Regional responses to future, demand-driven water scarcity

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Abstract

This paper explores regional response strategies to potential water scarcity. Using a model of integrated human-earth system dynamics (GCAM), we test a wide range of alternate water demand scenarios to explore regional response strategies. We create a typology that categorizes countries and basins according to their responses in electricity and agriculture to potential water scarcity. Three different categories are found. First, little response is observed for many basins because water demands do not increase enough to create scarcity. Second, the primary response is adjustments in the electricity sector (e.g. most basins in Western Europe, the United States and China) with a transition to water-saving cooling systems but marginal impact on total power generation or the fuel mix. Third, where there is a lack of sufficient responding capacity in the electricity sector (e.g. Pakistan, Middle East and several basins in India), additional response occurs through reduced irrigation water withdrawals, either by switching from domestic production to imports or from irrigated agriculture to rain-fed production. The primary response mechanism to demand-based water scarcity for individual basins is quite robust across the range of water demand scenarios tested. The results and typology in this paper will be valuable for future research exploring global water scarcity due to both demand and supply drivers.

1. Introduction

There are increasing concerns that water scarcity may serve as a critical constraint on future human development and welfare (Hanasaki et al 2013b, Hejazi et al 2014a, Schewe et al 2014, Schlosser et al 2014). Over 40% of the global population is already affected by a shortage of freshwater, and more than 1.7 billion people are currently living in highly water-scarce river basins (United Nations 2015). Future stress will be affected by changes in both water supplies and demands, and these stresses may vary significantly across regions (Hagemann et al 2013, Hanasaki et al 2013a, Hejazi et al 2014b, Schewe et al 2014, Fujimori et al 2017). This paper focuses on the implications of demand-driven stresses emerging from socioeconomic and technological changes. Several insights have already emerged from this literature. First, at the global level, total water demand is likely to increase throughout the century across a wide range of possible socioeconomic pathways due in large part to expected population and economic growth (Hanasaki et al 2013a, Hejazi et al 2014b). Demand-driven water stresses are expected to increase, in particular, in basins in which freshwater resources are limited, such as the Middle East, North Africa, Pakistan, India, and Northeast China (Hanasaki et al 2013a, Hejazi et al 2014a, Schlosser et al 2014, Damerau et al 2015). Second, sectoral (i.e., electricity and agriculture) water demand is highly dependent on decisions such as technological and crop choices, which, in turn will be influenced by broader societal goals such as clean air, electricity and food access, and reducing greenhouse gas emissions (Davies et al 2013, Kyle et al 2013, Damerau et al 2015, Bijl et al 2016, Fricke et al 2016, Ando et al 2017, Fujimori et al 2017, Srinivasan...
et al 2017). For example, thermoelectric generation technologies (e.g. nuclear, coal, bioenergy) can require large water withdrawals, while technologies such as wind or solar will have only modest demand for water withdrawals (Macknick et al 2012a, Kyle et al 2013, Liu et al 2015, Smith et al 2015). Likewise, crop choices (including bioenergy), conversion of rain-fed to irrigated cropland, as well as decisions about afforestation will have a large effect on water use in agriculture and land-use (Berndes 2008, Rockström et al 2012, Elliott et al 2013, Chaturvedi et al 2015). Third, response options in both electricity and agriculture are crucial for lowering water demand to alleviate water stress. For example, the adoption of water-efficient cooling technologies in power generation is expected to reduce future electricity water withdrawals in the United States (Macknick et al 2012b, Davies et al 2013, Liu et al 2015).

Irrigation water savings through improved efficiency and crop calendar adjustment are critical in water-stressed Asia (Hayashi et al 2013).

This paper explores both where demand-driven water scarcity might emerge in the future and the associated response strategies. Building on the work of Kim et al (2016), we use an integrated human-earth system model with representations of energy, water, land, the economy, and the climate (GCAM) to explore how changes in total and sectoral water demand driven by alternate socioeconomic and energy technology pathways might trigger different regional responses to potential water scarcity. We first look at the responses in energy and agriculture by comparing water withdrawals between scenarios in which there are no limits on water supplies and scenarios in which freshwater is limited at today’s level and groundwater supply is based on a number of interrelated factors including exploitability, extraction costs and depletion. To help understand the varying regional results, we present a typology of response types based on the relative responses in electricity and agriculture. To explore robustness against uncertainty, we test a number of alternate water demand scenarios to explore whether different assumptions about socioeconomic, or the cost and availability of energy technologies affect individual basins’ response mechanism, as well as which combination of these drivers has the largest impacts on different sectors.

2. Methodology

2.1. The integrated modeling framework

GCAM is a global integrated human-earth system model that represents and links the energy, water, agriculture and land-use, economy, and climate systems (Calvin et al 2017). GCAM is a dynamic-recursive and market-equilibrium model that solves at five-year intervals from 2010 to 2100. It disaggregates the globe into 32 geopolitical regions, where all energy and economy markets are balanced. This study uses a version of GCAM that endogenously balances water demand and water supply at each of 235 water basins (Kim et al 2016). Land allocation and agricultural production are modeled at the intersection of the 32 geopolitical regions and the 235 water basins. Primary energy (such as fossil fuels), agricultural products, and biomass are freely traded globally, while secondary energy (such as electricity) is traded regionally.

2.2. Water demand and water supply in GCAM

This version of GCAM represents water demand in agricultural, energy, industrial, and municipal sectors at different spatial resolutions. Detailed calculation of water demand in each sector are described in Kim et al (2016). In this study, we focus on water withdrawals, noting that in certain cases there are trade-offs between water withdrawal and consumption (Macknick et al 2012a, Davies et al 2013, Liu et al 2015).

Agricultural water demands are represented at the basin level. Electricity, industrial, and municipal water demands are represented at GCAM’s 32 geopolitical regions and are then downscaled to individual water basins.

Water supply includes three components: accessible freshwater, non-renewable groundwater and desalinated seawater. At each basin, freshwater availability is calibrated to recent history and is assumed to remain constant over time. Groundwater resources and costs are estimated based on a number of factors including exploitability, extraction costs and depletion. We assume that up to 25% of the total available groundwater is available (Turner et al 2018). Desalinated water can be extracted for a fixed cost.

Water demands and supplies are balanced in each water basin based on prices. Several response options are available for reducing water demands. Agriculture water uses can be reduced by converting irrigated to rain-fed technologies, changing the crops that are produced, or by switching domestic production to imports via international trade. Electric water demands can be lowered via the choice of alternative cooling as well as energy technologies. The choice of cooling-technology also alters the cost competitiveness of different energy technologies. Without a water price, the share of different cooling systems in electric power generation are estimated for individual regions (Davies et al 2013). When water availability is limited, a transition toward water-efficient cooling-technology can help alleviate the impact on the energy system.

2.3. Scenarios

To better understand possible future demands, we explore changes in water demand driven by alternate assumptions along three dimensions: population and GDP trajectories, greenhouse gas (GHG) emission pathways, and energy technology futures. In total, we explore 24 scenarios representing different levels of
future water demand (table S1 is available online at stacks.iop.org/ERL/13/094006/mmedia). In addition, for each of the alternative demand cases, we run two different supply simulations—one without any supply limitations and the other where water supply is constrained at today’s level. Therefore, we run 48 simulations in total.

To represent variation in socioeconomic dynamics, we employ three out of five of population and GDP trajectories defined as in the Share Socioeconomic Pathways (SSP) (O’Neill et al. 2015). The three chosen cases are intended to capture more extreme scenarios. Rapid population growth—as featured in SSP3—tends to drive up irrigation water use due to high total food demand, and rapid GDP growth—as featured in SSP5—is expected to drive up electricity water withdrawals due to high energy demand. We only use the population and economic assumptions from the SSPs, without changing other assumptions.

We apply two GHG emission pathways to explore the interactions between international efforts to reduce emissions and water constraints. We include a scenario with no international effort in this regard as well as one of the Representative Concentration Pathways (RCPs) that stabilizes radiative forcing at 4.5 W m⁻² in the year 2100 (Thomson et al. 2011). Because certain low-carbon technologies have high water footprints while others do not (Macknick et al. 2012b), the interactions between international efforts to reduce carbon emissions and water constraints can be either trade-offs or synergies, depending on the technology future (Webster et al. 2013, Huang et al. 2017).

With regards to technology, we explore four different assumptions about the cost and availability of different technologies in the energy system. The four assumptions are: all technologies are available (FullTech), conventional technologies dominate and renewables are limited (Conv), carbon capture and storage is not available (NoCCS), and all technologies are available but energy demand is lower (EE) (Kriegler et al. 2014).

In order to assess response options, we run all the 24 combinations of demand variations with two alternative supply simulations, respectively. The first one is ‘unlimited’ water supply where any level of water demand is met automatically without limitations—the equivalent to not balancing demand and supply at all, and the other balances demand to the ‘status quo’ water supply where freshwater are limited at current level and groundwater are based on basin-specific exploitability, extraction costs and depletion. To determine the responding changes, we look at the differences between the two water supplies simulations for each of the demand scenarios. We do not test different supply sensitivities, for instance, future climate change impacts on water supply are excluded, so that we can separate the effects and focus on demand variations.

3. Results

3.1. Categories of response

To illustrate the different response mechanisms across basins, we adopt a typology and identify three categories of response types and levels—‘limited response’, ‘electricity-focused response’, and ‘electricity and agricultural response’. These response categories are defined according to the changes in sectoral water withdrawals from the unlimited to the constrained water supply case. First, basins with ‘limited response’ are those in which electricity or irrigation water withdrawals are not substantially reduced (less than 10%) or not reduced at all. Second, basins with ‘electricity-focused response’ are those in which the primary response is to reduce electricity water withdrawals (more than 10%) without lowering irrigation water use. Third, basins with ‘electricity and agricultural response’ take additional responses in the agriculture and land-use sector, beyond those in electricity, to lower irrigation water withdrawals (more than 10%). Choice of the specific threshold does not affect our main findings. Sensitivity analysis of a range of the cutoff values between 5%–20% can be found in supplementary information (S3).

For the purposes of illustrating these categories, we provide examples based on a benchmark demand scenario in which population and GDP trajectories are defined under SSP1, there are no international efforts to reduce carbon emissions, and the FullTech energy future is used. An overview of results across scenarios is provided in figure 2 and discussed in section 3.2.

For each basin example, we first show water withdrawals by sector with the benchmark demand scenario under unlimited and constrained water supplies (figure 1(a)). According to the definition above, the La Plata basin in Brazil is an example of a basin with limited response, as neither irrigation nor electricity water withdrawals decrease from unlimited to constrained water supplies; the Yangtze basin in China is an example of a basin with an electricity-focused response in the benchmark scenario, with large decreases in electricity water withdrawals and small increases in irrigation water withdrawals; and the Indus basin in Pakistan is an example of a basin with electricity and agricultural response where both electricity and irrigation water withdrawals largely decrease through the century.

We then look at the implications on crop production (at the basin level) and electricity generation (at the country level where electricity supply and demand are balanced). First, for basins that have limited response such as the La Plata basin, impacts on crop production is trivial with slightly increased crop production when water supply is constrained in the model (figure 1(c)). Similarly, total electricity generation in Brazil is marginally affected—reduced by less than 1% by the end of the century from unlimited to constrained water supplies, and little impact is observed...
on fuel mix or cooling technologies. Many basins in Canada, Northern Latin America, Western Africa, Australia, and Japan are in this category under the benchmark demand scenario (figure S1).

Second, for basins that have electricity-focused response such as the Yangtze basin, demand for electricity water withdrawals are usually high and thus have a large potential for adaptation. Moreover, the large decline in electricity water withdrawals is achieved through more rapid advancements in water-saving technologies of the cooling systems, especially for coal, without affecting the fuel mix or total power generation (figure S2(b)). Because China has a sizable power sector and a large potential for adaptation in the cooling system (figure S2(a)), the water saved through cooling efficiency improvements can be used to expand irrigated crop production in the majority of basins. As a result, we observe increased irrigated production of wheat, rice, and miscellaneous crops in the Yangtze basin (figure 1(c)) that compensate the output losses domestically as well as in other regions through global agriculture trade (figure S3). The majority of basins in China, India, the United States, Russia, Eastern Africa, and Western Europe are in this category under the benchmark demand scenario (figure S1).

Third, basins with both electricity and agriculture response usually have high irrigation water demand and lack capacity to sufficiently respond through reductions in electric water use. In the Indus basin example, on one hand, demand for irrigation water withdrawals are high (figure 1(a)) because rain-fed agriculture is quite limited in this basin (figure 1(b)); on the other hand, electricity water withdrawals are already very low (figure 1(a)) so that there is little room for response and water savings. As a result, wheat, rice, miscellaneous crops and sugar crops production shift to other basins, such as Southern China (figure S3). In the Indus basin, irrigated water withdrawals and agricultural production quickly decline starting in 2030 because of constraints on groundwater. Groundwater continues to be exploited at very high rates in the next 10–15 years, which significantly increase costs of extraction (Turner et al 2018). By 2030, it becomes uneconomical maintain these high levels extraction.

It is important to note that nearly all basins in this category have large reduction in electricity water withdrawals (figure S1), suggesting that response in the agricultural and land-use sector are typically in addition to response in the electricity sector. Additional agriculture responses are found in in the Sabarmati basin in India (figure S6) and most basins in the Middle East—such as the Arabian Peninsula basin (figure S7), which are characterized as having a small power
sector with little water-saving potential and an agriculture sector that relies largely on irrigation. As a result, from unlimited to constrained water supplies, a large portion of crop production in these basins are shifted to other regions (figure S3).

A few other basins in Western US and Central China also take additional responses in the agriculture sector, while both countries have a sizable power sector and the capacity to adapt in electricity generation. In particular, the potential of adapting through cooling-technology mainly exists in Central and Eastern US where most once-through cooling systems are currently installed; while water is already limited in Western US and there is little room to further reduce electricity water withdrawals over the century (Macknick et al. 2012b, Averyt et al. 2013, Liu et al. 2015, Talati et al. 2016). The California River basin, for instance, already has very small electricity water withdrawals and thus takes additional responses in agriculture to reduce irrigation water withdrawals by lowering crop production that mainly relies on irrigated agriculture (figure S8). The Huang He basin in China, by contrast, has high electricity water withdrawals and a large potential to respond (figure S9). However, the saved electricity water withdrawals cannot offset the impact on irrigation when water availability is limited. As a result, additional response occurs in the agriculture and land-use sector due to insufficient responding capacity in power generation. Moreover, the Huang He basin has more adaptation options in the agriculture sector because rain-fed agriculture is available for certain crops (figure S9(b)). Specifically, irrigated wheat production largely decline and are replaced by rain-fed miscellaneous crops (figure S9(c)).

3.2. Response to varying changes in water demand
An important consideration in understanding future response strategies to changing water demands is how robust these strategies might be across different future demand scenarios. We find that although total and sectoral water demand vary largely along the alternate assumptions of socioeconomic, emission and technological drivers, for the majority of basins, the dominant response mechanism is quite robust across the range of demand scenarios tested. Specifically, basins with limited response to the constrained water supply often always have little change across the total of 24 demand scenarios—a fraction of one that is indicated by the darkest color (figure 2), basins with electricity-focused response often always adapt only in electricity sector, and basins with the electricity and agriculture response often always make additional changes in agriculture beyond electricity.

We do, however, find a relatively small number of basins change their response mechanism across scenarios. We find that basins may alternate between the limited response category and the electricity-focused response category or between the electricity-focused response and the electricity and agriculture response category when water demands change. No basins switch directly from the limited response category to the electricity and agricultural response category. At the global level, population and GDP trajectories have larger impact on total water withdrawals than emission pathway or energy technological assumptions (figure S10). Specifically, rapid population growth under SSP3 results in high irrigation water withdrawals, while rapid GDP growth under SSP5 leads to high electricity water demand, particularly when water-intensive technologies are available and combined with a low-carbon pathway (figure S10).

In basins where future water demand is close to but not constrained by today’s water availability, there is the potential to shift between the limited response and electricity-focused response categories. This includes basins such as the Great Lakes basin as well as several others in Southern South America (figure 2). Scenarios with high total water demand (e.g. SSP3 and SSP5 population and GDP trajectories) are more likely to drive the basin from a limited response to an electricity-focused response (figure S3(a)).

Basins where water is always a constraining factor across scenarios will generally always include an electricity-focused response but may add an additional agricultural response when sectoral water demand changes. This includes several basins in the United States, Northern Africa, and Central Asia (figure 2). Scenarios with low GHG emissions pathways (RCP4.5) are less likely to shift the basins response strategies to include a reduction in irrigation water withdrawals in addition to changes in electric water demand (figure 3(b)). For example in the Missouri River basin, we observe more responses in electricity and less responses in agriculture under the low GHG emission pathways (figures S4(a) and (d)). On one hand, limiting GHG emissions increases electricity water demand due to the adoption of water-intensive low-carbon technologies—particularly coal with CCS and nuclear power generation in the United States (figure S5(c)). It thus adds response potential in electricity mainly by advancing cooling technologies and partly by changing the fuel mix towards more water-efficient renewable energy technologies such as wind and solar (figure S5(d)). On the other hand, low GHG emission scenarios increase irrigation water demand due to bioenergy expansion in the United States (figures S4(b) and (e)), which makes it more difficult to respond in agriculture.

4. Discussion and conclusion
Three major themes emerge through our analysis. First, there is a consistent order to the response approaches regions might take when faced with water scarcity, at least with regards to electricity sector reductions and agricultural sector reductions. Reductions in withdrawals for electricity are undertaken...
first; responses in agriculture are generally undertaken after exhausting most of the options in electricity. In this case, the responses in electricity are mainly achieved through more rapid advancement in water-saving cooling systems but with little impact on total power generation or the fuel mix, and responses in agriculture are achieved by switching from domestic production to imports and from irrigated to rain-fed
agriculture. Second, because individual basins’ responses are fairly systematic, it is possible to develop a typology to classify different response types and levels into three categories—‘limited response’, ‘electricity-focused response’, and ‘electricity and agricultural response’. Third, although response mechanisms vary across basins, the dominant response strategy for individual basins is quite robust across the range of alternate water demand scenarios tested. This suggests that changes in sectoral and total water demand have little impact on where water scarcity might emerge in the future and the response strategies that are undertaken in response to such demand-driven water scarcity.

This overall line of argument is undoubtedly influenced by several aspects of our modeling approach, but we believe our finding that electricity tends to adapt before agriculture could have some real-world implications. First, GCAM uses a market-based approach to determine the water allocation across sectors in each basin. We mimic the lower water payments in agriculture than in industry or households ( Sağlam 2013, 2014) by implementing a subsidy on irrigated water in the model (Kim et al. 2016). Therefore, the agricultural sector only sees a fraction of the price seen by other sectors, making it less sensitive to price change. This assumption is held across all regions and scenarios for simplicity, but actual sectoral priority tends to be more variable as it depends on specific policy contexts. Second, investment decision-making is an extremely complex issue. We acknowledge that cooling-technology retrofits often require large time and financial investments, and thus in reality, responses in electricity may not occur at the scale or rate shown here due to the barriers that are outside the scope of our analysis. Meanwhile, retrofitting irrigation technologies—such as from flood to drip irrigation—also requires additional capital and operational costs that often hinder adoptions, especially for the poor households (Blanké et al. 2007, Maraseni et al. 2012). There are also a variety of non-financial factors that influence the adoption of water-saving technologies at farms (Khanal et al. 2018) and need policy incentives to implement (Nikouei et al. 2012). Third, we balance water withdrawals, not consumption, with supply, because it tends to be more relevant to the discussion of water scarcity as it is often measured as a ratio between water withdrawal and availability in the literature (Hejazi et al. 2014a). Balancing consumption with supply tends to encourage more adaptation that lower consumption, which may change the dynamics because water consumption is relatively low in electricity and less dependent on cooling system.

Moreover, there are several factors that would tend to either reinforce or diminish the logic of this paper. For example, on one hand, some lower-cost response options in the land-use and agriculture sector, such as water-efficient irrigation and better management practices, are not available in our analysis. The presence of these options would be expected to allow greater flexibility to undertake agricultural responses at low cost, blurring the separation between electric and agricultural responses. A more granular typology of responses might distinguish not only between sectors, but also between options within sectors. On the other hand, agricultural trade is quite flexible in the version of the model used in this analysis. Flexible international agricultural trade makes it easier to adapt through trade, particularly for basins in Pakistan and Middle East where production substantially declines when water availability is limited. A less flexible system of international trade would tend to make adjustments in agricultural water use even more costly.

There are several additional aspects of our methodology that could influence our results. First, our analysis focuses on the water basin level, but may still overlook the within-basin variations and sectoral interactions. For large basins, in particular, it is possible that certain areas are stressed while others are not, due to unbalanced distribution of water demand. Second, while we explore a large range of scenarios, we do not cover the full uncertainty range. Alternative scenarios may lead to different outcomes. Third, GCAM currently does not have technological innovation on the water supply side—such as water recycle and reuse, which may provide important alternative supply strategies in certain regions.

Finally, we would like to highlight that the approach developed in this paper can be applied to assess responses to water scarcity that is driven by changes in not only water demand but also water supply. Changes in future precipitation could potentially exacerbate scarcity for some regions, particularly those already under water stress, and alleviate it in others (Hagemann et al. 2013, Hejazi et al. 2014a, Schewe et al. 2014). We look to future research to explore the implications of these and other aspects of modeling and understanding water scarcity and response strategies many decades into the future.

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