Approaches to construct scenarios of future water demand

D2 – Future water resources for water intensive energy infrastructure

UK Government

CS-NOW

Climate services for a net zero resilient world

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About CS-N0W

Commissioned by the UK Department for Energy Security and Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5 million research programme that will use the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation ambitions.

CS-N0W aims to enhance the scientific understanding of climate impacts, decarbonisation and climate action, and improve accessibility to the UK's climate data. It will contribute to evidence-based climate policy in the UK and internationally, and strengthen the climate resilience of UK infrastructure, housing and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by **Ricardo** and includes research partners **University College London (UCL)**; **Tyndall Centre for Climate Change Research;** and institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH).

Contents

Executive Summary

A review of future water demand projections in the UK was undertaken to inform the formation of water abstraction and discharge projections for use in work package WPD2 "Future Water Resources for Water-intensive Energy Infrastructure".

The studies featuring demand projections reviewed are:

- water companies' Water Resource Management Plans (WRMP) (Anglian Water, 2019);
- Regional Water Resource Plans (Water Resources East, 2022; Water Resources West, 2022);
- the Environment Agency's (EA) National Framework for Water Resources (2020);
- Water UK's Water Resources Long Term Planning Framework (2016);
- the National Infrastructure Commission's (NIC) future infrastructure report (2018)
- the UK Climate Change Risk Assessment (HR Wallingford, 2020);
- the UK's Shared Socioeconomic Pathways (Pedde et al., 2021);
- the Department for Environment Food & Rural Affairs' (DEFRA) report on future demand outside the water industry (Wood, 2020);
- and the Joint Environmental Programme's (JEP) scenarios for water use in power production (Moores A. , 2022).

These projections have been produced for different purposes, so cover a range of spatial and temporal extents and resolutions, and use different datasets and methods. However, there are also many overlaps between them, with many studies directly informing later work, and various datasets, assumptions, and methods in common.

We make use of the best available information from these studies, and input from stakeholders, to derive future water demand projections which meet the requirements of work package WPD2, namely a small set of coherent, national scale water abstraction and discharge projections up to 2080 that can be used to drive the Grid-to-Grid model (a gridded, distributed 1 km hydrological model). A set of three projections were constructed to capture the range of impacts that artificial influences may have on future river flows and groundwater: an "Economic Growth" scenario which prioritises economic growth over sustainability, a "Business as Usual" scenario which continues current trends and ambitions, and a "Sustainability" scenario which prioritises sustainability.

1. Introduction

The objective of work package WPD2 “Future Water Resources for Water-intensive Energy Infrastructure” includes the generation of time-series of projections of water resources, river flows and groundwater resources (recharge and levels), in England to 2080, accounting for both climate change and future changes in abstractions and discharges.

As part of this, our aim was to produce water abstraction and discharge projections at a national scale up to the year 2080, using mean monthly historical abstraction records (from licensed abstraction data) for the period 2010 to 2014 (inclusive) as a baseline. Many different factors influence water demand, such as population, climate, technology, and environmental awareness; these are combined in a coherent manner to produce a manageable number of future scenarios. The water abstraction and discharge projections generated, will then be combined with 12 UKCP18 regional climate projections, and modelled using a gridded, distributed 1 km hydrological model (Grid-to-Grid) to explore a range of water resource futures.

This report presents the development of future scenarios of surface and groundwater abstractions and discharges, making use of existing research and data where possible. A significant amount of research has already been undertaken to quantify possible future water needs from different sectors under different scenarios. A review of the various scenarios currently available for future water demand in the UK are presented in Section 2, these were used to inform the approach adopted in the context of WPD2 which is presented in Section 3.

2. Review of future scenarios for water demand in the UK

Various aspects of future water demand in the UK has been projected for a range of studies and reports, including:

- as part of water companies' water resource management plans (WRMP) (Anglian Water, 2019);
- by regional water resource groups (Water Resources East, 2022; Water Resources West, 2022);
- the Environment Agency's (EA) National Framework for Water Resources (2020);
- Water UK's Water Resources Long Term Planning Framework (2016);
- the National Infrastructure Commission's (NIC) future infrastructure report (2018)
- the UK Climate Change Risk Assessment (HR Wallingford, 2020);
- the UK's Shared Socioeconomic Pathways (Pedde et al., 2021);
- the Department for Environment Food & Rural Affairs' (DEFRA) report on future demand outside the water industry (Wood, 2020);
- and the Joint Environmental Programme's (JEP) scenarios for water use in power production (Moores A. , 2022).

These projections vary in extent (spatial and temporal), detail, and assumptions, depending on their purpose. The methods used to project future demand depend on the available baseline data (e.g. water meters, abstraction licenses, water usage surveys) and on the type of model (if any) used in each investigation. The models vary in complexity from water balance models, such as the EA's national water resources supply-demand model, which aggregates demand and supply annually, through to the University of Oxford's WATHNET water resources model, both of which are employed by the EA in their National Framework for Water Resources (Environment Agency, 2020). We explore these future water demand projections and methods and use them to inform our work constructing future scenarios of surface and groundwater abstractions and discharges.

A short review of each source of projected water demand is provided in Sections 2.1 to 2.10, and briefly summarised in Section 2.11.

2.1 WATER RESOURCE MANAGEMENT PLANS (WRMPS)

Water companies produce WRMPs every five years, detailing plans to achieve a secure supply of water for their customers while protecting and enhancing the environment over a minimum of 25 years. Each company assesses future water demand and supply for their area, in consultation with stakeholders, regional groups, and regulatory bodies. Each area is split into Water Resource Zones (WRZ) (Figure 1), which are geographical areas with linked supply infrastructure, such that customers in the WRZ experience the same risk of supply failure. These plans inform the future public water supply projections for many of the other projections reviewed here; older studies use the 2014 plans (WRMP14), while more recent studies draw from the 2019 plans (WRMP19). Whilst this review was undertaken, the 2024 plans were underway, however these could not be considered in this review as they were not due to be published before this WPD2 activity had to be completed.

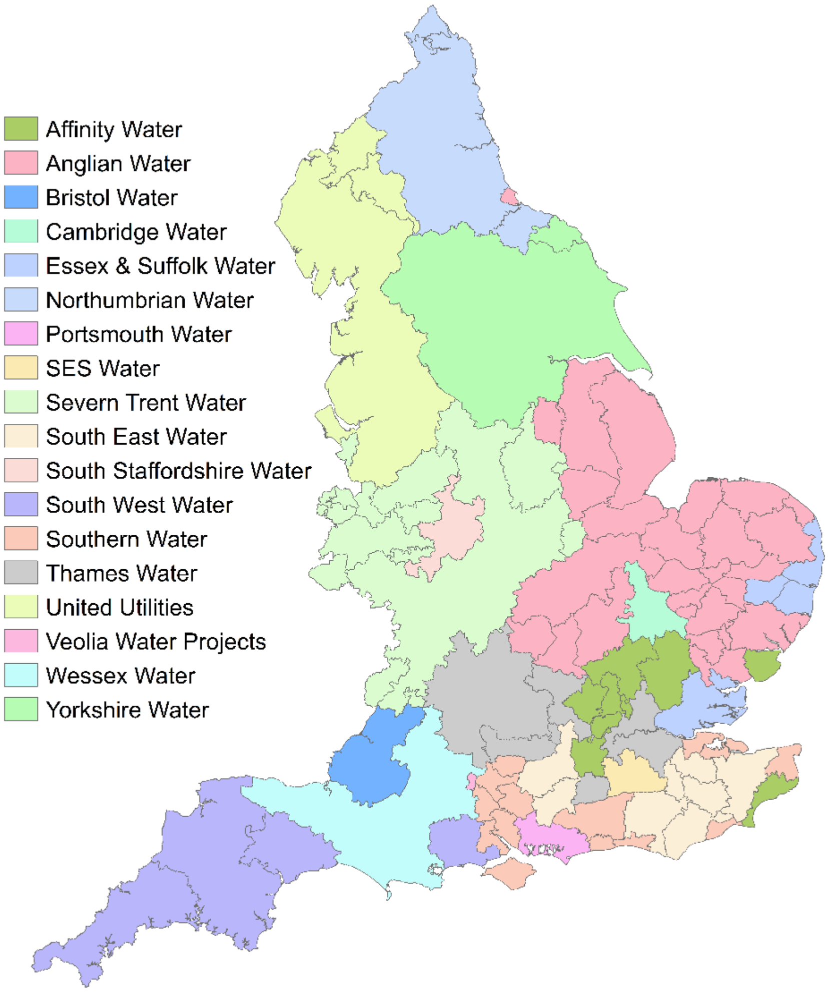

Figure 1 Water Resource Zones in England by water company

According to the Water Resources Planning Guideline published by the UK government (EA, 2020), the demand forecasts included in the WRMP should include estimates of demand from:

- household customers,
- non-household customers,
- water leakage from water company network pipes and that of customers,
- any other losses or uses of water such as water taken unbilled.

Amongst the future water demand projections reviewed in this study, the WRMP projections are generally the most limited in terms of spatial extent (WRZs in the remit of the water company) and temporal extent (statutory minimum period of 25 years; this varies, e.g. Thames Water WRMP extends to 2100). Despite limited temporal and spatial coverage, WRMPs have the highest level of detail for public water supply projections. They typically use a range of sources including the Office for National Statistics (ONS) population projections (Office for National Statistics, 2015), Local Authority/Unitary Authority (LAUA) planning data (e.g. local authority housing targets) and Department of Communities and Local Government (DCLG) household projections (Ministry of Housing, 2012). All the WRMPs provide future projections of water demand, and although there are variations in the assumptions and methods used, these projections have fundamental similarities (i.e. future demand is a function of projected changes in population, water use behaviors, etc.). Therefore, only one WRMP (that of Anglian Water) is presented here in detail to give the reader some idea of the policies and assumptions that are used to forecast water use at a fine spatial scale, particularly with regard to water use behaviors.

Example: Anglian Water's WRMP

In their WRMP19, Anglian Water project a baseline water demand scenario based on changes in population (Cambridge Econometrics, 2019), water use (driven by behavior and device efficiency change), metering, leakage, and climate. Weather is accounted for in these projections by providing a dry year annual average forecast and a peak demand forecast, using uplift factors calculated by comparing per capita consumption (PCC) values in a period of low rainfall and unrestricted demand to average PCC. Sustainability changes and mitigation options for environmental protection are agreed at a local scale in consultation with the EA and accounted for in the supply forecasts. Multiple sources, including the Water Industry National Environment Plan, the Water Framework Directive 2000, the Habitats Directive 1992, the Wildlife and Countryside Act 1981, and EA River Basin Management Plans, inform environmental measures, such as reducing surface or groundwater abstractions at sites where current abstractions were judged to be causing environmental issues (Anglian Water, 2019).

Three strategic demand management options are explored along with the baseline projection, with combinations of specific policy initiatives with targets (leakage reduction and efficiency savings) to be achieved by 2045 in the case of all scenarios but the baseline:

- **Baseline**: continued 'dumb meter' roll-out to 95% of properties, leakage held at 172 Ml/d, current activity continued ('Business as usual' water efficiency activity, the Potting Shed initiative (Anglian Water initiative to provide water efficiency advice to gardeners), communication campaigns).
- **Extended**: 15-year roll-out (from 2020) of Smart Meters to 95% of properties (leading to 50 Ml/d reduction from leakage and behavioural change), 10 Ml/d leakage reduction, and 11 Ml/d water efficiency saving (multi-utility consumption portal, Leaky Loos campaign, Bits and Bobs campaign, free installation of water butts).
- **Extended plus**: 10-year roll-out (from 2020) of Smart Meters to 95% of properties (leading to 51 Ml/d reduction from leakage and behavioural change), 42 Ml/d leakage reduction, and 30 Ml/d water efficiency saving (extended policies plus provision of water butts to certain customers, rebate to replace old toilets, retrofit 'smart devices' such as taps that send data to customer portal).
- **Aspirational**: 10-year roll-out of Smart Meters to 95% of properties (51 Ml/d), 77 Ml/d leakage reduction, and 40 Ml/d water efficiency saving (extended plus policies and provision of water butts to all customers, use of satellite technology to advise customers on garden watering).

2.2 REGIONAL WATER RESOURCE PLANS

Five regional water resource plans are being developed to provide more strategic solutions to future water supply and environmental protection across England, with final plans due to be published in 2023 (see Figure 2 for regional groups). The requirements for these regional plans were agreed through a collaborative process as part of the National Framework (Environment Agency, 2020). Water companies, large water users, local authorities, regulators, environmental groups, and others within each region are working together to ensure sustainable and resilient water resources into the future. These plans draw on the WRMPs to estimate future public water supply (PWS), but also consider non-PWS users, including agriculture, industry, and the environment. Adjustments have been made to PWS forecasts to reflect the changes in demand caused by COVID-19 (observed increases in PCC through 2021), which are likely to extend into the future as working patterns change.

Figure 2 Five regional water resources groups (from Environment Agency 2020)

2.3 THE EA: NATIONAL FRAMEWORK FOR WATER RESOURCES

In their National Framework for Water Resources (2020), the EA estimates future water needs in England, including likely changes to population, and requirements for industry, agriculture, and the environment. The primary model used in the National Framework is the national water resources supply-demand model, a spreadsheet based model which explores the impact of different assumptions around population growth, PCC, water use efficiency etc. Three potential demand management scenarios are considered:

- **'low demand':** includes more ambitious reductions in demand than are currently planned for both household (HH) and non-household (non-HH) through water efficiency.
- **'central demand':** is the central scenario designed to represent the ambition in current WRMPs.
- **'high demand'**: explores a scenario where the demand and leakage reductions being planned for are not achieved.

Numbers given in Table 3 (e.g. 50% leakage reduction) are for the period 2020 to 2050 and assumed to get there in a linear manner, using the WRMP19 data for the baseline values.

In addition to these scenarios, some high-level analysis on the impacts of changing environmental protections on water resources was undertaken using the EA's Water Resources Geographical Information System (WRGIS) database. This estimates water resources by combining natural flows with artificial abstractions and discharges, to determine the abstraction recovery necessary to meet the Environmental Flow Indicator (EFI) in all water bodies under a range of future scenarios:

- **'Business as usual':** continuing to protect the same percentage of natural flows.
- **'Enhanced':** greater protection for Protected Areas and Sites of Special Scientific Interest (SSSI) rivers and wetlands, by applying the most sensitive flow constraints to these areas.
- **'Adapt'**: lower protection in some heavily modified waterbodies (HMWB).
- **'Combined'**: a combination of the above scenarios, balancing greater protection for Protected Areas and SSSI rivers and wetlands with a view that good status (as defined under the Water Framework Directive) cannot be achieved everywhere in a shifting climate.

The EA report also explores future climate impacts on national water availability under a large number of climate change scenarios by combining the Weather@home2 (w@h2) modelling framework (Guillod, et al., 2017); a national hydrological model DECIPHeR

(Coxon, et al., 2019); the WaSIM irrigation model (Hess, 1996); and the WATHNET Water Resources Model.

The WATHNET Water Resources Model was initially developed under the NERC-funded MaRIUS project (2014-2020) and has been progressively developed and updated in cooperation with UK water industry practitioners, regulators, consultancies, etc.; becoming the Water Resources Model of England and Wales (WREW) (Slaughter, et al., 2021). It was used in the Water Resources Long Term Planning Framework (Water UK, 2016) (Section 2.4), the National Framework study, and the National System Simulation Modelling (NSSM) project (Section 2.10).

2.4 WATER UK: WATER RESOURCES LONG TERM PLANNING FRAMEWORK

In their long-term (2015-2065) planning framework, Water UK undertake a long-term, national scale analysis of future water supply and demand, to provide a strategic view of future public water needs and drought risks and resilience (Water UK, 2016). A total of 36 future scenarios were considered, a product of two environmentally driven abstraction changes (estimations based on the principals in the DEFRA document (DEFRA, 2016)); three population growth forecasts (Office for National Statistics, 2015); two climate change scenarios from the Future Flows dataset (UKCEH, 2012); and three levels of drought resilience (using drought configurations based on historic records and artificially generated drought events using a stochastic drought weather generator). They then apply four different demand management scenarios to these futures:

- **'Business as Usual' (BAU) – Upper**: this represents the situation that would occur if water companies continue with their current policies and methods for reducing demand, but the societal and policy support for demand management is low, i.e. WRMP14 measures to reduce PCC and leakage are ineffective. This does include an assumption of improvements in device efficiency and therefore a slight reduction in PCC over time.
- **'Business as Usual' (BAU) – Base**: as above, but with a greater degree of societal and policy support, i.e. WRMP14 proposed savings are achieved.
- **Extended**: this represents an ambitious extension to demand management, incorporating initiatives such as the use of differential tariffs to help reduce demand.
- **Enhanced**: this represents a 'step change' in demand management, incorporating initiatives such as grey water re-use and much tighter controls on water efficient design for new households. It accounts for the most ambitious water savings that should be

feasible technically and economically, but considerably more expensive than other strategies.

Changes in water use efficiency (PCC and leakage) are estimated through a linear regression of the WRMP14 target values, and assume a greater efficiency improvement in regions with higher starting PCC values and loss rates.

The water resource analysis was undertaken using a range of methods. For smaller surface waters and groundwater, a basic, data-driven approach was used based on WRMP14 technical data, aridity indices for the drought configurations, and expert judgement on percentage impact of historic drought. For larger, strategic surface water sources, the WATHNET model was used, with input from various rainfall-runoff models or regression analysis.

2.5 THE NATIONAL INFRASTRUCTURE COMMISSION (NIC): PREPARING FOR A DRIER FUTURE: ENGLAND'S WATER INFRASTRUCTURE NEEDS

The NIC report, 'Preparing for a drier future: England's water infrastructure needs' (National Infrastructure Commission, 2018), investigates future water balances under a range of droughts, and a twin-track approach of demand management (including leakage reduction) and investment in supply infrastructure to improve national drought resilience into the future. Future water balances in 2050 are modelled using the National Infrastructure Systems Model (NISMOD) under a range of scenarios, combining projected baseline water demand in line with Water UK's 'Business as Usual' scenario, with different population growth, climate change, and drought resilience options:

- **Population**:
  - Low - ONS 2014-based low migration population projection
  - High - ONS 2014-based high fertility population projection
- **Climate Change:**
  - Central – medium emission Future Flows (Prudhomme et al., 2012), average water balance scenario
  - Dry - medium emissions Future Flows, with less water in the South East
- **Drought:**
  - 1% annual chance, corresponding to a 1 in 4 probability of occurrence by 2050
  - 0.5% annual chance, corresponding to a 1 in 7 probability of occurrence by 2050
  - 0.2% annual chance, corresponding to a 1 in 17 probability of occurrence by 2050

These options were combined with BAU water use efficiency to calculate supply-demand balance.

A cost efficiency analysis was undertaken for various demand management options, such as increased water metering and leakage reduction, and supply side options, such as additional transfers and water storage. Based on this work, recommendations were provided to Ofwat and DEFRA, intended to feed into WRMPs.

2.6 THE UK CLIMATE CHANGE RISK ASSESSMENT: PROJECTIONS OF FUTURE WATER AVAILABILITY FOR 3RD UK CLIMATE CHANGE RISK ASSESSMENT

The 2020 report, 'Updated projections of future water availability…', by HR Wallingford for the third UK Climate Change Risk Assessment (CCRA3) (2020) provides a set of UK-wide water availability projections up to 2100. These projections were required to be: spatially coherent; consistent with the latest WRMPs; use the UKCP18 climate projections and be consistent with 2°C / 4°C global warming by 2100; use the socio-economic dimensions developed by Cambridge Econometrics (2019), and to consider adaptation, relative contribution of climate change and socio-economic factors, and sensitivity. A total of 21 scenarios are assessed, one baseline, and 20 combinations of time slices (mid-century and late-century); future climates (2°C / 4°C change considering 50th percentile of different climate model combinations); population changes (no change, central and high projections (Cambridge Econometrics, 2019)); environmental flow options (current protections maintained as proportion of flows or as an absolute value); and three water demand adaptation options:

- **No Additional Action (NAA)**: no interventions from water companies, slight reduction in PCC (as new houses are all metered), leakage maintained at 2019 levels, and non-PWS use scaled with regional population (baseline figures from WRGIS).
- **Current and Announced (C+A)**: interventions currently planned by water companies for PCC and leakage reduction are implemented but no other changes are made, non-PWS as in NAA.
- **Additional Adaptation (AA)**: further interventions are implemented in addition to those currently planned by water companies, PCC reduces according the "Enhanced" scenario from Water UK (2016), leakage reduced according to current and announced interventions then further reduced to 10% (of 2019 Distribution Input) by 2100, non-PWS demands change according to "Sustainable Regionalisation" scenario for industry and power, and "Sustainable Globalisation" for agriculture (Wood, 2020).

2.7 UK SHARED SOCIOECONOMIC PATHWAYS: UK-SSP SEMI-QUANTITATIVE TRENDS

Shared Socioeconomic Pathways (SSPs) are a set of potential future trajectories of societal development, considering factors such as changes in population, urbanisation, economic growth, and technological development. They are designed to be complementary to the four Representative Concentration Pathways (RCPs), which provide information on potential future radiative forcings, to allow for coherent future climate modelling at all scales. Developed for the IPCC Sixth Assessment Report (AR6), there are five SSP narratives (SSP1-5), describing broad socio-economic trends (IPCC, 2021):

- **SSP1, 'Sustainability'**: focus on sustainability, low consumption and population growth, effective international cooperation, reduced inequality.
- **SSP2, 'Middle of the Road'**: continuation of historical trends (slow progress towards sustainability, decreasing consumption, moderate population growth, continued inequality).
- **SSP3, 'Regional Rivalry'**: focus on domestic issues and security, low economic growth, variable population growth (low in rich countries, high in other countries), poor international cooperation, high inequality.
- **SSP4, 'Inequality'**: increasing disparity in economic opportunity and political influence, high consumption, variable population growth (low in rich countries, high in other countries), high inequality.
- **SSP5, 'Fossil-fuelled Development'**: focus on competitive markets and innovation, high consumption, low population growth, effective international cooperation, reduced inequality.

These SSPs have been interpreted for the UK by Pedde et al. (2021), to give semi-quantitative trends for 50 socio-economic variables up to 2100 including water abstraction. Future abstraction is considered holistically by combining changes in demand (e.g. behavioural change) and supply (e.g. supply management) across all water users, for example, for SSP1 water abstraction in the UK is deemed to decrease from current levels due to increased water use efficiency and increased rainwater harvesting and water recycling. The semi-quantitative trends are presented as a set of arrows representing three time slices (present to 2040; 2040 to 2070; and 2070 to 2100) indicating high increase; modest increase; no change; modest decrease; and high decrease compared to the present, and are UK wide.

2.8 DEPARTMENT FOR ENVIRONMENT FOOD & RURAL AFFAIRS (DEFRA): UNDERSTANDING FUTURE WATER DEMAND OUTSIDE OF THE WATER INDUSTRY

Current and future water demand outside the water industry (i.e. non-PWS) was investigated at a national scale to support the National Framework for Water Resources (Wood, 2020). In this work, three water use sectors were considered: agriculture, industry, and electricity generation. These sectors were prioritised since, between them, they are estimated to account for >60% of non-PWS consumptive freshwater abstractions nationally. Existing data and literature are combined with targeted stakeholder engagement to provide an assessment for these sectors of current and future factors affecting water use, knowledge gaps, and estimated growth factors (where possible). Growth factors were estimated for three industrial subsectors, namely, food and drink, chemicals, and paper and pulp; and for spray irrigation. A "best estimate" growth factor was determined for each subsector by combining the influence of different water demand drivers weighted by their likelihood (based on current trends and expert judgement), along with 25th and 75th percentile growth factors (based on estimated uncertainties of each driver). In addition, growth factors were calculated for the industrial and agricultural subsectors under four future socio-economic scenarios:

- **Sustainable Regionalisation (SR):** Focus on regional issues (security, regional markets and economy), users adopting low-tech, local water, waste and energy solutions to reduce dependence on national utilities.
- **Sustainable Globalisation (SG):** Focus on globalisation and sustainability, efficient and new technologies to reduce carbon and water use.
- **Uncontrolled demand, Regionalisation (UR):** Focus on regional issues and economic growth, highly consumptive lifestyles and a lack of global trade cause competition for natural resources.
- **Uncontrolled demand, Globalisation (UG):** Focus on globalisation and economic growth, highly consumptive lifestyles.

For the power sector, a "best estimate" growth factor was reported along with an upper and lower factor, based on previous work by the EA and Byers *et al*. (2014). The complexities and uncertainties associated with future water use in the power sector mean that the process used to derive growth factors for the industrial and agricultural sectors could not be applied to the power sector. This data gap has since been addressed by the JEP report on projections for water use in electricity production (Moores A. , 2021) discussed in Section 2.9.

2.9 JOINT ENVIRONMENTAL PROGRAMME (JEP): PROJECTIONS OF WATER USE IN ELECTRICITY AND HYDROGEN PRODUCTION TO 2050

In the JEP report, consumptive freshwater use in the power sector is modelled up to 2050 under eight possible future scenarios, which outline different pathways to achieving Net Zero (i.e. balancing greenhouse gas emissions with an equal quantity of carbon dioxide removal from the atmosphere) in the power sector. To address the inherent uncertainty about new power plant types and locations and closures of existing sites in the future, a Monte Carlo simulation framework, utilising simple rules, is used to select individual plant types and locations required to meet the optimal plant mix for a given scenario. Results are then presented at a regional scale with confidence intervals around the median Monte Carlo output. The study considers water used for cooling, which does not need to be of potable quality, and high-quality water required in power generation. The high-quality water may be sourced from non-HH PWS, a separate abstraction, or a third part supplier (e.g. industrial use). This study is solely focused on freshwater use in the power sector, and therefore does not consider water demand from any other sectors.

Of the eight possible future scenarios, four are based on the "Future Energy Scenarios" released by the National Grid ESO (2020):

- **Consumer Transformation (CT):** Net Zero is achieved in 2050 through consumer transformation, such as behavioural change, electrified heating, and high energy efficiency.
- **System Transformation (ST):** Net Zero is achieved in 2050 through system transformation, such as hydrogen for heating and supply side flexibility.
- **Leading the Way (LW):** the 'fastest credible decarbonisation' pathway, Net Zero is achieved before 2050 through a combination of lifestyle change and hydrogen and electrified heating.
- **Steady Progression (SP):** the 'slowest credible decarbonisation' pathway, Net Zero is not achieved before 2050, with minimal behavioural change and decarbonisation in power and transport but not heating.

The other four scenarios are based on the "UK's path to Net Zero" published by the Climate Change Committee (2020), all of which achieve Net Zero by 2050, by different mechanisms:

- **Headwinds (HW):** behavioural shifts and development of technology is in line with current projections, so there is a greater reliance on large hydrogen and carbon capture and storage infrastructure to achieve Net Zero.

- **Widespread Engagement (WE):** greater societal and behavioural change than in HW, reducing demand for high-carbon activities and increasing uptake of climate mitigation measures.
- **Widespread Innovation (WI):** greater technological development than in HW, allowing more widespread electrification, a more energy efficient economy, and more cost-effective carbon removal technologies.
- **Tailwinds (TW):** high levels of technological innovation and societal/behavioural change, so Net Zero is achieved before 2050.

2.10 THE REGULATOR'S ALLIANCE FOR PROGRESSING INFRASTRUCTURE DEVELOPMENT (RAPID): THE NATIONAL SYSTEM SIMULATION MODELLING (NSSM) PROJECT

The NSSM project was commissioned by RAPID and undertaken by a team comprising Oxford University, Ricardo, the University of Bristol, the EA, and DHCR (RAPID, 2021; 2022). This work builds on the National Framework for Water Resources, further developing the WREW model to more accurately represent water resources in England and Wales. This model is then used to explore potential supply side solutions to future water requirements at a national scale, including large regional and inter-regional options such as transfers, reservoirs, and effluent reuse, as well as policy decisions such as water demand management. The first phase (RAPID, 2021) focuses solely on supply side solutions, keeping water demands fixed (at 2020-21 values from WRMP19), so is not reviewed here. The second phase (RAPID, 2022) investigates the resilience and benefits of various supply side solutions in 2050, but does so under different climate change and water demand futures. Nine scenarios were used:

- **Central:** a reference scenario representing the regional water resources management plans, including estimated PWS demand in 2050 for the dry year annual average climate scenario assuming 50% leakage reduction from 2017/18 and PCC of 110 l/h/d, irrigation demand determined by the WaSIM model, other non-PWS demands from historic data (average abstraction over 1999 and 2015 from the EA’s national abstraction and returns database, NALD). Reductions in abstractions for environmental protection are based on the environmental destination specified in the regional plans. River flows and groundwater levels are forced by the near future ensemble of the w@h2 dataset (100 x 30-year, 2020-2050, forced with RCP8.5 emissions scenario).

- **Sensitivity, high ambition environmental destination:** similar to the central scenario, but with abstraction reductions for the "Enhanced" environmental scenario from the National Framework.
- **Sensitivity, high public water supply demand:** similar to the central scenario, but with estimated PWS demands assuming only 50% reduction in leakage and PCC targets are achieved.
- **Sensitivity, far future climate change:** similar to the central scenario, but with river flows and groundwater levels forced by the far future ensemble of the w@h2 dataset (100 x 30-year, 2070-2099, forced with RCP8.5 emissions scenario).
- **Stress test scenarios:** a set of four scenarios akin to the central one, but with different combinations of supply side solutions.

2.11 SUMMARY

A short summary of water demand projections described in the previous sections and their associated drivers is presented in Table 1. This table summarises which drivers are considered in each projection, and at what temporal and spatial extent and resolution. A more detailed compilation of these projections is presented in Table 3 in the Appendix, including short descriptions of the data and values used. Future supply is also considered in these projections and have been included in Table 3 for completeness. Primary drivers of future supply are climate change, drought resilience, and environmental protection. Since these drivers can also affect water demand, the impacts on water supply are also listed. The UK-SSP study has been excluded from Table 3 due to its qualitative nature.

It can be seen from Table 1 and Table 3 that, while a range of future water demand projections exist, many extend only to 2050 and are often limited to England, and for those that extend further into the future, various water demand drivers are often fixed at 2050 levels. The projections differ according to their purpose, for example, WRMPs are regularly produced to ensure water supply for consumers so focus on PWS at high spatial resolution and short time scale; the Water Resources Long Term Planning Framework considers a national view on public water needs so includes PWS at a national and a longer-term scale; while the National Framework for Water Resources has a national, long-term perspective with the addition of including water needs for sectors outside PWS.

Many of the projections are explicitly linked, with data, models and methods shared between them; and many make use of the same underpinning datasets (e.g. population change from ONS (2015) or Cambridge Econometrics (2019)). For PWS, WRMPs provide baseline data (for at least some of the scenarios and drivers) for most of the regional and national studies on PWS, such as the Water Resources Long Term Planning Framework, the National Framework, and regional water resource plans; although it is often necessary to change some aspects (such as population projections) to ensure spatially coherent projections. In turn, national studies provide a strategic assessment of future water needs which informs the next round of WRMPs.

In general, future PWS demand has been investigated in more depth, and has more detailed current and historical data available, compared to other sectors (a thorough review of the knowledge gaps and uncertainties in current and future non-PWS use is available in Wood (2020)). Non-PWS is highly localised, and any future projections face the question of if and how to forecast new instances of water demand (e.g. a newly built power plant). With these twin challenges, a certain level of uncertainty in forecasts of non-PWS demand is generally accepted and are often estimated at a low spatial resolution using simple scalings or regressions.

Agricultural demand, particularly irrigation, has a high dependence on the climate. Some studies (the National Framework and the NSSM project) allow for this by modelling irrigation demand using WaSIM, however, this makes the demand projections specific to the climate scenario used and does not account for future changes in irrigation habits. Other studies apply scaling factors or regressions, which neglects climate dependence but maintains the independence of the projections. There are limitations with both methods.

Table 1 Summary of drivers considered in future water demand projections reviewed in this work

				PWS				Non-PWS		
Study name/type	**Author**	**Year end**	**Spatial extent & resolution**	**Population**	**PCC**	**Leakage**	**Non-HH consumption**	**Industry**	**Energy**	**Agriculture**
WRMP19 (2019)	Water companies	2045-2100*	Water company area; WRZ	✓	✓	✓	✓	·	·	·
Regional water resource plans* (2022)	Regional water groups	2050-	Regional; WRZ	✓	✓	✓	✓	✓	✓	✓
National Framework for Water Resources (2020)	EA	2050	England; WRZ	✓	✓	✓	✓	✓	✓	✓
Water Resources Long Term Planning Framework (2016)	Water UK	2065	England and Wales; WRZ	✓	✓	✓	✓	·	·	·
Preparing for a drier future: England's water infrastructure needs (2018)	NIC	2050	England; water company area	✓	✓	✓	✓	·	·	·
Projections of future water availability for 3rd UK Climate Change Risk Assessment (2020)	HR Wallingford	2100	UK; WRZ	✓	✓	✓	✓	✓	✓	✓

Study name/type	Author	Year end	Spatial extent & resolution	PWS				Non-PWS		
				Population	PCC	Leakage	Non-HH consumption	Industry	Energy	Agriculture
UK-SSP Semi-quantitative Trends (2021)	Pedde et al.	2100	UK; UK	✓	✓	✓	✓	✓	✓	✓
Understanding Future Water Demand Outside of the Water Industry (2020)	Wood Environment & Infrastructure Solutions UK Limited	2050	England; England	.	.	.	.	✓	✓	✓
Projections of water use in electricity and hydrogen production (2021)	A. Moores	2050	England, WRR	.	.	.	.	.	✓	.
The National System Simulation Modelling Project (2022)	RAPID	2050	England and Wales; WRZ	✓	✓	✓	✓	.	.	✓

* Regional emerging water resource plans and WRMPs have been amalgamated for brevity, so the final year of those projections has been given as a range.

3. Our approach to constructing the scenarios

3.1 AIM

The eFLaG (enhanced Future Flows and Groundwater) project has produced a set of national, spatially consistent hydrological projections up to 2080 based on the UKCP18 12km, 12 ensemble member 'regional' climate projections (Moores, 2021). This work builds on that to produce hydrological projections up to 2080 accounting for artificial influences, i.e. the net impact of water abstractions and discharges. These hydrological projections will be produced using the Grid-to-Grid model (a gridded, distributed 1 km hydrological model) driven by the UKCP18 12km, 12 ensemble member regional dataset and a range of water abstraction and discharge projections.

The water demand projections developed for this study use mean monthly historical abstraction records (recent actual abstractions for the period 2010 to 2014 inclusive) as a baseline and must work within the gridded representation of these abstraction data in Grid-to-Grid. A particular challenge is how to extend current projections up to 2080. Due to budget and time restrictions, three set of scenarios were derived. While some driving datasets extend to 2080, e.g. population projections, others do not, e.g. the non-PWS growth factors reported by Wood which extend to 2050 (Wood, 2020). The EA is currently extending the water demand projections used in their work on the Water Resources National Framework (2020) out to 2100; to ensure a consistent approach between these studies, similar methodologies are employed.

3.2 THREE SCENARIOS

To capture the range of impacts that artificial influences may have on future river flows and groundwater, 'upper' and 'lower' demand projections are constructed along with a 'central' projection. These projections combine drivers in a coherent manner to give an indication of sensitivity to different assumptions; they should not be considered upper and lower limits of future abstractions. These demand projections are named as follows:

- **Upper, "Economic Growth", scenario:** economic growth is prioritised over sustainability, no water efficiencies, high population growth, continued use of fossil fuels and water-intensive agriculture (e.g. high meat consumption and increase of irrigated area), and some relaxation of environmental considerations.
- **Central, "Business as Usual", scenario**: current ambitions for water efficiency are achieved with no further efficiencies, best-estimate population growth, a move to green energy production consistent with current projections, and environmental protections kept at current levels.
- **Lower, "Sustainability", scenario**: sustainability is prioritised, high levels of water efficiency are achieved, low population growth, innovation and societal change to achieve Net Zero energy production ahead of schedule, reduction in meat consumption and food waste, additional environmental constraints.

These scenarios have been informed by the existing water demand projections reviewed in Section 2, drawing upon the existing data and research, and were developed in discussion with the EA and others. In particular, where there was a choice of several equally likely scenarios from existing datasets, stakeholders were consulted on the selection. For example, there are two potential "Business as Usual" scenarios for future power production (Moores A. , 2022), "Consumer Transformation" and "System Transformation", and stakeholders opted for "System Transformation" in this work. In a similar manner, the "Uncontrolled demand, Regionalisation" growth factors for agriculture and industry (Wood, 2020) were selected for the "Economic Growth" scenario, and "Sustainable, Regionalisation" growth factors for the "Sustainability" scenario.

For each water demand sector, spatial and temporal resolution are at the finest scale possible given the available data, while maintaining overall coherence and consistency. Details for each scenario are presented in Table 2, with discussion in the following Sections.

Table 2 Three water demand projections

	PWS				Non-PWS			
Scenario	**Population** (Cambridge Econometrics, 2019)	**PCC**	**Leakage**	**Non-household**	**Industry** (Wood, 2020)	**Energy** **JEP** (Moores A. , 2022)	**Agriculture** (Wood, 2020)	**Environment**
Upper “EG”	High scenario	127 l/p/d by 2050, fixed 2050-2080	30% reduction in leakage by 2050	Current estimates scaled with local population and PCC change	“Uncontrolled demand, Regionalisation” growth factor	Freshwater use for FES21 scenario “Steady Progression”	“Uncontrolled demand, Regionalisation” growth factor	HoF maintained at current levels (model results processed to inform future HoF limits)
Central “BaU”	Central scenario	Final Plan PCC from WRMP19, fixed at final value	Final Plan leakage from WRMP19, fixed at final value	Current estimates scaled with local population and PCC change	Best estimate growth factor	Freshwater use for FES21 scenario “System Transformation”	Best estimate growth factor	HoF maintained at current levels
Lower “Sus”	Low scenario	110 l/p/d by 2050, fixed 2050-2080	50% reduction in leakage by 2050	Current estimates scaled with local population and PCC change	“Sustainable, Regionalisation” growth factor	Freshwater use for FES21 scenario “Leading the Way”	“Sustainable, Regionalisation” growth factor	HoF maintained at current levels (model results processed to inform future HoF limits)

3.3 PUBLIC WATER SUPPLY (PWS)

Future changes in population, PCC, leakage, and non-household use should all be considered when projecting PWS demand. To apply these changes to the current baseline data (mean monthly PWS abstraction), they are converted to scaling factors, taking into account the different end points of PWS. To illustrate this, future PWS is calculated as:

$$PWS_{t+1} = \left(a_{leakage} S_{leakage} + a_{HH} S_{HH} + a_{nonHH} S_{nonHH}\right) \times PWS_t$$

Where PWS_t is PWS at time t; $a_{leakage}$, a_{HH}, and a_{nonHH} are the fraction of PWS that are attributed to, respectively, leakage, household demand and non-household demand respectively at the start of the projections (t=0); and $S_{leakage}$, S_{HH}, and S_{nonHH} are scaling factors representing changes in leakage, household demand and non-household demand, respectively, over the time-step. It is assumed that $\left(a_{leakage} + a_{HH} + a_{nonHH}\right) = 1$, which is a simplifying assumption that neglects some minor components of PWS.

The scaling factors for each scenario are detailed in Table 2. For each scenario, $S_{leakage}$ was chosen to match the low, central, and high scenarios used in the EA's National Framework (detailed in Table 3). Change in population and PCC are combined in S_{HH}. Population change is derived from the high, central, and low population change estimates from the Cambridge Econometrics Dataset (2019), and changes in PCC were chosen to match the EA's National Framework.

It is assumed that S_{nonHH} will vary with local population change and PCC. Non-household use covers a wide variety of water users; many will vary their water demand with changes in local population and PCC (e.g. local services will likely expand with an increasing local population, but also reduce water use with the more efficient water use behaviours and technological improvements which drive PCC change), however, other users will be influenced by other factors. The assumptions used here for S_{nonHH} are reasonable for a national level assessment.

These scaling factors are applied annually at the WRZ level to the baseline abstraction data (see Section 3.8). Since the scaling factors are applied to monthly baseline data, any seasonal variation in PWS is maintained into the future. However, no consideration is made for climatic conditions (e.g. if a climate scenario shows hotter summers and more frequent droughts, PWS demand will not increase during these periods to reflect this). This is a significant limitation, since the supply-demand balance during droughts is of critical importance for future planning, but it does mean that these projections are independent of the climate scenario used which gives them greater flexibility regarding future use.

3.4 NON-PWS

The primary users of freshwater outside PWS are hydropower and aquaculture. Since these are non-consumptive, they can be generally ignored, and focus is placed instead on industry, agriculture, and power production, which are the biggest consumers of water outside of PWS. Nationally, these demands are much smaller than PWS abstractions, but they can be significant in specific catchments and seasons, for example, demand for spray irrigation in summer in parts of East Anglia. There is greater uncertainty associated with projecting non-public water demand, due to a lack of data on historical demand and to their highly localised nature. There is also the challenge of co-dependency, for example, accurate future water demand for power production requires locations of new power production facilities, and site decisions for these plants will be dependent in part on predicted future water availability.

A report on future changes in non-PWS demand was produced by Wood (2020) to support the Water Resources National Framework, and provides national growth factors up to 2050 for all significant consumptive water users (outside of PWS). We use these values to project non-PWS demand for industry and agriculture (see Table 2 for details). As discussed in Section 3.11, using a growth factor for agriculture (particularly irrigation) neglects any dependence on climate. While abstraction for irrigation will still have a seasonal pattern in our projections (from the monthly baseline abstractions over a five year average), they will not vary with climate. We have chosen this method to maintain independence between these demand projections and the climate projections.

A range of scenarios for future consumptive water demand for energy production has been modelled in a study for the Joint Environmental Programme (2020), using a Monte Carlo simulation framework and simple ‘rules’ to handle uncertainties regarding placement and production type of future energy production sites. The median of predicted freshwater use has been projected up to 2050 nationally and is used to scale future demand, with the simplifying assumption of no site closures or openings. This data was used to produce scaling factors for power production in our projections (see Table 2 for details).

Projections in non-PWS are implemented in a similar manner to PWS, with scaling factors applied to associated abstractions as determined by their use codes, but at a national level.

3.5 ENVIRONMENTAL PROTECTION CONSIDERATIONS

It is necessary to consider the changes in environment-driven abstraction limits into the future to gain an accurate projection of water abstraction. The Grid-to-Grid model allows for a hands-off flow (HoF) limit to surface water abstraction, which is the most intuitive representation of environmental protection for the purposes of this study. However, since the HoF limits are applied to abstraction points, it is challenging to identify potential future changes to HoF, i.e. while it may be known that a water body requires additional environmental protection it may not be clear which abstractions these should be applied to, and to what degree. To avoid this uncertainty, we propose that current HoF limits are retained for all scenarios, and additional environmental protections are considered by analysing the influenced flow rates output by the model simulations. By comparing future river flows and surface water abstraction demand, we can inform decisions on the possible locations and volumes of new HoF limits. This method has the added benefit of being able to consider a range of future HoF conditions under specific climate scenarios.

There is no inbuilt mechanism within Grid-to-Grid to limit groundwater abstraction for environmental purposes. This could be addressed in the water demand projections, e.g. the balance of surface and groundwater demand could be altered to reduce groundwater abstraction, but it was decided not to implement this given the uncertainties involved.

3.6 SUPPLY SIDE – TRANSFERS AND RESERVOIRS

A number of inter- and intra-basin water transfers currently exist in England, and future transfers could be built to help supply water and increase drought resilience. There is no current representation of water transfers in the Grid-to-Grid model. The presence of transfers could be accounted for in this work by altering the water demand data prior to modelling, for example, by moving a fraction of water demand from a transfer destination to the transfer source. However, this is not a dynamic solution and could result in an unrealistic transfer of water from an area of scarcity to an area of surplus. Therefore, it is recommended that the model results be used to provide evidence for potential future water transfers rather than representing transfer explicitly. Possible future reservoirs will not be considered since there is no representation of reservoirs within the Grid-to-Grid model at present, this is a current limitation of the model which therefore extends to the present scenarios produced.

3.7 DISCHARGES

It is important to consider how future discharges will be modelled, since return flows from water recycling centres (WRCs, also known as sewage treatment works or wastewater treatment works), can be a significant contributor to flow in some rivers.

For the available discharge consent data, most discharges have a purpose recorded which can be used to assign discharges to the same water use sectors as the abstraction data. The discharges are scaled with the same factors as the abstractions at whatever spatial scale is used for the abstractions. Discharges related to PWS (e.g. those with a purpose or site name indicating they are from a WRC), are scaled similarly to PWS but with adjustments to remove the effects of leakage change. This scaling is applied locally, i.e. discharge points are scaled by the factor relevant to the WRZ they are located in. Many discharge purposes are ambiguous or missing, or related to uses which have no obvious scaling factor (e.g. fish farm, trade, private WRC), for the purpose of this study these will be kept constant. Discharges in these categories make up 20% of the total discharge volume.

Applying a scaling factor to current discharges is a simplifying assumption that does not allow for new WRC's or other discharge points to be built, or old ones to be closed or relocated.

3.8 SCENARIO SPECIFICATIONS

All the scenarios are derived from the 1 km gridded baseline artificial influenced data: mean monthly historical surface and groundwater abstractions, and discharges. The abstraction data is split into sectors (PWS, industry, energy, agriculture) according to the water-use information in the abstraction licence. Scaling factors are applied at the finest resolution available. Spatially, the grid will be subset as required for the different spatial resolutions of different sectors, e.g. if a sector has a national scaling factor then this will be applied to all the grid, if the scaling factor varies by WRZ then the specific scaling factor will be applied to the grid cells covered by each WRZ. Temporally, annual scaling factors are applied, with interpolation between specified time slices where necessary (note that the future demand projections have a monthly time step, since the annual scaling factors are applied to monthly baseline data).

The final product is three datasets for each scenario (surface water abstraction, groundwater abstraction, and discharge), on a 1 km grid over England, at a monthly time step from the present to 2080.

4. CONCLUSIONS

A set of three water abstraction and discharge projections have been produced for use in work package WPD2 “Future Water Resources for Water-intensive Energy Infrastructure”, one prioritising economic development, one following a “Business as Usual” approach, and one prioritising sustainability. These projections are at a national scale up to 2080 (at a monthly time-step with annual scaling) and consider a range of water users: PWS, industry, agriculture, and power production.

These projections draw upon the best information available from existing work and projections (reviewed in Section 3), as well as expertise from stakeholders. Drivers for future PWS were derived from the Cambridge Econometrics population forecasts (2019), and per capita consumption and leakage reduction ambitions in line with the National Framework for Water Resources (Environment Agency, 2020). Growth factors for industry and agriculture were drawn from the investigation into non-PWS water users (Wood, 2020) which also informs the National Framework, and scaling factors for the power sector were derived from the JEP’s investigation into water use in power production (Moores A. , 2021).

In general, it was possible to include a higher level of detail in the projections of PWS (i.e. variation at a higher temporal and spatial resolution) compared to non-PWS, due to the higher volume of quality data and analysis that has been undertaken in that area. Non-PWS sectors were projected using a national scaling factor at an annual time-step, and for industry and agriculture the temporal variation was assumed to be linear up to 2050. The projections are more detailed in the near future (generally up to 2050), and tend to remain fixed beyond that point, with the exception of population change. This reflects the increasing uncertainty of projections as they move further from the present.

Appendix

Table 3 Overview of existing future water demand projections in the UK. The impacts on water supply are listed in italics.

Study name	Purpose	Year end	Spatial extent & resolution	Population	Per Capita Consumption (PCC)	Leakage	Non-household consumption	Non-public water supply	Climate	Environment	Drought
WRMP19 (Anglian Water, 2019)	WRMP – to secure water supply to customers while protecting the environment. Baseline future & three demand management options: extended, extended plus, aspirational	2045	East England; WRZ	Combination of ONS, LAUA, & DCLG data on population & household occupation	Baseline: BAU, Extended: 11 Ml/d reduction, Extended plus: 30 Ml/d reduction, Aspirational: 40 Ml/d reduction. Dry year uplift factor calculated by comparing reference dry year to average PCC.	Baseline: 172 Ml/d, Extended: 10 Ml/d reduction, Extended plus: 42 Ml/d reduction, Aspirational: 77Ml/d reduction. Additional reduction in all demand management options of 28Ml/d from Smart Metering	Regression models by sector, using historical billing data for non-household properties and future forecasts of population, GVA and employment per sector	-	Annual percentage change factors applied to household demand, from UKWIR report (2019) *Using UKCP09 Spatially Coherent Projections, high, medium, and low.*	*Sustainability changes & mitigation options applied.*	*Severe drought resilience (1:200) used as reference drought, 1:500 also considered*
Regional water resource plan (Water Resources East, 2022)	Emerging regional water resource plan to ensure sustainable and resilient water resources – six demand	2050 +	East England; WRZ	Aligned with WRMPs, with an uplift for increased local housing completions and modifications for	Baseline: no impact from demand management options, potential for future increase, High: 10-1% reduction by 2050, >1%	Baseline: no reduction beyond 2025, High: 50% reduction by 2050 & >2% every 5 years	Included in PCC assessment. Baseline: no reduction, High: ~15% reduction by 2050, no	Agriculture Baseline: 190 Ml/d, Upper: +220 Ml/d, Lower: +59 Ml/d by 2050 (2022) Energy:	Used to estimate irrigation increase (assumed). *UKCP18 projections applied.*	*Multiple EA scenarios modelled.*	*1:500 year drought resilience*

Study name	Purpose	Year end	Spatial extent & resolution	Population	Per Capita Consumption (PCC)	Leakage	Non-household consumption	Non-public water supply	Climate	Environment	Drought
	scenarios and three environmental			COVID-19 effects	reduction every 5 years 2050-2100 (includes non-household savings)	from 2050-2100	change 2050-2100	Baseline: 61 Ml/d, Upper: +181 Ml/d, Lower: -38 Ml/d by 2050 (Knox et al., 2018)			
Regional water resource plan (Water Resources West, 2022)	Emerging regional water resource plan to ensure sustainable and resilient water resources	2085	West England; WRZ	Aligned with WRMPs	110 l/p/d by 2050	50% reduction by 2050	Best estimate future from Econometric multi-linear regression model (factors include COVID-19 impact, Brexit, HS2, population change)	Best estimate future consumptive demand for all non-PWS (agriculture, industry, energy, etc.) derived from Econometric multi-linear regression model.	*UKCP18 projections applied.*	*Aligned with WRMPs*	*1:500 year drought resilience*
National Framework for Water Resources (Environment Agency, 2020)	Estimate of future water needs (FW), and three demand reduction scenarios (low, central, high)	2050	England; WRZ	High population change used. Low and central projections used to investigate uncertainty (Cambridge Econometrics dataset(2020))	FW: fixed at 2025 estimation (average 132 l/h/d). Low, central, high: adjust WRMP19 scenarios to achieve an average of 110, 119, 127 l/p/d respectively	FW: 19% reduction in 2017/18 levels by 2025 (from planned investments in WRMP19), no change beyond 2025. Low: 50% reduction	FW: from WRMP19, little change. Low: 4% reduction Central: no change High: no change	'best estimate', & 'upper' scenarios. Focus on primary consumptive users: spray irrigation, livestock, protected edible and ornamental plants, electricity	1% increase in (all?) demand assumed. *FW: climate change from WRMP19 (mostly UKCP09 medium emissions scenario) Additional analysis using ensembles from*	*Upper level sustainability reduction from WRMP19 used. Additional scenarios also investigated: business as usual, enhanced, adapt.*	2% reduction in household demand during a 1:500 event (assumed Temporary Use Ban).

Study name	Purpose	Year end	Spatial extent & resolution	Population	Per Capita Consumption (PCC)	Leakage	Non-household consumption	Non-public water supply	Climate	Environment	Drought
					(based on Water UK report(2019))	Central: reduction from WRMP19 High: 30% reduction		production, food and drink, paper and pulp, chemicals manufacturing from wood (2020)). No regional variation, no change applied to livestock or protected edible and ornamental plants.	*Weather@home2 modelling framework*		*Drought resilience raised to 1:500 event.*
Water Resources Long Term Planning Framework (Water UK, 2016)	Focus on drought resilience. Three population growth futures (lower, medium, upper) and four demand management options (BAU upper, BAU base, extended, enhanced)	2065	England and Wales; WRZ	Lower, medium, upper forecasts from ONS 2014	Slight decrease for unmeasured properties PCC for all demand management options (assume device efficiency improvement). Each option has different: changes in measured properties	Varied in demand management options using linear regression of WRMP14 targets. Distribution losses and underground supply pipe losses considered separately.	Medium: Extrapolated from WRMP14, lower: adjusted down 20%, upper: adjusted up 20%	-	*'Dry' and 'median' climate scenarios using Future Flows dataset (2015)*	*Two scenarios: 'baseline', and 'extended', based on reduction suggested in NEP5 (5th phase of the National Environment Programme)*	*Three scenarios for drought resilience: historic (worst drought on record); severe (1:200 event in SE); extreme (1:500 event in SE)*

Study name	Purpose	Year end	Spatial extent & resolution	Population	Per Capita Consumption (PCC)	Leakage	Non-household consumption	Non-public water supply	Climate	Environment	Drought
					PCC based on linear regression from WRMP14; assumed PCC for new builds; and increase in number of properties metered.						
Preparing for a drier future: England's water infrastructure needs (National Infrastructure Commission, 2018)	Drought resilience – baseline demands (Water UK's BAU), combined with scenarios: two population growth; two climate change; three drought resilience	2050	England; company scale	Low: low migration, High: high fertility ONS 2014	In line with Water UK's BAU scenario	In line with Water UK's BAU scenario	In line with Water UK's BAU scenario	-	*'Central' and 'dry' scenarios based on Future Flows (2015)*	-	*Same as Water UK scenarios*
Projections of future water availability for 3rd UK Climate Change Risk Assessment	Water availability projections to inform CCRA3, three demand scenarios	2100	UK; WRZ	No change, central & high scenarios (Cambridge Econometrics	NAA: fixed at 2019 levels; C+A: planned interventions; AA: additional intervention	NAA: fixed at 2019 levels; C+A: 50% reduction by 2050, fixed 2050-2100; AA:	Aligned to WRMPs up to 2045, fixed 2045-2100	Industry & commerce, agriculture, energy considered. NAA & C+A: baseline figures from	*UKCP18 global projections*	*Proportional environmental flow requirement limits maintained*	*1:500 year drought resilience*

Study name	Purpose	Year end	Spatial extent & resolution	Population	Per Capita Consumption (PCC)	Leakage	Non-household consumption	Non-public water supply	Climate	Environment	Drought
(HR Wallingford, 2020)				dataset(2020))	s ("Enhanced-03" Scenario (2019) to 2065 then fixed)	50% reduction by 2050, 10% of distribution input by 2065, fixed 2065-2100		CCRA2 scaled with regional population; AA: percentage change value from 'sustainable' scenarios (2019) scaled to regional population.			
Understanding Future Water Demand Outside of the Water Industry (Wood, 2020)	Improving understanding of current and future water demand outside of the water industry.	2050	England, England	-	-	-	-	Growth factors by 2050 as % of baseline for industry (food and drink, paper and pulp, chemicals manufacturing), spray irrigation, & power: best estimate, upper & lower range; also under four scenarios: SR, SG, UR, UG	*Climatic drivers considered where relevant (e.g. impact of hotter summers on soft drink production)*	-	-
Projections of water use in electricity and	Consumptive water use for eight future	2050	England, WRR	-	-	-	High quality water consumption	Consumptive freshwater use for power production	-	-	-

Study name	Purpose	Year end	Spatial extent & resolution	Population	Per Capita Consumption (PCC)	Leakage	Non-household consumption	Non-public water supply	Climate	Environment	Drought
hydrogen production (Moores A. , 2021)	energy production profiles						considered for each scenario – could be sourced from PWS, direct abstraction, or third party supply	for eight scenarios: CT, ST, LW, SP from(2020), and HW, WE, WI, TW from (2020)			
The National System Simulation Modelling Project (RAPID, 2022)	To examine the benefits and resilience of supply side solutions under different climate and water demand futures.	2050	England and Wales; WRZ	Based on the regional water resources management plans	Central:110 l/h/d in 2050; High demand: midway between	Central: 50% reduction from 2017/18 in 2050; High demand: 25% reduction	Based on the regional water resources management plans	Average abstraction over 1999 and 2015 from NALD; irrigation modelled by WaSIM	*Central: near future ensemble from w@h2 (100 x 30-year, 2020-2050, forced with RCP8.5), Far future climate: far future ensemble (2070-2099)*	*Central: environmental destination specified in regional water resources management plans; High ambition environmental destination: "Enhanced" environmental scenario from the National Framework*	*Impact of drought events in the w@h2 ensembles analysed in each scenario*

5. REFERENCES

Anglian Water. (2019). *Water Resources Management Plan 2019.* Anglian Water.

Anglian Water. (2019). *WRMP 2019 Technical Document: Sustainable Abstraction.* Anglian Water.

Artesia. (2019). *Pathways to long-term PCC reduction.* Water UK.

Byers, E., Hall, J., & Amezaga, J. (2014). Electricity generation and cooling water use: UK pathways to 2050. *Global Environmental Change*, 16-30.

Cambridge Econometrics. (2019). *A consistent set of socioeconomic dimensions for the CCRA3 Evidence Report research projects.* Cambridge: Cambridge Econometrics.

Climate Change Committee . (2020). *The Sixth Carbon Budget - The UK's path to Net Zero.* https://www.theccc.org.uk/publication/sixth-carbon-budget/.

Coxon, G., Freer, J., Lane, R., Dunne, T., Knoben, W. J., Howden, N. J., . . . Woods, R. (2019). DECIPHeR v1: Dynamic fluxEs and ConnectIvity for Predictions of HydRology. *Geoscientific Model Development*, 2285-2306.

DEFRA. (2016). *UK Government response to consultation on reforming the Water Abstraction Management System.*

Dobson, B., Coxon, G., Freer, J., Gavin, H., Mortazavi-Naeini, M., & & Hall, J. W. (2020). The Spatial Dynamics of Droughts and Water Scarcity in England and Wales. *Water Resources Research*, 56.

Environment Agency. (2020). *Appendix 4: Longer term environmental water needs.* Environment Agency.

Environment Agency. (2020). *Meeting our future water needs: a national framework for water resources* . Bristol : Environment Agency.

Gasparino, U., & Edwards, N. A. (2021). *Projections of Water Use in Electricity and Hydrogen Production to 2050, under the 2020 Future Energy and CCC Scenarios including BEIS 2020 lowest system cost analysis – with a focus on the East of England.* RWE Generation UK for the Joint Environmental Programme, Energy UK.

Guillod, B. P., Jones, R. G., Bowery, A., Haustein, K., Massey, N. R., Mitchell, D. M., . . . and Allen, M. R. (2017). Weather@home2: Validation of an improved global-regional climate modelling system. *Geoscientific Model Development*, 1849-1872.

Hannaford, J., Mackay, J., Ascott, M., Bell, V., Chitson, T., Cole, S., . . . Wilcox, A. (in review, 2022). eFLaG: enhanced future FLows and Groundwater. A national dataset of hydrological projections based on UKCP18. *Earth Syst. Sci. Data Discuss.*

Hess, T. (1996). A microcomputer scheduling program for supplementary irrigation. *Computers and Electronics in Agriculture*, 233-243.

HR Wallingford. (2020). *Updated projections of future water availability for the third UK Climate Change Risk Assessment.* HR Wallingford.

Knox, J., Haro, D., & Hess, T. (2018). *Task 2 Agricultural demand forecasts (Part II): future demand. Final Technical Report.* Cranfield University for WRE.

Ministry of Housing. (2012). *Live tables on household projections.* Retrieved from https://www.gov.uk/government/statistical-data-sets/live-tables-on-household-projections; retrieved 14/09/2023

Moores, A. (2021). *Projections of Water Use in Electricity and Hydrogen Production to 2050, under the 2020 Future Energy and CCC Scenarios – Regional Analysis.* RWE Generation UK for JEP.

Moores, A. (2022). *Scenarios for the projection to 2050 of Water Use by Power Producers - updated using FES21.* JEP.

National Grid ESO. (2020). *Future Energy Scenarios.* https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2020-documents.

National Infrastructure Commission. (2018). *Preparing for a drier future: England's water infrastructure needs.* National Infrastructure Commission.

Office for National Statistics. (2015). *2014-based National Population Projections for England & Wales.* Office for National Statistics.

Pedde, S., Harrison, P. A., Holman, I. P., Powney, G. D., Lofts, S., Schmucki, R., . . . Bullock, J. M. (2021). Enriching the Shared Socioeconomic Pathways to co-create consistent multi-sector scenarios for the UK. *Sci Total Environ., 756*, 143172.

RAPID. (2021). *The National System Simulation Modelling (NSSM) Project, Phase 1 Report.* RAPID.

RAPID. (2022). *The National System Simulation Modelling (NSSM) Project Phase 2 Report.* Ofwat.

Slaughter, A., Harou, J. J., Tomlinson, J., Matrosov, E., Wilson, J., Dennis, J., & Read, M. (2021). *A water supply-demand model for England and Wales.* RAPID.

UKCEH. (2012). *Future flows climate data.* NERC Environmental Information Data Centre. (Dataset). https://doi.org/10.5285/bad1514f-119e-44a4-8e1e-442735bb9797 .

UKWIR. (2013). *Impact of Climate Change on Water Demand - Main Report.* UKWIR.

Water Resources East. (2022). *The Emerging Water Resources Regional Plan for Eastern England.* Water Resources East.

Water Resources West. (2022). *Emerging Regional Plan.* Water Resources West.

Water UK. (2016). *Water resources long term planning framework (2015-2065).* Water UK.

Wood. (2020). *Understanding future water demand outside of the water industry.* London: DEFRA.