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Estimating economic effects of changes in climate and water availability

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Abstract Social, economic, and environmental systems can be vulnerable to disruptions in water supplies that are likely to accompany future climate changes. Coupled with the challenges of tightening environmental regulations, population growth, economic development and fiscal constraints water supply systems are being pushed beyond the limits of their design and capacity for maintenance. In this paper we briefly review key economic concepts, various economic measures and metrics, and methods to estimate the economic effects on water resources from water supply changes that could accompany climate change. We survey some of the recent empirical literature that focuses on estimates developed for U.S. watersheds at both national and regional scales. Reported estimates of potential damage and loss associated with climate and water supply changes that we observe are significant, though often the metrics vary and make valid and consistent direct cross-comparisons difficult. Whether in terms of changes in GDP or in terms of estimated changes in economic welfare based on associated changes in economic costs and benefits, both national and regional estimates suggest that governments and organizations incorporate prudent steps to assess vulnerabilities to plausible future water supply and demand scenarios and develop responsive adaptation strategies.

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1 Overview

As the accumulation of science indicates the climate forcing of anthropogenic greenhouse gas emissions is highly likely to contribute to climate uncertainty and change (e.g., Parry et al. 2007). Both human and natural systems are vulnerable to long-run changes in climate and water supply. Extreme or persistent changes in temperature and precipitation will affect a variety of natural processes including evaporation and vegetative evapotranspiration, snowmelt, vegetation cover, and streamflows. Such changes and the resulting changes in surface- and ground-water supplies can directly and indirectly affect water users. Farmers, for example, must cope with the direct effects of increased crop irrigation requirements caused by higher temperatures and resulting higher evapotranspiration rates. In addition, farmers may also need to adjust to possible indirect effects that higher irrigation requirements entail, including rising irrigation costs that are the likely result of increased regional water demand and heightened competitive pressure on available water supplies. Together, these stresses may outstrip current capacities of water users and systems to cope and manage effectively for future variability and changes.

For many water systems — both municipal and agricultural — the challenges of tightening environmental regulations, population growth, economic development and fiscal constraints are taking these systems to the limits of their design and heightening their vulnerability to climatic changes. Water system engineers typically plan for mild fluctuations, moderate variability, even occasional extremes in climate and water supply. Water systems, infrastructure and institutions are designed to help communities cope with normal fluctuations in climate and water supply. Extreme events and significant and persistent departures from the normal conditions defined by the past record of 50 to 100 years are what concern water system managers most. And, notwithstanding acute stresses confronting some regional ecosystems (e.g., biodiversity), most U.S. communities, industries and consumptive water users — regardless of location — have typically installed systems that cope with moderate levels of variability in local water supply and climate.

There is, however, growing evidence of much greater variability and possibility for extreme events than indicated by the relatively short length of the historical record. As longer cycle phenomena are detected that can alter or disrupt climate patterns, for example the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO), the recorded climate history could prove far from adequate in expressing true climate variability and extremes. Tree-ring analysis is increasingly able to reconstruct much longer climate histories, especially pertaining to rainfall. For example, Margolis et al. (2011) have determined that the Upper Rio Grande watershed in southern Colorado and northern New Mexico has a long and highly variable history of precipitation and streamflow, punctuated with periods of high runoff and severe drought. Reconstructing streamflows for nearly the past five hundred years their research suggests that the recent 100 years of observed streamflow falls significantly short in accounting for the likelihood of climatic extremes. Including the potential for rising greenhouse gas concentrations to compound the disruptions of climate, the reconstructed streamflow records may themselves be considered conservative when identifying and characterizing likelihood distributions of climate and hydrologic patterns.

In the scientific literature there are far more studies linking climate change and hydrology than those considering economic endpoints. In fact there are surprisingly few studies that complete the linkages between climate change, water and economic consequences. In this paper, we briefly describe the principles and concepts for correctly and consistently measuring and estimating economic welfare changes, compare these measures of welfare change with other metrics and approaches to estimating economic effects, and then we survey some of the current and recent literature on economic effects of climate change on water systems and resources, with a focus on national and region-wide estimates and on the most recent studies where they have been conducted.

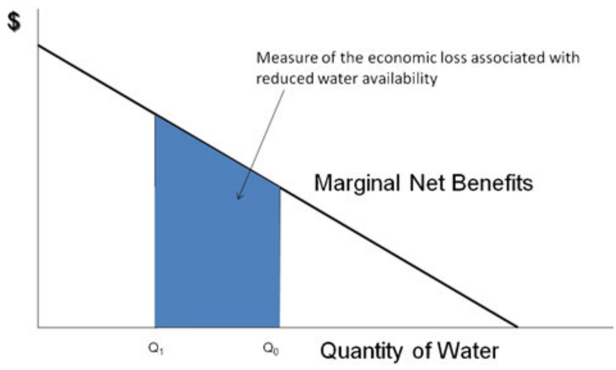
2 Estimating economic impacts

Climate change can lead to economic losses for water users in a variety of ways. Loss of revenue and utility from higher water prices, expenditures on water-saving devices, costs of changing behavior and limiting water use, and actions taken to avoid damages are all ways in which there are economic losses and damages from water shortages that might be attributable to climate change. These changes in economic welfare are measurable in terms of reductions in economic benefits or increases in opportunity costs. Economic value or welfare change from the perspective of those most affected by the change is the individual's maximum willingness to pay to avoid the change. Or inverse formulation, the least dollar amount that the affected user would be willing to accept as compensation for the imposition of such a change. The total economic value or welfare change could be approximated by adding up the estimated values across all affected individuals.

In practice, economists have developed various approaches for estimating the willingness to pay (WTP) or willingness to accept (WTA) to accept or avoid change, respectively (see Young 2005). Where water use approximates a private or market good — either in the production of goods and services or in the satisfaction of individual wants and needs — estimates of the change in WTP can be derived from an analysis of consumer and commercial water demand and cost schedules. And where the affected water use is more closely associated with public goods — for example water quality, recreation, wetland habitats and aesthetics — estimates of the change in WTP or WTA are statistically estimated by a variety of economic methods that are based on a sample of either observed or stated behavior and preferences (Hanemann 2006; Young 2005).

Economic benefits and costs — based on estimates of individual WTP or WTA and aggregated across affected individuals — are used to develop economic demand and supply schedules. Demand and supply schedules describe the marginal benefits and marginal costs, respectively, for varying quantities of the particular good or service. Subtracting the schedule of marginal costs from the schedule of marginal benefits (i.e., the water supply curve is

Fig. 1 Valuing changes in water supply: conceptual basis



subtracted from the water demand curve), the result is a schedule for the marginal net benefits. Shown in Fig. 1 for a given water use or collection of water users, the line labeled marginal-net-benefits corresponds to the marginal value of water. When water availability falls, for example, from Q_0 to Q_1, the shaded area is the loss in economic welfare arising from the reduction in water availability. This change in economic value is the damage or loss in economic welfare,, or equivalently the loss in producer and consumer surplus. Summing the value changes and water-supply costs for each water-using industry or sector, in each region gives an estimate of the total aggregate willingness to pay to avoid the loss of water.

2.1 Other economic measures

Economic impacts can be unclear and even misleading when describing the effects of shocks or changes to the economy. In many instances reported figures are not valid or consistent measures of changes in economic value or net economic benefits. These measures or metrics are not invalid, irrelevant, or inappropriate and can describe very important and socially or politically relevant consequences and characteristics. Some examples of these metrics — that measure something other than changes in economic value or net economic benefits — include changes in gross domestic product (GDP), income, employment or jobs, economic growth and development, economic performance indicators, consumer and producer price indices etc (Hanemann 2006; Young 2005).

However tempting it is to combine, compare, contrast and transform these various measures, it is important to maintain clarity about their intrinsic differences and distinguishing characteristics. Just as money does not equate to happiness, GDP is limited in its capacity to indicate and characterize economically desirable effects and actions. For example, a disaster can result in raised employment, incomes and GDP (at least in the short-run) as money flows from either savings or borrowing into reconstruction and restoration. In spite of the increased GDP and employment, the disaster is not a welcomed and desirable economic event (unless there are significant surplus and under-employed resources and even then someone has to pay for it). Consider the resources and the valuable time and effort of those that are redirected to rebuild that could have instead been employed in new construction or satisfying the wants and needs of so many others (Hanemann 2006; Young 2005).

GDP and employment can rise for both desirable and undesirable reasons. Climate change, for another example, may in the future necessitate the construction of long pipelines to bring water supplies to thirsty cities, the construction of energy-intensive and costly desalination facilities, and the expensive retro-fitting of buildings and municipal water systems. Many will be employed for these jobs and local incomes will rise, perhaps even drawing new residents to the area to service the new spurt in economic growth and development. The correct measure of benefit is the net economic gain in productivity and efficiency.

3 National scale estimates

There is tremendous variation in water resources and water systems across the U.S. Not only variation across regions but tremendous complexity within regions, and within particular watersheds. Such variation and complexity hinders the development of a comprehensive and consistent assessment of economic impacts on a national basis. Estimation approaches such as large-scale statistical studies that have been used in other sectors such as agriculture (e.g., Mendelsohn et al. 1994) are, however, not well suited for assessing water resource impacts because among other reasons there is significant uncontrolled variation within watersheds that impedes reliable statistical estimation.

Enumerative or aggregation approaches to measuring net economic benefits (i.e., the most relevant measures of economic desirability as described in the previous section) that build a national level estimate by aggregating regional estimates from each of the nation's watersheds is conceivable but very difficult and costly to execute. Perhaps the closest example of this approach is Hurd et al. (1999, 2004) where national-level estimates were derived on the basis of only a few large-scale regional estimates and heroic assumptions about the comparability and conformability of different regions with vastly different characteristics.

Sandia National Laboratories has taken a macro-economic approach and used regional economic impact models that estimate changes in economic activities such as gross domestic product (GDP), income, and employment to measure the effects of changes in inputs such as water. To estimate state-level economic impacts from reduced precipitation this study combines:

1. Regional Economic Impact, Inc. model (REMI) — estimates economic input, output and export flows
2. A system dynamics based hydrology model
3. Estimated precipitation changes that are based on the Intergovernmental Panel on Climate Change (IPCC), Special Report on Emissions Scenario (SRES) climate change scenario referred to as 'A1B' (which is characterized by relatively rapid economic growth, balanced use of all energy sources, and converging incomes and quality of life across regions).

This approach, however, does not estimate economic net benefits, and therefore cannot be considered an approach that gives accurate measures of economic losses or damages. With a key focus on macro-economic indicators, not actual economic benefits and costs, potential economic losses are understated. For instance, some resources used in response to adversity will counted toward increased GDP, income and employment, thus showing a positive economic effect or at least dampening the measured economic effect.

Research on climate change and its potential economic impacts has evolved from static models and fixed marginal values to those reflecting market dynamics. Early studies by Cline (1992), Fankhauser (1995), and Titus (1992) associated fixed economic values with projections of physical changes (e.g., runoff), with no attempt to account for changes in the marginal value of water or the response of water use to changes in marginal value. Both Cline's (1992) estimated cost of $7 billion and Fankhauser's (1995) estimated cost of $13.7 billion to consumptive water users in the United States are driven by an assumed 10 % decrease in water availability. Titus (1992) estimated costs ranging from $21 to $60 billion, including impacts to nonconsumptive users (primarily hydropower and water quality losses), which would most likely exceed the magnitude of impacts to consumptive users.

Hurd et al. (1999, 2004) approached the problem from a region-specific perspective using hydro-economic models of four major water resource regions (i.e., Colorado River, Missouri River, Delaware River, and the Appalachicola-Flint-Chattahoochie Rivers). They developed national-level estimates of economic damages for 15 scenarios of incremental climate change based on the regional model results and a model to extrapolate to un-modeled regions. They estimated total annual damages to consumptive and non-consumptive water users by as much as $43.1 billion (1994$) under an incremental level of climate change where temperatures rose by 5 °C and 0 % change in precipitation.

Backus et al. 2010 estimates there is a 50–50 chance that cumulative direct and indirect macro-economic losses in GDP through 2050 will exceed nearly $ 1.1 trillion (2008$), not including flood risks. That is approximately 0.2 % of the cumulative GDP projected between 2010 and 2050. They estimate a 50–50 chance of non-discounted annual losses of $60 billion (2008$) by 2050. Their estimation process uses the MIROC3.2 (medium resolution) and the A1B emissions scenario to guide the assignment of state-level precipitation changes and then uses results from the remaining available General Circulation Model (GCM) projections to characterize and assess uncertainty.

In Backus et al., water availability changes are assessed at the county-level using Sandia Water Hydrology model. State-level impacts on economic activity changes are analyzed using REMI. REMI — and other input–output type models — estimate changes in economic activity based upon fixed relationships between purchased inputs and the production, sale and export of intermediate and finished products. Input–output models do not estimate changes in willingness-to-pay associated with changes in water availability but rather simulate the resulting changes in production resulting from a change in exports. For example, a disaster can stimulate regional economies as recovery rebuilding efforts create jobs and raise incomes. In a similar fashion, persistent and severe water shortages can lead to adaptive responses, like building dams and power plants to replace storage and hydropower generation, thus stimulating employment and incomes.

There is great difficulty in deriving a valid and consistent national-scale estimate of the possible economic effects of climate change resulting from impacts on U.S. water resources. None of the available national-scale findings, therefore, can be considered reliable or accurate as a measure of the economic losses to U.S. water resources as a consequence of climate change. Table 1 consolidates and summarizes these independent measures that do report a dollar-based metric of economic effect but with no consistency with respect to the specific effect, therefore, these estimates are not intended for and should not be used to compare. In other words, any observed similarity is likely to be coincidental, and not attributable to any pattern, trend, or consensus.

4 Regional estimates

Developing valid and consistent estimates of the net economic effects of climate change on water resource users on a regional — and typically watershed-based — scale is more tractable than on a national basis. The conceptual foundation underlying most of the available estimates of regional water resource and economic impacts due to climate change, including that that use so-called hydro-economic models of watersheds, is estimating

Table 1 Summary of estimated national-level economic impacts of climate change on U.S. water resources

Study	Estimated national economic impact
Cline (1992)	$7 billion (~0.1 % of 1992 US-GDP $6.3 trillion)
Titus (1992)	$21–60 billion (~0.3–0.9 % of 1992 US-GDP $6.3 trillion)
Fankhauser (1995)	$13.7 billion (~0.2 % of 1995 US-GDP $7.4 trillion)
Hurd et al. (1999, 2004)	$9.4–43.1 billion (~0.13–0.58 % of 1995 US-GDP $7.4 trillion)
Backus et al. (2010)	$ 60 billion (~0.4 % of 2009 US-GDP $14.1 trillion)

changes in net economic benefits. Such hydro-economic models use mathematical programming techniques to describe and characterize the physical, economic and institutional properties of a watershed system. For example, often they model the storage, movement and flow of water from upstream to downstream regions, the diversity of diversions and instream uses, and the associated benefits and costs for these activities across many time periods. They also depict various physical and institutional features, including reservoirs, aquifers, rivers, water-sharing agreements, compacts and treaties. These models are typically used to analyze differences across scenarios, such as a baseline climate and a climate change scenario. Outcomes of interest include changes in the economic value produced by water and changes in the types and timing of water allocations and uses.

Here we summarize findings from several region-scale studies. These include the regions underlying the national-estimates of Hurd et al. (1999, 2004), namely the Colorado River, Missouri Basin, Delaware basin, and Appalachicola-Flint-Chattahoochie in the Southeast, and the state-level assessments provided in the Sandia report (Backus et al. 2010). Additional economic studies include California (Lund et al. 2003; Medellin et al. 2006), the Pacific Northwest (Climate Impacts Group 2009), and the Upper Rio Grande (Hurd and Coonrod 2012).

4.1 California

Medellin et al. (2006) perform a comprehensive assessment of climate change impacts on California water users. An example of their findings uses the relatively dry scenario referred to as GFDL-A2 to estimate a 27 % decrease in water availability and with modeled adaptive responses they find “an average annual scarcity of 17 %”. Water deliveries to agriculture fall by 24 % and urban deliveries fall by 1 %. They break down the impacts across three categories: scarcity costs, operating costs, and additional policy costs if interregional water transfers are limited. “Of the $360 million/year in average water scarcity costs for 2050 with dry climate warming, $302 million/year results from lost agricultural production and $59 million/year is from urban water shortages. … Dry climate warming imposes an additional increase of $384 million/year in system operating costs. … With the climate warming, the costs of policies limiting interregional water transfers increases to $250 million/year.” All together, these costs amount to $994 million per year, or less than 0.1 % of California’s $1.5 trillion/yr economy.

4.2 Columbia River & Pacific Northwest

The Climate Impacts Group at University of Washington assessed the impacts of climate change on the Pacific Northwest and the state of Washington, averaging across 20 GCMs under both SRES B1 and A1B (Climate Impacts Group 2009). Snowpack reductions were significant, with snow water equivalent falling by as much as 65 %. Although annual runoff shows an increase of 6 % there is a reduction of 43 % in runoff during the summer irrigation season by the 2080s. Without adaptation water delivery shortages to agriculture in the Yakima River basin, for example, could be significant. Estimated deliveries fall by as much as 77 % by the 2080s. In the 2020s, regional hydropower production increases by 0.5–4 % in winter, decreases by 9–11 % in summer, with annual reductions of 1–4 %. Economic losses of between $23 million and $70 million are estimated, with significantly greater probabilities of annual net operating losses for junior water rights holders.

4.3 Rio Grande

Hurd and Coonrod (2012) estimate economic impacts of climate change on water resources in the Upper Rio Grande (primarily New Mexico, El Paso, Tx, and the San Luis Valley of Southern Colorado). Under the relatively dry scenario (GFDL), runoff change was estimated to fall by 28 % (using WATBAL) and annual direct economic damages in 2080 were estimated at $100 million using a hydro-economic model of the watershed. This loss is approximately 0.2 % of the estimated GSP of $60 billion.

4.4 Colorado River

Christensen and Lettenmaier (2007), did a similar research on the Colorado River hydrology with the average of 11 GCM ensembles and two SRES emission scenarios: A2 and B1 (reference). Annual runoff reduction was between 0.0 (2020 B1) and 11.0 (2080 A2) percent. Average annual delivery shortage was estimated to be between 0.22 BCM/Yr (115.8 %) and 1.2 BCM/Yr (631.5). Energy Production is estimated to increase during 2020s by the maximum of 120.5 GWh/Yr (1.4 %) and experience a reduction during the rest of the century which will result in a maximum of 1,573.6 GWh/Yr (18.5 %) of negative production during 2080s.

Hurd et al. (1999), following the work of Booker and Young, modeled the hydro-economy of the Colorado River basin and the impacts of climate change using

Table 2 Estimated regional changes in runoff and economic welfare under selected incremental climate changes

Climate Scenario	Colorado	Missouri	Appalachicola-Flint-Chattahoochie	Delaware
Watershed				
Baseline				
Runoff (kaf/yr)	17,058	56,651	24,363	13,660
Annual Welfare (million 1994$)	$7,744	$10,804	$2,225	$6,565
Climate change scenario and changes from baseline				
+2.5 °C, +7 % P				
% Runoff chg	−4.2 %	−9.1 %	−0.3 %	−4.1 %
Ann. Welfare chg	−$102	−$519	−$15[a]	−$22
+2.5 °C, −10 % P				
% Runoff chg	−37.9 %	−42.5 %	−27.5 %	−33.2 %
Ann. Welfare chg	−$1,372	−$2,041	−$12[a]	−$187
+5 C, 0 % P				
% Runoff chg	−34.7 %	−42.4 %	−23.5 %	−33.9 %
Ann. Welfare chg	−$1,193	−$2,239	−$31[a]	−$207

[a] The estimated changes in welfare for the AFC basin show a mixture of effects including changes in flooding and water quality which confound simple comparison across scenarios. For example, a possible consequence of warmer and drier mean climate might be an expected reduction in average annual flood damages as represented in the above results. However, this analysis does not take into account possible changes in climate variability i.e., greater frequency and intensity of extreme events

Adapted from: Hurd, B. H., J. M. Callaway, J. B. Smith, and P. Kirshen. 1999. "Economic Effects of Climate Change on U.S. Water Resources." In *The Impact of Climate Change on the United States Economy*. ed. Robert Mendelsohn and James NeumannCambride, UK: Cambridge University Press, 133–177 incremental climate change scenarios and a macro-scale hydrology model (i.e., the Variable Infiltration Capacity (VIC) hydrology model). From an annual baseline of $7.7 billion (1994$) they estimated economic losses for a 5 °C rise with no change in precipitation of nearly $1.2 billion when runoff was estimated to fall by 35 %. Under a 2.5 °C rise and a 10 % reduction in precipitation the losses approached nearly $1.4 billion (1994$). A summary of region-specific model results is shown in Table 2.

5 Conclusions

For many purposes, in particular, the formation of national and regional climate-related policies and programs, it remains necessary and important to conduct empirical investigations on the effects of climate change on resources and economies. One of the principle reasons is to ensure that estimated policy and program costs conform — at least broadly — to estimated benefits. As we describe, valid, consistent, accurate and comprehensive assessment of the impacts of climate change on water resources and economies remains challenging. By their design, national-scale assessments cannot portray adequately the variation in regional and local water resource conditions. It is hard to know whether this loss of resolution leads to over- or under-estimating the magnitude of impacts. A key finding from this paper is that the magnitudes from both national and regional studies, at least as a share of GDP, show similar magnitudes. This suggests that if there is indeed a bias in the estimates, aggregation to regional and national scales may not be the culprit. Although there are macro-economic effects that will be generally felt through national and regional markets and changes in economic conditions, impacts to water resources are fundamentally very local and at much higher resolutions than any of the studies reviewed here. As a result, it remains prudent for communities to examine and assess their own vulnerabilities and opportunities to adapt and strengthen their preparedness in the face of climate changes, other stresses, and their unique water situations.

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