Economic impacts of climate change on water resources in the coterminous United States*

James Henderson, Charles Rodgers, Russell Jones, Joel Smith, Kenneth Strzepek and Jeremy Martinich

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Ronald G. Prinn and John M. Reilly,
Program Co-Directors

ORIGINAL ARTICLE

Economic impacts of climate change on water resources in the coterminous United States

James Henderson · Charles Rodgers · Russell Jones · Joel Smith · Kenneth Strzepek · Jeremy Martinich

Abstract A national-scale simulation-optimization model was created to generate estimates of economic impacts associated with changes in water supply and demand as influenced by climate change. Water balances were modeled for the 99 assessment sub-regions, and are presented for 18 water resource regions in the United States. Benefit functions are developed for irrigated agriculture, municipal and domestic water use, commercial and industrial water use, and hydroelectric power generation. Environmental flows below minimal levels required for environmental needs are assessed a penalty. As a demonstration of concept for the model, future climate is projected using a climate model ensemble for two greenhouse gas (GHG) emissions scenarios: a business-as-usual (BAU) scenario in which no new GHG controls are implemented, and an exemplary mitigation policy (POL) scenario in which future GHG emissions are mitigated. Damages are projected to grow less during the 21st century under the POL scenario than the BAU scenario. The largest impacts from climate change are projected to be on non-consumptive uses (e.g., environmental flows and hydropower) and relatively lower-valued consumptive uses (e.g., agriculture), as water is reallocated during reduced water availability conditions to supply domestic, commercial, and industrial uses with higher marginal values. Lower GHG concentrations associated with a mitigation policy will result in a smaller rise in temperature and thus less extensive damage to some water resource uses. However, hydropower, environmental flow penalty, and agriculture were shown to be sensitive to the change in runoff as well.

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1 Introduction and literature

Water resource systems are already under stress in many locations across the United States (US) (Karl et al. 2009). Projected changes in the timing, intensity, and variability of temperature and precipitation associated with climate change are anticipated to affect many aspects of water resource systems. As described in the United Nations Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4, Kundzewicz et al. 2007) and subsequent reports (e.g., Bates et al. 2008), the broad manifestation of climate change is an intensification of the hydrologic cycle, characterized by increases in atmospheric water vapor, precipitation, and evapotranspiration (ET_0). Induced changes in regional hydrology include alterations in patterns of stream discharge and groundwater recharge; changes in snowpack (which affect stream discharge); increased evaporation from lakes, reservoirs, and other freshwater bodies; increased incidence of severe flood and drought events; and changes in water quality.

Collectively, these impacts are likely to significantly alter future water supply conditions in the US. In addition, climate change is anticipated to influence, and possibly amplify, trends in the demand for water resources as affected communities attempt to adapt to warmer and, in many regions, drier and more variable physical environments. Thus climate change will affect both water supply and demand (Karl et al. 2009).

Changes in water demand are not the only water-related effects of climate change. Increases in population and economic activity within water-constrained regions of the western and southeastern US, along with the increasing long-term demand for electric power generation, create higher demand for instream and abstractive water use (Karl et al. 2009). Increasing societal concern with preserving and restoring the integrity and health of aquatic ecosystems also increases demand for fresh water.

To date, few attempts have been made to develop comprehensive estimates of the economic impacts of climate change in the U.S. water resources sector. Frederick and Schwarz (1999) estimated costs associated with changes in instream and abstractive water use, including environmental flow management and costs of adaptation to flow changes. Their analysis estimated the annual cost to the water resource sector of effects associated with climate change to be between \$136 and \$327 billion per year (adjusted to 2007\$), depending on scenario assumptions and choice of general circulation model (GCM) projection. Frederick and Schwarz (1999) used both an extremely wet GCM projection (HadCM2), which indicated increased flows within every U.S. WRR, and an extremely dry projection (CGCM), which projected major reductions in flow in all WRRs excluding California, leading to both very large (dry) and very small (wet) estimates of climate change costs. Hurd et al. (1999) also examined water resource flow and supply conditions, as well as the costs (i.e., benefits of avoiding impacts) associated with flooding and water quality. Hurd et al. (1999) estimated the national damages of climate change on U.S. water resources (2007\$) to range between a benefit of \$12.3 billion per year (associated with a hypothetical 15 % increase in precipitation and modest warming of 1.5 °C) and a cost of \$54.5 billion per year (associated with warming of 5 °C and no change in precipitation nationally).

Monetary estimates of the economic value of water use are more commonly undertaken for single watersheds or river basins. Some researchers have investigated the overall effects of climate change (e.g., Tanaka et al. 2006 and Medellin-Azuara et al. 2008), while others have focused on evaluating specific impacts, such as drought (e.g., Booker 1995; Cai et al. 2003; Cai and Rosegrant 2004).

The objective of our analysis is to provide a demonstration of concept for the model that quantifies and value the impacts of climate change on the supply and demand of water in the contiguous US. Our approach assesses these changes under two greenhouse gas (GHG) emission scenarios: a business-as-usual (BAU) future, and a GHG mitigation policy scenario assuming international action. This analysis is intended to provide information regarding the vulnerability of the U.S. water resource system, and to estimate the benefits of GHG mitigation policy.

2 Methods and model development

Our approach comprises five main steps: (1) developing, validating, and calibrating a water simulation-optimization model for multiple water resource sectors in the contiguous United States (Sections 2.1 and 2.2), (2) specifying functions describing the benefits of water use for each water-using sector within the models (Section 2.3), (3) projecting future climatic conditions under different GHG emission scenarios (Section 2.4), (4) calculating changes in streamflow based on disaggregated projections of temperature and precipitation (Section 2.5), and (5) running the simulation-optimization model (with results described in Section 3).

2.1 Water simulation-optimization model

We created a national-scale simulation-optimization model to generate estimates of the economic impacts associated with changes in both supply and demand as influenced by climate change. This is a spatial-equilibrium model written in the general algebraic modeling system (GAMS) programming language with the CONOPT3 non-linear optimization solver (Brooke et al. 2006). The hydrologic-economic simulation approach has been undertaken in several studies, especially to evaluate water scarcity and the effect of water transfers (e.g., Vaux and Howitt 1984; Booker 1995). The model maximizes the net benefits from water use subject to a wide range of constraints, such as the availability of runoff in space and time, topology of the flow-storage demand site network, storage and conveyance capacities, and sustainable groundwater recharge limits. Other constraints represent legal and institutional frameworks governing water allocation, and consideration of ecological needs.

There is a tradeoff in developing a national model of water resources between the detail gained by models of individual river basins and the availability of data to cover the nation in a consistent approach. To gain sufficient detail in tractable manner, we used the 99 assessment sub-regions (ASRs) defined by the Water Resources Council for the 1978 Second National Assessment. The ASR is a watershed unit, with boundaries defined by surface drainage patterns. This choice of modeling scale means that some detail is sacrificed compared to models of single watersheds or river basins. In particular, this means that actual operating rules for specific reservoirs cannot be simulated, resulting in loss of detail about existing reservoir management practices or agreements between water users.

Our choice of modeling scale and data source influences our definition of the water sector for modeling purposes. Base flows were determined using the Second National Water Assessment (WRC 1978), which is the most recent comprehensive national dataset of flows. The National Water Use Information Program (NWUIP) series of reports were relied upon for the most complete and detailed categorization of water use (e.g., Solley et al. 1993, 1998).

Our model depends on calculation of a water balance for each ASR. Figure 1 presents a schematic illustration of the model specification for a given ASR. Items within the shaded area are endogenous to the ASR, while items outside the shaded area are exogenous. The
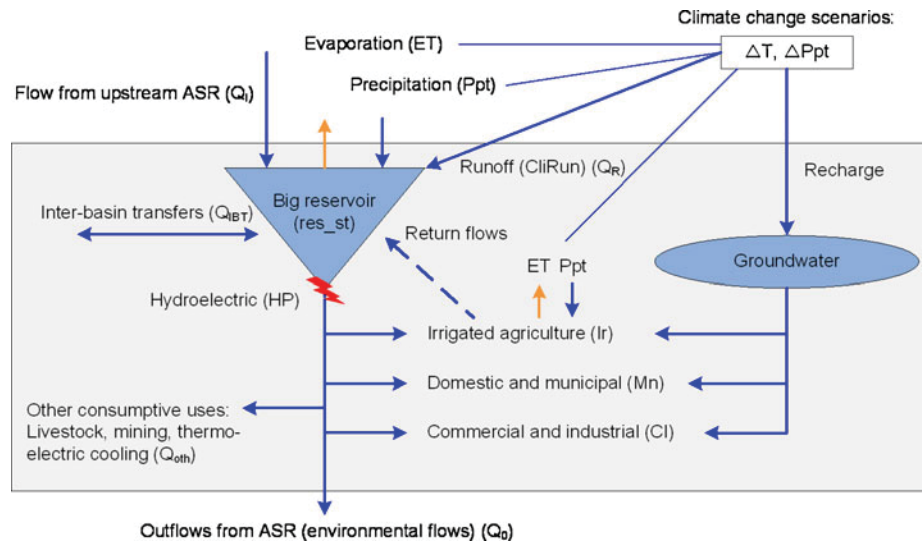
Fig. 1 Schematic of assessment sub-region water balance in the US

ASR serves as the fundamental water accounting framework or control volume, within which all fluxes and changes in storage must balance for each monthly time period. Water resources in an ASR consist partly of endogenous sources, including endogenous runoff (QR), which is the fraction of precipitation that does not evaporate or infiltrate to groundwater, as well as groundwater extracted and direct precipitation (Ppt). It also consists partly of exogenous sources, such as inflows from ASRs located upstream (QI) and inter-basin transfers (QIBT).

Climate change, as characterized by changes in temperature and precipitation, acts to influence each of these water resource supply components. Increases in temperature increase potential evaporation and transpiration, which then increases actual evaporation from soils and the reservoir surface, reducing both runoff and groundwater recharge. The effects of climate change with regard to precipitation vary among regions, such that increased precipitation in some areas will to some degree counteract temperature impacts on runoff production, while decreases in precipitation will amplify the temperature impacts on the water balance. The runoff response to changes in temperature and precipitation are modeled in climate and runoff (CLIRUN) (described in Section 2.3), which generates endogenous runoff (QR) as an output on the basis of precipitation and temperature fields. Direct impacts of temperature and precipitation on irrigation water demand and reservoir evaporation are also simulated within the model.

The monthly water balance is calculated on the basis of a "big reservoir," a heuristic device used to simplify the water balance calculation while preserving the essential features of the hydrosystem. In the model, the standard unit of water volume is millions of cubic meters per month (MCM). Total reservoir storage (S) and surface area (RA), derived from the U.S. Army Corps of Engineers' National Inventory of Dams (USACE 1996), are aggregated within each ASR using geographic information system techniques to form a single storage reservoir, which is assumed to receive all inflows and support all outflows within the ASR. Reservoir storage serves as a buffer to the stochastic behavior of climate and hydrology, improving the reliability of water resources deliveries to demand sites. Reservoir storage also imposes a cost in the form of water lost to evaporation from the reservoir surface. The normal and maximum storage and

surface area of the big reservoir are equal to the sum of the individual volumes and surface areas within the ASR. For each monthly period, the reservoir water balance equation is solved:

$$S_{(t-1)} + Q_{R(t)} + Q_{I(t)} + Q_{IBT(t)} + \left(PPT_{(t)} \cdot RA_{(t)}\right) + \sum RF_{(t)}$$
$$= S_{(t)} + SW_{(t)} + \left(k \cdot ET_{(t)} \cdot RA_{(t)}\right) + Q_{O(t)}$$

where:

$S_{(t)}$	storage in reservoir at the end of period t (in MCM)
$Q_{R(t)}$	runoff originating within the ASR during period t (in MCM)
$Q_{I(t)}$	inflow from upstream ASRs (if any) (in MCM)
$Q_{IBT(t)}$	net inter-basin transfers, defined as positive into ASR (in MCM)
$P_{PT(t)}$	direct precipitation on reservoir surface (in mm)
$RA_{(t)}$	reservoir surface area at end of period t (1,000 s Ha) (factor of 102 required for MCM)
$RF_{(t)}$	return flows from groundwater withdrawals (in MCM)
$SW_{(t)}$	surface water consumptive use (in MCM)
$ET_{(t)}$	ET_0 in period t (in mm)
k	converts reference ET_0 to open water evaporation (unitless)
$Q_{O(t)}$	reservoir outflow, routed to downstream ASR or sink (in MCM).

The subscript (t) indicates monthly time period. No year-to-year net drawdowns on reservoir storage within the ASR are permitted; this is to ensure that the simulated allocation strategy is sustainable. This is enforced by a model condition that the final storage in month 12 (December) must be greater than or equal to the initial storage in Month 1 (January). Net reservoir evaporation is the difference between direct precipitation and evaporation (each in depth units) multiplied by the monthly mean surface area, and adjusted by an appropriate constant to convert to appropriate volumetric units. Reservoir evaporation can be either positive (net evaporation loss) or negative (net precipitation gain).

All components of surface water (SW) withdrawn from the system for municipal, commercial, industrial, and agricultural (irrigation) purposes are expressed as depletions, or losses to the system. Return flows are assumed to reenter the system in the same ASR from which they are withdrawn. Total groundwater use is constrained to fall within sustainable limits such that groundwater mining is not permitted in the model, except for ASRs in the Great Plains and western US, where groundwater mining is an ongoing and established practice. The effect of this assumption on the value of overall water resource use depends on assumptions about how sustainable use of groundwater in these regions might be achieved. Modeling strict imposition of groundwater use limits without assuming changes in irrigation practices or voluntary retirement of agricultural rights would result in a significant increase in agricultural damages under business as usual conditions, and likely accentuate the agricultural damages under climate change.

Reservoir evaporation is an important component of the ASR water balance, particularly in the western US, where potential evaporation rates are high relative to precipitation on an annual basis. Evaporation rates are sensitive to temperature, indicating that climate change will result in increases in water depletions due to reservoir evaporation (Kundzewicz et al. 2007). To calculate reservoir evaporation, the surface area of the "big reservoir" is estimated by assuming that the surface area relative to its maximum extent is proportional to the current storage relative to its maximum value. Potential ET_0 is calculated in an auxiliary program using the Penman-Monteith combination method (Allen et al. 2005). For

simulations of future climate, the temperature term in the Penman-Monteith equation takes on the value generated using the approach described below in Section 2.3 for climate data generation, and in Section 2.4 for estimating runoff. Reservoir evaporation is calculated as the difference between direct precipitation and free water surface evaporation scaled by the surface area of the "big reservoir." The formula for reservoir evaporation is:

$$revap_{(t)} = \left(\frac{S_{(t-1)}}{S_{MAX}}\right) \cdot RA\_max \cdot \left(k \cdot ET0_{(t)} - Ppt_{(t)}\right) \cdot 0.00001$$

In this equation, k is an empirical constant that adjusts ET_0 (reference crop ET_0) in mm per day to open water surface evaporation. The final empirical constant converts units to millions of MCM.

2.2 Model aggregation

ASRs can be aggregated to level of U.S. Geological Survey (USGS) water resource regions (WRRs), of which there are 18 for reporting of results. WRRs have often been used to provide an analytical framework in national studies, e.g., Frederick and Schwarz's (1999) study of climate change and U.S. water resources, and Caldwell et al.'s (2012) analysis of impervious cover, withdrawals, and climate change on river flow. The location and boundaries of the 18 WRRs in the continental US are shown in Fig. 2.

The 18 WRRs are further grouped into 11 individual optimization models because they are hydrologically connected. Some WRRs contain ASRs that have independent outlets to the ocean (46 out of 99 ASRs) or, in some cases, flow to closed inland sinks. Each of these ASRs can be modeled as an independent water resources management problem. Occasionally, these independent ASRs are connected hydrologically via inter-basin transfers, but such transfers are represented explicitly in the model. Other WRRs have ASRs that are connected via flowpath (typically a major river corridor) to other ASRs, whether upstream or downstream. These must be treated in a different way within the model. Specifically, the water balance and allocation problems within linked or networked ASRs cannot be solved independently, because any actions taken in upstream ASRs will influence the quantity and timing of flows in all ASRs located downstream. When ASRs are connected hydrologically, they are always combined in a single networked model so that the solution takes full advantage of the connectivity.
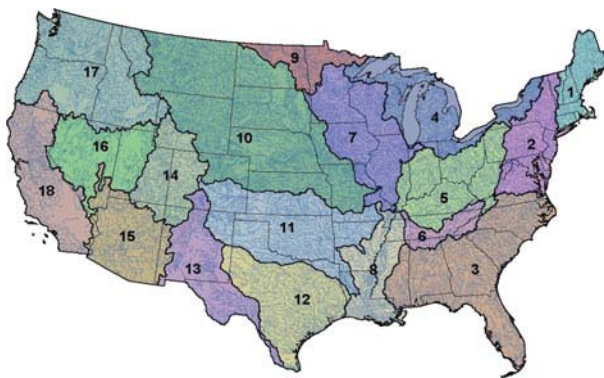

Fig. 2 water resource regions in the US

Within the coterminous US, most of the hydrologically connected ASRs belong to the greater Mississippi system. This system includes the Ohio (WRR 5) and Tennessee (WRR 6) systems in the East; and the Upper Mississippi (WRR 7), Lower Mississippi (WRR 8), Missouri (WRR 10), and Arkansas-White (WRR 11) systems draining the upper Midwest and much of the Great Plains. All are included in a single Mississippi model, comprising 35 ASRs, or roughly one-third of the national total. Other networked optimization models include the Hudson, Rio Grande, Colorado, and Columbia rivers. Figure 3 indicates the network flow topology for major river basins represented in the model.

2.3 Data and benefit functions for specific sectors

In constructing the overall simulation-optimization model, it is necessary to specify functions describing the benefits of water use for each water-using sector. Explicit benefit functions are developed for irrigated agriculture, municipal and domestic water use, commercial and industrial water use, and hydroelectric power generation. The economics of environmental flows are introduced via a damage (penalty) function, i.e., flows below minimal levels required for environmental needs are assessed a penalty in terms of a cost. The remaining categories of use, which include livestock, mining, and cooling of thermo-electric power generation, are not included as economic components of the model. The net consumption of water in each of these sectors is included as a static element of demand (i.e., water is diverted to these purposes without regard for the marginal value in use), so they are included as components of the water balance within each ASR.

Climate change could also influence water-dependent sectors in the US in ways that have not been captured in this model. These include the effect on commerce associated with river navigation, and the impact on flooding and water quality. Potential impacts from climate change on flooding may be significant, with impacts in many regions across the country, whereas potential climate change impacts from navigation may be less significant and relatively geographically constrained (see for instance, Hurd et al. 1999).
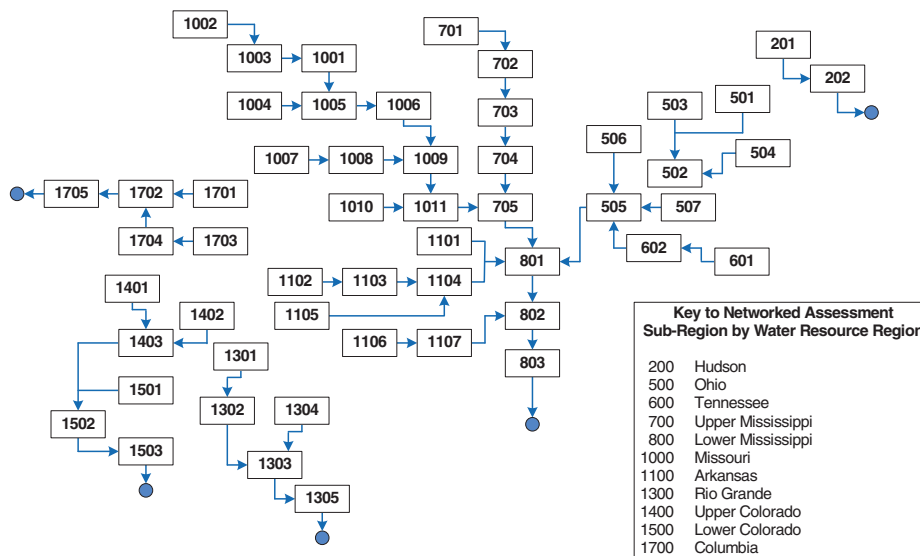

Fig. 3 Network flow typology in the US

2.3.1 Agriculture

We explicitly model the relationships between water use by crop, resulting productivity, and net economic returns under optimization. Data from the 2002 Census of Agriculture (USDA ERS 2008) were used to determine the extent of irrigated cropping, by crop, in each ASR. A total of 19 specific crops are modeled, covering a great majority of the irrigated acreage reported. Crop water demand is estimated using the United Nations Food and Agriculture Organization (FAO) crop coefficient method based on reference ET_0 calculated using the FAO Penman-Monteith approach, as described in FAO 56 (Allen et al. 1998). The model adjusts irrigation demand for each climate scenario by calculating ET using the Penman-Monteith equation. Constraints are imposed to ensure that minimum and maximum areas are respected for each crop in each ASR. The default lower bound on area cultivated by crop is 0.4 (40 %) of the area reported in the 2002 Census of Agriculture (USDA ERS 2008). In addition, overall constraints on irrigated area within each ASR are imposed. This ensures that the overall level of irrigated cropping is consistent with the area equipped for irrigation. Inclusion of new crop types due to changes in climatic conditions is not modeled.

Following the FAO 33 water-yield model (Doorenbos et al. 1979), a linear relationship is assumed between actual yield (Y) and its potential or reference value (Y_R). If the full water supply is available, then yield is equal to its reference or potential level:

$$Y_{(cp)} = YR_{(cp)} \cdot \left[1 - k_y \cdot \left(1 - \frac{ETAS_{(cp)}}{GWDS_{(cp)}} \right) \right]$$

In this expression, **ETAS** is the actual seasonal ET_0, supplied by both effective precipitation and irrigation water (a decision variable); **GWDS** is the seasonal gross or full water demand, and k_y is the FAO crop water yield coefficient. The extent to which a given crop is drought-tolerant ($k_y < 1.0$) or drought-sensitive ($k_y > 1.0$) can be captured explicitly in this function. The function is not defined for supplies relative to demand less than 0.5, and this is reflected as a constraint within the model. (If at least 50 % of gross water demand cannot be supplied through a combination of effective rainfall and irrigation, the crop cannot be grown.) Irrigation supply is also constrained not to exceed full seasonal water demand (GWDS). Reference yield was determined by selecting the highest county-level yield for each crop across all counties included in each ASR, and assuming that it reflected the yield potential under full water supply conditions.

The value and net returns to irrigated cropping are calculated in a straightforward profit function: profit ($/Ha) is equal to yield (MT/Ha) multiplied by farmgate price ($/MT) less fixed costs ($/Ha) and volumetric water charges:

$$\pi = \sum_{cp} \left(Y_{(cp)} \cdot fp_{(cp)} - fcc_{(cp)} \right) \cdot Area_{(cp)} - \left(\sum_{t} sw\_ir_{(t)} \cdot psw + \sum_{t} gw\_ir_{(t)} \cdot pgw \right)$$

In this expression, **fp** is the farmgate price of each crop and **fcc** is the fixed costs of cultivation per hectare. Costs and returns were derived from the USDA Economic Research Service costs of cultivation studies (USDA ERS 2008). 2002 costs and prices were used to maintain consistency with the US Department of Agriculture (USDA) 2002 Census of Agriculture (USDA ERS 2008) data whenever possible. The costs of surface water (**psw**) and groundwater (**pgw**) were taken from the 2003 USDA Irrigation Sample survey (USDA 2004). In the above expression, units were suitably transformed to yield profits in millions of $ per ASR.

2.3.2 Municipal, commercial, and industrial demand

The conceptual basis upon which municipal or domestic demand is calculated is different from that of agricultural demand, since the water diverted and consumed by households is not an input to a production process as such, but rather an end use that serves a variety of needs, including drinking, cooking, washing, and sanitation, which are typically not market transactions. The approach used to calculate the value associated with domestic consumption is to estimate the consumer surplus associated with each level of water use. The consumer surplus is the (positive) difference between what consumers are willing to pay for a given quantity of water and what they are in fact required to pay (Griffin 2006).

The most general form of the consumer (household) water demand function states that the quantity of water demanded (W) is negatively related to the price per unit (P). Following previous studies (e.g., Cai et al. 2006), a log-linear relationship is assumed:

$$\ln(W) = \alpha - \varepsilon \cdot \ln(P)$$

In this specification, $\mathbf{W}$ is expressed in cubic meters per household per month, and P in \$ per cubic meter. The parameter α is an intercept term, empirically determined, and ε is the elasticity of demand with respect to price. The value of ε has been the subject of much research (e.g., Espey et al. 1997), and for this study is assumed to be −0.5, which is the mean value reported by Espey et al. (1997). This expression is inverted to obtain the willingness-to-pay (WTP) curve, in which P is interpreted as marginal WTP (\$ per cubic meter) for a given quantity of water (W). To obtain the household consumer surplus (CS) estimate associated with a given level of monthly consumption, the WTP function is integrated between a minimum acceptable level of consumption (W_0) and the observed water consumption W. The price actually paid is subtracted from the result. The integrated expression takes the form:

$$CS = \sum_{t} \left\{ \frac{e^{\left(\alpha/\varepsilon\right)}}{\left(1 - 1/\varepsilon\right)} \left(W_{(t)}^{\left(1 - 1/\varepsilon\right)} - W_0^{\left(1 - 1/\varepsilon\right)} \right) - W_{(t)} \cdot dwp \right\}$$

The above expresses the CS for an individual household. To obtain the aggregate benefit associated with a given level of household consumption, the resulting CS is multiplied by the number of households within each ASR. Population projections are taken from the GCAM model (Kim et al. 2006).

The domestic price of water is found to be a declining function of household water use in most markets within the United States. Based on data from the American Water Works Association 2006 rate survey (AWWA 2006), a basic declining volumetric price equation was specified for each WRR by aggregating and weighting data for individual municipalities. This equation takes the general form:

$$dwp = \left(\frac{fcc\_m}{W}\right) + c_1 - c_2 \ln(W)$$

The first term is a fixed household base monthly fee, which is spread over the monthly volume of use ($\mathbf{W}$). The remaining terms express a log-linear declining tariff structure, as derived from the AWWA (2006) survey data. The two portions of the equation jointly define the household CS estimate. Figure 4 illustrates the relationship between WTP, price, and CS, for ε=−0.5. Note that in the supply-demand model, it is the change in CS rather than the absolute level of CS that determines the value of water for domestic uses relative to competing uses.
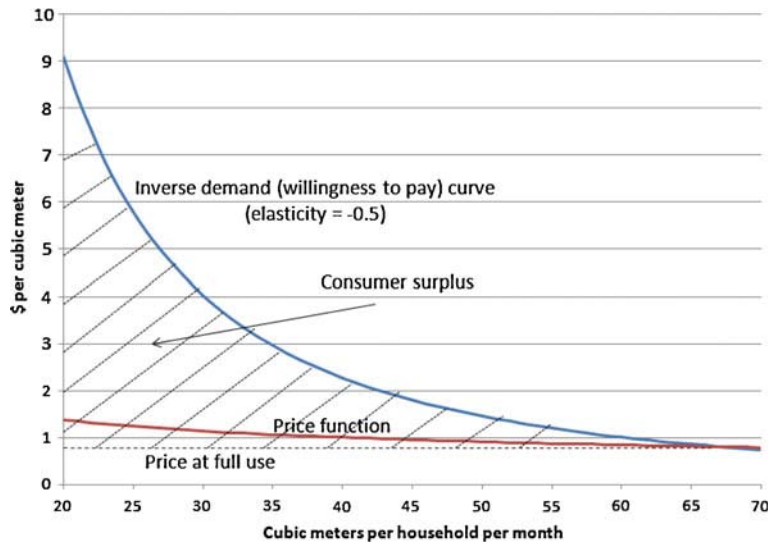
Fig. 4 Household consumer surplus calculation for the US

For commercial and industrial use, we have used a modified version of the approach used in estimating municipal and domestic use. Rather than estimating the surplus measure on a per-household (firm) basis, it was calculated on an aggregate level. Specifically, rather than specifying CS on a household basis and multiplying by the number of households per ASR to obtain the total CS, the WTP curve encompasses all water-using industries within the ASR, based on the NWUIP data for 1985–1995.

2.3.3 Hydropower

Hydropower generation for representative recent years is known from the periodic US Geological Survey (USGS) national water-use information program (NWUIP) studies (Solley et al. 1988 for 1985; Solley et al. 1993 for 1990; Solley et al. 1998 for 1995; Hutson et al. 2004 for 2000). Installed capacity in megawatt-hours (MWH) is assumed to be the maximum generation achieved from among the four most recent NWUIP study years (1985, 1990, 1995, and 2000), with a rounding-up factor added. Then, hydropower generation under each climate change scenario is obtained by scaling the available discharge to the discharge associated with maximum observed generation. Because hydropower generally occurs at the outlet of storage reservoirs, the impact of reservoir evaporation was also included. The relationship is specified as:

$$hpval = \left(\frac{\sum_t \left(Q_{R(t)} - revap_{(t)} \right)}{\sum_t \left(Q_{Rh(t)} - revap\_h_{(t)} \right)} \right) \cdot hp\_norm \cdot hp\_pr$$

In the above expression, the added subscript "h" indicates the historical value of the variable; **hp_norm** is the maximum historical observed generation level; and **hp_pr** is the regionalized wholesale price of power.

2.3.4 Instream flow valuation

The explicit valuation of instream flows can be challenging because formal markets for these services are often absent, or subject to a range of distortions and missing information. The Second National Water Assessment (WRC 1978) estimated, among other variables, the monthly flows required to support fish and wildlife, evaluated at the outlet of each ASR. Following the general example of Frederick and Schwarz (1999), any reduction in flow that encroached on the fish and wildlife minimum flow (**q_min**) incurred a penalty, which was based on Frederick and Schwarz (1999). Minimum flows were identified as below 20 % of long-term average. The penalty is zero if flows do not encroach into the fish and wildlife zone, and is greater than zero if they do. The penalty is equal to $0.40 per cubic meter of flow below the fish and wildlife threshold **q_min**, which is specified uniquely for each month. This penalty was based on the Frederick and Schwartz value, but was adjusted downward to reflect literature showing that the value of water for ecological use values and nonuse values may generally be lower than the Fredrick and Schwartz value. The value from Frederick and Schwartz was $597 per AF in 1995 dollars, or $812 per AF if adjusted to 2007 dollars using the CPI. The literature on the value of ecological flows is sparse, and even more limited for identifying that value of ecological flows when flows are less than critical levels. Raucher et al. (2005) report that values for ecological values based on the purchase prices for agreements to restore/protect instream flows for ecological purposes ranged from $89 to $567 per AF in 2007 dollars. Nonuse values held by those that value existence of a resource even though they are not a user (existence values), or the idea that a resource should be available to future generations (bequest values), ranged from $107 to $214 per AF. The value of ecological flows at or below critical flow levels chosen for this study was $0.40 per cubic meter, or $493 per AF, which is toward the higher end of the range of estimated values of critical flows.

2.4 Emission scenarios and climate projections

Future climate is projected for two GHG emissions scenarios: a BAU scenario where no new GHG controls are implemented, and an exemplary mitigation policy (POL) scenario where future GHG emissions are mitigated.

The BAU and POL scenarios are distinguished by the path they represent for future GHG emissions. The scenarios are derived from the analysis conducted for the American Power Act of 2010; however, the focus of this paper is not related to that analysis. The Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC Version 5.3; Wigley 2008) was used to analyze how U.S. GHG targets, combined with international actions, could affect global carbon dioxide (CO_2)-equivalent concentrations and temperatures in these scenarios. MAGICC is an upwelling-diffusion energy-balance model with atmospheric chemistry and carbon cycle components designed to be consistent with IPCC AR4 results. The critical elements of these scenarios can be briefly summarized as follows:

- **Business-as-usual:** reflects a path that GHG emissions are projected to follow if emissions continue on the current trajectory in the absence of new mitigation policy. By 2100, atmospheric concentration of CO_2 under this BAU scenario is projected to rise to 785 parts per million (ppm), nearly three times pre-industrial levels. U.S. GHG emissions are benchmarked to the U.S. Energy Information Administration's Annual Energy Outlook 2010 forecast, which reflects the US Energy Independence and Security Act of 2007 and the American Recovery and Reinvestment Act of 2009. International emissions projections under this scenario are based on the EMF-22 baseline (see Calvin et al. 2009).

- **Policy:** U.S. GHG emissions are consistent with targets included in the American Power Act of 2010, a comprehensive energy and climate bill proposed in the 111th U.S. Congress, along with other assumptions regarding future emissions from developed and developing countries. The assumptions about international action are based on targets set forth at the July 2009 Major Economies Forum (MEF 2009). Atmospheric CO_2 concentration rises to 427 ppm by 2100 under this scenario, a trajectory comparable to the more well known IPCC SRES B1 scenario (IPCC 2000).

The emissions scenarios were input into MAGICC to calculate the change in global average temperatures. Each scenario was run assuming a 3 °C climate sensitivity, or a 3 °C increase in global mean near-surface air temperature by 2100 following a prolonged doubling of the pre-industrial CO_2 concentration of 280 ppm. This value was the "most likely sensitivity" reported in the AR4 (Kaczmarek 1993). Spatially explicit gridded climate projections were generated using SimCLIM software (CLIMSystems 2010), which downscales the MAGICC projections to a 0.0083 by 0.0083° grid on a monthly timescale using bias-corrected pattern-scaling developed for 21 GCMs. Specific monthly climatic variables used in the simulation-optimization model include: average, minimum, and maximum temperature; total precipitation; relative humidity; and wind speed. Relative humidity and wind speed values, for the baseline and future periods, are provided by GCM projections produced in SimCLIM. Baseline values for temperature and precipitation come from the PRISM dataset (PRISM Climate Group 2007). Cloud cover values used to calculate net radiation are held equal to historical values.

Reported changes in monthly temperature and precipitation are averages of the values from 9 of the 21 GCMs available in SimCLIM that were used in the IPCC AR4 (BCCRBCM2, CCSM-30, ECHO-G, GFDLCM20, GFDLCM21, MPIECH-5, MRI-232A, UKHADCM3, and UKHADGEM) (Randall et al. 2007). They were selected as the most skilled at replicating recent climate patterns globally and over the coterminous US (Wigley 2008). The advantage of using averages across multiple GCMs is that multi-model averages, also known as ensembles, tend to be better than any one individual model at simulating present-day climate (Reichler and Kim 2008; Wigley 2008). Due to data limitations in SimCLIM from specific GCMs, estimates of changes in wind speed used the same 9 models except CCSM-30, while estimates of relative humidity used the same models except ECHO-G.

We present results using the mean of the ensemble in order to demonstrate that the water model can be used for policy analysis, not to present a full analysis of consequences of climate change. It should be recognized that there is substantial difference across individual model runs on the magnitude of projected temperature increase in the 21st century, and pattern of precipitation changes (Christensen, et al. 2007).

The baseline period used for comparison to future projections is 1971–2000. Climate change projections are made for timeslices at 2025, 2050, 2075, and 2100, with a 30-year time period surrounding and centered on each of these years. The 30-year window averaging is used to smooth out inter-annual variability. The net damages associated with climate change for each scenario and each timeslice are derived by comparing net impacts by sector, and in total, with comparable impacts generated under the appropriate baseline for that timeslice. Thus, the BAU and POL scenarios for 2025 are compared to the 2025 baseline, and similarly for 2050, 2075, and 2100.

2.5 Calculating changes in streamflow

Projections of future climate are used to estimate streamflow by applying the CLIRUN lumped integral water balance model (Kaczmarek 1993). This model uses monthly projections of changes

in temperature (average, minimum, and maximum) and precipitation to estimate changes in monthly streamflow. CLIRUN simulates the most important lumped hydrologic processes, including soil moisture storage, ET_0, surface runoff, subsurface runoff, and base flow. CLIRUN was developed and designed to simulate the impacts of climate change on the water balance of medium- to large-scale catchments (100–30,000 km^2) using a relatively restricted number of parameters (Kaczmarek 1993). CLIRUN is specified and parameterized at a 0.5° horizontal resolution, and most ASRs contain, on average, all or part of numerous CLIRUN gridcells.

CLIRUN is calibrated on the basis of the WRC (1978) estimates of natural discharge, and historical data from the gridded CRU 0.5° dataset. The CLIRUN gridcells associated with each ASR are calibrated as an ensemble using an automated parameter optimization routine.

3 Results

3.1 Runoff

Table 1 shows the average change in runoff across all WRRs by time period computed by CLIRUN. A ratio greater than one indicates an increase in runoff, while a ratio less than one indicates a decrease. Under the BAU scenario, average runoff across all WRRs becomes drier in 2,025, but gets wetter afterward. Under the POL scenario, all time periods show a decrease in runoff.

For most WRRs in 2025, runoff ratios are projected to be close to one, and BAU and POL scenarios produce very similar runoff projections. The time period of 2050 has a similar pattern, with a few WRRs, such as the Rio Grande, starting to show a larger divergence between the BAU scenario and the POL scenario. In general, from 2050 onward, many WRRs have a BAU runoff ratio that is higher than the POL runoff ratio—reflecting that for many WRRs, the policy scenario results in less runoff. Figure 5 shows that by 2100, the largest divergences between the scenarios occur in the Missouri, Rio Grande, and Great Basin WRRs. Only California and the Texas Gulf show POL runoff ratios greater than the BAU runoff ratio, and then only by a small amount.

3.2 Total damages

Table 2 gives a summary comparison of damages to water resources from climate change by time period. Damages are projected to grow during the 21st century, and are projected to be less under the POL scenario compared to the BAU scenario. In 2025, damages total $734 million per year under the BAU scenario, and $690 million per year under the POL scenario. By 2100, damages total $4.2 billion per year under the BAU scenario, and $3.6 billion per year under the POL scenario.

Table 1 Average change in runoff across all water resources regions by time period (runoff ratios)

Runoff ratio > 1 denotes increase in runoff, < 1 denotes decrease in runoff

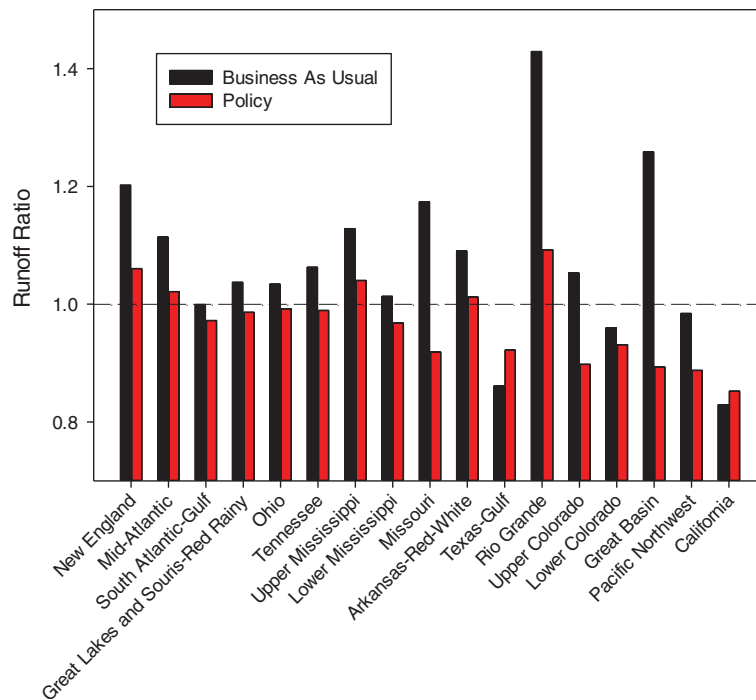| Time period	Business as usual	Policy
2025	0.994	0.989
2050	1.003	0.978
2075	1.032	0.971
2100	1.072	0.967

Fig. 5 Runoff ratios 2100, business-as-usual vs. policy scenario in the US

Figure 6 shows the distribution across WRRs of total water resources damages (or benefits) from climate change by 2100. There is a slight benefit to the Northeastern United States under climate change for all time periods including 2100. For the eastern and central portions of the country, damages under the BAU scenario are generally greater than under the POL scenario. For the western WRRs, including the Pacific Northwest, the Upper Colorado, the Lower Colorado and the Great Basin, damages are greater under the POL scenario than the BAU scenario. This is because of the switch from a gain in runoff for these WRRs under the BAU scenario to reduction in runoff under the POL scenario.

Reductions in damages between the BAU and POL scenarios result from a smaller rise in temperatures under the POL scenario, which results in a reduction in evaporation, leaving more water available for use. Nationally, net evaporation increased as a function of emission scenario as well as over time. By 2100, climate change will have resulted in the loss of between 9.3 billion cubic meters BCM (BAU) and 4.0 BCM (POL) of water availability relative to the historical climate baseline (30 BCM). Although this is small compared with overall U.S. water resources, it nevertheless contributes significantly to availability of water for diversion.

3.2.1 Agriculture

Table 3 shows damages from climate change for all sectors by 2100 (benefits from climate change are shown as negative numbers). Agriculture has the second largest total dollar damages by 2100 for any sector modeled for the BAU scenario, and the third largest dollar damages by 2100 for the POL scenario. Impacts to agriculture are expected, as water is reallocated to uses with a higher marginal value when less water is available. By 2100,

Table 2 Total damages in all WRR by scenario and time period (millions of 2007 U.S. dollars per year)

Year	2025	2050	2075	2100
Business-As-Usual (BAU)				
Agriculture	404.6	882.4	1173.3	1559.7
Environmental flow penalty	−7.6	295.7	1442.0	1904.4
Hydropower	338.2	702.6	795.3	696.5
Commercial and industrial	0.0	18.2	4.5	7.5
Domestic	−0.9	213.7	−2.7	1.4
Total	734.3	2,112.5	3,412.5	4,169.4
Policy (POL)				
Agriculture	372.0	676.8	703.3	790.2
Environmental flow penalty	−8.4	160.6	1103.6	1386.1
Hydropower	326.7	830.2	1121.9	1350.8
Commercial and industrial	−0.2	20.2	3.5	5.9
Domestic	0.2	238.0	−1.7	2.4
Total	690.3	1,925.9	2,930.6	3,535.4
Difference (BAU-POL)				
Agriculture	32.6	205.6	470.1	769.4
Environmental flow penalty	0.9	135.0	338.4	518.3
Hydropower	11.5	−127.7	−326.5	−654.3
Commercial and industrial	0.1	−2.0	0.9	1.6
Domestic	−1.1	−24.3	−1.0	−1.1
Total	44.0	186.7	481.9	634.0

Totals may not sum due to rounding

annual agricultural damages total $1.5 billion under the BAU scenario, compared to $790 million under the POL scenario. The largest agricultural damages are projected in the Missouri, Arkansas-Red-White, and the Texas-Gulf WRRs, with significant reductions in damage from the BAU to the POL scenario, despite lower runoff ratios for the Missouri and Arkansas-Red-White WRRs in the POL scenario compared to the BAU scenario. This is due to reduced evaporation under the POL scenario compared to the BAU scenario, both in terms of agricultural water usage and reduced reservoir evaporation making more water available for water use sectors.

3.2.2 Environmental flow penalty

The category with the largest damage is environmental flows. Environmental flow penalties total $1.9 billion per year under the BAU scenario and $1.4 billion per year under the POL scenario by 2100. WRRs with the largest environmental flow penalties by 2100 include the Atlantic Gulf, Great Lakes and Souris Red-Rainy, Texas-Gulf, Lower Colorado, and California. Environmental flow penalties under climate change result from reductions in runoff accompanying climate change, reallocation of water to meet increasing domestic and commercial consumption levels, and the increase in agricultural water demand on a per-hectare basis as higher temperatures lead to higher potential crop ET_0. For most WRRs, environmental flow penalties are larger under the BAU scenario than under the POL
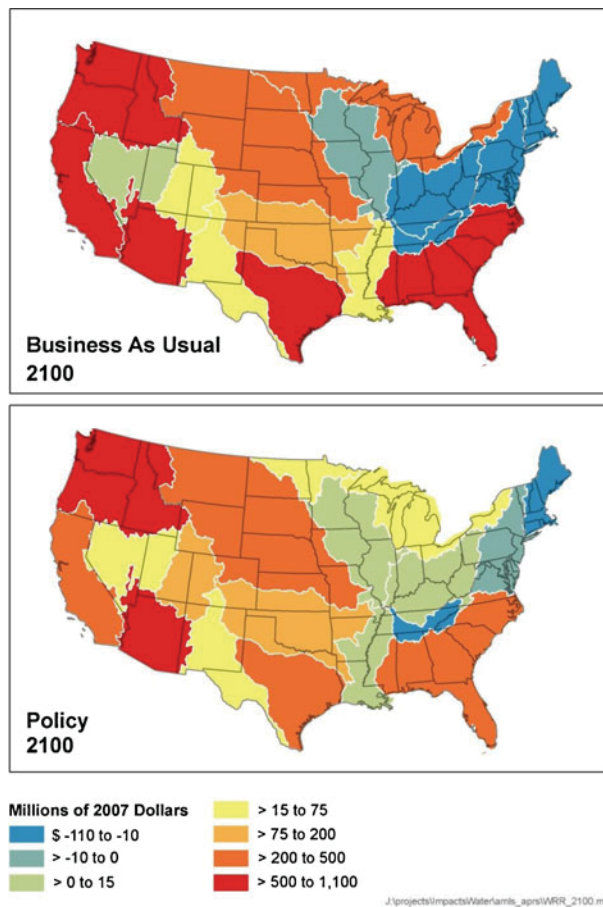
Fig. 6 Annual damages from all US sectors in 2,100, business-as-usual vs. policy scenario

scenario. This reflects the reduction in reservoir evaporation and an increase in runoff for two WRRs in the POL scenario compared to the BAU scenario. In the case of the Lower Colorado, Pacific Northwest, and Great Basin, the environmental flow penalty is larger under the POL scenario than it is under the BAU scenario. In basins where ASRs are components of larger basin networks, particularly the greater Mississippi and Columbia systems, modest reductions in flow can lead to large changes in the environmental flow penalty at the WRR level. This is because the penalty is evaluated at the outlet of each individual ASR, and shortages upstream can cascade through the system, multiplying the environmental impact. This is a realistic specification, and serves to standardize environmental flow penalties to stream miles.

3.2.3 Hydropower

Hydropower is the third largest category of damages under the BAU scenario, and the second largest under the POL scenario. Annual hydropower damages are projected to total $697 million under the BAU scenario and increase to $1.35 billion under the POL scenario by 2100. Damages from hydropower reflect reallocation of water to meet increasing domestic and

Table 3 2,100 damages (benefits) from climate change, all sectors and WRR (millions of U.S. dollars)

Year 2100		Business-As-Usual						Policy					
Water Resource Region	Water Resource Region name	Agri-culture	Environmental flow penalty	Hydro-power	Commercial and industrial	Domestic	Total damages	Agriculture	Environmental flow penalty	Hydro-power	Commercial and industrial	Domestic	Total damages
WRR01	New England	0.3	0.0	−76.5	0.0	0.0	−76.2	0.0	0.0	−21.6	0.0	0.0	−21.6
WRR02	Mid-Atlantic	0.8	0.0	−52.5	0.0	0.0	−51.7	0.3	0.0	−9.6	0.0	0.0	−9.3
WRR03	South Atlantic-Gulf	129.6	511.9	−56.1	0.0	−0.2	585.2	15.1	303.0	11.4	0.0	0.2	329.7
WRR04 WRR09	Great Lakes and Souris-Red Rainy	8.0	278.4	−14.7	0.2	0.0	271.9	2.8	0.0	59.6	0.0	0.0	62.4
WRR05	Ohio	3.2	0.0	−15.1	0.0	0.0	−11.9	1.1	0.0	0.1	0.0	0.0	1.2
WRR06	Tennessee	0.2	0.0	−111.2	0.0	0.0	−111.1	0.1	0.0	−16.4	0.0	0.0	−16.4
WRR07	Upper Mississippi	2.4	0.0	−6.4	0.0	0.0	−4.0	0.9	0.0	0.2	0.0	0.0	1.1
WRR08	Lower Mississippi	24.1	0.0	−5.7	0.0	0.0	18.4	8.7	0.0	1.3	0.0	0.0	10.0
WRR10	Missouri	390.7	0.0	12.8	0.1	0.0	403.5	244.6	0.0	76.5	0.2	0.0	321.3
WRR11	Arkansas-Red-White	195.9	0.0	−33.9	0.4	0.0	162.3	71.9	0.0	14.3	0.1	0.0	86.3
WRR12	Texas-Gulf	562.2	163.6	9.2	1.1	−0.8	735.2	216.6	0.0	5.2	0.0	0.0	221.9
WRR13	Rio Grande	18.7	43.2	−10.8	0.4	0.5	52.0	15.3	8.5	1.4	0.3	0.3	25.9
WRR14	Upper Colorado	56.6	0.0	15.2	0.1	0.0	71.9	56.2	0.0	55.6	0.1	0.0	111.9
WRR15	Lower Colorado	53.8	553.7	−67.3	5.1	1.8	547.0	53.4	986.9	−41.5	5.1	1.8	1005.7
WRR16	Great Basin	10.5	−10.9	2.1	0.0	0.0	1.7	14.7	5.9	4.8	0.0	0.0	25.4
WRR17	Pacific Northwest	36.5	22.6	729.0	0.0	0.0	788.1	64.2	24.5	932.1	0.0	0.0	1020.9
WRR18	California	66.4	341.8	378.5	0.2	0.1	787.1	24.3	57.3	277.5	0.0	0.1	359.2
	Total	1,559.7	1,904.4	696.5	7.5	1.4	4,169.4	790.2	1,386.1	1,350.8	5.9	2.4	3,535.4

Totals may not sum due to rounding

commercial consumption levels, higher reservoir evaporation compared to the baseline, and changes in runoff under climate change. Larger hydropower damages under the POL scenario compared to the BAU scenario reflect decreased runoff under the POL scenario compared to the BAU scenario. Hydropower damages increase from the BAU to the POL scenario in every WRR where runoff under the POL scenario is less than the BAU scenario. Hydropower damages are greatest in the Pacific Northwest and California under both the BAU and POL scenarios. For the Pacific Northwest, damages are larger under the POL scenario than the BAU scenario, as runoff is projected to decrease under the POL scenario. For California, however, the damages are greater under the BAU scenario and less under the POL scenario, as runoff is projected to increase under the POL scenario. The decrease in runoff in the Pacific Northwest under the POL scenario compared to the BAU scenario is the most significant reason for the national increase in hydropower damages under the POL scenario as compared to the BAU scenario. It is not the only reason, however, as there are relatively smaller increases in hydropower damages under the BAU scenario as compared to the POL scenario for all WRRs except the Texas Gulf and California.

3.2.4 Domestic

Domestic and municipal uses are well protected from climate change in the national model, as water is reallocated to meet existing demand and growth in demand for relatively high marginal value domestic and municipal uses. Domestic and municipal damages reach $1.4 million per year in 2100 under the BAU scenario and $2.4 million in 2100 under the POL scenario. Higher domestic and municipal damages under the POL scenario as compared to the BAU scenario are due to reduced runoff under the POL scenario for most WRRs, but the difference in national damages between the two scenarios is very small.

3.2.5 Commercial and industrial

Commercial and industrial uses are not highly sensitive to climate change scenarios, and are therefore similar to domestic and municipal uses because of their high marginal value. Damages to commercial and industrial uses reach $7.5 million per year in 2100 under the BAU scenario and $5.9 million in 2100 under the POL scenario.

4 Discussion and limitations

4.1 Discussion

The annualized cost estimates of roughly $4 billion per year under the BAU scenario are in the low range of estimates reviewed from the literature. Estimates presented here may not be directly comparable to previous studies reviewed, such as Frederick and Schwarz (1999), because the present study is confined to water supply and demand, and excludes flood damages and water quality impacts, which were among the largest categories of cost in the previous studies. Another reason for the lower damage estimates compared to those of Frederick and Schwartz is that their study used comparatively drier and wetter models to produce future climate scenarios. Our study used an ensemble average of GCM projections rather than individual GCMs, and therefore represents less extreme potential changes in temperature and precipitation.

Model results were unsurprisingly found to be very dependent on change in runoff and evaporation. Compared to the BAU scenario, there was a reduction in runoff for every WRR

except two under the POL scenario, and the gain in runoff for those two WRRs was comparatively very small. However, the gain from the BAU scenario to the POL scenario in water available for use due to reduced reservoir evaporation compensated for reduced runoff in many WRRs. Reduced reservoir evaporation is a main driver of reduced damages under the POL scenario compared to the BAU scenario, as more water is available to meet growing demands in water-constrained WRRs. Greater water availability due to reduced evaporation helped reduce damages to agriculture in all WRRs, except for small increases under the POL scenario compared to the BAU scenario for the Great Basin and Pacific Northwest. Municipal and domestic as well as commercial and industrial damages were slightly less under the POL scenario compared to the BAU scenario.

In most WRRs, environmental flow penalties were less under the POL scenario than under the BAU scenario. There were three WRRs in which environmental flow penalties were higher under the POL scenario than under the BAU scenario, including the Great Basin, the Lower Colorado, and the Pacific Northwest. However, only one of those WRRs, the Lower Colorado, showed a large increase in environmental flow penalty under the POL scenario compared to the BAU scenario. For each of these WRRs, runoff was projected to be less under the POL scenario than under the BAU scenario, and in the case of the Lower Colorado, the reduction in runoff was a larger factor than the savings in evaporation.

Hydropower damages are also very sensitive to changes in runoff. Hydropower damages increase from the BAU to POL scenario in every WRR where runoff decreases between the two scenarios.

Generally, our results show that the effect on evaporation from climate change is often more important than the effect of change in runoff on streamflow. However, there are some cases, particularly for hydropower and environmental flow penalty, in which the change in streamflow had a greater effect.

These results suggest several key strategies for adapting to the effect of climate change on U.S. water resource use. Increased evaporation projected into the future suggest benefits from increased use of groundwater aquifers to store and recover surface water supplies when needed to significantly reduce evaporative losses compared to reservoir storage. Increased use of recycled municipal wastewater by municipal and agricultural users will allow reduced demand for freshwater supplies, and water transfers will reduce the total value of losses if water is transferred from relatively lower valued uses to higher valued uses.

4.2 Key limitations

The results we present carry a number of important limitations and caveats associated with the details surrounding our simulation-optimization modeling approach. A modeling exercise on this scale requires a large number of assumptions and simplifications. It should be recognized that while the "big reservoir" heuristic used in each ASR helps convey the basics of the water balance in each ASR, there is significant detail that cannot be represented, for instance regarding the particulars of how reservoirs are operated (such as how much emphasis is placed on hydropower production compared to maintaining downstream flows).

Some of the specific caveats, along with their potential implications, are discussed below.

- **Omitted sectors:** Our approach omitted several important water-using sectors from the economic component of our approach, including livestock, mining, and thermoelectric power generation cooling. While these sectors do not necessarily consume all or part of what they withdraw, the omission of these sectors may result in underestimates of damages associated with climate change. For example, 91 % of total U.S. electricity is produced by

thermoelectric power plants, and these operations depend on the supply and temperature of nearby water sources for cooling. A recent study suggests a potential 4–16 % decrease in summer average generating capacity in U.S. power plants by 2060, with results depending on cooling system type and climate scenario (van Vliet et al. 2012).

- *Use of general circulation model ensemble averaging:* We employed an ensemble of GCMs to project future climatic conditions. Since the outputs of specific GCMs can vary widely within the same emission scenario (Burke et al. 2006), employing ensemble means has become common practice in climate science research, because ensembles have been shown to best replicate past climatological averages (Gleckler et al. 2008). However, use of ensembles means that we show climate projection scenarios that reflect the average projection across GCMs, and not the uncertainty reflected in the range of projections across models. Future work will focus on estimating damages using specific GCM runs to test functioning of the U.S. water resources model under a range of climate projection scenarios by emission scenario (e.g. models with hotter and drier, or cooler and wetter projections compared to other models) (e.g. Strezepek, et al. submitted).

- *Variations of modeled climate sensitivity:* Although all of the scenarios in this analysis assumed a climate sensitivity of 3 °C, the use of different values would likely affect the damage estimates reported here. Higher climate sensitivity values would likely drive greater perturbations from the historical trend in the GCMs, potentially increasing damages. Conversely, climate sensitivity values less than 3 °C may result in lesser damages, compared to those presented in this paper. However, we are unable to test these hypotheses at this time. Additional work is planned to investigate how variations in climate sensitivity would affect water supply and demand damages.

- *Environmental flow penalties:* During drought events, policies could be enacted to ensure adequate environmental flows, at the expense of other water uses. These policies, which are not estimated or included in our approach, could potentially increase or decrease total damages, depending on the location of the event and what water uses are disadvantaged by the policy. Our estimate of the value of preserving flows above critical levels for ecological purposes includes some uncertainty and perhaps some bias. The value used based on Frederick and Schwartz may be high compared to literature on the value of environmental flows, but the literature is limited and it is difficult to distinguish the value of ecological flows at critical levels.

- *Stranded costs and transaction costs:* The specification of the national supply-demand model assumes implicitly that transfers of water from one sector to another or from one region to another in response to changing patterns of scarcity are accomplished at little or no cost to the economy. This is unlikely to be the case, however, for a variety of reasons. Transfer of water out of irrigated agriculture, for example, leaves extensive capital investment in the form of water pumping, storage, and application infrastructure stranded, possibly well before its service lifetime is over. In addition, in the western United States where water rights are based on the Doctrine of Appropriation ("first in time, first in right"), transfers of water from existing uses to meet new or expanding demand typically require sale or lease agreements. Although such transactions could in theory be considered zero-sum games from the standpoint of damage assessment, every transfer actually involves transaction costs, which are often substantial. Thus damages from climate change-induced reductions in flow are likely to exceed estimates generated in the model.

- *Adaptation actions not estimated:* In response to decreased water supply, adaptive actions will likely be taken that either increase supply to a particular region (e.g., construction of pipelines/aquifers from water-rich areas, or increases recycled water use or in desalinization capacity) or decrease demand (e.g., implementation of water efficiency standards, planting

of drought-tolerant crops). These actions are not included in our analysis, as adaptive responses are likely to be locally driven and therefore difficult to model at a national scale. Similarly, the capital expenditures necessary to make these investments are not included in the damages presented in this paper.

- **_Carbon dioxide fertilization:_** Bias is introduced by ignoring the potential impacts of CO_2 fertilization on both yields and irrigation water use. Elevated CO_2 levels have two primary impacts on growing plants: photosynthetic activity increases and stomatal conductivity decreases relative to baseline CO_2 concentrations, all other factors held equal. The result is that many plants require less water per unit of carbon assimilated, leading to predictions of reduced canopy transpiration under-elevated CO_2 concentrations and increases in biomass production (particularly for C3 plants), other factors held equal (Ainsworth and Long 2005). By excluding the potential impacts of CO_2 fertilization, the model may both understate yields and overestimate crop water demand under climate change scenarios, each having the impact of reducing benefits relative to a model that included fertilization and stomatal conductance impacts.

5 Conclusions

Compared to a BAU future, the results presented here show benefits of mitigating GHG emissions, as the overall damages to U.S. water resource uses from climate change would be reduced. Our analysis shows that the largest impacts from climate change are projected to be on non-consumptive uses (e.g., environmental flows and hydropower) and relatively lower-valued consumptive uses (e.g., agriculture), as water is reallocated during reduced water availability conditions to supply domestic, commercial, and industrial uses with higher marginal values. The primary driver of these changes is increased evaporation associated with warming temperatures. Lower GHG concentrations associated with a mitigation policy will result in a smaller rise in temperature and thus less damage to some of the water resource uses. Hydropower, environmental flow penalty, and agriculture, however, were shown to be sensitive to the change in runoff as well. In some regions with higher GHG concentrations, precipitation can increase; thus the relationship between GHGs and the water resource damages that result from changes in precipitation is more complex, and requires additional analysis to identify key drivers of change and to address areas of uncertainty.

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