	(spray irrigation)	(rain-fed agriculture)	
S4	Emergency Drought Order	Emergency Drought Order	Ordinary Drought Order (demand-side) *	Full S57 restriction	Fourth	Fourth
S3	Temporary Use Bans	Ordinary Drought Order (demand-side)	Ordinary Drought Order (demand-side)	Full S57 restriction	Third	Third
S2	Temporary Use Bans	TUB (for the few affected activities)	Hands off Flow limits apply	Partial S57 restriction	Second	Second

Source: NERA

** At the point where Emergency Drought Orders are applied to PWS customers, we presume the EA/ NRW imposes a more severe level of demand-side Ordinary Drought Order restrictions on non-household non-PWS abstractors. We note that as for EDOs this step would be regarded as "system failure", has not been experienced since 1976 in the UK, and is not set out in any detail in drought management guidance; VIVID (2013) does not model any further restriction scenario than the first imposition of Ordinary Drought Orders on private abstractors; AECOM (2016) does make some assumptions about what might be done at this step.*

3. Household Valuation of Reduced Drought Risk

3.1 Stated preference valuation of household consumer preferences

Estimating household preferences to avoid restrictions to water service is not straightforward. In the absence of complete retail markets, households cannot act on their preferences for different degrees of service quality by switching between suppliers offering different packages of quality and price.[64] That is, customers cannot choose to pay a different price for a higher or lower level of service, an act which would reveal the value they place on having a lower risk of restrictions, assuming they are well informed. In the absence of this market information or "revealed preference", a technique widely adopted at PR14 and at previous price controls to elicit customer valuation for different levels of service is stated preference studies.

Stated preference studies measure the *"willingness to pay"* (WtP) of consumers for changes in service levels. Typically SP studies consist of a choice experiment, in which customers are surveyed and asked to make a series of choices between service packages with different service level attributes and different bill levels. Econometric "discrete choice" models can then be used to infer a willingness-to-pay for specific changes to service level by comparing the service-level choices made to the bill changes in each selection.

Our review of previous stated preference studies has shown that on average households are willing to pay relatively little to avoid temporary use bans (similar to what were previously known as hose-pipe bans), which do not affect in-home uses. Willingness to pay to avoid more extreme restrictions (i.e. rota cuts or supply via standpipes only) is much higher, as would be expected.

We have collected studies undertaken by a range of water companies, including previous work undertaken by NERA. Given the range of evidence reviewed, and the challenges in forming a function representative of customer preferences that can be scaled to different regions and different points in time, we provide a central figure as well as a low and high sensitivity. Table 0.2 presents these household valuations for each of the severity 2&3 and severity 4 restrictions levels. The evidence reviewed confirms that avoiding the consequences of "severity level 4" restrictions is much more highly valued than avoiding "severity level 3" – by a factor of 80 in our central estimate.

Table 0.2
Estimated Value of Avoiding Household Restrictions
(£ / HH / yr per avoided expected day of interruption/ year)

	S2 – S3 – TUBs	S4 – EDOs
Low	£0.25	£40
Central	£1.00	£80
High	£2.50	£160

TUBs – Temporary Use Bans, comparable to previously called Hosepipe Bans.
EDOs − Emergency Drought Orders are the most severe type of restrictions on household use and can imply the use of standpipes and/or rota cuts.
Source: NERA review of company stated preference studies.

We present the ranges of relevant figures across all sources reviewed for severity Level 2 and 3 in Figure 0.2, and for severity Level 4 in Figure 0.3. Some of the data has been provided under confidentiality agreements, and is therefore anonymised. In both figures we present all the evidence that we have been able to state on a comparable basis of GBP per expected day of restriction per

64 NERA (2007) *"The Line in the Sand – the shifting boundary between markets and regulation in network industries"*, p.485

year. This measure may be based on change in either, or both, the probability of the event occurring and the duration of the event.

In each figure, the blue bars show the ranges we have converted from relevant studies of long restrictions, which we consider most relevant for the purposes of the current study. That is, we only consider evidence from studies that have evaluated the consequences of restrictions lasting more than 14 days. The grey bars show figures from other studies that we have reviewed, but that we do not take into account directly when forming our estimates. This may be because the duration was too short, was undefined, or it was not clear that the study was measuring drought-restriction severity for a comparable type of event.

We have restated the results of all studies in 2015 prices, inflating using the ONS annual average RPI. Where the original study does not appear to precisely define duration, we sense-check the results by applying a range of 2-6 months for TUBs and 14-90 days for emergency drought orders, but do not rely on these results.

While this puts the studies into the same price base and unit of measurement, caution should be taken when comparing studies directly. For example, the estimates from Accent's study for Yorkshire in 2002 are lower than those from the London studies undertaken by NERA for Thames Water not long afterwards, possibly because incomes are lower, and the baseline level of service higher, in Yorkshire compared to London; but possibly for other reasons of local preferences or attitudes to water restrictions and paying to lower the risk of them.

In addition to the quantified WtP evidence set out above, there are a number of factors that may be masked in the WtP averages. We provide a description of some key findings from previous studies below, and discuss various dimensions that may affect valuation estimates in our companion paper "Drought Consequences: Overview" paper, which includes dimensions that could affect estimates of household welfare loss. In the bullets below, we summarise the impact of these dimensions specifically on estimating household welfare consequences:

- **Duration**. As the duration of the restriction extends, we might expect the willingness to pay to avoid a further day of restriction to change. This relationship may be non-linear – the willingness to pay to avoid 1 more day of restriction may be higher when the starting point is 2 days of restriction than, say, 3 months of restriction. The reason lies on the difference in perceived inconvenience depending on the reference point, as well as on the customer's budget constraint. However, at the moment there is insufficient available evidence to form the basis of a robust relationship between duration and willingness to pay. Therefore, for the purposes of this project, we model a linear relationship between duration and willingness-to-pay.

- **Severity.** We model severity as defined by the two levels of household restriction that could be implemented by the PWS water licensee and summarised in Table 0.1. As discussed above, the estimated welfare consequences of droughts at different severities have a wide range – with avoiding our most severe situation, where standpipes and rota cuts could be introduced, valued at as much as 80 times more than avoiding temporary use bans.

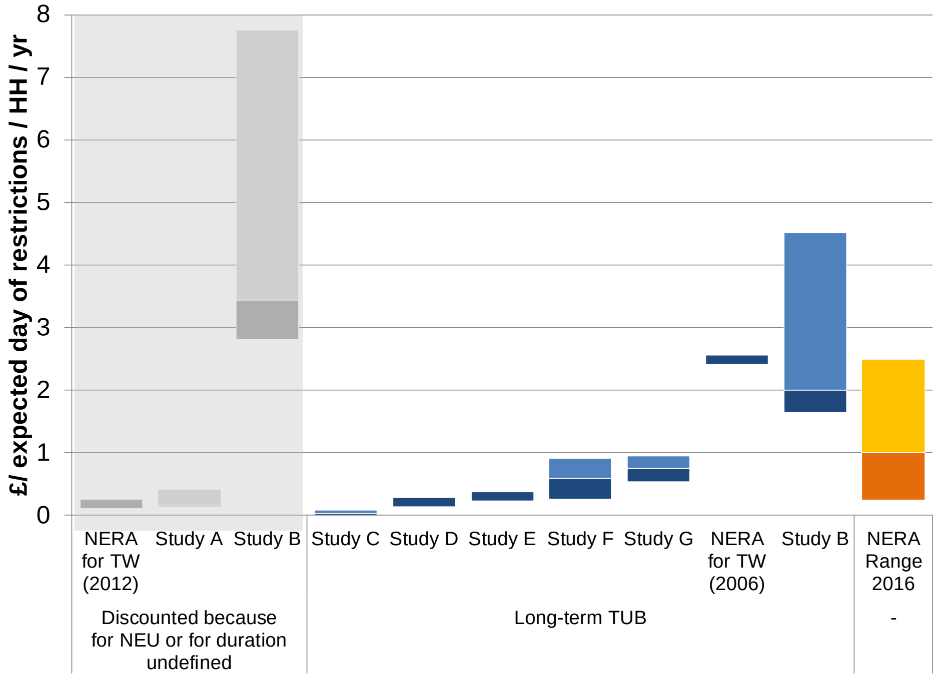
- **Frequency**. In previous studies, various stakeholders have said that the frequency of droughts could affect the consequences. For example, in places where drought is more common (e.g. California and parts of Australia), households may be more resilient to, or able/willing to adapt to droughts as they are more used to experiencing them. Were drought events to become more frequent, UK consumer perceptions of what is and is not acceptable may change and their ability to adapt to and thereby mitigate welfare losses may increase. We are not aware of any studies that have been able to quantify the effect of drought frequency and welfare implications in the UK.

- **Baseline level of service**. The baseline level of service might be expected to affect the marginal willingness to pay for a change in service levels. We would typically expect preference to be "convex"; that is to say that willingness to pay for a marginal improvement for an additional unit (LOS) should be declining as the LOS increases. This is intuitive, as customers typically would prefer to pay more to improve a very poor level of service by an increment, than they would to improve a relatively better level of service by the same increment.

We are not aware of any studies that have explicitly pinned down the relationship between baseline LOS and welfare losses from restrictions. However, we have seen one stated preferences study which estimates a higher willingness to pay to avoid hosepipe bans in a region that has experienced more hosepipe bans in the recent past, than in a region with less recent experience of hosepipe bans. Those with a recent experience of drought also had different preferences for types of resource schemes to address supply shortages.

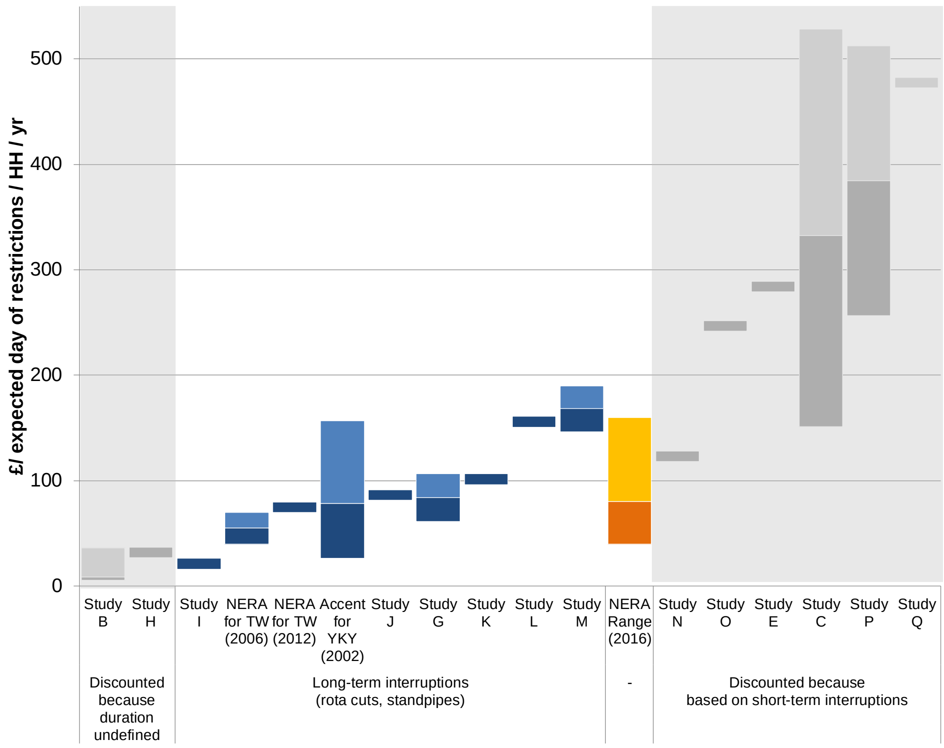
Table 0.3 summarizes the level of restriction that was measured in each of the studies we have reviewed and notes the key findings of each.

Figure 0.2
S2 & S3: Evidence on TUB Valuation by Households



Source: NERA analysis of compiled WtP studies

Figure 0.3
S4: Evidence on Emergency Drought Order Valuation by Households



Source: NERA analysis of compiled WtP studies

Table 0.3
Summary of WtP Evidence from Studies

Study	Sample Size	Evaluated Restriction	Estimated Average Household WtP − in £/ (expected day * hh * year) (2015 GBP)
NERA (2006)	302	"Level 3" restriction: Hosepipe Bans (eq. to TUBs) "Level 4" restriction: Emergency Drought Order restrictions, including rota cuts and standpipes.	£2.4 p.a. to avoid one expected day of L3 restrictions, and £54.8 p.a. to avoid one expected day of L4 restrictions (average between Contingent Valuation, £40, and Choice Experiment, £69.6).
NERA (2012)	302	Based on NERA (2006) adjusted for income growth. "Level 3" restriction: Non-Essential Use Bans (eq. to Ordinary Drought Order) "Level 4" restriction: Emergency Drought Order restrictions, including rota cuts and standpipes.	£0.1 p.a. to avoid one expected day of L3 restrictions further to hosepipe ban, and £69.7 p.a. to avoid one expected day of Level 4 restrictions (only Choice Experiment available).
Accent (2002)	1000	2-3 months of no running water on the premises. NERA (2006) restated the WtP values into £/ exp. day.	£78.3 (range: £26.1 to £156.5) p.a. to avoid one expected day of long-term restriction.
Study A	1500	Water restrictions (type and duration undefined). Expressed in terms of WtP for an increase in LoS.	£0.2 (range: £0.1 to £0.4) p.a. to avoid one expected day of restriction.
Study B	629	Hosepipe bans, eq. to TUBs (duration undefined). Non-Essential Use bans, eq. to Ordinary Drought Orders (duration undefined). Rota cuts (duration undefined). Expressed in terms of WtP for an increase in LoS.	£2 (range: £1.6 to £4.5) p.a. to avoid one expected day of hosepipe ban, £3.4 (range: £2.8 to £7.8) p.a. to avoid one expected day of NEU, and £8.4 (range: £5.6 to £36) p.a. to avoid one expected day of rota cuts.
Study C	1000	Hosepipe bans, eq. to TUBs, for 5 months. Unplanned interruption of 12-24h. Expressed in terms of WtP for an increase in LoS.	£0.04 (range: £0.01 to £0.09) p.a. to avoid one exp.day of hosepipe ban, and £332.3 (range: £151.2 to £528.3) p.a. to avoid one expected day of unplanned interruption.
Study D	800	Hosepipe bans, eq. to TUBs, for 5-6 months. Expressed in terms of WtP for an increase in LoS.	£0.1 p.a. to avoid one expected day of hosepipe ban.
Study E	1101	Hosepipe bans, eq. to TUBs, for 5 months. Short-term interruptions (3-6h). Expressed in terms of WtP for an increase in LoS.	£0.2 p.a. to avoid one expected day of hosepipe ban. £279.1 p.a. to avoid one expected day of short-term interruption.

Study	Sample Size	Evaluated Restriction	Estimated Average Household WtP – in £/ (expected day * hh * year) (2015 GBP)
Study F	346	• Hosepipe bans, eq. to TUBs, for 2 months. Expressed in terms of WtP for an increase in LoS.	• *£0.6* (range: *£0.3* to *£0.9*) p.a. to avoid expected day of hosepipe ban.
Study G	600	• Hosepipe bans, eq. to TUBs. • Stoppage for 2-3 weeks.	• *£0.7* p.a. to avoid one expected day of hosepipe ban (average between Contingent Valuation, *£0.5,* and Choice Experiment, *£0.9*). • *£83.9* p.a. to avoid one expected day of stoppage (average between Contingent Valuation, *£61.1,* and Choice Experiment, *£106.6*).
Study H	N/A	• Water supply stoppages (long-term interruption, duration undefined). Expressed in terms of WtP for an increase in LoS.	• *£26.7* p.a. to avoid one expected day of stoppage.
Study I	1000	• Severe disruption, implying standpipes and rota cuts for 21 days.	• *£16.2* p.a. to avoid one expected day of severe disruption.
Study J	N/A	• 1 property affected by an unexpected interruption for 2 weeks.	• *£81.4 p.a.* to avoid each day of a 2-week unexpected interruption.
Study K	N/A	• 14 days of interruption.	• *£96.2* p.a. to avoid each day of a 2-week interruption.
Study L	N/A	• 1 property affected by an unexpected interruption for 2 weeks.	• *£150.8* p.a. to avoid each day of a 2-week unexpected interruption.
Study M	N/A	• 30 days of interruption. • 22 days of interruption.	• *£189.8* to avoid each day of a 1-month interruption. • *£146.4* to avoid each day of a 22-day interruption.
Study N	N/A	• 1 property affected by an unexpected interruption for 1 week.	• *£118.1* to avoid each day of a 1-week unexpected interruption.
Study O	N/A	• 1 property affected by an unexpected interruption for 12-24h.	• *£241.9* to avoid a 12-24h unexpected interruption.
Study P	N/A	• Planned water supply interruption of 12-24h. • Planned water supply interruption of 24-48h.	• *£256.3* to avoid a 12-24h planned interruption. • *£512.7* to avoid a 24-48h planned interruption. Central estimate (24h): average between the two values above.
Study Q	1003	• Unexpected supply interruption for 3-6h. Expressed in terms of WtP for an increase in LoS.	• *£472.3* to avoid one expected day of unexpected interruption.

Source: NERA Analysis.

3.2 Valuing public health and wider social knock-on effects

Public health

The HPA and DWI (2012) study notes that *"[d]espite the number of published reports and reflective reviews following extreme events, these do not contain rigorous scientific evidence on the health outcomes of these same episodes".*[65] In the literature we have checked we have not found any quantified estimates of the consequences of drought on public health.

In the event of a severe drought, and as Codes of Practice and other guidance emphasise, it is reasonable to assume that PWS companies and the authorities would focus substantial efforts on supplying vulnerable customers and on guaranteeing a minimum daily amount of water available for household use. We understand that following the Mythe Flooding Severn Trent Water rapidly built up supply of bottled water to 20 litres / head / day.

Accordingly we do not provide a further metric or valuation of the effect of drought specifically on vulnerable customer groups, beyond the general household welfare losses described *in "Drought Consequences: PWS Households".* Costs may also be picked up in the *"Drought Consequences: non-Households and PWS Companies"*, to the extent that the PWS company costs include the provision of alternative supplies of sufficient quantity and quality to vulnerable customers.

Nevertheless, the public health implications could be substantial; a range of health issues may arise as a result of water quality issues under situations of water shortages. We understand from discussions with the DWI that reduced pressure and fluctuating flows in the networks due to altered operation in droughts can result in quality changes, including increased turbidity from stirring up sediments. Furthermore, if transfers from other areas are imported, this can change the composition of water delivered to customers. The consequences thus range from aesthetics (odour and discolouration), to the need to guard against hazardous chemical and biological changes.[66]

In the absence of any studies that provide a scalable metric or valuation, we account for these public health impacts through qualitative description only. This may be an area for future studies, to fully understand the potential water quality and health implications of altered network flows, reduced pressure, and the risks associated with importing water across different resource areas.

Civil unrest and political impact

We have not identified any UK studies that have looked at the effect of drought on the potential for unrest. It is possible that the UK government may undertake work along these lines, but if so at the time of writing such studies are not accessible to us.

AECOM (2016) note the possibility of civil unrest events and cite Hsiang et al. (2013), as an example of evidence linking the impacts of climate change with civil unrest.[67] AECOM also mention the riots that took place in London in August 2011, as an indication of the social and financial consequences of widespread civil disorder within the capital. The riots are estimated to have cost almost £300m.[68]

While we recognise the potential importance of civil unrest events, the link between droughts of different severities and durations, and the way in which civil unrest would occur is not well understood. Similarly, we have not found any evidence which attempts to provide an indicator of, or place a value on, political consequences. In the absence of robust, quantified and scalable supporting evidence from existing studies, we consider one candidate indicator for the drought

65 HPA and DWI (March 2012) *"Health impacts from extreme events water shortages"*, p.5

66 NERA teleconference with DWI held on the 29th January 2016

67 Hsiang, S.M, Burke, M., and Miguel, E. (2013) *Quantifying the Influence of Climate on Human Conflict*

68 Metropolitan Police Service report (2012) *"4 days in August: Strategic Review into the Disorder of August 2011"*

modelling:

- **Societal knock-on indicator**. defined as the number of urban conurbations of more than 150,000 inhabitants that face a severe water use restriction of more than a week.[69,70] The number of people affected is an important metric for measuring the size of welfare impacts, and as such we use it as a scaling factor in our valuation, as described in our companion sub-Appendix "Drought Consequences: Scaling to Specific Regions and Years". However, for our evaluation of civil unrest risks, we rather focus on concentration effects, since conflicts and large-scale protests are more likely to take place in large, dense urban areas.

4. Concluding Remarks

For the purposes of this study, we reviewed available evidence on household preferences for water services, and available evidence of the welfare consequences of usage restrictions that could be applied by the PWS companies for different drought severity situations.

We draw on a collation of willingness to pay to avoid restrictions of two different severities to form a valuation range, in terms of pounds per expected day of restrictions, per household, per year.

Beyond the direct economic, welfare and environmental consequences of drought, drought could have important economic and social knock-on effects. We have described some of the potential societal knock-on effects, in particular with respect to public health but also considering potential for civil unrest and for political impacts. The mechanisms through which these consequences would emerge or be mitigated / avoided are not well understood.

[69] E.g. a 150,000 population cut-off, as this is the population of Gloucester. We understand that management of the Mythe floods in 2007 affected Gloucester and did not result in any major unrest.

[70] As described in AECOM (2016) - Annex C, p.15, Defra defines a Part 2 incident as *"a major water or sewage incident of a size that is greater than the response capability of the water company even with any mutual aid and the planning and response required is likely to involve a number of agencies"*. This definition applies to a situation where more than 200,000 people lose access to piped water for a week.

F.3. Non-Household and PWS-Company Effects

1. Introduction

The project forms qualitative, quantitative and monetised estimates of the consequences of modelled drought events. The estimates are based on a review of existing evidence on the consequences of and economic valuation of drought events. This sub-Appendix is one of a five on the identification and evaluation of consequences of drought events, and follows the NERA methodology paper shared with the Steering Group and Review Panel in January 2016 then interim drafts dated February and May 2016:

- Drought Consequences Overview
- Household and Wider Societal Effects
- **Non-Households and PWS Companies**
- Environmental Consequences and Valuation
- Scaling to Regions Years and Multiplier Effects

The scope of work is to use existing literature to identify the consequences of drought events and where possible to place a value on prospective drought events, to aid the evaluation of the appropriate levels of service for, and investments in, water resources infrastructure and demand management interventions.

This sub-Appendix summarises our review of available literature and studies on the consequences of drought events on PWS business customers and on non-PWS abstractors, and provides the valuation framework incorporated into the project's main resilience evaluation tool (RET).

The remainder of this sub-Appendix is structured as follows:

- Section 2 describes how droughts affect non-household PWS customers and PWS companies and sets out the link between the main RET and our valuation framework;
- Section 3 presents evidence from previous studies of the economic consequences of usage restrictions on non-household water users/abstractors and on PWS companies;
- Section 4 concludes and summarises the main results to be linked into the RET for cost benefit comparisons.

2. Consequences of Drought

2.1 Describing the raw consequences of drought

Water restrictions could have a range of consequences on businesses and public sector bodies connected to the public water supply, and on sectors wholly or partially reliant private abstraction sources.

- A limited set of water sensitive companies including landscaping services, house and car cleaning services, sports grounds and golf course operators could be impacted early, by application of Temporary Use Bans (TUBs) or Ordinary Drought Orders. These sectors are heavily reliant on water for provision of their services.
- ***Agricultural yields could be affected by water availability.***
  - Irrigated crops. Water availability affects both yield and quality of produce. Irrigating farmers draw water from a range of sources: abstraction from rivers or groundwater; abstraction from on-farm reservoirs (e.g. filled during the winter); and PWS.
  - Rain-fed crops. The main consequences of low rainfall in the spring and summer would again be both crop yields and quality. Soil degradation and increased pollution could also result from insufficient uptake of nutrients.
  - Livestock. Uses water from private boreholes and public water supplies for drinking water and sanitation. In an extreme drought, farmers may have to reduce herd size by slaughtering, or selling or temporarily re-locating animals to farmers in regions not affected by drought.

  We consulted with the EA, and the Water for Food group, who thought that drought events could have important consequences on some crop types after just five days without rain. However, the effects are seasonably variable − April to August being typically the critical season. Furthermore, as the drought develops, the farmer is likely to ration his remaining water in a way that prioritises use towards higher value crops.

  They also reiterated that an important component in loss of economic value is quality of produce, not just quantity. For most crop-types, switching to PWS supplies would not be feasible – this would likely be limited only to high-value crops.
- ***Horticultural crops could experience important losses if affected by water restrictions.*** We worked with the EA sector leads to consult with stakeholders in various sectors on the impact of drought. One respondent (a nurseries owner via the Horticultural Trades Association) stated that a lack of water would result in the death of his plants within four days during the summer months. These container-grown crops require water to be added to the pot either by rainfall or irrigation. The more efficient the system, the less "reserve" of moisture there is within the plant, implying more reliance on continuous water supply. Horticultural crops are highly valued, ranging from £0.4m to £1.14m per ha.[71]
- ***Energy production could be significantly affected by water shortages/restrictions***. Energy production relies on availability of abstracted water for cooling. For example, Energy UK has investigated the potential effects of a country-wide drought on generation output, identifying that of plants on rivers or estuaries using water abstraction for cooling, about a quarter of the capacity is at specific sites with "potential for impact" (i.e. where abstraction licences contain requirements for set levels of river flow that could potentially affect production), as shown in Table 3.4. The potentially impacted total of 9,405 MWe is relatively small in the context of e.g. significant

[71] Response to consultation by EA sector experts

capacity of coastal power stations including the 11 GWe of the UK nuclear fleet,[72] and overall declared generating capacity (from all types of generation) of over 70 GWe.[73]

Table 0.4
Generation capacity potentially impacted by drought restrictions

	Generation capacity (MWe)	Generation capacity as percentage of total capacity of plant on rivers or estuaries (%)
Potentially impacted by drought	9,405	24%
Unlikely to be impacted by drought	30,444	76%

Source: Energy UK (2015) *"Assessment of drought effects 2015 – Potential impact on cooling water abstraction"*

- ***Manufacturing businesses in England using privately abstracted water sources.*** The food, paper and chemicals industries are large consumers of water. A consultation reported in AECOM (2016) suggested that, in a severe drought situation, where private supplies became unavailable or were restricted, the majority of abstracting firms would attempt to switch to PWS where and for as long as such supplies were available. AECOM also found that if PWS back-up supplies were to be unavailable, most firms did not have a contingency plan in place to allow them to continue to produce with a reduced private water supply, which would imply a fall in production at such locations and for the period when private water was unavailable.

We consulted with EA sector leads, and received responses from several manufacturing industries:[74]

- The paper industry uses primarily privately abstracted surface water, followed by ground water. If these were not available, it is unlikely that a sufficient PWS supply would be available due to the large quantities usually needed by paper mills. The EA encourages paper mills to re-use water within the process as much as possible without harming product quality, which would make the sites more resilient to water shortages.

  Climate Ready (2013) provides a case study of a paper mill in the Midlands that was affected by the dry conditions of summer 2011.[75] The mill's supply of water was reduced by around 35%, which had a significant impact on operations as the mill had no alternative source of supply. To alleviate the problem the mill diverted one arm of the adjacent river, with permission from the EA for only 12 months, as it caused a short section of river to dry up.

- For the chemicals industry, we received a response from one refinery, which is fully supplied by privately abstracted water from a river. If there was a drought and the river levels were very low, the site has a public water supply, but the flow volumes would not be sufficient for firefighting purposes, and therefore production would have to cease.

- Cement and lime manufacturing processes involve mixing and washing which can only operate with water; the industry would have to close if water was not available. Most cement and lime works have large quarries that act as catchments and there is a high degree of internal water recycling. However, water is lost from the process due to evaporation. If onsite water sources become unavailable there would be a reliance on PWS to operate to the extent available.

- ***The food sector may be especially vulnerable***. While food and drink manufacturers generally do not rely on a single source for ingredients, small retailers tend to have direct relationships with

[72] Energy UK (May 2015) *"Assessment of drought effects 2015 – Potential impact on cooling water abstraction"*, report provided to NERA

[73] UK Government Digest of UK Energy Statistics

[74] Response to NERA consultation by EA sector experts

[75] Climate Ready (2013) *"Preparing a Climate Change Action Plan: Paper & Pulp Sector Guidance – A support service led by the Environment Agency"*

producers of, for example, fresh produce, and may be less able to substitute using overseas / out-of-area supplies.

Furthermore, in food manufacturing processes, water is critical to food hygiene, and it would be difficult to find alternative sources of sufficient quantity/quality. However, there is apparently an understanding in the industry that the food and drink industry would have some priority over other "non-essential" uses and would only have supplies restricted in extreme cases.[76]

There may also be consequences from restricted public sector water usage, both for the functioning of general public offices just as for business offices, and for the provision of acute services such as healthcare.

2.2 Defining severity situations for drought consequences

For non-household business and public sector water users, we distinguish between drought restrictions to supplies from PWS systems, and drought restrictions applying to private abstraction of water by non-household users.

For the restrictions on non-households' use of PWS supplies, as shown in Table 0.1 we read-across from the two severity levels used for households. So at Severity 2 TUBs are assumed to restrict the few relevant business and public activities, and the extreme Severity 4 EDO restrictions apply to all non-households as well as households. As well we introduce an intermediate level of restriction, Severity 3, that applies to non-households as implemented by the PWS company, the Environment Agency (EA) or Natural Resources Wales (NRW) through a different instrument, the demand-side Ordinary Drought Order.

- *Severity 3: Non-household restrictions applying under a demand-side Ordinary Drought Orders.* Ordinary drought orders apply to all non-households and restrict much the same kind of usage as TUBs do for households and a subset of businesses, but as well they restrict non-household use of water for a defined set of "non-essential" purposes. This includes restricted usage of water for commercial car washing, cleaning services on non-domestic premises, and filling of non-public non-domestic swimming pools. [77]

The water supplies that non-household users obtain by their own abstractions are subject to a different restrictions regime that depends in part on the sector concerned. In a drought, a Hands Off Flow condition in a water abstraction licence will act to limit the allowable abstraction when river flows fall below a specified point. The Environment Agency (EA) and Natural Resources Wales (NRW) can also apply water law provisions (known as Section 57) to restrict abstraction of water for spray irrigation, and can apply Ordinary Drought Orders to limit any abstraction. Accordingly, we apply the following three severity steps in considering the consequences of drought for non-household non-PWS water users:

- *Severity 2 or greater: Limits on water use apply, following from prevailing Hands off Flow (HOF) conditions.* HOF conditions are typically the first restrictions to apply5 before any specific intervention such as S57 restrictions are implemented. We assume that HOF conditions would be applying under the same drought conditions that would result in TUBs being implemented in PWS.
- *Severity 2 or greater: partial or full restrictions on spray irrigation under Section 57*. Under Section 57 of the Water Resources Act 1991, the EA and NRW can reduce or stop spray irrigation under certain conditions. If an irrigator's licence includes HoF conditions, then it is likely that these will already be operating before the EA or NRW introduces a Section 57 restriction. A partial Section 57 restriction is assumed by us to apply whenever a TUB is in place in the same

[76] Vivid et al. (2013) *"The impacts of a drought in England"*, p. 129.

[77] Drought Direction 2011

area, so is applied at our Severity 2. Imposition of a full S57 restriction usually coincides with application of an Ordinary Drought Order limiting other business uses of water,[78] so this restriction forms part of our Severity 3 or greater.

- *Restrictions on non-household use applied by the EA/ NRW under a demand side Ordinary Drought Order*. Under an Ordinary Drought Order, the EA and NRW can prohibit or limit the abstraction by any license holder (including PWS companies) of water from a source specified in the order.[79] We model these restrictions on abstraction and use in two stages: the first stage applies at our Severity 3, when full Section 57 restrictions are also applied, and the second stage applies at our Severity 4, when EDOs are applied to PWS customers.
- We also consider a linked set of consequences, having three severity levels, for rain-fed agriculture. The consequences of drought for rain-fed crops will be dependent on hydrologically effective rainfall, which depends on seasonal timing as well as total precipitation. For simplicity and completeness we consider three severity situations, read across from the three severities of restrictions applying to supplies from PWS systems and from private abstraction licences.

Table 0.5
Water use restrictions classified over three degrees of drought severity

Severity:	Households	Non-households				Environment
	(PWS supplies)	(PWS supplies)	(private abstraction)	(spray irrigation)	(rain-fed agriculture)	
S4	Emergency Drought Order	Emergency Drought Order	Ordinary Drought Order (demand-side) *	Full S57 restriction	Fourth	Fourth
S3	Temporary Use Bans	Ordinary Drought Order (demand-side)	Ordinary Drought Order (demand-side)	Full S57 restriction	Third	Third
S2	Temporary Use Bans	TUB (for the few affected activities)	Hands off Flow limits apply	Partial S57 restriction	Second	Second

Source: NERA
** At the point where Emergency Drought Orders are applied to PWS customers, we presume the EA/ NRW imposes a more severe level of demand-side Ordinary Drought Order restrictions on non-household non-PWS abstractors. We note that as for EDOs this step would be regarded as "system failure", has not been experienced since 1976 in the UK, and is not set out in any detail in drought management guidance; VIVID (2013) does not model any further restriction scenario than the first imposition of ordinary drought orders on private abstractors; AECOM (2016) does make some assumptions about what might be done at this step.*

2.3 Approaches to measuring the consequences

There are several approaches to measuring the importance of a reliable supply of quantity and quality of water to non-household PWS users and private abstractors.

A survey from YouGov for CCW shows that a reliable supply of water can be very important for small and medium enterprises in some sectors, both in terms of requiring a reliable supply of water, and the reputational risk of not having an adequate quantity/quality of supply.[80] There may be some

78 EA (2012) *"Section 57 spray irrigation restrictions - Working together to make water last longer"*

79 Water Resources Act 1991, Section 74(1)(c)

80 For example, a reliable quantity is essential for cement mixing and landscaping services. For cleaning and valeting services, reputational concerns may preclude the use of "grey" water.

instances of businesses that benefit from usage restrictions (to the extent that they are exempt, or can provide substitute services).

This finding is supported by customer research submitted to us by the companies as part of a consultation process for this project, where business customers typically ranked reliability of supply (/avoiding restrictions) as the top priority

The scope of this sub-Appendix is to provide an estimate of the value of avoiding drought situations for non-household PWS customers and for non-PWS abstractors. There are a number of possibilities:

- **Economic losses from reduced production, as estimated by reduction in Gross Value Added (GVA).** This approach focuses on the costs to the nation associated with lost output. The GVA approach does not capture:
  - Welfare losses associated with reduced water consumption for personal domestic use;
  - Welfare losses associated with loss of or damage to public, non-market, amenities such as the appearance of parks and gardens, or the cleanliness of the urban environment;
  - Welfare losses associated with loss of consumption of marketed goods and services.
- **Stated preference surveys**. As described in our companion paper "*Drought Consequences: PWS Households*", in the absence of a market through which "revealed preferences" can be obtained, stated preference studies provide an alternative to provide valuation for service attributes such as reliability of supply.

  A drawback of the SP approach when applied in particular to business customers is that it is hard to capture sufficient detail of the businesses surveyed so as to be able to draw inferences outside of sample. For example, a representative set of businesses in London may be different to a representative set for some other part of England or Wales. Furthermore, the value of avoiding interruptions to supply may vary widely depending on:
  - Industry: there are a large range of industries by sector, occurring in different proportions across the 29 different regions in England and Wales that will be modelled in this project. Each will have a different degree of dependence on PWS versus non-PWS water supplies, and may value avoiding restrictions differently;
  - Size and water sensitivity of the business. In general, smaller businesses tend to place a lower value on avoiding PWS water supply restrictions.[81] Businesses using different technologies will have different abilities to continue production in case of water shortage, and different abilities to make –up production by importing from other locations or taking stocks from storage to be made up later.
  - Survey implementation including who the respondent is within the business. Survey research has shown that the more senior the level of manager responding to the questionnaire, the higher the value placed on avoiding interruptions to supply.
- **Cost of alternative supplies**. The cost of restrictions to PWS non-household customers could be estimated by the cost of sourcing this portion of supplies from alternative sources or from investments in resilience to outages. For example, the cost of tankered supplies in the event of shortages, or investments into water storage facilities.
- Similarly, an estimate of the value of restrictions on non-PWS abstraction could be elicited from any **alternative back up supplies and investments**. For example, AECOM (2015) has

81 NERA (2006) estimates that PWS-supplied firms with more than 200 employees are willing to pay an amount equivalent to more than 100% of their annual bill to avoid "Level 4" restrictions (standpipes and rota cuts) and 6% to avoid "Level 3" restrictions (hosepipe bans and drought orders), while companies with less than 10 employees are only willing to pay 27.9% and 1.6% of their annual bills, respectively.

collected evidence on the cost of switching to PWS supplies in the event of abstractions restrictions. On average, the study found that the cost of PWS supplies on a per unit basis was about five times higher than the cost of private abstraction licences (£110/Ml in the case of PWS, compared with approximately £18/Ml for privately-abstracted water).[82]

Some stated preference valuation information is available. However, given the complexities involved in drawing on Stated Preference studies of specific local businesses to form estimates to apply on a national basis, and the fact that we are not aware of any such studies that cover non-PWS abstractors, we do not propose to rely on the SP evidence to form an estimate of the economic losses resulting from water shortages and restrictions applied to non-households. We do however present the range of SP evidence we have reviewed in Annex B for information, and consider that it is not inconsistent with the results of our other methods. Annex C summarises evidence from previous work undertaken by NERA that found that the GVA approach to measuring economic losses associated with business interruptions gave results of the same order of magnitude as the estimates from stated preference techniques.

While there are some estimates of the cost of alternative supplies for specific locations and industries available from selected studies, scaling these to full coverage of non-household effects is not feasible, and nor would be calibrating them to the 29 areas modelled in the RET, and to future years.

The most tractable approach to forming estimates of losses for all non-household sectors, and to tailoring these to the 29 areas and to future years, is to model GVA loss as a result of water shortages and restrictions, drawing on a number of previous UK studies that have adopted this approach:

- **Vivid et al. (2013)** provides a model that estimates the economic impact of the drought that took place in England in 2011/12, and how this would have changed had the drought been managed differently. The model estimates that about £165 million in revenue and £96 million in profit were forgone by some firms and sites in the second quarter of 2012, when some water companies introduced TUBs, and the EA encouraged agricultural irrigators to voluntarily cut their use.
- **NERA (2006)** estimates the loss of GVA by industry sector in London arising from business interruptions directly caused by the water use restrictions that would occur given 1975/76 rainfall patterns, with the dry-year demand levels and available resources at the time of the study. The model estimates a total loss in London GVA of £4,929 million if no further action were to be taken.
- **AECOM (2016)** estimates the economic costs of a range of hypothetical drought scenarios, which differ in duration (1 or 3 years), severity (1 in 100 or 1 in 500 years) and decade of occurrence (2010s or 2050s). The estimated economic impact ranges from £261m in a one-year severe drought in the 2010s to £43,488m in a three-year extreme drought in the 2050s.

In our modelling of consequences, we have drawn on some of the parameters used by Vivid et al. (2013) and NERA (2006). Further details on our approach are described in Section 3.

[82] AECOM (2015) Annex C p.18

3. Valuation of Drought Events

3.1 PWS Non-Households, Non-PWS abstractors and Rain-Fed Agriculture

We estimate the economic costs that would be incurred by each sector per day of reduced water availability for each of the three drought severity situations described in our companion report *"Drought Consequences: Overview".* As set out in Section 2, we use a modelled reduction in GVA to estimate the economic value of avoiding restrictions.

The sectors covered in the GVA approach encompass all the industries in the economy,[83] including rain-fed agriculture and public sector institutions − to the extent that the value added created by public administration, health and education institutions is reduced in the event of water use restrictions. We acknowledge that rain-fed agriculture would not be affected by either PWS or non-PWS water use restrictions; however, for completeness, we include them in the model to the extent that they would be affected by the meteorological drought directly. We do not estimate a reduction in GVA for the water supply, sewerage sector; instead, the costs directly borne by PWS companies are estimated separately, as described in Section 3.2.

The Table below sets out assumed GVA losses for each sector and drought severity level. These reductions draw primarily on NERA 2006 for most sectors, and on Vivid (2013) for specific sectors and severity where experience has been gained from the 2011 drought. Note that the severity level S1 is shown for illustrative purposes only, but will not be included in the model due to its limited economic impact on non-households.

We set out our approach to scaling the consequences to each of the 29 geographic areas modelled in the RET and to the GVA make-up of future years in our companion sub-Appendix *"Drought Consequences: Scaling to Regions and Years"*.

83 We use SIC07 industry classification, in correspondence with ONS GVA datasets.

Table 0.6
Mapping of Drought Consequences across Studies

	Current Study	Vivid et al. (2013)	AECOM (2016)	NERA (2006)
PWS	S4	*Not modelled*	**"PWS emergency drought order"**	**"Level 4"**
	S3	**"PWS drought orders with no concessions"** **"PWS drought orders with concessions"**	**"PWS ordinary drought order"**	**"Level 3"**
	S2	• **"PWS TUBs with no concessions"** • **"PWS TUBs with concessions"**	**"PWS TUBs with no concessions"** • **"PWS TUBs with concessions"**	
	S1	• **"PWS communications"**	*Not modelled*	*Not modelled*
Non-PWS	S4	*Not modelled*	**"Private abstraction severely restricted"**	*Not modelled*
	S3	**"EA full S57 restrictions"** **"PWS drought orders on supply-side"** **"EA drought orders"**	**"EA full S57 restrictions"** **"Private abstraction partially restricted"**	*Not modelled*
	S2	**"EA partial S57 restrictions"** **"EA enforcing Hands-off flow conditions"**	**"EA partial S57 restrictions"**	*Not modelled*
	S1	**"EA encouraging voluntary reductions in spray irrigation"**	*Not modelled*	*Not modelled*

Source: NERA analysis.

The colour scale in Table 0.7 indicates the source of each of the estimated GVA percentage reductions included in the table. We have used NERA (2006) estimated GVA percentage reductions for all sectors, except from those modelled by Vivid (2013), supplemented where new sub-sectors need to be modelled. A discussion on the assumptions behind these numbers can be found in Annex D.

When interpreting the percentages included in Table 0.7, it is worth highlighting that these percentage reductions will be applied to area-sector GVA for each day that restrictions are in place. So, while a reduction in GVA of up to 75% for some sectors would be very large over the course of a full year, we would expect the impact generally to be substantially smaller, as severe restrictions would not usually be expected to be in place for a very long duration: however the range of durations (under good or optimal portfolios) is ultimately for the model to reveal.

Given the uncertainties around exactly how different sectors would be affected by restrictions, we adopt a range of +/- 50% for high (capped at 100%) and low sensitivities respectively. For example, for sectors that have a 50% reduction in production in our central case, they will have a 25% reduction in the low sensitivity and a 75% reduction in GVA in the high sensitivity.[84]

[84] The NERA 2006 study for Thames Water applied specific Low, Medium and High ranges to five broad industry classifications. Given the more disaggregated sector approach taken in this paper, we consider it more appropriate to consider a single high-level sensitivity range of +/- 50%, which is similar to the order of magnitude of sensitivity ranges in the NERA 2006 study.

Table 0.7
GVA Losses per Sector by Drought Severity Level

			PWS			Non-PWS		
Industry			**S2**	**S3**	**S4**	**S2**	**S3**	**S4**
Agriculture, forestry and fishing	Rain-fed agriculture	Cereals	N/A	N/A	N/A	0%	15%	30%
		Potatoes rain-fed	N/A	N/A	N/A	0%	15%	30%
		Other rain-fed crops	N/A	N/A	N/A	0%	15%	30%
	Irrigated crops	Potatoes irrigated	N/A	N/A	N/A	53%	59%	59%
		Strawberries	0%	100%	100%	0%	100%	100%
		Other irrigated crops	N/A	N/A	N/A	24%	37%	37%
	Livestock	Livestock	0%	0%	25%	0%	10%	25%
Wholesale and retail trade; repair of motor vehicles	Retail sale of flowers, plants, seeds, fertilizers, etc.		0%	30%	30%	15%	30%	30%
	Other wholesale and retail		0%	0%	25%	0%	0%	25%
Administrative and support services	Landscape service activities		25%	100%	100%	0%	0%	25%
	Other administrative and support services		0%	0%	25%	0%	0%	25%
Arts, entertainment and recreation	Sports activities		50%	50%	50%	50%	50%	50%
	Other arts and entertainment		0%	0%	25%	0%	0%	25%
Manufacturing	Food products, beverages and tobacco		1%	10%	75%	1%	10%	75%
	Textiles, wearing apparel and leather products		1%	10%	75%	1%	10%	75%
	Wood and paper products and printing		0%	0%	50%	0%	0%	50%
	Coke and refined petroleum products		0%	0%	50%	0%	0%	50%
	Chemicals and chemical products		1%	10%	75%	1%	10%	75%
	Basic pharmaceutical products and preparations		1%	10%	75%	1%	10%	75%
	Rubber and plastic products		0%	0%	50%	0%	0%	50%
	Basic metals and metal products		1%	10%	75%	1%	10%	75%
	Computer, electronic and optical products		0%	0%	50%	0%	0%	50%
	Electrical equipment		0%	0%	50%	0%	0%	50%
	Machinery and equipment not elsewhere classified		0%	0%	50%	0%	0%	50%
	Transport equipment		0%	0%	50%	0%	0%	50%
	Other manufacturing and repair		0%	0%	50%	0%	0%	50%
Mining and quarrying			0%	0%	50%	0%	0%	50%
Electricity, gas, steam and air-conditioning supply			N/A	N/A	N/A	0%	0%	50%
Water supply; sewerage *			0%	0%	0%	0%	0%	0%
Construction			0%	0%	50%	0%	0%	50%
Transportation and storage			0%	0%	50%	0%	0%	50%
Accommodation and food service activities			0%	0%	50%	0%	0%	50%

		PWS			Non-PWS		
Industry		**S2**	**S3**	**S4**	**S2**	**S3**	**S4**
Information and communication		0%	0%	25%	0%	0%	25%
Financial and insurance activities		0%	0%	25%	0%	0%	25%
Real estate activities		0%	0%	25%	0%	0%	25%
Professional, scientific and technical activities		0%	0%	25%	0%	0%	25%
Public administration and defence; compulsory social security		0%	0%	50%	0%	0%	50%
Education		0%	0%	25%	0%	0%	25%
Human health and social work activities		1%	10%	75%	1%	10%	75%
Other service activities		0%	0%	25%	0%	0%	25%
Activities of households		0%	0%	50%	0%	0%	50%

Source: NERA analysis drawing on Vivid (2013) and NERA (2006).
**** We model PW--company costs separately and therefore do not model any sectoral reduction in GVA.*
Legend: based on: Blue –Vivid et al. (2013), Green –NERA (2006); White – NERA 2016 supplement

3.2 PWS company-borne effects

PWS companies will face direct consequences from drought events: they will have to manage the process of engagement with their customers and the authorities, and will incur costs associated with minimising the impact of drought events. These costs are different from the cost of investing in options that reduce the risk of drought affecting supply capability, although we need to be careful of double count issues. For example, if a drought event accelerates capex, this timing should only really be considered as a cost to the extent that it brings expenditure forward and therefore increases the NPV of these costs.

We categorise these costs into two broad categories:

- **Direct financial expenditures** borne by the PWS company during the management of the drought, such as the costs of running communication campaigns, extra staff dedicated to manage the drought restrictions, extra investment to enhance short-term capacity, or the costs of providing alternative supplies to the customers. Further details on the drought management options for PWS companies can be found in our companion paper *"Drought Consequences: Overview".*

  The PWS companies are also subject to licence conditions and could incur financial penalties if there are interruptions to supply, of the order of £10 per day for household customers and £50 per day for business customers.[85] However, we do not consider these effects here as (i) in aggregate such fines represent a transfer not a loss (the company is fined but government receipts offset this, so the impact is distributional), and (ii) it is unclear how the penalties would operate in the case of extreme drought events – they would not be applied under circumstances where it would be unreasonable to expect the interruption to have been avoided.

- **Other effects**. These would include income loss through reduced volumes sold, fines, compensation, fall in shareholder value and reputational costs.

Vivid et al. (2013) collected evidence from the water companies affected by the 2011/12 drought. Most of the companies interviewed did not have a detailed split of costs either by activity or by operating

[85] Company Licence Condition Q

expenditure or capital expenditure category; in these cases Halcrow used professional judgment to assign costs between capital expenditure and operating expenditure.

Table 0.8 summarizes the evidence collected and modelled by Halcrow. Three regions incurred costs in the baseline scenario – i.e. in the actual 2011 drought. The extended case scenario is a continuation of the baseline drought from the beginning of April 2012 through a serious drought event to June 2013. The extended scenario is a serious, multiple-season drought affecting England. While the most severe restrictions that took place in the baseline drought were TUBs (S2), the extended scenario assumes the implementation of drought orders with no concessions and full S57 restrictions (S3).

In both cases the total PWS sector costs are expressed in the Vivid study terms of sector GVA percentage loss. In the baseline case the modelled impact on sector GVA was a reduction of just 0.2%, whereas in the modelled extended drought, the modelled impact would have been a reduction of 8.4% in sector. We do not include these GVA percentage reductions in our non-household GVA model in Section 3.1. Instead, we evaluate PWS companies' drought costs using the estimation method described below.

Table 0.8
Costs of 2011-12 Drought borne by PWS Companies

	GVA	Baseline					Extended Case				
Region	**GVA**	**Opex (£m)**	**Capex (£m)**	**Lost Rev (£m)**	**Total Cost**	**% GVA**	**Opex (£m)**	**Capex (£m)**	**Lost Rev (£m)**	**Total Cost**	**% GVA**
South East	2,694	7.5	2.5	0.7	10.7	0.40%	187.0	50.5	1.3	238.8	8.87%
Anglian	1,131	4.0	1.0	0.2	5.2	0.46%	68.6	22.9	0.9	92.5	8.18%
North West	852	1.9	0.6	0.2	2.7	0.31%	43.9	14.2	0.5	58.6	6.88%
South West	1,011	0	0	0	0	0.00%	58.2	15.2	0.4	73.8	7.30%
Midlands	1,772	0	0	0	0	0.00%	124.3	31.1	0.6	156.0	8.80%
North East	1,251	0	0	0	0	0.00%	84.1	22.5	0.6	107.3	8.57%
Wales	-	-	-	-	-	-	-	-	-	-	-
Total	**8,711**	**13.4**	**4.1**	**1.1**	**18.6**	**0.21%**	**156.4**	**566.1**	**4.4**	**726.9**	**8.35%**

Source: Vivid et al. (2013) model – back end.

Note: We are seeking clarification on the make-up of the GVA data used in this table.

We have compared the company cost data collected by Halcrow with information we have collected from PWS companies as part of this study. In order to put the data in comparable terms, we have divided the total costs incurred by the companies by the number of connected properties.[86] The results of this comparison are shown in Figure 0.4. The mapping to severity levels in which the comparison was based is displayed in Table 0.10.

[86] Data collected on connected properties from the June Returns 2009-10.

The estimated costs for the PWS companies of a drought of Severity 2 (S2) – implying mainly the implementation of TUBs and the application for drought permits – roughly coincide across companies. For Severity 3 (S3) – the application of ordinary drought orders – the estimated cost range is wider.

In both cases, we form a range (lower-median-upper) for the cost evaluation. This range will estimate the one-off costs for PWS companies incurred when the drought arrives at each corresponding severity level, scaled by population served by the company. We do not have enough data points for a robust estimate at Severity 4, where emergency drought orders would be implemented, as there are very few examples of companies in a comparable situation in recent years. For S4 we therefore propose to take double the cost of the S3 range, and note that this is likely to be a conservative estimate.

In general, the cost estimates presented below include revenue losses for the water company. This could potentially represent a transfer – not a true economic loss – if it matches a reduction in bills paid by customers. With respect to household customers, the stated preference evidence presented in our companion sub-Appendix "Drought Consequences: PWS Households" does not take into account the effect of lower bills as an offset to the welfare loss. We note that a large proportion of households in the UK are not metered, and it is not clear that companies would necessarily offset interruptions to supply with bill reductions.[87] Given the likely modest size of the revenue effects overall we do not consider this to be a large area of uncertainty, compared to uncertainty around other modelling assumptions that we are making to estimate the economic and societal consequences of drought events in this project.

We adopt the following cost ranges for direct company costs, for each level of severity.

Table 0.9
Direct Company Costs - £ / Property / Event

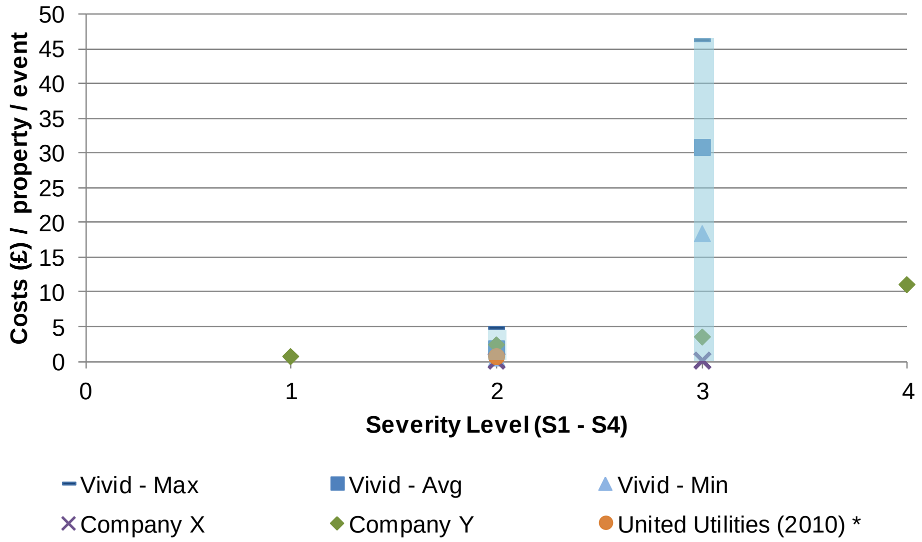
	S2	S3	S4
Central	2.5	25	50
Low	0	10	20
High	5	45	90

There may be additional consequences beyond those described above, such as reputational damage to the water companies involved, or a fall in shareholder value. Although Yorkshire Water did not have to impose rota cuts on customers to manage demand during the 1995-6 drought, it suffered major reputational damage and was fined more than £40m by Ofwat.[88]

87 For example, we understand that in response to the Mythe flooding in 2007 Severn Trent did not offer direct bill reductions for interruptions to supply, but did set up a compensation fund for particularly affected communities

88 AECOM (2016) *"The Socio-Economic and Environmental Impacts of Drought"*, p.19.

Figure 0.4
PWS Company Costs by Severity Level (£/ property)



Source: NERA Analysis.
Note (*): The United Utilities estimate corresponds to the 2010 drought, where TUBs and drought permits (supply side) were implemented. The data point can be found in UU's Report and Financial Statements 2011, p.9.

Table 0.10
Mapping of Collected PWS Companies' Costs Data to Severity Levels

<table>
<tr><th>Current Study</th><th>Vivid et al. (2013)</th><th>Company X</th><th>Company Y</th><th>United Utilities</th></tr>
<tr><td>S4</td><td>Not Available</td><td>Not Available</td><td>Compulsory essential use restrictions</td><td>Not Available</td></tr>
<tr><td>S3</td><td>Extended Scenario:
• Baseline Scenario
• Drought orders with no concessions
• HoF conditions
• Full S57 restrictions</td><td>Non-Essential Use ban

Estimates based on staff hours only</td><td>Drought orders for non-essential use</td><td>Not Available</td></tr>
<tr><td>S2</td><td rowspan="2">Baseline Scenario:
• Communication campaigns
• TUBs with concessions
• Drought permits and drought orders (supply side)</td><td>Temporary Use Ban (TUB)

Estimates based on staff hours only</td><td>Hosepipe bans</td><td>• TUBs
• Drought permit (supply side)</td></tr>
<tr><td>S1</td><td>Not Available</td><td>Voluntary / non-essential water reduction</td><td>Not Available</td></tr>
</table>

Source: NERA Analysis.

3.3 PWS public sector users

Drought events resulting in PWS restrictions have the potential to affect public sector services – from general functioning of public offices, to operation of acute services such as the running of hospitals or fire-fighting. These services are heavily dependent not only on the availability of supplies but in many cases also on the quality of water. Fire-fighting in urban settings requires access to the pressurised mains, which could be cut off by district metering zone in the case of PWS rota-cut restrictions, while hospitals may require a high quality (and large volume) of water in order to treat patients.

Hospitals and other critical infrastructure sites could be supplied to some degree using tanker operations. The Mythe 2007 floods provide a recent example of managing a disruption to services provided by Gloucester Hospitals NHS Foundation Trust; the floods led to 10,000 episodes of cancelled care and 11 weeks of interrupted water supply.[89] The Trust was supplied by tankers and was required to minimise water usage leading to the loss of all non-emergency or urgent clinical treatment for a ten day period, while several Trusts in neighbouring counties helped provide for e.g. dialysis and radiotherapy patients. This kind of local response may be more difficult in a wide-spread regional drought, where neighbouring hospitals and community health centres may also be affected. This would not only raise the medical costs, but could have important political implications too.

Information on the impact of water resources shortages on the public sector is very limited. AECOM (2015) does not consider specific impacts on the public sector, beyond noting that acute public sector customers such as hospitals would likely be prioritised and the direct effects are therefore likely to be minimal.[90] Vivid et al (2013) also do not directly consider the impact of restrictions on the public sector.

Portsmouth Water's customer research provides anecdotal evidence that public sector customers have differing degrees of resilience. One prison stated that it has back-up supplies in the event that access to PWS supplies is restricted:[91]

> *"the only one which would concern us really, would be the … interruptions of the water supply, but to be honest we've got back up so if the mains went off outside, we would be able to cope for a while"*

Some schools and hospitals do hold limited stocks of water in the case of a PWS outage, but would likely only hold for the first couple of days:[92]

> *"We have contingency for 3 days on-site water regardless… after that we'd shut down anyway" [School]*

> *"being a Hospital here we have quite a large storage capacity so we're fairly resilient towards anything to do with interruptions. I think the only thing would be a serious long-term interruption, nearer the 48 hours. We've actually worked with Portsmouth Water to develop an emergency plan whereby we can drop on to that in the event that there is an outage which is going to extend anywhere beyond 24 hours" [Hospital]*

The WHO cites The Sphere Project (2004) in defining minimum requirements for drinking water services in an emergency.[93] This provides an estimate of the minimum requirement for acute public sector services, as set out in Table 0.11.[94]

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89 Gloucester Hospitals NHS Foundation Trust *"Annual Report and Accounts 2007 – 2008"*, p.5

90 AECOM (2015), Annex C p.74

91 mva consultancy Report for Portsmouth Water (March 2013) *"Engaging with Customers Market Research to Inform Business Planning"*

92 Ibid.

93 The Sphere Project (2004) *"Humanitarian Charter and Minimum Standards in Disaster Response"*, cited by: WHO (2011) *"Technical Notes on Drinking-Water, Sanitation and Hygiene in Emergencies"*.

94 Presented for illustrative purposes only. The Sphere handbook is designed for use in disaster response and is most applicable to situations where relief is required, including natural disasters etc.

Table 0.11
Minimum Water Quantities for Institutions and Other Uses in Case of an Emergency

Institution	Minimum Quantity Needed
Health centres and hospitals	• 5 litres/out-patient • 40-60 litres/in-patient/day • 1 toilet to 20 beds • Additional quantities may be needed for laundry equipment, etc.
Cholera centres	• 60 litres/patient/day • 15 litres/carer/day
Therapeutic feeding centres	• 30 litres/in-patient/day • 15 litres/carer/day
Schools	• 3 litres/pupil/day for drinking and hand washing (use for toilets not included) • 1 toilet to 30 girls • 1 toilet to 60 boys
Public toilets	• Public toilets 1-2 litres/user/day for hand washing • 2-8 litres/cubicle/day for toilet cleaning

Source: Adapted from The Sphere Project (2004).

The impact of restrictions on public sector output is captured in the GVA approach summarised in Table 0.7, which includes lines for "*Public administration and defence; compulsory social security", "Education"*, and "*Human health and social work activities*".

We interpret this to capture the impact of restrictions on general public sector services and productivity. However, as noted in Section 2.3, this does not capture any externalities arising from welfare losses associated with provision of non-market public services, such as cleanliness of the urban environment and maintenance of public parks and gardens.

We also do not consider the GVA approach appropriate to capture the potential consequences of severe restrictions on acute public sector services, such as schools and hospitals. We discuss alternative metrics to indicate the potential consequences of drought on these acute public sector services in our companion sub-Appendix "*Drought Consequences: Scaling to Regions and Years*".

4. Concluding Remarks

We reviewed and collected a range of evidence on the potential consequences and economic costs associated with the consequences of drought events for non-households. For the purposes of this national study, we consider a GVA-reduction approach to measuring the economic losses associated with interruptions to non-household PWS customers and non-PWS abstractors to be appropriate, and we have been able to identify three recent studies to form the basis for this approach.

As discussed in Section 3, the extent of the losses depends on the sector make-up in the region affected by drought, and the RET results listed in the main report use the specific local sector make-up to model the consequences of restrictions for each of the specific regional droughts considered. High level "average" figures may therefore be misleading. However, to provide context for the scale of impact, under the sector make-up for England and Wales as a whole our estimates suggest a 37% loss of non-household GVA at times when Level 4 restrictions are applied to all non-households, within a wide plausible range of 20% to 60%. Applying the 37% central figure to the 2013 GVA level (approximately £3.8 billion per day for England and Wales) suggests that Level 4 restrictions across the whole of both nations would cause GVA loss of approximately £1.4 billion per day – a figure that must be scaled down to match the affected-GVA of the smaller affected region and actual local sectors of any specific drought scenario.[95]

With respect to costs borne by PWS companies in drought situations, we draw on Vivid et al (2013) estimates of company costs, and on data submitted by companies as part of this project, to develop a range of one-off costs, scalable in terms of pounds per property affected.

[95] See Annex E for a short description of how this figure has been estimated

Annex A. PWS and non-PWS Usage by Sector

Table 0.12 shows the assumed PWS/non-PWS water volume split by sector, drawing largely on AECOM (2015), Vivid et al. (2013). For the sectors not explicitly modelled by either of these sources, we have generally assumed that these sectors would be less reliant on large volumes of water supply (and therefore not directly mentioned by Vivid or by AECOM) and therefore do not have access to private abstraction sources. An exception to this assumption is "*Mining and quarrying*", for which we assumed an even split for the purposes of this note.

Table 0.12
PWS and non-PWS Usage by Sector

Industry		PWS	Non-PWS	Source
Agriculture, forestry and fishing	Cereals	0%	100%	AECOM (2016) / Vivid (2013)
	Potatoes rain-fed	0%	100%	AECOM (2016) / Vivid (2013)
	Potatoes irrigated	0%	100%	AECOM (2016) / Vivid (2013)
	Strawberries	50%	50%	Vivid (2013)
	Other irrigated crops	0%	100%	AECOM (2016) / Vivid (2013)
	Livestock	62%	38%	AECOM (2016)
	Others	0%	100%	AECOM (2016) / Vivid (2013)
Wholesale and retail trade; repair of motor vehicles	Retail sale of flowers, plants, seeds, fertilizers, etc.	40%	60%	Vivid (2013)
	Other wholesale and retail	100%	0%	NERA Assumption
Administrative and support service activities	Landscape service activities	100%	0%	Vivid (2013)
	Other administrative and support services	100%	0%	NERA Assumption
Arts, entertainment and recreation	Sports activities	45%	55%	Vivid (2013)
	Other arts and entertainment	100%	0%	NERA Assumption
Manufacturing	Food products, beverages and tobacco	55%	45%	AECOM (2016)
	Textiles, wearing apparel and leather products	10%	90%	AECOM (2016)
	Wood and paper products and printing	10%	90%	AECOM (2016)
	Coke and refined petroleum products	10%	90%	AECOM (2016)
	Chemicals and chemical products	10%	90%	AECOM (2016)
	Basic pharmaceutical products and preparations	10%	90%	AECOM (2016)
	Rubber and plastic products	10%	90%	AECOM (2016)
	Basic metals and metal products	10%	90%	AECOM (2016)
	Computer, electronic and optical products	10%	90%	AECOM (2016)
	Electrical equipment	10%	90%	AECOM (2016)
	Machinery and equipment not elsewhere classified	10%	90%	AECOM (2016)
	Transport equipment	10%	90%	AECOM (2016)
	Other manufacturing and repair	10%	90%	AECOM (2016)
Mining and quarrying		50%	50%	NERA Assumption
Electricity, gas, steam and air-conditioning supply		0%	100%	AECOM (2016) / Vivid (2013)
Water supply; sewerage and waste management		100%	0%	NERA Assumption
Construction		46%	54%	AECOM (2016)

Industry		PWS	Non-PWS	Source
Transportation and storage		100%	0%	NERA Assumption
Accommodation and food service activities		100%	0%	NERA Assumption
Information and communication		100%	0%	NERA Assumption
Financial and insurance activities		100%	0%	NERA Assumption
Real estate activities		100%	0%	NERA Assumption
Professional, scientific and technical activities		100%	0%	NERA Assumption
Public administration and defence; compulsory social security		100%	0%	NERA Assumption

Source: NERA Analysis, based on Vivid et al. (2013) and AECOM (2016).

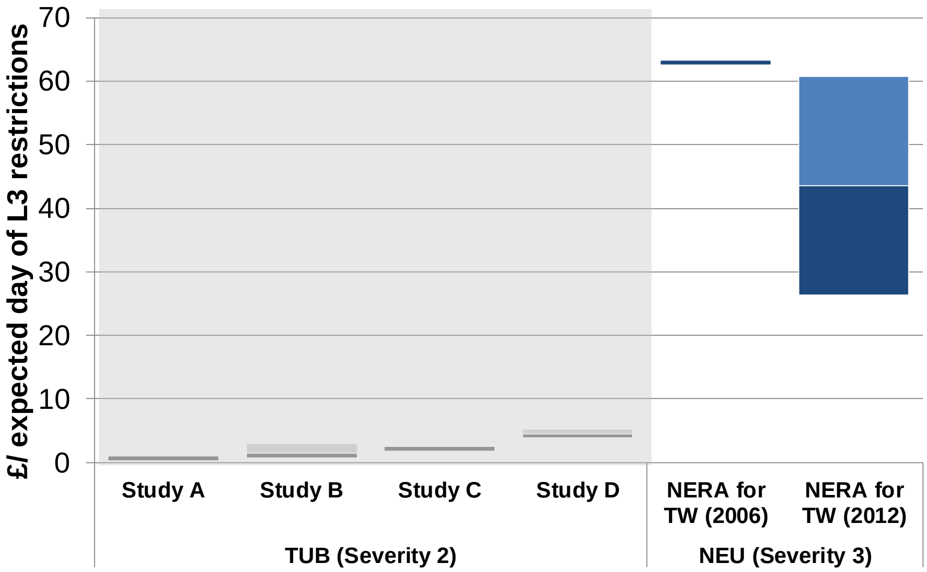
Annex B. Stated Preference Evidence for Non-HH Users

Figure 0.5 and Figure 0.6 present a summary of survey evidence on non-household willingness to pay to reduce the number of expected days for each severity situation.

In Figure 0.5, we note that the majority of studies reviewed only estimate the impact of TUBs on businesses. As noted above, this effect is typically very small and only affects a limited subset of business customers. NERA (2012) for Thames Water is the only study we are aware of that directly estimates the incremental cost to business customers, above the impact of TUBs.

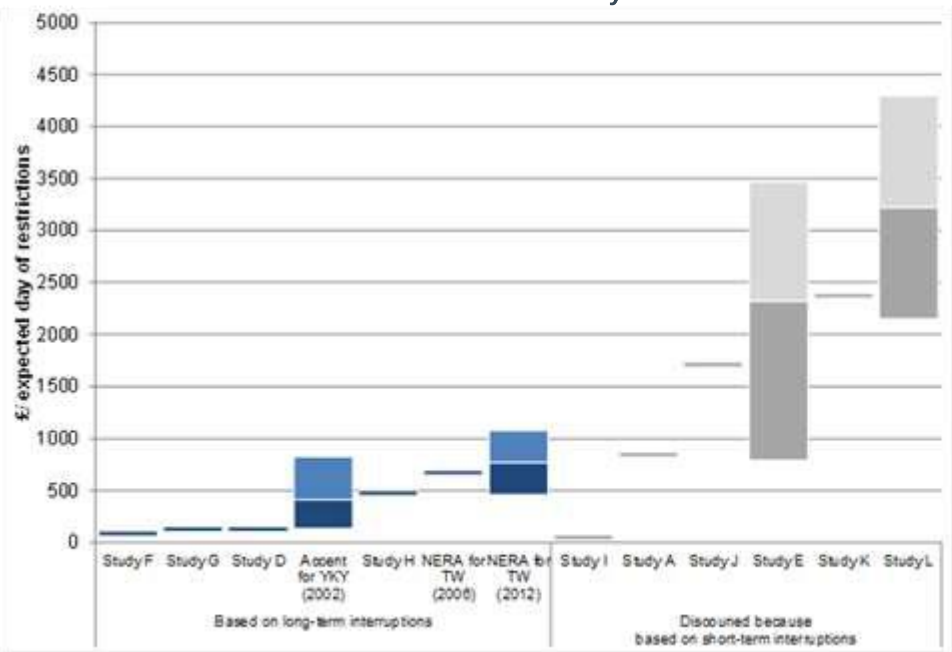
The estimates below are presented at an aggregate level for companies of all sizes and across multiple sectors. While stated preference surveys could in principle capture a richer level of detail – for example identifying different willingness-to-pay for different sectors of the economy and for companies of different sizes, this would require a much larger survey, which is not reported in the published literature and which is outside of the scope of the current project. This is an important reason why, as discussed in Section 2.3, we rely on a GVA-based approach to measuring the value of business interruptions in the main body of this report.

Figure 0.5
Non-Household WtP to Avoid Restrictions



Source: NERA analysis of various sources
Note: NERA 2006 and 2012 are based on the same survey results from 2006, with different weightings applied across businesses of different size based on updated information in 2012.

Figure 0.6
Non-Household WtP to Avoid Severity 4 Restrictions



Source: NERA analysis of various sources

Annex C. Cross-Check of GVA Approach to Stated Preference Valuations in NERA 2006

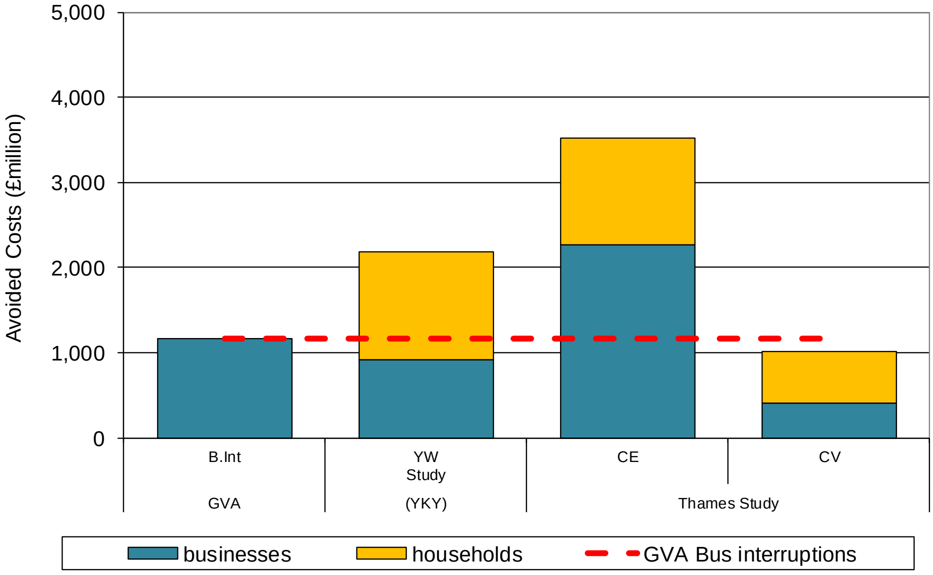
For the purposes of the current study, we use the GVA approach to estimating the value of interruptions, as discussed in Section 3. In this annex we provide a brief comparison of the results of stated preference valuation techniques compared to the GVA business interruptions approach, from a study undertaken by NERA for Thames Water in 2006. This gives us further degree of confidence that the GVA based approach produces reasonable valuations for the cost of restrictions.

Figure 0.7 shows the results from both the GVA approach to measuring the economic losses resulting from interruptions, and the estimated scaled results of various stated preference the London area.96 We were able to do this for the London region, drawing on census information about the numbers of comparisons in the region, which could be used to scale the WTP evidence. It is not clear that this would be meaningful for the current project.

In Figure 0.7, the first column shows the GVA-based estimate of the cost of business interruptions, while the remaining columns present willingness to pay evidence for both non-households in blue) and households (in orange) from the same study and from a study undertaken by Yorkshire Water in 2002.

We take the evidence presented in Figure 0.7 to indicate that the GVA approach to measuring business interruptions is a reasonable approximation of the costs of business interruptions – above the estimated costs when using a contingent valuation approach, but below the estimated costs from choice experiments.

Figure 0.7
GVA and WTP: Evidence on Water Restrictions Costs



Source: Update of NERA (2006) Figure 9.1 for illustrative purposes

A conversion of the GVA losses into pounds per property per expected day of restrictions for the London area (in 2006 prices) is shown in Table 0.13: The range presented in this table is broadly supported by the stated preference estimates of economic losses to business in pounds per business per day for our severity 4 situation, which are in the range of around £200 to £1,000 as shown in Figure 0.6.

96 For full details, refer to the original study: NERA (13 April 2006) *"The Cost of Water Use Restrictions - A Report for Thames Water"*, p.106

Table 0.13
GVA Losses for the London Region in Terms of £ / Business / Day

	Scenario		
	Low	Mid	High
Total Loss in GVA (London) Per Day of "Level 4" Restrictions (£000s)	83,600	174,100	297,900
Number of Businesses Supplied by Thames Water	385,300	385,300	385,300
GVA Loss per Day per Business (London average) (£)	217	452	773

Source: Update of NERA 2006,Table 4.5 using National Statistics (2005) "Region in Figures: London", for an estimate of total businesses in March 2003

Annex D. Assumptions behind Estimated GVA Percentage Losses

Table 0.7 shows the estimated GVA percentage losses by sector and severity level. The colour scale indicates the source of each of the values included in the table. We have used NERA (2006) estimated GVA percentage reductions for all sectors, except those sectors modelled at a more disaggregated level by Vivid (2013), where additional sub-sectors are modelled. This annex provides further details on the assumptions behind those values.

D.1. Vivid et al. (2013)

Vivid et al. (2013) led other consultancies in modelling only those sectors that were most affected by the 2011-12 drought in England, with a high level of granularity. Based on the economic size of the sectors, and the quality of the available GVA data, we have modelled a selection of these sectors. For these sectors, we have used Vivid's estimated GVA percentage reductions (or turnover, when the former was not available).

Vivid did not model the severity level corresponding to our S4 in the current study. The reason is that the 2011-12 events did not reach that level of severity. The sectors modelled by Vivid are those whose water use was already assumed to be fully restricted at our S3. Hence, for these sectors the same percentage reduction has been assumed by us for S4.

The percentage losses estimated by Vivid are "first-round" results, i.e. before considering offsetting gains in other regions not affected by drought, whose businesses might have benefitted from the losses faced by their competitors.

The assumptions behind each value depend on the specific sector:

- **Irrigated crops**. For irrigated potatoes and onions (the reference crop for other irrigated crops), Cranfield University base their estimation of the change in turnover on assumptions on the change in price/tonne and in yield/ha for a reduction in water of 50% (or partial S57 restrictions, our severity level S2) and for a reduction of 100% (or full S57 restrictions, S3), and on baseline price/t and yield/ha values. For strawberries, Vivid assumes a linear relationship between water reduction and output loss.
- **Retail nurseries**. The GVA percentage reductions are based on multiplying the assumed water availability percentage reductions caused by each water restriction by the percentage of the industry value that corresponds to plant sales, sourced from Vivid's interview with Horticultural Trades Association.
- **Landscape service activities**. Vivid assumes a linear relationship between water reduction and output loss. For TUBs, they assume that 25% of the industry corresponds to the domestic services that are curtailed under TUBs.
- **Golf**. Vivid assumes that the golf industry would be 100% restricted by the time TUBs were implemented. They further assume that 100% restriction in water would imply 50% reduction in turnover.

D.2. NERA (2006)

NERA (2006) modelled virtually the same sectors as those included in the ONS Regional GVA dataset at the NUTS2 level. As shown in Table 0.6, the 2006 study focused on two PWS restrictions: "*Level 3*" (Hosepipe bans and Drought Order restrictions) and "*Level 4*" (Emergency Drought Order restrictions, such as standpipes and rota cuts).

We take the proportion of GVA losses for "*Level 3*"restrictions in NERA (2006) and map this to our severity 3 situation. This is broadly appropriate because the "*Level 3*" in NERA (2006) represents both TUBs (which is broadly equivalent to hosepipe bans) and Ordinary Drought Orders.

The impacts on non-households of severity 2 restrictions are much more limited, as only a subset of sectors and activities would be affected by TUBs through for example voluntary reductions. For simplicity, we assume any sector affected at S3 would also make some small (potentially voluntary) reductions at as S2.

NERA (2006) establishes five classes of businesses depending on how they will be affected by water use restrictions and their own direct mitigation possibilities, (complete shutdown, partial output loss, etc.) and establish "*high", "mid"* and *"low*" percentage losses of output for each class, as shown in Table 0.14.

Table 0.14
NERA (2006) Output Loss Assumption by Class and Severity

Class	Description of Impact on Sector	Low	Mid	High
1	No loss of production	0%	0%	0%
2	Partial loss of production with limited mitigation possibilities	0%	10%	20%
3	Partial loss of production with no mitigation possibilities; or, severe loss of production with limited mitigation possibilities	10%	25%	50%
4	Severe loss of production with limited, or no mitigation possibilities	25%	50%	75%
5	Complete loss of production with limited, or no mitigation possibilities	50%	75%	100%

Source: NERA (2006).

These estimates are intended to capture the costs of lost output for every day in which restrictions take place. The costs of adaptive responses by businesses to the threat of, or actual, water use restrictions can also be considered to be reflected, though imperfectly, within the estimates.

Then, each industry sector is assigned to one of the five classes, based on a judgement of how businesses in that sector would tend to be impacted by water use restrictions. These judgements are informed by a review of materials documenting the 1976 drought in the Thames Water supply area and the 1995/96 drought in the Yorkshire Water supply area.

The values included in Table 0.7 correspond to the estimates for the "*mid*" scenario. As explained in section 3.1, the "*high*" and the "*low*" estimates are used for sensitivity analysis.

D.3. AECOM (2015)

AECOM (2015) considered virtually the same sectors as those included in the ONS Regional GVA dataset at the NUTS2 level, aggregating them into 11 sectors for model simplicity. Their assumed default base percentage water volume reductions – before further restrictions are applied if necessary to balance demand with available supplies and eliminate the deficit - are the same across all non-PWS sectors, except for spray irrigation and services. We do not draw on these AECOM default baseline percentages for our GVA reductions reported in Table 0.7, as they have been developed for different purposes.

As stated above, NERA (2006) assumed a single percentage reduction in GVA per day of restriction for PWS and non-PWS supplies for each sector under the equivalent of our current Severity 4 situation. The 2006 study did not consider switching between non-PWS and PWS in response to restrictions.

AECOM (2015) hypothesises separate water volume reductions for PWS and non-PWS usage, by sector. The baseline assumption is that in a severe drought, consumption of PWS water supplies would reduce by 25% (or more see below) in almost every sector, while water taken from private abstraction sources would reduce by 15% (or more see below) for all sectors except spray irrigation, which would face a reduction of 100% (through the application of S57). However, in the AECOM methodology, these reductions are only the baseline - if these demand reductions are not enough to eliminate a given drought deficit, modelling is undertaken to find the point at which demand WILL be suppressed enough to eliminate the deficit: at this step volumes taken from PWS supplies are reduced further by assumption, up to 100%, while as reported the private abstraction reductions are held constant at 15%. AECOM also allows for the possibility that of the 15% reduction in private abstraction, some may be made up by businesses which switch to PWS supplies. AECOM then take the GVA loss proportion to be the same as the volume-reduction proportion, sector by sector.

AECOM's derived volume reductions in modelled severe droughts are therefore very different numbers in concept to the parameters we need for the present study, which are the losses of GVA per day when set levels of severity restriction are applied to water supplies.

Annex E. Deriving a high-level estimate for GVA impact

We use GVA figures from the ONS 2013 to derive a high-level estimate for the scale of the potential impact of our most severe restrictions severity (Severity 4). This would imply an estimated loss of 37% of GVA per day of interruption, or of c. £1.4bn of a total GVA stock of c. £3.8bn. This figure is indicative only, and represents the impact of one day of severe nationwide (affecting all of England and Wales) restrictions. In practice, for each of the droughts modelled in the RET, the actual impact (both in percentage terms and in GBP) will vary depending on the sector make-up of the regions affected.

In order to derive an estimate of the nationwide impact of one day of restriction, we went through the following steps:

- Calculate GVA for each sector in Table 0.7, by allocating the ONS estimate of overall GVA to sectors (including a sector breakdown for most of the sectors and subsectors included in Table 0.7), using 2013 GVA.
- For certain categories, we have included a greater degree of disaggregation than that included in the ONS statistics. For these sectors we allocated the overall sector's GVA to subsectors using proportions derived from other sources (as described in Section 3.1).
- Allocate the proportion of GVA that is supplied by PWS and by non-PWS sources, in order to have the flexibility to model different impact of restrictions to PWS and non-PWS supplies
- Multiply annual GVA through by the proportion of GVA reduced in Severity 4 situations as set out in Table 0.7, sum, and divide this figure by 365 to derive a daily estimate of GVA loss in GBP. Convert to a percentage of daily total GVA.

F.4. Environmental Consequences and Valuations

1. Introduction

The project forms qualitative, quantitative and monetised estimates of the consequences of modelled drought events. The estimates are based on a review of existing evidence on the consequences of and economic valuation of drought events. This sub-Appendix is one of a five on the identification and evaluation of consequences of drought events, and follows the NERA methodology paper shared with the Steering Group and Review Panel in January 2016 then interim drafts dated February and May 2016:

- Drought Consequences Overview
- Household and Wider Societal Effects
- Non-Households and PWS Company Effects
- **Environmental Consequences and Valuation**
- Scaling to Regions and Years and Multiplier Effects

The scope of work is to use existing literature to identify the consequences of drought events and where possible to place a value on prospective drought events, to aid the evaluation of the appropriate levels of service for, and investments in, water resources infrastructure and demand management interventions.

This sub-Appendix describes the literature we have reviewed on the environmental consequences of drought events, discusses valuation techniques and proposes metrics to indicate the environmental consequences of drought events to link to the main Resilience Evaluation Tool. It also proposes potential areas for further work, to develop a better understanding of the environmental consequences of droughts.

The remainder of this note is structured as follows:

- Section 2 summarises the potential environmental consequences of drought events;
- Section 3 describes studies that have attempted to quantify environmental consequences, and proposes metrics to indicate environmental consequences for the purposes of this study;
- Section 4 provides concluding remarks and highlights areas for further study.

2. Environmental Consequences of Drought

Drought events may have direct and indirect effects on the environment. These effects may operate on terrestrial ecosystems, for example through impacts on soil or hydrological ecosystems as the water level in rivers and lakes are reduced.

The paragraphs below provide a brief literature review of drought consequences on the environment, while the "*Box: Environmental Consequences of Drought*" provides a short summary of Vivid et al (2013) work for Defra, which contains a description of the potential consequences of drought events on different environmental attributes.[97]

The current study is centred on modelling the consequences of drought to inform thinking on very long-term water resource infrastructure arrangements and in particular planning by PWS companies. Not all of the environmental consequences described above will be substantially impacted by the modelled investment portfolios. That is, there may be some (potentially substantial) environmental impacts of drought that have very little scope to be reduced by the investment and demand management options modelled and would therefore have a common valuation across all of the modelled investment portfolios.

Only those environmental consequences that are (significantly) affected by the modelled investment portfolios will impact on the relative merits of investment portfolios in this analysis. This is not to abstract from the importance of highlighting other environmental consequences common to all portfolios, to develop a better understanding of these and to inform wider infrastructure investment decisions, beyond those undertaken by the PWS companies.

A selection of environmental consequences of drought from the literature is discussed below:

- **Effects on the value of elements of Natural Capital.** In the UK, the ONS identifies various categories of "natural capital", some of which are environmental services which are "used" (e.g. water abstraction, fishing for commercial and recreational purposes, inputs to hydropower etc.), some of which are "non-use" (e.g. spiritual, inspiration and aesthetic value, fire regulation, educational, biodiversity etc.), and many of which would be affected to some degree by drought conditions.
- **Impact on navigation canals**, through closing routes if flows are below the required level, and the cost of repairing dried out canals.[98]
- **Inter-relationship between wetlands and water resource planning**. A TEEB report in 2013 notes that "wetlands provide natural infrastructure that can help meet a range of policy objectives. Beyond water availability and quality, they are invaluable in supporting climate change mitigation and adaption, support health as well as livelihoods, local development and poverty eradication".[99] The report goes on to note that maintaining and restoring natural infrastructure, such as wetlands, can lead to cost savings in relation to man-made infrastructure solutions.

[97] This case study relies heavily on Vivid et al (March 2013) *"The impacts of drought in England - R&D Technical Report WT0987/TR"*

[98] Raised in a workshop with environmental NGOs held on the 16th February 2016

[99] The Economics of Ecosystems & Biodiversity (2013) *"The Economics of Ecosystems and Biodiversity for Water and Wetlands"*

Box: Environmental Consequences of Drought (summary of evidence from Vivid et al 2013)

The Vivid Consortium undertook a study for Defra in 2013, setting out and providing a valuation of the impacts of drought in England, and in particular of the prolonged drought experienced in 2011. The study provides a rich qualitative description of the potential consequences of drought events on various environmental factors and makes a distinction between aquatic and terrestrial ecosystems, noting that while drought management options "could affect the water table in some locations", they are unlikely to have any effect on the drying of the top soil layer. Drought management options do however have the potential to affect the outcomes for aquatic ecosystems, through river flows and levels.

Aquatic ecosystems

In aquatic systems, wetlands and rivers, reduced flows and water levels can result in a fall in the fish biomass, changes in the populations of invertebrates and changes to the composition of plant populations Information on rivers benefits from a wealth of published studies.

Although there is scarce information on the effect of drought on the function of river ecosystems as a whole, the UK has one of the few experimental drought simulations for rivers, which shows large shifts in invertebrate and algal community structure and food web structure.

The consequences of drought events on river ecosystems will depend on various dimensions, such as: seasonal timing, speed of onset, duration and frequency of occurrence over longer time spans. There may also be important local characteristics that mean that the drought consequences vary widely for different water bodies in different catchments.

With respect to seasonality, many organisms are adapted to summer low flows, particularly the timing of life cycles of fauna and flora. Plants and animals may be more sensitive to winter droughts. Furthermore, aquifers normally recharge over winter, so winter droughts can evolve into a "supra-seasonal" drought.

The impact of drought is also in part mediated by changes in water temperature. As flow is reduced, air temperature and solar radiation have a greater influence on water temperature, which increases. Higher water temperature causes heat stress to biota but also increases decomposition rates and reduces dissolved oxygen, impairing water quality. Water temperature is also a major determinant of algal blooms.

The ecological effects of drought are dependent on certain environmental thresholds being met, in relation to drought magnitude and duration. Impacts may be disproportionately severe when critical thresholds are exceeded; e.g. cessation of flows causing abrupt loss of some habitats, alteration of physicochemical conditions in pools, and fragmentation of the river ecosystem.

Many ecological responses of plants and animals to drought depend on the rapidity of hydrological transitions across these thresholds, as this shapes a stepped response alternating between gradual change while a threshold is approached followed by a swift transition when habitat disappears or is fragmented.

Terrestrial ecosystems

In terrestrial systems, a drought affects fire-protection, carbon and nutrient fluxes in soils, microbial and soil fauna dynamics, plant production and biodiversity of plants and of butterflies, moths and beetles, by lowering water tables and by drying of the top soil layer.

The impact of changes in soil layer moisture and composition are not well understood.

Experiments have been carried out in which vegetation was shielded from rain, which could provide descriptive examples of the potential impact of droughts. However, in general the shields were put in place during the summer only, so the effect of sustained low rainfall in both winter and summer are not well understood.

There is evidence of increased fire occurrences in periods of lower than usual precipitation. For example, sites with Nature Conservation Interest in the UK experienced a greater incidence of fires in heathlands during the 1976 drought.[100] Fires cause a decline in vegetation and soil flora and fauna and an increase in carbon loss.[101]

The impact of drought events on UK birdlife is hard to quantify – presumably because birds tend to be mobile and can escape localised drought conditions. Bird populations and biodiversity more generally would be affected by a reduction in habitats and food availability.

There is evidence for example of changes in the species composition of butterflies in drought conditions, and a summer drought of two years is typically considered long enough affect the populations and diversity of other anthropod groups (e.g. beetles).

Among plants, the general pattern found across studies is that repeated experimental droughts of two summers or longer do not necessary lead to large scale species loss in grasslands. They do lead to substantial changes in species composition. Most studies observing vegetation changes before and after natural drought events indicate that compositional changes can be transient and reversible if the drought is followed by non-drought years. However, the change in this recovery potential, with the length of the drought is poorly understood.
In woods and forests, droughts decrease the growth of adult trees and increase the mortality rates of younger trees. Forest structure is expected to be recoverable, although it can take up to 15 years to regain similar stand demography after events like the 1976 drought

Long-term (5-8 years) experiments on UK heathlands show that repeated drought can change soils from being net carbon sinks to becoming net sources, through increased carbon leakage in ground water and increased respiration of CO_2 into the atmosphere

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100 on Vivid et al (March 2013) *"The impacts of drought in England - R&D Technical Report WT0987/TR"* (original reference to Hearn & Gilbert, 1977)

101 Vivid 2013 Op Cit.

3. Valuing Environmental Consequences of Drought

3.1 Review of existing quantification of environmental consequences

The Government's White Paper "The Natural Choice" highlights that "*[n]ature is sometimes taken for granted and undervalued*".[102] The Institution of Environmental Sciences has provided updated guidance, highlighting the importance of understanding the value of ecosystem services and cross-disciplinary benefits.[103]

In the run-up to PR04, the EA published guidance for companies on how to undertake environmental valuations, known as the Benefits Assessment Guidance (BAG):[104] The BAG sets out a methodology for value-transfer; that is, how to apply estimates of environmental value from previous work, to a new study. There have been subsequent workshops, revisions and updates to the BAG.

Studies have provided estimates of household willingness to pay for changes in river status quality. However, the range of evidence is large and often not readily applicable outside of the context of the original study. For example, the EA notes that the "*key problem identified in relation to non-use values and bathing waters was that transfer values were being drawn from only a limited number of studies and these studies report quite different findings and in some cases odd results*".[105]

While the BAG remains applicable today as a potential methodology for estimating environmental impacts, we have not come across any studies that could be reliably applied to the environmental effects of droughts (and associated severities) as modelled across the nation in this project. In the development of current WRMP guidance there is a move away from the BAG, towards having water companies value or incorporate environmental and social costs/benefits through more direct and local application of qualitative and quantitative techniques. Monetisation is only one option for incorporating environmental priorities into resource planning.

The UN Millennium Assessment (2005) taxonomy provides a different framework under which to consider the value of Natural Capital services including those provided by the river environment. This method classifies the benefits provided by an ecosystem into four types of services – supporting, provisioning, regulating and cultural – as set out in Figure 0.8.[106]

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[102] HM Government (2011) *"The Natural Choice: securing the value of nature"*,

[103] IES (October 2013) *"Ecosystem services assessment: How to do one in practice"*.

[104] EA 2003a *" Guidance for the Assessment of Benefits for Water Quality and Water Resources Schemes in the PR04 Environment Programme"*

[105] EA (May 2003) *"The Benefits Assessment Guidance for PR04: Review of Non-use Values for Water Quality and Water Resources and Values for Bathing Water Improvements – Report of an Expert Workshop in Peterborough"*

[106] UN Millennial Ecosystem Assessment (2005) *"Ecosystems and Human Well-Being",* p.50

Figure 0.8
Linkages Between Ecosystems and Well-Being

Source: UN Millennial Assessment (2005)

The ONS (2015) uses this taxonomy to estimate the economic value of the UK freshwater ecosystem assets. Table 0.15 shows the ecosystem services that the study considered; supporting services were not included, to avoid double-count. The study estimated that the total "asset" value of these services was of *£39.5 billion* (NPV) in 2012. The value of UK freshwater ecosystems in terms of an annual flow of service (2012) was £2,080m as shown in Figure 0.9.[107] This result should be considered as a lower bound, since it did not include many of the service categories listed.

This could provide a helpful starting point for drought effects valuation work; much in the same way as the GVA approach applied to non-household users in our companion sub-Appendix "*Drought Consequences: Non-Household and PWS Company Effects*" takes the total annual or daily gross value added of different sectors of the economy and assumes a reduction in GVA proportional to the extent to which each sector is dependent on water supplies for production.[108] A similar approach could be imagined to estimate the value of environmental consequences, using natural capital value estimates as the starting point, and modelling reduction in the value of natural capital services under different drought scenarios.[109] However, a more complete assessment of the value of ecosystems and environmental services and in particular of how they change under drought conditions is required for this purpose.

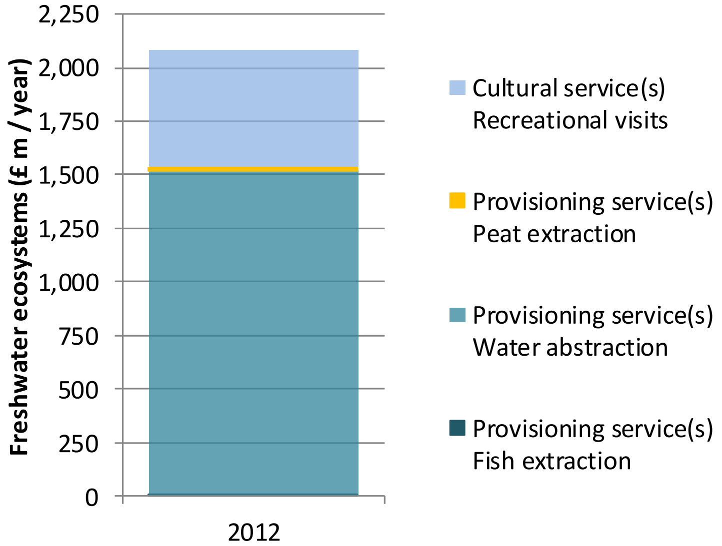
We are not aware of any study that has undertaken such an approach and we do not have a basis for the assumed proportional impact of droughts for each of our severity situations (S2 to S4, as set out in "*Drought Consequences: Overview*"). Substantial further work would be required to get to a reasonable estimate of environmental consequences using this approach.

107 ONS (2015) *"UK Natural Capital – Freshwater Ecosystem Assets and Services Accounts"*

108 NERA (February 2016) *"Drought Consequences: Non-Household and PWS Companies"*

109 NERA discussed potential for such an approach for future studies with a workshop of NGOs held at the Countryside Link Offices on the 16th February 2016

Figure 0.9
Value of Freshwater Ecosystem Services



Source: NERA drawing on ONS (2015) "UK Natural Capital – Freshwater Ecosystem Assets and Services Accounts"

Table 0.15
Ecosystem Services Assessed by ONS

Provisioning Services	Regulated Services	Cultural Services
Fish extraction (✓)	Carbon sequestration (✓)	Recreational (✓)
Water abstraction (✓)	Hydrological regimes	Educational (✓)
Peat extraction (✓)	Pollution and detoxification	Recreational fishing
Hydropower	Erosion protection	Spiritual, inspirational and aesthetic
Navigation	Flood protection	
Plants	Fire protection	

Source: Adapted from ONS (2015)
Note: services marked with a (✓) were monetised.

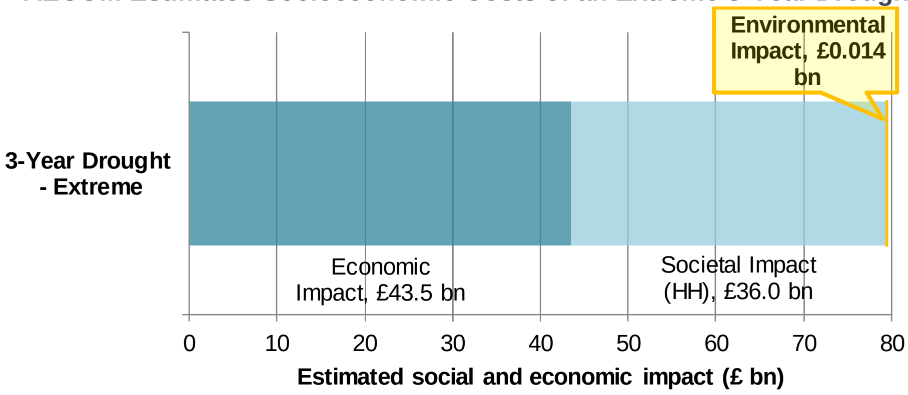
AECOM (2015) provides an estimate of the value of the consequences of drought events on the environment, focussing on the impact of shortages on environmental water quality. AECOM draws on willingness-to-pay survey based estimates of the value of water quality improvements, in particular NERA's 2007 study for Defra to estimate willingness to pay for improvements in water body status in line with EU WFD water quality objectives.[110,111] AECOM's approach is to estimate the area of water bodies that would experience a drop in WFD water quality status as a result of drought events, by assuming all water bodies start at "medium WFD quality" and deteriorate to "low WFD quality".

The AECOM work provides a rare attempt at making a monetised estimate of the environmental costs associated with widespread drought events that could be scaled to different regions, and to droughts of different duration. However, it is only a partial estimate, and does not account for many of the major environmental consequences described in Section 2. As shown in Figure **0.10**, the estimated environmental impacts using this approach appear very small when compared to AECOM's estimates of non-household GVA economic losses, or of the welfare losses to households of drought events. We do not consider this to be a complete assessment of the full range of potential environmental consequences and it should not be generalised to the droughts modelled in the Resilience Evaluation Tool for this project. We consider this interesting but too incomplete to use to produce environmental valuations for our current study.

110 Metcalfe, P.J. et al. (2012) *"An assessment of the nonmarket benefits of the Water Framework Directovie for households in England and Wales"*, Water Resource. Res., 48

111 NERA and Accent (November 2007) *"The Benefits of Water Framework Directive Programmes of Measures in England and Wales"*

Figure 0.10
AECOM Estimates Socioeconomic Costs of an Extreme 3-Year Drought



Source: NERA analysis of AECOM Annex C p.73

An important factor in considering the environmental consequences of drought events is the degree to which ecosystems can adapt or recover. Many of the studies cited in this section relate to long-term or permanent changes in environmental quality. In reality, ecosystems have shown a strong ability to recover once conditions revert which will limit the consequences on the environment (see the technical box on "Environmental Consequences of Drought" above, and for more details refer to Vivid Economics, CEH et al (2013)).

3.2 Proposed environmental consequence metrics for this study

As set out in Section 3.1, there is very limited evidence that informs the monetised valuation of the potential environmental consequences of drought, and none that can be robustly and readily scaled to the drought events modelled in this project (in terms of severity, geographical extent and duration), the 29 geographic areas of the RET, or to future snapshots in 2040 and 2065.

Given the sparsity of the valuation evidence, and the insensitivity of much of the environmental drought effects to the PWS supply portfolios examined in the wider study, we do not propose to provide a monetary valuation of environmental consequences of drought events. While it may be possible to monetise some aspects of environmental consequences and to proxy for others, we do not have enough evidence to provide a reliable valuation of drought impacts considered nationwide.

Section 2 provides a summary of the key consequences of droughts on the environment, drawing largely on Vivid (2013). Given that public water supply investment and demand management decisions are more likely to have implications for aquatic ecosystems than for terrestrial ecosystems, we focus on evaluating the environmental consequences of the former.

A selection of possible qualitative and quantitative indicators to use in reporting environmental consequences of drought is set out in the bullets below:

- **Area of water bodies in zones affected by restrictions, multiplied by duration.**
- **Flow indicators, which represent environmental thresholds.**
  - The number of days at Hands-Off-Flow levels is a useful indicator of risk, to the extent that they identify water stress in the river environment. Another alternative is the number of days that environmental flow indicators (EFIs) are reached or breached - that figure may provide a more accurate representation of environmental consequences, but we understand these are also taken into account when determining HOF levels;
  - Application of supply-side drought permits (and the quantity of water allowed for under these) which give water companies the authority to extract beyond the usual levels allowed, possibly to the detriment of the environment.
- **Number of specific sites where environmental consequences could be most important,** multiplied by the number of days at each level of severity. For example, the number of days that areas containing (a number of) Sites of Specific Scientific Interest (SSSIs) face restrictions. This measure will be crude, in that

it does not place a weight on one site as compared to another, and the potential loss of environmental value at each site may vary greatly.[112]

We also considered other potential indicators of environmental consequences of drought in the light of our review of the literature and following discussions with key stakeholders, which might provide evidence of drought consequences, but which we will not be able to implement within the timescales of the current project:

- **Effects on invertebrate populations**, such as crayfish populations, which have been studied under drought conditions and could be used to estimate a potential consequence of drought.
- **Occurrence of algae blooms** which respond within a period of months to changes in the aquatic environment, such as water temperature. We understand that the extent of algal blooms is monitored by the Rivers and Canals Trust. This could provide a useful real time indicator of the consequences of drought on the environment, but modelling the likely nation-wide occurrence is beyond the scope of this study.

4. Concluding Remarks

For the purposes of this study, we need to reflect that there are two different types of environmental consequences of drought:

- Consequences that are identical (more-or-less) across all investment and demand management portfolios. That is, environmental consequences that are not substantially affected by the investment choices and drought management strategies of public water supply companies; and,
- Consequences that depend on the investment and demand management portfolios. These will be largely focussed on aquatic ecosystems.

While the former effects may be substantial – and could form the basis of further research and policy recommendations for public infrastructure decisions, the latter effects are the core focus of this study.

We have reviewed available studies, and consulted, to investigate possible measures for this latter set of environmental consequences. Our review of the evidence suggests that monetisation of environmental consequences of drought is not appropriate for the purposes of this project; quantitative and qualitative indicators are used.

112 We discussed the potential use of this indicator at a workshop of environmental NGOs held on the 16th February 2016. SSSIs could be mapped to specific regions using GIS tools, and it may be possible to differentiate those heavily dependent on water.

F.5. Scaling to Regions and Years and Multiplier Effects

1. Introduction

The project forms qualitative, quantitative and monetised estimates of the consequences of modelled drought events. The estimates are based on a review of existing evidence on the consequences of and economic valuation of drought events. This sub-Appendix is one of a five on the identification and evaluation of consequences of drought events, and follows the NERA methodology paper shared with the Steering Group and Review Panel in January 2016 then interim drafts dated February and May 2016:

- Drought Consequences Overview
- PWS Households and Wider Societal Effects
- Non-Households and PWS Companies
- Environmental Valuation
- **Scaling to Regions Years and Multiplier Effects**

The scope of work is to use existing literature to identify the consequences of drought events and where possible to place a value on prospective drought events, to aid the evaluation of the appropriate levels of service for, and investments in, water resources infrastructure and demand management interventions.

This sub-Appendix summarises our approach to scaling the consequences and valuations to different regions of England and Wales, and to two future snapshots in 2040 and 2065.

Our approach to regional representations is based on available data and studies, noting the short timescale of this project. We also note caveats and limitations and suggest areas which should be developed in future work and/or subsequent iterations of this kind of national resources planning exercise.

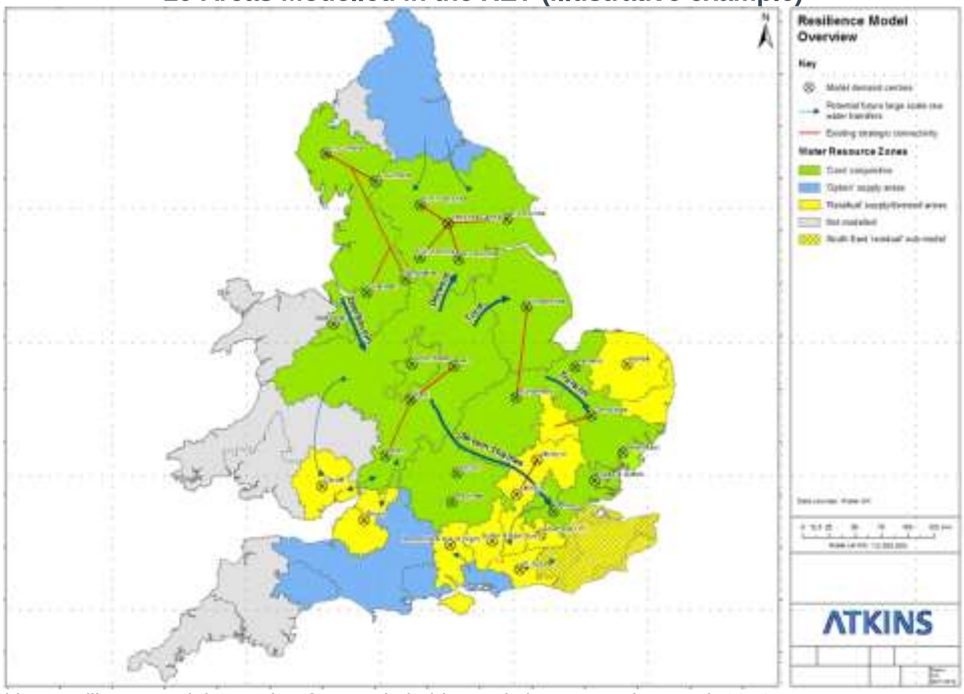
The remainder of this note is structured as follows:

- Section 2 summarises the 29 areas included in the RET and explains how the consequences and valuations are scaled to these areas;
- Section 3 sets out our approach to forecasting economic consequences and valuations to each of the resilience snapshots coming out of the RET, in 2040 and in 2065;
- Section 4 describes our approach to scaling direct impacts to account for broader multiplier effects on the economy;
- Section 5 concludes and highlights key limitations and recommendations for future studies.

2. Scaling to Specific Regions

The RET modelling is based on the 29 areas shown in Figure 0.11. These are largely based on Water Resource Zones, but some areas incorporate a number of WRZs where this has been considered to be appropriate on a strategic basis.

Figure 0.11
29 Areas Modelled in the RET (illustrative example)



Illustrative only, Atkins Resilience Model Overview from stakeholder workshop on Tool, 1st Feb 2016

The consequences and valuations need to be scaled depending on how each of the 29 areas in Figure 0.11 is affected. Each of the drought events simulated will impact on each of the 29 areas in a different way, both in terms of severity of the drought and associated usage restrictions, and in terms of duration.

2.1 Scaling PWS household welfare valuations to regions

Scaling welfare valuations is discussed in the EA's Benefits Assessment Guidance and subsequent notes. Particular aspects of the context and sample for stated preference survey evidence would ideally be accounted for. For example: income level/elasticity,[113] baseline level of service, scale of change examined etc.[114] However, accounting for such factors would require a much more extensive body of research than currently exists and conducting new primary research on consequences is outside of the scope of this project

We discuss the issue of baseline level of service (LOS) in the companion sub-Appendix "*Drought Consequences: PWS Households*". While we recognise that the baseline LOS will vary across the 29 regions in the RET, we adopt a nationwide estimate of WTP for reliability requirements. The uncertainties around the WTP estimates are sufficiently large that we do not think it would be appropriate to add another layer of adjustment complexity within the short timescales of this project.

The scale of the reliability change examined is captured in the severity and duration of the drought events modelled, which vary by region. We use different WTP estimates for each of the drought severities modelled.

With respect to income, we recognise that there are good reasons to think that willingness to pay may vary according to income levels. There has been an account for this relationship in some previous studies, for example in work undertaken for Thames Water in 2006.[115] However, we do not have a sufficiently broad range

113 Different regions may have different income levels and different income elasticity (cultural or behavioural patterns may vary from region to region) with respect to water consumption

114 See EA (2003) *"The Benefits Assessment Guidance for PR04: Review of Non-use Values for Water Quality and Water Resources and Values for Bathing Water Improvements. Report of an Expert Workshop in Peterborough, May 2003"*

115 NERA (2006)

of evidence to form the basis of a robust relationship between income and willingness to pay area by area, for the 29 areas used in this study. In addition, given the objective of this study, to formulate national value estimates for water resource planning, there may be equity issues in down-rating the value of improvements in some regions compared to others on the basis of income. Given the uncertain nature of this relationship, we do not include income as a regional scaling factor for household welfare consequences; we do not have a robust empirical basis on which to form sensitivity analysis within the timescales of this project.

To scale the household consequences across regions, we need to be able to scale the valuations from stated preference studies to each of the 29 areas. The WTP estimates are on the basis of an average household, which we can scale to region based on the number of households affected (we take the number of households affected in each region and multiply by the national average household WTP).

We scale the costs per day of restriction to the duration of the event on a linear basis. That is, each additional day of restriction has the same associated cost as the first. As we explain further in our companion sub-Appendix "*Drought Consequences: PWS Households*", we acknowledge that this is a limitation in our estimation. However, at the moment there is insufficient available evidence to form the basis of a robust non-linear relationship.

2.2 Scaling non-household and private abstractor consequences to regions

For non-household water users and abstractors, we estimate the value of economic losses resulting from drought restrictions, as described in the companion "*Drought Consequences Non-HH and PWS Companies*" report.[116] The GVA levels that we use are taken primarily from the ONS NUTS2 dataset, which includes 40 regions. These have been mapped to the 29 "areas" in the RET. The valuations are therefore scaled to represent the sector composition in each region, and the extent to which the production of these sectors is reliant on an uninterrupted quantity/quality of water supply.

As for scaling household consequences, we scale the costs per day of restriction to the duration of the event on a linear basis. That is, each additional day of restriction has the same associated cost as the first.

2.3 Scaling public sector, environmental and wider societal consequences to regions

There are some consequences where we have not found evidence of a complete monetised evaluation of the consequences of drought. These are summarised in two of the accompanying sub-Appendices .[117] For some of these, we identify candidate quantitative indicators of the raw consequences of drought to given weight alongside the monetised factors in any cost benefit assessment. We explain an approach to mapping these indicators to the 29 RET areas below and discuss limitations to interpretation of this evidence:

- **Number of acute hospitals in drought affected zones**. From a list of acute NHS trusts and their postcode locations,[118] map these to latitude and longitude locations, which can be linked to the 29 areas modelled in the RET;
- **Surface area of water bodies in drought affected zones.** Draw on a mapping of water body surface areas to the areas of the RET;
- **EFIs, HOFs, etc**. We understand that HOFs and EFIs can be mapped using shape files to the 29 areas of the RET.

As above, we scale the impacts per day of restriction to the duration of the event on a linear basis. That is, each additional day of restriction has the same associated impact as the first.

116 NERA (February 2016) *"Drought Consequences Non-HH and PWS Companies"*

117 NERA (February 2016) *"Drought Consequences: Societal Knock-on Effects and Valuation", and*
NERA (February 2016) *"Drought Consequences: Environmental Valuation"*

118 Available from http://www.nhs.uk/servicedirectories/pages/acutetrustlisting.aspx

3. Forecasting Effects and Values for Future Years

3.1 Forecasting sector growth for GVA analysis

Our approach to estimating the economic loss to businesses of drought events is to model them as assumed reductions in gross value added, which will be different for each sector, as set out in the "*Drought Consequences Non-HH and PWS Companies*" sub-Appendix.[119]

There are very few long term forecasts of economic growth and even fewer that break expected growth down by industry/sector. It is likely that the sectoral make-up of the economy in 2065 will be different to that of today.

To estimate the economic costs of water restrictions arising in drought events we need to make assumptions about the constitution of the economy for each snapshot in 2040 and in 2065. We forecast growth in GVA by sector and by region drawing on government five-year forecasts for different sector classifications and in different regions. The level of detail of these forecasts is not as granular as that included in our economic valuation work, so we map the sectors and regions based on the closest aggregation fitting the economic growth data.

The UK Commission for Employment and Skills published a report on "Working Futures 2012-2022", which included forecasts of expected growth in GVA for the following sectors and regions:[120,121] We roll these values forward to 2050, in the absence of any better basis for forecasting sectoral GDP growth.[122]

119 NERA (February 2016) *"Drought Consequences Non-HH and PWS Companies"*

120 UKCES (March 2014) *"Working Futures 2012-2022"*. Evidence Report 83

121 http://webarchive.nationalarchives.gov.uk/20140108090250/https://almanac.ukces.org.uk/context/A2/Forms/AllItems.aspx

122 We are not aware of any longer term growth forecasts by sector.

Figure 0.12
Average growth forecast 2015-2020 (%)

	London	South East	East	South West	West Midlands	East Midlands	York & Humb	North West	North East	Wales
Agriculture, forestry, hunting and fishing	1.1	0.8	0.7	1.1	1.1	0.8	0.8	0.9	1.1	1.0
Mining and quarrying	-4.6	-3.2	-3.6	-1.3	-1.5	-1.8	-1.9	-1.6	-1.3	-1.5
Manufacturing	1.2	2.1	2.0	1.9	1.7	1.7	1.6	2.2	2.1	1.9
Electricity, gas and water supply	0.0	0.3	0.4	0.9	-0.7	0.6	-0.5	0.2	1.0	0.6
Construction	2.6	3.0	3.0	3.0	2.9	2.7	2.6	2.5	2.7	2.3
Wholesale and retail trade	2.8	3.1	3.1	3.2	3.0	3.2	2.8	2.8	2.6	2.8
Hotels and restaurants	3.6	3.7	3.5	3.9	3.7	3.4	3.2	3.2	3.0	3.3
Transport, storage and comunications	3.9	5.0	5.0	4.6	3.8	4.3	3.8	3.9	3.5	1.5
Financial services	3.7	3.7	3.7	3.7	3.5	3.5	3.4	3.3	3.2	3.4
Real estate, renting and business activities	3.9	3.6	3.7	3.6	3.8	2.7	3.4	3.6	3.0	3.7
Public admin. and defence; compulsory social	1.3	1.5	1.3	1.6	1.6	1.5	1.4	1.9	1.4	1.5
Education	1.1	1.9	1.7	1.8	1.8	2.0	1.6	1.6	1.4	1.6
Health and social work	3.5	4.2	3.8	3.4	3.5	6.0	3.5	3.4	3.1	3.6
Community, social and personal service activities	0.7	-0.2	-0.1	-0.2	0.0	-0.2	-0.4	-0.3	-0.3	0.3
Total	3.1	3.0	2.9	2.7	2.6	2.6	2.4	2.6	2.3	2.3

Source: NERA analysis of Working Futures forecast data available from http://webarchive.nationalarchives.gov.uk/20140108090250/https://almanac.ukces.org.uk/context/A2/Forms/AllItems.aspx :

The resilience of different sectors to drought events may evolve over time, as the technology mix changes. Furthermore, if the risk of severe drought events is perceived to be increasing over time, businesses may invest in their own resilience to mitigate the future impact of usage restrictions.

We are not aware of any studies that have investigated how sector-wide resilience to extreme drought events may change in the future. Given the challenging timescales of the current project we therefore assume that the percentage reductions in GVA under each severity situation will be the same in 2040 and 2065 as today. This is a strong assumption, and one that would benefit from a more in-depth investigation in future studies.

3.2 Forecasting willingness to pay

There are good reasons to believe that customer preferences will not be the same in 2065 as they are today. For example, customer expectations with respect to levels of service may be expected to rise with income, and tolerance for interruptions to service to fall correspondingly. Behavioural change may also affect the way that today's services are valued in the future.

For the purposes of this exercise, we assume that the ranges of willingness to pay we have formed in "*Drought Consequences: PWS Households*" do not change over time.[123] Noting the discussion above, this is a strong assumption, but we have not found any evidence which would allow us to form a reliable alternative assumption. For example, we implicitly assume that:

- Household composition does not change over time (nor by region). Clearly, both household size, and the age of occupants, could affect willingness to pay to avoid restrictions. In general we would expect larger households to be willing to pay more to avoid an interruption to supply, and households with a larger share of vulnerable customers – e.g. the very young or the elderly – would also be willing to pay more. We might expect to see an increase in lower occupancy households in the future, which would reduce the average willingness to pay to avoid restrictions per household;
- Water efficiency is likely to change, both for households and for businesses. It is not clear in which way this would change our valuation estimates for the economic losses resulting from interruptions of water supply to businesses, or welfare losses from interruptions of water supply to households. Greater water efficiency, resulting in lower base consumption, could make consumers more highly dependent on this (reduced) consumption if they are less able to flex their consumption. On the other hand, increased water efficiency could result from technological and/or behavioural changes, which also make households and businesses better able to react to shocks. In all it is not clear how increased water efficiency will change resilience to shocks – and this may be an area for further research.

3.3 Indexing and discounting

We work with costs and values in real terms through the project. Where it is necessary to change the price base the general consumer price index, RPI.

When forming present values of benefits we take the conservative approach of discounting future benefit streams using the same discount rate as used for discounting the costs of interventions, namely 4.5% as specified for cost discounting at PR14. This is unlikely to have a material effect on the implications of the study, by comparison with using the Treasury Green Book discount rate of 3.5% to discount benefits.[124]

[123] NERA (February 2016) *"Drought Consequences: PWS Households"*

[124] HMT (2011) *"THE GREEN BOOK - Appraisal and Evaluation in Central Government"*, p.98

4. Scaling for Economic Multiplier Effects

4.1 Raw multiplier effects of drought events

In other sections we have considered the consequences of the direct loss of output or welfare borne by a stakeholder experiencing a reduction in available water. These "direct" consequences of drought –and our approach to measuring them – are set out for each of PWS households, non-households and PWS companies, and the environment respectively. Here we consider the indirect and wider effects.

Firstly, the activity levels and value-added of different sectors of the economy may be altered as a result of indirect, or "ripple", effects of droughts across the value chain.

The Leontief Inverse matrix provided by ONS (2015) gauges the effect of changes in final demand on output and related aspects of the economy. These effects have three different economic drivers:

- **Direct effects**: This type of effect is defined as "*the immediate effect caused directly by the change in final demand*". Final demand for products other than water itself is unlikely to change in the event of a drought. Therefore, for the purpose of this study, direct effects should rather be defined as being caused *directly* by a change in the supply of an input, i.e. water. These are the costs that have been analysed evaluated in our companion papers.
- **Indirect effects**: This is "*the subsequent effect caused by the consequent changes in intermediate demand*". For the purposes of our study, we identify two sub-types of effect within this category:
  - *Forward linkages*: Industries further down the value chain that depend on obtaining output from directly drought-affected sectors (as an input for their own production) may be affected; and
  - *Backward linkages*: Directly affected entities may reduce their demand for input products from further up the value chain;
- **Induced effects**: This is "the effect attributable to the ensuing change in compensation of employees and other incomes, which may cause further spending and hence further changes in final demand". Indeed, if production is affected by drought so owners lose profits and dividends, and employees see a reduction in their wages, their reduced incomes may lower aggregate demands as they no longer spend elsewhere in the economy – with consequent economy-wide effects.

4.2 Estimating the potential size of multipliers

Estimates of the "ripple effects" described above can be made by drawing on macro-economic models. For example, general equilibrium models study the interactions between economic agents, and how an external shock affects the whole system. However, we are not aware of any UK study using general equilibrium models applied to estimating the costs of drought events, or of reduced water resource availability.

The ONS Input-Output Analytical Tables offer a simpler approach, using a vector of multiplier effects for each sector of the economy, which quantify the effects of the "indirect" effects described above.[125]

To estimate the knock-on effects of the modelled GVA reductions by sector that are set out in "*Drought Consequences: non-Household and PWS Companies*", we use the ONS GVA multipliers by sector,[126] which estimate the effect on total GVA resulting from a one unit change in the GVA of a specific sector, all else equal. For example, the ONS GVA multiplier for agriculture is 1.8; that implies that for a shock resulting in a 1.0 percent reduction in agricultural GVA, the impact on total economy-wide GVA would involve a further reduction in total GVA equal to 0.8 percent of the sector reduction by the time the ripple effects had all been allowed for.

125 Note that the "induced" effects are not estimated by these tables, as explained in ONS (2015) *"United Kingdom Input-Output Analytical Tables 2010"*, p. 17.

126 Illustrated in Annex A Only the 60 industries (out of 127) with the highest multipliers are displayed.

A simple approach is to:

1. Calculate each sector's direct GVA loss per day for the drought severity modelled;
2. Multiply this sectoral loss by the corresponding multiplier to form the additional indirect loss.
3. Do the same for all sectors, and add up the results. The result is the total indirect GVA loss caused by supply chain effects only.
4. Add the direct and indirect effects.

The multipliers are calculated using the coefficients of the Leontief Inverse matrix, which is formed from the input-output table to show the effect of changes in final demand on total GVA. The Leontief Inverse matrix coefficients capture the infinite chain of effects on total demand from a change in final demand. The first effect will be the loss of intermediate demand directly generated from the final demand. The second effect will be the loss of the further intermediate demand generated from this first direct intermediate demand, and so on.

However, that simple application of the GVA multipliers to our assessment of the economic impact of droughts has some very substantial limitations:

- **It does not fully account for substitution effects**. In the case of a drought, four types of substitution could occur and limit the knock-on effects:
  - Substitution across regions, where products are made elsewhere if the drought is not nation-wide;
  - Substitution across countries, where products are imported if only the UK is being affected by a drought;
  - Substitution across products, if there is an alternative input available whose production process has been less affected by a drought;
  - Substitution across time, where stocks of products are run down and made up later, or the delivery of products is delayed by a period so that production is not wholly lost.
- **The coefficients assume that only one industry is affected at a time**. For example, a drought will have direct effects on both agriculture and food industry GVA. The multiplier effect on agriculture covers the fact that the food industry will produce less if it receives less input from agriculture. However, the food industry is already producing less because of the drought. This suggests some interaction that might alter our "national average" coefficients.

The factors above would all tend to make the real ripple effect lower than that suggested by the national IO coefficients; the modelled effect would be an upper bound at best.

Crawford-Brown et al. (2013) evaluate London's economic vulnerability to climate change with the aid of an Adaptive Regional Input-Output model (ARIO).[127] For its generation of Input-Output tables, the model uses the pre-damage matrix of technical coefficients from a Multi-sectoral Dynamic Model (MDM) of the British Economy.[128] The model then estimates the scale of the indirect losses and the length of economic disruption resulting from shocks. The losses and length depend on the size of the initial damage, the structure of the economy prior to the damage, and the ability of individuals, businesses, and markets to adapt in the event aftermath. The results show that for a range of simulated events of differing severity, the indirect losses motivate a multiplier of between 1.3 and 2 depending on the scale of the initial damage. [129]

Outside of the UK, we are aware of one study that has reviewed the application of input-output and CGE models to water supply shortages. The study found that:[130]

> *"in a detailed CGE study of water supply shortages in the Portland metropolitan area, Rose and Liao [Rose and Liao, 2005] found that estimated indirect impacts were only about 22 percent of estimated direct impacts (equivalent to a multiplier effect of 1.22), and that both positive and negative indirect effects were observed. Thus, given that the data requirements for a well-executed I-O or CGE model are large and that previous studies suggest that differences in estimated impacts may be relatively small*

[127] Crawford-Brown, Syddall, Guan, Hall, Li, Jenkins and Beaven (2013) *"Vulnerability of London's Economy to Climate Change: Sensitivity to Production Loss"*, published in Journal of Environmental Protection, Vol 4

[128] Barker et al. (2001) *"The Cambridge Multi-sectoral Dynamic Model of the British Economy"*, Cambridge Studies in Applied Econometrics, Number 5.

[129] Barker et al. (2001) *"The Cambridge Multi-sectoral Dynamic Model of the British Economy"*, Cambridge Studies in Applied Econometrics, Number 5.

[130] Brozovic, Sunding, Zilberman (August 2007) *"Estimating business and residential water supply interruption losses from catastrophic events",* published in Water Resources Research, Vol 43

> *overall and of ambiguous sign by industry, we argue that a simple business loss estimation methodology [direct] is both extremely useful for decision makers and easy to implement and interpret".*

Due to the above limitations, we consider that the estimation of total indirect economic costs using national-level GVA multipliers should only be interpreted as an upper bound, probably a large one. We consider we should be guided by sensible figures allowing for substitution, notably the 1.22 quoted in the US study, and the 1.3 – 2.0 range derived by Crawford Brown et al. (2013), and so adopt the multiplier range of 1.2 to 2.0 for use in the appropriate sensitivities, beyond the main results which are for direct effects only.

5. Concluding Remarks

We have set our approach to scaling value estimates and quantified indicators, to the 29 areas modelled in the RET, and to each time snapshot at 2040 and to 2065.

This approach is necessarily simplistic given the limitations of available evidence and the short timescale of this project. We have identified a number of areas where we have had to make simplifying assumptions, which could be progressed by future work, or for subsequent iterations of this type of national exercise. For example:

- Differences in household composition across regions and over time. This may affect willingness to pay to avoid restrictions, as discussed above.
- Water efficiency changes over time, both for households and for businesses. It is not clear in which way this would change our valuation estimates for the economic losses resulting from interruptions of water supply to businesses, or welfare losses from interruptions of water supply to households.

We account for economic knock-on effects of production (GVA) losses, drawing on the ONS input output tables and the literature on the effects of shocks, to scale up the economic losses from supply interruptions to businesses as a sensitivity to our main direct economic impact assessment.

Annex A: GVA Multipliers from ONS (2010)

Product	GVA multiplier
Dairy products	5.14
Veterinary Services NPISH	4.91
Creative, Arts And Entertainment Services Non-market	4.18
Electricity, transmission and distribution	3.76
Prepared animal feeds	3.36
Grain mill products, starches and starch products	3.25
Preserved meat and meat products	3.14
Gas; distribution of gaseous fuels through mains; steam and air conditioning supply	3.09
Social care services non-market	2.77
Soft drinks	2.74
Waste Collection, Treatment And Disposal Services; Materials Recovery Non-market	2.63
Water transport services	2.58
Basic iron and steel	2.57
Motor vehicles, trailers and semi-trailers	2.55
Other transport equipment - 30.2/4/9	2.50
Dyestuffs, agro-chemicals - 20.12/20	2.47
Products of forestry, logging and related services	2.41
Petrochemicals - 20.14/16/17/60	2.35
Repair and maintenance of aircraft and spacecraft	2.34
Other basic metals and casting	2.26
Manufacture of cement, lime, plaster and articles of concrete, cement and plaster	2.24
Other chemical products	2.24
Sports services and amusement and recreation services	2.22
Rail transport services	2.20
Industrial gases, inorganics and fertilisers (all inorganic chemicals) - 20.11/13/15	2.20
Sports services and amusement and recreation services Non-market	2.19

Product	GVA multiplier
Insurance, reinsurance and pension funding services, except compulsory social security & Pensions	2.18
Processed and preserved fish, crustaceans, molluscs, fruit and vegetables	2.16
Alcoholic beverages	2.14
Air and spacecraft and related machinery	2.11
Other food products	2.09
Soap and detergents, cleaning and polishing preparations, perfumes and toilet preparations	2.08
Warehousing and support services for transportation	2.05
Coke and refined petroleum products	2.02
Weapons and ammunition	1.95
Waste collection, treatment and disposal services; materials recovery services	1.93
Construction	1.89
Rest of repair; Installation - 33.11-14/17/19/20	1.88
Products of agriculture, hunting and related services	1.88
Furniture	1.88
Air transport services	1.87
Motion picture, video and TV programme production services, sound recording & music publishing & programming and broadcasting services non-market	1.87
Coal and lignite	1.84
Wood and of products of wood and cork, except furniture; articles of straw and plaiting materials	1.84
Glass, refractory, clay, other porcelain and ceramic, stone and abrasive products - 23.1-4/7-9	1.83
Wholesale trade services, except of motor vehicles and motorcycles	1.82
Paper and paper products	1.81
Scientific research and development services	1.80
Remediation services and other waste management services	1.79
Advertising and market research services	1.79

Note: We only show the largest 60 from 127 sectors. All figures are national and based on annual average coefficients

Appendix G. Water Resource and Resilience Modelling

Purpose and Core Concepts

The modelling within Aquator and Wathnet had two key objectives:

A. To provide an understanding of system storage responses for all surface water systems > 30Ml/d for each of the Drought Configurations, which allowed for:

   - 'Tier 3' estimate of yields in those systems
   - Failure duration responses under different drought severities for input to the consequence modelling

B. To allow the 12 detailed Portfolios generated by the options appraisal to be run through the Wathnet system to review how they performed when subject to system drought stresses

Aquator models are very familiar to the water industry and were available for most of the strategic resource systems that required analysis outside of the Wathnet model.

Wathnet is a simulation model based on a network linear program formulation, which was developed by the University of Newcastle (NSW, Australia). It was adopted for this project because it is relatively simple (relying on 'hard' constraints and costs only), fast and highly programmable. It does not include some of the more advanced elements of packages such as Aquator or Miser (and in particular there is no 'resource state' type calculation), but it was considered to be adequate for this level of strategic analysis.

Methodology

All Aquator modelling was based on existing company models. The analysis therefore consisted of:

- Configuring and checking the flow inputs generated through the hydrological modelling described in Appendix B.2 so that they could be run in the models
- Carrying out an incremental demand run based on the 'Scottish DO method'. This allowed matrices of failure duration against demand to be generated for each drought within the Drought Configuration timeseries (see Appendix B.2 for an example output).

It should be noted that Atkins already had access to much more detailed stochastic analysis for Southern Water, which was carried out as part of the WRMP14 submission. The incremental demand matrices from that analysis were therefore used in preference for the three Southern Water Areas.

The Wathnet model was developed to cover the UU, Severn Trent, South Staffs, Thames, Anglian and Yorkshire resource systems, along with a number of supply options from DCWW and Northumbrian Water. The project team was provided with access to all of those companies' existing water resource system models, and Wathnet was constructed from that information. The following general process was used for the Wathnet model development:

- Review, simplify, code and validate the strategic supply systems based on companies' own data
- Generate inputs from the Drought Configurations and then test through the Scenario 0 configurations
- Introduce 'scaling' adjustments where required to improve the match to historic droughts in the water company models (this was only needed following the Scenario 0 analysis in the Thames and Yorkshire areas, and consisted of demand scaling factors that were less than 5% in both cases).
- Formulate and code the following attributes of the 12 portfolios for each demand and climate change scenario:

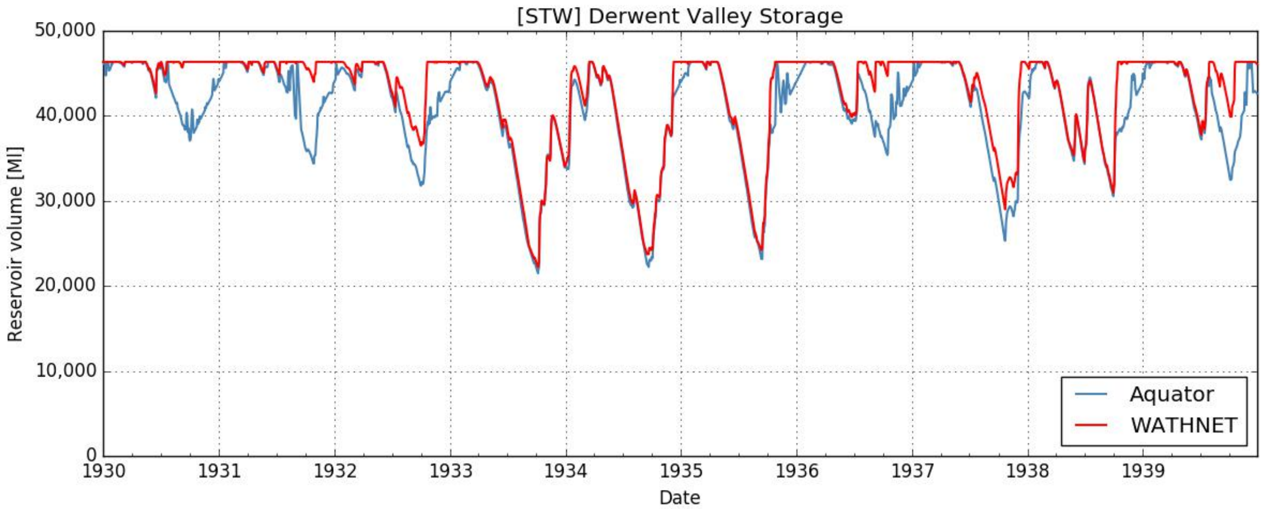
- ‘Simple’ new supply schemes: these were aggregated and incorporated as a simple single new source for each of the demand centres within the model, with a yield that varied according to the Portfolio.
- Sustainability reductions, outage, process losses and base year headroom allowances: these were incorporated as a demand uplift for each of the relevant demand centres for each Portfolio.
- Demand management strategy effects: these were incorporated as demand reductions, netted off against the sustainability reductions etc. described above.
- Strategic schemes: these were specifically modelled according to their attributes. In total there were 19 strategic schemes, covering sources such as the Lake Vyrnwy redeployment, the Trent to Rutland support scheme, the Middle Severn transfer schemes etc. These were switched on and off as relevant for each Portfolio.
- Major strategic transfers were coded into the model as specific pipelines with the relevant engineering attributes, and used as required according to the Portfolio.

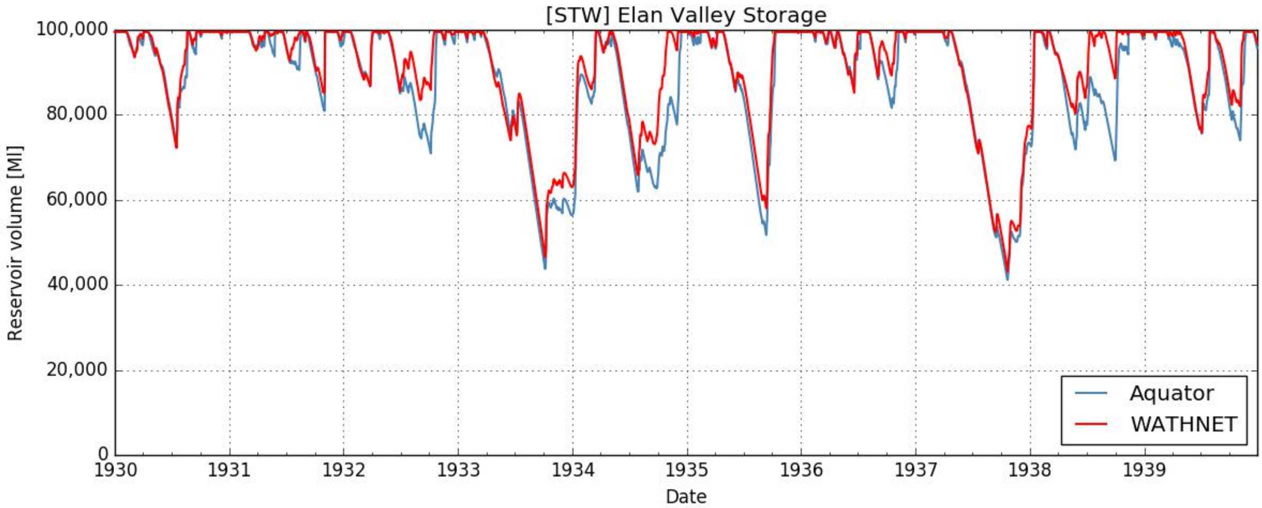
Validation

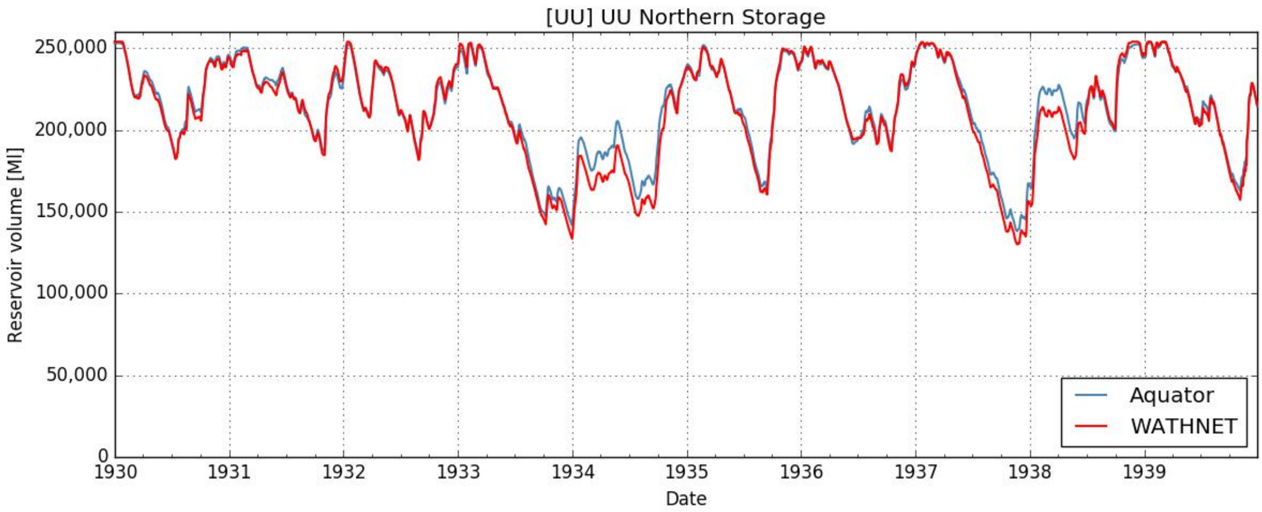
The Aquator outputs were validated by comparing the level of demand failure in the matrix for historic droughts use matrices to check historic droughts reconcile against expected demand failure levels (DOs). Results were discussed with individual water companies.

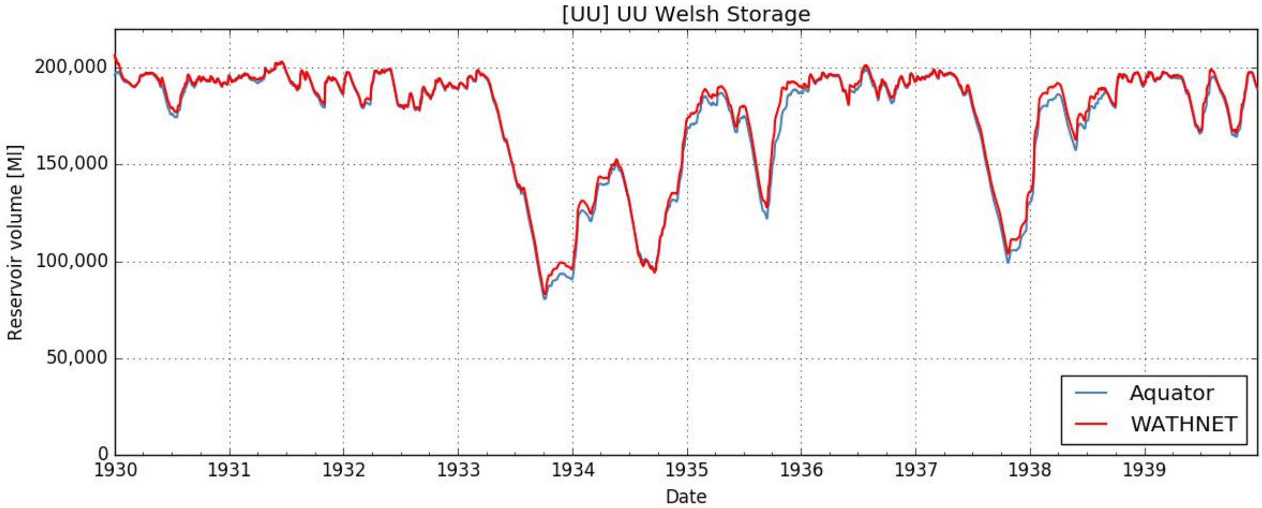
The first key validation for Wathnet was against aggregate storage behaviour, where historic data were run through Wathnet and compared against the water company own outputs. This was done for all reservoirs within each system, and key flows and transfers were also checked. Some localised differences were to be expected, and the primary confirmation of adequate validation was focused on aggregated storage across the main areas in each resource system. It should be noted that the validation was only required during the drought stress periods – normal operation outside of drought stress periods was not simulated to any degree of complexity. An example set of validation results, for the widespread drought year of 1933/34, is provided in Figure App-46 below

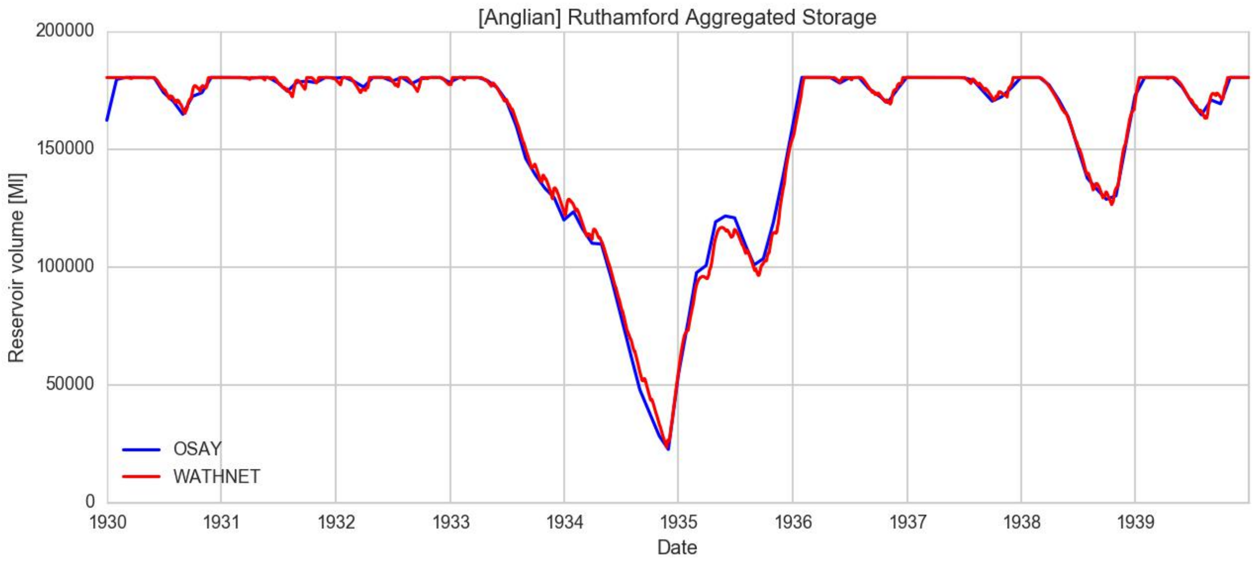
Figure App-46 Example Wathnet Storage Validation Results for the 1933/34 Drought

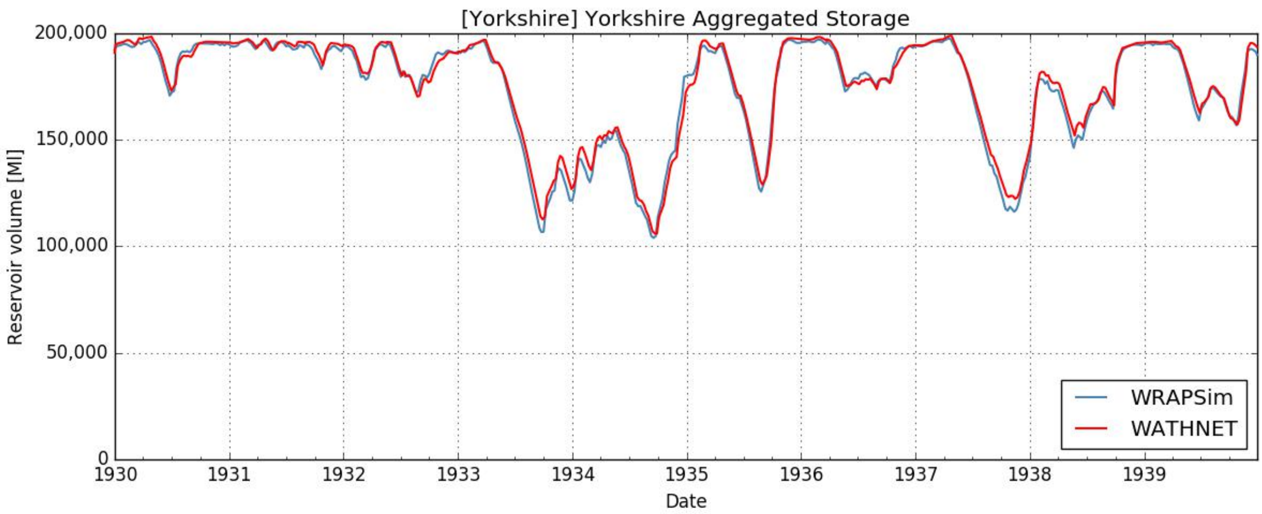



[STW] Elan Valley Storage
Reservoir volume [Ml]
100,000
80,000
60,000
40,000
20,000
0
1930
1931
1932
1933
1934
1935
1936
1937
1938
1939
Date
Aquator
WATHNET


[UU] UU Northern Storage
Reservoir volume [Ml]
250,000
200,000
150,000
100,000
50,000
0
1930
1931
1932
1933
1934
1935
1936
1937
1938
1939
Date
Aquator
WATHNET


[UU] UU Welsh Storage
Reservoir volume [Ml]
200,000
150,000
100,000
50,000
0
1930
1931
1932
1933
1934
1935
1936
1937
1938
1939
Date
Aquator
WATHNET





The second key form of validation for Wathnet was achieved through the Scenario 0 results. These are fully described within Section 6 of the main text, and in all cases the worst historic events within the Drought Configurations matched well with the equivalent storage outputs from the company WRMP14 resource models.

Key Uncertainties and Assumptions

Although Wathnet was only validated for aggregated storage, the uncertainty associated with yield and resilience was relatively minor and the use of Scenario 0 checks further reduced the level of uncertainty. The biggest uncertainty therefore came from the fact that a limited number of drought events were being analysed, and the stochastic droughts had been selected based on an aridity index. However, as noted previously in Appendix B.2, these risks were managed as far as possible by using the outputs in a semi-qualitative fashion for the resilience testing, and by applying expert review when the storage was being analysed for the Tier 3 resource assessment.

Outputs

All of the main Wathnet outputs and findings are incorporated into Sections 6 and 8 of the main Technical Report.

An example matrix output from Aquator is provided in Appendix B.2. Equivalent matrices were produced for all Drought Configurations under the baseline and all three climate change scenarios.

Appendix H. Evaluating consequences of failure (Consequence Models)

Purpose and Core Concepts

The consequence models were created to provide three key pieces of evidence:

A. **NPV comparison of costs and consequences of adopting each of the 36 potential Portfolios generated under the BAU demand management strategy.** This was based on the probability weighted *expected* consequences (in terms of Level 4 failures) that would occur if a given Portfolio, which is based on meeting a certain level of drought resilience (worst historic, severe or extreme) under one of the 12 possible futures, were constructed. This needed to be expressed in NPV terms over 25 years (2015 to 2040) to be comparable with the cost of the Portfolio.

B. **NPV comparison of the costs and benefits of increasing resilience.** This was based on the *expected* reduction in consequences that would occur if planning assumptions are changed so that national water supply systems are built to be resilient to drought planning scenarios beyond the standard 'worst historic' level.

C. **Analysis of the Probability-Consequence Behaviour of each Deficit sub-Region at 2040**. This was based on the *expected* consequences at 2040 that would occur if the current standard planning assumptions are maintained (i.e. worst historic drought resilience, medium growth, median climate change and baseline sustainability reductions). Consequence risks were displayed cumulatively against decreasing probability, and were separated out into 'baseline' drought risk, risk increments associated with a drier climate and risks associated with higher growth and sustainability reductions.

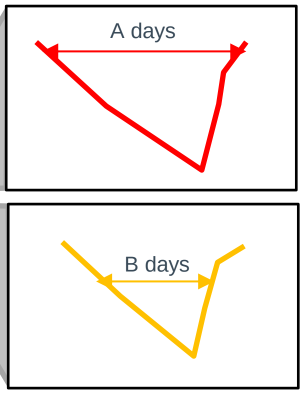
The consequence models that were used for the analysis were therefore based on a number of key criteria that allowed consequences to be expressed in terms of the expected numbers of days that customers would experience Level 2, 3 and 4 demand restrictions, given the different levels of investment and uncertainties in future risks that might occur up to the 2040 period. *The key underlying concept behind the models is that there is an observable relationship between supply/demand deficit and the frequency (annual probability) at which an event of a given consequence will occur*. This was calculated based on the reciprocal of the rate of change in yield according to drought severity, as described below.

Conceptual Illustration of the Deficit-Consequence Relationship

Example outputs of net yield changes according to drought severity – based on SEEL Region Resource Evaluation

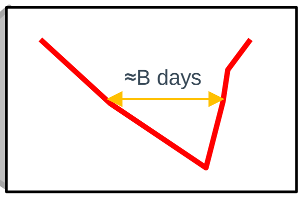
Typical aggregate storage timeseries responses, showing days below L4 trigger threshold

Drought severity	Relative Change in yield (Ml/d)
Extreme Drought	-119
C Severe Drought	-63
Historic Drought	0
1 in 50	214
1 in 33	262
1 in 20	320
1 in 10	357



1. Under a ‘Standard’ planning situation, where supply=demand for a worst historic event, Wathnet/Aquator analysis shows that a ‘Severe’ event would result in a consequence of *A* days of Level 4 failure, and an ‘extreme’ event would result in a consequence of *B* days duration.

Drought severity	Relative Change in yield (Ml/d)
Extreme Drought	-56
C Severe Drought	0
Historic Drought	63
1 in 50	157
1 in 33	205
1 in 20	264



2. If the supply/demand balance is improved so that there is no deficit under a severe event (i.e. the assumed yield of the reservoirs in this region is reduced by 63Ml/d, and alternative resources or demand management are put in place), then there is no consequence at ‘severe’. The consequences when an ‘extreme’ event occurred would be less, much closer to *B* days duration.

Drought lookup	Relative Change in yield (Ml/d)
Extreme Drought	-182
C Severe Drought	-119
Historic Drought	-63
1 in 50	0
1 in 33	214
1 in 20	262

3. However, if a supply/demand deficit is allowed to build, then the reverse happens – L4 events are then expected during a worst historic event, and the duration of consequence for severe and extreme events increases.

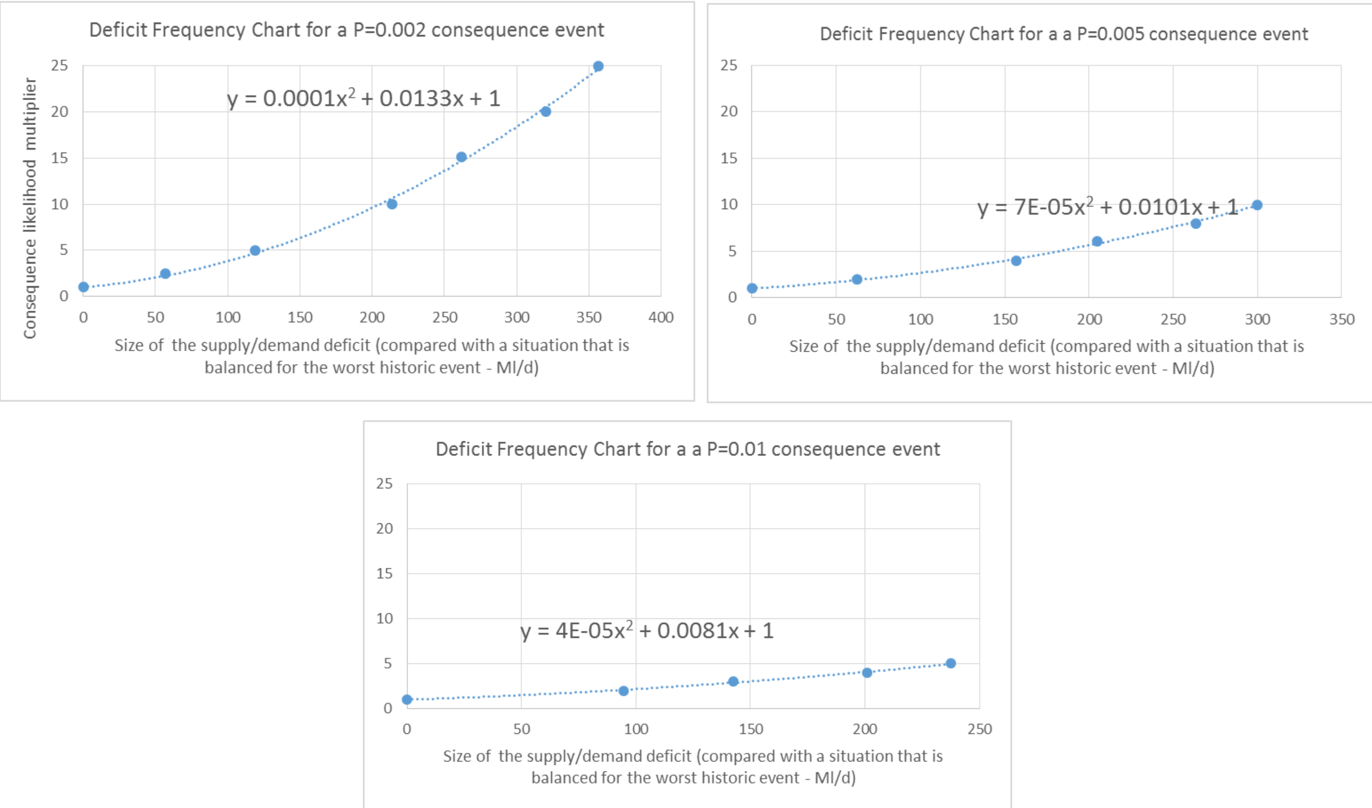
4. Trying to directly use deficit-duration relationships would require highly complex, computationally unrealistic analysis involving multiple thousands of runs of Wathnet or similar. However, it is possible to use the above relationships to re-structure the problem so that it becomes one where the *frequency of occurrence* of a given set of consequence events is analysed according to deficit. To do this, three relationships were analysed, based on the *typical* consequence that would be expected when there is a zero supply/demand deficit (for the worst historic event) and an event equal to the mid-point of the probability ranges that lie between the ‘worst historic’ and ‘severe’, ‘severe’ and ‘extreme’, and beyond ‘extreme’ occurs. These are approximately represented by the following ranges:

    a) Band A: 0.01 > P >0.005
    b) Band B: 0.005> P >0.002
    c) Band C: 0.002 > P

5. The average expected duration for an event within each of these consequence probability bands was estimated from the Scenario 0 Wathnet and Aquator runs, and the variability was expressed as a ratio compared to the expected duration of a 1 in 200 event (P=0.005). **For example**, across the SE excluding London, the mean duration of Level 4 restrictions for a P=0.005 event is approximately equal to 60 days. Examination of the Aquator outputs indicated that, based on this, the average expected duration for each of the above bands was equal to:
    a. Average duration for band A was approx.. 0.33 times the P=0.005 event
    b. Average duration for band B was approx.. 1.33 times the P=0.005 event
    c. Average duration for band C was approx.. 2.33 times the P=0.005 event

6. For each of the above bands, a **Deficit-Frequency Chart** was then drawn which shows how the frequency of occurrence of a ‘typical’ event that starts at the upper end of that band then changes as the supply/demand deficit increases. This is calculated according to the difference in yield (DO) that would need to be allowed for to create the relevant stepped change in occurrence. For example, as shown in step 3 above, if the overall supply/demand balance for SEEL is reduced by 63 Ml/d, then a typical consequence event lasting 60 days would be expected to move from a 1 in 200 frequency of occurrence to a 1 in 100 frequency of occurrence. At the same time, a typical consequence event that lasts 120 days is expected to change from a 1 in 500 frequency of occurrence to something just less than a 1 in 200 frequency of occurrence (63 Ml/d is larger than the 56Ml/d difference between 1 in 200 and 1 in 500, so the change in frequency would be more than this). The Deficit-Frequency charts that were generated based on the observed yield-severity relationships for the SEEL region are provided below. All of the charts have an intercept of 1 (e.g. a P=0.002 consequence event would be expected to occur *once* every 500 years when the supply/demand balance is zero for a worst historic event), and increase in line with the Return Period assessment points included in the resource evaluation (See Section 6 of the main report, and shown in the example tables above).

Figure App-47 Example Deficit Frequency Charts (SEEL sub-Region)



7. These Deficit-Frequency charts can then be combined with the ‘exemplar’ Level 4 duration for a p=0.002 per year event and the duration multipliers for each of the probability bands described in step 5 above to provide an understanding of how the expected consequence for each sub-Region varies according to the relative deficits that might occur under each future scenario, given that a particular Portfolio is built.

There were 12 equally likely ‘futures’ included in the analysis. These included representations of the full range of growth and sustainability reductions scenarios, but did not allow for climate change scenarios that would be wetter than the median. The probability of each future is therefore equal to 1/12 * 0.5 = 0.042. The 0.5 was used because the consequence evaluation works by examining the consequences of future scenarios that are *equal to, or worse than*, the future and level of drought resilience (i.e. the ***scenario***) that a given Portfolio has been constructed for. All climate futures wetter than the median were therefore not covered by the analysis, so an assumption was made that only half of the potential futures were included within the calculations. It was recognised that this was potentially conservative, as some ‘wetter’, but higher growth, higher sustainability futures may have a worse supply/demand balance than the low growth, baseline sustainability, median climate change scenario that formed the most favourable future considered in this analysis. However, trying to include such scenarios would not have changed the conclusions of the study, so this was considered to be an acceptable assumption.

The three probability bands described above were used for the Level 4 failure analysis to allow for more detailed deficit-frequency relationships, and to ensure that the requirements of Objective B (NPV analysis of the cost:benefit ratio of increasing drought resilience) could be met. This meant that 36 scenarios were analysed, each of which represented the given consequences associated with building a particular Portfolio. **All of these Portfolios were taken from the ‘Business as Usual’ (lower) demand management strategy, as these represented the most cost effective method for addressing future supply/demand deficits.** This ensured that the analysis for Objectives A and B focused on the least advantageous set of possible cost:benefit ratios.

Because the potential Level 4 consequences for each 'future' were split into three different bands of consequence probability, care was needed to ensure that the total *expected* consequence outputs did not end up 'triple counting' the associated probability of each future. This was simply done by adjusting the probability of occurrence into bands, as shown in Table App-26 below.

Table App-26 Calculation of the Probability Band Covered by Each Consequence Event

Consequence Severity Calculator				
Band	*Upper bound Return period*	*P(X>x)*	*Probability in band*	*Expected Occurrences in 25 years*
'Extreme' consequence event	500	0.002	0.002	0.05
'Severe' consequence event	200	0.005	0.003	0.075
'Worst historic' consequence event	100	0.01	0.005	0.125

The sum of the probability bands is therefore equal to 0.001, which equals the probability that any event with a frequency less than 1 in 100 would occur in each year under a given future. When the probability of a given set of consequences was being calculated this meant that the probability weighted consequence for a given future could be calculated as:

$$C(x|I_y) = P(x) * (C(Sa|Iy) + C(Sb|Iy) + C(Sc|Iy))$$

Where:

$C(x \mid I_y)$ = total expected consequence of future x, given that Portfolio Y is built

P(x) = probability of future x occurring (0.04 in all cases)

$C(S_a \mid I_y)$ = *expected* consequences of Scenario A (P<0.002 when supply/demand balance = 0) within future x, given that Portfolio Y has been built

$C(S_b \mid I_y)$ = *expected* consequences of Scenario B (0.002 <P<0.005) when supply/demand balance = 0) within future x given that Portfolio Y has been built

$C(S_c \mid I_y)$ = *expected* consequences of Scenario C (0.002 <P<0.005) when supply/demand balance = 0) within future x given that Portfolio Y has been built

For Level 3 'failures' the calculation concept was similar to that described for Level 4 above, but more straightforward. A mean *expected* duration of failure was calculated for all events with P(event) <LoS (LoS = Level of Service frequency, usually either 0.05 or 0.033), and a deficit-frequency analysis was carried in a similar way to the Level 4 failures. Because a single band was used and an average duration assigned, a simple average of the frequency across all futures that were worse than a given scenario could then be taken and assigned as the consequence of that portfolio, multiplied by 0.5 to account for the fact that only half of the futures had been considered in the analysis.

Each of the three objectives required slightly differing applications of the above concepts, which can be described in general terms as follows:

A. NPV Comparison of the Costs and Consequences of Adopting each Portfolio. For each Portfolio a matrix was used to calculate the probability weighted aggregated consequence using the following calculation:

$$Cx = \sum_{x=36}^{x=i} P(x) * \ CS_x \qquad [for\ x \geq \ i]$$

$$+ \sum_{x=i}^{x=1} P(x) * \frac{CS_i}{(i-x)*2} \qquad [for\ 0\ x \leq \ i]$$

Where:

Cx = total consequence for investment Portfolio i

i = the rank of the scenario that is being considered. To do this analysis, all scenarios were ranked in order of increasing supply/demand deficit, so for each Portfolio the consequences of each scenario that is 'worse' are multiplied by the assigned probability of that scenario (0.04 in all cases) and added together. Where scenarios are 'better' than the scenario/Portfolio being analysed, then it was assumed that the consequences halved for each rank above the current (i). This is conservative, but the analysis was not particularly sensitive to that assumption.

$CS_{x} = \left(C(Sax|Ii) + C(Sbx|Ii) + C(Scx|Ii)\right)$ = consequence of event type A, B and C for each scenario, given the Portfolio I has been constructed.

The above calculation provided the expected consequence at 2040. In order to be comparable against the NPV cost of the Portfolio, it was necessary to evaluate the average consequence that would occur across the 2015 o 2040 period. This was done by adjusting the calculation of CS_x so that the frequency multiplier was assumed to be equal to the average between 1 (current day) and the 2040 value.

B. **NPV comparison of the costs and benefits of increasing resilience*.*** The benefit at 2040 was calculated by taking the difference between the expected cumulative consequences (Cx) for the three scenarios (and associated Portfolios) that related to 'standard' future planning assumptions (medium growth, median climate change and baseline sustainability reductions) at the worst historic, severe and extreme levels of resilience. Because the differences in expected consequences between these Portfolios is equal to the expected benefits of changing the level of resilience, this analysis provided the *expected* consequence benefit at 2040. As with Objective A, an NPV calculation of the benefit between 2015 and 2040 was required, so it was assumed that resilience would be built in at approximately the half way point (i.e. 2028) and the benefits of resilience would change linearly between the *current day* expectations and the 2040 value. The benefits of resilience in the *current day* were estimated using a simple probability calculation based on the change in the frequency of occurrence of events in each of the three bands, caused by moving to a zero supply/demand (and hence zero rate of occurrence of consequences) at the P=0.01, P=0.005 and P=0.002 level of drought risk.

C. **Analysis of the Probability-Consequence Behaviour of each Deficit sub-Region at 2040.** The purpose of this analysis was to examine the risk consequences associated with maintaining current planning assumptions right through to 2040. The only separate analysis required for this objective was therefore the calculation of the individual expected consequences of each future (CSx) *given* that a Portfolio is constructed to meet the 'standard' planning assumptions only (i.e. investment is carried out to produce a zero supply/demand balance for the scenario that contains the current planning assumptions of worst historic drought resilience, medium growth, median climate change and baseline sustainability reductions). Once this calculation was done, then the rest of the analysis simply relied on re-ordering the results to allow a cumulative representation of the consequence as they increased according to a reducing level of probability (i.e. as futures became more adverse), and to identify how the introduction of drier climate futures contributed to the total risk as the supply/demand stresses increased, but the probability of the actual future being equal to or worse than a given future decreased.

Methodology

Each of the three objectives were achieved based on the same spreadsheet model, which incorporated the following broad calculation process:

1. Re-structure the supply/demand balance scenario inputs used in the Options appraisal so that all scenarios are ordered according to increasing supply/demand deficit (for the analysed sub-Region)

2. Set up Deficit-Consequence algorithms for the analysed sub-Region, including the estimates of L3 and L4 durations during relevant events, based on the Aquator or Wathnet outputs

3. Set up global assumptions: probability of each future, expected event occurrence under each scenario, number of years in planning period, discount factor

Objectives A and B (consequence NPV &resilience benefits)

4. For each portfolio, set up matrices to calculate the cumulative, probability weighted, expectation of consequence events (Cx) (average between current and 2040)

A4. Generate annual profile for each scenario based on linear change (from current to 2040)

A5. Monetise (incl GVA uplifts to 2040), discount and sum to generate NPV of expected consequence if each Portfolio (equivalent to each scenario) is constructed

A6. Compare NPV of aggregated consequences for each Portfolio against the NPV cost of each Portfolio

B4. Calculate the difference in the cumulative, probability weighted, expectation of consequence events (Cx) between Portfolios designed to meet the worst historic, severe and extreme drought events under 'baseline' planning assumptions. Multiply by 2 to generate values at 2040 (i.e. remove the averaging).

B5. Calculate the benefits from improving current day resilience (simple probability calculation)

B6. Calculate estimated annual consequence benefits between 2015 and 2040 based on linear interpolation

B7. Monetise according to WTP and GVA (incl. GVA uplifts for growth to 2040). Discount and sum for NPV

Objective C (risk-consequence analysis)

C4. Calculate the individual expected consequences of each future (CSx) *given* Portfolio construction designed to meet the standard planning scenario (i.e. the scenario that contains the planning assumptions of worst historic drought resilience, medium growth, median climate change and baseline sustainability reductions)

C5. Use the outputs of the resilience analysis to identify the 2040 risks inherent within the 'baseline' future (i.e. before additional growth, climate change or sustainability reductions have affected the frequency of occurrence of the consequence events)

C6. Re-order other futures to identify the differential cumulative impacts of drier climate change compared with growth and sustainability reductions

C7. Process and generate Risk-Consequence graphs

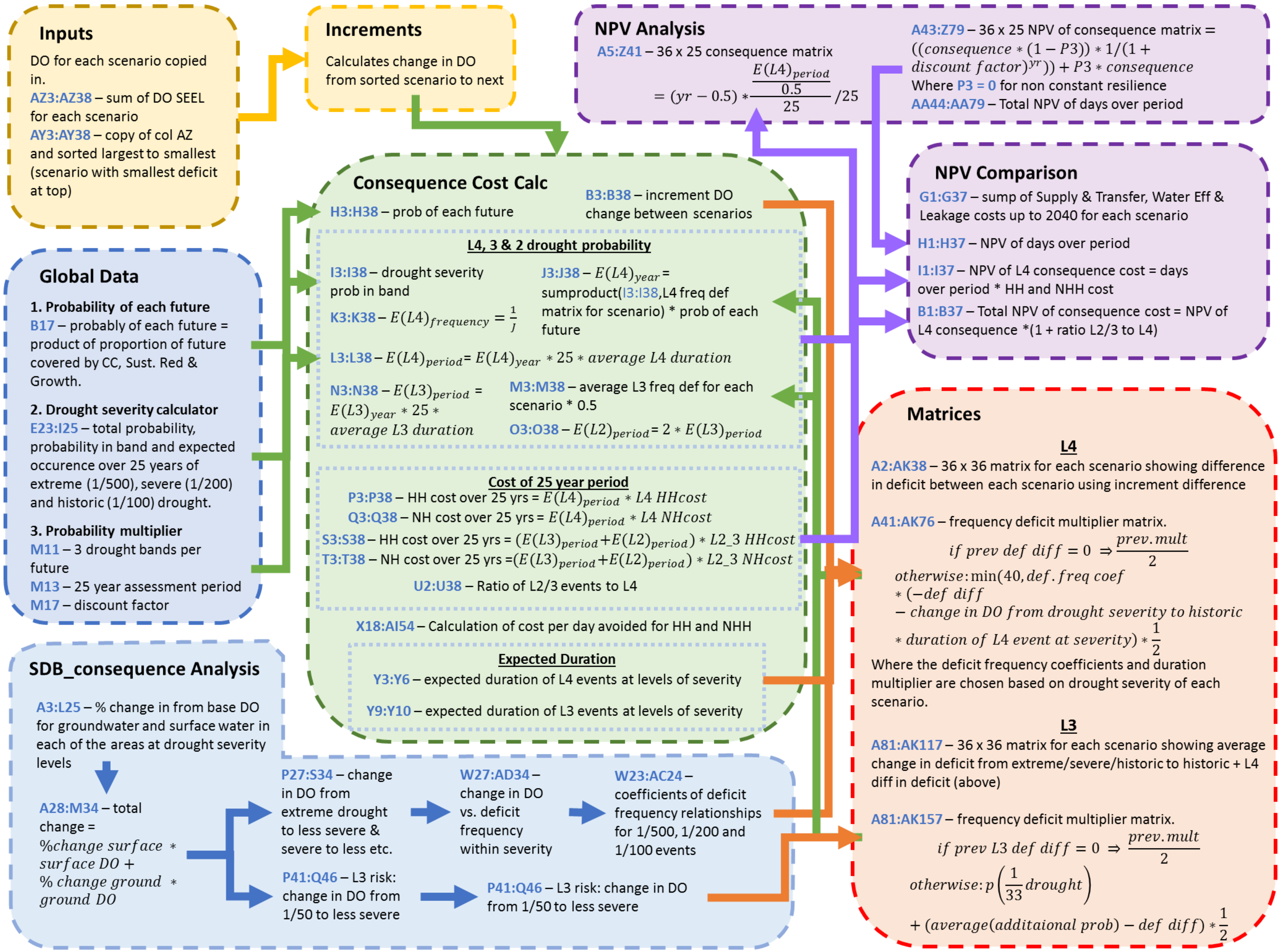
Key points to note in relation to the calculations are:

- The NPV discounting rate was set to be equal to the discounting rate used in the Portfolio cost assessment (4.5%)
- Monetisation was carried out based on the Willingness to Pay values (households) and percentage impact on GVA values (non-households), as described in the main Technical Report Section 7. For households the calculations used medium growth WRZ level population figures for 2040 (as calculated in the SDB calculations for the Options appraisal). For non-households, GVA by SIC code in each WRZ was calculated based on the ONS NUTs 2 database using a GIS based analysis.
- Growth in GVA to 2040 was calculated based on extrapolation of UKCES Bi-Annual forecast data
- The consequences of Level 2 failures were simply calculated by doubling the expected duration of Level 3 failure and then multiplying by the relevant monetising value.

Validation and Checks

A full audit of the spreadsheet was completed by a member of staff not involved in the model creation. The flowchart generated as part of this audit is provided in Figure App-48 below.

Figure App-48 Flowchart of Spreadsheet Calculations



As well as the audit checks, a number of cross-calculations and 'sense checks' were carried out to provide a top down check on model outputs. These included:

- Checks between the total expected Level 3 and Level 4 days for each scenario/Portfolio. Although these were based on different Deficit-Consequence curves, and hence the results varied depending on the deficit and how many 'futures' were worse than the scenario represented by a given Portfolio, logic and analysis of the relative frequency of such events would indicate that the ratio of L3:L4 days should lie within the range of 2 to 3.

- Checks on the consistency between the simple calculation used to estimate the benefits of resilience in the current year, and the more complex calculation used to calculate the probability weighted benefit of resilience in 2040. Although differences were expected, these were not expected to be very large.

- Summary checks on total probabilities of all futures and scenarios.

- Checks on the ratios between NPV totals and aggregate input values to the NPV calculations.

Key Uncertainties and Assumptions

The key uncertainties in the analysis relate to:

- The estimated average duration of failure for Level 3 and 4 events under given levels of drought severity in the baseline condition. Although these were based on Aquator and Wathnet outputs, these only incorporated a small number of droughts and the level of uncertainty is large. However, logic does indicate that the duration during a severe event would be in the order of a few months, so the error is limited to within something in the order of +/-50%.

- The rate at which the frequency of given consequence events varies according to deficit. Although this is based on the detailed resource assessment of the change in yield according to drought severity, there is still a fairly high degree of uncertainty in the charts.

- The monetisation of expected consequences, and in particular:

    - The large range associated with household WTP

    - The percentage of GVA activity affected by different levels of restrictions for different SIC groups, and whether or not potential GVA impacts on non-household customers would materialise as a result of severe demand restrictions being placed on public water supplies.

Because of all of the above uncertainties, the consequence outputs for objectives A and B were analysed based on a range of values. It was found that the case for adopting a fairly cautious planning risk allowance (Objective A) and the case for resilience (Objective B) were still both very strong, even when lower bound values were taken (see Technical Report Section 8).

Outputs

All model outputs are fully contained within Section 8 of the main technical report

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