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Economic effects of climate change on US water resources

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Water is a critical resource in many activities, including domestic use (e.g. cooking, cleaning, and drinking), food production, power generation, transportation, many commercial and manufacturing processes, pollution assimilation, recreation, and many biological and ecological processes. Changes in the spatial and temporal distributions of runoff, and in the quality of water, can have profound social and economic consequences. Such changes are projected by some climate researchers as a result of increased atmospheric concentrations of greenhouse gases (IPCC, 1996). The symptoms of climate change, including sustained changes in temperatures, precipitation patterns, and the frequency and intensity of droughts and storms, may signal the need for changes in water-use patterns and other strategies to mitigate the impacts of climate change.

In a comprehensive assessment of possible climate change effects, it is important to consider both the physical and economic dimensions of the change. Existing assessments of climate change impacts on water resources have been largely based on the results from physical models, which have simulated changes in runoff and occasionally in water-use patterns. The value of these assessments, however, is limited by the absence of economic adjustment, specifically the response of water users to changes in water scarcity (i.e. prices). To describe more completely how the changes in water availability and climate affect social welfare, it is necessary to integrate models describing the physical effects (e.g. hydrologic changes) with models describing economic and institutional responses.

In this assessment of climate change impacts on US water resources, we have responded to the limitations of existing studies by developing methods that integrate models of physical change and economic response. This assessment consists of two parts. First, we construct spatial equilibrium (SE) models of four selected US river

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basins: the Colorado, Missouri, Delaware, and Apalachicola–Flint–Chattahoochee (A–F–C). These models depict the physical movement of water and its economic use within a basin, and are used to analyze the optimal response of water users to changes in water availability and runoff. Second, we extrapolate from the river basin models to larger regions and then to the national level.

This chapter is organized into six sections. Section 6.1 summarizes the literature on water resources and climate change, and provides the context for our assessment. Relevant economic concepts and a description of our methods, data, and models are given in Section 6.2. Scenario and model assumptions are the subject of Section 6.3 Individual basin results are presented in Section 6.4, and Section 6.5 presents the national level results. Section 6.6 presents the conclusions.

6.1 Literature review

Studies of the effects of climate change on water supply and allocation have evolved from physical assessments of runoff changes to integrated assessments from runoff to water management and planning. Early studies of the effects of climate change (e.g. Stockton and Boggess, 1979; Revelle and Waggoner, 1983) were based on statistical models relating annual temperature and precipitation to annual runoff levels at the basin level. These studies, however, suffered from the inadequacy of statistical models to account for changes in underlying physical mechanisms. Improvements to this approach were made by Němec and Schaake (1982), who calibrated a rainfall and runoff model to the Pease River in Texas, and projected the effects of changes in daily temperature and precipitation on runoff. This effort was followed by a number of studies, the most important of which was Gleick's (1987) study of the Sacramento Basin, which found (using general circulation model – GCM – results) that winter runoff would increase and summer runoff would decline. The Lettenmaier *et al.* (1992) study of the American River in Washington pointed to similar effects in the Cascades, where shifts in the runoff peak would exacerbate the conflicts between power production, irrigation, and salmon protection. These studies and others like them (e.g. Frederick, 1993) helped to advance the state of the art in hydrologic modeling, and raised interesting issues about how climate change might influence the existing competition for water. However, these studies did not grapple directly with allocation issues in a quantitative fashion.

Existing studies of the response of water users and water institutions to runoff changes generally fall into three categories. The first integrates reservoir and system management models with rainfall/runoff models to determine how to best adapt reservoir operation to climate change. For example, Lettenmaier and Sheer (1991) examined the implications of climate change for management of the Central Valley and State Water Projects in California using the California Water Planning Model. They combined results from the hydrologic modeling of GCM outputs with a water management model simulating water delivery requirements. They concluded that, even under scenarios of increased annual runoff, increased winter runoff would not be retained by California's reservoir system and would result in decreased water supplies during the rest of the year. Perhaps the most comprehensive study of this kind is Nash and Gleick's (1993) study of the Colorado River basin. They used the National Weather Service rainfall and runoff model in conjunction with the Colorado River Simulation System (CRSS) to evaluate the impacts of both hypothetical and GCM projected changes in temperature and precipitation on water withdrawals, power production, salinity, and storage. Their results indicated that projected climate changes for the region could have potentially severe impacts on all of the above indicators of system performance, especially if the runoff peak were displaced from April to May. Studies like these are important because they deal directly with the attempts of water resource managers to adapt to climate change; however, they are limited by the absence of explicit water demand schedules and economic responses. In particular, these studies do not account for endogenous adjustments to changes in the relative value of water, or for how these changes in value provide economic signals of a need to allocate water more efficiently in a market system.

The second type of study focuses on the issue of the economic valuation of water resources, but in a context that divorces the issue of valuation from that of economic response (e.g. reallocation of resources). Noteworthy among these efforts are the "back of the envelope" calculations of the economic value of climate change damages at the national level by Cline (1992) and Titus (1992). Cline assumed climate change would cause a 10 percent decrease in water supplies across the country. Using an average value of water of $250 per acre foot (af) for municipal and industrial uses, and $100 per af for irrigation, he estimated that the reduction in supplies would result in damages of $7 billion per year. Titus (1992) estimated changes in supply and demand for surface and groundwater state by state. In his analysis, he used estimates of changes in water availability based on Waggoner (1990) and changes in water demand based on Gibbons (1986), and incorporated some adjustments and adaptations in his analysis by estimating the cost of additional point source controls for water pollution and accounting for changes in hydropower production. He concluded that annual damages to water resources would be between $21 and $60 billion, with $15 to $52 billion of that due to the increased costs of water pollution controls. Although these studies have been useful in establishing some "first-order" estimates of the magnitude of the economic effects of climate change on water users, these estimates were not based on a consistent model of economic behavior.

In the third type of study, information about the physical effects of climate change is integrated with a model of resource allocation based on economic theory. Vaux and Howitt (1984) pioneered this approach in their application of spatial equilibrium (SE) models to water resources in California. Their SE model of the state joins the regional water supply functions and demand functions for specific uses with a linear representation of the water delivery system. The model maximizes the sum of producer and consumer surplus in all regions, subject to the constraints imposed by the water distribution system. This approach effectively simulates competition among water users everywhere in California. When water supplies in the model were reduced through reductions in system inflows, Vaux and Howitt showed how water everywhere would be allocated to more highly valued uses. In an unpublished paper, the authors showed that in the face of a 50 percent reduction in water supplies, it would be less costly to society to redistribute supplies based on economic principles than to construct additional storage capacity in the state.

To value the impacts of climate change on water resources, we have expanded on Vaux and Howitt's approach by integrating river basin SE models with hydrologic models within a multiregional framework. By using this physical/economic framework, we provide a more thorough and detailed analysis than either Cline or Titus, and we do it in a framework that is grounded in economic theory.

6.2 Methods and data

The components and information flow of our basin-level approach to modeling climate change impacts on water resources are shown in Figure 6.1. The first step in the methodology is characterizing a climate change scenario. The study adopts ten climate change scenarios including most of the scenarios discussed in Chapter 1. These climate change scenarios are then used to model changes in hydrology and runoff. Projections of the hydrologic impacts for the scenarios were developed by Lettenmaier and Wood (1994), using a variable infiltration capacity (VIC) model to translate the changes in monthly average precipitation and temperature into changes in monthly runoff.[2]

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[2] The resolutions of the hydrologic models are 1° latitude and longitude for the Colorado and Missouri basins, and 0.5° for the Delaware and A–F–C basins. The monthly runoff data were then aggregated to match the basin models, both spatially and temporally.

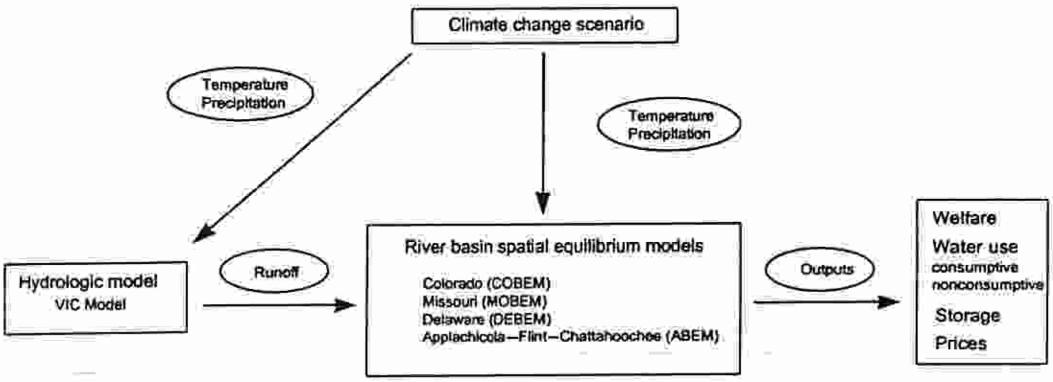

Figure 6.1 Information flow in the assessment of climate change effects on water resources.

Hydrologic model

The river basin models require hydrologic input data. These data must be matched to the inflow points of the river model, and must be consistent with the temporal scale of the model. These data represent the contribution of runoff from precipitation and snowmelt to the volume of water flowing in the river system, net of evapo-transpiration and groundwater losses. The hydrologic data used in the individual river basin models were produced by hydrologic models.

Hydrologic models simulate streamflow at varying spatial and temporal resolutions. They do this by translating the climatic events and factors, such as precipitation and temperature, into runoff while taking into account the dynamics of soil, vegetation, and atmospheric water transfers. Many of the complexities of river basin hydrology are difficult to capture. These complexities are reflected in the variations between actual and modeled streamflow. The calibration and validation of hydrologic models, therefore, depend on how well the model captures and mirrors variation in the observed streamflow data at various points along the river system.

The hydrologic input data are, therefore, important to the analysis of water resource impacts. The hydrologic data that we use derive from regional variants of the two-layer, Variable Infiltration Capacity (VIC-2L) model (Nijssen *et al.*, 1997; Liang *et al.*, 1994; Lettenmaier and Wood, 1994). The VIC-2L is a hydrologically based soil–vegetation–atmosphere transfer scheme designed to represent the land surface in climate and weather models. The model was designed to work in an integrated fashion with GCMs. It can, however, perform analyses off-line, as was done for these studies. In this case, the model simulated the incremental changes in precipitation and temperature that were prescribed in the study design.

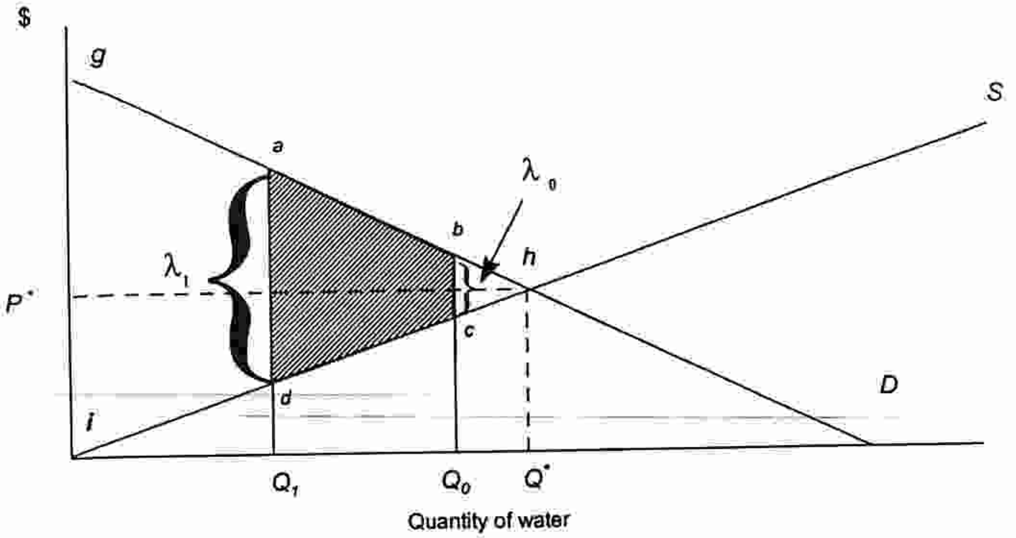

Figure 6.2 Efficient water use in a single water market.

Spatial equilibrium models

The river basin SE models are the primary assessment method. These models use the runoff data from the hydrologic models as model input. Model inputs also include demand parameters (for agriculture only) that are scenario/climate dependent. For example, the agricultural water demands are climate sensitive, typically increasing in response to greater temperatures. The basin models optimize welfare derived from water use and storage, and result in estimates of water use, price, storage, and sector welfare.

The river basin SE models are basically economic models that allocate water to different activities (both consumptive and nonconsumptive) over space and time. The solutions to these models are water allocations, storage levels, and regulated river flows that generate the maximum economic welfare across all water uses, i.e. the maximum consumer and producer surplus. In other words, redistributing water away from the modeled allocations would result in a net welfare loss to the system.

The economic principles at work in these models can be understood by considering Figure 6.2, which shows a supply (*S*) and demand (*D*) schedule for a typical water use. The demand schedule results from water users optimizing their use of water (e.g. to maximize utility or expected profits) in a productive activity, and describes how the marginal value (benefit) of water in this activity varies inversely with the quantity of water used. The total value of water in this activity (i.e. the total willingness to pay of the consumers) is measured by the area under the demand curve up to the quantity consumed. Consumer surplus is defined by this area less the total amount paid (price multiplied by quantity).

In a similar fashion, the supply schedule describes the marginal resource costs required to supply a given quantity of water. In general, the marginal costs of providing water (e.g. pumping, storing, distributing, and treating) vary directly with the level supplied (in particular, if the costs of developing new supplies are included). Total resource costs are measured by the area below the supply curve, and producer surplus is equal to the amount paid by the consumer less total resource costs. In the absence of competing uses and supply constraints, welfare is maximized at the intersection of supply and demand (Q^*), where marginal benefits equal marginal costs. This allocation is achieved in a market setting, with consumer surplus shown by the area ghP^* and producer surplus shown by the area iP^*h.

The introduction of water supply (runoff) constraints or competing uses (e.g. downstream users) alters the mechanism of efficient allocation slightly. When runoff is limited and insufficient to reach Q^*, marginal benefits (MB) may exceed marginal costs (MC). This difference, defined as $\lambda = MB - MC$, is the implicit marginal value or shadow price of water, and reflects the value of an additional unit of water to the system. This shadow price is a complex function of available water (runoff), the marginal value of its use (both consumptive and nonconsumptive), the costs of supplying water, and return flows (see Appendix A6 for a discussion of how return flows affect the analysis and determination of water value). A change in any one of these factors could change the shadow price, and affect the efficient allocation of water.

In Figure 6.2, assume initially that the available runoff results in a shadow price equal to λ_0. At this price, water use is Q_0 at the point where the shadow price equals the net marginal value of that use. A decrease in runoff, as some models of climate change predict, increases the shadow price of water to λ_1, and results in a lower level of water use at Q_1.[3] The change in economic welfare associated with this reduction in runoff is measured by the shaded area *abcd*, which is the change in consumer and producer surplus.

Several other important economic concepts can be conveyed by examining the case of two competing uses with different demand elasticities. Figure 6.3 shows two demand curves, D_1 and D_2, that compete for water at the same point in the system. The horizontal sum of these demands is the total demand curve (shown in bold), and water supply is shown as S. Initially, the shadow price of water in the system is equal to λ_0, and total water use is equal to Q_0. The share of this total that is allocated to each use is determined by equating the total demand price (P_0) with the demands associated with each respective use, Q_{10} and Q_{20}, respectively.

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[3] Alternatively, we could show the change in runoff directly in Figure 6.2 as an inelastic supply curve that shifts exogenously (by the amount corresponding to the shift in λ). However, we want to emphasize the generalized nature of the economic response in these models to system-wide changes in either physical or economic dimension, such as the important effects of other competing users.

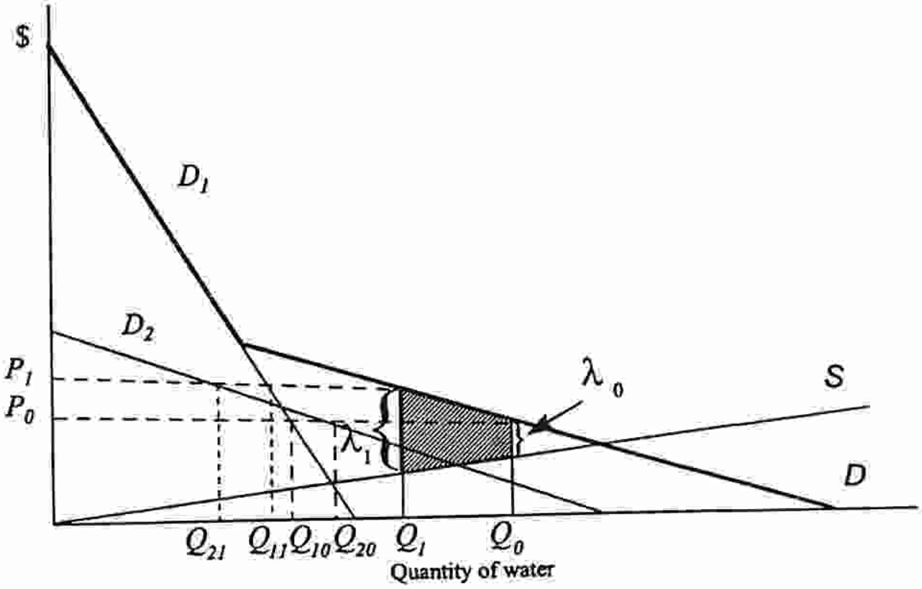

Figure 6.3 Efficient water allocation and welfare change in a two sector market.

When runoff is reduced, the shadow price increases to λ_1, total water use falls to Q_1, and the total demand price rises to P_1. Equating this new price with the demands in each use results in a greater reduction in the more elastic use, D_2, compared to the less elastic use, D_1. Compare the reduction by the former, $Q_{20}-Q_{21}$, with that of the latter, $Q_{10}-Q_{11}$. A greater share of water is retained in the use with the higher marginal values and lower elasticities. The shaded area in Figure 6.3 shows the net change in consumer and producer surplus associated with a reduction in runoff. These results suggest that in a competitive market for water, reductions in runoff are not shared equally across uses. A corollary is that if uniform reductions are imposed, as is often assumed by researchers using physical response models alone, then it stands to reason that welfare losses are greater than they would be if market adjustments are allowed. These economic principles characterize the fundamental nature of the allocation decisions made in the river basin SE models.

The river basin SE models are dynamic and nonlinear, patterned after the spatial equilibrium models first described by Samuelson (1952) and further developed by Takayama and Judge (1964). They account for important spatial features in resource supply and demand, and model the flow of resources between regions. SE models are widely used to characterize market behavior in natural resource sectors, and have also been used to model the agricultural, forestry, water, and energy sectors. Vaux and Howitt (1984), for example, developed an SE model of California's water resources to measure the potential benefits of relaxing restrictions on water markets.

We developed (or, for the Colorado river, modified) models for each of four river basins: the Colorado, Missouri, Delaware, and Apalachicola–Flint–Chattahoochee rivers. These models maximize the sum of consumer and producer surplus subject to physical, economic, and institutional constraints, and consist of the following two basic elements:

- a nonlinear *objective function* containing consumer and producer surplus value functions
- a set of *constraints* describing physical and institutional dimensions of water flow, distribution, storage, exports, and use within a basin.

The objective function consists of benefit and cost functions relating water use and river flow to economic welfare. The economic surplus of consumptive uses, for example, are modeled generally as quadratic functions derived from linear demand and supply schedules. Consumptive water uses include agriculture, municipal and industrial, and thermoelectric energy. The parameters that define these demand and supply functions were based on available data and information (including Gardner and Young, 1985; Gibbons, 1986; Ogg and Gollehon, 1989; Griffin and Chang, 1990, 1991; Booker and Young, 1991; Schneider and Whitlatch, 1991; US Bureau of Reclamation, 1991; Nieswiadomy, 1992; Gutwein and Lang, 1993; Solley *et al.*, 1993).

Nonconsumptive uses, which depend on river flows and runoff directly, were also modeled when and where the data were available. In general, the modeled nonconsumptive uses included hydropower, navigation, flood damages, and three measures of value associated with water quality/pollution assimilation. The water quality measures include thermal waste heat from once-through cooling plants, secondary municipal wastewater treatment, and advanced municipal wastewater treatment. The Colorado model contains a different mix of economic sectors than the other models; for example, it includes flatwater recreation on reservoirs, instream recreation (rafting through the Grand Canyon), and salinity damages in the lower basin (see Booker and Young, 1991).

The functional form of the value functions for nonconsumptive water users varied across economic sectors, depending on the data and the assumed relationship between river flows and the generation of economic benefits or costs. For example, flood damages were approximated by an increasing quadratic function in the Missouri basin model, and by an increasing linear function in the A–F–C model.[4] Table 6.1 describes the nature of the nonconsumptive sectors and functions represented in the models.

Model constraints define the physical and institutional dimensions of the river

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[4] Parameters for flood damage functions vary by location and were derived off-line based on available data on flood damages and associated flow rates.

Table 6.1. *Nonconsumptive economic sectors in the regional basin models*

Sector/basin model	Valuation method	Data description/source
Hydropower/all models	The value is modeled as the avoided cost of lost hydropower. This is modeled as a function of the release rate from reservoirs and average hydraulic head which is a quadratic function of reservoir storage.	US Army Corps of Engineers (1981, 1993a, 1994a, b); Gibbons (1986); US Bureau of Reclamation (1986).
Navigation/Missouri and A–F–C	The value is modeled as an S-shaped logistic function of the rate of flow at one or more specified reaches.	US Army Corps of Engineers (1993a, 1994b).
Flood damages/ Missouri, Delaware, and A–F–C	Linear or quadratic flood damage parameters are estimated for flows above the threshold flow. Estimates of flood damages primarily reflect urban flooding except in the Missouri which includes agricultural damages.	US Water Resources Council (1978) and US Army Corps of Engineers (1993b, 1994a, b).
Thermal waste heat/ Missouri, Delaware, and A–F–C	Costs from lost electricity production of thermal electric plants are modeled as an exponential function of reduced river flows.	Regional power authorities in each basin.
Secondary wastewater treatment/Missouri, Delaware, and A–F–C	The net benefits are modeled as a linear function of flow. They proxy the value of the river for diluting and assimilating biochemical oxygen-demanding (BOD) materials.	Gibbons (1986).
Advanced wastewater treatment/Missouri, Delaware, and A–F–C	The costs are modeled as a function of the volume of the return deficit below which water quality standards are satisfied.	Regional water authorities and from US EPA (1978a, b).
Flatwater recreation/ Colorado	The value is the product of visitation, which is a quadratic function of reservoir surface area, and $16 to $35 values per visitor day.	Booker and Young (1991).
Instream recreation/ Colorado	The value is a quadratic function of river flow.	Booker and Young (1991).
Salinity damages/ Colorado	Damages are modeled as an increasing function of salt concentrations, which are assumed to vary inversely with the flow of water.	Booker and Young (1991); Gardner and Young (1985); Lohman *et al.* (1988).

basin system so that the models are physically faithful to the spatial distribution of major tributaries, reservoirs, and points of water use. The spatial structure of the model is typically patterned from a schematic diagram of the basin showing major points: basin inflows (i.e. runoff), tributaries, major water diversions, and reservoirs. Physical continuity is maintained in the model by a system of mass balance equations that define both spatial and temporal water balances. Institutional constraints, which depict important basin-specific legal and regulatory provisions (e.g. the Colorado River Compact and the Mexican Treaty), can also be incorporated into the model.

Flow balance constraints define water flow and distribution to mimic the physical behavior of river systems. The flow balance acts like a network, connecting points where runoff enters the system to points where the water is used, stored, or passed to another region. Within each time period the flow balance is modeled as

$$F_n = F_{n-1} + I_n + r_n W_{n-1} + R_n - W_n,$$

where the flow from node n (F_n) is equal to the flow from the node $I-1$ (F_{n-l}) plus inflows from tributaries or runoff (I_n), plus return flows from previous uses (nW_{n-l}), plus net reservoir releases (R_n), less withdrawals (W_n). Evaporation from streamflow is not explicitly modeled. Evaporation losses are accounted for in the reservoir storage balances, and are assumed to reflect the overall evaporation losses in the system. Return flows are assumed to occur within the same period as the associated withdrawals.

Storage balance constraints maintain the physical continuity of reservoir storage levels across time periods. Storage decisions are made in each time period about the net volume of water to release downstream or store for future use. These decisions account for both inflows into the reservoir system and evaporative losses. Reservoir storage balances are maintained by the following equation:

$$S_{t1} = S_{t0} - R_{t1} - E_{t1},$$

where ending storage in period 1 (S_{t1}, with t a time step) must be equal to the ending storage from the previous period (S_{t0}), less any net reservoir releases in period 1 (R_{t1}), less net evaporation losses in period 1 (E_{t1}).

In addition to physical continuity, we model important institutional relationships that regulate the pattern of river flow and water use. For example, the Colorado basin model includes constraints representing the Colorado River Compact of 1922, which requires that the upper basin states (i.e. Wyoming, Colorado, Utah, and New Mexico) release a minimum of 75 million acre-feet (maf) of water during each consecutive 10-year period. This type of institutional requirement can be approximated by a set of minimum flow constraints.

Table 6.2. *Summary of river basin planning model components*

Sector/Component	Colorado	Missouri	Delaware	A–F–C
Number of consumptive uses by sector				
Agriculture	16	6	3	4
Municipal and industrial	5	6	4	4
Thermoelectric	4	6	2	4
Number of nonconsumptive uses by sector				
Hydropower	7	3	1	3
Navigation	not applicable	1	not applicable	1
Flood damage	not modeled	8	3	4
Pollution assimilation	4 salinity damages	2 M&I 3 thermal heat	2 M&I 3 thermal heat	2 M&I 2 thermal heat
Number of modeled reservoirs, inflow points, and river reaches				
Recreation	2 instream 7 flatwater	not modeled	not modeled	not modeled
Reservoirs	7	4	3	3
Inflow points	14	8	4	4
Mainstream reaches	21	13	7	9
Tributary reaches	6 Green	3 Platte, 3 Kansas, 2 Osage	3 Lehigh, 3 Schuykill	3 Flint

Regional basin models

In this section we briefly describe each of the river basin models: the Colorado Basin Economic Model, the Missouri Basin Economic Model, the Delaware Basin Economic Model, and the Apalachicola–Flint–Chattahoochee Basin Economic Model. The structure and composition of each basin model is summarized in Table 6.2.

Colorado basin model

The Colorado River is the dominant source of surface water in the arid Southwest, supplying a drainage area of more than 244 000 square miles. In addition to supplying water for consumptive water users, the Colorado River generated over 11 million megawatt-hours (MWh) of hydroelectric power in 1990 (Solley *et al.*, 1993). The model extends Booker and Young (1991) by lengthening the optimization period, separating municipal and industrial uses, and incorporating temperature sensitivity

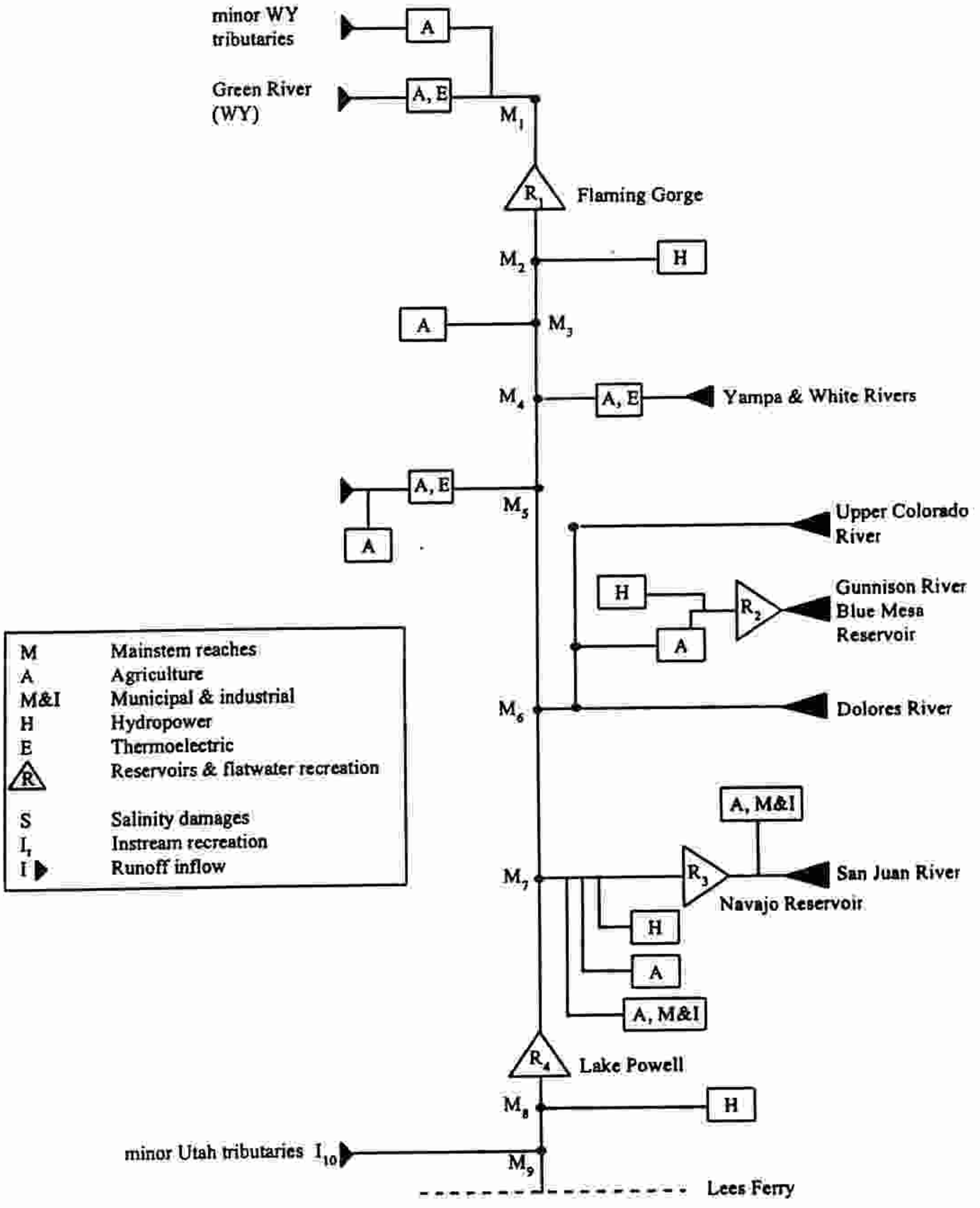

Figure 6.4 Colorado basin model schematic diagram.

(continued overleaf)

into the agricultural demand schedules. The spatial dimensions of inflows, water use, and storage facilities are shown in the schematic diagram in Figure 6.4.

The Colorado model (COBEM) is the most detailed basin model used in this study with more spatial and intertemporal detail than the other basin models. The demand functions are approximate Cobb–Douglas demand functions, which depict demand

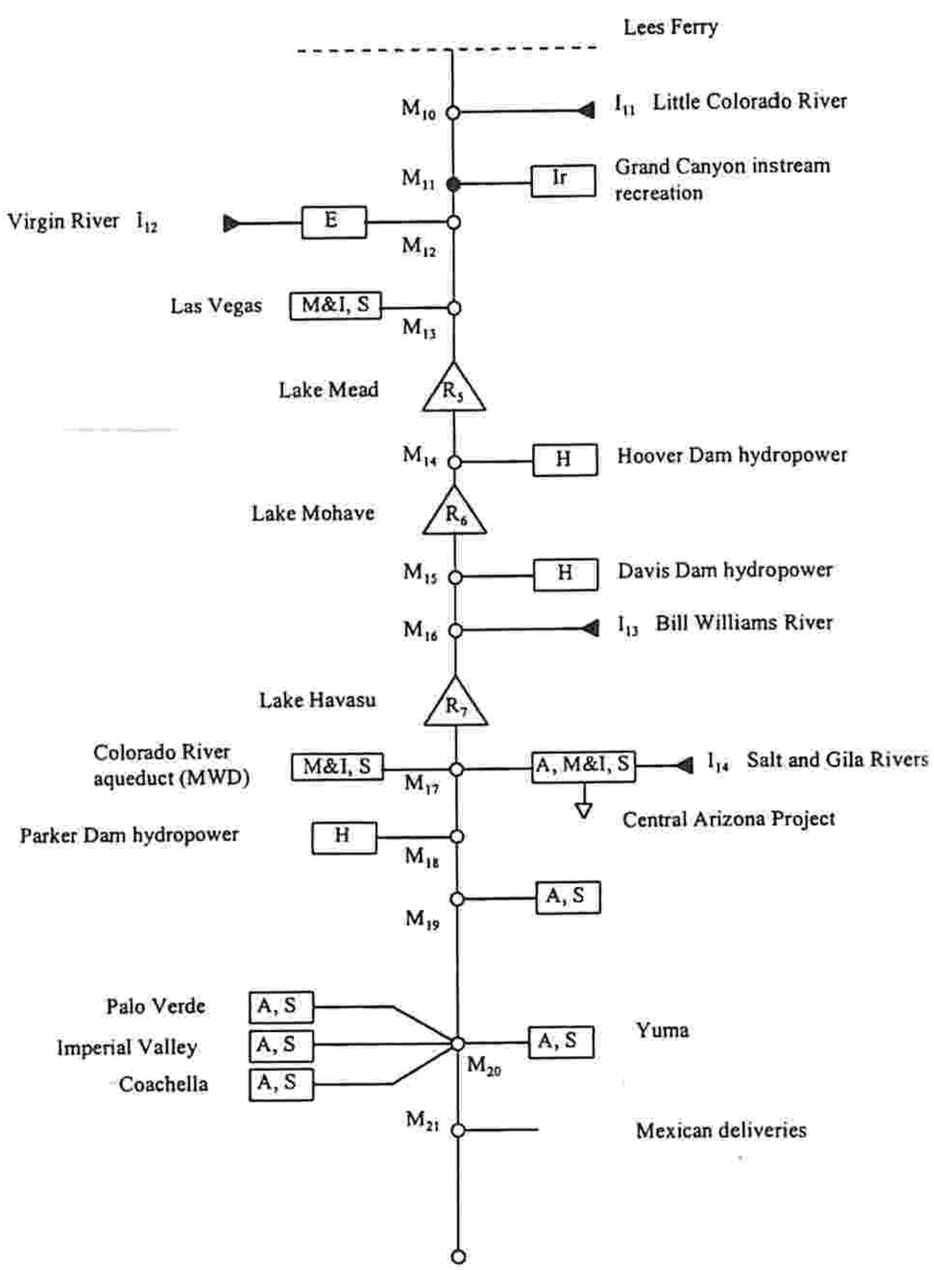

Figure 6.4 (*cont.*)

prices rising asymptotically with decreasing quantities. There are more non-consumptive sectors in this model including salinity and recreation. Salinity damages vary with salt concentration and have been documented for agricultural and municipal and industrial (M&I) users in the lower basin of the Colorado River (Gardner and Young, 1985; Lohman *et al.*, 1988; Booker and Young, 1991).

Institutional constraints are also important in the Colorado basin. The Colorado

River Compact and Mexican Treaty obligations apportion water between the upper and lower basins and Mexico, respectively. These institutions are modeled by defining the minimum annual flow rates at each of two specific reaches (i.e. Lees Ferry and the Mexican border). A penalty function is used to model these constraints and penalize the objective function for failure to meet the required flows.

Missouri basin model

The Missouri River and its tributaries are important to a large agricultural region of the United States. The river basin drains a region of more than 500 000 square miles of the Midwestern United States, a region that produces a variety of grain, oilseeds, and livestock products. The river is a primary source of drinking and industrial water for the region as well as an important transportation resource for moving raw agricultural and mineral products downstream. The Missouri River cools thermoelectric plants which generate more than 159 million MWh and powers 12 million MWh of hydroelectric power (Solley *et al.*, 1993). The river is also used as a sink for industrial and municipal wastewater.

The Missouri model, and also the Delaware and A–F–C models, rely upon linear demand functions for the consumptive sectors. Two nonconsumptive uses were added for navigation and flood damage. The model contains fewer nodes, inflow points, reservoirs, and diversion points than the Colorado model. This greater regional aggregation allows for greater temporal resolution and flexibility, particularly for many of the economic sectors with pronounced seasonal variations such as agriculture, flooding, and navigation. The Missouri model is illustrated in Figure 6.5.

Delaware basin model

The Delaware River flows from its headwaters in the Catskill Mountains of New York and along the border between Pennsylvania and New Jersey. The river drains nearly 15 000 square miles before it empties into Delaware Bay. The Delaware River is a primary source of municipal and industrial water in the mid-Atlantic region, serving water users in New York, New Jersey, Pennsylvania, and Delaware. Water use is governed by a multipurpose compact among the states. Agricultural use of the Delaware River is relatively small compared to that used in the arid Colorado and Missouri basins. Annual agricultural withdrawals in 1990 were estimated at 17.5 thousand acre feet per year (kaf/yr) (Solley *et al.*, 1993). The Delaware River assimilates wastes from many of the cities and towns that use its waters, and it provides water for thermoelectric generation and agriculture.

The Delaware River model is shown in Figure 6.6. There is no significant navigation on the Delaware River above Philadelphia, and navigation to the port of

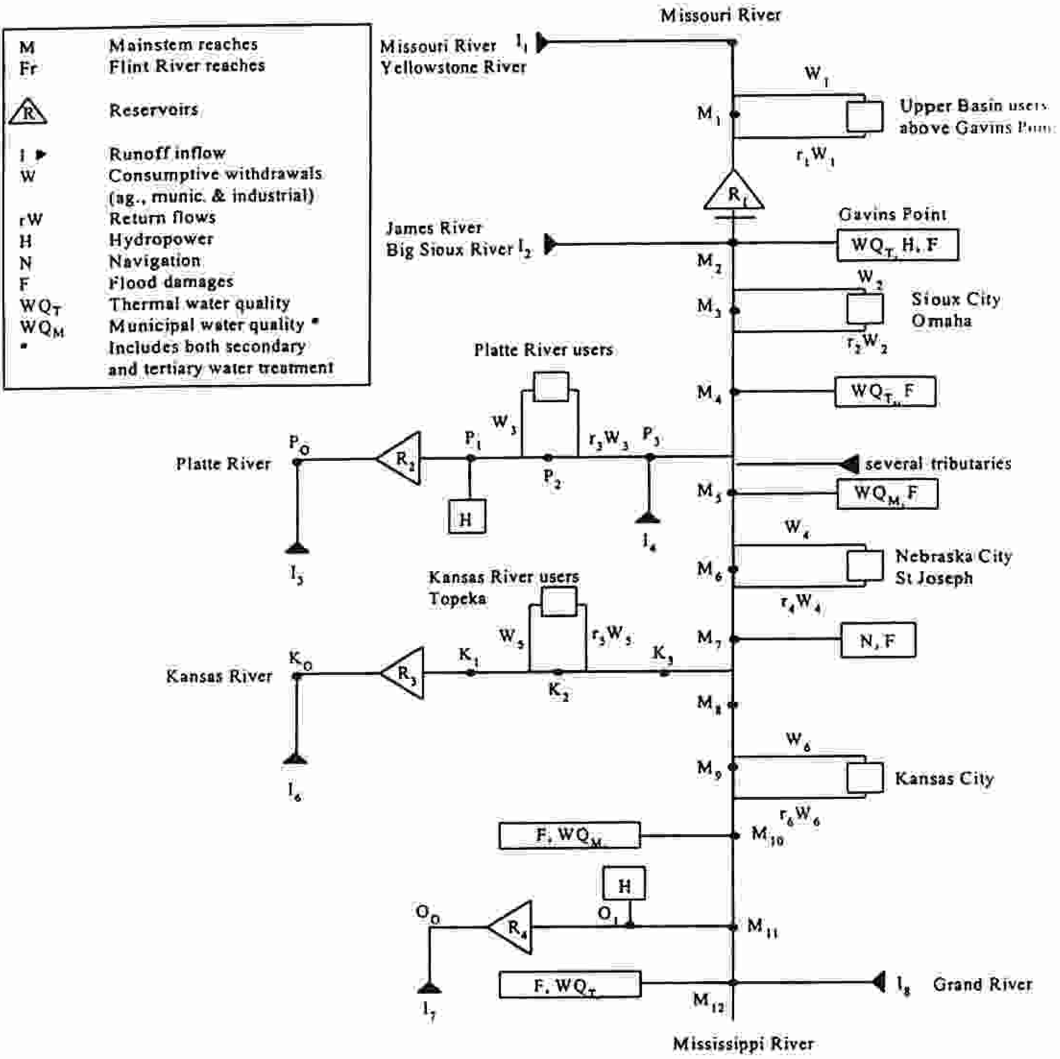

Figure 6.5 Missouri basin model schematic diagram.

Philadelphia is maintained by tidal flows. The consumptive water use in the Delaware basin is dominated by and approximately equally split between municipal and thermal energy uses. Together these two sectors account for over 99 percent of withdrawals for consumptive use (Solley *et al.*, 1993). Withdrawals from the Delaware River averaged 6.8 maf/yr whereas annual average runoff was over 13.5 maf/yr. The Delaware and other eastern basin systems may be less vulnerable to climate change and runoff reductions because they currently use only a fraction of the available runoff.

A–F–C basin model

The Apalachicola, Flint and Chattahoochee (A–F–C) rivers together form an important waterway system serving central and western Georgia, eastern Alabama,

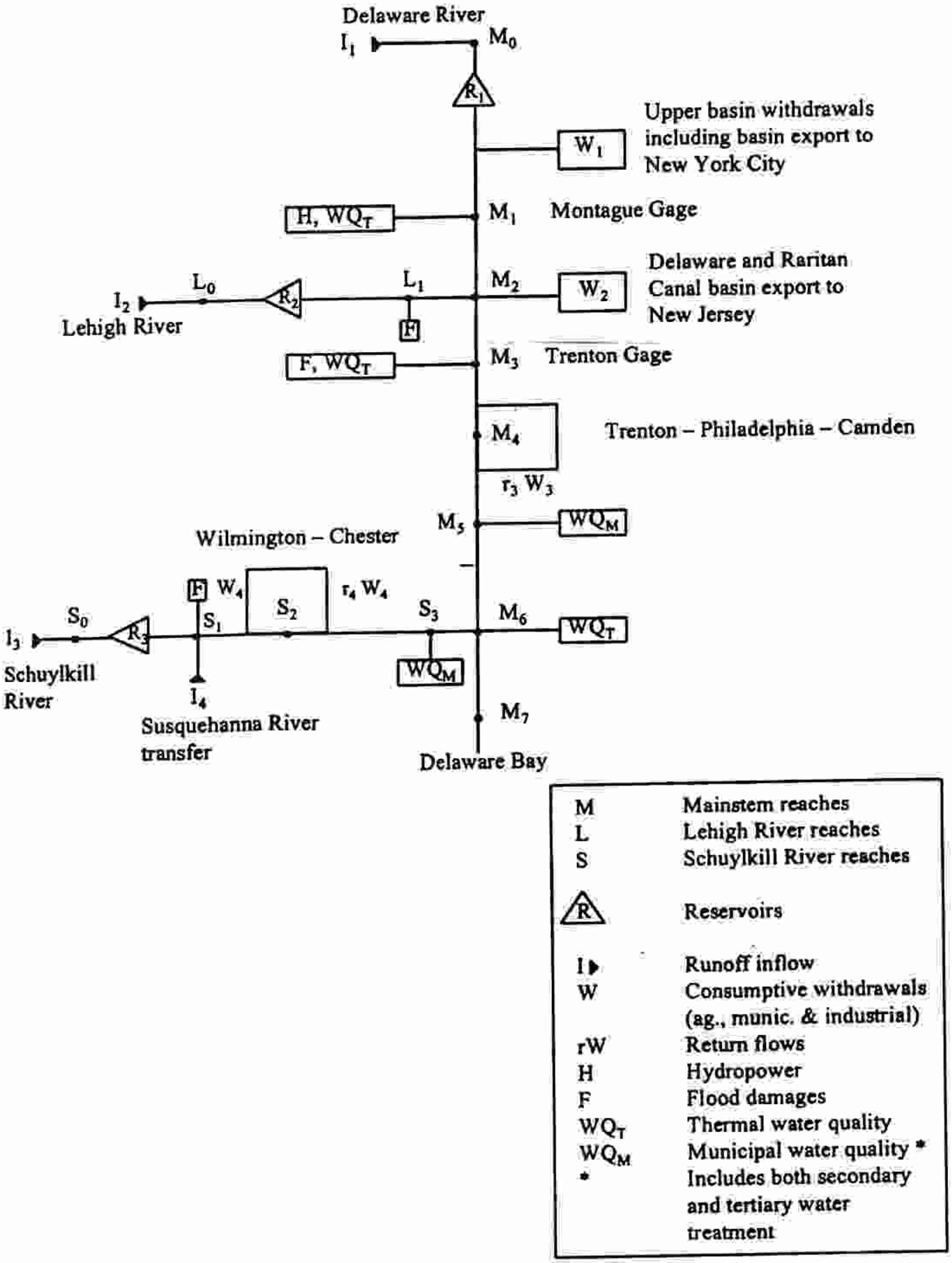

Figure 6.6 Delaware basin schematic diagram.

and the Florida Panhandle. The surface area drained by these rivers is approximately 20 000 square miles. These three rivers are used to transport minerals, timber, and agricultural products to the Gulf of Mexico, in addition to serving as a freshwater resource for municipal and industrial water users in cities such as Atlanta, Columbus, and Bainbridge, Georgia, and Phoenix City, Alabama. The rivers are also used to assimilate wastewater from cities and thermal plants, and to generate steam and hydroelectric power. These rivers are also susceptible to major flooding events, as recently seen along the Flint River in southwestern Georgia. This area may also be more susceptible to droughts because the A–F–C river basin, unlike the basins of the western United States, does not have sufficient reservoir storage capacity to mitigate against prolonged drought conditions.

The A–F–C model includes both consumptive and nonconsumptive water use, and is similar in composition and scale to the Missouri and Delaware models. The physical structure and network of inflows, reservoirs, and water uses are different, as illustrated in Figure 6.7.

National models

National estimates of the economic impacts of climate changes were developed for both consumptive and nonconsumptive water uses. These estimates extrapolate the impacts derived from the four regional models to other regions and to the whole of the United States. Each of the four modeled regions is paired with a set of similar basins from the remaining US water regions (pictured in Figure 6.8), as given in Table 6.3.

The extrapolation method for consumptive uses relies on the modeled regional estimates of economic impacts, and on data from all regions regarding water-use characteristics and changes in runoff.[5]

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:

$$\Delta\ \textit{National consumptive} - \textit{use welfare} = \sum_j \sum_i \Delta R_{ij}, \tag{6.1}$$

where ΔR_{ij} is the change in consumer and producer surplus in sector i and region j. This surplus change is defined as

$$\Delta R_{ij} = (\bar{\$}_{ij_0} \times \Delta \bar{W}_{ij}) + \tfrac{1}{2}(\Delta \bar{\$}_{ij_0} \times \Delta \bar{W}_{ij}), \tag{6.2}$$

where $\bar{\$}_{ij_0}$ is the estimated net marginal value of water under baseline conditions for the reference model, and $\bar{W}_{ij}$ is the baseline annual surface water withdrawal for sector

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[5] Hydrologic data for the national assessment were provided by Battelle Pacific Northwest Laboratories. Data on water-use characteristics was derived from Solley *et al.* (1993).

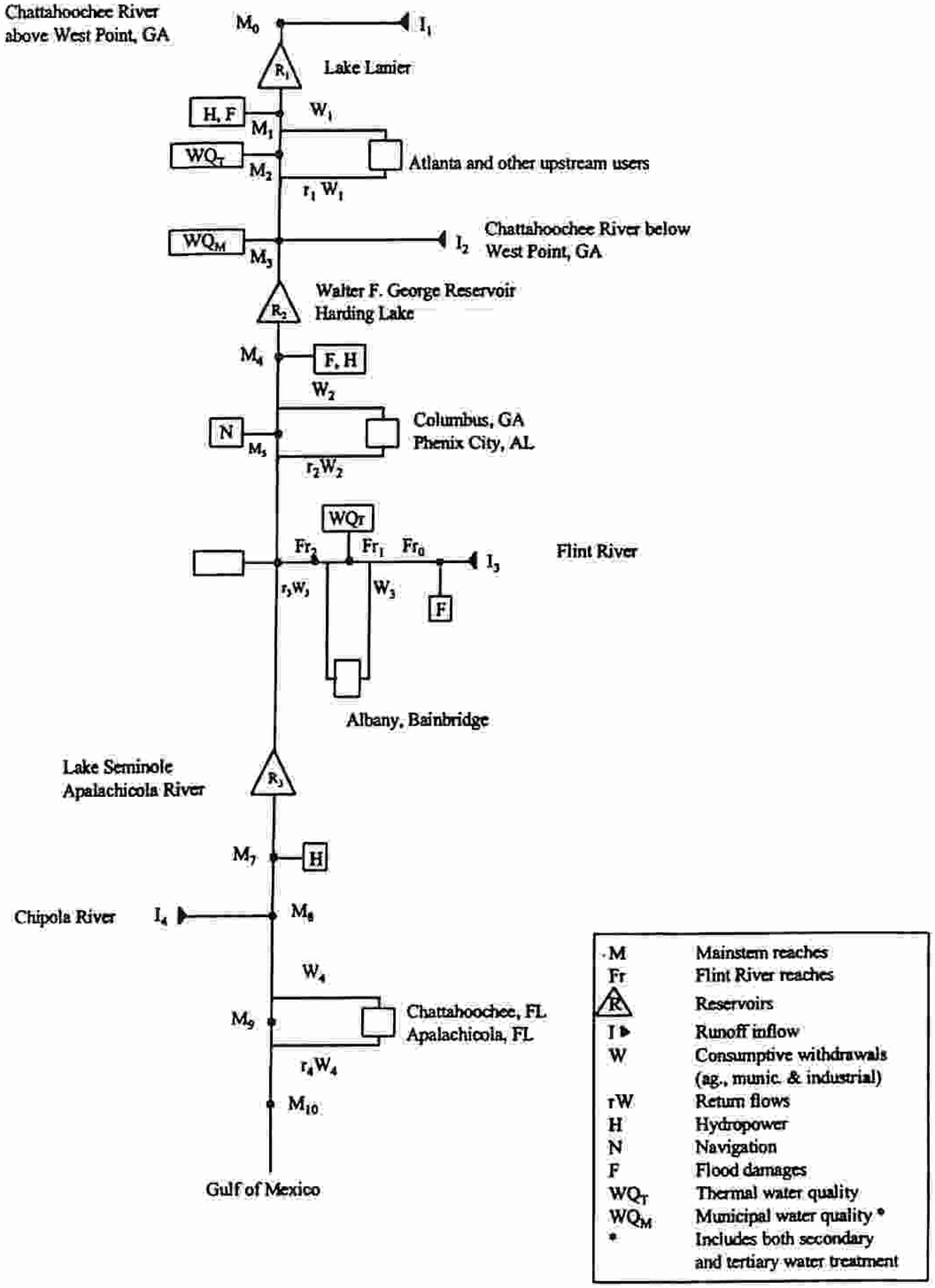

Figure 6.7 A–F–C Basin Model schematic diagram.

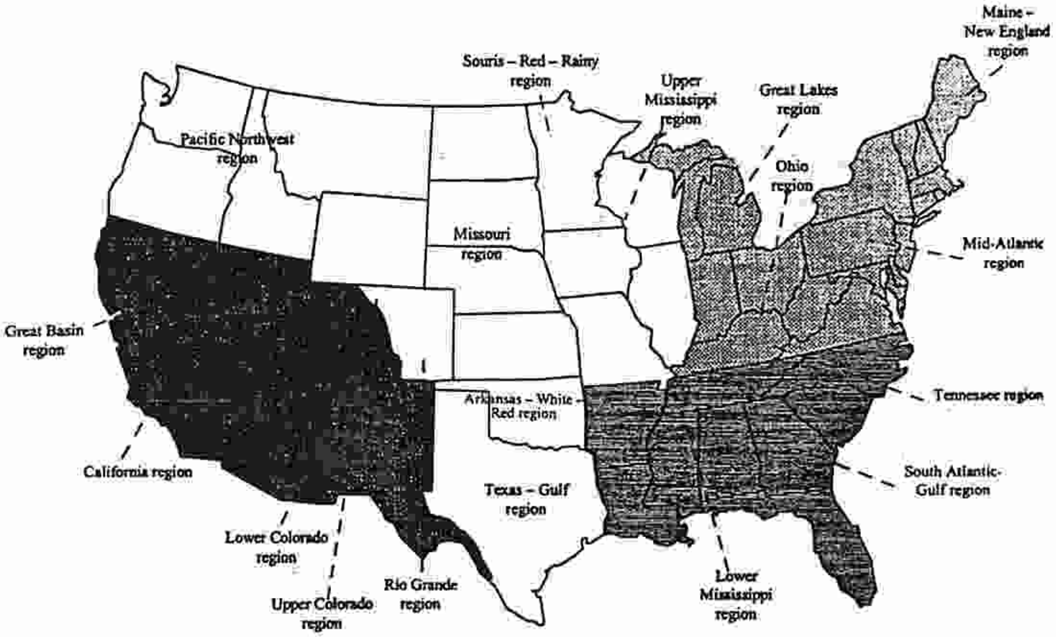

Figure 6.8 United States water resources regions established by the US water resources council in 1970 (from Solley *et al.*, 1993).

i and region *j* (based on estimates from Solley *et al.*, 1993)[6]. $\Delta \overline{W}_{ij}$ is the change in water use by sector *i* in region *j*, and is a function of baseline-water-use patterns in region j_0, the simulated changes in sector water use in the modeled region j_0, and relative runoff changes between target region *j* and modeled region j_0, given as

$$\Delta \overline{W}_{ij} = \overline{W}_{ij}[(1 + \%\Delta W_{ij_0}) \times \frac{(1 + \%\Delta Q_j)}{(1 + \%\Delta Q_{j_0})} - 1], \tag{6.3}$$

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 procedure accounts for differences in runoff and scale 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. For example, this implies that agricultural water use in the upper Mississippi region has the same demand elasticity as agricultural water use in the Missouri region.

It is important to account for nonconsumptive water use at the national level.

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[6] We recognize the difference between *withdrawals* and *consumptive use*, and that efficient use depends on equalizing the marginal value across consumptive uses, i.e. after accounting for return flows as described in Appendix A6. 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.

Table 6.3. *Pairing of river basins to US water resource regions*

Modeled basin	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	Maine–New England, Mid-Atlantic, Great Lakes, Ohio
Apalachicola–Flint–Chattahoochee Rivers	South Atlantic–Gulf, Tennessee, Lower Mississippi

However, it is also subject to greater uncertainty given the difficulties in measuring values associated with nonconsumptive use. 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 the relative scale of nonconsumptive values across regions, the ratio of water used in hydropower production between the two regions is used.[7] The change in national welfare derived from nonconsumptive water uses is defined as

$$\Delta\, National\ nonconsumptive - use\ welfare = \sum_j \Delta R_{ncj}, \tag{6.4}$$

where R_{ncj} is the change in the welfare of nonconsumptive users in region j. This change in welfare is given by:

$$\Delta R_{ncj} = \Delta(\bar{\$}_{ncj_0} \times \frac{(1 + \%\Delta Q_j)}{(1 + \%\Delta Q_{j_0})} \times \frac{H_j}{H_{j_0}} \tag{6.5}$$

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[7] Hydropower was observed in the model results to relate more directly to the estimates of nonconsumptive welfare than to annual water volume. Hydropower accounted for more than 60% 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.

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.

6.3 Scenario and model assumptions

The scenarios were developed to project water-use conditions in 2060. The models projected demands in 2060 and simulated water use for 39 years (holding parameters constant and equal to the 2060 projections). The hydrologic data used in the 39-year simulations were based upon the historical period from 1949 to 1987. The assumptions needed to generate baseline projections, climate change scenarios, and an institutional scenario are discussed below.

Projections of water demand in 2060 were derived by scaling current demands using estimated growth rates, which accounted for changes in population, income, and recent historical trends in consumptive water use. These historical data suggested that water demand in the energy and municipal sectors has been growing over time, whereas irrigation demand has been relatively constant. The growth of water demand by thermal energy producers has been considerably less than the growth by municipal users. In addition, we hypothesized that the future growth in electricity demand will be increasingly met by technologies that are less water intensive. Based on these historical trends, demand for water in 2060 is estimated to be 23 percent and 10.2 percent greater than current demand by the municipal and thermal energy sectors, respectively.

Irrigation demand has been relatively constant over the last 20 years. Future projections of irrigation demand assume that no new significant federal water supply projects will be built, and that changes in irrigation technology will offset increases in the demand for irrigation water. That is, the overall demand for irrigation water will remain constant at current levels under baseline climate conditions.

Ten climate change scenarios are analyzed in this study. These scenarios span a wide range of changes in annual average temperature and precipitation. These changes in climate are likely to have an effect on the demand for water by consumptive users. Warmer temperatures and changes in precipitation will affect evapo-transpiration rates in crops as well as gardens and golf courses. A study of municipal water demand in the Great Lakes region found there could be a small rise in water demand under climate change (Cohen, 1987). In modeling climate change, we assume that agricultural water demand will vary with climate change, but that municipal and thermal energy water demand will remain the same. Because M&I (municipal and industrial users) use very little water, a small change in their demand functions is not likely to bias the results to a great degree. We rely upon the results reported by Peterson and Keller (1990) to assess the effect of climate change on agricultural water demand. They use a soil–crop–water simulation model to analyze changes in net irrigation requirements resulting from changes in climate. They show how net irrigation requirements vary across the United States, and how these requirements might be affected by changes in average temperatures and precipitation levels. In the Missouri basin, for example, Peterson and Keller show that the net irrigation requirement for central Montana increases from 400 mm to 500 mm under a +3 °C temperature change and a −10 percent change in precipitation, a 25 percent irrigation increase. Extrapolating their results to our 10 scenarios in an approximately linear fashion, agricultural demand in the Colorado and Missouri models increases between 2 and 26 percent. In the Delaware and A–F–C models, irrigation demands increase between 0 and 25 percent, depending on whether precipitation increases. Carbon fertilization may reduce the demand for irrigation, however, resulting in much smaller demand increases.

We have emphasized the role of economics in both the assessment of impacts and the adaptive response to climate change. By this emphasis we have largely assumed that water institutions will respond to changes in economic conditions, and, more important, that they will transmit these economic signals (i.e. prices) to water users. History and experience, however, have shown that this assumption is probably optimistic and that institutions are more often slow to adapt to changing conditions. As part of our analysis, we used the Colorado model to examine the effects of different assumptions concerning institutional adaptation. Specifically, we used the model to assess the welfare and water-use implications of a regulated scenario depicting current institutional constraints and an unregulated scenario free of institutional constraints under both baseline and +2.5 °C, +7 percent precipitation climate change scenarios.

The *regulated* scenario depicts a set of institutions that resemble existing institutions in the Colorado basin. Specifically, this scenario models the Colorado River Compact and Mexican Treaty provisions and a constraint that simulates prior appropriation doctrine. The prior appropriation constraint requires that water allocations in the upper basin of the Colorado River must satisfy at least 85 percent of historical agricultural uses. These agricultural uses generally have the most senior rights in the basin, and this constraint restrains the transfer of water to other sectors or downstream users. By comparison, we also simulate an *unregulated* case in which all institutional constraints are removed. Comparing welfare levels under these two extreme cases highlights the magnitude and importance of institutions in adapting to the potential consequences of climate change.

6.4 Results

The basin models were programmed using the GAMS language (Brooke *et al.*, 1988), and were solved with the MINOS solver (Murtagh and Saunders, 1980). The solutions generated by the models depict perfect foresight in a competitive market for water. That means that the models solve for the optimal values of all the decision variables (e.g. water withdrawals and use, reservoir storage and release) simultaneously, and in a manner consistent with the intertemporal maximization of total net economic welfare.

In this section, we compare the sensitivity of various measures to different climate change assumptions, and therefore focus on relative (percentage) changes. The results for the Colorado River basin are presented in detail because the model was the most carefully developed basin and the institutional sensitivity analysis was conducted only on this basin. Discussion of the remaining basins focuses mainly on the welfare results.

Colorado basin results

Tables 6.4 (a and b) show the physical and economic responses to climate change in the Colorado basin. We distinguish between results for the upper (Table 6.4a) and lower (Table 6.4b) basins to highlight some important geographic and institutional features within the basin. The second column shows the change in annual average basin runoff. The hydrologic model is sensitive to both temperature and precipitation. For example, runoff rises by 23.5 percent under the 1.5 °C, +15 percent precipitation scenario, decreases by 4.2 percent under the 2.5 °C, +7 percent precipitation scenario, and decreases nearly 35 percent under the 5.0 °C scenario. Annual average reservoir storage patterns track runoff changes across the climate scenarios. The variability of reservoir storage in some cases increases under the drier scenarios.

The economic responses to changes in runoff are described by the sector prices and allocations shown in Tables 6.4. Reduced runoff has three important effects: (1) water prices are higher and withdrawals fall; (2) prices and allocations respond to a greater degree in the lower basin; and (3) the Colorado River Compact constraint increases

Table 6.4a. *Climate change impacts on consumptive use and implicit prices in the Colorado River basin: upper basin*

		Agriculture			M&I		Thermoelectric (upper basin only)	
Climate change scenario	% Change in basin-wide annual average runoff	% Shift in demand	% Change in average withdrawals	Net marginal price ($/af)	% Change in average withdrawals	Net marginal price ($/af)	% Change in average withdrawals	Net marginal price ($/af)
Baseline[a]	17 058 (kaf/yr)	0	903.5 (kaf/yr)	77.3	473.9 (kaf/yr)	80.2	205 (kaf/yr)	82.7
1.5 °C +15%P	23.5	2.2	4.5	74.0	0.5	76.6	1.2	79.1
2.5 °C +15%P	14.1	3.7	5.2	75.3	0.4	77.9	0.8	80.4
5.0 °C +15%P	−6.9	7.4	5.5	80.2	−0.4	83.2	−0.9	85.7
1.5 °C +7%P	4.0	3.3	3.6	76.9	0.1	79.7	0.1	82.2
2.5 °C +7%P	−4.2	5.5	4.3	79.1	−0.3	82.1	−0.6	84.6
5.0 °C +7%P	−22.4	11.0	−0.3	97.3	−3.1	102.1	−6.1	104.5
5.0 °C 0%P	−34.7	16.2	−26.8	213.9	−49.4	1012.2	−52.3	1248.4
1.5 °C −10%P	−32.1	7.8	−23.4	179.2	−18.5	248.3	−25.7	248.1
2.5 °C −10%P	−37.9	12.9	−31.4	218.3	−59.2	1283.9	−60.6	1640.8
5.0 °C −10%P	−50.4	25.8	−33.2	253.4	−79.4	1655.8	−79.8	2085.2

Notes:

[a] The figures shown in the row labeled "Baseline" report the baseline level from which the percentage change or absolute difference is calculated.

Table 6.4b. *Climate change impacts on consumptive use and implicit prices in the Colorado River basin: lower basin*

Climate change scenario	% Change in basin-wide annual average runoff	Agriculture			M&I	
		% Shift in demand	% Change in average withdrawals	Net marginal price ($/af)	% Change in average withdrawals	Net marginal price ($/af)
Baseline[a]	17 058 (kaf/yr)	0	10 490.8 (kaf/yr)	11.5	1367 (kaf/yr)	19.9
1.5 °C +15%P	23.5	2.0	37.6	8.1	0.5	16.5
2.5 °C +15%P	14.1	3.0	22.4	9.3	0.3	17.7
5.0 °C +15%P	−6.9	6.5	−11.6	14.3	−0.4	22.9
1.5 °C +7%P	4.0	3.0	6.1	11.0	0.1	19.5
2.5 °C +7%P	−4.2	5.0	−7.1	13.3	−0.2	21.8
5.0 °C +7%P	−22.4	10.0	−35.3	21.8	−1.4	30.5
5.0 °C 0%P	−34.7	12.3	−49.0	28.3	−2.2	37.3
1.5 °C −10%P	−32.1	5.5	−47.3	25.3	−1.8	34.2
2.5 °C −10%P	−37.9	9.2	−52.6	30.0	−2.4	39.0
5.0 °C −10%P	−50.4	18.4	−66.9	71.0	−7.6	83.1

Notes:

[a] The figures shown in the row labeled "Baseline" report the baseline level from which the percentage change or absolute difference is calculated.

losses if runoff falls severely. In most cases higher prices lead to reductions in withdrawal; but there are exceptions. Agricultural withdrawals (in relation to baseline levels) can rise with increasing prices because of the outward shift in agricultural demand due to increases in net irrigation requirements associated with greater temperatures. We observe this phenomenon, for example, in the +2.5 °C, +7 percent precipitation scenario results in the upper basin. Under this scenario, upper basin agricultural prices increase by $1.8/af in response to a runoff reduction of 4.2 percent at the same time that withdrawals rise by 4.3 percent. The change in withdrawals in this case is lower than the amount of the 5.5 percent shift in demand, and therefore shows a slight displacement in demand as a result of reduced runoff.

Note that although the absolute change in the shadow prices in both basins is roughly equal, there are large disparities in the relative price changes and relative allocations between the basins. This significant price difference is the result of hydropower's relatively large marginal value for upper basin water. The valuable hydropower is located between the two basins. With a value of nearly $65/af in producing electricity (based on data provided in Gibbons 1996), water in the upper basin has a very high shadow price (opportunity cost) because every unit of water consumed in the upper basin never goes through the dams. This high price in the upper basin discourages low valued upper basin users. It is also worth noting that when runoff falls dramatically, the Compact requirements are violated. This is modeled as a violation cost which also adds to the price of upper basin water.

The bottom line is the change in welfare for the entire Colorado basin presented in Table 6.5. With low temperature and high precipitation increases, runoff increases and so does welfare. However, with low precipitation increases or with high temperature increases, runoff declines and welfare falls as well. In the central case of 2.5 °C, +7 percent precipitation, welfare declines by $102 million. Two-thirds of these losses are in hydropower and one-third is in salinity damages. Increasing temperature by 5.0 °C with the same precipitation increases damages to $572 million. Over 50 percent of these damages are hydropower losses, with another 35 percent of the losses coming in increased salinity. The remaining damages are shared by agriculture (7 percent), industrial (4 percent), and recreation (1 percent).

We also analyzed the welfare impact of the central case warming using two alternative institutional settings. The regulated scenario characterizes the current institutional setting with the Colorado River Compact and Mexican Treaty constraints and prior appropriation constraints. The unregulated setting removes all of these institutional constraints. With the regulations in place, the damages from the central case warming are $105 million. In the unregulated setting, the damages are only $65 million. The additional flexibility allowed by removing the regulations can

Table 6.5. *Climate change impacts on welfare in the Colorado River basin (millions of 1994$)*

Climate change scenario	Change in total impact welfare	Change in agri. welfare	Change in M&I welfare	Change in thermo-electric welfare	Change in hydropower value	Change in recreation value	Change in salinity damages
Baseline[a]	7744	307.3	5371.3	385.8	1035.5	644.1	−244.7
1.5 °C +15%P	486	38	5	0.5	281	1	160
2.5 °C +15%P	294	29	3	0.3	159	1	102
5.0 °C +15%P	−175	−1	−4	−0.4	−112	−1	−57
1.5 °C +7%P	85	13	1	0.1	40	0.2	31
2.5 °C +7%P	−102	−2	−3	−0.2	−66	−0.5	−34
5.0 °C +7%P	−572	−40	−20	−3	−300	−7	−202
5.0 °C 0%P	−1193	−112	−263	−63	−436	−18	−301
1.5 °C −10%P	−899	−99	−76	−16	−401	−16	−291
2.5 °C −10%P	−1372	−127	−332	−81	−468	−28	−336
5.0 °C −10%P	−2087	−221	−494	−110	−654	−96	−512

Notes:

[a] The figures shown in the row labeled "Baseline" are baseline welfare estimates. Negative values indicate baseline damages.

significantly reduce the damages from global warming. Rather than losing hydropower from runoff reductions, the unregulated model forces a larger reduction in consumptive use in the upper basin, saving $40 million.

Missouri basin results

The change in runoff in the Missouri basin due to climate change is summarized in column two of Table 6.6. The changes in runoff are similar in sign and in some cases slightly greater in magnitude than the runoff changes in the Colorado basin. For example, projected runoff falls by over 42 percent under the +5.0 °C scenario compared to a reduction of 35 percent in the Colorado basin. In the +2.5 °C, +7 percent precipitation and +1.5 °C, +15 percent precipitation scenarios, projected runoff changes by −9 percent and +20 percent, respectively. These changes in runoff alter withdrawals for the agricultural, municipal, and thermoelectric sectors. Agriculture is the most affected sector in the Missouri basin with withdrawals falling by 54 percent under the +5.0 °C scenario. In the same scenario, municipal and thermoelectric withdrawals fall only by 0.9 and 1.8 percent, respectively. This result reflects the much greater price elasticity for agricultural versus municipal and thermoelectric water use.

In scenarios where runoff increases, welfare also increases. However, in most cases, runoff declines and welfare falls as well. With the central case climate scenario, welfare losses are $519 million throughout the basin. Two-thirds of these losses are due to water quality problems and one-quarter of the losses are lost hydropower. With the 5 °C and zero precipitation case, losses climb to $2.2 billion. Sixty percent of these damages are water quality effects whereas only 17 percent are hydropower losses. Agriculture absorbs most of the remaining loss (22 percent).

Delaware basin results

Runoff changes are summarized in column two of Table 6.7. The hydrology simulations predict increases in runoff with little warming and high precipitation increases but otherwise project runoff will decline. Changes in withdrawals are closely linked to changes in runoff. The agricultural sector has the greatest change in withdrawals because of its highly elastic demand, whereas municipal and industrial withdrawals are hardly affected.

Changes in total welfare vary much less in percentage terms than runoff changes. In the central case, runoff falls by 4 percent and welfare falls by only 0.3 percent ($22 million). Even with the severe scenario of 5 °C with no precipitation increase, runoff falls by 34 percent and total welfare falls by only 3 percent ($207 million). Most of the damages are from water quality costs. Under the central scenario, water quality

Table 6.6. *Climate change impact on the Missouri River basin (millions of 1994$)*

Climate change scenario	Runoff % change	Total welfare	Agriculture		M&I		Thermoelectric		Hydropower welfare	Navigation welfare	Flooding welfare	Water quality welfare
			% Withdraw	Welfare	% Withdraw	Welfare	% Withdraw	Welfare				
Baseline[a]	56 651 (kaf/yr)	$10 804.8	13 322 (kaf/yr)	$1097.8	2124 (kaf/yr)	$4021	12 890 (kaf/yr)	$5658.3	$558.8	$3.8	−$14.5	−$520.4
1.5°C +15%P	20.5	314	14.3	94	0.04	0	−0.4	0.1	66	3	−39	190
2.5°C +15%P	9.1	2	3.7	47	−0.01	0	−0.3	0	−16	−0.1	−10	−19
5.0°C +15%P	−15.5	−1172	−27.5	−213	−0.3	−0.3	−0.4	−1	−245	−3	13	−723
1.5°C +7%P	1.0	−95	1.2	33	−0.04	0	−0.05	−0.1	−40	−1	1	−88
2.5°C +7%P	−9.1	−519	−9.1	−39	−0.1	−0.1	−0.1	−0.3	−133	−3	12	−356
5.0°C +7%P	−30.6	−1945	−47.9	−433	−0.7	−2	−1.4	−18	−348	−4	15	−1155
5.0°C 0%P	−42.4	−2239	−54.0	−498	−0.9	−3	−1.8	−24	−381	−4	15	−1344
1.5°C −10%P	−35.3	−1437	−32.6	−248	−0.3	−0.4	−0.4	−2	−282	−3	15	−917
2.5°C −10%P	−42.5	−2041	−48.9	−427	−0.7	−1	−1.0	−7	−361	−4	15	−1256
5.0°C −10%P	−56.8	−2292	−53.7	−480	−0.8	−1	−0.9	−6	−379	−4	15	−1437

Notes:

[a] Figures in this row are baseline welfare estimates. Negative values indicate baseline damages.

Table 6.7. *Climate change impacts in the Delaware River basin (millions of 1994$)*

			Agriculture		M&I		Thermoelectric				
Climate change scenario	Runoff % change	Total impact welfare	% Withdraw	Welfare	% Withdraw	Welfare	% Withdraw	Welfare	Hydropower welfare	Flooding welfare	Water quality welfare
Baseline[a]	13 660 (kaf/yr)	$6564.9	14.7 (kaf/yr)	$1.0	3399.5 (kaf/yr)	$5085.7	3416.4 (kaf/yr)	$1560.6	$4.0	−$0.0148	−$86.3
1.5 °C +15%P	16.8	48	3.4	0	0.2	1	0.5	2	0	0	45
2.5 °C +15%P	9.9	25	1.4	0	0.1	0.2	0.2	1	0	0	24
5.0 °C +15%P	−8.7	−49	−5.4	−0.1	−0.3	−2	−1.4	−7	0	0	−40
1.5 °C +7%P	2.7	6	0.0	0	0.01	0	−0.01	−0.1	0	0	6
2.5 °C +7%P	−4.1	−22	−2.7	−0.1	−0.1	−1	−0.6	−3	0	0	−18
5.0 °C +7%P	−22.3	−119	−12.9	−0.1	−0.9	−5	−3.5	−20	0	0	−94
5.0 °C 0%P	−33.9	−207	−8.2	−0.1	−2.0	−12	−7.4	−45	−0.1	0	−150
1.5 °C −10%P	−26.8	−134	−4.8	0	−0.9	−5	−3.7	−20	0	0	−109
2.5 °C −10%P	−33.2	−187	−6.1	−0.1	−1.6	−9	−6.2	−36	−0.1	0	−142
5.0 °C −10%P	−49.8	−418	−40.1	−0.4	−5.4	−41	−17.6	−128	−0.2	0	−248

Notes:

[a] The figures shown in the row labeled "Baseline" report the baseline value level from which the percentage change or absolute difference is calculated. Negative values indicate baseline damages.

accounts for over 80 percent of the damages and under the severe climate scenario, water quality accounts for almost three-quarters of the damages. The bulk of the remaining damages are from lost thermoelectric generation.

A–F–C basin results

The A–F–C basin results are given in Table 6.8. There are many similarities between the results of the A–F–C and the Delaware basins. In both cases, the available freshwater easily exceeds the consumptive withdrawals. The bulk of the damages in both systems are consequently due to nonconsumptive uses such as water quality and hydroelectricity.

The changes in runoff in response to climate change in this basin are less severe than in the other regions. Runoff changes are summarized in column two of Table 6.8. Average annual runoff increases under five climate scenarios (compared to three in the other basins). Reductions in runoff, when they occur, are smaller in magnitude. Changes in withdrawals in the A–F–C basin are relatively small. Municipal withdrawals hardly vary at all and thermal withdrawals fall by only a small amount even in severe scenarios. Agricultural withdrawals under many of the climate changes actually increase because of the outward shift in agricultural demand for irrigation water.

Changes in welfare across the climate scenarios show two important results. First, runoff reductions result in negligible changes in the welfare of agricultural, municipal, and thermal energy users. Second, the biggest damages once again are in the nonconsumptive sector. In the central case, total damages are $15 million with damages in navigation, hydroelectricity, water quality and flooding. With the more severe 5 °C case, total damages are $31 million with the bulk of damages in hydroelectricity, navigation and water quality and substantial flooding benefits.

6.5 National results

There are important regional differences in the distribution and magnitude of climate change effects on water resources which must be taken into account in estimating national effects. We begin with the basin studies above and extrapolate to the paired regions for each basin using region-wide estimates of runoff by climate scenarios. We then sum these results across regions to arrive at our national estimates. The change in total national withdrawals is presented in Table 6.9.[8] When national

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[8] Estimates in Table 6.9 for the zero percent precipitation change scenario are based on linear interpolation between the comparable + 7 percent and –10 percent precipitation scenarios. While the – 10 percent precipitation scenarios are plausible at the regional level, they are unlikely outcomes for uniform national scenarios, and therefore are not presented in the table.

Table 6.8. *Climate change impacts on the A–F–C basin (millions of 1994$)*

Climate change scenario	Runoff % change	Total impact welfare	Agriculture % Withdraw	Agriculture Welfare	M&I % Withdraw	M&I Welfare	Thermoelectric % Withdraw	Thermoelectric Welfare	Hydropower welfare	Navigation welfare	Flooding welfare	Water quality welfare
Baseline[a]	24 363 (kaf/yr)	$2225	84.9 (kaf/yr)	$4.8	771.3 (kaf/yr)	$1575	1304 (kaf/yr)	$589.07	$93.4	$23.8	$−77.9	−$16.6
1.5 °C + 15%P	18.7	−37	0.1	0	0.03	0	0.2	0	9	1	−53	6
2.5 °C + 15%P	13.7	−36	0.1	0	0.01	0	0.1	0	6	1	−47	4
5.0 °C + 15%P	0.5	−36	−1.6	0	−0.08	0	−0.4	−0.2	−8	−4	−18	−6
1.5 °C + 7%P	5.1	−15	0.1	0	−0.0	0	0.01	0	0.2	−0.1	−16	1
2.5 °C + 7%P	0.3	−15	−0.8	0	−0.03	0	−0.2	0	−3	−0.3	−10	−2
5.0 °C + 7%P	−12.4	−28	−1.6	0	−0.12	0	−0.8	−0.3	−20	−8	14	−14
5.0 °C 0%P	−23.5	−31	−16.7	1	−0.3	−0.1	−1.6	−1	−31	−12	39	−27
1.5 °C − 10%P	−23.1	−4	−8.1	0.4	−0.16	0	−0.9	−0.3	−24	−10	48	−18
2.5 °C − 10%P	−27.5	−12	−15.7	1	−0.23	0	−1.4	−1	−28	−10	51	−25
5.0 °C − 10%P	−38.9	−55	−17.2	1	−0.6	−0.3	−3.8	−4	−47	−17	65	−53

Notes:

[a] The figures shown in the row labeled "Baseline" report the baseline value level from which the percentage change or absolute difference is calculated. Negative values indicate baseline damages.

Table 6.9. *Welfare impact of climate change on US water users (billions of 1994$)*

Climate change scenario	Total withdrawals (maf/yr)	Agriculture withdrawal (maf/yr)	Total welfare	Agriculture welfare	M&I welfare	Thermo-electric welfare	Hydropower welfare	Other nonconsumptive welfare
Baseline[a]	377	157	$131.87	$13.70	$44.94	$29.88	$14.70	$28.65
1.5°C+15%P	27.1	25.8	9.76	0.07	0.0	0.02	0.69	8.98
2.5°C+15%P	9.8	9.6	2.59	−0.32	−0.01	0.02	−0.78	3.68
5.0°C+15%P	−35.6	−32.5	−17.91	−1.73	−0.01	−0.03	−4.65	−11.49
1.5°C+7%P	0.9	1.2	−1.53	−0.47	0.0	0.01	−1.15	0.08
2.5°C+7%P	−16.4	−14.1	−9.41	−0.94	−0.03	−0.01	−2.75	−5.68
5.0°C+7%P	−66.7	−60.0	−31.76	−2.90	−0.02	−0.12	−6.50	−22.22
1.5°C 0%P	−17.0	−15.0	−9.53	−1.0	−0.02	−0.01	−2.8	−5.7
2.5°C 0%P	−34.0	−31.0	−18.06	−1.8	−0.03	−0.03	−4.7	−11.5
5.0°C 0%P	−83.0	−69.8	−43.14	−3.67	−0.05	−0.57	−7.43	−31.42

Notes:

[a] Figures in this row represent baseline welfare estimates. Results for the three zero percent precipitation scenarios were derived from linear interpolation between results for the comparable +7 percent and −10 percent scenarios.

runoff increases (decreases), total withdrawals increase (decrease). The bulk of the change in withdrawals is limited to the agricultural sector. As water becomes more scarce, farmers cannot afford to pay more for the same amount of water and so are forced to reduce use. Because changes in withdrawal are largely limited to agriculture, agriculture bears the brunt of the welfare losses amongst consumptive users. However, it is important to note that welfare losses to consumptive users of water are actually relatively small in all but the most severe climate scenarios.

The largest source of damages in the model are to nonconsumptive users, specifically water quality. For example, in the central climate scenario, national welfare losses are estimated to be $9.4 billion. Of this amount, over $5 billion was associated with water quality damages, with a remaining $2.8 billion for hydroelectric losses. Only $1 billion of this loss was associated with consumptive users and most of this was agriculture. Even with the 5.0 °C, zero percent precipitation severe scenario, water quality accounts for $31 billion of the total $43 billion damage. Hydroelectricity accounts for another $7 billion and consumptive uses for another $4 billion.

It should be understood that there are many uncertainties inherent in these national estimates. The extrapolation from individual basins to regions is imperfect. The basins represent large complex river systems which have been extensively studied before. There is much less information on the remaining rivers in each region. Further, some regions, such as the Pacific Northwest, are really quite different from the four basins in this study. The estimates in this study presume that water will flow towards the highest value users. However, in cases where existing laws protect low value users, this assumption may be violated, adding to the damages.

6.6 Conclusions

This study uses four carefully planned basin studies in order to estimate the national damages from climate change on water systems. The four basin studies indicate that climate change is likely to have very different regional impacts. The Western states are semi-arid so that water can be a limiting factor for development. If climate change reduces runoff, agriculture in these regions will be affected and could well shrink. The eastern basins, in contrast, withdraw only a fraction of the available water. Reductions in runoff will have only a minimal effect on consumptive uses in the East.

The results also imply that it is not consumptive users but rather nonconsumptive users who will bear the bulk of the damages. Total damage and benefit estimates for virtually all scenarios are most heavily influenced by estimates for the nonconsumptive sectors. The nonconsumptive sector estimates are, in turn, dominated by estimates for changes in water quality (and influenced to a lesser degree by navigation and flooding estimates). Another large nonconsumptive loss is from hydroelectricity. In the central climate scenario, nonconsumptive uses account for 60 percent and hydroelectricity for almost 30 percent of the damages from warming. In the more severe 5 °C scenario, nonconsumptive uses account for over 70 percent of the damages and hydroelectricity another 17 percent.

A third important result is that rising temperature, even with moderate precipitation increases, is likely to lead to average runoff reductions nationwide. As runoff falls, total withdrawals fall proportionately. The severity of these reductions determine the damages. For the central climate scenario, total withdrawals are projected to fall by 4 percent, resulting in damages of $9.4 billion. For the more severe 5 °C scenario, total withdrawals are projected to fall by 22 percent, leading to damages of $43 billion.

Another critical issue in this analysis concerns adaptation. We have modeled changes in water allocations assuming that scarce water goes to the highest bidder. However, our analysis of the Colorado River reveals that low valued water users are protected under current agreements. If these protections are allowed to be sustained even as runoff falls, damages will be higher. The extent of institutional adaptation in the face of long-term water shortages is an area which requires more analysis.

Our estimates of water damages from warming are consistent with previous aggregate estimates. Cline (1992) estimates damages of $7 billion and Fankhauser (1995) estimates damages of $13.7 billion for the central case scenario. In comparison, we estimate only $9 billion from this scenario. For the more severe climate scenario, Titus (1992) estimates damages of between $21 and $60 billion. For this scenario, we estimate damages of $43 billion. However, even though our aggregate estimates are consistent with these previous authors, our estimate of what is causing those damages is different. All of the losses in the Cline and Fankhauser studies were predicted for consumptive users while we predict these users suffer losses of only $1 billion. Only Titus predicted that hydropower and water quality would bear the majority of the damages from warming.

This chapter attempts to improve upon earlier studies to estimate the economic damages from warming on the water sector. However, there are a number of caveats which must be repeated so that readers do not get overconfident in the accuracy of the results. First, the estimate of national runoff reductions are very crude as we have limited information about how many basins will react to climate change. Partly, we are highly uncertain about regional precipitation levels given any global climate forecast. Even if the climate forecast were known, we are also uncertain how runoff across unstudied basins would change in response to vegetation adjustments to the new climate, to carbon dioxide levels, and to the changing hydrology.

Second, we have studied four basins in detail in order to try to understand how the economy surrounding different river systems would adjust to runoff changes. We have discovered that there is substantial regional variation in how different river systems will adjust. We are not confident that the four basins we have studied fully capture the range of responses likely across the country. For example, none of the four river systems studied closely resemble the unstudied Columbia River basin. In addition, smaller river systems in each region may behave quite differently from the larger examples which we studied. The national extrapolation is consequently highly uncertain.

Third, this chapter models water quality effects assuming that rivers will have to maintain current pollution concentrations. As runoff falls, the study assumes that polluters will have to reduce emissions proportionately. These increased abatement costs are assumed to reflect the damages which would occur in each river system. Although reasonable as a first approximation, this methodology is clearly inappropriate in the long run given the large damages in this sector. A more accurate approach to modeling water quality is needed which tries to quantify ecological, recreational, and drinking water damages.

Fourth, the interactions between water and related systems must be carefully modeled. Although this study is careful to be consistent with the other studies in this book, a general equilibrium analysis may be able to provide even more careful interactions. For example, a general equilibrium analysis of agriculture and water might be able to predict a more accurate demand for water under different climate scenarios, taking into account the adjustments by farmers and markets. Although the efforts to remain consistent across the studies in this book have eliminated any first-order effects, theoretical improvements could still be achieved through a general equilibrium approach.

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Appendix A6

A6.1 Spatial effects and valuing return flows

Hartman and Seastone (1970), in their analysis of the consequences of return flows on water-use efficiency, observed that optimal (or efficient) water allocations are a function of return flow rates, and therefore, these return flows affect the marginal value of water in different uses. Specifically, the shadow price for water at the optimum is a function of return flow rates, and therefore, generally differs across users. For example, at the optimum, withdrawals by users with high return flow rates (or conversely, low rates of water consumption) are consistent with low marginal values for water, compared to the withdrawals of users with low return flow rates, which are consistent with high marginal values, as described in the following example.

Consider a river basin with three water users, two upstream consumptive users and a downstream user, and available water that exceeds possible consumptive requirements. The upstream users (e.g. a city and an agricultural user) are assumed to have return flow rates of 80 percent and 50 percent, respectively. Water is freely available to each user (i.e. they divert as much water as they wish until the marginal value for further withdrawals is zero), and water in excess of their demands flows to the downstream user. Further assume that this downstream user is, for example, a hydroelectric producer who has a marginal value (i.e. willingness to pay) for water equal to $40/af.

The welfare of both upstream and downstream users can be improved in this situation. Consider, for example, that the downstream user offers each upstream user a payment of $40 for each additional acre foot of water that is made available for downstream use (i.e. for water that is not consumed upstream). This acre foot is in addition to the flows already received, and importantly, includes return flows. To yield this additional acre foot downstream, the agricultural user could reduce diversions by 2 af (i.e. by 1/(1−return flow rate)), or the city could reduce its diversions by 5 af. In the first case, the payment of $40 to the agricultural user for reducing diversions by 2 af is in effect a payment of $20/af. Therefore, the agricultural user would be willing to reduce diversions up to the point where the marginal value of using the water for irrigation was equal to $20/af. Similarly, for the city user the payment of $40, for foregoing the use of 5 af, results in an average payment of $8/af. And therefore, the city would be willing to forego diversions up to the point where the net marginal revenue from supplying municipal users equaled $8/af.

In general, total welfare is maximized where the marginal value of water is adjusted for return flows and is equated across all users, such as:

$$MV_1/(1-r_1)=MV_2/(1-r_2)=MV_3, \tag{A6.1}$$

where MV is the marginal value, r is the return flow parameter (i.e. the share of diverted water that is returned to the river), subscripts 1 and 2 refer to the upstream users, and subscript 3 to the downstream user. At the optimum, users with lower return flow rates have greater implicit marginal values for water than those with higher return flow rates. This is an important result that characterizes optimal allocations in a river basin SE model with return flows.

Analytic derivation

To derive the above result for the two user case, consider an upstream and a downstream user who withdraw W_1 and W_2 from the river, respectively. The economic problem is to maximize the welfare of these two users subject to water availability and flow continuity, for example:

$$\max_{W_1, W_2} \quad f(W_1) + g(W_2)$$

s.t.

(1) $W_1 \leq K$

(2) $W_2 \leq K - W_1 + r_1 W_1$

(3) $W_i > 0 \quad i = 1,2,$

where f and g are single-valued functions reflecting the net benefits from water use for an upstream user (subscript 1) and a downstream user (subscript 2), respectively. K is a constant equal to the fixed quantity of water available, and r_1 is the return flow parameter. The first two constraints describe the availability and continuity of water to each of the two users, and the third constraint ensures that water use is positive for both users.

The Lagrangian function for this optimization problem is given as:

$$L = f(W_1) + g(W_2) + \lambda_1(K - W_1) + \lambda_2(K - W_1 + r_1 W_1 - W_2),$$

where λ_1 and λ_2 are the shadow prices for each of the two constraints, respectively. These shadow prices represent the marginal value of additional water to the system at each use. The first-order conditions, characterizing optimal withdrawals are:

$$f_{W1} - \lambda_1 - \lambda_2(1 - r_1) = 0, \text{ and} \tag{A6.2}$$

$$g_{W2} - \lambda_2 = 0, \tag{A6.3}$$

where first derivatives are indicated by subscript notation (i.e. $\delta f / \delta W_1 = f_{W1}$). By substitution, and assuming that W_1 does not deplete the entire flow of the river (i.e. there is slack in the first constraint resulting in ($\lambda_1 = 0$), the following relationship characterizes the optimal allocation of water:

$$f_{W1}/(1 - r_1) = g_{W2}. \tag{A6.4}$$

This is the relationship expressed above in Equation (A6.1).

A6.2 General form of the basin economic models

The general structure and composition of the river basin SE models is presented below, in which we describe some of the technical aspects of the models. The model description is general and contains features of all the models, and therefore, some equations may not be defined for a specific model. The objective function and its components is first defined, and this is followed by descriptions of the constraints. All variables are assumed to be positive except the objective variable (*CPS*), reservoir releases (R_{nt}), and net reservoir evaporation (E_{rt}) which can all vary freely. Definitions of indices, variables, and parameters follow the model description.

Objective Function: Max *CPS* by choosing $F_{nt}, S_{rt}, X_{it}, H_{rt}$

$$CPS = \sum_t DF_t \times \Big[\sum_i (a_{ni} + 0.5\, b_{ni} W_{nit} - 0.5\, c_{ni} W_{nit}^2) \mathrm{W}_{nit} \quad \text{consumptive use}$$

$$+ \sum_i W_{ni0}(\bar{V}_{ni} - V_{ni0}) + V_{ni0}\left(\frac{W_{nit}}{W_{ni0}}\right)\beta_{ni} \quad \text{(COBEM only)}$$

$$+ \sum_{r \in N} h_r \times P \times H_{rt} \quad \text{hydropower benefits}$$

$$+ \sum_n (1 + \mathrm{e}^{ln + mnFnt}) \quad \text{navigation benefits}$$

$$- \sum_n (f_n + g_n FL_{nt}) FL_{nt} \quad \text{flood damages (above threshold)}$$

$$- \sum_n K_n [1 - (1 - \mathrm{e}^{knFnt})] \quad \text{thermal waste heat (opportunity costs)}$$

$$+ \sum_n q_n F_{nt} \quad \text{secondary wastewater treatment benefits}$$

$$- \sum_n \Big[\left(\frac{SL_{nt}}{\overline{F}_n}\right) \times C \times \sum_i 2 r_{ni} W_{nit}\Big] \quad \text{advanced wastewater treatment costs}$$

$$+ \sum_r \$ \times VIS_r \sqrt{\frac{(ar_{r0} + ar_{r1} S_{rt} + ar_{r2} S_{rt}^2)}{S_r^{\max}}} \quad \text{flatwater/reservoir recreation}$$

$$+ \sum_n \$ \,(i_1 + i_2 F_{nt} + i_3 F_{nt}^2) \quad \text{instream recreation benefits}$$

$$- \sum_i SD_{ni} W_{nit} \frac{(NA_{n-1,t} + INA_{nt})}{(F_{nt} + W_{nit})} \Big] \quad \text{salinity damages}$$

$$- \mathrm{DC}_{n,t} \times \mathrm{D}_{n,t} \quad \text{penalty for compact violation (COBEM only).}$$

Subject to:

$$F_{nt} = F_{n-1,t} + I_{nt} + R_{nt} + \sum_i r_{ni} W_{n-1,i,t} - \sum_i W_{nit} \quad \text{flow balance}$$

$$\mathrm{S}_r^{\min} \leq S_{rt} - S_{r,t-1} + R_{rt} + E_{rt} \leq \mathrm{S}_r^{\max} \quad \text{storage balance}$$

$S_{rT} = S_{r0}$ terminal storage constraint

$FL_{nt} \geq F_{nt} - FT_{n}$ flood level constraint

$GW_{nit} \leq \overline{GW}_{ni}$ groundwater supply

$H_{nt} - F_{nt} + SP_{nt} \leq \bar{H}_{r}$ hydropower capacity constraint

$E_{rt} = 0.5(PET_{rt} + \frac{PET_{rt}}{S_{r}^{\max}} S_{rt})$ reservoir evaporation constraint

$$NA_{nt} = NA_{n-1,t} + INA_{nt} - \frac{(NA_{n-1,t} + INA_{nt}) \times \sum_{i \in export} W_{nit}}{(F_{nt} + \sum_{i \in export} W_{ni}t + 1)} \quad \text{salt balance (COBEM)}$$

$F_{n,t} + D_{n,t} \geq 8230$ Colorado River Compact constraint, in force for $n = 8$

where *export* is the set of sectors that include export of salt from the Colorado basin.

Definitions:

Indices

i	consumptive users, i = agriculture, municipal, thermoelectric
n	model nodes (reaches), $n = 0,1,3,\ldots,N$
t	model time step (annual for COBEM, seasonal for all others), $t = 1,2,3,\ldots,T$
r	model reservoirs, $r = 1,2,3,\ldots,R$.

Variables

CPS	consumer plus producer surplus
F_{nt}	river flow leaving node n at time t (includes tributaries)
S_{rt}	reservoir storage volume, reservoir r at time t
R_{nt}	net reservoir release, into node n at time t
H_{rt}	reservoir release for hydropower production, into node n at time t
SP_{nt}	reservoir release spill into node n at time t in excess of hydro capacity
I_{nt}	exogenous inflow (including tributaries) into node n at time t
FL_{nt}	river flow in excess of flood damage threshold at node n at time t
SL_{nt}	slack variable reflecting deviation from minimum flow requirements for water quality
GW_{nit}	groundwater use by user i at node n at time t
W_{nit}	withdrawal of water by user i at node n at time t
E_{rt}	reservoir evaporation at time t
NA_{nt}	salinity quantity (thousands of tons) at node n at time t
$D_{n,t}$	deficit from Colorado River Compact, for $n = 8$.

Constants and parameters

DF_t	discount factor (set to zero for purposes of this analysis)
a_{ni}	intercept of linear demand functions, user i at node n
b_{ni}	slope of linear demand functions, user i at node n
c_{ni}	slope of linear cost (supply) functions, user i at node n
β_{ni}	elasticity coefficient for nonlinear value functions
$\bar{V}_{ni}, V_{ni0}$	value parameters for nonlinear value functions
W_{ni0}	climate adjusted depletion request in COBEM
$ar_{r0}, ar_{r1}, ar_{r2}$	reservoir surface area parameters
r_{ni}	return flow coefficient for user i at node n
f_n	slope of flood damage function, node n
FT_n	flood damage threshold at node n
g_n	quadratic term in flood damage function, node n
l_n, m_n	location and slope coefficients for navigation benefits at node n
K_n	maximum value of OTC power production
k_n	slope term for thermal waste heat opportunity costs
h_n	average reservoir head
P	constant term for power production efficiency, utilization, and valuation
q_n	slope of linear secondary treatment benefits
$\bar{F}_n$	minimum flow requirement to maintain water quality at node n
C	average cost per acre foot of advanced wastewater treatment
$\overline{GW}_{ni}$	groundwater supply capacity
$\bar{H}_r$	hydropower release capacity
$\$$	user day value for recreation benefits
PET_{rt}	exogenous potential evaporation level
VIS_r	historical visitation rates at Colorado basin reservoirs
i_1, i_2, i_3	quadratic parameters for instream recreation benefits
SD_{ni}	salinity damage coefficient for lower Colorado basin users
INA_{nt}	exogenous salt loadings in Colorado basin
$DC_{n,t}$	unit cost of Compact violation, for $n = 8$.