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Spatially-Explicit Impacts of Carbon Capture and on Water Supply and Demand

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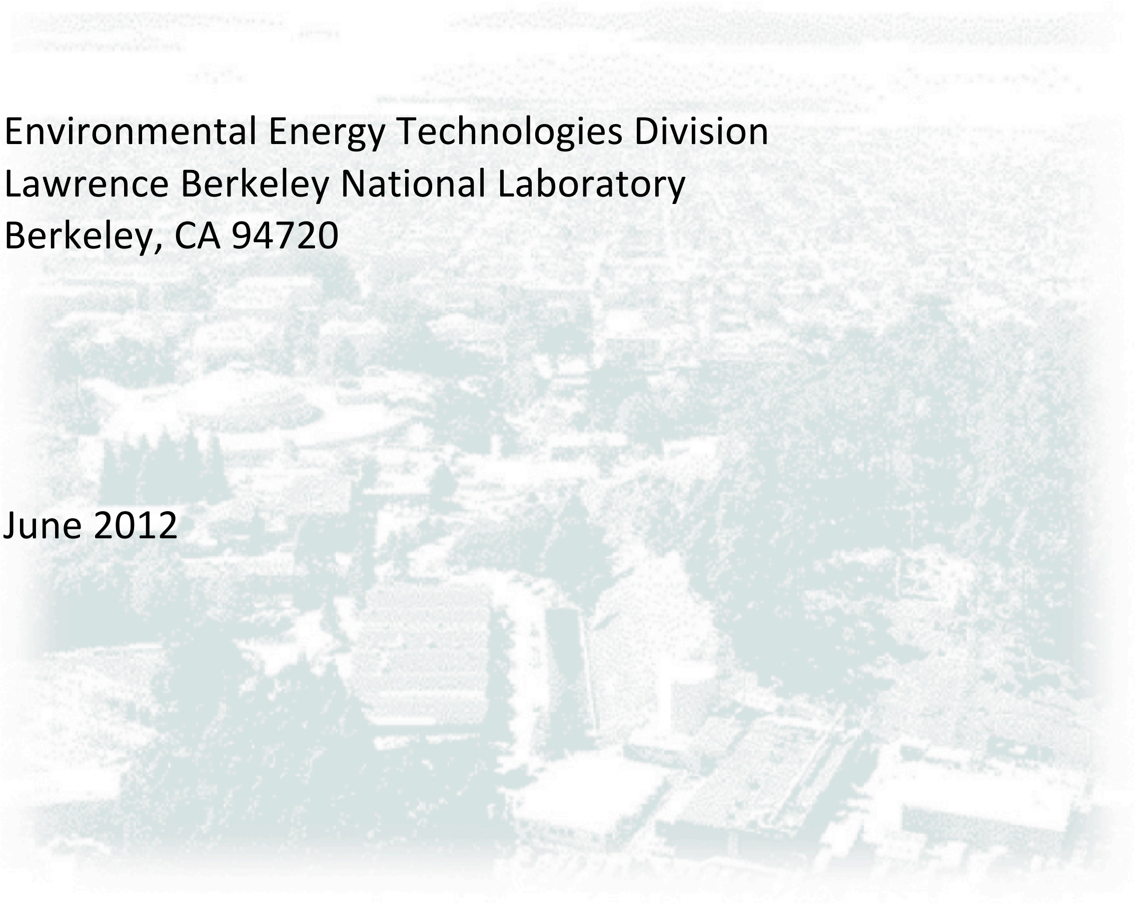

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Spatially-explicit impacts of carbon capture and sequestration on water supply and demand

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Abstract

We conduct a geospatial analysis detailing how carbon dioxide capture and sequestration (CCS) implementation affects the county-level balance of water supply and demand across the contiguous United States. We calculate baseline water stress indices for the year 2005, and explore CCS deployment scenarios for the year 2030 and their impacts on local water supply and demand. We use GIS mapping to identify locations where water supply will likely not constrain CCS deployment, locations where fresh water supply may constrain CCS deployment but brine extraction can overcome these constraints, and locations where limited fresh water and brine availability are likely to constrain CCS deployment. We conduct sensitivity analyses to determine bounds of uncertainty and to identify the most influential parameters. We find that CCS can strongly affect freshwater supply and demand in specific regions, but overall it has a moderate effect on water balances. The use of extracted brine to overcome local water constraints may enable the capture and sequestration of about 100 Mt CO_2 annually over what would have been possible without brine extraction.

1. Introduction

Carbon dioxide capture and sequestration (CCS) must be implemented on a very large scale to contribute significantly to climate change mitigation (Herzog 2011). Decision-makers who wish to avoid unintended consequences from development of CCS must carefully consider its interrelations with water use. On one hand, power plants equipped with CO_2 capture will require more cooling water than plants without CO_2 capture. Water withdrawal per kWh could be 41% to 96% greater for power plants with carbon capture relative to plants without carbon capture (Shuster and Hoffman 2009). On the other hand, injection of captured CO_2 into saline aquifers may require that brine be extracted to manage the pressure within the geologic formation. The extracted brine can be desalinated and used as a fresh water resource, though this may only be economically feasible in areas where water is particularly scarce.

Water stress varies geographically−both within the United States (US) and globally. Areas with greater water stress may be less suited for expansion of water-intensive activities such as electricity production and CO_2 capture. Water supply and demand also vary over different time scales. Spatially and temporally dynamic factors that affect a region's water balance include demand from agriculture, industry, and domestic consumption; demand for electricity and the share of electricity produced by fossil fuels and other sources; the rate and extent of CCS deployment; potential extraction of brine to manage pressure in saline aquifers used for CO_2 sequestration; and the effects of climate change on water supply patterns.

In this analysis, we explore how CCS implementation may affect the balance of water supply and demand. We expect the results to vary from place to place. For that reason, we conduct a spatially-explicit analysis at the county level. A major focus of the analysis is to explore the main drivers of uncertainty and variability in the system. We do not seek a single "correct" answer, but are interested in the range of possible outcomes. Given the dynamic nature of the system across multiple dimensions, we ask how potential variations in local water balances due to CCS (resulting from both the increased cooling water demand and brine availability) compare with other sources of variability such as climate change, population change, and water demand in other sectors. In the following section, we describe our data sources and methods. In Section 3 we present the results of our analysis. We then conclude with a summary of our findings and offer a description of future research topics.

2. Methods

We conduct a geospatial analysis of the interactions between CCS deployment, water supply, and water demand, and the resulting implications of local water balance on CO_2 emission reduction potentials of CCS. The geographic scale of the analysis is the contiguous US, with spatial resolution at the county level. The temporal scale of the analysis includes a baseline of 2005 and a projection to 2030 to identify constraints to initial CCS deployment. For each county we estimate the water supply and the water demand, and we calculate a Water Stress Index (WSI). We determine how scenario conditions and system parameters affect the WSI for each county, and collectively how these factors may affect CCS deployment and national-level CO_2 emissions. The modeling framework is shown schematically in **Figure 1**.

Water supply

Local water supply projections are based on the WaSSi model (Sun et al. 2008). The WaSSi model estimates local water supplies at the level of US Geologic Survey (USGS) 8-digit Hydrologic Unit Code (HUC) watershed regions. Water supply for each HUC region is the sum of surface water supply, groundwater supply, and return flows. Surface water supply is estimated using a hydrological water balance model that predicts water yield as a function of monthly precipitation received, potential evapotranspiration, land use type, canopy interception capacity, soil moisture content, and plant rooting depth (Zhou et al. 2008). Groundwater supply is based on historical annual groundwater withdrawal records from USGS. Return flow is based on historical return flow rates multiplied by water use in different sectors such as domestic, industrial, irrigation, and thermoelectric power generation.

Future water supply varies according to climate change projections based on IPCC emission scenarios (IPCC 2000). Climate change projections in the WaSSi model are based on downscaled climate modeling by Coulson et al. (2010) comprising monthly precipitation, monthly means of daily maximum air temperature, and monthly means of daily minimum air temperature. Our base-case climate projection uses the IPCC emission scenario B2, modeled using the CSIRO MK2 climate model. In a sensitivity analysis, the projected climate change associated with the IPCC A1B emission scenario is also analyzed.

We consider a nine-year window around the nominal analysis year (i.e., the four preceding years, the target year, and the four following years) to incorporate the effects of inter-annual variability in water supply. The "average annual water supply" and the "minimum annual water supply" for the nine-year span are used in county-level water balance calculations. Intra-annual (e.g. seasonal) variability is not considered in this analysis.

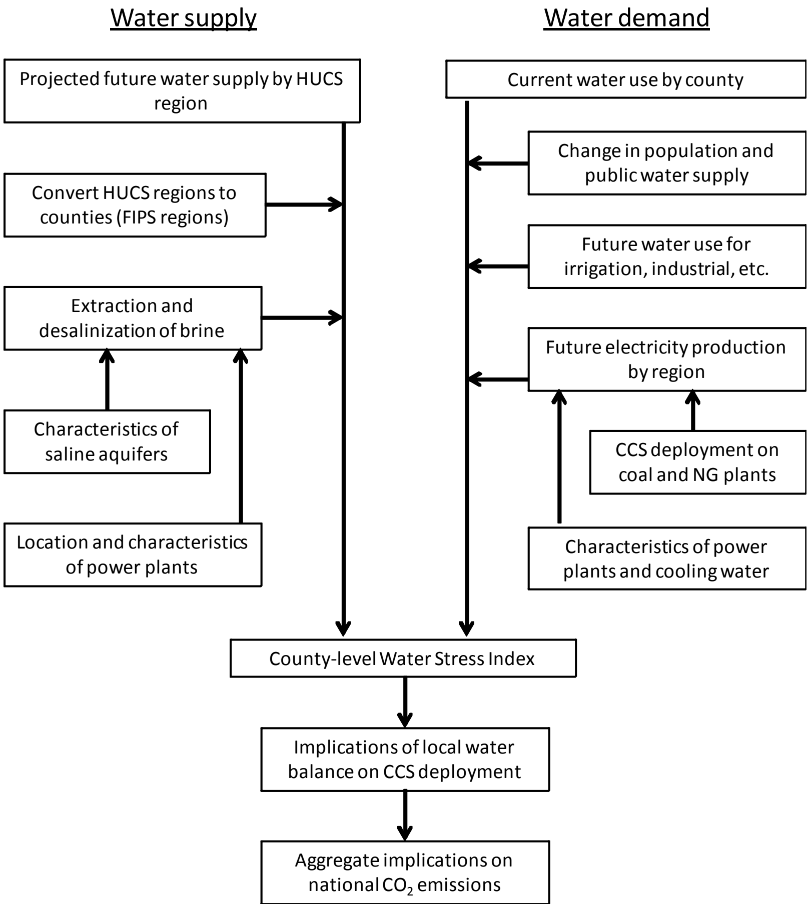

Figure 1. Schematic diagram of the modeling framework.

The geographic resolution of WaSSi water supply data is HUC watershed regions, while the water demand analysis is resolved into political county regions (5-digit FIPS regions). The analysis therefore required intersecting two national scale GIS map coverages, one comprised of 3,109 FIPS regions and the other comprised of 2,106 HUC regions. ArcGIS software was used to first re-project the county coverage so that both county and HUC coverages were in the same coordinate system. The HUC and county coverages were combined in a single feature resulting in more than 15,000 separate polygons, and the area of these polygons was calculated in units of km^2.In order to reduce the number of polygons to a manageable number, an arbitrary decision was made to limit the analysis to HUC polygons of greater than 10 km^2 that lie within a given county. The percentage of each HUC that lies within a particular county was calculated by dividing HUC area by county area and multiplying by 100.A 3,109 x 2,106 matrix was then created to allow the conversion of water supply at the HUC level to approximate water supply at the county level, based on the proportion of coinciding land area in each.

An additional potential source of fresh water is desalination of brine extracted from saline aquifers used for CO_2 sequestration. The locations of saline aquifers in the US are based on the NATCARB GIS database (NETL 2012). In addition to the location of aquifers, a suitability rating is provided by NATCARB which indicates whether the aquifer is suitable for use in geologic carbon sequestration projects. Aquifers that are suitable for CO_2 capture meet geologic and economic criteria. The primary characteristics required include high permeability and porosity, an impermeable seal, conditions that isolate the CO_2, and an adequate depth that yields supercritical CO_2 (Bachu et al. 2003; NETL 2010). We selected aquifers with high suitability and characterized the total dissolved solids (TDS) concentrations within the aquifer using USGS data on produced water sampled at appropriate depths. We used spatial analysis tools in ArcGIS software to determine the distance from the nearest region of a suitable saline aquifer to a county's center point. In our base-case we limit CCS to counties within 100 km of a suitable aquifer, beyond which we do not consider CCS as on option for power plants located in the county. To determine the significance of this parameter, we also consider cutoff distances of 25 km and 250 km in a sensitivity analysis. **Figure 2** shows the counties that are within 25 km, 100 km, and 250 km from a suitable aquifer. We also consider in a sensitivity analysis the possibility of sequestering CO_2 in depleted oil and/or gas reservoirs, for example in support of enhanced oil recovery (EOR). Initial CO_2 sequestration is likely to take place into depleted oil and/or gas reservoirs, which are well characterized and may generate revenue through EOR. However, the total capacity of these reservoirs is much more limited than saline aquifers (IPCC 2005).

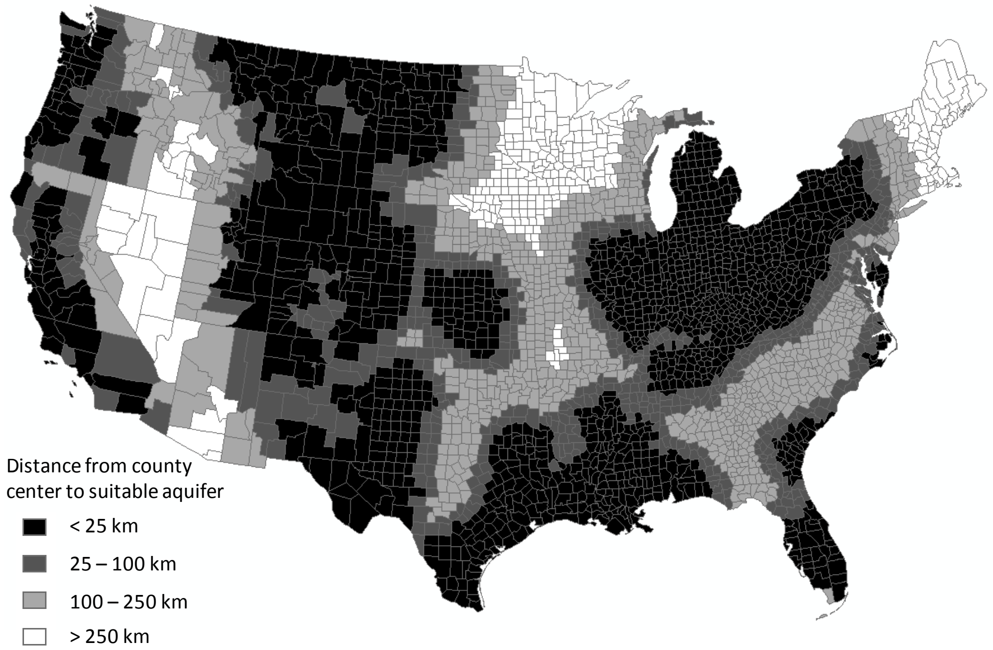

Figure 2. Distance from the center of each county to the edge of the nearest saline aquifer suitable for CO_2 sequestration.

To estimate quantities of extracted brine, we assume a density of supercritical CO_2 of 0.60 t/m^3, and we assume a brine-to-CO_2 displacement ratio of 1.0 by volume; in other words, for each m^3 of supercritical CO_2 injected into a saline aquifer, 1.0 m^3 of brine is extracted. A brine-to-CO_2 displacement ratio of 0.5 is also explored in the sensitivity analysis. The salinity of the extracted brine (measured as TDS) limits the fraction of freshwater that can be produced via reverse osmosis (RO) desalination. In our desalination analysis we adapt data from Bourcier et al. (2011) and Aines et al. (2011) and assume that brines with TDS greater than 100 g/L cannot be treated by standard RO. We make a conservative assumption that brines with TDS less than 50g/L can be treated with a 50% recovery fraction of freshwater, meaning that for every 2 L of brine treated, one L of freshwater and one L of concentrated brine are produced. For brines with TDS less than 100g/L and greater than 50g/L we use the following equation to determine the recovery fraction:

$$Recovery\ Percent = \left(1 - \frac{[TDS]}{[100\ g/L]}\right) \times 100\%$$

where *Recovery Percent* is the maximum recovery fraction achievable using current RO technology, and [*TDS*] is the TDS concentration of brine at a sample point in an aquifer. This equation reflects current RO membrane thresholds for osmotic pressure (Bourcier et al. 2011). It implies, for example, that brine with TDS of 80g/L can be treated with a 20% freshwater recovery fraction. We assume that the concentrated brine produced by the desalination process is disposed of in a manner that does not affect the fresh water balance, e.g., by reinjection. For each county, quantities of freshwater recovered from brine desalination are added to quantities of freshwater from the WaSSi model to determine the total water supply.

Water demand

In this analysis, annual water use within each county is based on USGS data describing water withdrawn in 2005 for public supply, self-supplied domestic use, irrigation, livestock, aquaculture, industrial, and mining (Kenny et al. 2009). The USGS data also includes water used for thermoelectric power generation, though we chose to use power plant data from Ventyx (2012) instead, as described below, due to its greater transparency. In 2005, water withdrawals in the US averaged approximately 1.5 trillion liters per day (Kenny et al. 2009). Domestic and commercial uses make up only 12% of total US withdrawals. The sectors responsible for the majority of water use are agriculture and thermoelectric power generation, contributing 31% and 49% of total water withdrawals, respectively. Other sectors contribute smaller fractions, including industrial facilities (4%), aquaculture (2%), mining (1%), and livestock (<1%) (Kenny et al. 2009).

We then modify the 2005 annual data to account for projected future changes in county-level water use by 2030. Exploring how water use in these sectors has changed in recent history and the factors driving those changes can offer insight into how water use will evolve in the coming decades. Between 1950 and 1980, total US water withdrawals grew at a rate that significantly outpaced population growth, peaking at 1.6 trillion liters per day. More recently, however, water use intensity (measured, for example, in m^3 of water per unit of economic output) has increased steadily in most sectors (Brown 2000). This has resulted in total water use remaining fairly stable in spite of increased economic activity. For example, water resource limitations and federal regulations resulted in increased use of recirculating cooling systems for power plants, which withdraw approximately 98% less water than once-through systems per unit of power output (NETL 2008). Industrial water use has been similarly impacted. Because water is often used to transfer heat within an industrial facility and remove waste heat, energy efficiency improvements provide the indirect benefit of reducing water requirements (Ellis et al. 2001). The result of these changes has been an overall decrease in US water withdrawals since 1980, despite increasing population and economic activity.

The question of how water requirements will change in coming decades is complex because it relies on a variety of climatic, economic, and regulatory factors. Agriculture serves as a useful example. The amount of irrigation water required to avoid crop loss and achieve desirable yields is highly reliant on rainfall, temperature, humidity, and other climatic variables. Weather has always varied from year to year, but climate scientists are now projecting long-run, increased frequency and severity of droughts in large parts of the US (Strzepek et al. 2010). If farmers are able to access sufficient water, they may continue to grow crops, requiring more irrigation water. However, it is plausible that some farmers may choose to cease production of particular crops because of insufficient water resources or prohibitively high irrigation costs.

To accommodate these considerable uncertainties, we take a simplified approach and assume base-case water use in each sector remains constant. To determine the significance of potential changes in water use, we vary water use in each sector by a fixed amount in a sensitivity analysis. For water used for public supply and self-supplied domestic use, our base-case considered that *per capita* water use remains constant, thus county-level water use changes linearly with changes in county population. In a sensitivity analysis we consider changes in *per capita* water use of plus/minus 20%. County population projections are based on Zarnoch et al. (2010) who developed three sets of population growth projection (low, medium, and high). We use the medium growth projection in our base-case modeling, and the low and high growth projections in a sensitivity analysis to determine the significance of population on local water balance. Our base case considers that county-level water use for irrigation, livestock, aquaculture, industrial, and mining purposes remains constant. To determine the significance of changes in water use in these sectors, we conservatively vary water use in each sector by plus/minus 20% in a sensitivity analysis.

For estimation of current and future water use in the thermoelectric power sector, we developed a dataset of coal- and natural gas-fired power plants in the contiguous US, based primarily on Ventyx (2012) data. The dataset includes all power plants that emitted at least 100,000 tCO_2 in 2005. Carbon capture is less economically feasible at scales smaller than this plant size (IPCC 2005). In total, 757 power plants are included, of which 355 are fueled by coal and 402 are fueled by natural gas. Collectively the plants produced a total of 2,510 TWh of electricity and emitted 2,170 Mt of CO_2 in 2005. The average emissions intensity of the coal-fired plants was 1.11 tCO_2/MWh, and that of the natural gas-fired plants was 0.57 tCO_2/MWh.

We model future changes in electricity production based on Annual Energy Outlook (AEO) regional projections for 2030 (EIA 2011). We scale the current electricity production of each county in proportion to the AEO projections for the NERC subregion the county is in, for both coal- and gas-fired production. This results in unrealistic incremental changes in electricity production in any given county, rather than more realistic quantized changes that occur when a complete power plant is commissioned or decommissioned. Nevertheless, because we do not know in which specific county future power plants will be built, this approach allows us to evaluate large-scale regional trends and their local implications.

We developed a set of criteria for determining which of the 757 power plants are suitable for retrofitting with CO_2 capture equipment. Plants that satisfy all of the following four criteria were deemed suitable: a nameplate capacity of 200 MW or more, a capacity factor in 2005 of 50% or greater, an average heat rate of 12,000 Btu/kWh or less, and construction year of 1960 or later. A total of 217 plants met these criteria, of which 168 are coal-fueled and 49 are natural gas-fueled. Collectively the plants emitted about 1320 Mt of CO_2 in 2005. **Figure 3** shows the locations and CO_2 emissions of the power plants. These criteria were relaxed in a sensitivity analysis to determine the significance of a greater number of retrofitted plants. In addition to these plant-level criteria, the distance from the county to the nearest suitable sequestration formation (described above) also determines suitability for CO_2 capture in any given plant.

Our power plant dataset also includes information on types of plant cooling systems, including rates of water withdrawal, discharge, and consumption, and the source of the cooling water (Ventyx 2012). Cooling system data for 2005 were available for plants responsible for 94% of the total CO_2 emissions. 2005 cooling system data were not available for the remaining plants so we used 2010 data for plants responsible for 4% of CO_2 emissions and proxy average cooling data for the remaining 2% of plants. We assumed that water withdrawals per kWh for plant cooling would increase by 80% when CO_2 capture equipment is installed (Zhai et al. 2011). This value is broadly consistent with the findings of Macknick et al. (2011). We further assumed that the CCS energy penalty, defined as the percent increase in fuel input per unit of delivered electricity, is 35%. The total CO_2 production increases proportionally with the fuel use, and we assume that 90% of the CO_2 in the flue gas is captured and sequestered. Water use by nuclear power plants was assumed to remain unchanged. Water use by power plants that use saline cooling water is not accounted for in the analysis.

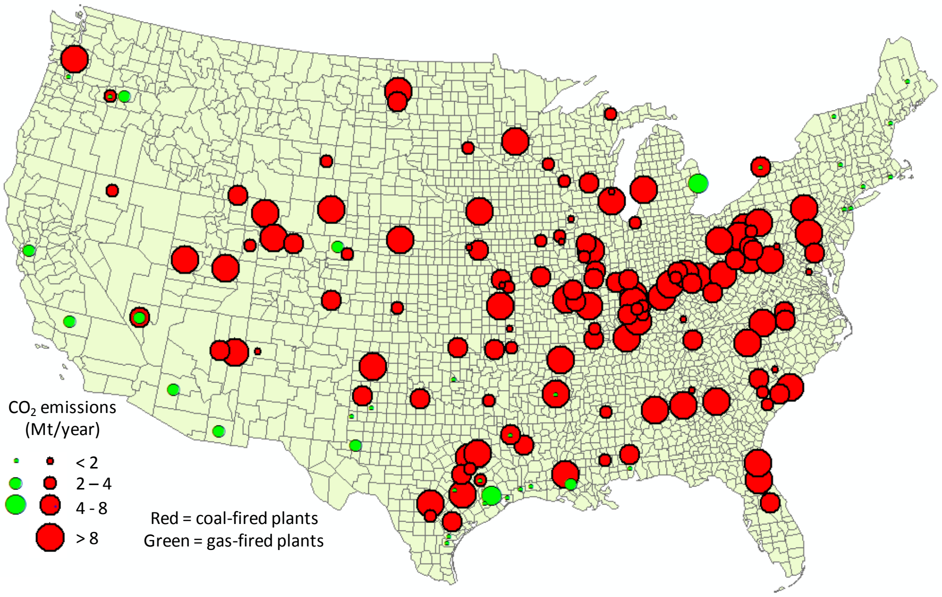

Figure 3. Locations of 217 coal-fired (red) and natural gas-fired (green) power plants that meet criteria for CO_2 capture. Size of circle corresponds to amount of CO_2 emission in 2005.

Water Stress Index

Using the water supply and water demand estimates described above, we calculate a Water Stress Index (WSI) for each county. We use the approach developed by Sun et al. (2008) and define the index as:

$$WSI = \frac{WD}{WS}$$

where *WSI* is the Water Stress Index; *WD* is total fresh water withdrawals for public supply, self-supplied domestic use, irrigation, livestock, aquaculture, industrial, mining, and thermoelectric power, in m^3/day; and *WS* is total fresh water supply from surface water, groundwater, return flows, and desalinated brine, in m^3/day. The WSI is dimensionless, and a lower value implies less water stress and a higher value implies greater water stress. The WSI includes fresh water only.

We calculate the WSI for each county under a variety of scenarios including no CCS implementation, CCS without brine extraction, and CCS with brine extraction and desalination. We consider a WSI value of unity to be a threshold, as this value implies that water demand equals water supply. We calculate the number of counties in which the county-level WSI crosses the threshold due either to the implementation of CCS (requiring additional cooling water and causing the WSI to increase from <1 to >1) or to the extraction and desalination of brine (providing additional fresh water supply and causing the WSI to decrease from >1 to <1). We sum the CO_2 emissions that would be avoided by the use of CCS in these critical counties, and determine the national-level CO_2 emission implications of CCS projects that are impeded by water constraints, and of CCS projects that are enabled by brine extraction and desalination.

3. Results

Figure 4 shows the baseline WSI for counties in 2005, assuming average annual water supply and minimum annual water supply. In the average annual water supply map, the US mean WSI is 0.19 and 117 counties have a WSI greater than 1. Not surprisingly, water stress is higher in the minimum annual water supply scenario (US average of 0.29, 189 counties with WSI greater than 1). The area most critically affected by water stress is the desert Southwest, but highly populated counties in other regions also experience water stress.

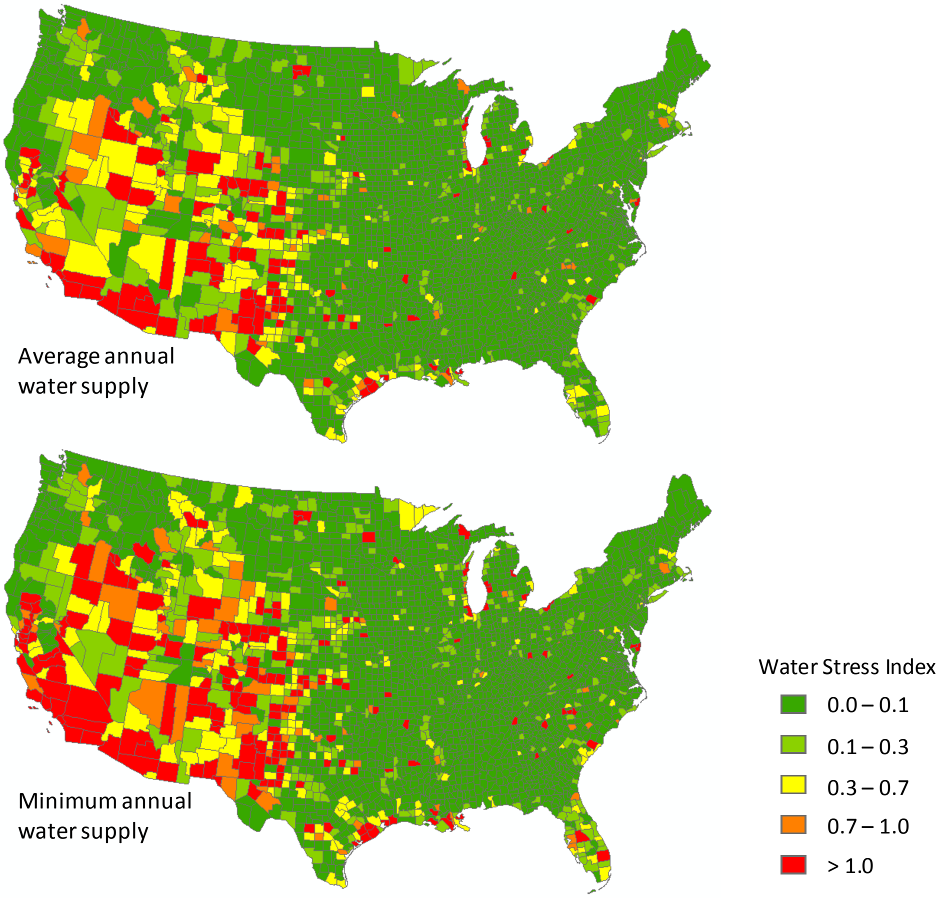

Figure 4. Baseline Water Stress Index for counties in 2005, with average annual water supply (top) and minimum annual water supply (bottom).

Figure 5 shows the WSI for all counties in 2030 with average annual water supply under three scenarios: No CCS, CCS without brine extraction, and CCS with brine extraction and desalination. The increased water stress due to additional cooling water use for CO_2 capture, and the reduced water stress due to additional water supply from desalinated brine, are evident but are not overwhelming. **Figure 6** shows similar results with minimum annual water supply. Overall the water stress level is greater due to the lower water supply, but the impacts of CCS and brine extraction on water stress remain moderate.

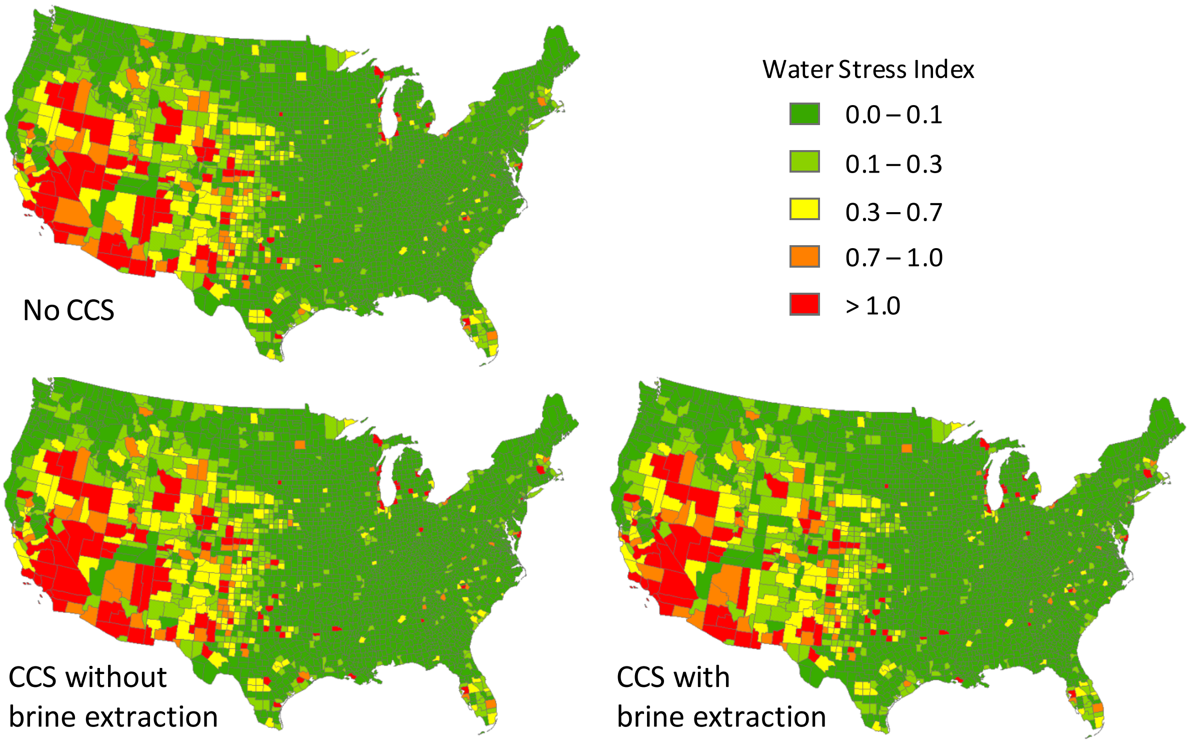

Figure 5. Water Stress Index for counties in 2030 with **average** annual water supply, for three CCS scenarios: No CCS, CCS without brine extraction, and CCS with brine extraction and desalination.

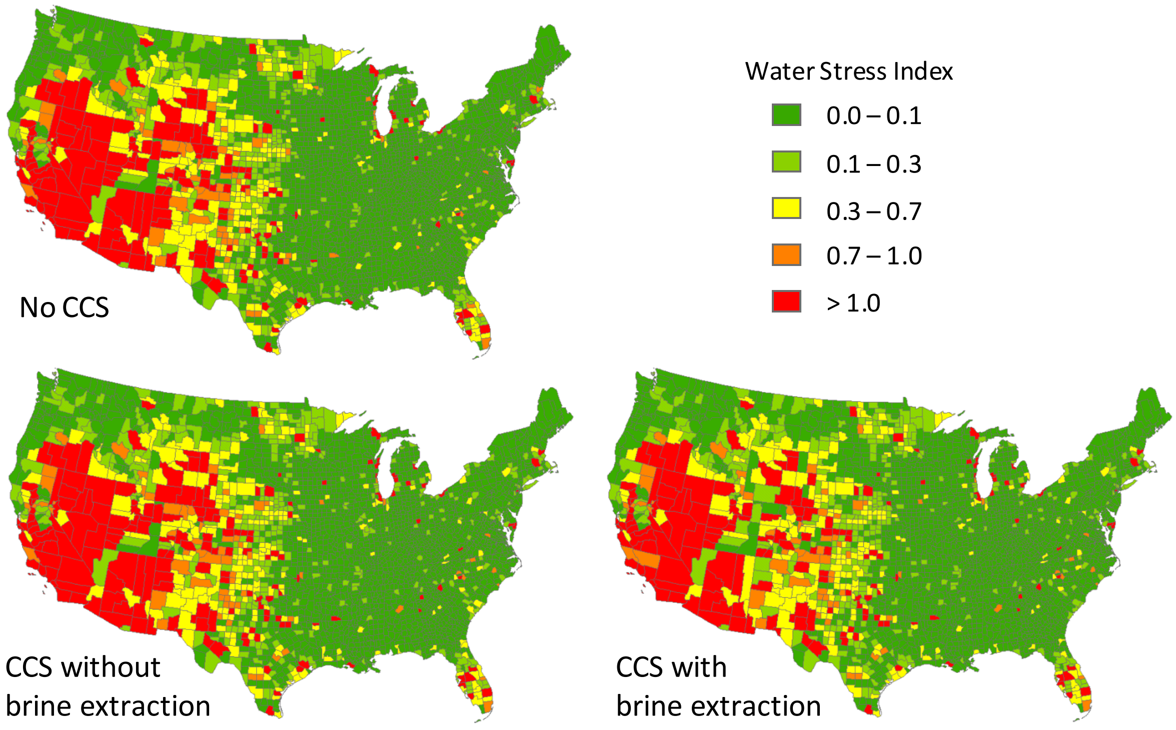

Figure 6. Water Stress Index for counties in 2030 with **minimum** annual water supply, for three CCS scenarios: No CCS, CCS without brine extraction, and CCS with brine extraction and desalination.

Figure 7 shows the increase in county-level WSI due to increased water use for CO_2 capture in power plants, as well as the decrease in county-level WSI due to the additional fresh water available from extraction and desalination of brine, under average annual water supply conditions in 2030. The WSI in some counties is strongly affected by both factors, while other counties are affected more by one or the other. These differences are caused by the variations in absolute and relative changes in water supply and demand in each county brought about by CCS.

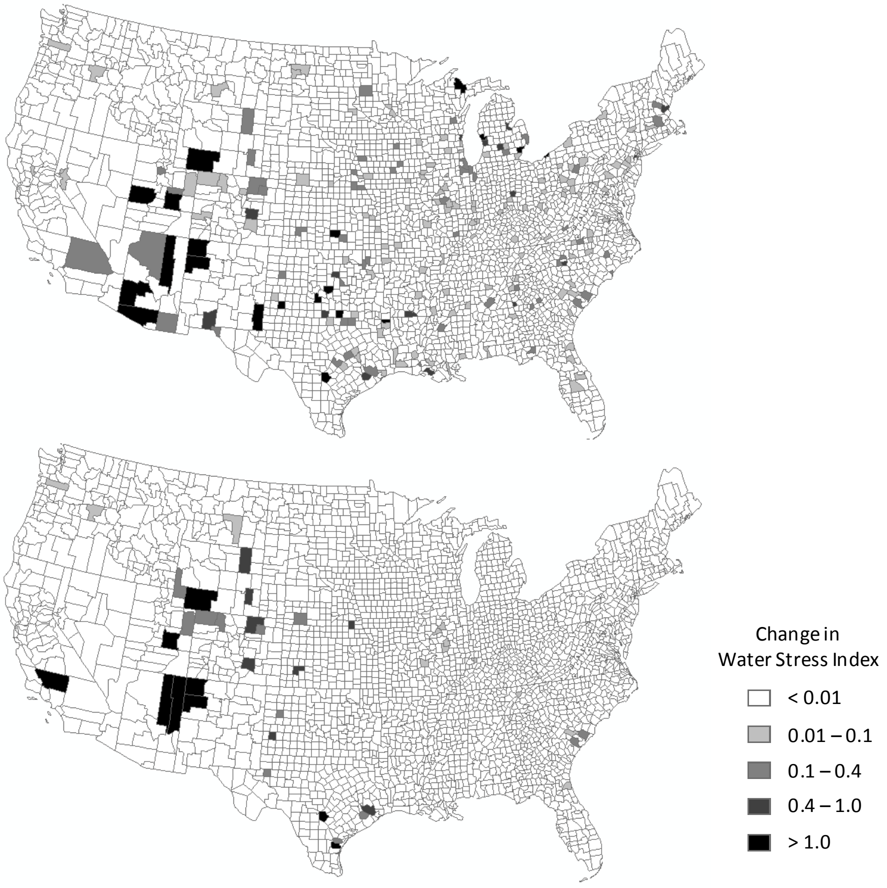

Figure 7. Increase in county-level WSI due to increased water use for CO_2 capture installations (top), and decrease in county-level WSI due to extraction and desalination of brine (bottom), under average annual water supply conditions in 2030.

Figure 8 shows annual CO_2 emissions from the 757 power plants modeled in the analysis. Emissions in 2005 were about 2170 Mt CO_2, which increases to about 2340 Mt CO_2 in 2030 if CCS is not implemented. Of the 757 plants, 217 meet the technical criteria established for suitability for retrofitting for CCS, but only 136 of those plants are located in a county less than 100 km from a suitable saline aquifer. If CCS is deployed only in counties where the deployment does not increase the county-level WSI above 1, CO_2 emission would decrease to about 1470 Mt CO_2 in the absence of brine extraction. If brine is extracted and desalinated, the additional fresh water supply would allow the deployment of CCS in 11 more counties, decreasing the CO_2 emissions to about 1390 Mt CO_2. However, it should be noted that these emissions totals do not include the energy use and resulting CO_2 emissions from brine desalination.

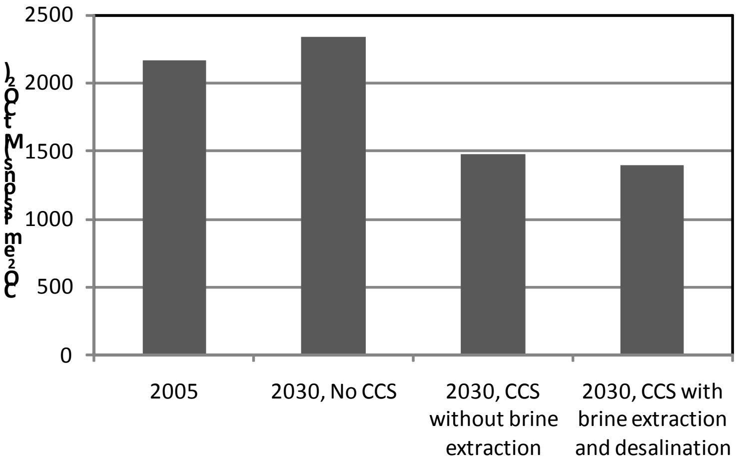

Figure 8. CO_2 emissions from modeled coal- and natural gas-fired power plants in 2005 and in 2030 under three scenarios, assuming average annual water supply.

Table 1 lists the results of a sensitivity analysis of various system parameters. Four indicators are quantified for each change in parameter value: emission reductions (Mt CO_2) from CCS projects that are made possible due to brine extraction that shifts county-level WSI from >1 to <1; nationwide fresh water balance (km^3/day), defined as the total water supply minus the total water demand; nationwide average of Water Stress Indices of all counties; and the number of counties with WSI greater than 1. The results show that most parameters have little effect on water stress and CO_2 emission reduction potentials, though several parameters are quite important.

If CO_2 is sequestered in depleted oil or gas reservoirs instead of saline aquifers, the water supply benefits of brine desalination are not realized and CCS implementation is restricted in some counties due to water stress. The allowable distance between the power plant location and the geological sequestration formation is also quite significant. If the maximum distance to an aquifer is extended from 100 km to 250 km, CO_2 capture can occur at 179 of the 217 plants that meet the technical criteria established for suitability for retrofitting. At a distance of 25 km, CO_2 capture can occur at only 112 of the plants. Altering the climate change scenario from IPCC B2 to A1B scenario results in a significant change in water balance. This is due to the difference in future climate patterns between the scenarios, with the A1B scenario having higher average water supply but also higher variability, thus lower minimum water supply.

Population growth rate, CCS energy penalty, per capita water use, and variation in water use for livestock, aquaculture, and industrial purposes have little impact on the system indicators. Increased water use for irrigation has a moderately large effect. An interesting phenomenon occurs with mining water use. Increasing water use for mining has little effect on overall water balance, but strongly affects local water balance in 12 counties with both mining and power generation. In these counties, brine extraction shifts the WSI below the threshold of unity and has a disproportionately strong impact on CO_2 capture.

Changing the criteria for which plants are retrofitted with CO_2 capture equipment result in a modest reduction of CO_2 emissions. This sensitivity analysis considers all plants larger than 100 MW nameplate capacity (instead of 200 MW), with a capacity factor greater than 40% (instead of 50%), a heat rate less than 11,000 Btu/kWh (instead of 12,000 Btu/kWh), and built after 1955 (instead of 1960). Under these less stringent criteria, an additional 21 coal-fired plants and 39 gas-fired plants can be retrofitted.

Table 1. Sensitivity of key indicators to changes in selected parameters, with average and minimum annual water supply in 2030.

			Average annual water supply				Minimum annual water supply			
Parameter	Base-case parameter value	Adjusted parameter value	Emission reduction due to brine (Mt CO_2)	Fresh water balance (km^3/day)	Average Water Stress Index	Number of counties with WSI>1	Emission reduction due to brine (Mt CO_2)	Fresh water balance (km^3/day)	Average Water Stress Index	Number of counties with WSI>1
Base-case	**See below**	**N/A**	**79.1**	**95.9**	**0.15**	**83**	**112.6**	**60.9**	**0.27**	**167**
CCS deployment	Yes	No	-79.1	-0.92	-0.003	-7	-112.6	-0.92	+0.010	+3
Brine extraction	Yes	No	-79.1	-1.34	+0.024	+11	-112.6	-1.34	+0.073	+16
Climate scenario	IPCC B2	IPCC A1B	-4.8	+4.62	-0.039	-22	+30.9	-29.13	+0.026	+23
CO_2 capture water use	80%	40%	-2.1	+0.21	-0.009	-6	0.0	+0.21	-0.017	-5
Energy penalty	35%	20%	0.0	-0.15	0.000	+1	-0.4	-0.15	0.000	+1
Distance to aquifer	100 km	25 km	-12.2	-0.24	+0.012	+2	-14.0	-0.24	+0.046	+3
Distance to aquifer	100 km	250 km	+24.5	+0.54	-0.005	-3	+42.8	+0.54	-0.011	-4
Brine:CO_2 volume ratio	1:1	0.5:1	-4.6	-0.67	+0.002	+3	-2.3	-0.67	+0.002	+1
Oil and gas reservoirs	No	Yes	-68.9	-1.07	+0.012	+10	-96.2	-1.07	+0.027	+13
Plants retrofitted	217	277	-0.6	-0.08	-0.001	-3	-0.7	-0.08	-0.004	-2
Population growth	Medium	Low	0.0	+0.01	-0.001	0	0.0	+0.01	-0.002	-3
Population growth	Medium	High	0.0	-0.01	+0.001	+1	0.0	-0.01	+0.003	0
Per capita water use:										
Public and domestic	Unchanged	+20%	0.0	-0.05	+0.006	+2	0.0	-0.05	+0.011	+4
Public and domestic	Unchanged	–20%	0.0	+0.05	-0.006	-4	0.0	+0.05	-0.011	-4
County-level water use:										
Industrial	Unchanged	+20%	0.0	-0.01	0.000	0	0.0	-0.01	+0.001	0
Industrial	Unchanged	–20%	0.0	+0.01	0.000	0	0.0	+0.01	-0.001	-1
Irrigation	Unchanged	+20%	+8.5	-0.11	+0.012	+14	+17.0	-0.11	+0.023	+16
Irrigation	Unchanged	–20%	-2.1	+0.11	-0.012	-11	+0.9	+0.11	-0.023	-20
Livestock	Unchanged	+20%	0.0	0.00	0.000	0	0.0	0.00	0.001	+1
Livestock	Unchanged	–20%	0.0	0.00	0.000	-1	0.0	0.00	-0.001	0
Aquaculture	Unchanged	+20%	0.0	-0.01	+0.001	0	0.0	-0.01	+0.002	0
Aquaculture	Unchanged	–20%	0.0	+0.01	-0.001	0	0.0	+0.01	-0.002	0
Mining	Unchanged	+20%	2.9	0.00	0.000	0	0.0	0.00	+0.001	0
Mining	Unchanged	–20%	0.0	0.00	0.000	0	0.0	0.00	-0.001	0

4. Conclusions and Future Research

In this analysis we have considered how CCS implementation affects water stress, and how water stress in turn affects CCS implementation. Because water stress varies from place to place, we have conducted a geospatial analysis detailing the county-level balances of water supply and demand across the contiguous United States. Our focus has been to identify and understand the major sources of uncertainty and variation regarding the water-CCS nexus.

We find that CCS can strongly affect freshwater supply and demand in specific regions, but overall it has a moderate effect on water balances. The use of extracted brine to overcome local water constraints may enable the capture and sequestration of about 100 Mt CO_2 annually over what would have been possible without brine extraction. The importance of extracted brine increases as the water supply becomes more limited, a condition that is increasingly likely to occur as future climate becomes more unstable.

There are several issues that introduce uncertainty and may affect the results of this analysis, and we intend to improve upon these areas in subsequent analyses. For example, the WaSSi water supply model does not consider water storage (e.g. in reservoirs), which could moderate inter-annual variability in water supply. Furthermore, the contributions of return flow to total water supply are held constant in our modeling, though in fact return flow quantities will vary due to changes in water use or return flow rates.

We used regional climate projections from the CSIRO MK2 climate models of Australia's Commonwealth Scientific and Industrial Research Organisation. To determine the significance of the particular climate model, projections from other climate models, for example GCGM2 (Climate Centre for Modelling and Analysis) and HadCM3 (Hadley Centre for Climate Prediction and Research UK), should be compared. In all cases, however, the definitive effects of future climate change on water supply are uncertain, and include both spatial variation and temporal variation. In this analysis we have defined the minimum annual water supply for each HUC unit as the lowest value of each county among the 9-year sampling period. This represents an extreme case of drought across the entire country. In practice, drought in some HUC units will likely be moderated by average or above-average water supply in other, upstream HUC units. Sampling each county separately would account for this factor, though some measure of regional correlation in weather and climate should be included.

This analysis has considered only one management option for extracted brine: desalination for use as fresh water. A range of other potential uses for brine exist, such as mineral recovery, algae ponds, and de-icing salt production (Breunig et al. 2011). Extracted brine can also potentially be used directly for power plant cooling without desalination (Kobos et al. 2011). In addition, brine extraction can have negative effects on water balances if freshwater is needed for dilution. The significance of these potentials should be explored further.

We have only considered water withdrawals in this analysis, which is an important metric but does not fully describe the implications of water use. Water consumption, resulting from e.g., evaporation or transpiration, is important as well. An expanded analysis quantifying both the withdrawals and consumption associated with CCS would be illuminating. This could include, for example, the differing impacts of once-through and recirculating cooling systems.

In a more sophisticated analysis, water stress could be considered as a proxy for the cost or value of water. Local water stress could be used as a criterion for weighing the need or likelihood of applying various options (e.g., in a water-stressed area, water will be more “valuable” and it may be more economically feasible to use brine as a water source). The attractiveness of using desalinated brine as a water source would likely depend on the water stress of a region. Areas with greater water stress may be more likely to transport CO_2 and brine across further distances. The potential impacts on water balance of dry cooling methods, which are generally more expensive than water-based cooling methods, could also be elaborated.

In summary, this analysis is offered as an initial exploration of the potential local implications of CCS. We have observed some overall trends and identified some of the factors that appear to influence them. Additional work is needed, however, to further solidify the understanding we have gained here and to extend the analysis to address new questions.

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