WATER RESOURCES IMPLICATIONS OF GLOBAL WARMING: A U.S. REGIONAL PERSPECTIVE

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Abstract. The implications of global warming for the performance of six U.S. water resource systems are evaluated. The six case study sites represent a range of geographic and hydrologic, as well as institutional and social settings. Large, multi-reservoir systems (Columbia River, Missouri River, Apalachicola-Chatahoochee-Flint (ACF) Rivers), small, one or two reservoir systems (Tacoma and Boston) and medium size systems (Savannah River) are represented. The river basins range from mountainous to low relief and semi-humid to semi-arid, and the system operational purposes range from predominantly municipal to broadly multi-purpose. The studies inferred, using a chain of climate downscaling, hydrologic and water resources systems models, the sensitivity of six water resources systems to changes in precipitation, temperature and solar radiation. The climate change scenarios used in this study are based on results from transient climate change experiments performed with coupled ocean-atmosphere General Circulation Models (GCMs) for the 1995 Intergovernmental Panel on Climate Change (IPCC) assessment. An earlier doubled-CO_2 scenario from one of the GCMs was also used in the evaluation. The GCM scenarios were transferred to the local level using a simple downscaling approach that scales local weather variables by fixed monthly ratios (for precipitation) and fixed monthly shifts (for temperature).

For those river basins where snow plays an important role in the current climate hydrology (Tacoma, Columbia, Missouri and, to a lesser extent, Boston) changes in temperature result in important changes in seasonal streamflow hydrographs. In these systems, spring snowmelt peaks are reduced and winter flows increase, on average. Changes in precipitation are generally reflected in the annual total runoff volumes more than in the seasonal shape of the hydrographs. In the Savannah and ACF systems, where snow plays a minor hydrological role, changes in hydrological response are linked more directly to temperature and precipitation changes.

Effects on system performance varied from system to system, from GCM to GCM, and for each system operating objective (such as hydropower production, municipal and industrial supply, flood control, recreation, navigation and instream flow protection). Effects were generally smaller for the transient scenarios than for the doubled CO_2 scenario. In terms of streamflow, one of the transient scenarios tended to have increases at most sites, while another tended to have decreases at most sites. The third showed no general consistency over the six sites. Generally, the water resource system performance effects were determined by the hydrologic changes and the amount of buffering provided by the system's storage capacity. The effects of demand growth and other plausible future operational considerations were evaluated as well. For most sites, the effects of these non-climatic effects on future system performance would about equal or exceed the effects of climate change over system planning horizons.

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1. Introduction

Of the potential effects of global warming, the implications for water resources are among the most important to society. An adequate supply of potable water is essential for human habitation. In many parts of the world, including much of the U.S., the demand for consumptive (e.g., water supply) and non-consumptive (e.g., navigation, hydroelectric power generation, industrial cooling, instream flow) uses of fresh water is barely balanced by sustainable surface and groundwater sources. In addition, water is essential for crop growth and water management is an important factor in the reliability of food supplies. Water management has important implications for hydropower generation and cooling of thermal power plants, for navigation, flood control and recreation as well.

The possible effects of global warming on water resources have been the topic of many recent studies. For instance, Chapters 10 and 14 of the 1995 IPCC report (Watson et al., 1996) reference dozens of site-specific studies of the sensitivity of hydrology and water resources to climate change. Most of these studies, however, are based either on arbitrarily prescribed steady-state changes in precipitation and/or temperature, or on steady state GCM simulations, typically for global concentrations of CO_2 doubled from present. Few of the studies cited have assessed the effects of transient changes in greenhouse gases, such as the GCM runs made by three major climate modeling centers (United Kingdom Meteorological Office Hadley Center, Max Planck Institute, Geophysical Fluid Dynamics Laboratory) specifically for the 1995 IPCC update (Houghton et al., 1996). Likewise, the studies cited focus much more on hydrologic sensitivities to climate change than they do on the sensitivity of the performance of water resources systems. The distinction is important, because the effect on water users is effectively an ‘end-of-the-pipe’ question: that is, how much water will be available, where, and when? In the U.S., where water resources are highly developed, it is important to understand how the operation and management of, e.g., reservoir systems and coupled groundwater-surface water systems, would respond to climate change. It is the integration of the changes in the natural system and water management activities that is arguably of the greatest practical concern.

In recent years, media attention to the potential effects of global warming has intensified, in part due to the occurrence of such extreme events as the flooding on the Mississippi River in 1993, and in part because of an ongoing debate in the political arena over policies to slow global warming, such as the institution of a carbon tax and the signing of international emissions limiting agreements. Although the Intergovernmental Panel on Climate Change (IPCC) prepared reviews of the status of global warming in 1990 and 1995, and preparation of a year 2000 report is underway, many of the central uncertainties hampering the interpretation of climate change scenarios and impact assessments remain. These uncertainties are well-documented in the atmospheric modeling literature but are less thoroughly emphasized in published impact assessments, such as those cited in the IPCC 1995

Working Group II report (Watson et al., 1996). One of the most commonly cited obstacles to the formation of policies to manage or mitigate climate change is the lack of consistency among global warming scenarios as to the direction and magnitude of climatological changes at the regional scale. The effect of this uncertainty (among others) as it propagates through the sequence of impact assessment steps is apparent in the work summarized in this paper, and illustrates the difficulties facing policy makers on the issue of climate change. A fuller discussion of the uncertainties present in many water resources impact assessments is also given in Wood et al. (1997).

This paper summarizes six studies (Lettenmaier et al., 1998a–f) of the sensitivity of U.S. water resource systems to climate change. The objectives of these studies were to evaluate and generalize the potential effects of global warming on the performance of multiple use water resources systems throughout the U.S. and to determine the relative effects of climate change and long-term demand growth on water resource system performance. The studies were designed with several considerations in mind. First, they were to reflect the most current, transient GCM predictions of climate change effects, applicable over the planning horizon for water resource system operation (typically several decades, and certainly much less than 100 years). Second, they were designed to investigate the end user effect of climate change on water resources, and not just the sensitivity of the hydrologic system. Third, sites were selected to provide a reasonable representation nationally in terms of water use characteristics, geography and related climatic and hydrologic conditions. Finally, the studies were to use models and methods of analysis that are, to the extent possible, standard across the six sites.

2. Study Sites and Site Characteristics

The six water resource systems studied were the Green River (Tacoma, WA, water supply system), the Boston water supply system, the Savannah River system, the Columbia River system, the Missouri River system and the Apalachicola-Chattahoochee-Flint River (ACF) system. Figure 1 shows the location of these systems, which are situated in the Northwest (Tacoma and Columbia River), the Northeast (Boston), the Midwest (Missouri River) and the Southeast (Savannah River and ACF basin). Large, multi-reservoir systems (Columbia River, Missouri River, ACF basin), small, one or two reservoir systems (Tacoma and Boston), and medium size systems (Savannah River) are represented. The river basins range from mountainous to low relief and semi-humid to semi-arid, and the system uses range from predominantly municipal water supply to broadly multi-purpose. Brief summaries of the six study sites are given below. For details, the reader is referred to Lettenmaier et al. (1998a–f).

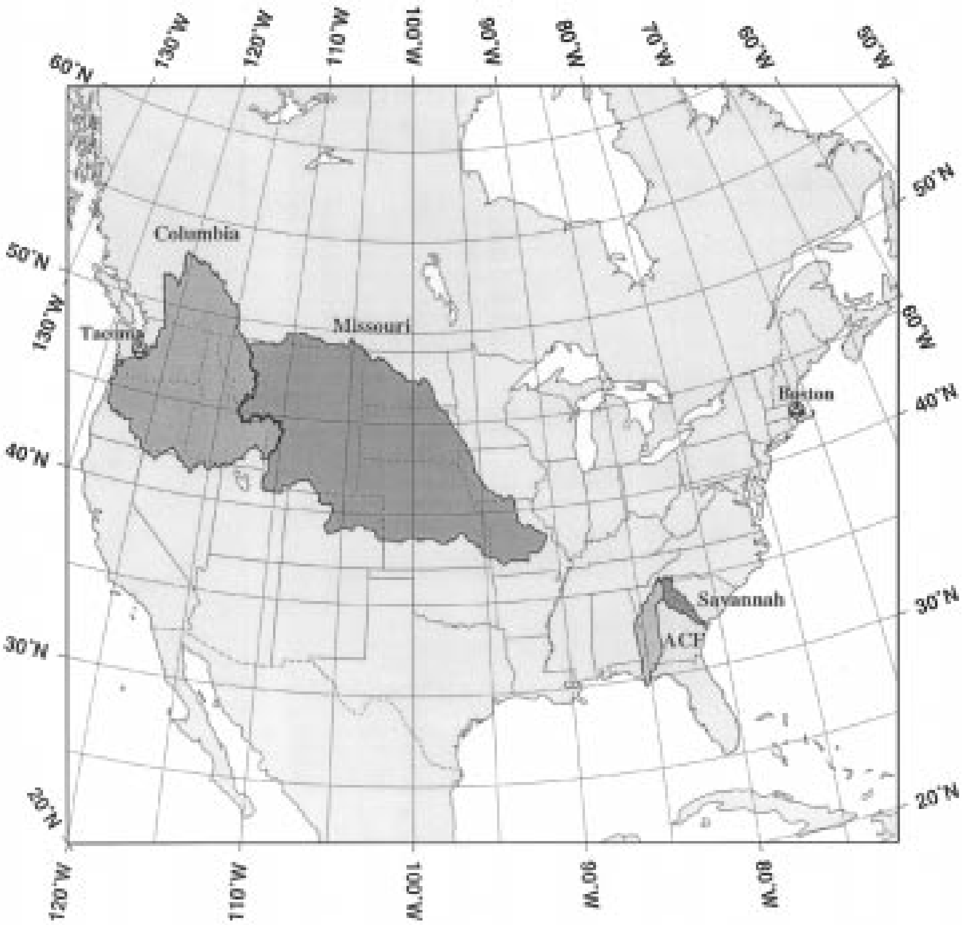

Figure 1. Location map of the six case study sites: The ACF River basin, Tacoma water supply system (Green River), Boston, Savannah River, Columbia River and Missouri River. Individual sites are shown in detail in Figure 2.

2.1. TACOMA WATER SUPPLY SYSTEM (GREEN RIVER)

The Tacoma water supply system serves a population of about 215,000. The primary water source is the Green River, with augmentation by wells. The Green River drains 1,251 km^2 of the southern portion of King County, Washington (Figure 2a). It heads on the Cascade Crest and terminates as the Duwamish River in Elliott Bay, which forms the port for the city of Seattle. The Green River produces salmon and steelhead trout for Indian and commercial fisheries; hence water quality is a major concern, especially during low flow periods. Howard A. Hanson (HAH) Dam (0.0297 billion m^3 active storage), which regulates the upper 243 km^2 of the basin, is operated by the Corps of Engineers primarily for winter flood control storage and also to augment instream fish flow requirements (3.11 cms). The project

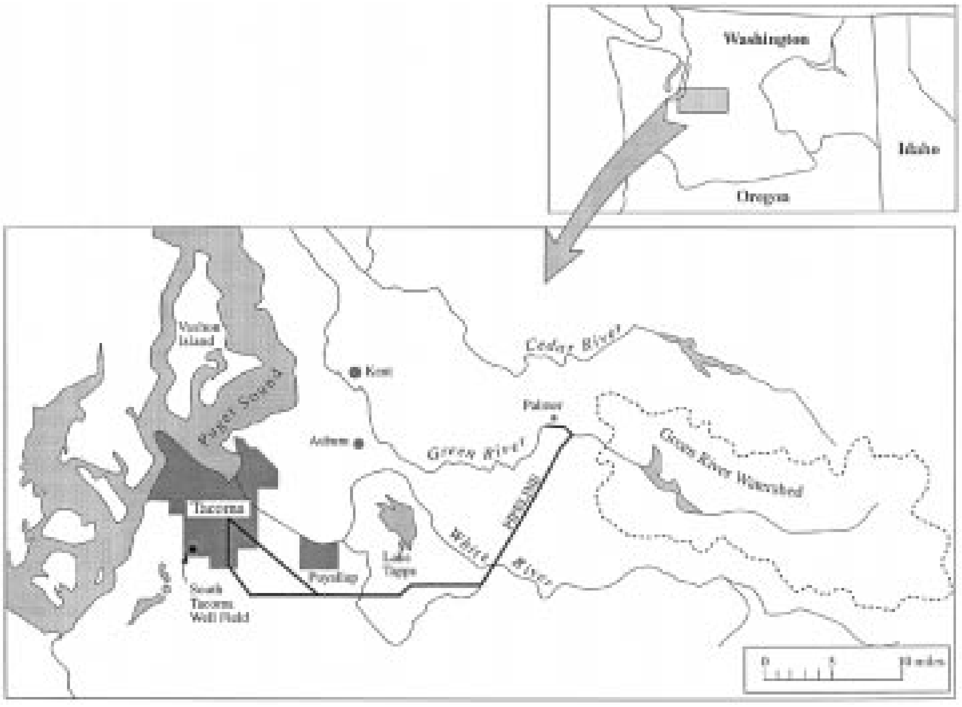

Figure 2a. Tacoma water supply system, with major reservoirs and system features.

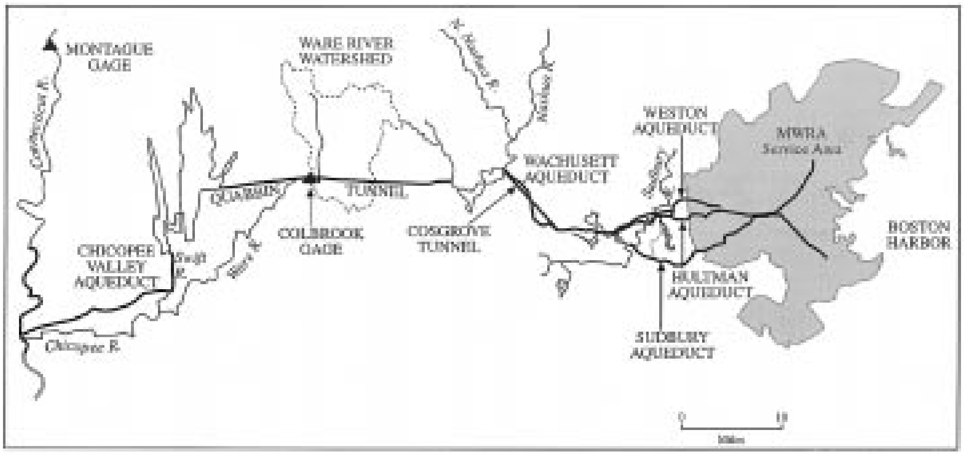

Figure 2b. Boston water supply system, with major reservoirs and system features.

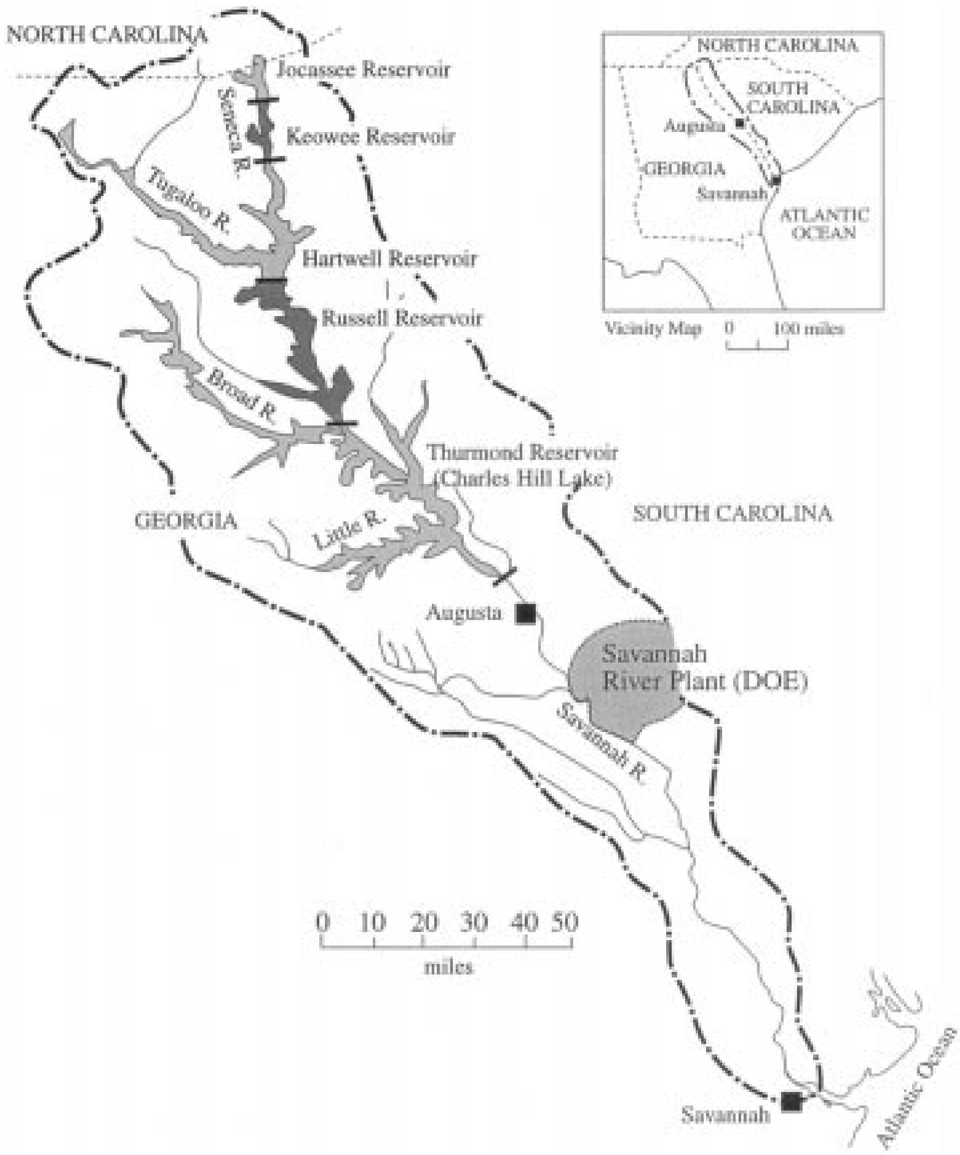

Figure 2c. Savannah River system, with major tributaries and reservoirs.

operating policy provides 500 year flood protection to the lower Green River valley by maintaining flood flows below 340 cms at the city of Auburn, WA. The City of Tacoma's water supply diversion from the Green River (3.17 cms) has priority over the instream flow requirements for fish; shortages in instream flows for the protection of fish habitat, however, are currently rare.

Figure 2d. Apalachicola–Chattahoochee–Flint River system, with major tributaries and reservoirs.

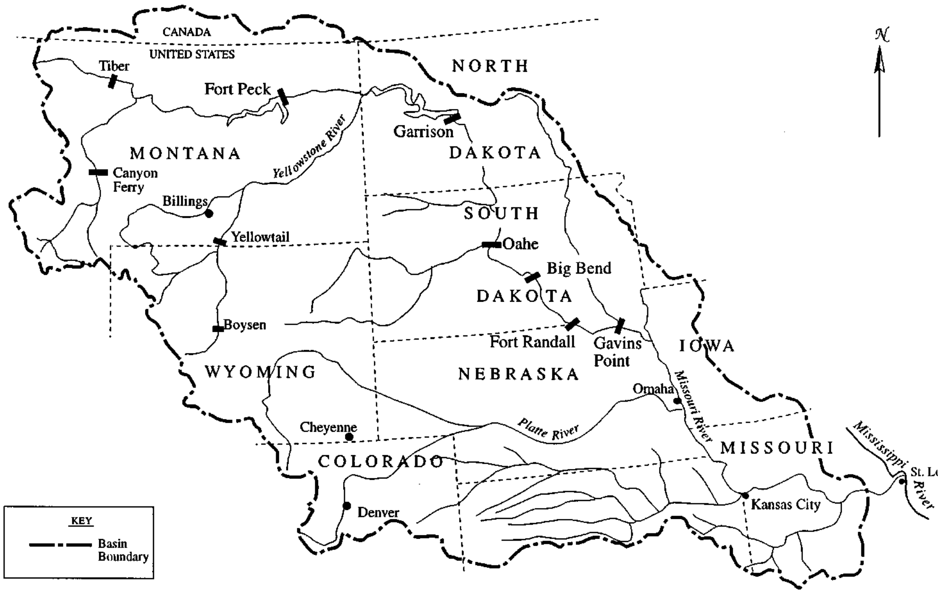

Figure 2e. Missouri River system, with major tributaries and reservoirs.

2.2. BOSTON WATER SUPPLY SYSTEM

The Massachusetts Water Resources Authority (MWRA) provides the water and sewer service for Boston and many of the surrounding communities. A population of around 2.4 million is served in part or whole by MWRA. The MWRA water supply system (Figure 2b) consists of two major reservoirs, Quabbin (1.56 billion m^3) and Wachusett (a 0.246 billion m^3 distribution reservoir), along with an additional source, the Ware river. Besides supplying municipal demands, Quabbin's releases (into the Swift River) are strictly controlled to meet minimum flow requirements for fish. These releases are given priority over water supply releases at present, and the system has never been unable to meet these requirements. In addition to the sources controlled by MWRA, there are several local aquifers and small reservoirs, which yielded 1.36 cms in 1990. In 1992, the MWRA supplied an average of 4.70 cms, down from an average demand of 5.92 mgd in 1987 and 5.21 cms in 1990. The reduction has been attributed to the MWRA's aggressive leak detection and demand reduction program, to water price increases and to reduced economic activity (COE, 1994).

Despite the four year average detention time in Quabbin Reservoir, water quality is a concern because MWRA does not filter the water before distribution. MWRA assessed the minimum reservoir level that would avoid violating water quality standards (MWRA/MDC, 1989) as 38 percent of capacity. If Quabbin Reservoir were to reach this level regularly, construction of expensive treatment

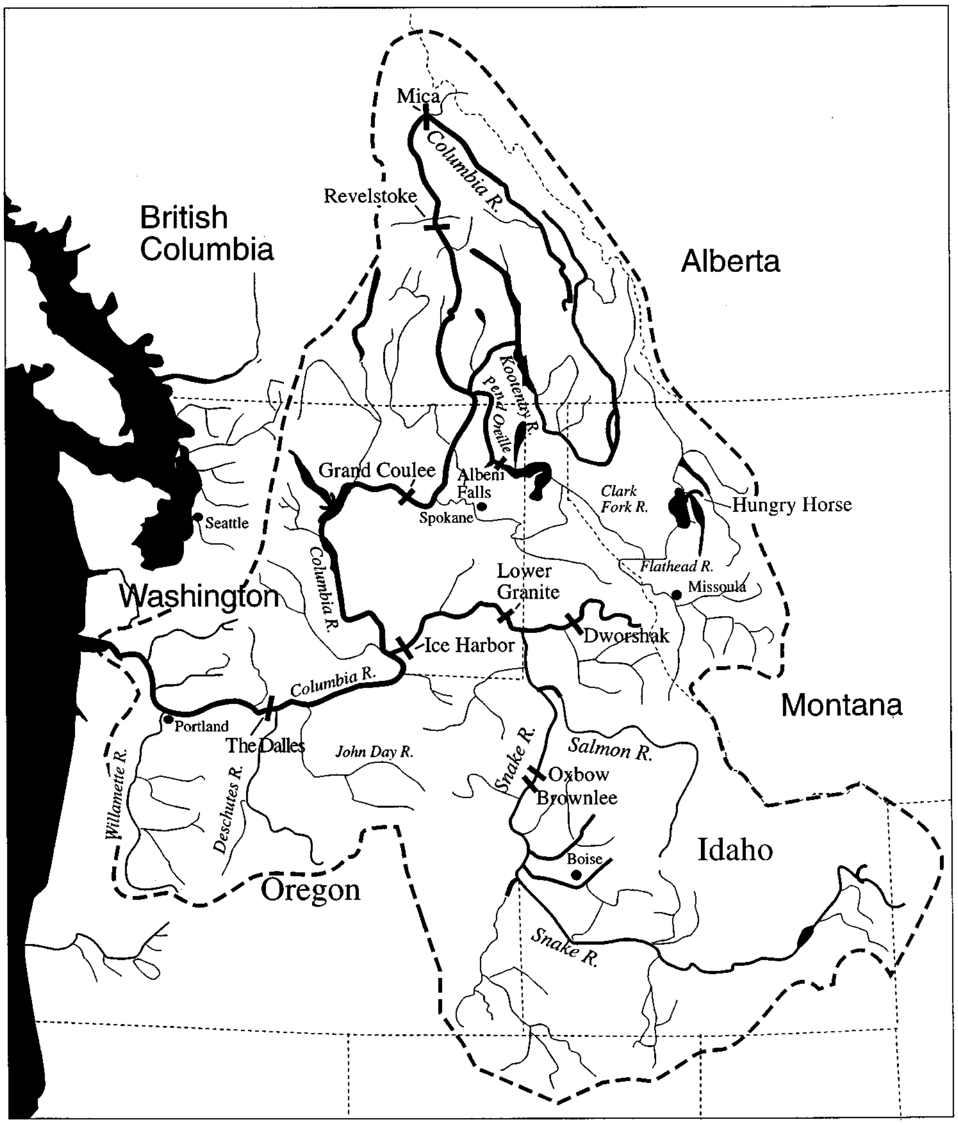

Figure 2f. Columbia River system, with major tributaries and reservoirs.

plants would be necessary. Quabbin Reservoir's lowest storage of record was 45 percent of capacity during the New England drought of the 1960s.

2.3. SAVANNAH RIVER BASIN

The Savannah River (Figure 2c) heads in the Blue Ridge mountains of North Carolina. From Hartwell Dam, at the confluence of the Tugaloo and Seneca Rivers, the Savannah River flows southeasterly for 500 km, forming the border between

South Carolina and Georgia. Together with Hartwell Dam, the Richard B. Russell and J. Strom Thurmond reservoirs downstream form a chain of lakes 190 km long. The Savannah River drains an area of about 30,000 km^2, most of which is forested. Annual rainfall ranges from 1000 to almost 2000 mm.

The most significant economic effects of the Savannah River system operation relate to hydropower generation, recreation and flood protection. The largest population centers in the basin are Savannah and Augusta, with 200,000 and 60,000 people, respectively. The Department of Energy's Savannah River Plant was the largest user in the basin until 1990, when it ceased operation of three nuclear reactors. The Savannah River Plant's demand for water was the basis for minimum releases from Thurmond Reservoir of 102 cms, which now amply supplies lower basin withdrawals for municipal and industrial (M&I) and limited agricultural use. Five water use objectives are currently defined for the COE reservoirs (COE, 1989): fish and wildlife management, hydropower, recreation, water quality and water supply.

2.4. APALACHICOLA–CHATTAHOOCHEE–FLINT RIVER (ACF) SYSTEM

The ACF basin system extends from the Blue Ridge Mountains (north of Atlanta) south to the Gulf of Mexico (Figure 2d), draining 50,800 km^2, with a semi-humid climate and mean annual runoff of about 480 mm. The ACF system comprises two major tributaries of roughly equal drainage area, the Chattahoochee and the Flint Rivers, which combine to form the Apalachicola River. The Apalachicola River is home to a diverse range of fish species and greatly influences the nutrient inflow and productivity of Apalachicola Bay. Regulation of the main stem of the Apalachicola River is minimal. The upper Flint River is also essentially unregulated, while the Chattahoochee River has about 15 dams and locks operated for navigation, flood control, water supply, recreation and hydropower generation. The reservoir system is operated for the benefit of stakeholders in three states (Alabama, Florida and Georgia) that have different water management priorities. The largest five projects, including Lake Sydney Lanier, are COE reservoirs.

The general operating policy for the federal dams is to release as much water as possible for hydropower generation during the peak demand summer months, subject to the need to retain water in storage for navigation releases in the low flow months of fall, and to meet water quality and water supply objectives during droughts. Reservoirs with flood control objectives have seasonally variable flood control pools, and flood operation overrides other objectives when high runoff causes encroachment on flood control storage.

2.5. MISSOURI RIVER

The Missouri River heads on the Continental Divide and flows almost 6,400 km to its confluence with the Mississippi at St. Louis (Figure 2e). The drainage area of 1.37 million km^2 constitutes over one-half of the drainage area of the Mississippi

River. In the downstream reaches, the climate is semi-humid and relatively temperate, whereas a more severe semi-arid continental climate prevails in the upper reaches. The headwater tributaries are alpine, in an area with strong orographic variations in precipitation. The Missouri River reservoir system consists of six Corps of Engineers reservoirs, the primary purposes of which are flood control, water supply (e.g., municipal and agricultural), navigation and power generation (recreation and fish and wildlife habitat are still incidental project uses). These reservoirs have aggregate active storage capacity of about 90 percent of the mean annual flow of the river at St. Louis. In addition, there are many reservoirs on the major tributaries, notably the Platte and Kansas Rivers, which serve to regulate flow for the lower half of the basin.

2.6. COLUMBIA RIVER

The Columbia River is the fourth largest river by discharge in North America, draining 567,000 km^2 in the Pacific Northwest and 102,000 km^2 in British Columbia, Canada (Figure 2f). The Columbia River originates at Columbia Lake on the western slope of British Columbia's Rocky Mountains and flows over 1900 km to its mouth near Astoria, Oregon. The basin's climate ranges from maritime near the mouth of the main stem to arid in some of the inland valleys. The Cascade Mountains separate the coast from the interior of the basin and have a strong influence on the runoff in both areas. Occasionally, rainfall adds to the runoff, but east of the Cascades, spring snowmelt is the dominant mechanism controlling the shape of the seasonal hydrograph. At its mouth, the Columbia River has an average annual discharge of about 7,800 cms.

More than 250 reservoirs and 100 hydroelectric projects have been built on the Columbia River and its tributaries, capturing only a third of the river's mean annual flow. Approximately 75 of these projects represent the coordinated Columbia River reservoir system, which is operated by the COE and Bureau of Reclamation (BuRec) for hydropower (18,500 megawatts of firm power annually), flood control, fish migration, fish and wildlife habitat protection, water supply and water-quality maintenance, irrigation, navigation and recreation. In the last decade, growth in the region and changing priorities have placed the river system under increasing stress, necessitating controversial tradeoffs between operating priorities such as fisheries protection and hydropower.

3. Climate Scenarios and Downscaling

The climate change scenarios used in this study are based on results from transient climate change experiments performed with coupled ocean-atmosphere GCMs for the 1995 IPCC assessment (Houghton et al., 1996). The approach used in the GCM transient simulations is described in detail by Viner et al. (1994) and is summarized by Greco et al. (1994), from which the information in this section is taken.

TABLE I

Summary of the coupled ocean-atmosphere GCMs used in IPCC transient climate change experiments (from Greco et al., 1994)

Model	GFDL89	ECHAM1-A (MPI)	UKMO
Reference	Manabe et al. (1991, 1992)	Cubash et al. (1992)	Murphy (1995), Murphy and Mitchell (1995)
Atmospheric levels	9	19	11
Resolution (degrees lat. by long.)	7.5×4.5[a]	5.62×5.62	3.75×2.5
Integration length, yrs	100	100	75
Forcing scenario, control[b]	300 ppmv	330 ppmv	323 ppmv
Climate change emission scenario	1%/yr	IPCC90 Scenario A[c]	1%/yr
CO_2 560 ppmv[d]	Year 57	Year 47	Year 64
Year of doubling	70	60	70
$\Delta\bar{T}$, $2 \times CO_2$[e]	2.3	1.3	1.7

[a] Ocean model 3.75×4.5.
[b] Equivalent global average trace gas concentration as CO_2, ppm by volume.
[c] IPCC, 1990.
[d] Year in which global average CO_2 concentration reaches 560 ppm.
[e] Global average temperature (°C) in year of doubled CO_2 concentration associated with sulfate aerosols and stratospheric ozone depletion (Greco et al., 1994) for a mid-range forecast of global economic and population growth. The actual rates of increase in atmospheric equivalent CO_2 concentrations assumed by the models are slightly greater than the IS92a scenario, for reasons not made clear by Greco et al. (1994).

The GCM simulations were produced by three modeling centers: The Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO, also referred to as the Hadley Centre), and the Max Planck Institute (MPI). The relevant references to the coupled model runs are GFDL (model referred to internally as GFDL89): Manabe et al. (1991, 1992); UKTR: Murphy (1995), Murphy and Mitchell (1995); MPI (model referred to internally as ECHAM1-A): Cubasch et al. (1992). Each of the models is designated by the name of the institution and the suffix TR for transient: GFTR, HCTR and MPTR. A summary of the models and the climate change experiments is presented in Table I.

For each of the models, a base case (current climate) run was made, assuming the atmospheric greenhouse gas concentrations (equivalent CO_2) shown in Table I. Each of the models was then run with transient equivalent CO_2 concentrations starting at the base case (control) values and increasing annually following the scenarios given in Table I. The GCMs used to produce these simulations are coupled ocean-atmosphere models which simulate the time-dependent response of climate to increases in atmospheric CO_2. All model runs were made by the respective modeling centers and were archived by the National Center for Atmospheric Research (NCAR).

The three GCM transient runs are nominally based on emissions scenarios that most closely resemble the forcing used in the IPCC IS92a scenario (IPCC, 1990, 1992). The IS92a scenario is an estimate of the equivalent CO_2 concentration scenario that 'would produce radiative forcing equal to that of all the greenhouse gases, including the negative forcing associated with sulfate aerosols and stratospheric ozone depletion' (Greco et al., 1994).

Greco et al. (1994) note several problems with the IPCC transient simulations: the use of different concentration scenarios in both the climate change runs and the control runs; the existence of a 'cold start' problem identified by Hasselmann et al. (1992) that occurs because the models neglect the thermal lag effect associated with ocean-atmosphere coupling; and inherent drift in the model simulations, which becomes increasingly important as the length of the model simulations increases. To deal with these problems, the IPCC transient climate scenarios are based on what Greco et al. (1994) term the 'simple linked method', which couples interpretation of the GCM (three-dimensional) simulations to predictions from a simple one-dimensional climate model of Wigley and Raper (1992). As described by Greco et al. (1994), the one-dimensional model starts with a pre-industrial climate and incorporates the effects of greenhouse gas forcing and ocean lag on a global average basis to predict the rate of change of climate beginning in 1990, using the IPCC IS92a emissions scenario and a 'warm start' approach (that is, it accounts for warming effects from emissions prior to 1990). Using the one-dimensional simulation, Greco et al. (1994) estimated global average temperature changes for years 2020 and 2050, and used them to identify the corresponding decades (with the same global average temperature change) for each of the GCMs. These decades were specified as IPCC Decades 2 and 3, respectively (Decade 1 corresponds to the control run). Table II lists the model-equivalent years for each model and decade.

For the six studies reported here, the objective was to model the effect of transient climate change on water resource system performance. The analysis of transient climate change on land surface hydrology is complicated by the confounding of natural variability (which would occur in the absence of climate change) with the long-term climate change signal. For this reason, forcing hydrological models directly with a single GCM transient precipitation and temperature scenario could well lead to misleading results. Ideally, assessments would be made using ensembles of GCM scenarios, each representing different statistical realizations of the surface hydrologic forcings corresponding to a given emissions scenario.

Given only one set of climate scenarios, and the record length limitation imposed by the IPCC decadal analysis, such an approach was not feasible. Instead, multiple steady state analyses were performed by imposing the mean monthly (constant but seasonally varying) precipitation, temperature and solar radiation changes for IPCC Decades 2 and 3 on the historic period of (daily) precipitation

TABLE II

GCM decades (relative to arbitrary start date) for which global average temperature changes are equivalent to years 2020 (0.53 °C) and 2050 (1.16 °C) in STUGE model of Wigley and Raper (1992)

	IPCC Decade 2 (STUGE 2020)	IPCC Decade 3 (STUGE 2050)
GFTR	18–27	36–45
HCTR	35–44	48–57
MPTR	24–33	49–58

and temperature records (the periods vary for the specific case studies as described below, but generally are of length 40–60 years). To further resolve the GCM transient response, three additional decades were formed by interpolating monthly precipitation, temperature and solar radiation changes from the GCM simulations between (a) the base climate and IPCC Decade 2 (one additional case), and (b) IPCC Decades 2 and 3 (2 additional cases). For the purposes of this study, these are designated equilibrium climate Decades 1–5. The IPCC Decade 2 and 3 forcings, however, must be regarded as approximate. Based on ten-year averages in the warming trajectory, they not only include error in estimation of the decadal means, but also, to some extent, incorporate the noise associated with short term (annual to subdecadal) variability, which can obscure the long term mean change signal. The linear interpolation of forcings for the intermediate decades (1, 3 and 4) likewise incorporates the same effects of shorter timescale variability in the endpoints from which they are interpolated. For these reasons, the climate scenario progressions should be understood simply as possible future scenarios for individual decades, each set of which has been arranged into a possible progression. The correspondence between our decades and IPCC decades is summarized in Table III. Note that our Decade 2 is IPCC Decade 2 and our Decade 5 is IPCC Decade 3.

In summary, rather than performing a true transient analysis, five steady-state analyses were performed for each GCM, where the five analyses tracked the transient nature of the climate forcing. In addition to the transient GCM scenarios, we tested a doubled-CO_2 scenario to provide a basis for comparison with the results of earlier studies (e.g., Smith and Tirpak, 1989) which generally were based on doubled-CO_2 scenarios. The GFDL doubled CO_2 scenario was taken from a set of GCM results archived by NCAR for use in the Country Studies Program (U.S. Country Studies Management Team, 1994). Unfortunately, the GFDL scenario is not directly comparable with the GFTR scenarios because our choice of doubled-CO_2 GCM runs was constrained to those GCM runs that were provided to NCAR

TABLE III

Summary of steady state simulations making up the quasi-transient analysis

Equilibrium climate decades	Correspondence to IPCC decades	Year correspondence[a]
0	IPCC ‘Decade 1’ (base case)	1990
1	Interpolation	2005
2	IPCC ‘Decade 2’	2020
3	Interpolation	2030
4	Interpolation	2040
5	IPCC ‘Decade 3’	2050

[a] Assuming, as per STUGE simulations, that Decade 2 is centered on year 2020, and Decade 3 is centered on year 2050.

by the various GCM modeling centers. As a result, the GFDL model resolution and other model options differed from those used in the IPCC transient scenarios. For instance, the transient scenarios used R15 resolution (about 7.5 by 4.5 degrees longitude by latitude) whereas the R30 resolution (3.75 by 2.25 degrees) was used in the doubled-CO_2 run. Therefore, while the GFDL doubled-CO_2 run can, for instance, be interpreted in comparison with other doubled-CO_2 evaluations performed with that set of model archives, it is difficult to interpret the results relative to the GFDL transient run prepared for IPCC.

4. Approach

To the extent possible, the assessment approach was the same for all six case studies. A standard experimental design, consisting of specific base case and hypothetical altered climate simulations and similar evaluation measures for all sites, was used to maintain consistency between the six parts of the study. Nevertheless, various intermediate steps, such as hydrologic and water resource system modeling and specific system operating objectives, differed slightly from site to site. The standard approach and site-specific variations are discussed in the remainder of this section.

A sequence of models was used to infer the water resources effects of each of the climate change scenarios. The first step was to downscale precipitation, temperature and solar radiation changes from each of the GCM scenarios to produce forcing sequences for hydrologic models of each of the river basins. The hydrologic models generated time series of streamflow, which in turn were the forcings to water resource management models (WRMMs) of each of the reservoir systems. Finally, the WRMMs simulated system performance for each scenario using similar sets of performance evaluation metrics. The models used for each case study are summarized in Table IV.

4.1. DOWNSCALING GCM SCENARIOS

The GCM downscaling method is identical to that used in the Sacramento-San Joaquin study (Lettenmaier and Gan, 1990) included in the EPA Reports to Congress (Smith and Tirpak, 1989). It simply adjusts historical observations of daily temperature maxima and minima by adding a fixed amount to the observed values, and multiplies historical observations of daily precipitation and solar radiation by a fixed amount. The adjustment factors for temperature, precipitation and solar radiation are the monthly average changes (from base case climate to altered climate) for the five quasi-equilibrium states sampled from the transient climate runs.

These monthly adjustments (for each steady-state 'decade') were interpolated from the gridded GCM output fields to specified locations required for hydrologic model inputs (i.e., grid-cell centers for the semi-distributed models of the Columbia, Missouri and ACF sites; or basin centroids for the Savannah, Boston and Tacoma studies). Tables Va and Vb summarize the basin-wide average temperature and precipitation adjustments used for each of the transient GCM scenarios.

Downscaling of the GCM simulations is necessary because GCMs' ability to reproduce observed precipitation and temperature at the regional scale (less than 10^7 km^2) is widely recognized as poor, and there is little agreement at this scale among GCMs as to the magnitude and direction of changes in precipitation. A partial discussion of this issue is given in IPCC (1996), Section 6.6.1. Detailed comparison of precipitation and temperature fields between the GCMs and observations are not available specifically for the regions we studied. For central North America (35–50° N, 85–105° W), however, the IPCC found that the best reproduction of observed precipitation among the three models was obtained by MPTR in winter and HCTR in summer, while the worst performance was for MPTR in summer and GFTR in winter. In the worst case, a bias of minus 70 percent (MPTR in winter), many times larger than the sensitivity of the estimated MPTR doubled CO_2 precipitation, was reported. For temperature in central North America, all three models underestimated current temperatures in winter (by 5, 3 and 5 °C for GFTR, MPTR and HCTR, respectively) and two out of three overestimated temperatures in summer (by 3 and 6 °C for GFTR and MPTR, respectively), while HCTR reproduced climatological temperatures with relatively accuracy. Better matches between observed and control run (current climate) values provide higher confidence in future climate projections, but, in general, the reliability of GCM-derived forcings at the regional scale must still be regarded as low. More detailed analyses of transient model run results for central North America are given in Cubasch et al. (1994), Whetton et al. (1996) and Kittel et al. (1996).

TABLE IV

Water Resources Management Model Summary

Models	Basins					
	Tacoma	Boston	Savannah R.	ACF basin	Missouri R.	Columbia R.
GCMs	GFTR, MPTR, HCTR, GFDL 2 $\times$ CO_2					
Hydrologic	NWSRFS snowmelt and soil moisture accounting				NWS snowmelt and VIC-2L	
WRMMs						
Type	Simulation (STELLA® II)	Simulation (STELLA® II)	Simulation (FORTRAN)	Simulation (STELLA® II)	Optimization (HEC-PRM)	Simulation (STELLA® II)
Reference	Karpack and Palmer (1992)	COE (1994)	by Water Resources Management, Inc.	Palmer et al. (1995)	COE (1991b)	Hamlet et al. (1997)
Years	60	60	59	52	39	59
Timestep	Weekly	Weekly	Weekly	Monthly	Monthly	Monthly
Demand/operating scenario sensitivity?	Yes	Yes	Yes	Yes	Yes	No
Primary uses						
M&I supply	X	X	X	X		
Water quality		X				
Instream flow	X	X		X	X	X
Flood control	X		X	X	X	X
Hydropower			X	X	X	X
Recreation			X	X	X	X
Navigation				X	X	X
Irrigation				X	X	X
Fish and wildlife			X		X	X

‘STELLA® II’ is the name of a commercial simulation software by High Performance Systems, Inc.

4.2. HYDROLOGIC MODELS

The application of hydrologic models depended on basin size. At all sites, the temperature-indexed National Weather Service River Forecast System (NWSRFS) snow model (Anderson, 1973) was used to estimate rain plus snow melt (when snow is not present, the snow model simply passes the precipitation through to a rainfall-runoff model). In the large basins – the Columbia, ACF and Missouri – the snow model output became input for the semi-distributed two layer variable infiltration capacity model (VIC-2L) described by Nijssen et al. (1997). In the smaller Boston, Tacoma and Savannah River basins, the lumped NWSRFS Sacramento soil moisture accounting model of Burnash et al. (1973) was used to simulate streamflow. Tables Vc and Vd summarize the basin-wide average annual percent changes in PET and streamflow for each of the transient GCM scenarios.

The use of different hydrologic models for different study sites is not likely to have much effect on the results, insofar as a calibration process (to current climate) was undertaken for each site. The most problematic aspect of the use of precipitation-runoff models for climate change assessment is the implicit assumption that parameter estimates obtained from historical data are applicable to alternative climates. As long as the differences between current and altered climate are modest compared to the observed interannual and interseasonal variability in the historical records of the atmospheric forcings, which is usually the case, this should not be a serious issue. Furthermore, for assessments that use the perturbation method of climate scenario development, changes are interpreted relative to a base case hydrological simulation using historical observed data. Because the altered climate scenarios are variations of the same input used in the base case hydrological model simulations, and hence should induce a positive correlation in the base case and altered climate simulation errors, differencing should result in errors in predicted effects that are smaller than the model verification error.

Regardless of which hydrologic model was used, calibration was first performed by examining observed time series of precipitation and temperature (for at least a ten-year period) and comparing observed and simulated streamflow. Model parameters were adjusted within physically plausible ranges so that the daily streamflow peaks, baseflow recession, monthly flow volumes and long term average flow volumes matched as closely as possible. The primary calibration parameters for the NWSRFS model were the moisture storage zones (5) and the recession constants (k_1 and k_2), and for the VIC-2L model were the moisture storage zones (2) and the infiltration parameters. Greater detail about model calibration is given in Lettenmaier et al. (1998a–f).

4.3. WATER RESOURCE MANAGEMENT MODELS (WRMMS)

The WRMMs take output from the hydrologic models (streamflow) and, in some cases, physical climate variables such as precipitation and temperature, which are used in the demand estimates. Given sequences of streamflow, the models predict the performance of the systems in terms of variables such as flows and storages, hydropower production, and the ability of the system to meet demands for water and to meet constraints such as minimum instream flows. The six WRMMs were adapted from existing models for each site. The WRMMs use longer time steps than the hydrologic models – either weekly (e.g., for Tacoma and Boston) or monthly.

The WRMMs used for the Tacoma, Boston, ACF and Columbia systems were detailed simulation models that track water through the reservoir system and include the effects of reservoir regulation through representation of the rule curves that are, at least nominally, used in practice. In each of these cases, the process of model development involved participation and review by water users, who insisted on demonstration of model validity. This was generally accomplished via replication of observed storage and flow levels given observed inflows, evaporation, withdrawals and other system parameters. The WRMM used in the Savannah River study was a FORTRAN-based simulation model which incorporated a routine that optimized power production given prescribed end-of-period releases. The model (developed by the South Carolina Division of Water Resources) incorporated current power production targets, reservoir rule curves and environmental flow constraints. The Missouri River system was modeled in HEC-PRM, a U.S. Army Corps of Engineers optimization package that maximizes reservoir system performance relative to operating objectives (such as power production) given a set of system constraints (e.g., economic penalty functions for flood control, power releases or agricultural withdrawals). The model and modeling framework (HEC-PRM) are described in COE (1991a, b). Based on validation runs, the optimization model reproduced observed storages and discharges somewhat less faithfully than did the simulation models.

4.4. SYSTEM PERFORMANCE METRICS

A standard approach for evaluating system performance under the climate scenarios was taken for all of the case studies. The intent of the studies was to provide results in terms that might be useful to system managers and decision-makers. Two types of system performance metrics were used: threshold-type metrics and absolute metrics. Absolute metrics are simple measurements of system states or outputs, such as reservoir elevations, flow levels, electricity generation (e.g., in MWh) or its economic value. Threshold metrics are defined relative to a performance target, such as a minimum instream flow level, and measure success or failure relative to the target. The threshold metrics were three indices proposed by Hashimoto et al. (1982) – reliability, resiliency and vulnerability. Reliability is defined as the percentage of time that the system operates without failure (the number of successful periods divided by the total number of simulation periods). Resiliency is a unitless coefficient relating to the ability of the system to recover from a failure, defined as the probability that a shortfall event lasts only a single period. Vulnerability

TABLE Va

Average annual temperature changes for the transient and 2 × CO_2 simulations

Case study	Decade 1	Decade 2	Decade 3	Decade 4	Decade 5	2 × CO_2
	Average annual temperature change (°C) for GFTR, HCTR, MPTR respectively					
Tacoma	0.8, 0.4, 0.3	1.6, 0.8, 0.5	2.2, 1.4, 0.9	2.7, 1.9, 1.4	3.3, 2.5, 1.8	3.5
Boston	1.8, 1.9, 1.2	1.8, 3.8, 3.4	2.5, 4.2, 2.6	3.3, 4.7, 2.8	4.0, 5.1, 3.0	5.9
Savannah	1.1, 1.3, 0.8	2.1, 2.5, 1.5	2.5, 2.7, 1.7	3.0, 2.9, 1.8	3.4, 3.1, 2.0	5.9
ACF	0.9, 1.1, 1.0	1.8, 2.1, 2.0	2.2, 2.4, 2.1	2.7, 2.6, 2.3	3.1, 2.9, 2.4	3.8
Missouri	1.0, 1.5, 1.1	1.9, 3.0, 2.2	2.5, 3.1, 2.5	3.0, 3.3, 2.9	3.6, 3.4, 3.2	4.4
Columbia	0.9, 0.8, 0.6	1.8, 1.5, 1.2	2.3, 2.0, 1.7	2.9, 2.5, 2.1	3.4, 3.0, 2.6	3.9

is defined as the average severity (magnitude) of failures. Several absolute metrics and the three threshold metrics were calculated to characterize system performance for each system operating objective, so as to give a multi-faceted, comprehensive measurement of the system's performance for each objective. Because the multiple metrics used for each site are too numerous to present here, a single representative metric for each operating objective, for each system, is displayed in the results summaries of Figures 3–8.

4.5. Demand Growth and Alternative Operational Scenarios

Where possible, the effects of climate change were compared with the effects of non-climate related changes that could plausibly take place over the same period as the climate changes measured in these assessments (1990–2050). These non-climate changes might arise due to predicted demand changes (for instance, due to population growth) or shifts in other factors affecting system operation. For example, the current debate over the importance of hydropower relative to fisheries protection on the Columbia River could lead to a prioritization of instream flow augmentation releases over releases for hydropower, a significant change on which one of the alternative operational scenarios for that system was based. Similarly, for the Savannah River and ACF basin study sites, alternative operational scenarios were created to examine such changes as discontinuation of navigation support, increased instream flow requirements and increased hydropower demand. For largely municipal supply systems, such as Boston and Tacoma, the effects of demand growth were examined in detail. Table VI describes the demand growth/operational scenarios by site.

TABLE Vb

Average annual precipitation changes for the transient and 2 × CO_2 simulations

Average annual precipitation change (%) for GFTR, HCTR, MPTR, respectively						
Case study	Decade 1	Decade 2	Decade 3	Decade 4	Decade 5	2 × CO_2
Tacoma	6, 2, –1	11, 3, –2	10, 3, –2	8, 2, –2	7, 2, –2	24
Boston	3, 6, –2	5, 12, –4	7, 11, –5	9, 10, –5	10, 9, –6	15
Savannah	2, 4, 2	5, 8, 3	9, 9, 3	13, 9, 3	16, 9, 3	13
ACF	2, 5, 2	3, 9, 4	7, 7, 3	11, 5, 3	14, 4, 3	–4
Missouri	3, –5, –11	6, –10, –22	7, –5, –22	8, –1, –23	8, 3, –23	9
Columbia	6, –1, –5	11, –2, –11	9, –1, –10	7, –1, –9	5, 0, –9	25

TABLE Vc

Average annual PET changes for the transient and 2 × CO_2 simulations

Average annual PET changes (%) for GFTR, HCTR and MPTR, respectively						
Case study	Decade 1	Decade 2	Decade 3	Decade 4	Decade 5	2 × CO_2
Tacoma	4, 0, 0	10, 0, 1	14, 4, 4	17, 8, 8	18, 14, 12	20
Boston	1, 6, 6	4, 10, 10	7, 12, 13	9, 13, 13	10, 13, 13	19
Savannah	1, 3, 2	7, 9, 3	10, 10, 4	11, 11, 6	11, 11, 6	18
ACF	4, 4, 3	7, 7, 7	10, 9, 8	12, 11, 9	14, 12, 10	18
Missouri	7, 11, 7	14, 23, 16	18, 24, 18	22, 25, 21	19, 24, 19	32
Columbia	6, 5, 4	12, 11, 8	16, 14, 11	21, 18, 15	27, 21, 18	28

TABLE Vd

Average annual system inflow changes for the transient and 2 × CO_2 simulations

Average runoff changes (%) for GFTR, HCTR and MPTR, respectively						
Case study	Decade 1	Decade 2	Decade 3	Decade 4	Decade 5	2 × CO_2
Tacoma	10, 7, 2	19, 11, 4	17, 10, 4	16, 10, 4	15, 9, 4	33
Boston	4, 9, –3	7, 19, –3	9, 16, –3	12, 14, –3	15, 13, –1	17
Savannah	5, 3, –3	7, 5, –4	11, 3, –4	17, 3, –5	23, 3, –4	7
ACF	4, 2, –5	11, 8, –5	15, 3, –7	20, –1, –7	25, –3, –6	–21
Missouri	3, –26, –20	6, –34, –36	1, –31, –35	–3, –27, –35	–6, –24, –34	2
Columbia	6, –2, 8	11, –3, –15	6, –4, –16	2, –6, –16	–1, –6, –16	23

TABLE VI

Description of alternative demand/operational scenarios

Case study	Alternative demand or operational scenarios Scenario
Tacoma	Detailed water demand forecasts were supplied by the Tacoma Water Department. The forecasts account, on a sectoral basis, for regional growth and system capacity improvements. The two demand forecasts used were: • medium 2020 water demand growth (*Scenario a*) • medium 2050 water demand growth (*Scenario b*)
Boston	• High M&I demand growth scenario based on the (pre-conservation) average water demand level of 1987 (325 mgd) (*Scenario a*) • Medium M&I demand growth scenario based on the (pre-conservation) average water demand level of 1992 (285 mgd) (*Scenario b*)
Savannah	• A 2050 demand/operations scenario (*Scenario a*) was based on: 1. population increases of 20 percent from 1990 levels (based on extrapolations of 2030 and 2040 census figures) 2. the maximum legal reallocation for water supply from the COE reservoirs (based on guidelines of the Federal Water Supply Act of 1958) 3. a large incremental change in the required minimum flow at Augusta, GA (from the present minimum of 3600 cfs to nearly 4600 cfs to support a new raw water pumping facility in the Augusta area) • A 2020 demand scenario was formed using 2020 population forecasts and interpolating elements (b) and (c) of the 2050 scenario between present and 2020 (*Scenario b*)
ACF	One demand growth and two alternative operations scenarios were evaluated: • a detailed, multi-sectoral 2050 (with 1990 as the backcast year) demand projection which assumed 'reasonable' conservation measures for 2050 (*Scenario a*) • a scenario in which releases supporting navigation, an operating objective of possibly minor value to the system, are discontinued, allowing use of water for other purposes such as hydropower and water supply (*Scenario b*) • a scenario in which the four-hour daily peaking power target was prioritized, such that cutbacks to 2 hours during low flow periods are not made (*Scenario c*)
Missouri	No demand scenarios were calculated
Columbia	• instream flow targets for fish habitat protection are supported by releases from all the major storage reservoirs, giving fish protection a higher priority in system operations (*Scenario a)* • recreation-prioritization scenario: supplemental hydropower releases that cause deviations from assured reservoir refill curve are not allowed, ensuring that reservoir pools are full in summer (*Scenario b*)

5. Results

Tables Va–d showed average annual changes in temperature, precipitation, potential evapotranspiration (PET) and streamflow (system inflow), respectively, associated with each decade and GCM, for the six case studies. Figures 3 through 8 summarize the results of these changes for system performance, categorized by system operating objective. A table entry or figure annotation of 'NC' indicates that the statistic was not calculated for a particular case study. In one case (flooding on the Savannah River), results were interpolated to estimate results for decades for which the metric had not been calculated.

5.1. CLIMATIC CHANGES

Table Va shows that the temperature changes from each case study and for each GCM differ appreciably from the global average warming predicted for Decades 2 and 5 (0.53 °C and 1.16 °C, respectively). Notably, for the Savannah River, ACF basin and Missouri River case studies, most of the Decade 5 increase in warming would occur by Decade 2, in contrast to the steadier trend of the global average. Temperatures would increase between each decade (from the base case through Decade 5) and in all but one instance, the increases would be larger than the predicted global averages. The range of temperature increases in Decade 2 were from 0.5 °C for MPTR, for Tacoma, to 3.8 °C for HCTR for Boston. The $2 \times CO_2$ scenario, in every case, showed larger temperature increases than any of the transient climate scenarios; the largest increase, 5.9 °C, occurred for the Boston and Savannah River sites.

The precipitation changes, shown in Table Vb, were less consistent from site to site than the temperature changes. At most sites, the GFTR scenarios produced the largest increases in precipitation, especially by Decade 5. For Tacoma and the Columbia River, the increases leveled off or grew smaller after Decade 2, whereas for the other sites the increases progressed by decade. The MPTR scenarios, in all sites except for the ACF basin and Columbia River, had the smallest increases or largest decreases in each decade. In every case, these changes leveled off or reversed direction after Decade 2. Changes for the HCTR scenarios behaved similarly. In magnitude, HCTR precipitation changes tended to fall between the GFTR and MPTR changes for the Tacoma, Columbia and Missouri River sites, but could be larger than the GFTR or smaller than the MPTR scenario precipitation in individual scenarios for the other sites. Precipitation changes for the $2 \times CO_2$ scenarios for the Tacoma and Boston systems were larger than for the transient scenarios, whereas for the Savannah and Missouri River sites, the $2 \times CO_2$ scenario change was about equal to the GFTR scenario changes in later decades. In the ACF basin, the $2 \times CO_2$ scenario produced precipitation decreases, in contrast to all of the ACF basin transient scenarios. The Columbia River $2 \times CO_2$ scenario's large (25 percent) increase in precipitation also contrasted with the transient scenarios.

5.2. HYDROLOGIC CHANGES

Table Vc shows changes in PET. Mostly driven by temperature changes, PET changes were positive for every scenario at every site. The largest average annual increases for the transient scenarios were 27 and 24 percent for the Columbia (GFTR) and Missouri (HCTR) River basins, respectively, in Decade 5. The smallest Decade 5 increase was 6 percent, for Savannah (MPTR). The $2 \times CO_2$ scenarios had slightly higher PET than the highest Decade 5 scenario for every site.

In general, changes in PET were consistent with temperature changes in direction, timing (i.e., relative interdecadal changes, such as the majority of the warming for HCTR occurring by Decade 2) and magnitude. Precipitation changes also appeared to moderate PET changes, however. Exceptions to the general relationship between temperature and PET also resulted from variations in the seasonal distribution of temperature changes among the climate change scenarios (increased temperatures in the summer months contribute disproportionately to annual changes in PET); hence comparison of annual temperature changes with annual PET could be misleading. For example, although the temperature changes for the MPTR scenarios in the Boston study were little over half those of the HCTR scenarios, the PET increases for the two sets of scenarios were very similar.

Table Vd shows changes in system inflows (streamflow) for each case study. For most of the case studies, there is little agreement between the GCM scenarios in terms of magnitude or direction. In some series of scenarios – e.g., the Savannah River (GFTR) – increases or decreases progressed monotonically from Decade 1 through Decade 5. In other cases – the Missouri River (all GCMs), for Tacoma (GFTR and HCTR), Boston (HCTR), the Savannah River (HCTR), the ACF basin (HCTR) and the Columbia River (GFTR) – changes in streamflow in Decade 2 were reversed in Decades 3, 4 and 5. These reversals generally can be traced to opposing hydrologic effects of increased temperature (which tends to result in streamflow decreases) and increased precipitation (leads to increased streamflow). For several sites, such as Tacoma, for at least one GCM series, the largest runoff changes occurred between the base case and Decade 2, with little to no further change between Decade 2 and Decade 5. Annual average changes ranged from a 25 percent increase in the ACF basin (GFTR) to a 34 percent decrease for the Missouri River (MPTR) in Decade 5.

5.3. SYSTEM PERFORMANCE EFFECTS

Figures 3 through 8 show system performance results categorized by objective (hydropower, M&I and agricultural supply, flooding, recreation, instream flow augmentation and navigation, respectively) for all sites, using the metrics listed in the figures. Although a suite of metrics was used in each of the studies to characterize each system's performance with respect to each major operating objective, we focus here on a single metric for each site and objective that appeared to represent adequately the system's sensitivity to the climate change scenarios.

Where possible, percent changes in absolute measures of system state or output (such as energy generation or recreation-related income) are shown in Figures 3–8. Otherwise, the net changes in the system's reliability in satisfying a prescribed threshold of performance (such as meeting contractual monthly energy targets) are shown. Note that not all operating objectives are relevant in each case study. Also shown in Figures 3–8 are the results of the 'demand/operational scenarios' discussed in Section 4.5 (and detailed in Table VI).

Figure 3 shows that power operations would be most sensitive to climate change for the Missouri River, where both the HCTR and MPTR scenarios would result in declines (in reliability of meeting monthly energy targets) of between 15 and 35%. Small increases in reliability were found for GFTR in Decades 1 through 3 and for the $2 \times CO_2$ scenario. For the Columbia River, reliability of firm energy showed progressive declines in the transient scenarios, while the $2 \times CO_2$ scenario had only a negligible decrease. Changes for the two alternative operational scenarios were on the order of those for the most severe climate scenarios. For the Savannah River, two out of the three GCMs led to increases in power production of between 3 and 25 percent, while the MPTR scenarios had slight declines. The $2 \times CO_2$ scenario led to increases in the range of the GFTR Decade 2 and 3 scenarios, while demand growth effects lie at the lower end, in magnitude, of the range of all of the climate change effects. For the ACF basin, the effects for GFTR and MPTR were generally in the same direction as those for the Savannah River, but smaller. The largest changes (declines) were for the HCTR scenarios and the $2 \times CO_2$ scenario. The system's sensitivity to demand/operational changes was comparable to the sensitivity to climate change effects. It should be noted that the Columbia River system has by far the largest installed hydropower generating capacity (18,500 MW) of the systems studied; by comparison, the installed generating capacity of the Missouri River system, the Savannah River system, the ACF basin are 6,770, 1,990 and 560 MW, respectively.

Figure 4 shows that M&I supply would be fairly robust to climate change for the smaller systems, while moderate declines in performance would occur for the Missouri and Columbia River systems. It should be noted, however, that for the Missouri River, M&I supply accounts for a relatively minor portion of system water allocation, whereas for the smaller Boston and Tacoma systems, M&I supply is a first priority use (the Tacoma system also prioritizes flood control). Despite their relative insensitivity to climate changes, the Boston and Tacoma systems are highly sensitive to demand growth: 3 and 39 percent declines in reliability would result from returns to (the higher than present) 1992 and 1987 levels of demand for Boston; and for Tacoma, 3 and 20 percent declines in reliability would result from demands levels current forecasted for 2020 and 2050. For the Columbia River system, where M&I use is trivial, agricultural withdrawals (measured by Snake River irrigation) showed minor to moderate ($\sim$15 percent) responses to climate change, while the operational scenarios system had no effect on withdrawals. In

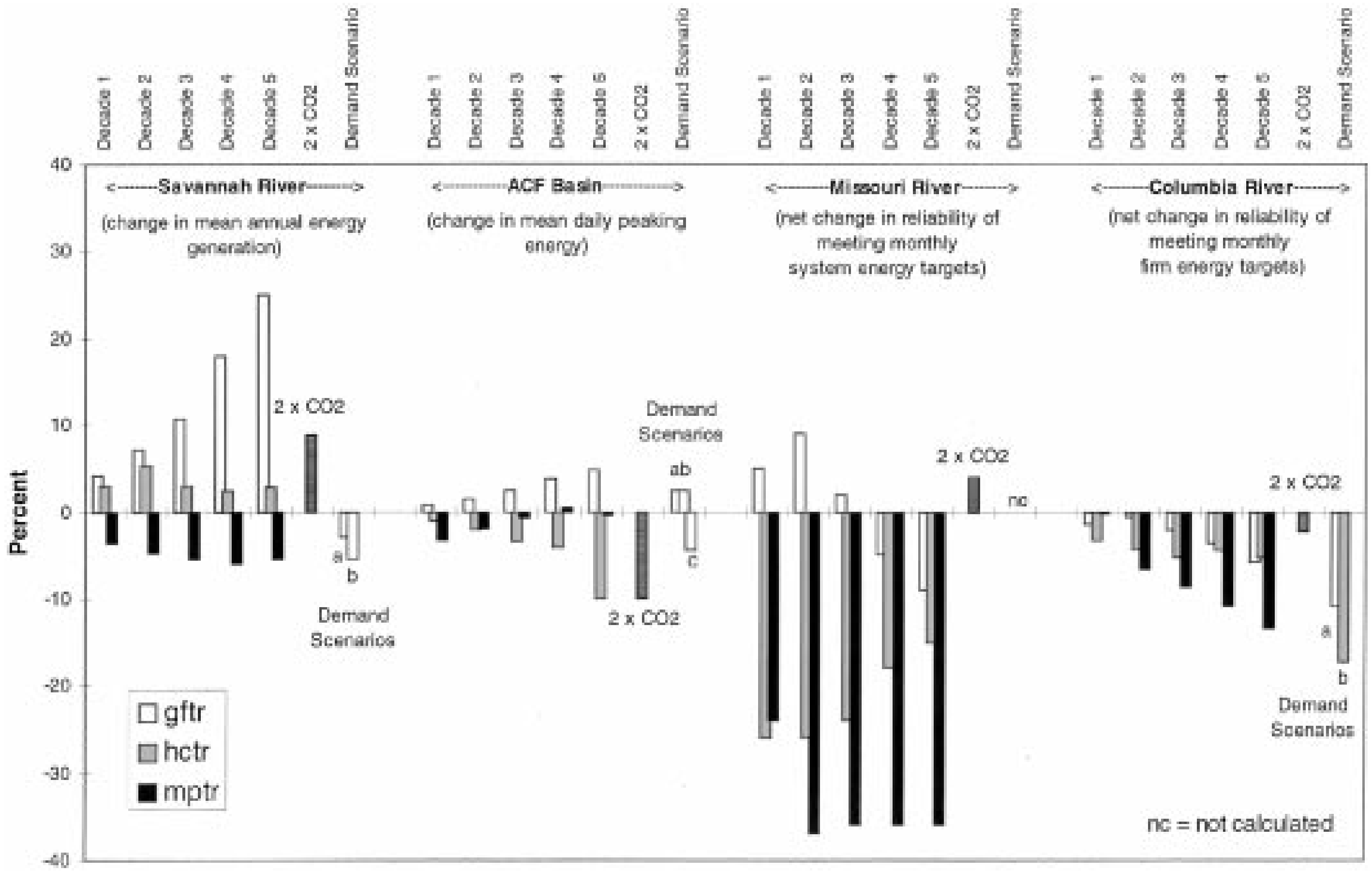

Figure 3. Climate and demand change effects on hydropower for each system as measured by either percentage changes in an absolute measure or net changes in a hydropower-related reliability metric (see Table VI for description of demand scenarios).

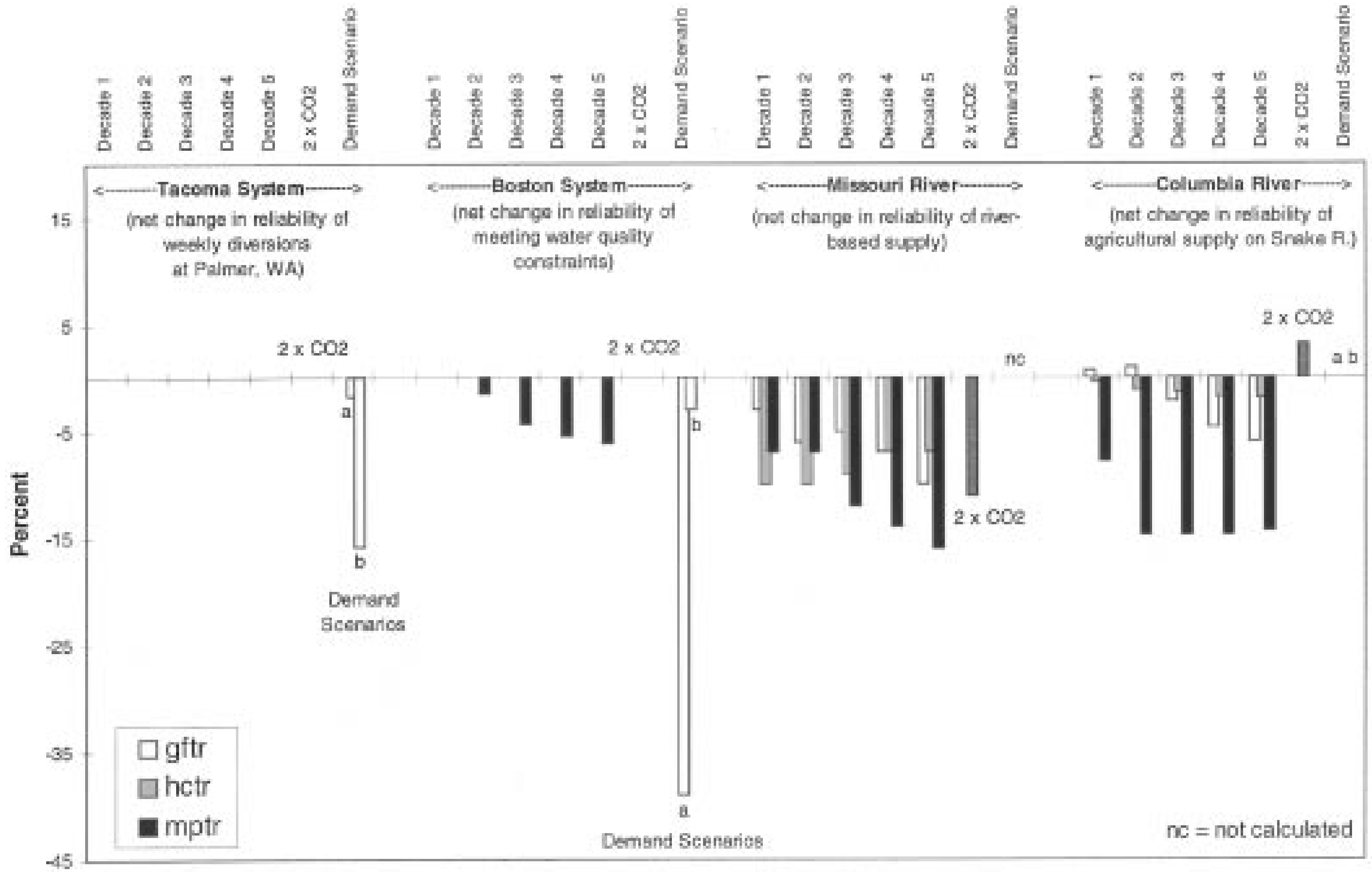

Figure 4. Climate and demand change effects on M&I or agricultural supply for each system as measured by either percentage changes in an absolute measure or net changes in a M&I supply-related reliability metric (see Table VI for description of demand scenarios).

the Savannah River and ACF basin systems (not shown), M&I supply performance was insensitive to the climate and demand/operational changes evaluated here.

As shown in Figure 5, climate change would cause flood risk to increase for several of the climate change scenarios, at all of the sites except for the Columbia River basin. For Tacoma and the Savannah River, flooding effects increased substantially and progressively for all scenarios. For the ACF basin, substantial changes in flood risk occurred for the transient scenarios, but the changes varied in direction for the different climate scenarios. For the Columbia River system, flood risk changed most (decreased) for the $2 \times CO_2$ scenario. For the Missouri River, flooding effects increased for all scenarios, but to a smaller degree than at other sites. For the Tacoma and ACF River systems, the $2 \times CO_2$ scenario also led to changes much larger than for the transient scenarios, in various directions. In comparison to the climate scenarios, the demand growth/operational changes had little or no effect on flooding. Note that due to the long timesteps (week or month) of the WRMMs, the estimation of flood related effects is at best approximate; hence, the metrics shown here are more qualitative than quantitative.

Figure 6 summarizes the results for recreation-related effects. For the Savannah site, climate change effects led to increases in recreation-related regional income, but were smaller than the effects of population (based on year 2020 and 2050 population projections). For the ACF basin, results were conflicting for both the climate change scenarios and the alternative operational scenarios, but indicate that the climate change effects, while significant, would be smaller. The $2 \times CO_2$ scenario for the ACF basin was significantly worse than the transient scenarios. For the Missouri River system, climate change had little effect on recreational uses, while the Columbia River experienced considerable (10–50 percent) declines in recreation-level reservoir elevation reliability for all of the transient scenarios, worsening over time. The fishery preservation operational scenario affected recreation to about the same degree as climate change, while the recreational alternative improved it only slightly.

Figure 7 shows the sensitivity of instream flow requirements for the Tacoma, Savannah River and Columbia River systems. For all three systems, effects of climate change would be on the order of the effects of demand/operational changes: the largest change in instream flow reliability due to climate change was just over 10% (a decline) from the base case. For all three systems, the largest declines occurred for the MPTR scenarios and the only increases occurred for the GFTR scenarios. The $2 \times CO_2$ scenarios led to smaller effects in each case than the later decades of the transient scenarios. For both the Tacoma and Savannah River systems, demand/operations changes would be on the order of the results for the Decade 5 scenarios. For the Columbia River system, however, the fishery protection scenario significantly improved the reliability of instream flow, while the recreation pool protection scenario had little effect.

As shown in Figure 8, the influence of climate change on navigation for three case studies varies. For the ACF basin, the transient scenarios caused slight changes

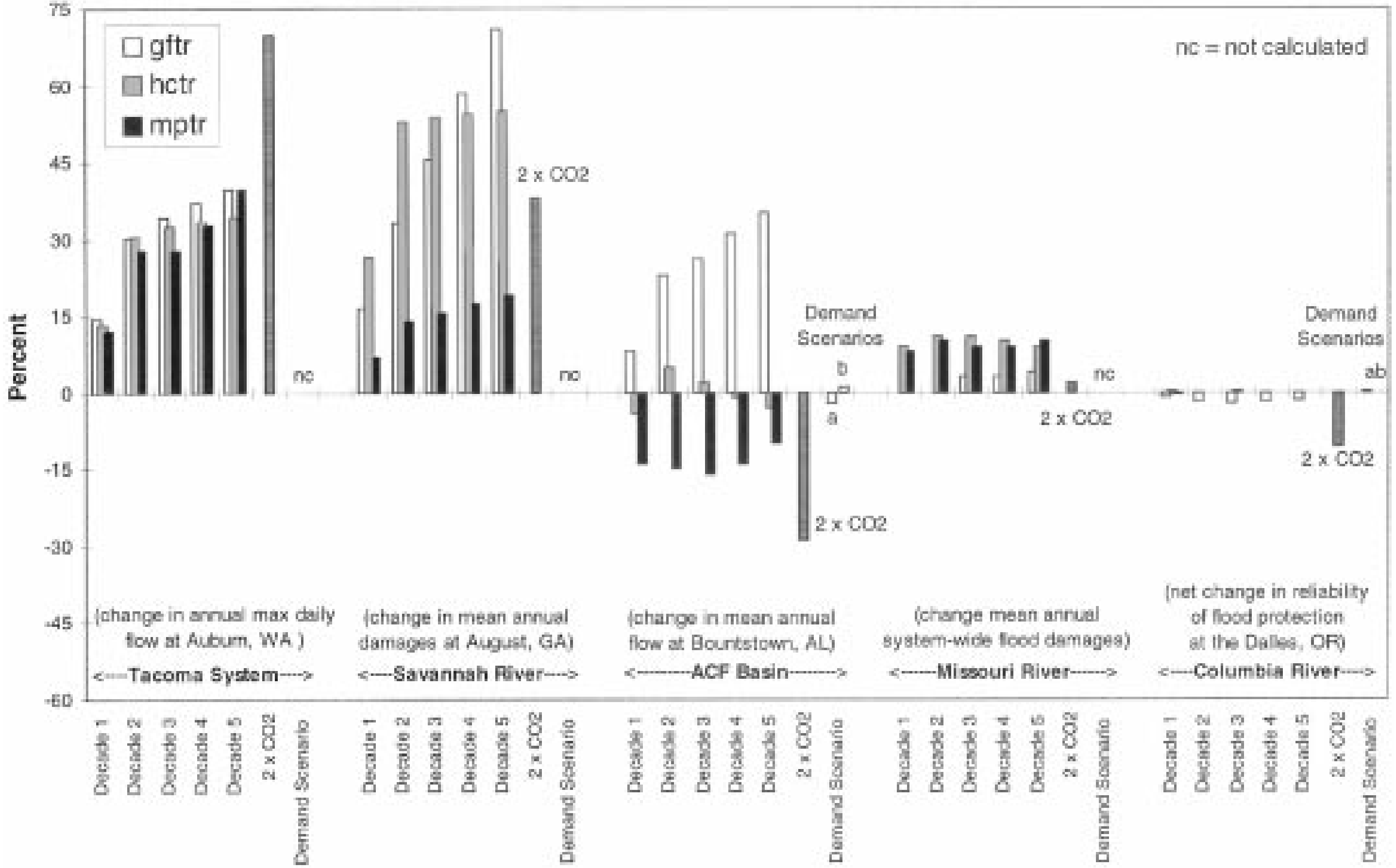

Figure 5. Climate and demand change effects on flooding for each system as measured by either percentage changes in an absolute measure or net changes in a flooding-related reliability metric (see Table VI for description of demand scenarios). Decades 1, 3 and 4 for the Savannah River basin are interpolated.

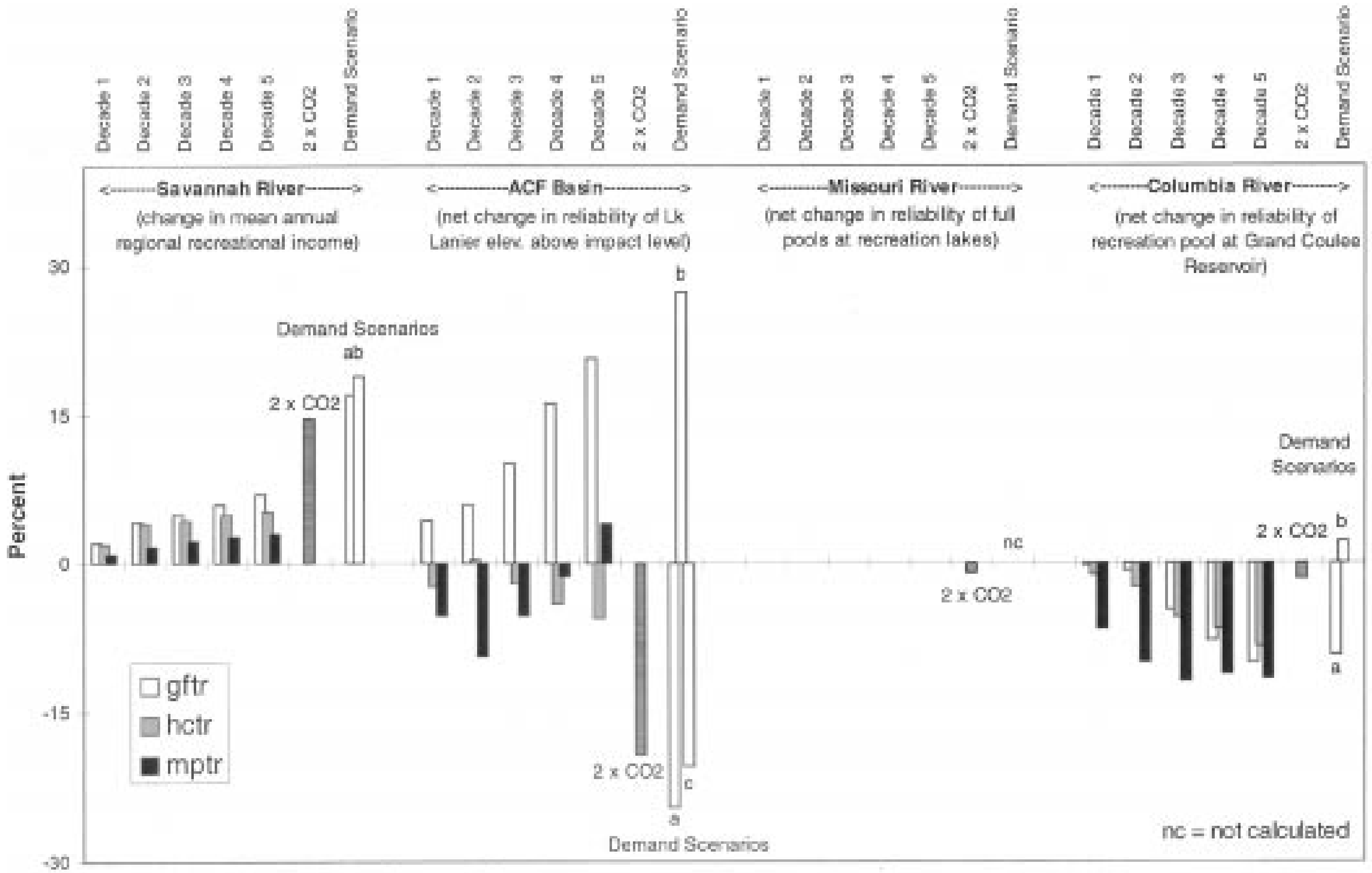

Figure 6. Climate and demand change effects on recreation for each system as measured by either percentage changes in an absolute measure or net changes in a recreation-related reliability metric (see Table VI for description of demand scenarios).

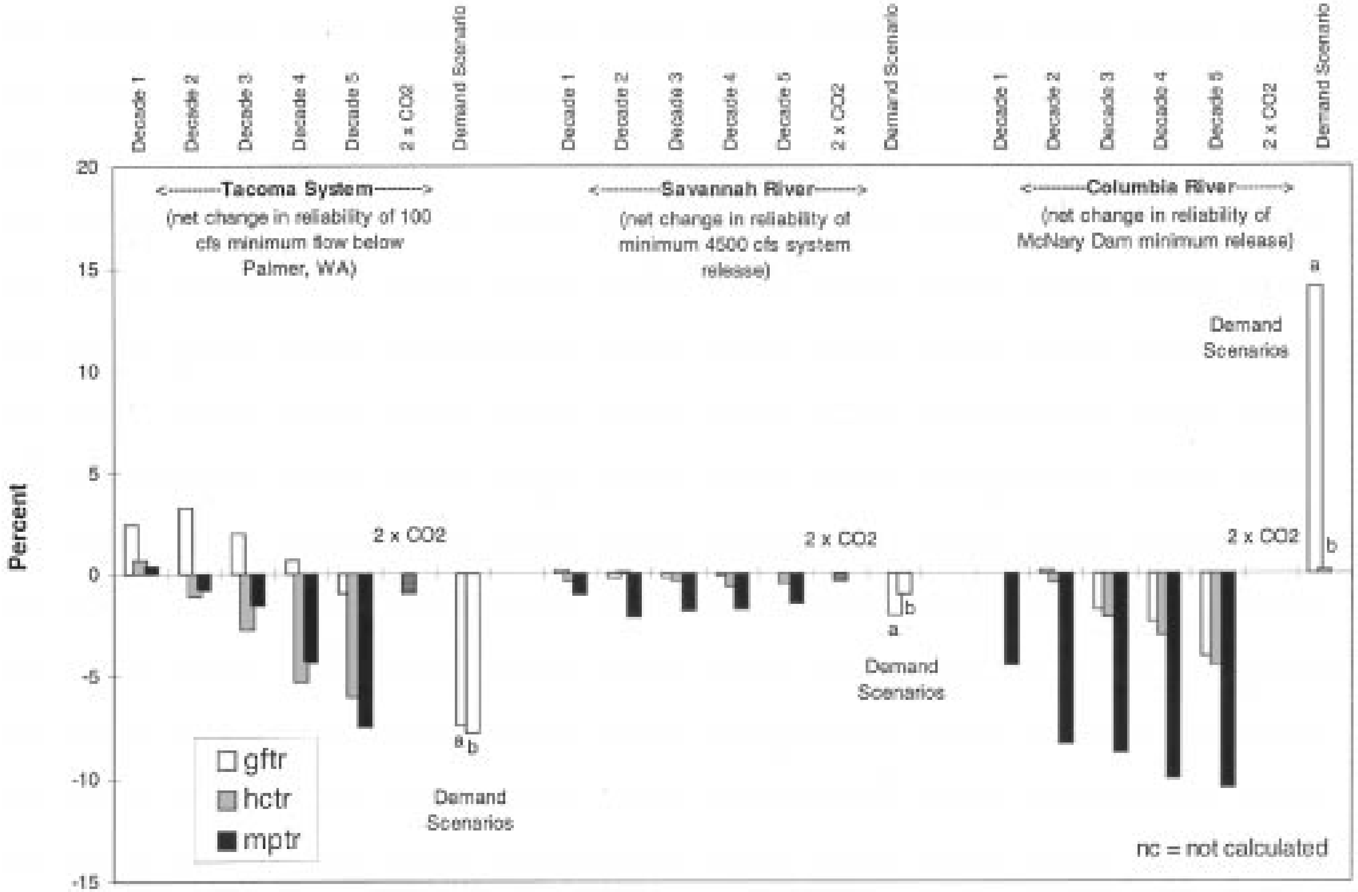

Figure 7. Climate and demand change effects on instream flows for each system as measured by either percentage changes in an absolute measure or net changes in a instream flow-related reliability metric (see Table VI for description of demand scenarios).

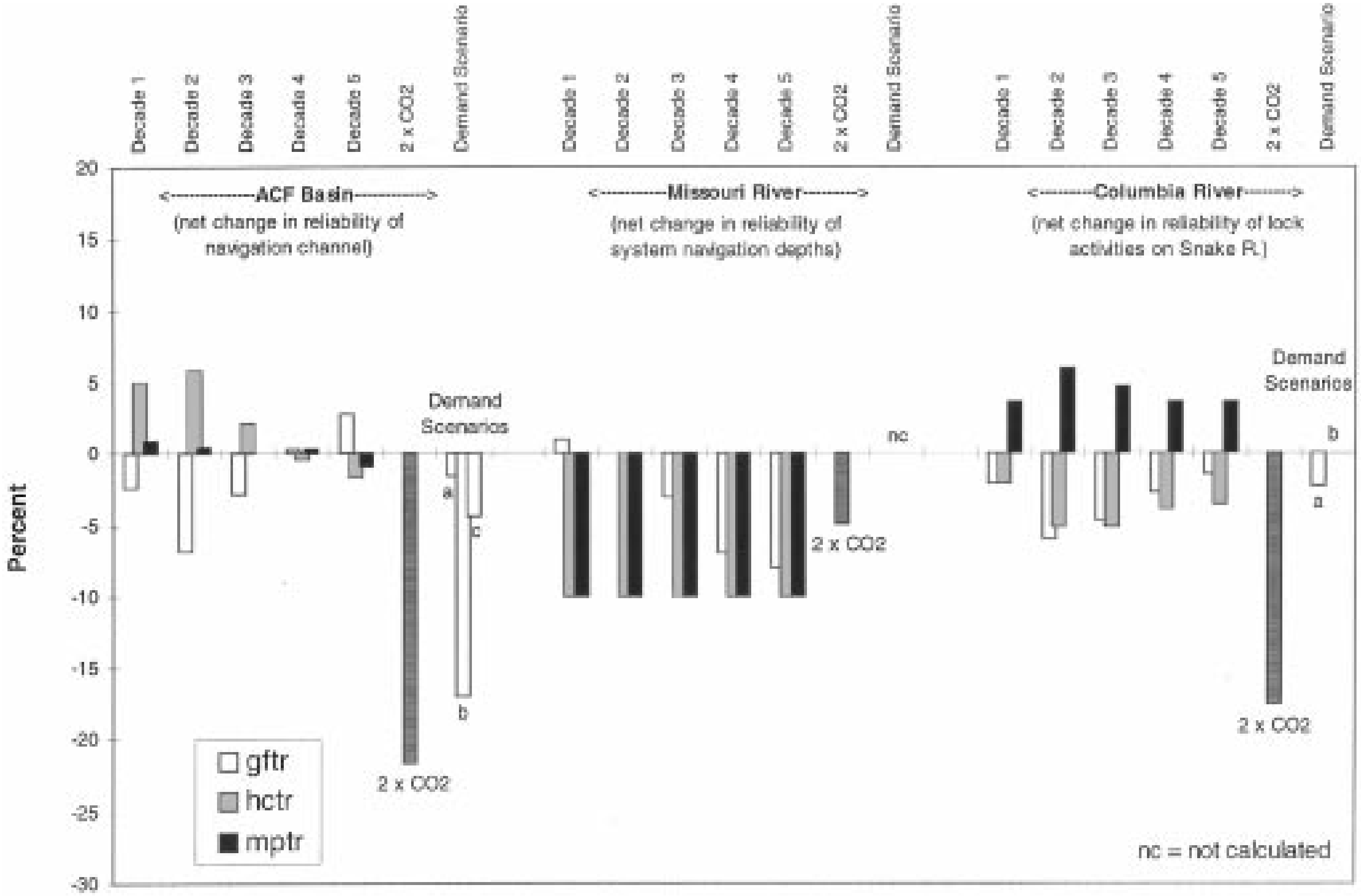

Figure 8. Climate and demand change effects on navigation for each system as measured by percentage changes in absolute performance measures or net changes in navigation-related reliability metrics (see Table VI for description of demand scenarios).

in the reliabilities of maintaining sufficient channel depths, while the $2 \times CO_2$ scenario and one operational change scenario (cessation of navigation support) caused larger declines in reliability. Navigation in the Columbia River system is represented by the reliability of lock operations on the Snake River. The $2 \times CO_2$ scenario showed a large decrease in this reliability, while for the transient scenarios, changes in reliability were smaller, peaked in Decade 2, and varied in direction between the GCM series. For the Missouri River, where the base case reliability of meeting system-wide navigation targets was only 10 percent, the GFTR Decade 1 scenario increased by 1 percent before decreasing almost to zero, which was the reliability for all of the MPTR and HCTR scenarios. The $2 \times CO_2$ scenario showed a smaller decrease of 5 percent.

6. Interpretation

6.1. TACOMA SYSTEM

Streamflow changes (Table Vd), in contrast to PET changes, were consistent with changes in precipitation, although these were influenced secondarily by changes in PET and temperature. Temperature changes were important because the hydrograph of the major component of system inflows (which are derived from the Cascade Mountain headwaters) exhibits a strong spring snowmelt signal that is progressively shifted earlier in the year, toward winter, by the increasing temperatures of the scenarios. In progressive decades, a smaller portion of the annual precipitation falls as snow, causing slightly increased runoff magnitudes that compound the overall changes in annual precipitation volume.

These two effects of climate change on runoff – changes in magnitude and seasonality – were the primary factors affecting system performance. Increases in flooding (Figure 5) reflected an increase in both the average magnitude of runoff and in the variability of the runoff scenario. M&I supply reliability (Figure 4), which is 100 percent for the base case, was unaffected by increases in runoff, despite increases in base water demand as a results of temperature increases. In all cases, M&I supply was protected by legal priority from even large declines in system inflows. Instream flow requirements (Figure 7), however, were met less frequently despite the overall runoff increases due to the shift in seasonality of runoff (unfortunately, this dynamic cannot be seen from the annual summary of statistics presented in Section 5; greater detail is given in Lettenmaier et al. (1998a)). HAH reservoir refills in the spring, too late to capture winter runoff; thus for the later decades, HAH does not always refill and has difficulty augmenting flows during the drawdown period in autumn, when instream flow requirements are highest.

The demand growth scenarios were based on medium M&I use forecasts for 2020 and 2050. In contrast to climate change effects, this growth in demand greatly degraded the reliability in M&I performance and caused a comparable decline in the reliability of meeting instream flow requirements (because the priority M&I demand leaves less water in the Green River). The effects of demand changes on flood control operations were not measured.

6.2. BOSTON SYSTEM

As with the Tacoma system, changes in runoff for the Boston system (Table Vd) were influenced mainly by precipitation changes and changes in PET. GFTR runoff increased progressively, MPTR runoff diminished as precipitation declines were exacerbated by PET increases, and the initial HCTR increases in runoff were in the later decades slightly eroded by weaker precipitation increases relative to PET increases. Although the Boston system inflow hydrograph has a snowmelt component, it is less significant than for Tacoma. For this reason, the sensitivity of runoff to temperature changes for the Boston site acted primarily through changes in PET.

For the Boston system, runoff changes coupled with climate-driven changes in demand, estimated via the IWR-Main model (PMCL, 1994), were the primary factors affecting system performance. M&I supply reliability (Figure 4), which is 100 percent for the base case, was obviously unaffected by the increases in runoff associated with the GFTR, HCTR and $2 \times CO_2$ scenarios. For the MPTR scenarios, however, decreasing runoff compounded by increasing demand (due mainly to increasing temperature) led to slight declines in water supply reliability. The vulnerability of the system to demand increases is underscored by severe degradation of supply reliability in response to the demand growth scenarios (base demands equivalent to 1987 and 1990 levels). Because the Boston system is used primarily for water supply, climate change and demand growth effects on other aspects of system performance were not measured.

6.3. SAVANNAH RIVER SYSTEM

Changes in runoff (Table Vd) for the Savannah River basin reflected mainly precipitation changes, and to a lesser extent, changes in PET. For example, runoff in the HCTR scenarios increases through Decade 2 but decreases thereafter, perhaps as a result of the interaction between the initial increase (in Decades 1–3) and leveling off (Decades 4–5) in precipitation, and the continuing increase in PET. Likewise, the small decreases in runoff for the MPTR scenarios probably derived from combination of modest increases in precipitation and greater increases in PET.

For the Savannah system, the primary factor affecting system performance in most categories was runoff changes – both magnitude and variability. For all scenarios, runoff variability increased progressively and significantly as compared to the base case. Hence, while not all scenarios had mean runoff increases, all scenarios did have progressively increasing flood damages (Figure 5). Changes in power production (Figure 3) were consistent with system inflow changes, as were effects on instream flow reliability (Figure 7), although the priority of power production among operating objectives prevented gains in instream flow reliability that might otherwise have been possible given the increased runoff of the GFTR and HCTR scenarios. Due to the large amount of storage in the basin relative to withdrawal or non-power release demands, M&I supply reliability (Figure 4) was insensitive to the changes in runoff associated with the climate scenarios. Reservoir pools were barely affected by the modest changes in runoff of the climate change scenarios. Finally, recreation performance (Figure 6), measured in terms of recreation-related regional income, increased for all of the scenarios in proportion to increases in temperature, which spurred recreation demand (visitation).

The two demand growth scenarios, based on projected increases in population, withdrawals and system release requirements, had the general effects of removing water from the system while also constraining its releases. Hence, power production declined and instream flow releases were curtailed, both to an extent comparable to the MPTR climate change effects. Recreation performance increased as a result of increased population growth in the region. Flooding was mostly unaffected because, on average, reservoir pools did not drop much due to the greater withdrawals and the variability of inflows was unchanged by the demand scenarios. In contrast to the Tacoma and Boston systems, the demand scenarios for the Savannah River system generally led to effects that were smaller or comparable in size to the climate change effects.

6.4. ACF BASIN SYSTEM

The relatively large increases in runoff in the GFTR scenarios and in the early HCTR decades can be attributed to precipitation increases. For the MPTR and HCTR scenarios, declining runoff in later decades resulted from faltering increases in precipitation coupled with continuing increases in PET. In the $2 \times CO_2$ scenario, the notably large decrease in runoff resulted from a minor decrease in precipitation combined with a large increase in PET.

There is relatively little consistency among climate scenarios as to the implications of climate change for the ACF system. System performance changes can largely be explained by the average changes in inflow, relative to the base case, that characterize each climate scenario. Effects on navigation (Figure 8) and flooding (Figure 5) metrics are related to average changes in inflows for the *entire* basin because measurement of effects on these objectives occurs downstream of all system inflow points. In contrast, effects on recreation (Figure 6), which depends on full reservoirs, on power generation (Figure 3), which is proportional to flow and reservoir elevation, and on water supply (Figure 4) are determined by average changes in *upper* basin inflows, which constitute most of the system storage inputs. Upper basin inflow changes differ somewhat from changes in total system inflow. For the ACF River basin, different GCMs lead to various estimations of hydrology (Table Vd) under climate change, and the water resources management implications for the GCMs vary accordingly.

M&I supply, unlike other system objectives, was insensitive to differences in the climate scenarios. Under current operations, M&I supply has by default the highest priority of all system objectives, so unlike other objectives, water supply is not explicitly curtailed if reservoirs are drawn down. Thus water supply (as modeled here) is relatively invulnerable to hydrologic changes that would be wrought by global warming (as interpreted from the GCM scenarios).

Given the same flow regime in the base case and the operational alternative scenarios, system performance under the alternative operational scenarios was determined mostly by changes in system storage that resulted from alternative operations. The peak power operational scenario reduced reservoir storage relative to the base case, thereby limiting recreation and navigation (due to the greater constraint placed on the timing of releases), but few of the other objectives. In the 'no-navigation support' scenario, the system was freed from the constraint of flushing water downstream to maintain a full channel depth at Blountstown, AL, allowing system storage to remain high relative to the base case. Accordingly, the storage-dependent recreation measures improved significantly, as did power metrics, while navigation, no longer a driver of system operations, suffered. The M&I demand growth scenario simply extracted more water from the system, an effect that was concentrated at the upstream end of the basin. The change in flow going through the system, however, was still smaller than the changes associated with many of the alternate climate scenarios. System storage was marginally low relative to the base case, causing power metrics to decline slightly and recreation performance measures to decrease as well. Navigation reliability also declined, but minor flood reduction resulted from greater consumptive use in the upper end of the basin.

With regard to system objectives other than flood control, the GFDL 2 $\times$ CO_2 scenario produced the worst system performance of the alternate climate scenarios, particularly compared to the GFTR scenarios, as a result of substantial decreases in inflows.

6.5. MISSOURI RIVER SYSTEM

Annual runoff changes, the largest for any study site, again reflected the moderation of changes in precipitation by changes in PET. Snow accumulation and ablation, which would be affected directly by temperature increases, are important on the western margin of the basin but make only a modest contribution to total runoff. For the MPTR and HCTR scenarios, declining precipitation coupled with increasing PET led to substantial decreases in runoff, making the Missouri River site the most sensitive to global warming of all the study sites from a hydrologic standpoint. The small increases in precipitation (Table Vb) for the GFTR scenarios led to small increases in runoff in the initial decades, but these gains were erased in later decades by rising PET. For the GFDL 2 $\times$ CO_2 scenario, the precipitation increase led to a slight increase in runoff despite a significant increase in PET.

As in the Savannah River and ACF basin sites, changes in system performance primarily reflected changes in streamflow. In general, the large flow reductions for the HCTR and MPTR scenarios favored flood control, but were detrimental to all other system objectives. Hence, for water supply, navigation, hydropower and river-based recreation, the altered climate scenarios resulted in modest to major impairments for the HCTR and MPTR scenarios, but small improvements in hydropower and navigation for the earlier GFTR scenarios.

6.6. COLUMBIA RIVER SYSTEM

While the results at most sites demonstrate that PET would increase significantly as a result of climate change, causing reduced runoff, the $2 \times CO_2$ scenario for the Columbia River site shows that concurrent, significant precipitation increases may be able to more than offset the effects of increased PET and support increases in runoff. From a water supply perspective, then, site specific assessments must consider precipitation changes to be at least as important as temperature changes in determining runoff.

For the Columbia River system, changes in system performance for energy, flood control and fishery protection can be explained mainly as a result of mean streamflow changes for the various scenarios. The large decrease in streamflow that occurred under the HCTR and particularly the MPTR scenarios degraded energy performance (Figure 3), instream flow reliability (Figure 7) and irrigation withdrawal reliability (Figure 4). The increased streamflow for the GFTR and $2 \times CO_2$ scenarios resulted in nearly opposite effects for these objectives. Navigation, measured via flows on the Snake River, was more limited by high flows than low flows – hence, the flow increases for the $2 \times CO_2$ scenario translated into a large decline in reliability. Changes for the transient scenarios were modest in comparison, peaked in Decade 2, and varied in direction between GCM series. The reliability of full recreation pools was eroded by streamflow decreases in the transient scenarios, particularly the MPTR scenarios, but it was difficult to see why, for example, the effects for the GFTR and HCTR scenarios were so similar, given the differences between them in terms of streamflow. The lack of a consistent relationship between streamflow changes and system performance changes on the annual scale indicates that subtleties of timing of runoff and volume of seasonal runoff for individual runs were also important determinants of performance. For example, the seasonal timing of runoff associated with the warmer climate scenarios benefited hydropower production, for which demand is highest in the winter, because earlier timing of snowmelt was compensated by increased winter runoff.

In general, the performance of the Columbia River system would be fairly robust to the effects of climate change. For most objectives, performance depended on the ability of the system to maintain full reservoirs and support minimum releases, and was affected at most to the degree of the largest streamflow reductions (around 15 percent for the MPTR scenarios).

7. Summary and Conclusions

Although this paper is directed primarily toward inferring the possible effects of climate change on the performance of water resource systems, an integral part of each of the studies was downscaling of climate scenarios and modeling their effects on the hydrology of the six systems. While the six sites differ in their climatology, hydrology, system configurations and operating purposes, there are nonetheless some commonalties in the climate scenarios and responses. We attempt to identify these below.

7.1. CLIMATE CHANGE

Temperature changes (increases) for the transient scenarios tended to be smaller than the temperature increase for the $2 \times CO_2$ scenario used in this and many earlier studies. The transient scenario temperature increases grew progressively from Decade 1 through Decade 5 for all basins, although for several studies, particularly for the HCTR scenarios (Tacoma, Boston, Savannah River, Missouri River) the warming was not evenly distributed between all decades: half or more of the increases occurred by Decade 2. In general, the GFTR scenarios tended to have the greatest warming and the MPTR scenarios the least, although there were exceptions to this observation. The range of changes for Decades 2 and 5 and the $2 \times CO_2$ scenarios (centered around the years 2020, 2050 and 2060, respectively), were 0.5–3.8 °C, 1.8–5.1 °C, and 3.5–5.9 °C.

Precipitation changes, on the whole, were less consistent than temperature changes and followed few monotonic trends. Decreases in precipitation occurred most often for the MPTR scenario, followed by the HCTR scenarios, while the GFTR scenarios had only increases in precipitation. The $2 \times CO_2$ scenarios tended to have the largest changes in precipitation, although the total range of changes in precipitation for all the scenarios was no greater than about 25 percent.

7.2. HYDROLOGY

From a hydrologic standpoint, changes in temperature produced corresponding changes in potential evapotranspiration (PET). In general, though, the modeled sensitivity of streamflow to temperature tended to be less than to precipitation, and changes in runoff mostly followed changes in precipitation. However, in some basins (especially Savannah River and Missouri River), changes in PET significantly moderated the response of streamflow to precipitation changes: in a few cases, PET increases were large enough to offset the effect of precipitation increases, and in others increased PET compounded the effect of precipitation decreases.

In four of the basins, snowmelt plays a role in shaping the seasonal hydrograph. For Tacoma, the temperature increases associated with global warming caused a significant shift of the spring runoff signal to earlier in the year, with an increase in the percentage of precipitation falling as rain rather than snow. A similar effect was apparent for Boston, although it was somewhat less prominent due to the larger fraction of annual precipitation that occurs during the warm season. In the Missouri River basin, snowmelt affects only the western headwaters of the basin, which contribute less to streamflow than do the more humid central and lower parts of the basin, so changes in seasonality of the overall basin hydrograph were minimal. For the Columbia River site, snowmelt-related seasonal shifts were superimposed on changes in mean annual flow (mostly decreases), disrupting, for example, hydropower generation schedules and instream flow requirements, which are conditioned on the historic hydrograph.

7.3. WATER RESOURCES MANAGEMENT

Changes in runoff were by far the most important determinant of the climatic sensitivity of system performance for nearly all system uses, notwithstanding that direct effects of climate change on system demand were modeled for several of the systems. The vulnerability of system performance to runoff changes varied from system to system but even more so from purpose to purpose. The main reason for the relative invulnerability of some operational purposes for some systems (e.g., water supply reliability for Tacoma and Boston) was the priority of that use and the amount of reservoir and/or groundwater storage available to buffer demands or changes in supply. Examples of the latter case are the large reservoir capacities of the Boston and Savannah River systems.

Temperature increases (and to a lesser extent precipitation changes) played a lesser, but potentially important, role where direct linkages to demand were modeled. For example, M&I demand levels for the Boston and Tacoma systems increased throughout each series of GCM scenarios as a result of higher temperatures. But, although the resultant demand increases degraded the M&I supply performance for these systems, the degradation was minor, especially in terms of system reliability because of the availability of storage to buffer the demand. However, especially in the Tacoma system, this buffering would come at the cost of increased groundwater pumping costs. For the Savannah River system, demand for recreation (visitation levels) was driven by temperature increases, thereby increasing recreation-related regional income resulting from system operation for recreation.

Among the important effects not captured by the annually aggregated system performance statistics discussed in this paper are changes in streamflow variability and seasonality. System response to climate change was influenced by progressively increasing streamflow variability (in the Tacoma, Savannah and ACF systems) that either offset mean flow decreases or exacerbated flow increases to cause increased flood damages. Changes in the seasonality of system inflows, for some scenarios, caused a mismatch of current operating rules with hydrologic inputs to the system or with demands on the system, such as minimum releases for anadromous fish runs in the Tacoma system. Significant shifts in the system inflow hydrograph occurred only in basins having snowmelt as a major component of runoff.

The influence of long-term demand growth on system performance was illustrated by the much greater sensitivity of M&I supply reliabilities to projected increases in demand for systems such as Boston and Tacoma, in which M&I supply is a major purpose. For these sites, projected changes in demand caused a much greater imbalance between water availability and demand than did the changes in availability resulting from climate changes, such as declines in flow. In sites where M&I supply was a relatively minor concern, demand growth effects tended to be limited to the scale of climate change effects. Altered operational scenarios, with the exception of the discontinuation of navigation in the ACF River basin, tended also to affect system uses to about the same extent as the climate change scenarios. A general conclusion that may be drawn from this comparison is that climate change effects may be smaller than, or in the range of, the effects of reasonable growth in demand or of other, non-climate related changes in operation.

Because reservoir systems are able to buffer modest hydrologic changes through operational adaptations, there was a tendency in all of the case studies for the effects of climate change on system performance to be smaller than the underlying changes in hydrologic variables. Furthermore, because the scale of water management infrastructure is determined by economic decision rules (e.g., maximization of net benefits) as well as system reliability, it may be that significant changes in design or scale for these systems to accommodate climate changes alone would not be warranted. Rather, concerted effort would need to be employed to adjust current operating rules or demand patterns to better balance the existing allocated purposes of the reservoirs.

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