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CLIMATIC CHANGE AND U.S. WATER RESOURCES: FROM MODELED WATERSHED IMPACTS TO NATIONAL ESTIMATES[1]

Brian H. Hurd, Mac Callaway, Joel Smith, and Paul Kirshen[2]

ABSTRACT: Water is potentially one of the most affected resources as climate changes. Though knowledge and understanding has steadily evolved about the nature and extent of many of the physical effects of possible climate change on water resources, much less is known about the economic responses and impacts that may emerge. Methods and results are presented that examine and quantify many of the important economic consequences of possible climate change on U.S. water resources. At the core of the assessment is the simulation of multiple climate change scenarios in economic models of four watersheds. These Water Allocation and Impact Models (Water-AIM) simulate the effects of modeled runoff changes under various climate change scenarios on the spatial and temporal dimensions of water use, supply, and storage and on the magnitude and distribution of economic consequences. One of the key aspects and contributions of this approach is the capability of capturing economic response and adaptation behavior of water users to changes in water scarcity. By reflecting changes in the relative scarcity (and value) of water, users respond by changing their patterns of water use, intertemporal storage in reservoirs, and changes in the pricing of water. The estimates of economic welfare change that emerge from the Water-AIM models are considered lower-bound estimates owing to the conservative nature of the model formulation and key assumptions. The results from the Water-AIM models form the basis for extrapolating impacts to the national level. Differences in the impacts across the regional models are carried through to the national assessment by matching the modeled basins with basins with similar geographical, climatic, and water use characteristics that have not been modeled and by using hydrologic data across all U.S. water resources regions. The results from the national analysis show that impacts are borne to a great extent by nonconsumptive users that depend on river flows, which rise and fall with precipitation, and by agricultural users, primarily in the western United States, that use a large share of available water in relatively low-valued uses. Water used for municipal and industrial purposes is largely spared from reduced availability because of its relatively high marginal value. In some cases water quality concerns rise, and additional investments may be required to continue to meet established guidelines.
(KEY TERMS: climate change; economics; modeling; impacts; watershed; management.)

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INTRODUCTION

Water is one of the vital resources that are sensitive to climatic changes (IPCC, 1996; Gleick, 2000; Water Resources Update, 2003). Knowledge and understanding continue to evolve about the nature, extent, and distribution of the physical effects of possible climate change on water resources – for example, effects on snowpack and runoff. However, much less is known about the economic responses and impacts that may emerge. The recent report by the National Water Assessment Group (Gleick, 2000, p. 7) finds: “On top of the uncertainties in evaluating both climate change and potential impacts, evaluating the economic implications of the diverse impacts is fraught with additional difficulties, and few efforts to quantify them have been made.” The present study contributes by providing both an empirical approach and quantitative estimates for some of the most important economic consequences.

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[2]Respectively, Assistant Professor, Department of Agricultural Economics and Agricultural Business, New Mexico State University, Box 30003, MSC 3169, Las Cruces, New Mexico 88003-8003; Senior Economist, UNEP Collaborating Centre for Energy and the Environment, Risoe National Laboratory, P.O. Box 49, DK4000, Roskilde, Denmark; Vice President Stratus Consulting, P.O. Box 4059, Boulder, Colorado 80306; and Research Professor, Civil and Environmental Engineering Department, and Director of Tufts Water, Sustainability, Health and Ecological Diversity (WaterSHED) Center, Anderson Hall, Tufts University, Medford, Massachusetts 02155 (E-Mail/Hurd: bhhurd@nmsu.edu; Callaway: mac.callaway@risoe.dk).

In sectors such as agriculture, the integration of physical and economic models has spawned a new generation of impact models with greater resolution of impacts and sensitivity to human response and adaptation (e.g., Ausubel, 1991; Rosenzweig and Parry, 1994; Darwin *et al.,* 1995; and others surveyed in Adams *et al.,* 1998). Estimates of climate change impacts to water resources, however, have lacked sensitivity to human response and adaptation. Studies by Cline (1992), Titus (1992), and Fankhauser (1995), for example, attach a fixed economic value to projected changes in runoff with no attempt to account for changes in either the marginal value of water or the mitigative response of water users. 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 percent decrease in water availability. Titus (1992) estimated impacts ranging from $21 to $60 billion, including hydropower losses and diminished water quality that he observed could exceed the magnitude of impacts to consumptive users. In contrast to these studies, the present study has developed national level estimates of economic damages related to water resources and climate change based on a set of forward looking, regionally based models of selected U.S. river basins.

Many researchers have related climate (i.e., temperature and precipitation) to runoff at a river basin scale using statistical models and historical data (e.g., Stockton and Boggess, 1979; Němec and Schaake, 1982; Revelle and Waggoner, 1983; Gleick, 1987; Kirshen and Fennessey, 1992; Lettenmaier *et al.,* 1993; see survey of studies in Frederick and Gleick, 1999, and the special issues of JAWRA on the topic in Volume 35, Number 6, 1999; and Volume 36, Number 2, 2000). These studies, however, did not address issues of response and adaptation of water users to changes in runoff and the effects of competition. Studies that begin to consider the response of water users and water institutions to climate change generally fall into three categories. First are studies that have used physical management response models to integrate reservoir and system management models with rainfall/runoff models (e.g., Lettenmaier and Sheer, 1991; Nash and Gleick, 1991; Frederick, 1993; Miles *et al.,* 2000; Miller *et al.,* 2001; Wilkinson, 2002). These studies combined hydrologic models, based on output from general circulation models (GCMs), with water management models simulating water delivery requirements. Second are studies that have used economic valuation models to value the impacts of runoff changes and have assumed equivalence between runoff and allocation changes in response to climate change (e.g., Cline, 1992; Titus, 1992). Studies in these two categories are limited because they do not account for changes in the marginal value of water or for how, in a market system, these changes provide economic signals for allocating water more efficiently among users.

The third category consists of studies that have adapted the spatial and temporal price and allocation-modeling framework developed by Samuelson (1952) and Takayama and Judge (1964) for use in river basin modeling. This study refers to these models as Watershed Allocation and Impact Models (Water-AIM). These models link the investment decisions of water resource planning authorities, the water allocation decisions of water managers, and the water consumption decisions of water users together in a spatially and temporally differentiated framework that is consistent with the geophysical features of individual basins. Sometimes referred to as "price-endogenous spatial equilibrium models" (McCarl and Spreen, 1980), these types of models are widely in use as policy models in the energy, agricultural, and forest sectors in the United States. Vaux and Howitt (1984) pioneered their use for regional water assessment in examining water transfer issues in California. Booker and Young (1991) extended the approach to the Colorado River watershed, and Hurd *et al.* (1999a) and Hurd and Harrod (2001) used the approach to examine the subject of climate change.

The central objective of this paper is to describe and demonstrate how the results from Water-AIM models for several "representative" river basins in the United States can be used to estimate national level lower bound estimates of the potential economic impacts of climate change on water resources. The focus is notably on surface water supplies and uses because of their direct linkage to precipitation and temperature regimes of the prevailing climate. The authors note that ground water use in the short run and ground water availability in the long run can be affected by climate changes; however, information and knowledge regarding both of these responses are significantly lacking at present. This paper is primarily focused on the methods that aggregate model results to the national scale. This paper shares some of the principal findings contained in Hurd *et al.* (1999a); however, the description, discussion, and presentation of the analytic methods is updated to include recent studies and findings. Additionally, some slight revision in the underlying methods in the aggregation analysis has been necessitated by some of the discoveries in Hurd and Harrod (2001), and the revision has led to slightly different estimates. This work, therefore, makes progress in the efforts to understand the potential impacts of climate change on water resources.

The paper begins with a discussion of the regional basin level approach and results from the watershed specific Water-AIM models. Next, the extrapolation and aggregation methods used to assess national level impacts are described and results presented. The results show that the welfare impacts to consumptive water users are potentially much less in percentage terms than the associated change in runoff; however, the percentage change to the welfare of nonconsumptive water users may be as large as or larger than the percentage change in runoff.

WATER-AIM REGIONAL WATERSHED MODELS

Watersheds are a natural unit of analysis when considering regional water resource impacts. Watersheds typically comprise a spatially differentiated system of regional water sources and users; they often span across political boundaries and contain natural and man made features that affect the timing and use of available water supplies. Water-AIM models can reflect each of these aspects in an integrated and unified manner.

The results from simulating scenarios of climate change and subsequent runoff changes across a set of four nationally representative watersheds and associated Water-AIM models form the basis of this national scale assessment. In contrast to the broader approach taken in earlier national studies (e.g., Cline, 1992; Titus, 1992; Fankhauser, 1995), this approach is to build up to a national perspective while preserving regional differences in response and adaptation. This is particularly important where the subject of the assessment, the United States, has distinctive river basins with significant differences in water resources and water uses. Selected on the basis of regional and national significance, diversity of climate, geography, and water use patterns, the four selected watersheds for this Water-AIM approach were the Colorado (upper and lower basins), Missouri, Delaware, and Apalachicola-Flint-Chattahoochee River basins. The Colorado River Water-AIM was originally developed by Booker and Young (1991) and modified by the authors of the present study to simulate the economic impacts of climate change; the authors of the present study developed Water-AIM models for the remaining three watersheds.

Model Framework

Each Water-AIM model is an economic model that assumes competition for water among water users who maximize their expected net economic returns to water over both space and time. The model uses a partial equilibrium framework to examine water use at a regional level. This framework focuses, in particular, on the spatial trade of water within a specific watershed (allowing for the explicit treatment of existing water imports and exports from the watershed in a parametric fashion). The authors note that, in theory, a general equilibrium framework has desirable properties in that it permits not only trade of water within a watershed, as in the current framework, but also trade of goods, services, resources, and labor within and across watersheds (many of which implicitly require a certain quantity of water). However, such a model has yet to be developed and is beyond the present scope of this research effort.

The model structure depicts key physical characteristics of the natural and man made water supply system, including tributaries, inflows, and return flows, diversion points, reservoirs, and basin imports and exports. Seasonal runoff into each basin is based on historical records, and the models solve simultaneously for water allocations and implicit water prices for both consumptive and nonconsumptive uses, reservoir storage and releases, and instream flows over a multiseason (three annual seasons), multiyear (39-year) planning period.

Each Water-AIM model consists of the following.

1. A nonlinear **objective function** that measures the expected net economic returns of water users (sum of consumer and producer surplus) as a function of both consumptive and nonconsumptive uses of water over time and space.

2. A system of linear **constraints** that characterizes seasonal runoff (i.e., inflows) into the basin at aggregate points along tributary rivers and the main stem; spatial linkages between runoff into the basin, main stem and tributary flows, surface water diversions, and subbasin water transfers; intertemporal balances in reservoirs between runoff into the reservoir, water storage, water losses, and storage releases; and initial and terminal conditions on reservoir storage.

The basic structure and model components are summarized in Table 1.

Objective Function

The objective function integrates and aggregates all the sources of economic value in the watershed. Comprised of both benefits and costs, the objective function quantifies the relationship between the net economic returns to water, water use levels, and instream flows at each modeled spatial point in the watershed. In this case, the net economic returns to water are measured by the willingness of water users to pay for water for consumptive uses and some nonconsumptive services, such as hydropower and navigation, less the costs of providing water and the costs related to flood damages and diminished water quality. The objective function also captures the intertemporal tradeoffs between the value of current and future water use as reflected in the reservoir storage decisions. Sources of value in the model include three types of consumptive uses – agriculture, municipal and industrial, and thermoelectric power – and five nonconsumptive uses – hydropower, navigation, flood control, thermal waste heating, and water quality (divided into secondary and advanced wastewater treatment). Consumptive use value functions are quadratic in water use – quantifying the net consumer surplus represented by the area below the linear demand curve of water consumers. The value functions for nonconsumptive water users are described briefly in Table 2. The objective function parameters are based on available data and information concerning: (a) historical patterns of water use; (b) potential baseline (without climate change) changes in these patterns based on trends, income, and population growth projected to 2060; and (c) the available literature on valuation, prices, and productivity.

TABLE 1. Summary of River Basin Planning Model Components.

Sector/ Component	Missouri	Delaware	A-F-C
Number of Consumptive Uses by Sector			
Agriculture	6	3	4
M&I	6	4	4
Thermoelectric	6	2	4
Number of Nonconsumptive Uses by Sector			
Hydropower	3	1	3
Navigation	1	Not Applicable	1
Flood Damage	8	3	4
Water Treatment			
Secondary	2 M&I	2 M&I	2 M&I
Tertiary	2 M&I	2 M&I	2 M&I
Thermal heat	3	3	2
Reservoirs	4	3	3
Number of Modeled Reservoirs, Inflow Points, and River Reaches			
Inflow Points	8	4	4
Main stem Reaches	13	13	9
Tributary Reaches	3 Platte 3 Kansas 2 Osage	3 Lehigh 3 Schuylkill	3 Flint

Constraints

In a model, constraints describe resource availabilities and various physical and institutional processes that govern water flow and use within a watershed. In Water-AIM, constraints include the spatial network of major tributaries, reservoirs, and points of water use, capacity levels on flows, stocks, and diversions, the Compacts (or "laws of the river") that regulate specific water flows for particular regions or uses, and the intertemporal storage of water in reservoirs. The most important sets of constraints, after the fundamental supply of water as runoff, are those that define the spatial structure of a Water-AIM model. The spatial structure characterizes where water enters the system, how it travels and is distributed, where it is used, and how it leaves the system. Schematic diagrams are a convenient way to illustrate the spatial features of a Water-AIM and to indicate the relative locations of upstream and downstream water supplies and users. Figure 1 presents the Missouri Water-AIM as an example of a schematic diagram.

Seasonal runoff is modeled as a parameter input to the model that enters the system at various locations and rates (as shown, for example, in Figure 1). In this assessment, seasonal runoff is given as sequences of flows based on historical volumes that have been hydrologically adjusted to reflect each of the given climate change scenarios.

Finally, in each model there are initial and terminal conditions for reservoir storage. To determine a satisfactory level for these constraints, without being either overly arbitrary or simplistic, the model is allowed to determine the levels endogenously in a manner that balances the desirability, within an optimizing framework, of full reservoirs in the initial time period and empty reservoirs in the terminal time period. The models are constrained to equalize the initial and terminal period storages in each reservoir, though this level is chosen endogenously in optimizing the model's objective function. Explicit details of the model framework can be found in the technical appendix in Hurd *et al.* (1999a), and Hurd and Harrod (2001) use the model to examine regional differences.

Marginal Value of Water: Implicit Prices

Water-AIM provides estimates of the implicit price or marginal value of water for every time period and location. Implicit refers to the fact that the pricing mechanism is internal or endogenous to the model framework. As described above, the model's objective

TABLE 2. Summary of Nonconsumptive Economic Sectors Used in the Regional Basin Models.

Sector/ Basin Model	Valuation Method	Data Description/Source
Hydropower/ All Models	The value of hydropower is treated as the avoided cost of substituting hydropower for alternative sources. Hydroelectric production is treated as a function of the release rate from reservoirs and average hydraulic head (subject to capacity constraints). In the Colorado model, hydraulic head is varied as a quadratic function of reservoir storage.	Data on hydroelectric production are obtained from both regional and general sources, including U.S. Army Corps of Engineers (1981, 1993, 1994a,b), U.S. Bureau of Reclamation (1986), and Gibbons (1986).
Navigation/ Missouri and A-F-C	The value of navigation is treated as a function of the rate of flow at one or more specified reaches. An S-shaped, logistic function to model navigation benefits is assumed. This functional form allows the models to reflect a minimal benefit during low flows, and rising benefits as flow increases. As full flow levels are reached, maximum benefits from navigation are attained.	Logistic function parameters are estimated from regional and general data on the net value of river transport; sources include U.S. Army Corps of Engineers (1993, 1994b).
Flood Damages/ All Models	Linear or quadratic flood damage parameters are estimated for flows above the threshold flow. To reflect differences between peak (flood-causing) flows and average seasonal flows, a peak-to-average flow factor is used to adjust estimated flood damage parameters. Estimates of flood damages primarily reflect urban flooding; however, in the Missouri basin, agricultural damages are also included in the flood damage function.	Estimates of flood damages and corresponding flow levels are obtained from regional sources, including U.S. Water Resources Council (1978), and the U.S. Army Corps of Engineers (1992, 1994a, b).
Thermal Waste Heat/ All Models	An exponential function is used to model the opportunity costs associated with reduced river flows and the loss of power production at once through cooling (OTC) thermal electric plants. To maintain acceptable temperature tolerances, discharges are reduced from plants during periods of low flow. The opportunity cost associated with lost electric production capacity is greatest at low flows and declines toward zero as river flows rise.	Data on OTC plant capacities and minimum flow levels for full utilization are obtained from regional power authorities in each basin.
Secondary Wastewater Treatment/ All Models	The net benefits from secondary wastewater treatment, used by most municipalities discharging into U.S. rivers, are treated as a linear function of flow below major municipal water users. These linear parameters reflect the costs of pre-treating effluent and proxy the value of the river for diluting and assimilating biochemical oxygen-demanding (BOD) materials.	The values presented in Gibbons (1986) are adjusted for inflation to estimate the linear parameters of the models.
Advanced Wastewater Treatment/ All Models	The costs of advanced wastewater treatment are treated as a function of the volume of return flows from municipal users and the deficit in flow below which water quality standards are satisfied (i.e., advanced treatment is required).	Estimates of minimum flow requirements and advanced wastewater treatment costs are obtained from regional water authorities and and from U.S. EPA (1978a,b).

function consists entirely of a series of valuation functions for each benefit and cost in the system. The value of water for consumptive users, for example, is derived from the economic demand function net of supply costs. Known by economists as economic surplus (i.e., the sum of producer and consumer surplus), this measure of economic welfare indicates the net willingness of a particular user to pay for a given quantity of water. In contrast, flood damages are quantified in the objective function as a cost. Estimates for specific flood damage functions were developed by Dr. Paul Kirshen based on historical flood damage estimates and flood stage curves as reported in Table 2. When considered in aggregate across all users and time periods, the optimization framework in the model distributes the available water to each user such that the marginal values are equalized. This equalized marginal value, therefore, is the implicit price of water and represents how much value would be added to the economy of the watershed by one additional acre foot of water.

An important limitation of this approach to valuation is the notable absence of estimates for a variety on nonmarket services, including environmental, cultural, and heritage values that can be regionally important. The authors acknowledge this limitation

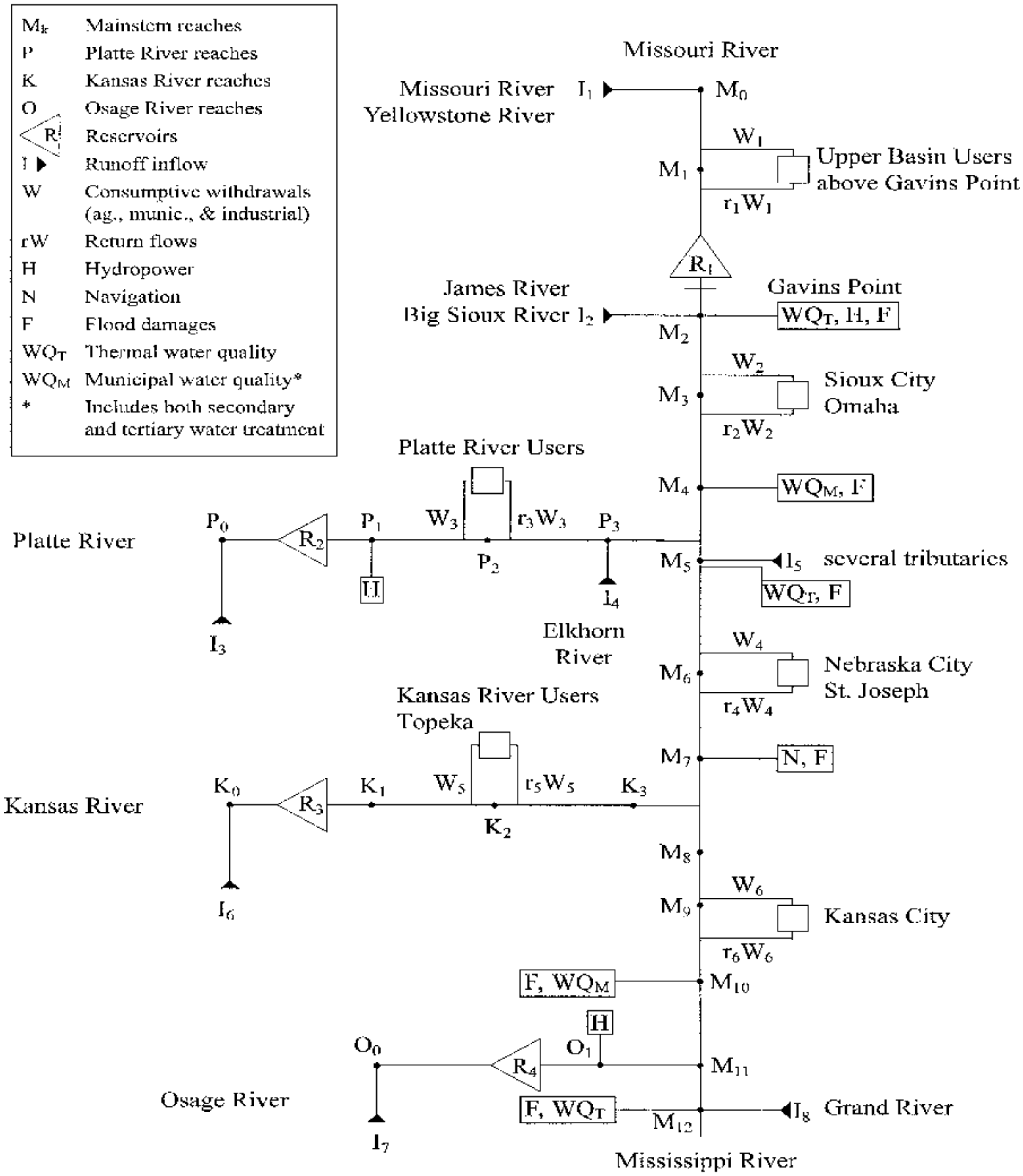

Figure 1. Schematic Representation of the Missouri River Basin Hydroeconomic Model.

as further support of the "lower-bound" nature of the findings contained herein. This is more of a limitation in knowledge rather than the capability of the overall approach to watershed management. Whether reflected explicitly through quantified value functions as part of the model objective, or as additional constraints to the allocation of water to various users, these additional sources of value can be accommodated in the model to the extent that information is available.

Key Assumptions

Water-AIM seeks to balance water use across both time and space such that the value of economic uses and services of available water supply is maximized. This overarching watershed perspective is achieved and embedded in the operational assumption that water allocations can be freely determined. This is equivalent to the assumption that water is tradeable in competitive markets where traders have full information and there are no externalities, significant transactions costs, or other impediments to trade.

The model framework assumes that all available water can be freely allocated to any and each user as long as all constraints are satisfied, including delivery constraints under river compacts. This assumption ensures that the value of water – at the margin – is appropriately equalized across all users, and that economic welfare throughout the watershed is at a maximum. This is equivalent to assuming that individual water users maximize private net economic returns in competitive water markets and that water managers, in turn, make seasonal deliveries with a long run perspective based on the marginal benefits of releasing water in the current period versus storing it for later periods.

This long run perspective is highlighted in the present formulation that assumes that the trajectory of future runoff is known with certainty (methods for relaxing this assumption are the subject of ongoing research). The perfect foresight assumption enables managers to foresee the future course of changes in relative scarcity and of demand and the implicit prices determined by the competitive water markets.

These two assumptions, competitive water markets and perfect foresight, obviously deviate from actual water allocation mechanisms in the United States. How, therefore, is this research useful? First, it provides a conservative lower bound benchmark for estimating impacts, and, second, it provides a measure of support for evolving the flexibility of current institutions to better account for relative values and changes in water scarcity. Markets and institutions that are less than competitive tend to restrict and retard long-run adjustments to scarcity changes and hence lower the capability of mitigating potential economic damages or leveraging beneficial changes. Such evolving institutions are a growing trend and are emerging in many jurisdictions as a flexible and equitable response to offset increased competition over fixed water supplies.

Perfect foresight is consistent with estimating lower bound estimates on the damages due to climate change, in that it assumes that all agents in the model base their current behavior on rational expectations about future events. This approach is consistent with both optimal capital planning and the development of optimal reservoir operating rules in the face of risk associated with stochastic streamflows. An often used alternative approach (e.g., Booker and Young, 1991; Ward *et al.,* 2001) is to treat each year as an independent optimization without regard to expectations of the future. This alternative, however, is notably strong in assuming, for example, operating rules for reservoirs that are exogenously specified such as specific conditions on initial and terminal storage levels.

Climate Change/Runoff Scenarios

The four Water-AIM models were used to simulate the watershed economic impacts of 10 climate change scenarios (Table 3). These scenarios spanned a plausible range of changes in annual average temperature and precipitation that might be induced by greenhouse gases. The scenarios were used to determine runoff under climate change and to condition irrigation demands. To convert the climate scenarios into hydrologic impacts (runoff), runoff projections were used from a methodology developed by Lettenmaier and Wood (1994, unpublished report). They used a variable infiltration capacity (VIC) model to translate changes in monthly average precipitation and temperature into changes in monthly runoff at a resolution well suited to the basin models (resolutions of the hydrologic models are 1 degree latitude and longitude for the Colorado and Missouri basins and 0.5 degree for the Delaware and A-F-C basins). These monthly data were then temporally aggregated to the seasonal level and reported so as to coincide with the inflow points for each of the basin models. The percent change in average annual runoff associated with VIC model runs are also shown in Table 3. As these projections show, there are significant differences in the hydrologic impacts projected across the basins under a given change in climate. These differences highlight the importance of spatial scale, differences that might be blurred at a greater spatial resolution.

Outputs from the Water-AIM models include net returns to water for consumptive and nonconsumptive services, damage costs, optimized regulated river flows, consumptive withdrawals, reservoir storage, and welfare levels over 117 time periods (39 years times three seasons per year) under each of the climate scenarios. Using these outputs, comparisons can be made both within a basin and across basins on the possible impact of climate change on economic welfare (the sum of net economic value generated under each

TABLE 3. Climate Change Scenarios and Changes in Average Annual Runoff in the Modeled River Basins.

Scenario	Δ Average Temperature (°C)	Δ Average Precipitation (percent)	Percent (%) Change in Basin Wide Annual Average Runoff: Colorado	Missouri	Delaware	Apalachicola-Flint-Chattahoochee
Baseline	0	0	0.0	0.0	0.0	0.0
1	+1.5	-10	-32.1	-35.3	-26.8	-23.1
2	+1.5	+7	4.0	1.0	2.7	5.1
3	+1.5	+15	23.5	20.5	16.8	18.7
4	+2.5	-10	-37.9	-42.5	-33.2	-27.5
5	+2.5	+7	-4.2	-9.1	-4.1	0.3
6	+2.5	+15	14.1	9.1	9.9	13.7
7	+5.0	0	-34.7	-42.4	-33.9	-23.5
8	+5.0	+7	-22.4	-30.6	-22.3	-12.4
9	+5.0	+15	-6.9	-15.5	-8.7	0.5

scenario) and water use patterns. These results are used as inputs into a national assessment model to indicate the potential magnitude of climate change damages.

The results from the basin level models show regionally distinct patterns of response to climate change, in particular between eastern and western watersheds. Figures 2, 3, and 4 compare and contrast these patterns and summarize the effects of climate change on prices, allocations, and welfare across the basin models. Rather than present the full range of climate scenarios, prices, allocations, and welfare are compared for the following scenarios: +1.5°C +15%P, +2.5°C +7%P, and +5.0°C with no change in precipitation (referred to as +5.0°C).

In the basin level models, water allocations change in response to runoff changes and their effect on prices. The three charts in Figure 2 show percentage changes in instream level prices (not consumer level prices) resulting from climate induced runoff changes. The distinction between instream level and consumer level prices is important because water users respond to changes in consumer prices, which include the resource costs of supplying water. Instream prices, however, are net of marginal supply costs and measure the difference between consumer price and the marginal supply cost, and therefore, changes in instream prices are calculated from a smaller basis than changes in consumer prices (e.g., a 100 percent increase in instream level price from $5/af to $10/af may result in only a 4 percent rise in consumer level prices, from $125/af to $130/af). Each chart shows the pattern of rising prices as runoff is reduced from the levels under the +1.5°C +15%P climate scenario to the levels under the +5.0°C scenario. In general, prices decrease under conditions where average annual runoff increases (e.g., under the +1.5°C +15%P scenario) and increase where average annual runoff decreases. The charts in Figure 2 show that instream prices are very sensitive to changes in runoff and that they can change by several orders of magnitude in response to moderate changes in runoff. Instream prices to the municipal and industrial sectors (shown in Figure 2b) show pronounced price increases under the +5.0°C scenario and slight decreases when average runoff rises (as under the +1.5°C +15%P scenario). The low price elasticities of demand in the thermal energy sector insulate it from the effects of climate change and rising instream prices. The greatest climate change impact is in the Colorado basin because of the location of thermal energy producers in the upper basin and the severe effects of the Colorado River Compact constraint on instream prices.

Allocations are significantly affected by the relative change in price in the agricultural sector, as Figure 3a shows. This results from agriculture's relatively low marginal supply costs and relatively high price elasticity of demand. Allocations to the municipal and industrial sector, shown in Figure 3b, do not change significantly across the climate scenarios because of the municipal and industrial sector's relatively inelastic demand schedule and the high marginal cost of supplying water to this sector. In fact, Figure 3b shows that municipal allocations do not change appreciably (less than 3 percent) except under the +5.0°C scenario. Under this scenario the effect is greatest in the Colorado basin because of the requirements to deliver set volumes of water downstream under the Colorado River Compact. The changes in allocation are slightly higher in the thermoelectric generating sector than in the municipal and industrial sector (because marginal supply costs are lower), but they are still less than 10 percent in most cases.

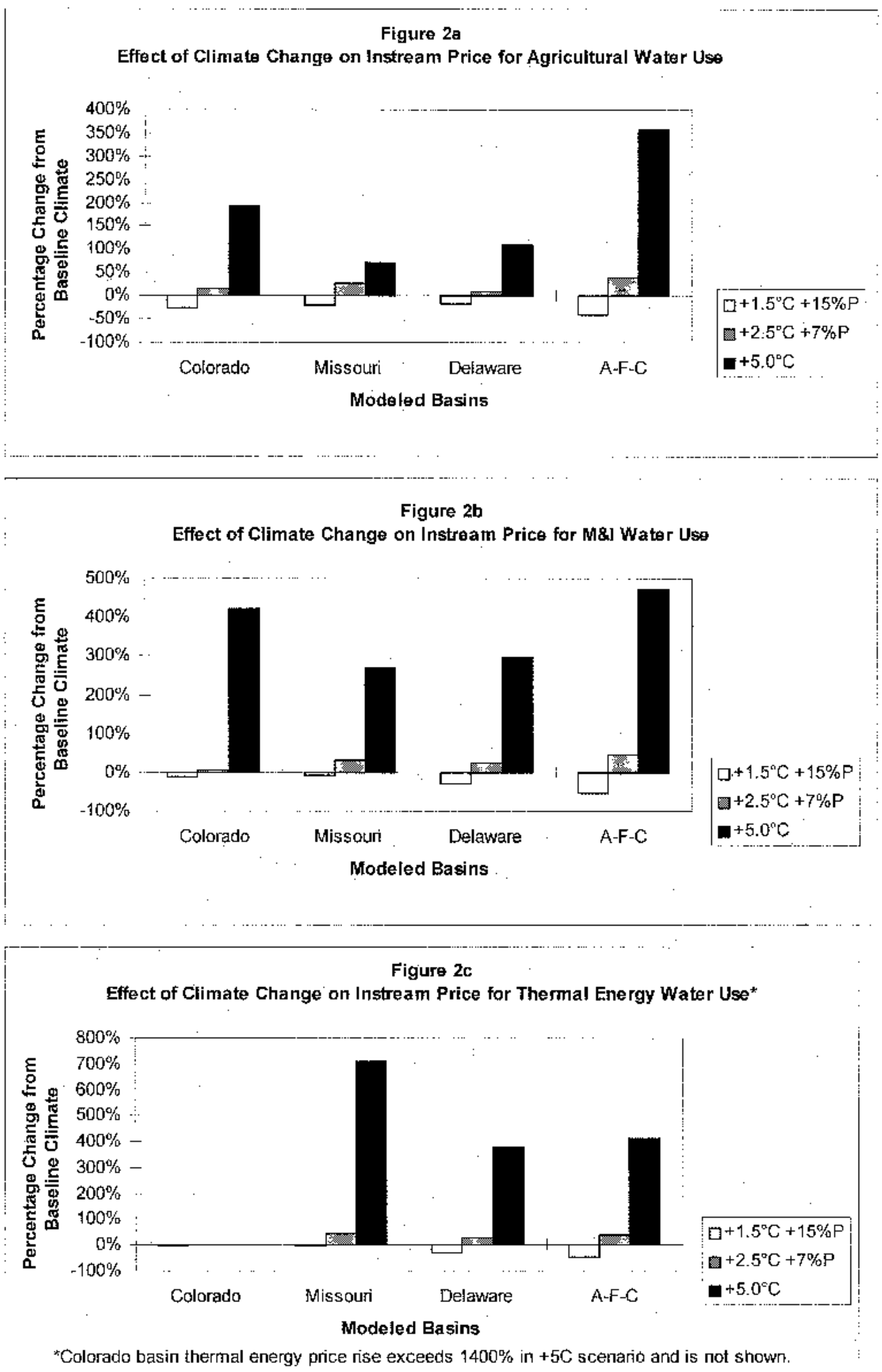

Figure 2. Effects of Climate Change on Simulated Instream Prices for (a) Agricultural, (b) Municipal and Industrial, and (c) Thermal Energy Water Use.

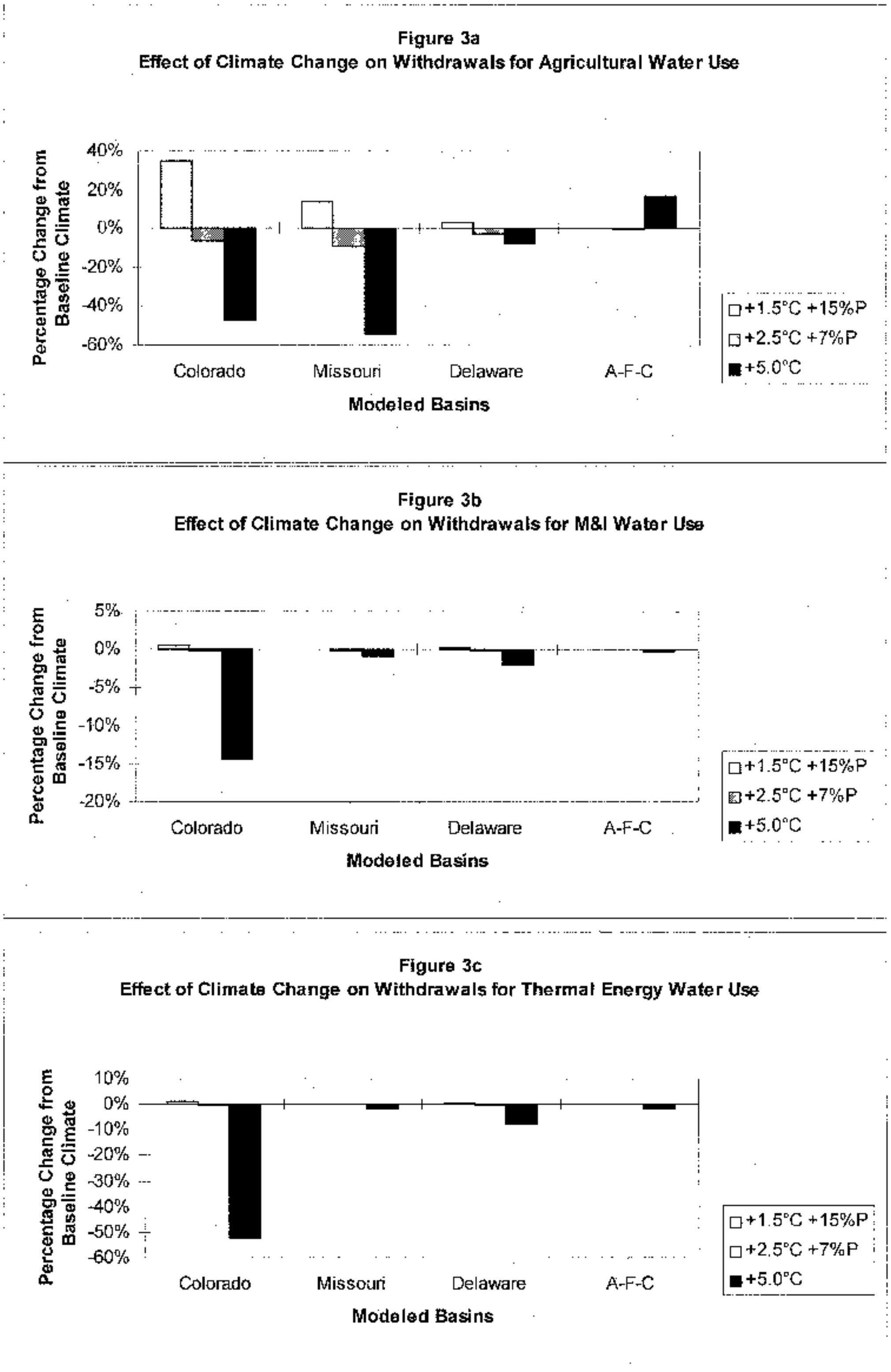

Figure 3. Effects of Climate Change on Simulated Withdrawals for (a) Agricultural, (b) Municipal and Industrial, and (c) Thermal Energy Water Use.

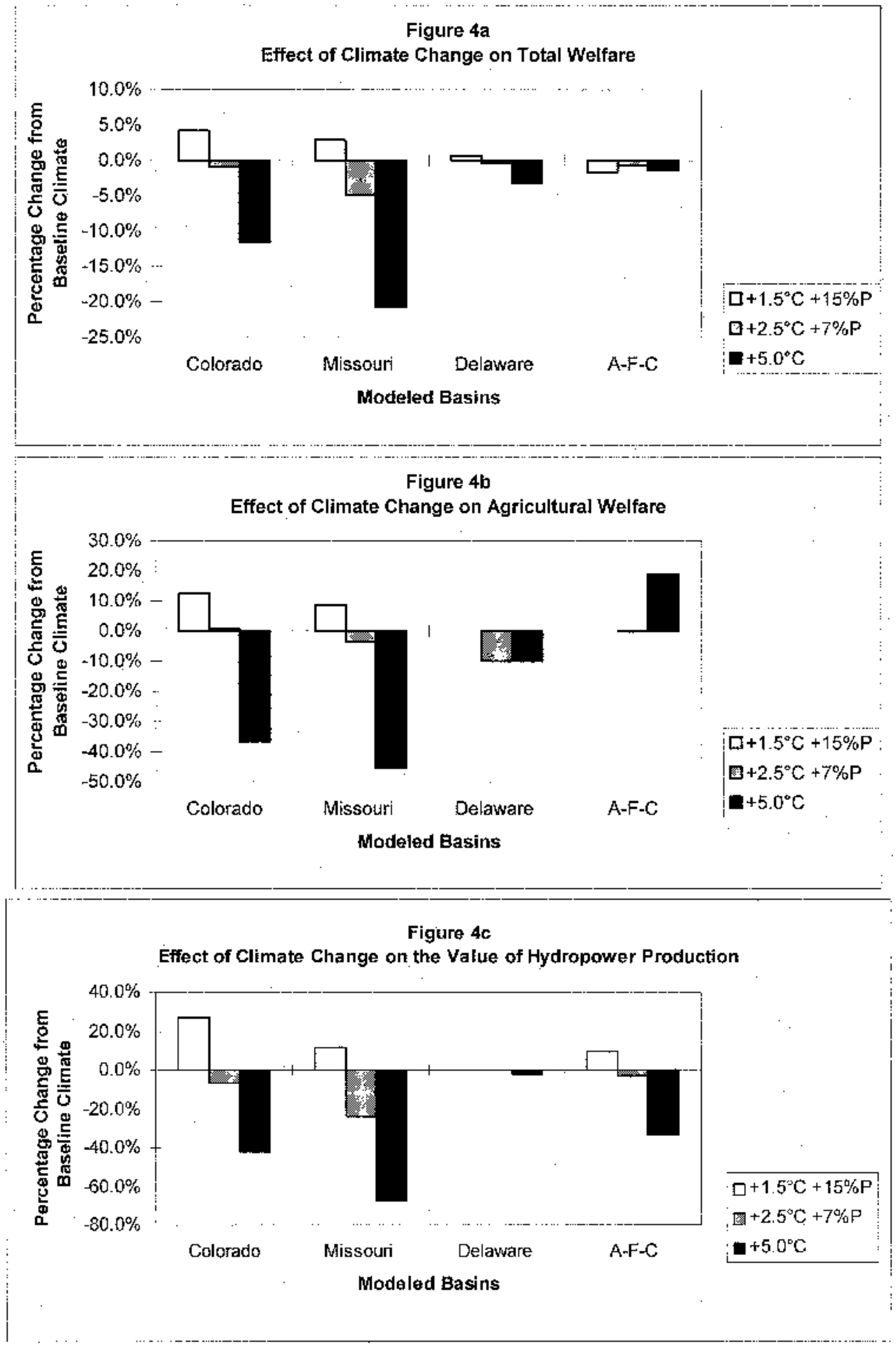

Figure 4. Effects of Climate Change on (a) Total Welfare, (b) Agricultural Welfare, and (c) the Value of Hydropower Production.

Welfare changes are summarized in Figures 4a, 4b, and 4c by basin for total welfare, agricultural welfare, and the value of hydropower production, respectively. Welfare changes for both consumptive and nonconsumptive water uses in the climate change scenarios are measured relative to the base case. These welfare changes are measures of "climate change damages," taking into account market adjustments. Total welfare varies the greatest in the western basins (Colorado and Missouri), which have significant agriculture and hydropower sectors. In these two basins, total welfare drops between 10 percent and 20 percent under the +5.0°C climate scenario, whereas the total welfare loss in the eastern basins drops by less than 5 percent. Welfare increases generally occur under the scenarios where runoff increases (e.g., +1.5°C +15%P) except in the A-F-C, where increased flooding results in net welfare losses under this scenario.

Agricultural welfare falls considerably under the +5.0°C scenario except in the A-F-C basin. The loss is approximately 40 percent in the Colorado and Missouri basins and 10 percent in the Delaware basin. In contrast, agricultural welfare in the A-F-C basin rises under the +5.0°C scenario. This increase is attributed to the climate-induced shift in agricultural water demand and the subsequent rise in the measure of agricultural consumer surplus (which may reflect adjustments to higher valued crops). Agricultural withdrawals can rise under this scenario in spite of a significant drop in runoff because of this basin's relatively low ratio of annual average withdrawals to annual average runoff.

The hydropower sector shows significant variability in the effects of climate change in all the regions except the Delaware basin, where hydroelectric capacity is small and constrained. Hydropower welfare falls by at least 35 percent under the +5.0°C climate scenario, with losses in the Missouri basin greater than 60 percent. On the other hand, hydropower production rises under scenarios with increased runoff (e.g., +1.5°C +15%P), increasing between 10 percent and 25 percent in the Colorado, Missouri, and A-F-C basins. Changes in welfare in the municipal and industrial sector are relatively small, generally less than 1 percent.

NATIONAL LEVEL ASSESSMENT

Using the results from the basin level models, an aggregation model was constructed to extrapolate impacts to the national level. In building up to the national level, the basin level impacts were first extrapolated to the remaining U.S. water resource regions. To accomplish this, modeled basins were paired with the remaining water resource regions on the basis of geographic and climatic similarities, as given in Table 4 and pictured in Figure 5. So, for example, the Colorado River was assumed to be the most representative of other basins in the Southwest (e.g., Rio Grande, California, and Great Basin). The Pacific Northwest – Columbia River basin – in contrast, is quite different in many dimensions from any of the modeled basins. However, given the dimensions of its runoff, the Missouri River basin was believed to be a better proxy than the Colorado River basin in this instance. Using region specific data on water use and projections of runoff changes, impacts to the remaining basins were extrapolated based on these pairings. In the final step, basin level impacts were summed to provide a national estimate for both consumptive and nonconsumptive water uses.

TABLE 4. Pairing of Modeled River Basins to Remaining U.S. Water Resource Regions.

Modeled Basin	Paired Water Resource Regions
Colorado River	Rio Grande Great Basin California
Missouri River	Upper Mississippi Souris-Red-Rainy Arkansas-White-Red Texas-Gulf Pacific Northwest
Delaware River	New England Mid-Atlantic Great Lakes Ohio
Apalachicola-Flint-Chattahoochee Rivers	South Atlantic Tennessee Lower Mississippi

Consumptive Use Model

The procedure for extrapolating and aggregating welfare impacts associated with consumptive water use combines estimates from the basin models with data on water use and runoff from the subject region. The consumptive use model uses the basin model results and data on water use and runoff changes in each region; hydrologic data for the national assessment, consisting of average runoff by scenario, were provided by Battelle Pacific Northwest Laboratories,

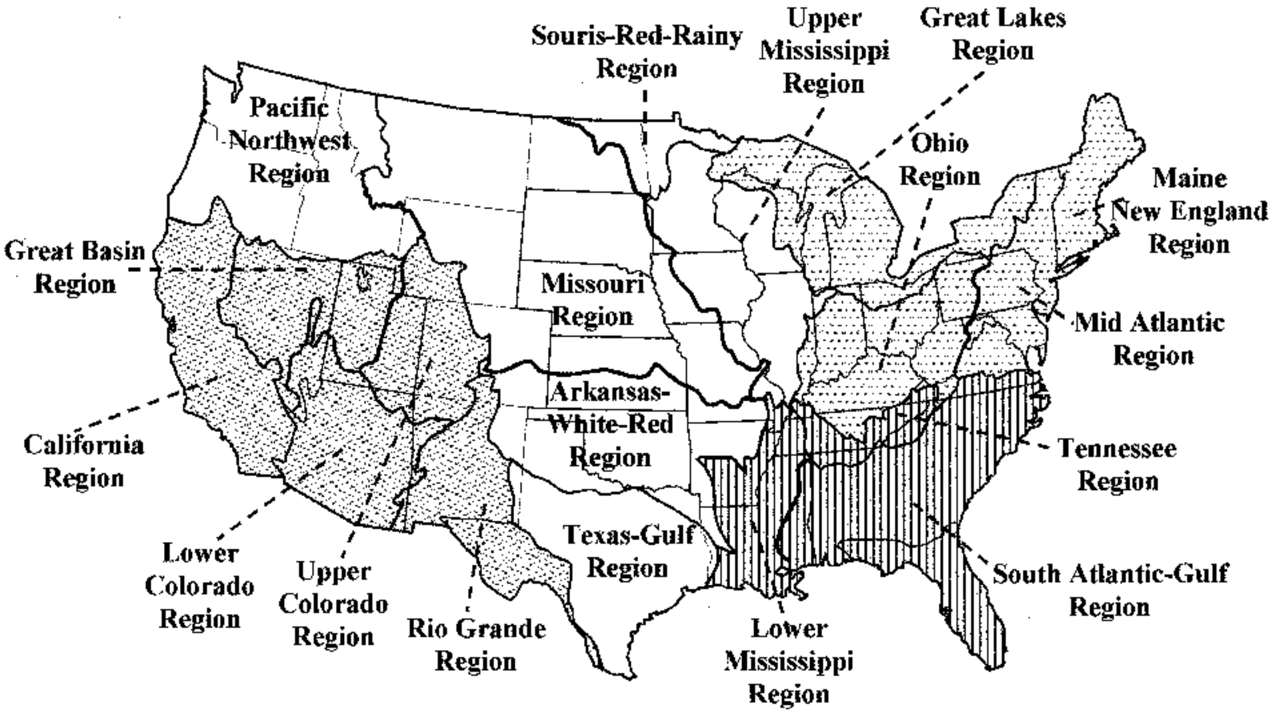

Figure 5. U.S. Water Resources Regions and Paired Regions Used in the Extrapolation.

and data on water use characteristics were derived from Solley *et al.* (1993). The change in national welfare for consumptive uses is equal to the sum of net changes in consumer and producer surplus across sectors and regions and is given as

$$\Delta\ National\ Consumptive\ Use\ Welfare = \sum_j \sum_i \Delta R_{ij} \tag{1}$$

where ΔR_{ij} is the change in consumer and producer surplus in Sector i and Region j. Conceptually, the net change in consumer and producer surplus associated with a change in water use is measured by the change in the area below the net demand curve (i.e., demand-supply). The net demand curve was assumed to be linear (which would be the case if the underlying demand and supply curves were also linear). Hence, the surplus change is defined for each sector in each region as

$$\Delta R_{ij} = \left(\overline{\$}_{ij_0} \bullet \Delta\overline{W}_{ij}\right) + \frac{1}{2}\left(\Delta\$_{ij_0} \bullet \Delta\overline{W}_{ij}\right) \tag{2}$$

where $\overline{\$}_{ij_0}$ is the estimated net marginal value of water under baseline conditions for the basin model and $\bar{W}_{ij}$ is the baseline annual surface water withdrawal for Sector i and Region j (based on estimates from Solley *et al.,* 1993). $\Delta\bar{W}_{ij}$ is the change in water use by Sector i in Region j and is estimated by the baseline (i.e., current climate) water use patterns in Region j, the simulated changes in sector water use in the modeled Region j_0, and relative runoff changes between paired region j and modeled region j_0, given as

$$\Delta\overline{W}_{ij} = \overline{W}_{ij}\left[\left(1+\%\Delta W_{ij_0}\right)\bullet\frac{\left(1+\%\Delta Q_j\right)}{\left(1+\%\Delta Q_{j_0}\right)}\right] \tag{3}$$

where W_{ij0} is the efficient water withdrawal to sector i determined in basin model j_0, and Q_j is a measure of simulated runoff conditions. This term, therefore, assumes that changes in water use patterns are proportional across paired regions and sectors, adjusting for differences in projected runoff between the regions. It is recognized that there is a difference between withdrawals and consumptive use and also that efficient use depends on equalizing the marginal value across consumptive uses (i.e., after accounting for return flows). However, consistent data on consumptive use were not available. If average return flow rates are approximately the same within a given sector across regions, then no particular bias is introduced.

This procedure accounts for differences in both runoff and river volumes across regions; however, it assumes that the response of water users to price changes (within each economic sector) is the same between the modeled regions and paired regions. It assumes, for example, that agricultural water use in the upper Mississippi region has the same demand elasticity as agricultural water use in the Missouri region.

Nonconsumptive Use Model

Nonconsumptive water use is vital to the economy and is a significant source of welfare, as shown by the regional level model results. However, accounting for changes in nonconsumptive welfare is more tenuous at the national level because of greater uncertainty in measurement and the greater impact of regional differences (e.g., hydraulic parameters for hydropower).

A slightly different approach than the one presented above is used because of the absence of water use data. Instead, the extrapolation is based on the estimated change in nonconsumptive welfare from the regional models; this value is then scaled by two factors to account for regional differences in runoff under climate change and scale (absolute magnitude) differences across river basins. For the first factor, the ratio of percentage changes in runoff between the two regions is used. Scaling by the ratio of runoff changes, as in the consumptive use procedure above, accounts directly for regional variation in runoff and water availability. Accounting for regional differences in the nature (and scale) of nonconsumptive water use is more uncertain.

To account for relative scale of nonconsumptive values across regions, a second factor, the ratio of water used in hydropower production between the two regions is used. Hydropower was observed in the model results to relate more directly to the estimates of nonconsumptive welfare than to annual volume. Hydropower accounted for more than 60 percent of estimated nonconsumptive welfare in three of four basins (the Delaware was the exception with a relatively low share). At the national level, this assumption does not appear to introduce significant bias into the estimates. However, extrapolating to specific regions, particularly the Northeast and mid-Atlantic, is not advised because of the relatively small capacity for hydropower production in the Delaware basin and the potential for bias at the regional level.

The change in national welfare derived from nonconsumptive water uses is defined as

$$\Delta\ \textit{National Nonconsumptive Use Welfare} = \sum_j \Delta R_{nc,j} \tag{4}$$

where $\Delta R_{nc,j}$ is the change in the welfare of nonconsumptive users in Region j. This change in welfare is given by

$$\Delta R_{nc,j} = \Delta\overline{\$}_{nc,j_0} \bullet \frac{1+\%\Delta Q_j}{1+\%\Delta Q_{j_0}} \bullet \frac{H_j}{H_{j_0}} \tag{5}$$

where $\overline{\$}_{nc,j_0}$ is the value of nonconsumptive water use in modeled region j_0, Q_j is runoff in Region j and H_j is the quantity of water used in hydropower production in Region j in 1990 (Solley *et al.,* 1993).

The accuracy of this procedure depends critically on two premises: first, the assumption that the value of water in a modeled region is largely similar to those in the extrapolated regions; second, the assumption that hydropower is representative of scale differences across regions. These assumptions may be valid for estimating national level impacts but could be very misleading if applied to extrapolating specific regional estimates.

RESULTS

National allocation changes by sector and climate scenario are shown in Table 5 in both absolute and percentage changes. The agricultural sector shows the greatest responsiveness to changes in climate and runoff. Agricultural water use is very susceptible to long-term changes in runoff, with changes ranging between -45 percent and +16 percent. Agriculture shows this range of effects because of its relatively large share of total consumptive water use and its relatively low marginal values and high price elasticities (i.e., small price changes can cause relatively large displacements in water use). Municipal and thermal energy withdrawals show significant but limited reductions in response to reduced runoff.

The magnitude of national level changes exceeds that of the basin level results. The measure of this difference is small but significant. For example, municipal withdrawals fall by 0.03 percent to 0.3 percent under the +2.5°C +7%P climate scenario in the upper and lower basins of the Colorado basin, in the Missouri basin, in the Delaware basin, and in the A-F-C basin. However, the national assessment shows withdrawals falling by 1.9 percent under the same scenario. This difference in response at the two levels is explained by differences in regional runoff changes

TABLE 5. Simulated Effect of Climate Change on Withdrawals of U.S. Water Users.

Climate Change Scenario	Change in Total Withdrawals (percent)	Change in Ag Withdrawals (percent)	Change in M&I Withdrawals (percent)	Change in Thermoelectric Withdrawals (percent)
Baseline* (maf/yr)	377	157	74	146
1.5˚C -10%P	-15.7	-32.6	-2.4	-4.1
1.5˚C +7%P	0.2	0.7	-0.8	0.2
1.5˚C +15%P	7.2	16.4	-0.8	1.3
2.5˚C -10%P	-21.1	-42.5	-4.8	-6.3
2.5˚C +7%P	-4.3	-9.0	-1.9	-0.5
2.5˚C +15%P	2.6	6.1	-1.1	0.7
5.0˚C	-22.0	-44.5	-4.9	-6.5
5.0˚C +7%P	-17.7	-38.2	-2.4	-3.4
5.0˚C +15%P	-9.4	-20.7	-1.9	-1.2

*The numbers shown in the row labeled "baseline" report the baseline value level from which the percentage change or absolute difference is calculated.

and in particular by the differences between the modeled response of runoff in the Missouri basin relative to the regions that are extrapolated from the Missouri basin (i.e., Pacific Northwest, Upper Mississippi, and Texas Gulf). For example, runoff is reduced by only 18 percent in the Missouri basin, whereas it is reduced by 28 percent in the Upper Mississippi under the +2.5˚C -10%P scenario. This relative difference between the Missouri basin and the extrapolated regions is sufficient to cause the estimate of national changes to exceed the basin model changes.

In dollars, national consumptive welfare increases by $0.085 billion and falls by $4.3 billion under the +1.5˚C +15%P and +5.0˚C scenarios, respectively. Total welfare is estimated to fall by $0.98 billion annually under the +2.5˚C +7%P scenario. The national welfare changes for consumptive sectors are given in Table 6. The most significant result is the effect of reduced runoff on the welfare of the agricultural sector compared to the effect on the municipal and thermal energy sectors. This result mirrors the change in withdrawals and underscores the vulnerability of this sector to long term changes in climate. Irrigated agriculture, as an example, gains nearly $65 million under the +1.5˚C +15%P scenario and loses $3.7 billion under the +5.0˚C scenario. The welfare of the municipal and thermal energy sectors is relatively unaffected by runoff changes. As is the case in the basin level results, the price changes are small relative to market prices. Small relative changes in prices and allocations lead to small welfare changes. For example, the welfare of M&I drops by $3 million under the +1.5˚C +15%P scenario and by nearly $49 million under the +5.0˚C scenario. Changes in the welfare of thermal energy users range from losses of $622 million to a gain of $23 million across the scenarios.

Changes in total consumptive welfare are generally far less than the associated change in runoff. Changes in relative scarcity are efficiently conveyed to water users through market signals to consumers with low marginal valued uses (e.g., agriculture, which bears a proportionally larger share in reduction). Changes in consumptive welfare range between +0.1 percent and -4.8 percent, far less than the change in runoff, which is more than 40 percent in some basins under the +5.0˚C scenario.

Climate effects on the national welfare of nonconsumptive sectors are shown for hydropower and total nonconsumptive welfare in Table 7. The dependence of nonconsumptive uses on streamflow makes them particularly vulnerable to climate change, as seen in the basin level models. In these sectors, losses cannot be allocated to those with the lowest marginal benefits. The relative effects of climate change are greater for nonconsumptive uses than in any of the consumptive sectors. Although the consumptive sectors may combine to a larger share of total welfare than the nonconsumptive sectors, the relative effect of climate change is generally greater on the nonconsumptive sectors.

TABLE 6.Simulated Effect of Climate Change on the Welfare of Consumptive Water Users in the U.S. (millions of 1994$).

Climate Change Scenario	Change in Cons. Welfare ($)	Percent (%) Change in Cons. Welfare	Change in Ag Welfare ($)	Percent (%) Change in Ag Welfare	Change in M&I Welfare ($)	Percent (%) Change in M&I Welfare	Change in Thermoelectric Welfare ($)	Percent (%) Change in Thermoelectric Welfare
Baseline*	88,519	0	13,699	0	44,939	0	29,881	0
1.5˚C -10%P	-2,734	-3.1	-2545	-18.6	-19	-0.041	-170	-0.570
1.5˚C +7%P	-462	-0.5	-465	-3.4	-3	-0.006	6	0.021
1.5˚C +15%P	85	0.1	65	0.5	-3	-0.008	23	0.078
2.5˚C -10%P	-4,216	-4.8	-3,544	-25.9	-49	-0.109	-622	-2.082
2.5˚C +7%P	-981	-1.1	-9,41	-6.9	-31	-0.069	-9	-0.031
2.5˚C +15%P	-314	-0.4	-324	-2.4	-5	-0.011	15	0.050
5.0˚C-	4,292	-4.8	-3,674	-26.8	-49	-0.109	-569	-1.905
5.0˚C +7%P	-3,040	-3.4	-2,901	-21.2	-16	-0.035	-123	-0.411
5.0˚C +15%P	-1,773	-2.0	-1,733	-12.7	-11	-0.024	-29	-0.096

*The numbers shown in the row labeled "baseline" report the baseline value level from which the percentage change or absolute difference is calculated.

TABLE 7. Estimated Effect of Climate Change on the Welfare of Nonconsumptive Water Users in the U.S. (millions of 1994$).

Climate Change Scenario	Change in Nonconsumptive Welfare ($)	Percent (%) Change in Nonconsumptive Welfare	Change in the Value of Hydropower ($)	Percent (%) Change in the Value of Hydropower
Baseline*	43,350		14,702	
1.5˚C -10%P	-28,858	-66.6	-5,503	-37.4
1.5˚C +7%P	-1,073	-2.5	-1,152	-7.8
1.5˚C +15%P	9,670	22.3	691	4.7
2.5˚C -10%P	-36,542	-84.3	-6,998	-47.6
2.5˚C +7%P	-8,435	-19.5	-2,752	-18.7
2.5˚C +15%P	2,895	6.7	-781	-5.3
5.0˚C	-38,841	-89.6	-7,423	-50.5
5.0˚C +7%P	-28,714	-66.2	-6,499	-44.2
5.0˚C +15%P	-16,147	-37.2	-4,653	-31.7

*The numbers shown in the row labeled "baseline" report the baseline value level from which the percentage change or absolute difference is calculated.

The value of foregone hydropower production as a result of climate change is directly related to reduced runoff and evaporation losses. Using the extrapolation procedure for nonconsumptive uses, the estimated change in the value of hydropower production ranges from losses of $7.42 billion to gains of $691 million. The welfare losses to hydropower exceed those from all the consumptive sectors combined under the +5.0˚C scenario ($7.4 billion versus $4.3 billion). This striking result is compounded when other nonconsumptive sectors are considered.

Table 7 also shows the effects of climate on the aggregate nonconsumptive sector, which includes sectors such as hydropower, navigation, flooding, and secondary and advanced water treatment to the extent that they are modeled at the basin level. Changes in total nonconsumptive welfare (including hydropower) range from losses of $38.8 billion to gains of +$9.7 billion. These results do not include the welfare impacts associated with ecosystem and wildlife disruption resulting from reduced runoff, nor do they reflect damages from lost thermal energy production (e.g., resulting from reduced capacity to assimilate waste heat) because of the inconsistencies of measuring this loss across regions. These nonconsumptive welfare estimates are based on conservative assumptions that most likely do not capture the full range of the impacts.

Table 8 summarizes total welfare effects for three climate scenarios. There is a wide range in annual welfare changes across the set of climate scenarios, with total welfare rising by $9.8 billion under the +1.5˚C +15%P scenario and falling by $43.1 billion under the +5.0˚C scenario. Total welfare falls by $9.4 billion under the +2.5˚C +7%P scenario. These totals are more uncertain than the consumptive or hydropower estimates because of the uncertainties in extrapolating the remaining nonconsumptive sectors to other regions.

CONCLUSIONS

Several inferences can be drawn regarding the economic effects of climate change on water resources. First, the watershed level results clearly show that an important measure of economic vulnerability is the relative magnitudes of annual average consumptive withdrawals and annual average runoff. These two measures taken together provide an important indicator of the relative scarcity of water with respect to consumptive uses that is important in determining the degree of the response of water users to changes in runoff (see also Gleick, 1990; Hurd et al., 1999b; Lane et al. 1999). The economic costs to consumptive users of reduced runoff were much less in the eastern U.S. basins than in the western basins.

Second, the measures of use and flow do not readily describe the effects on nonconsumptive water users. The importance of nonconsumptive water use is underscored by the significant welfare changes shown in the basin-level models. Hydropower production is particularly susceptible to long-run changes in climate that affect the distribution of runoff. This analysis has shown that changes in the value of hydropower alone are likely to be of the same order of magnitude as changes in the welfare of consumptive water users. Add to this the effects of other nonconsumptive sectors such as water quality, flooding, and navigation (as well as ecological effects that were not considered), and the potential impacts on nonconsumptive users may exceed those on consumptive sectors. Flooding may be particularly important in many regions as continued population and economic growth compound the exposure to possible flood risks.

Third, the estimates contained herein stand in contrast to those that do not implicitly (or explicitly) consider adaptation, particularly through market incentives. Cline's (1992) estimate of a cost of $7 billion is based on a nationwide 10 percent decrease in water availability and assumed prices for water that do not reflect adaptation. Fankhauser (1995) estimates a loss of $13.7 billion for consumptive water users in the United States based on a doubling of CO_2 and a decrease in runoff of about 10 percent; he also does not consider market adaptation. It is difficult to compare these estimates directly to ours, given differences in assumptions concerning runoff; however, market adaptation is an important response to take into account in estimating impacts. Titus (1992)

TABLE 8. Estimated Total Economic Welfare Impacts on U.S. Water Resource Users (billions of 1994$).

Climate Scenario	Consumptive Use	Nonconsumptive Use: Hydropower	Nonconsumptive Use: Other Nonconsumptive Sectors	Total
+1.5˚C +15%P	0.085	0.69	8.98	9.8
+2.5˚C +7%P	-0.98	-2.75	-5.68	-9.4
+5.0˚C	-4.29	-7.42	-31.4	-43.1

Not including damages from thermal heat pollution.

included nonconsumptive users (primarily hydropower and water quality losses) in his estimation of the effects of climate change on water resources. He observed that the effects to nonconsumptive users would likely exceed the effects to consumptive users and estimated the total range of losses between $21 and $60 billion. When nonconsumptive sectors are included, the estimates rise considerably, ranging between +$9.8 billion under the +1.5ºC +15%P scenario and -$43.1 billion under the +5.0ºC scenario (under the +2.5ºC +7%P scenario the loss is estimated at $9.4 billion annually).

These findings may be of interest to decision makers and managers of water resources (or of activities dependent on water resources) as an indicator of the scope and range of possible changes in the conditions under which long-run planning is conducted, such as the investment planning surrounding long-lived assets and infrastructure. Given the lower-bound nature of the specific findings, managers and decision makers might take from this study the need to carefully consider revisions in water resource institutions, allocation mechanisms, and the potential gains from increasing the flexibility and adjustment capacity of water use patterns both in the short run and long run. Several plausible scenarios heighten concern over flooding and the magnitude of potential damages. This observation might give support for reevaluating local land use planning and zoning regulations in light of possible changes in risk exposure and vulnerability to flooding. Flood relief and insurance institutions might be given cause to review their flood relief and compensation programs, particularly with the intent to increase the use of incentives that reduce flood risk exposure.

Finally, one needs to be cautious about interpreting the results from partial equilibrium models like the Water-AIM models used in this study. These results present the estimated welfare impacts of climate change on water users in a basin, not on society as a whole. In this study, the impacts of climate change are estimated on several sectors that use water as an input. The authors believe that these sectoral impacts are correctly estimated. However, the welfare impacts that appear as benefits or costs in one sector are transmitted to other sectors through inter-industry transactions, affecting different sectors differently. Thus a technological externality that increases the producer surplus of one sector may increase the costs to other sectors of purchasing goods from this sector if the input demand lacks price elasticity. This is because revenues increase in the input sector but appear as higher costs to purchasers of these inputs.

A good example of this issue arises in climate-induced shifts in the demand for irrigation water. Increases in temperature increase potential evapotranspiration, and more water must be applied to achieve a given yield level (abstracting from the complications of the fertilization effect of higher CO_2 levels). This simultaneously appears as a shift to the right of the derived demand curve for water and for the supply curve of the agricultural producer. Thus, the water costs more, and the agricultural producer will always be worse off at the old level of production, that is, the level before climate change. However, because of shifts in crop mixes and other types of adjustments to climate change, the farmer could also be better off, as shown by Mendelsohn *et al.* (1994). These effects are hard to incorporate into the partial equilibrium demand curves for water, especially for the agricultural sector.

One final caveat: there are many water uses, primarily ecological and recreational, that have not been explicitly taken into account. At first it may appear that the omission of these sectors suggests that the estimates contained herein are perhaps biased downward. However, this conclusion is not necessarily warranted, given the use of water quality standards in determining the benefits and costs associated with wastewater assimilation. These standards presumably embody both ecological and recreational concerns. Therefore, to some extent the analysis reflects these omitted sectors.

There is considerable room for continued research using river basin spatial equilibrium models. Expanded national (and international) coverage would improve the ability to estimate aggregate level effects. For example, the Columbia basin in the Pacific Northwest is important to the welfare of both consumptive and nonconsumptive sectors. This basin is significantly different in many respects from any of the basins that were modeled; therefore, it is difficult to extrapolate the effects of climate change to that region.

Improvements in the modeling of different sectors, institutional regulations, and reservoir operations could be made to the existing models. For example, the modeling of agricultural water demand could be better adjusted for changes in crop yields and acreage response to climate change. Additionally, the modeling of ground water use and supply for all uses could be improved to better reflect ground water supply costs and resource constraints. Reservoir operating constraints could be added to depict operating rules regarding release rates and target storage levels.

Finally, the models contained herein do not currently consider possible ecological effects of sustained runoff changes, except indirectly through water quality standards. Runoff changes will most likely affect riparian ecosystems and have measurable nonconsumptive welfare effects that are independent of water quality concerns. These effects may be of greater economic significance than those from some of the sectors that modeled here. Incorporating such effects within the present framework is possible and, perhaps, will be the subject of future research. This work, however, will require data and a better understanding of the physical response of ecosystems to water supply changes as well as information on society's valuation of such ecosystem changes.

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