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Water and climate risks to power generation with carbon capture and storage

E A Byers[1], J W Hall[2], J M Amezaga[1], G M O'Donnell[1] and A Leathard[1]

[1] School of Civil Engineering & Geosciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK
[2] Environmental Change Institute, University of Oxford, Oxford, OX1 3QY, UK

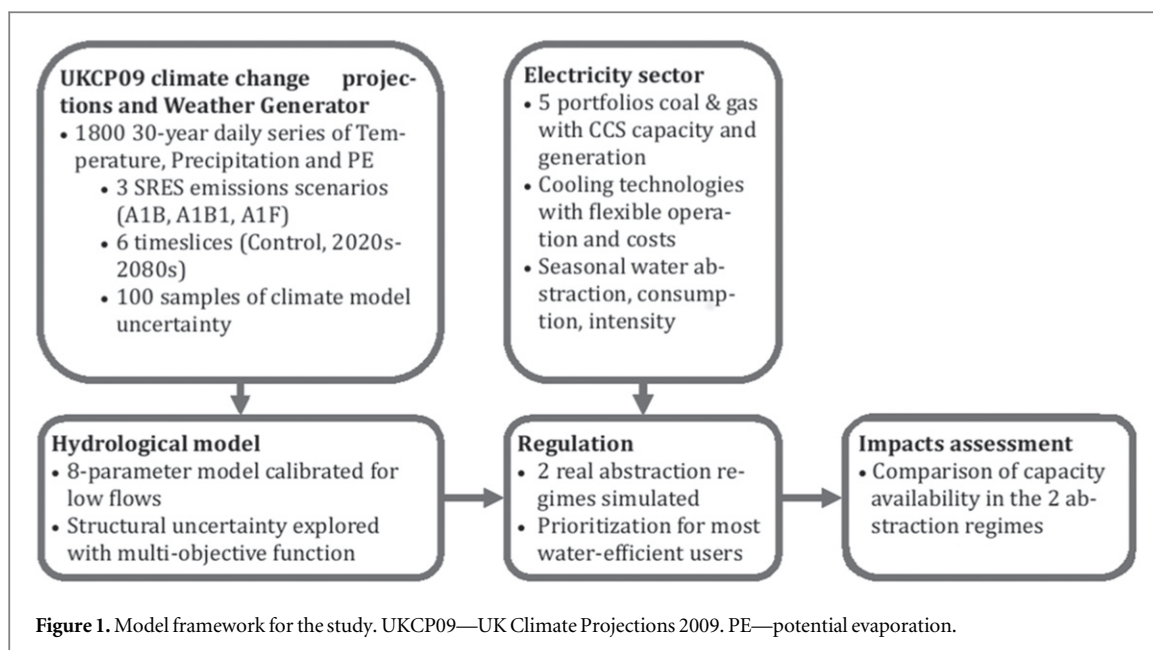**E-mail:** byers@iiasa.ac.at

Abstract

Carbon capture and storage (CCS) provides the opportunity to minimize atmospheric carbon emissions from fossil fuel power plants. However, CCS increases cooling water use and few studies have simulated the potential impacts of low flows on CCS power plant reliability. We present a framework to simulate the impacts of natural hydrological variability and climatic changes on water availability for portfolios of CCS capacity and cooling technologies. The methods are applied to the River Trent, the UK's largest inland cooling water source for electricity generation capacity. Under a medium emissions climate change scenario, the projected median reductions in river flow by the 2040s was 43% for $Q_{99.9}$ very low flows and 31% in licensable abstractions between $Q_{99.9}$ and Q_{91}. With CCS developments, cooling water abstractions are projected to increase, likely exceeding available water for all users by the 2030s–2040s. Deficits are reduced when wet/dry hybrid tower cooling is used, which may increase reliability at low flows. We also explore alternative water licensing regimes, currently considered by the UK Government. Climate change and growing cooling demands, individually and jointly present risks that will be prominent by the 2030s, if unaddressed. These risks may be managed if water-efficient abstraction is prioritized when supplies are limited.

1. Introduction

Carbon capture and storage technology (CCS) offers significant potential to mitigate greenhouse gas emissions from coal, gas-fired or biomass electricity generation, although it has not yet been commercialized on a scale greater than 120 MW$_e$. Coal contributes 44% of global energy-related emissions, with consumption expected to increase 50% by 2040 [1]. However, carbon capture is an energy-intensive process resulting in parasitic loads and reductions of net thermal efficiency output on a power plant, that can increase cooling water use in the order of 90% (ranging between 44% and 140%) [2–4]. In the EU, all new power stations above 300 MW$_e$ must be 'CO$_2$ Capture Ready', by ensuring there are sufficient space and retrofit provisions for when the technology becomes commercially viable [5, 6] (EU Directive 2009/31/EC). It is likely that *CCS clusters* of power stations and

high carbon emissions industries (like cement production) will be established, in order to reduce the costs of CO$_2$ compression and transport infrastructure and lower barriers to market entry. Hence, the pressure on local water resources in these areas will likely be exacerbated [7, 8].

One barrier to CCS development is the confidence that the increased cooling water demands can be met, especially at times of low flows. Climate change is expected to impact on future patterns of rainfall and evaporation, with climate models indicating possible changes to the mean, variance and seasonality of rainfall and evapotranspiration. In the UK, amongst many other places, hotter and drier summers are expected with implications for water resource availability [9–11]. Reducing the dependency on freshwater for cooling is an important step towards increasing resilience of generation capacity to expected impacts of climate change, such as low flows, droughts and higher

Figure 1. Model framework for the study. UKCP09—UK Climate Projections 2009. PE—potential evaporation.

streamflow temperatures [12–21]. Whilst a number of studies have made important contributions towards simulating hydrology and power sector water use [8, 22–27], few consider the impacts of CCS in detail. Similarly, very few studies thoroughly explore uncertainties in hydrological and climate models through simulation [28–31]. Methods for the use of probabilistic climate projections in risk-based water resources management and planning are also developing [32–34], and need to be applied to this area.

The aim of this paper is to determine, through simulation at the catchment level, how portfolios of high-CCS electricity capacity may be impacted by low flows as a result of hydrological variability, climate change and changes in the regulation of water abstractions. Through our use of probabilistic climate projections and simulation of the regulatory regimes, this work demonstrates the use of advanced water resource planning methods for investigating water use by the power sector. We test this on the River Trent in the East Midlands and Humber area of the UK, a region expected to have considerable CCS development [35] and that is projected to be impacted by climate change in ways that are uncertain but may increase the frequency of low flows.

1.1. Framework
For consistency with the UK regulatory context, we use the UK term *water abstraction* to describe the withdrawal of water from a water body, of which *water consumption* is the volume abstracted but not returned to the waterbody. Collectively, these are primarily referred to as *water use*, apart from in hypothetical instances where it is uncertain whether the *water demands* of a user will be met.

The general framework (figure 1) describes the structure and implementation of this study: (i) probabilistic projections of future climate and hydrology,

(ii) projections of future electricity capacity, generation and cooling water use, (iii) simulation of abstractions under alternate abstraction regimes and (iv) assessment of capacity availability under low flows. Together these components allow the estimation of the probability of insufficient licensed cooling water according to the physical water availability, simulated under a variety of hydroclimatic, technological and regulatory conditions.

Interactions between these natural and technological systems are governed by a range of policy and regulation instruments, both directly and indirectly. For example: regulation of abstractions determines the water availability for different water users and the regulator has influence over cooling system choice [36]; wider subsidies for CCS or gas technologies may drive changes in technology choice, subsequently altering water use by the electricity sector.

1.2. UK study context
In the UK, currently 63% of the thermoelectric generation capacity is located on rivers, two-thirds of which is on non-tidal freshwater reaches. From 2007–2011, around 200 000 Ml yr^{-1} of freshwater was abstracted by thermoelectric power stations, of which approximately 60% was consumed [7, 37]. This has likely decreased in recent years, due to the decommissioning of 11 GW$_e$ of less efficient plant under the EU large combustion plant directive (LCPD, 2001/80/EC). However, the consumption of freshwater from thermal power could rise considerably with widescale adoption of CCS, with potentially a doubling of freshwater consumption from 2010 levels by 2050 [7, 35, 38, 39]. Similar projections of increasing water use in high CCS scenarios have also been reported for the United States [40].

The UK Government CCS roadmap has encouraged development of a CCS cluster in the East
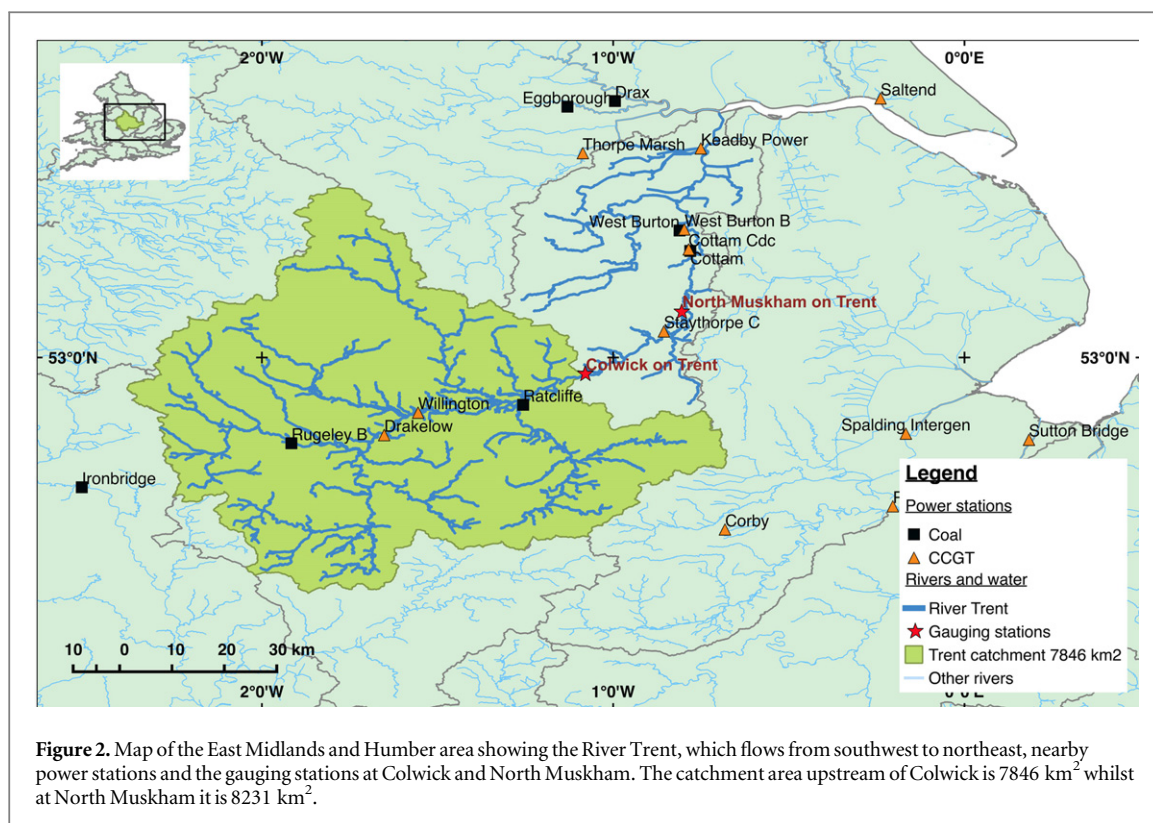
Figure 2. Map of the East Midlands and Humber area showing the River Trent, which flows from southwest to northeast, nearby power stations and the gauging stations at Colwick and North Muskham. The catchment area upstream of Colwick is 7846 km^2 whilst at North Muskham it is 8231 km^2.

Midlands [41, 42], possibly using the River Trent as a cooling source. The Trent has been an important cooling water source in the UK since the 1940s, with ten concurrently operational plants in the 1970s. Currently the Trent supports the most generation capacity of any river in the UK, with 4.65 GW$_e$ on freshwater stretches, and 8 GW$_e$ on stretches with tidal influence (figure 2). Already consented plans could potentially bring the capacity on freshwater to 7.87 GW$_e$ within a few years [43].

This study focuses on potential freshwater-cooled power plants, upstream of Colwick gauging station, the hydrological point of focus for this study. The tidal reach of the Trent extends to a weir located at North Muskham (28 km downstream of Colwick), 60 km south the Humber estuary.

Whilst the current abstraction and licensing regime in England and Wales has mostly worked well for over 30 years, the UK Government intends to reform the current system by 2020. The two new regimes under consideration, *Current System Plus* (CSP) and *Water Shares,* are intended to be more dynamic and responsive: to facilitate water trading; to adapt to pressures such as climate change and population growth; and to soften the abrupt thresholds at which hands off flow (HOF) restrictions on abstraction are imposed [44, 45].

HOF levels are commonly used by water and environmental regulators around the world (often referred to as *environmental flows, instream flows, minimum flows* [46]) to limit abstractions when river discharge falls below a threshold level. This ensures

that sufficient resources are available downstream for economic and environmental purposes. In England and Wales, the rules for setting these thresholds are generally the same, with the resulting values being calculated according to the historical flow record. The proportion of flow embargoed from abstraction is known as the minimum residual flow (MRF), typically set at 75% of the naturalized 99.9% exceedance percentile daily flow, $Q_{99.9}$ [47]. The proportion of naturalized flows available for abstraction is determined primarily by the abstraction sensitivity bands and environmental flow indicators [48, 49]. Once this volume has been licensed to abstractors, further volumes can be licensed but abstraction can only take place when higher flows are available. For example, HOF1 is often set at a flow level between Q_{90} and Q_{95}, respectively flow levels that have been exceeded 90% and 95% of the time. A license with a HOF condition subsequently has less security of supply that may not be acceptable to some industries.

Both of the new regimes under consideration will maintain the principle of HOFs. However, abstractors will be expected to reduce abstractions on a graduated basis as opposed to abruptly in the current system, before reaching the HOF and MRF levels, in what is termed a *soft-landing* approach [47]. The aim is to enable sustainable water abstraction that reacts to changing flow conditions when flows are between HOF levels. The MRF and HOF levels set by regulation are critical to the availability of water for all users, including the power sector.
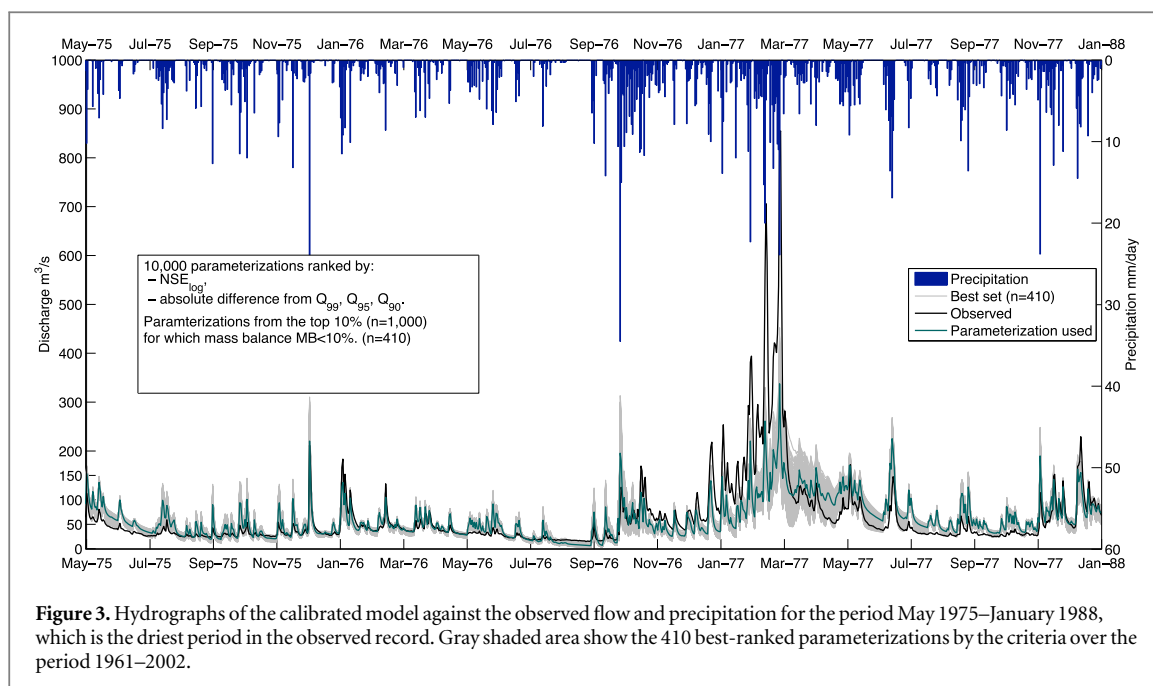
Figure 3. Hydrographs of the calibrated model against the observed flow and precipitation for the period May 1975–January 1988, which is the driest period in the observed record. Gray shaded area show the 410 best-ranked parameterizations by the criteria over the period 1961–2002.

## 2. Methods and models

2.1. Hydrological model

A lumped hydrological model was used to simulate mean daily discharges for the Trent catchment, driven by rainfall and potential evaporation forcings. The model uses a two-layer characterization of the catchment, comprising a fast responding upper soil layer and a slower groundwater store. For calibration, historical observations of temperature (to derive evaporation) and rainfall were obtained from gridded datasets [50, 51] and flow data for Colwick from the National River Flow Archive for the period 1961–2002 [52].

Structural performance of the model was evaluated by simulating 10 000 parameter sets, using Latin Hypercube sampling from predefined ranges specified for the eight model parameters (supplementary data table S2). The goodness-of-fit of the parameterizations was evaluated by combining 5 metrics in a ranking procedure [53]: the Nash–Sutcliffe efficiency [54], performed on the log transformed flows (NSE_{log}), mass balance of flows and the absolute difference between the simulated and the observed flows for the Q_{99}, Q_{95} and Q_{90} flow percentiles (figure 3). These measures were chosen to place emphasis on the accurate simulations of both the frequency and volume of low flows, which are of primary concern in this study. From the best performing 10%, 410 simulations had an absolute mass balance error MB ⩽ 10% and $0.603 \leqslant NSE_{log} \leqslant 0.746$; the highest ranked parameterization had an NSE_{log} of 0.71 and MB error of −0.37%. In figure 3, the 410 parameterizations are shown as the shaded area and the hydrograph for the best performing simulation is in solid black, given for the driest period on record, 1975–77. Compared to the

observed flows from June 1975 to November 1976, the model has a very slight bias to overestimate (∼5%) the frequency of very low Q_{99} flows; during this 18 month period there were 87 days below Q_{99} whilst our model predicted 93. This bias is visible on the FDCs in figure 4 at very low flows between the observed flows and the model with observed climate, noting that this error's appearance is accentuated by the log-scale of the *y*-axis. Most crucially however, this parameterization reproduced very well the low flow section of the flow duration curves (FDC) for the synthetic control climate timeseries. As future climates are based on the control timeseries, the control climates are our key point of reference for this study (figure 4).

2.2. Climate projections

The UK Climate Projections 2009 (UKCP09) are the principle set of projections of climate change for use in impact assessment in the UK [9]. UKCP09 uses a perturbed physics ensemble of General Circulation Model (GCM) projections that account for uncertainties arising from the representation of physical processes and the effects of natural climate variability. These projections and uncertainties in UKCP09 are supplemented by an additional estimate of the variance in projection from the GCMs from other global modeling centers included in the ensemble of the Coupled Modeling Intercomparison Project Phase 3, a framework that supports the validation and comparison of outputs from different GCMs. These projections are downscaled using the HadRM3 Regional Climate Model to a 25 km scale. These probabilistic projections were accompanied by a stochastic weather generator (WG), trained on observed climatology and perturbed by change factors derived from the downscaled projections [55]. The WG was used to generate
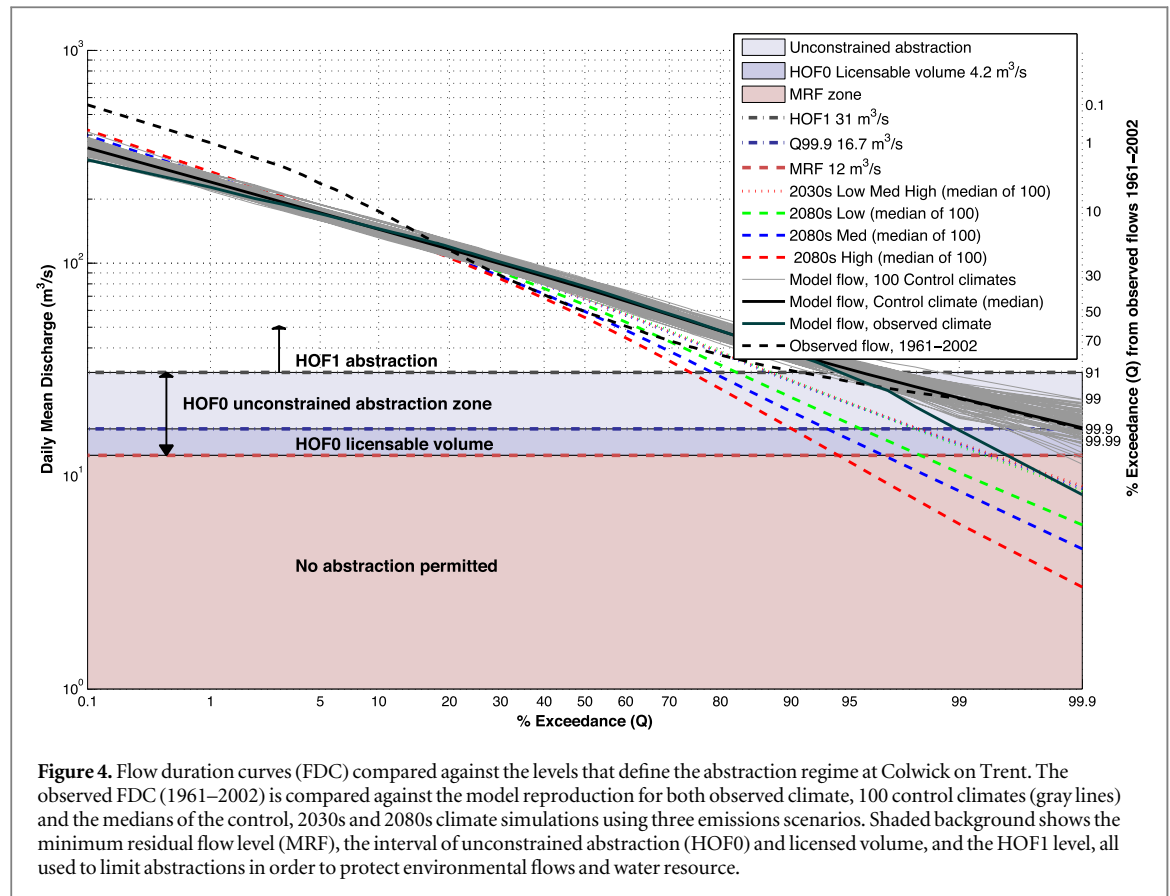
Figure 4. Flow duration curves (FDC) compared against the levels that define the abstraction regime at Colwick on Trent. The observed FDC (1961–2002) is compared against the model reproduction for both observed climate, 100 control climates (gray lines) and the medians of the control, 2030s and 2080s climate simulations using three emissions scenarios. Shaded background shows the minimum residual flow level (MRF), the interval of unconstrained abstraction (HOF0) and licensed volume, and the HOF1 level, all used to limit abstractions in order to protect environmental flows and water resource.

daily input time series for the hydrological model for five time slices (2020s, 2030s, 2040s, 2050s and 2080s) under three Special Report Emissions Scenarios (A1B (low), A1B1 (medium), A1F (high)) [56] (see [32, 57, 58] for similar uses of the WG). (The 30 year records are centered on the time slice, e.g. the 2020s represents the period 2010–2039, and so forth.) For each emissions scenario and time slice, one hundred 30 year WG realizations were produced, sampling from the full range of uncertainties.

In figure 4 the mean FDC for the 2030s and 2080s time slices and the WG control runs (representative of the historical period 1961–90) and observed profiles are shown against the regulatory flow levels.

Based on the FDC of the simulations above, the MRF and HOF levels for the time-slices have been determined using the timeseries of historical flows and the current rules of abstraction; MRF at 75% of the $Q_{99.9}$, HOF1 at 85% of the Q_{91} and licensable volumes constituting the remainder (25% and 15%, respectively), (table 1). Refer to section 1.2 and S2.4 for further explanation.

2.3. Energy portfolios and abstraction demand calculation

On the non-tidal freshwater Trent there is currently 3 GW$_e$ of wet tower cooled coal-fired power (Ratcliffe on Soar and Rugeley), and the 1.65 GW$_e$ hybrid cooled Staythorpe C combined cycle gas turbine (CCGT) power plant. Five alternative portfolios of power plant

development on the Trent were developed to explore the possible range of future freshwater demands from the sector on the river from 2020 to 2050 at 5 year time steps (table 2 and figure 5). All portfolios transition from, currently unabated CCGT and coal-fired capacity, to 50% CCS for both new and existing capacity in 2025, to 100% CCS on all capacity by 2030. The introduction of CCS results in parasitic loads, reducing the overall efficiency and the dispatchable output of the power plants, by 25% for CCGT and by 31% for coal-fired plant. All portfolios result in approximately 7.2 GW$_e$ capacity by 2040, consistent with strong regional population growth and government subsidies for 'low-carbon' and CCGT capacity [59]. However, these portfolios differ primarily by cooling systems, as described by their names and descriptions in table 2. Hybrid cooling also reduces the dispatchable output over wet tower cooling by 0.3%, 0.4%, 0.7% and 0.8% for CCGT, coal, CCGT + CCS and coal + CCS, respectively (table S11). Portfolios 1 and 2 remain with low levels of hybrid cooling, whilst portfolios 3 to 4 increase to have 70% and 100% hybrid cooling, respectively. Portfolio 5, *gas future*, with only gas-fired CCGT and CCGT + CCS capacity from 2025 onwards, is 57% hybrid cooled. A further 2 GW$_e$ of CCS capacity (before capacity reductions), half coal and half CCGT, is added in 2040, except for Portfolio 5 for which 2 GW$_e$ of CCGT + CCS is added. Future coal plants with CCS are assumed to be super-critical.

Table 1. Projected median $Q_{99.9}$ and Q_{91} flows, the derived minimum residual flow (75% of the $Q_{99.9}$) and licensable volumes for each timeslice for the medium emissions scenario.

$m^3 \, s^{-1}$	Current	2020s	2030s	2040s	2050s	2080s
HOF0 licensing (between $Q_{99.9}$ and Q_{91}) [a]						
$Q_{99.9}$	18.0	13.5	11.2	10.2	9.6	7.6
MRF	13.5	10.1	8.4	7.7	7.2	5.7
Q_{91}	36.9	30.2	27.4	25.4	23.0	20.3
Licensable	5.5	4.5	4.1	3.8	3.5	3.0
Δ% from current licensable	0%	−18%	−26%	−31%	−38%	-45%
HOF1 licensing (between Q_{91} and Q_{71})						
Licensable	4.4	3.9	3.5	3.2	3.0	2.7
Δ% from current licensable	0%	−11%	−20%	−27%	−32%	−39%

[a] Normally Q_{95}, but for the Trent this is Q_{91}.

Table 2. Portfolio names, descriptions, capacity and cooling types between 2010 and 2040. Detailed in supplementary data, S4.3.

2040–2050	Portfolio	2010	2020	2025	2030
		Output capacity (MW$_e$) [a]			
#1–4	Coal/Coal + CCS:	3000	3000	2533	2067	2756
	CCGT/CCGT + CCS:	1650	4870	4261	3648	4398
#5	Coal/Coal + CCS:	3000	3000	0	0	0
	CCGT/CCGT + CCS:	1650	4870	6511	5898	7395
% of capacity of which CCS (#1–5)		0%	0%	50%	100%	100%
		Output capacity split by cooling system type (MW$_e$) [b]			
		Closed loop wet tower cooling on all capacity (wet)			
#1 *Business as usual* (*BAU*)	Wet:	3000	6220	5351	4482	5921
	Wet/dry:	1643	1643	1438	1233	1233
		All new coal-based capacity uses hybrid wet/dry tower cooling			
#2 *Coal new hybrid*	Wet:	3000	6220	5351	4482	5232
	Wet/dry:	1643	1643	1438	1233	1916
		All new capacity uses hybrid wet/dry tower cooling			
#3 *New hybrid*	Wet:	3000	3000	2533	2067	2067
	Wet/dry:	1643	4851	4244	3638	5065
		All new capacity is hybrid cooled, existing capacity is retrofit from 2025–2030			
#4 *All hybrid*	Wet:	3000	3000	1500	0	0
	Wet/dry:	1643	4851	5269	5688	7118
		Only CCGT capacity, half of new and replacement capacity is hybrid wet/dry tower cooling			
#5 *Gas future*	Wet:	3000	6220	4318	2415	3165
	Wet/dry:	1643	1643	2558	3469	4216

[a] Including efficiency and capacity reductions due to CCS parasitic loads, but not including efficiency and capacity reductions from hybrid cooling.

[b] i.e. *according to output capacity above and* not the cooling system capacities in MW$_{th}$.

Electricity generation was calculated using 70% average annual load factor and 100% peak load factor, consistent with scenarios with high penetration of CCS [38, 60]. Generation figures are made monthly according to distributions that vary by generation class, as well as the changing seasonality of consumer demands, such as lighting, heating and cooling, affected by technological and climatic changes [60–64]. By 2050, it is likely that seasonal peaks in winter and summer are accentuated whilst spring and autumn generation are lower, detailed further in the supplementary data (figure S7). Water use factors are used to estimate abstraction and consumption, by each generation class and cooling system [7]. Water use factors are based on a variety of sources [2–4, 7, 65] (table S14). For closed loop wet tower cooling, abstraction factors are 0.97, 1.93, 1.92 and 3.62 Ml GWh^{-1} (or l kWh^{-1}), for CCGT, coal, CCGT + CCS and coal + CCS, respectively. Consumption factors are approximately 75% of the abstraction values. For wet/
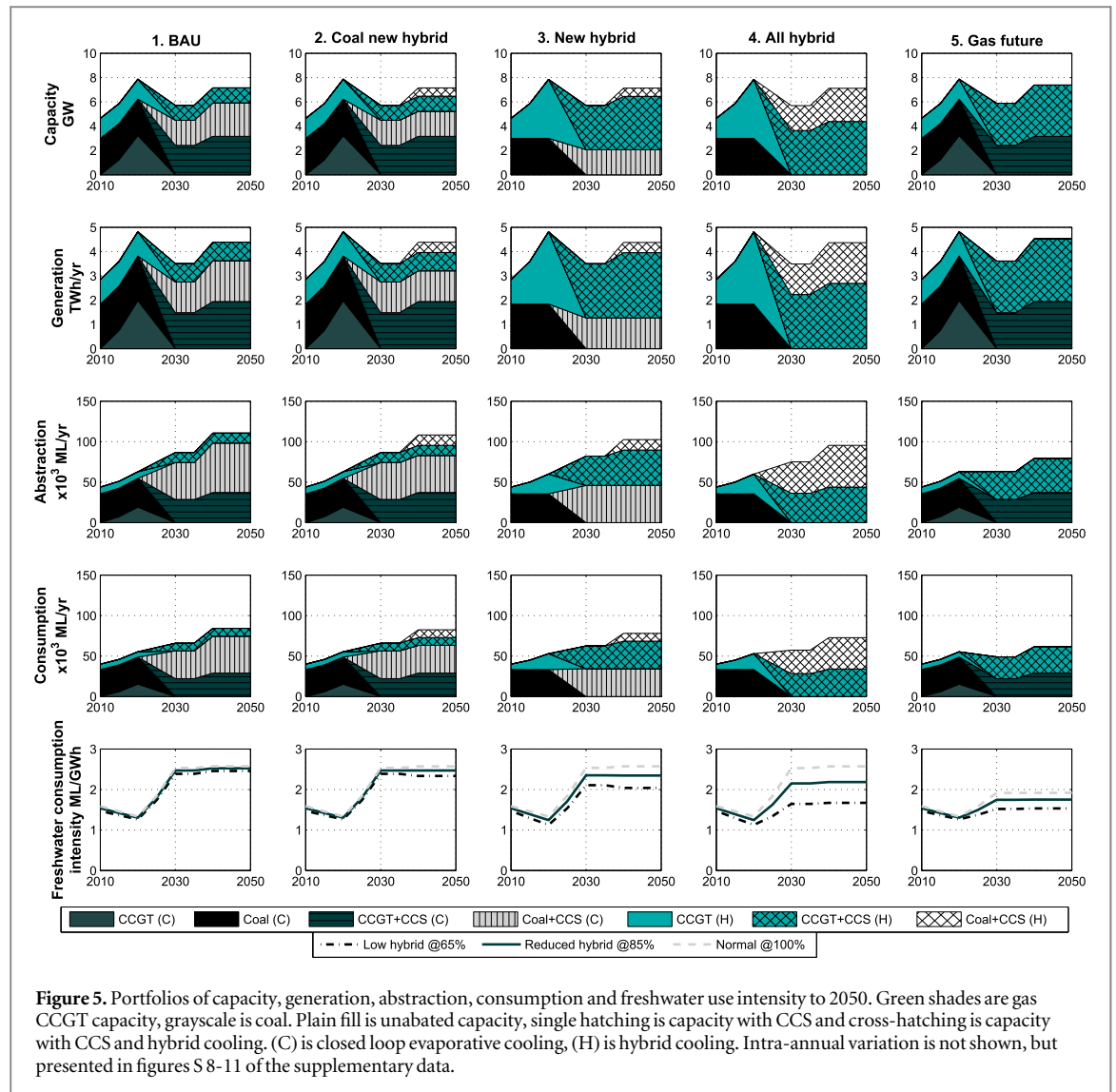
Figure 5. Portfolios of capacity, generation, abstraction, consumption and freshwater use intensity to 2050. Green shades are gas CCGT capacity, grayscale is coal. Plain fill is unabated capacity, single hatching is capacity with CCS and cross-hatching is capacity with CCS and hybrid cooling. (C) is closed loop evaporative cooling, (H) is hybrid cooling. Intra-annual variation is not shown, but presented in figures S 8-11 of the supplementary data.

dry hybrid cooling, three operational modes are assumed to test the operational sensitivity when combining dry and wet aspects of cooling systems, corresponding to the values for the wet tower cooling. These range between normal (100% wet cooled water use), reduced (85%) and low (65%—high mechanical air draft), respectively.

3. Results and analysis

3.1. Water abstraction and consumption

Figure 5 presents the five portfolios (table 2) with a 5 year time step resolution in terms of capacity on freshwater, generation, abstraction, consumption and freshwater abstraction intensity from 2010 to 2050, split by generation class and cooling type. Excluding the gas future portfolio (#5), water use ('Abstraction' and 'Consumption') increases of 103%–143% are expected by 2040, between the all hybrid (#5) and BAU (#1) portfolios, respectively, assuming the reduced hybrid operation mode. Almost half of these changes are attributable to the widespread use of CCS,

which almost doubles the intensity of water use (bottom row). The differences in performance between portfolios are primarily dictated by the cooling systems used. Both the increases in, and the majority of, water use is attributable to the coal + CCS capacity. For this reason, the gas future portfolio with no coal-fired capacity from 2025, is the most water efficient with only 75% increase, despite having less hybrid cooling than portfolios 3–5.

3.2. Future hydrology simulation

In figure 6 river flows at Colwick are compared against the current MRF, the lowest level at which it is likely that abstraction restrictions would be imposed. The MRF is set at 75% of the $Q_{99.9}$, thus an extreme low flow exceeded more than 99.9% of the time, and in this case is lower than the lowest observed flow in the historical record (Q_{100}). Thus, there is an increasing possibility with time of the MRF being breached compared to the control profile.

The '% time MRF breach' is the total number of days on which the daily flows fall below the MRF as a
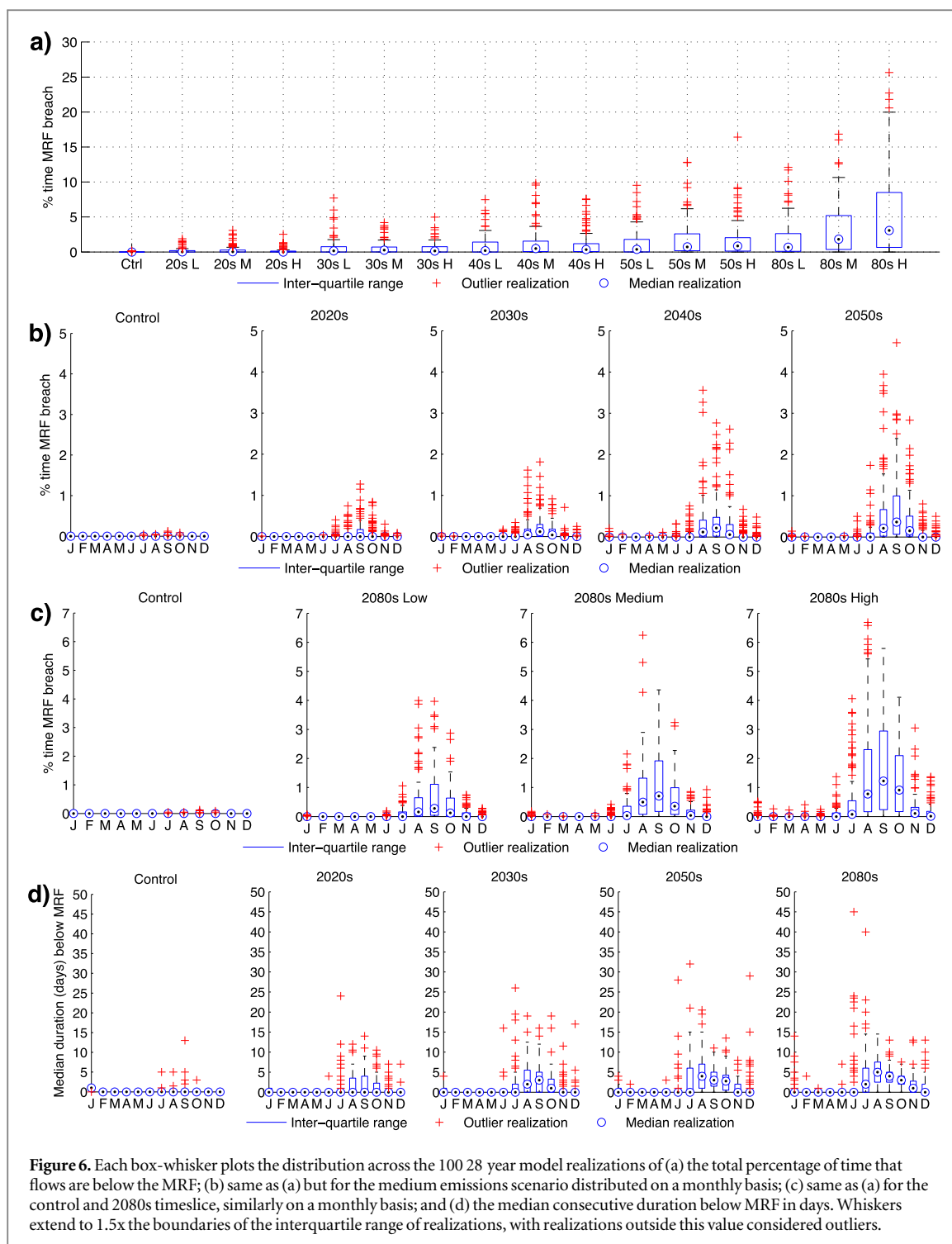
Figure 6. Each box-whisker plots the distribution across the 100 28 year model realizations of (a) the total percentage of time that flows are below the MRF; (b) same as (a) but for the medium emissions scenario distributed on a monthly basis; (c) same as (a) for the control and 2080s timeslice, similarly on a monthly basis; and (d) the median consecutive duration below MRF in days. Whiskers extend to 1.5x the boundaries of the interquartile range of realizations, with realizations outside this value considered outliers.

proportion of the total number of days in each 28 year realization (reduced from 30 years for a 2 year hydrological model spin up period). In figure 6 the individual box-whisker plots present the distribution of results across the 100 28 year simulations for each timeslice-emissions combination. Such that in figure 6(a) the median percentage of time that the MRF is breached over a timeslice increases from 0.0% in the control simulations, to 0.5% and 1.8% in the 2040s and 2080s medium emissions scenarios, respectively. The outliers represent extreme cases arising

from the sampled natural and climate change variability in UKCP09, so whilst these outliers are expected they should be used with caution. Worth noting in figure 6(c) is that even the low emissions scenario in 2080s only delays the expected effects of climate change, similarly experienced by the medium scenario in the 2050s.

In figures 6(b) and (c) MRF breaching is separated out by month and similarly presented for consideration over the timeslice. In figure 6(b), up to the 2050s, the median MRF breach increases from 0.0% in the
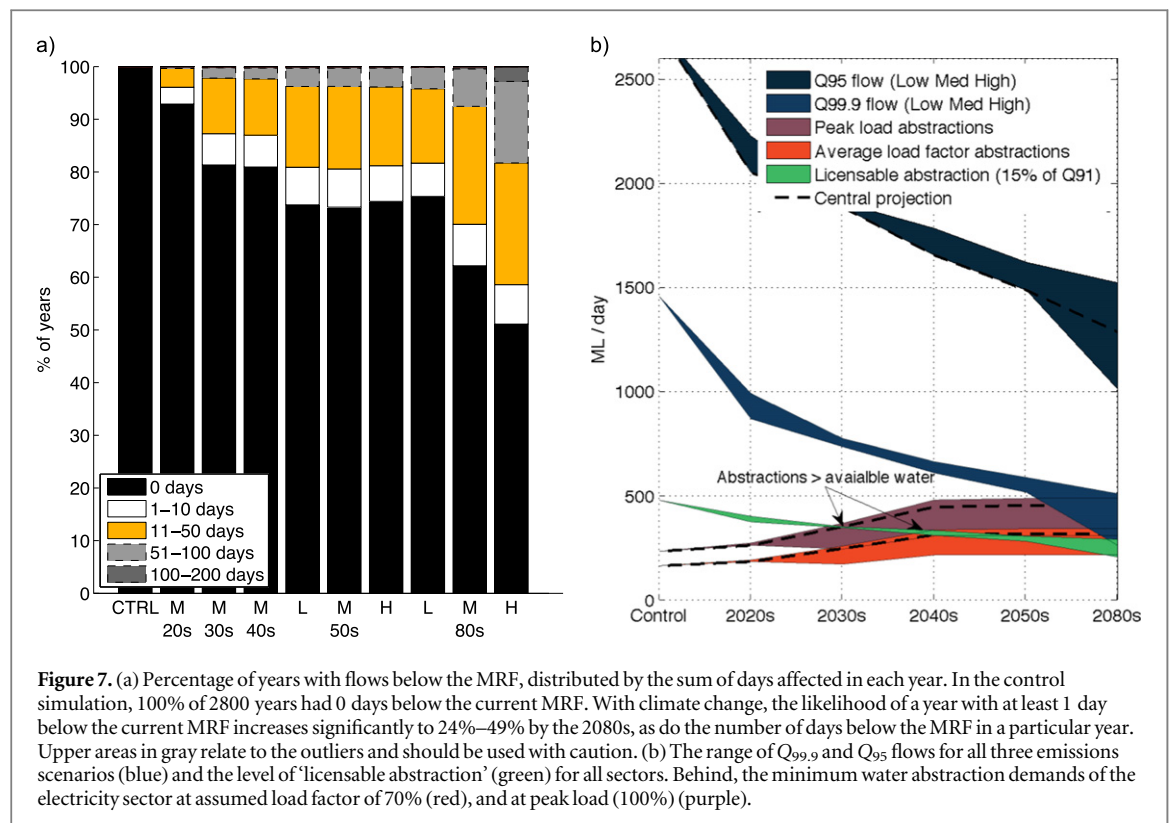
Figure 7. (a) Percentage of years with flows below the MRF, distributed by the sum of days affected in each year. In the control simulation, 100% of 2800 years had 0 days below the current MRF. With climate change, the likelihood of a year with at least 1 day below the current MRF increases significantly to 24%–49% by the 2080s, as do the number of days below the MRF in a particular year. Upper areas in gray relate to the outliers and should be used with caution. (b) The range of $Q_{99.9}$ and Q_{95} flows for all three emissions scenarios (blue) and the level of 'licensable abstraction' (green) for all sectors. Behind, the minimum water abstraction demands of the electricity sector at assumed load factor of 70% (red), and at peak load (100%) (purple).

control simulations to 0.2%–0.4% in the 2050s for August and September medium emissions case. In extreme cases the whiskers extend to over 2.4%, equating to 20 days of outage for that month over the 28 year period. The interquartile ranges for September, between 0.0%–1.1% and 0.2%–2.9%, give a good indication to the amount of time the MRF is expected to be breached over the period of the 2080s timeslice. In extreme cases, the upper whiskers for the 2080s extend to 2.4%–5.8% of September flows below the MRF. Whilst seemingly small numbers, they are unprecedented in the historical flow record. Furthermore, the frequency of breaching the MRF does not occur uniformly, neither between years, nor between realizations; it occurs during the driest years only. Figure 6(d) shows the median consecutive duration in days below the MRF for each realization. For some samples, MRF breaching may occur relatively frequently with short duration (<5 days), whilst in the more extreme cases, very infrequently with longer durations (>15 days). When the threshold sensitivity is changed to no more than 7 days between breaches, the upper quartile duration of these prolonged events was 20 days for July and August in the 2050s.

Figure 7(a) summarizes the simulation data on an annual basis, by summing the number of days each year below the current MRF. The distribution of each bar is based on 100 model realizations of 28 years of simulation (total 2800 years) for each timeslice and emissions scenario, sampled from the full distribution of UKCP09

change factor vectors. Firstly, the frequency of MRF breaching in any year will likely increase, as shown by the decreasing black bars. Secondly, the number of days breaching the MRF within a year is also expected to increase, shown by the different colors above the black bars. Figures 6(b) and (c) clearly indicate the increased likelihood of MRF breach in July through November, and hence the likelihood that these low flows occur consecutively in an extreme year.

Hence, figure 7(b) presents the growing demands of the electricity sector against the diminishing water resource of the Trent at low flows. The overlap of the peak load abstractions and $Q_{99.9}$ flows shows that in some cases there would not even be enough water for other users, let alone maintaining the minimum environmental flows. Currently, and as demonstrated in the control simulation, thermoelectric abstractions do not exceed the maximum permitted value, allowing abstraction from other sectors. Going forwards, not only is the regulator likely to reduce the amount of available water to maintain environmental protection (figure 6), but abstractions are projected to increase. Figure 7 allows us to consider the uncertainty of power sector demands against uncertainties in water availability. Unless the most water-efficient capacity and cooling configurations are used, normal operation may not be possible under low flow conditions in the future. To what extent electricity generation would need to be ramped down to protect environmental flows is now investigated.
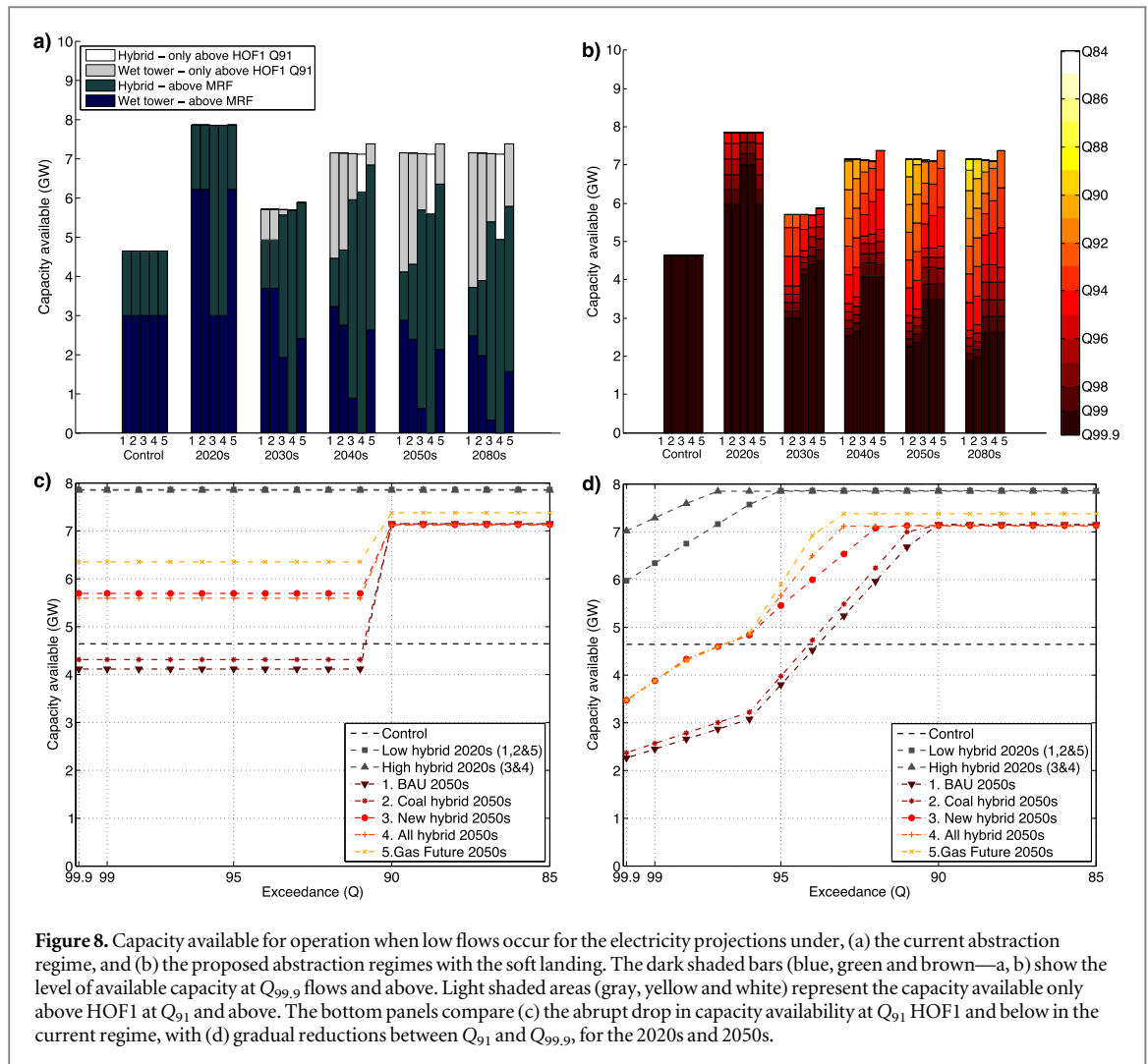
Figure 8. Capacity available for operation when low flows occur for the electricity projections under, (a) the current abstraction regime, and (b) the proposed abstraction regimes with the soft landing. The dark shaded bars (blue, green and brown—a, b) show the level of available capacity at $Q_{99.9}$ flows and above. Light shaded areas (gray, yellow and white) represent the capacity available only above HOF1 at Q_{91} and above. The bottom panels compare (c) the abrupt drop in capacity availability at Q_{91} HOF1 and below in the current regime, with (d) gradual reductions between Q_{91} and $Q_{99.9}$, for the 2020s and 2050s.

3.3. Capacity deficits under the different abstraction regimes

For each energy portfolio, we calculated the most efficient use of the water available at different flow intervals whilst maximizing electricity generation and protecting environmental flows (detailed in supplementary data S2). Figure 8 compares two key dimensions of this study at low flow percentiles: the operation of the two abstraction regimes and the performance of the different CCS portfolios.

For the current abstraction regime (figures 8(a) and (c)), the abruptness of the HOF1 at Q_{91} is evident in future timeslices, as more capacity is added and less water is available. The marginal advantages of hybrid cooling for reducing water use, particularly for coal + CCS plants, are evident when comparing the capacity availability of portfolios 1 and 2 (52%–54%) with 3 and 4 (69%–76%) in a 2080s medium emissions scenario at $Q_{99.9}$ flow. However, the gas future portfolio (5) consistently performs best, maintaining 93%–78% capacity availability in the lowest flows through the 2040s–2080s medium climate scenarios, respectively. Portfolios 1 and 2, with low hybrid-cooled capacity and high water intensity from coal + CCS,

are increasingly vulnerable in climates from the 2030s, struggling to maintain even $3\,GW_e$ online in a $Q_{99.9}$ low flow.

By comparison, the proposed abstraction regime (figures 8(b) and (d)) affords gradual increases in capacity availability between $Q_{99.9}$ and Q_{91}. However, the caveat is that less capacity (32%–66%) is available at very low flows between $Q_{99.9}$ and Q_{96}, and more capacity (53%–100%) is available at low flows between Q_{95} and Q_{91}, evident in figure 8(d). The more flexible and water-efficient portfolios [3–5] maintain close to 100% availability as low as Q_{93}.

Taking the integral of these capacity curves results in significant differences in long-term capacity availability across the portfolios, but almost negligible between the abstraction regimes. Differences across the whole FDC were on average only 0.4%. However, between $Q_{99.9}$ and Q_{90} capacity availability for the current regime is between 2.7% and 6.7% higher than the proposed CSP regime. This was due to the mostly concave shape of the FDC in this range, which has the effect of slightly reducing water availability compared to the current abstraction regime. Comparing portfolios, availability in portfolios 3–5 drops from 100% as

present to 97%–98% in the 2080s whilst for portfolios 1 and 2 availability drops from 100% to 95%–96%. Whilst a seemingly small difference equivalent to 7 d yr^{-1}, during low flows ($Q_{99.9}$–Q_{90}) capacity availability is approximately a quarter less for the portfolios with low hybrid (54%-59%) compared to high hybrid cooling (72%–80%).

This analysis supports that 3–4.5 GW$_e$ of CCS capacity similar to portfolios 3–5, may be operated on the Trent with a high level of reliability, under the median FDC in a medium emissions scenario. Only lower levels, of roughly 2 to 3 GW$_e$ CCS capacity could likely be operated in portfolios 1 and 2 in order to maintain similar levels of reliability.

4. Discussion

This work presents decision makers with a methodology for exploring the impacts of hydrological variability, climate change and regulatory arrangements on the performance of different thermoelectric cooling and CCS technologies. Besides the variety of climate and hydrological uncertainties, this study has tested two key aspects that typically lie within the influence of the environmental regulator: cooling system choice and the water licensing and abstraction regime. More water efficient electricity production, influenced by both the cooling system (wet/dry hybrid over wet) and the generation technology (CCGT over coal + CCS) are shown to facilitate higher reliability. Given the high costs of CCS infrastructure, this is beneficial as it increases the utilization of shared infrastructure. Furthermore, long life of power plants and expected CCS infrastructure, along with the tendency to build new plant on the same sites, means that these infrastructure developments could become *locked in* for decades. In the UK, for example, electricity generators and the consenting Secretary of State are obliged to account for potential climate impacts in planning applications for power plant development. Under the circumstances, exploring the possible impacts of climate change through to the 2080s is warranted.

As expected, the soft landing approach to low flows management proposed by UK Government, changes the availability of water to abstractors. Less would be available at the very lowest flows ($Q_{99.9}$–Q_{96}), but more would be available at low flows that occur more regularly (Q_{95}–Q_{90}). Depending on the way that the soft landing is apportioned and the river's FDC shape, there may be small discernible differences between the two abstraction regimes in terms of water availability. Nonetheless, in the soft landing approach, proactive water management, or trading, when low flows start (Q_{90}–Q_{95}), could possibly avoid the more drastic reductions required under the very low flows ($Q_{99.9}$–Q_{96}).

One key assumption is that when facing water shortages, CCS power plant operation is prioritized according to water efficiency in order to maximize generation output. Regulatory measures to either maximize economic benefit when water is scarce, or to minimize the risk to energy security, could establish such prioritization of water use within the sector. Water trading mechanisms promote market efficiency by enabling more water-efficient operators to temporarily purchase the water rights of less efficient operators, given their increased profitability per unit of water. Without such prioritization (or arguably optimization) however, electricity sector impacts would be more severe than those presented, and potentially worse in the proposed system than in the current system during very low flows.

In order to maintain the same principles of environmental flows (in this case protected by the EU Water Framework Directive) in a changing climate with low flows, we have a tradeoff between volume availability and volume reliability. Either the volume available to abstractors decreases for the same level of reliability, or the volume available is maintained but with reduced reliability. We have assumed the former case of maintaining reliability alongside environmental protection, as large investments like power plants require regulatory and operational certainty. This work demonstrates the importance of considering, both in future studies and policy-making, potential future changes when setting ecological flow indicators that may impact on long-term investments.

Three climate change emissions scenarios were tested by sampling from the full distribution of UKCP09 change factor vectors whilst keeping constant assumptions about how abstractions are licensed and MRFs. The hydrological model, specifically developed for analysis of low flows, has explored a range of future flows that may be experienced in the Trent in both median and extreme circumstances and under emissions uncertainty. Even low emissions climate projections in the near term (2020s and 2030s) indicate substantial reductions in $Q_{99.9}$ flows and subsequent volumes of licensable abstractions (figure 7(b)), that would likely place even the current 4.65 GW$_e$ generation capacity at greater risk. By the 2030s, the median duration of flows below the MRF in summer months is expected to be around 5 days, however in more extreme cases this may be in excess of 15 days. One option during prolonged low flows, to the authors' knowledge not yet suggested in the literature, would be the temporary unabated operation of CCS power plants so as to reduce water use. In addition to this, it would be prudent for power plants to schedule maintenance and outages during weeks when low flows are most likely, whilst collaboratively ensuring that excessive capacity is not simultaneously offline.

Finally, we note that the additional capital and operational costs of hybrid cooling are an important consideration, and may be expected to add 3%–5%

over the costs of wet tower cooling, on a levelised cost of electricity basis [2]. Thus, we recommend further investigation of the extent to which these costs are covered by water savings and the benefits of additional reliability.

5. Conclusions

This research has simulated in depth the interactions between electricity sector water use and hydrological variability, with inclusion of uncertainty that matches or exceeds a number of prominent studies [23, 26, 28–31, 66–70]. This work has used a hydrological model at daily timestep, forced by 100 realizations of three emissions scenario climates at daily timestep for timeslices up to the 2080s. Against this, the dynamic performance of five portfolios of CCS capacity with different cooling systems has been simulated against two different abstraction regimes, currently under consideration by UK Government. This in particular makes it a novel and timely contribution to the science from the water-energy perspective, and serves to illustrate the importance of considering alternative policy and regulation in addressing global water-energy challenges. With CCS development very much on the horizon, proactive approaches to manage potential increases in water intensity of electricity production are required.

With expected climate change impacts on the Trent's hydrology, the projected growth of cooling water abstractions due to CCS development are anticipated to reach the licensable abstraction limit for all sectors by the 2040s. If water demands by the sector are not addressed, under our growth projections and a changing climate the water deficit at a Q_{95} low flow on the Trent in the 2050s is in the range of 42%–46% for the business as usual portfolio. We conclude that further water-intensive electricity capacity development on the freshwater River Trent could present risks at low flows to both the energy sector as well as other water users, significantly compounded by the impacts of climate change on the hydrology of the River Trent. Our analysis has shown that these risks may be reduced, if:

- Water allocation is prioritized on an efficiency basis when limited quantities are available (either through market, cooperative or regulatory mechanisms), such that a less efficient water user would be required to reduce abstraction before a more efficient user, e.g. by choosing CCGT + CCS over coal + CCS, or hybrid cooled plants over wet tower equivalents.

- Higher proportions of wet/dry hybrid tower cooling is used at new power stations, particularly coal and coal + CCS, in order to maximize water-efficient operation and increase flexibility under low flows and drought conditions.

- Development of CCGT and CCGT + CCS power plants is prioritized over coal equivalents in areas of potential water stress, as demonstrated by the most water efficient *gas future* portfolio.

The simulation of different abstraction regimes has found very little difference between the two proposed allocation arrangements when capacity availability is summed across the whole FDC, but appraisal at different flow intervals does have an impact. In the proposed regime, less water and hence capacity is available at very low flows whilst more is available at low flows. These differences in capacity availability can now be scrutinized by the regulators and water users. Operators may identify preferences between the two depending on their expected operation at different flow intervals and in different months. Advantages of either regime in this respect may yet be identified through extreme value analysis of individual time series.

This work also builds a case for considering the cooling water demands of CCS cluster developments in a more integrated fashion. Given that the economic case for CCS is based on facilities sharing pipeline infrastructure, we recommend that cooling water use is evaluated in a similar way so as to ensure sustainability and reliability of both water resources and electricity supply.

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