Incorporation of Climate Change in Water Availability Modeling

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Abstract: The state of Texas recently implemented a water-availability modeling (WAM) system to support planning and regulatory activities. River basin hydrology is represented in the WAM system by sequences of historical monthly naturalized streamflows and net reservoir evaporation rates. This paper describes a case study investigation of the potential effects of climate-change on assessments of water-supply capabilities and focuses on whether and how climate change considerations should be incorporated in the WAM system. A modeling approach was adopted to explore the impacts of climate change on hydrologic and institutional water availability for the numerous water users who depend on supplies provided by the 118,000 km^2 Brazos River Basin. Analyses of historical naturalized streamflows indicate hidden but significant multiple-year cycles but no long-term trends during the twentieth century. A climate model and watershed hydrology model are used to adjust the WAM system hydrology to reflect anomalous climate during 2040–2060. The future climate scenario generally results in decreased mean streamflows and greater variability. However, the effects on water availability vary significantly in different regions of the river basin and among water users.

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Introduction

The impacts of global warming on hydrology and water-resources management have been addressed by various global, regional, and national assessments (Frederick et al. 1997; van Dam 1999; Lettenmaier et al. 1999; Gleick 2000; National Assessment Synthesis Team "Climate" 2000; Inter-Government Panel on Climate Change 2001; Arora and Boer 2001). During the twentieth century, the average temperature of the United States rose by about 0.6°C. The National Assessment Synthesis Team (2000) concluded that if no interventions to reduce continued growth of world greenhouse gas emissions occur, average temperatures in the United States will rise by about 3 to 5°C during the twenty-first century. This temperature rise is likely to be accompanied by more extreme precipitation and faster evapotranspiration, thereby leading to greater frequency of both very wet and very dry conditions.

The Texas Commission on Environmental Quality (TCEQ), its partner agencies, and contractors developed a water availability modeling (WAM) system from 1997 to 2004, pursuant to water management legislation enacted by the Texas Legislature in 1997 (Sokulsky et al. 1998; Wurbs 2001). The WAM system consists of the Water-Rights Analysis Package (WRAP) model (Wurbs 2003a,b) and input data sets for the 23 river basins in the state. Consulting firms employed by the TCEQ have developed WRAP input data sets for each river basin for use throughout the water-management community. The generalized simulation model and its hydrology and water-rights input files are applied by water-management agencies and their consultants in regional and statewide planning studies. Changes in water use or management practices or the development of new water projects require TCEQ approval of either new water-right permits or revisions to existing permits. Such changes or developments require assessments of whether sufficient water is available to supply proposed uses and assessments of the impact on other water users. Water-right permit applicants apply the WAM system in preparing permit applications. The TCEQ applies the modeling system in evaluating permit applications.

Historical sequences of monthly naturalized streamflows and net reservoir evaporation rates are incorporated in the WAM system to capture the hydrologic characteristics of a river basin without anthropogenic influence. The TCEQ and its contractors developed sequences of naturalized flows at numerous locations throughout Texas by adjusting recorded gauged flows to remove the effects of water-resources development and management activities. The naturalized flow data sets for most of the 23 river basins begin with January 1940 and extend almost to the present. The net evaporation depth data sets incorporated in the WAM system are from evaporation and precipitation databases dating back to 1940 that are maintained by the Texas Water Development Board. Net evaporation is reservoir surface evaporation less precipitation, adjusted for the precipitation that is already reflected in the naturalized inflows.

Other than the adjustments of the research effort reported by this paper, no adjustments have been made to the WAM system to reflect climate change. The motivating questions addressed by the

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case-study investigation presented here are as follows: Do potential impacts of climate change on assessments of water availability warrant adjusting the hydrology in the WAM system to reflect climate change? If so, what methods should be adopted for the adjustments?

The possible impacts of climate change on WAM system hydrology are viewed from two time frames: changes during the twentieth century, and future changes during the twenty-first century. In developing naturalized flows for each of the 23 river basins, the TCEQ consultants performed trend-detection analyses to confirm that the adjustments to remove the effects of historical water resources development had resulted in homogeneous sequences of naturalized flows. The adjusted flow sequences at most locations were generally demonstrated to exhibit no detectable long-term trends. Although the flow naturalization process dealt only with adjustments for historical human water management, the lack of long-term trends in the resulting flow sequences implies that any effects of climate change since 1940 have been minimal. In the research reported here, naturalized flows dating back to 1900 were examined to detect trends and cycles. The more difficult task addressed by the research was assessing the effects of climate change during future decades.

The research objective was to evaluate potential impacts of climate change on Texas WAM system assessments of water-supply capabilities. The Brazos River Basin served as a case study. Trend analyses applied to 1900–1997 naturalized flow sequences show pertinent cycles but no long-term trends. Significant effects of future climate change reflected in a potential 2050 climate scenario were found in a modeling effort that is based on adjusting streamflows and net reservoir evaporation rates by using data from the Soil and Water-Assessment Tool (SWAT) watershed model and Canadian Center for Climate Modeling (CCCMA) climate model.

Texas Water-Availability Modeling System

WRAP is the river-basin water-allocation model adopted for the Texas WAM system. The generalized WRAP model is designed for assessing hydrologic and institutional water availability and reliability for water-supply diversions, environmental instream flow needs, hydroelectric power generation, and reservoir storage. The model dates back to the 1980s but has been greatly expanded and improved since 1997, in conjunction with the Texas WAM system (Wurbs 2003a,b; http://ceprofs.tamu.edu/rwurbs/wrap.htm).

In the model, water-use targets are met, subject to water availability, by following specified water-management practices during a hypothetical repetition of historical hydrology. A typical period of analysis for the Texas WAM system is 1940–1997, which includes the 1951–1957 record drought, as well as a full range of fluctuating wet and dry periods. Capabilities for meeting specified water-use requirements are analyzed with basin hydrology represented by sequences of monthly naturalized streamflows and reservoir net evaporation less precipitation depths at all pertinent locations for each of the 696 months of the 1940–1997 hydrologic period of analysis. The simulation process consists of the following tasks:

1. Complete sequences of monthly naturalized flows covering the specified period of analysis at selected gauging stations have been developed, as previously discussed.
2. Naturalized flows are distributed from gauged to pertinent ungauged locations within the simulation model.
3. The water-management system is simulated, with water being allocated to each water right in priority order each month.
4. The simulation results are organized; and water-supply reliability indexes, flow and storage frequency relationships, and other summary statistics are computed.

WRAP allocates naturalized streamflows to meet water-right requirements, subject to net reservoir evaporation and channel losses. Naturalized flows represent natural conditions without water-resources development and use. Regulated and unappropriated flows computed by WRAP reflect the effects of reservoir storage and water use associated with the water-right requirements. Unappropriated flows are the amounts of streamflow still uncommitted after all water users have received their allocated share of water. Regulated flows represent actual physical flows and may be greater than unappropriated flows at the same site because of instream flow requirements at the site or water-right commitments at downstream locations.

Simulation results may be organized in various formats but are typically viewed from the perspective of frequency or reliability of meeting water-supply, instream flow, hydropower, and storage requirements. Volume and period reliabilities may be computed for either water-supply diversion or hydroelectric energy generation targets for individual water rights or the aggregation of selected groups of rights. Volume reliability is the ratio of the water volume supplied or energy generated to the demand target, expressed as a percentage. Period reliability is the percentage of months in the simulation for which a specified demand target is met. Reliability indexes also include tabulations of both the percentage of months and the percentage of years during the simulation for which the amounts supplied equaled or exceeded specified percentages of a target. Streamflow and reservoir storage frequencies are determined by counting the number of months during the simulation that particular flow or storage amounts are exceeded.

River-Basin Hydrology

Hydrology is represented by naturalized flows and net reservoir evaporation less precipitation depths for each month of the hydrologic period of analysis. Streamflow naturalization procedures result in a homogeneous set of flows representing the natural flows that would have occurred in the absence of the water users, water-management facilities, and practices reflected in the water-rights input data set. The extent of the adjustments made to historical gauged flows to reflect natural conditions depends on the circumstances of the particular river basin. Naturalized flows are developed by adjusting recorded flows to remove the impacts of upstream reservoirs, water-supply diversions, return flows from surface and groundwater sources, and possibly other factors.

The WRAP model includes several alternative methods for transferring naturalized flows from gauged to ungauged sites. Most applications in Texas have used an option that is based on the Natural Resource Conservation Service (NRCS) relationship between precipitation depth P and runoff depth Q in which the curve number CN is a watershed parameter reflecting land cover and soil type (National Resource Conservation Service 1985). WRAP applies the CN method in a way that differs from conventional use. Given the naturalized monthly flow at the gauge, precipitation P is computed by the NRCS equation with the CN for the gauged watershed; P is substituted back into the NRCS runoff equation with the CN for the ungauged watershed to determine

Fig. 1. Brazos River Basin

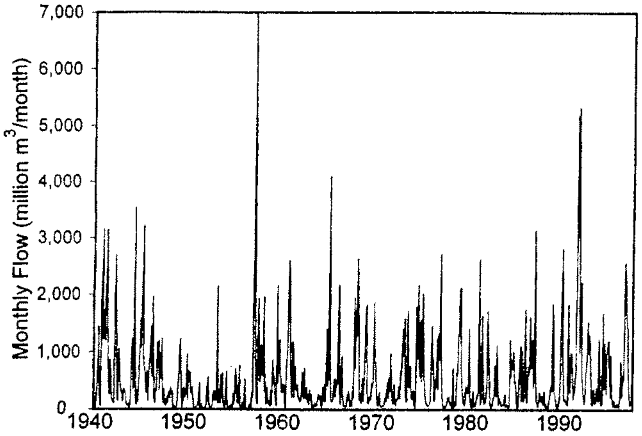

Fig. 2. Naturalized 1940–1997 monthly flows at the Hempstead gauge

the flow at the ungauged site. If the *CN* values are the same for the gauged and ungauged watersheds, this method reduces simply to distributing streamflow in proportion to drainage area.

WRAP hydrology input also includes net evaporation less precipitation rates from reservoir water surfaces. Net evaporation rates (depth/month) are used within the model in combination with reservoir storage versus surface area relationships in the water-accounting computations to determine monthly net reservoir evaporation volumes.

The impacts of climate change on Texas WAM system estimates of water availability and reliability were investigated from two perspectives: (1) past effects of climate change on the historical hydrology data adopted for the WAM system that might cause the data to be nonhomogeneous; and (2) future effects requiring adjustments to the streamflow and reservoir net evaporation rates to make the river-basin hydrology representative of the future climate. Statistical analyses were used to investigate trends and cycles in historical naturalized streamflows for the Brazos River Basin. Climate and watershed models were used to adjust the naturalized flows and net reservoir evaporation rates to reflect a specified future climate scenario.

Brazos River Basin

As shown in Fig. 1, the 118,000 km^2 Brazos River Basin extends from New Mexico across Texas to the Gulf of Mexico. Mean annual precipitation varies from 380 mm in the upper basin to 1,320 mm near the coast. Traveling from west to east, the mean annual precipitation increases slightly more than 1 mm per kilometer. About 25,000 km^2 of the flat semiarid upper basin, including the area in New Mexico and the adjoining area in Texas, contribute essentially no runoff to the river. The much wetter climate and rolling topography of the middle basin and the humid coastal plain of the lower basin result in much more runoff per unit of watershed area than in the upper third of the basin. The great temporal variability characteristic of streamflow in Texas is illustrated by the naturalized monthly flows at the Hempstead gauge, as plotted in Fig. 2.

More than 1,000 cities, water districts, companies, and individual citizens hold one or more water-right permits to divert or store water from the Brazos River and its tributaries. Water is diverted for municipal uses (55%), industrial uses (23%), irrigation uses (18%), and other uses (4%). More than half of the total water supplied by the basin is diverted from the lower reach of the Brazos River for use in the adjoining coastal region, which includes the cities of Houston and Galveston and vicinity.

WRAP determines reliabilities for each individual water right. In implementing the WAM system, the TCEQ has provided the approximately 7,000 permit holders in the state with information regarding reliabilities associated with their individual water rights. However, for purposes of this paper, the rights to store and divert water from the Brazos River and its tributaries are divided into two groups: Brazos River Authority (BRA) permits and all others. As indicated in Table 1, BRA permits account for 27% of the total annual volume of authorized water-supply diversions.

The 12 BRA reservoirs shown in Fig. 1 contain 63% of the total conservation storage capacity of the 590 reservoirs included in the model. The BRA controls the water-supply pools in nine multiple-purpose reservoirs operated by the U.S. Army Corps of Engineers and operates three nonfederal water-supply reservoirs. The BRA makes significant lakeside diversions, but most of the water it supplies is diverted from the lower Brazos River and regulated by multiple-reservoir system operations. Two of the BRA reservoirs generate hydroelectric power, but releases through the turbines are incidental to downstream water-supply needs. The 578 reservoirs not controlled by the BRA account for 37% of the total conservation storage capacity. Most of this non-BRA storage capacity is contained in several major municipal water-supply reservoirs and seven reservoirs used to supply cooling water for thermal electric power plants. Numerous smaller

Table 1. Authorized Water-Supply Diversions and Reservoir Storage Capacities

Water-right permit owner	Water-supply diversions (million m^3/yr)	Number of reservoirs	Storage capacity (million m^3)
Brazos River Authority	760	12	3,437
All others	2,058	578	1,991
Brazos Basin total	2,818	590	5,428

reservoirs providing agricultural, municipal, and industrial water supply, as well as water for recreation, are scattered throughout the basin.

Compilation and Analyses of Naturalized Streamflows

The WAM system includes a WRAP input data set for the Brazos River Basin. Sequences of 1940–1997 naturalized monthly flows were developed by adjusting observed flows at 72 U.S. Geological Survey (USGS) gauging stations to remove the effects of upstream reservoirs, water-supply diversions, and return flows (*Naturalized* 2001; *Water* 2001). Approximately 600 reservoirs and numerous diversions and return flows were included in the adjustments. Channel losses were considered in translating the adjustments downstream. Regression analyses were applied to the naturalized flows to fill gaps in the records. This historical hydrology data set was used in the WRAP simulation studies reported in this paper. As subsequently discussed, later, the flows are further adjusted to reflect future climate conditions.

In conjunction with the initial development of WRAP, Wurbs et al. (1988) compiled 1900–1984 naturalized flows at 23 USGS gauging stations in the Brazos River Basin. Two of the stations date back to 1899, and nine stations have records that begin between 1900 and 1924. Gauged flows were adjusted to remove the effects of several large water-supply diversions and the effects of evaporation and storage in 21 reservoirs that accounted for more than 90% of the total storage capacity in the basin in 1984. Complete 1900–1984 monthly naturalized flow sequences were developed, and gaps were filled in by using regression analyses.

Naturalized flows from the two alternative flow naturalization efforts are similar for the common period 1940–1984, indicating that the few very large reservoirs and water users account for most of the adjustments between gauged and naturalized flows. Trend analyses reported here are based on 1900–1997 naturalized flows at selected gauging stations compiled by combining 1900–1939 flows from Wurbs et al. (1988) with 1940–1997 flows from the WAM system.

Various analyses to detect trends and cycles were performed by using the 1900–1997 sequences of naturalized streamflow (Felden 2002). No long-term trends were detected. The process of adjusting gauged flows to develop naturalized flows resulted in homogeneous streamflow sequences. Long-term climate-change trends, if any, are hidden in the natural stochastic variability of the streamflows. Annual seasonality is evident. Significant multiple-year cycles were also found. The following discussion focuses on certain statistical analyses of annual series for seven gauging stations, which were selected because of their location and long period of record. For each station, the following three annual series were analyzed: annual flow volume, maximum monthly flow in any month for each year, and minimum monthly flow in any month for each year. The annual naturalized flows plotted in Fig. 3 demonstrate the great annual variability, with no detectable long-term trends characteristic of streams throughout the basin.

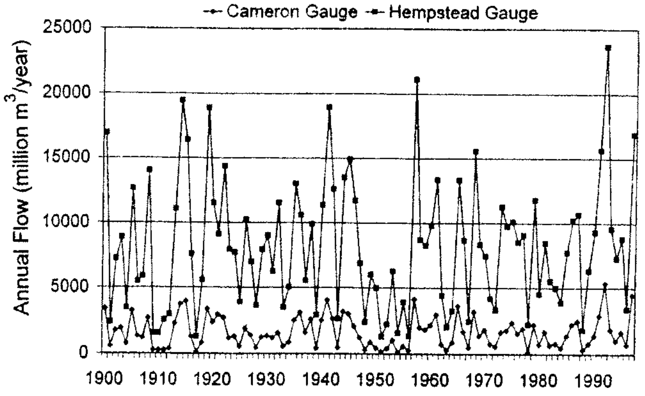

Fig. 3. Naturalized 1900–1997 annual flows at the Cameron and Hempstead gauges

Trend Analysis

A four-step trend analysis procedure was adopted that is similar to the methodology used by Cluis and Laberge (2001), consisting of the Hubert segmentation procedure, the choice of adequate statistical tests, an independence test, and the actual trend-detection tests. Hubert's segmentation procedure determines the optimal segmentation of a series into two or more segments of constant levels and is based on minimizing the root-mean-square error between the measured data and the model given by the segmentation (Hubert et al. 1989). The segmentation was applied to the 21 series (three annual series at seven gauging stations) as a preliminary analysis. This test acts as a filter, allowing nonsegmented series to be removed from further analysis. A negative response to the segmentation indicates an absence of trends. However, segmented series do not necessarily involve the presence of a trend. For a significance level of 0.05, 16 of the 21 series are segmented and thus kept for further statistical analysis.

Most of the classical statistical tests have been developed with restricting hypotheses of normality and independence. Streamflow data often diverge from these conditions by simultaneously exhibiting Markovian persistence, annual seasonality, and long-term trends. This outcome suggests using nonparametric tests. However, nonparametric tests do not directly address the problems of temporal persistence and temporal fluctuations. Thus, Lettenmaier (1976) adapted nonparametric tests to allow trend detection, without being influenced by other types of short-term interdependence. To know the type of adapted nonparametric tests to use, the independence of the series must be evaluated.

The 16 remaining series were tested for independence with the Wald-Wolfovitz test. Seasonality was automatically removed by aggregating monthly to annual flows. As a result of the test, 15 of the 16 series were found to be independent. The one series with persistence was removed from further analysis because it had values of zero during 90% of the years. Then, following the procedure developed by Lettenmaier (1976), Kendall's test was chosen for the linear trend detection and Mann-Whitney's test was chosen for the stepwise trend analysis.

With Kendall's test, 14 of the 15 series showed no significant linear trend over the 98 years. Only the series of minimum flows at a site on the upper Brazos River showed a linear trend. To implement the step-trend analysis by using the Mann-Whitney tests, the annual, maximum, and minimum series of streamflows were partitioned. The 14 series tested did not show the presence of a stepwise trend. During the twentieth century, no significant long-term trends or stepwise trends were detected in the series of naturalized streamflows selected for analysis.

Cycle Detection and Analysis

The seven annual flow series exhibit similar types of cycles. Fast Fourier transform and spectrograms along with segmentation results indicate that powerful signals of 3.8, 5, 7, and 24 years were detected. The 3.8-year cycle appeared in five of the seven series, the 5-year cycle in four series, and the 7-year cycle and 24-year cycle in six series. Six of the seven series have almost the same spectrum. The only flow series with a spectrum that differed slightly different from the others was at a site in the extreme upper Brazos River, with a 12-year cycle instead of a 24-year cycle.

The cycles were compared with El Niño-Southern Oscillation (ENSO) events. Average flows under ENSO conditions were compared with the average flows for non-ENSO periods. The BEST index (Smith and Sardeshmukh 2000), used as an indicator of ENSO events lists the months when sea surface temperatures and the southern oscillation index both exceeded the 20th percentile. The years from 1900 to 1997 were associated with ENSO if at least one month experienced an ENSO-type event in the BEST index. Of the 98 years, 26 were classified as having ENSO conditions so El Niño events occurred on average every 3.8 years during the past century. A 7-year period was also highlighted. These observations tend to match the strong signals detected with both the fast Fourier transform and spectrogram analyses. The flows during El Niño periods are 168 to 180% higher than those experienced at other times.

Annual flow volumes during the years just before and just after ENSO events were also compared with flows during the event. Results show that 83% of annual flows in the year before the events are less than those during El Niño. Almost 50% of the flows one year before an event are 50% lower than those during an El Niño period. Two years before an event, 76% of flows are less than the flows during the event. Almost 80% of annual flows in the year after an event are less than those during an El Niño period, as are approximately 70% of the annual flows 2 years later.

Assessing the Effects of Future Long-Term Climate Change

Climate changes during the twenty-first century are expected to be significantly greater than those during the twentieth century. A modeling strategy was adopted for incorporating the effects of future long-term climate changes reflecting global warming into the WAM simulation. To develop adjustments to the WAM naturalized climate flows that could represent a future climate scenario, output from a global circulation model (GCM) was used to adjust input to a watershed hydrology model. Net reservoir evaporation rates were also adjusted for the future climate scenario by using data from the GCM.

Various combinations of GCMs modeling global climate processes and watershed models representing precipitation-runoff processes have been used to predict the effects of climate change on water resources in various regions of the world (Miller and Russell 1992; Brumbelow and Georgakakos 2001; Matondo and Msibi 2001; Arora and Boer 2001). A number of alternative climate models (van Dam 1999) and watershed hydrology models (Singh 1995) are available. The Canadian Center for Climate Modeling and Analysis (CCCMA) GCM and the Soil and Water Assessment Tool (SWAT) watershed model were adopted for this investigation.

Soil and Water-Assessment Tool

SWAT is a comprehensive watershed modeling package developed by the USDA Agricultural Research Service (ARS) and Texas Agricultural Experiment Station (Neitsch et al. 2002a,b; http://www.brc.tamus.edu/swat/). SWAT was developed during the 1990s, incorporating features of earlier ARS models. It continues to be expanded and improved. The daily time-step watershed hydrology model generally uses as input measured precipitation and maximum and minimum temperatures. Other climatic variables such as relative humidity, solar radiation, and wind speed are generated from databases contained within the modeling system. SWAT simulates routing and landscape hydrologic processes in a watershed. Options for simulating the movement of sediments, nutrients, and pesticides are also available in SWAT but were not needed for the present study. A river basin may be divided into any number of subwatersheds. Inputs on land use, soils, land management practices, topography, hydrogeology, and weather are required to run the model. For agricultural lands, inputs are specified regarding the type of crop grown, planting and harvest dates, and management practices. SWAT outputs consist of the watershed water-balance components (runoff, evapotranspiration, soil–water storage, and deep percolation) and stream-routed hydrographs.

The application of SWAT is facilitated by the hydrologic unit modeling of the United States (HUMUS) database of climate and land use that was developed in a previous project that involved applying SWAT to the river basins of the contiguous U.S., subdivided by hydrologic cataloging units (Srinivasan et al. 1995; Arnold et al. 1998). The HUMUS database was used in modeling the Brazos River Basin.

Canadian Center for Climate Modeling and Analysis Global Circulation Model

The CCCMA GCM is a coupled atmosphere–ocean dynamics model (Flato et al. 2000). Terrestrial components have 10 vertical levels discretized by rectangular finite elements. Globally, the land resolution is about $3.75\times3.75°$; but for Texas, it is $2.5\times2.5°$. Oceans are modeled on a $1.875\times1.875°$ grid with 29 vertical levels. Soils on the land are modeled by using a one-layer bucket model while accounting for runoff and soil–water storage with depth that is spatially variable and depends on soil and vegetation type. Inland lakes, ice sheets, and soils provide radiation and moisture feedback from land to the atmosphere. The ocean component of the model provides sea surface temperatures to the atmospheric component, and the heat and freshwater flux is provided to the oceans. Modeled and observed climate means and variability over the period 1900–1995 significantly agree at the 95% confidence level for North America for land surface temperature and land precipitation (Zweirs 1996).

A climate-change scenario called IS92a, which has a carbon dioxide (CO_2) concentration increase of 1% per year, has been modeled. Daily and monthly output data are available over the Internet (http://www.cccma.bc.ec.gc.ca). Daily time-series observations of precipitation and maximum and minimum temperatures during the period 2040–2060 were adopted for this study from the

Table 2. Adjustment Factors for Soil and Water Assessment Tool Input

	Precipitation ratios (multiply)		Maximum daily temperature (add)		Minimum daily temperature (add)	
Month	Mean	Range	Mean (°C)	Range (°C)	Mean (°C)	Range (°C)
January	0.877	0.741–1.095	4.02	2.49–5.67	2.71	1.42–6.51
February	0.806	0.563–0.979	3.99	2.28–5.98	2.39	1.43–4.19
March	0.700	0.558–0.988	3.00	1.95–5.16	2.23	1.28–3.02
April	0.783	0.631–0.992	2.94	1.69–4.24	2.69	1.72–3.57
May	0.803	0.574–0.991	3.09	1.83–4.37	2.70	1.55–3.04
June	0.833	0.774–0.929	3.58	1.85–4.49	2.93	1.36–3.75
July	0.866	0.579–1.171	3.38	2.06–3.89	2.93	2.02–3.41
August	0.979	0.670–1.259	3.53	2.26–4.37	2.71	1.04–3.52
September	1.026	0.607–1.347	2.41	1.26–4.00	2.73	1.59–3.45
October	1.100	0.598–1.403	2.73	1.87–4.70	3.88	2.26–4.55
November	0.960	0.891–1.046	3.36	2.59–5.12	3.64	2.01–4.81
December	0.974	0.691–1.187	4.15	2.71–5.86	2.88	1.81–4.26
Average	0.892	0.815–0.987	3.35	2.19–4.54	2.87	2.22–3.10

coarse grid ($2.5\times2.5°$) First Generation Coupled Model (CGCM1), which models vertical and horizontal diffusion in oceans (Gent and McWilliams 1990).

Methods to temporally and spatially downscale GCM precipitation for hydrologic applications include improved high-resolution climate models with boundary conditions supplied by the global GCM (Giorgi et al. 1994), statistical downscaling that considers such GCM atmospheric variables as pressure and local climate observations (Semenov and Barrow 1997; Burlando and Russo 1991), and simple interpolation of GCM results for hydrologic applications without absolute corrections (Prudhomme et al. 2002). Considerable uncertainty is associated with each of these methods. The first approach relies on correct GCM predictions, and prediction errors can get large as the area of analysis gets smaller (Christensen et al. 1997). The statistical approach assumes the same physical relationship between climate variables with and without climate change, which may not necessarily be the case (Prudhomme et al. 2002; Solman and Nuñez 1999). Simplly using GCM results without correction ignores spatial variability issues. Since we wished to capture future forcing to historical regional climate from anomalous effects of greenhouse gases, we directly used CCCMA grid data in our downscaling.

Simulation of Hydrology and Water Management under Historical and Future Climate

Conventional WRAP analyses that are based on 1940–1997 naturalized flows and net reservoir evaporation depths reflect historical climate and hydrology, referred to here as the historical climate scenario. WRAP simulation studies of the Brazos River Basin comparing historical and 2050 climate are based on adjusting the naturalized flows and net reservoir evaporation rates to reflect a 2040–2060 climate, as modeled by the CCCMA GCM IS92a scenario, which assumes a CO_2 concentration increase of 1% per year. The adjusted WRAP hydrology is referred to as the 2050 climate scenario. Experimentation with variations of methods for connecting the CCCMA GCM, the SWAT watershed model, and WRAP river/reservoir system water-allocation model resulted in the following approach:

1. Two sets of 2040–2060 precipitation and temperature, reflecting climate conditions with and without the increase in CO_2 concentrations and obtained from the CCCMA, were used to develop adjustments to SWAT precipitation and temperature input to reflect the 2050 climate.
2. SWAT was executed with historical and adjusted future climate input to obtain sets of 1971–1990 daily streamflows, which were used to develop adjustments for 1940–1997 monthly WRAP naturalized flows. The SWAT precipitation and evaporation rates were used to develop adjustments for WRAP net reservoir evaporation rates.
3. WRAP was executed with the 1940–1997 historical hydrology and 1940–1997 hydrology adjusted to reflect 2050 climate. Water-supply capabilities were assessed on the basis of simulation results.

Adjustments to Historical Climate Input to Soil and Water Assessment Tool to Reflect 2050 Climate

SWAT input was adjusted to reflect the nominal 2050 climate scenario from output covering the period 2040–2060 provided at the CCCMA Web site for two alternative runs of the GCM: (1) base scenario with no increase in CO_2 concentrations, and (2) IS92a scenario with an increase in CO_2 concentration of 1% per year. The CCCMA discretization resulted in a 4×3 grid for the Brazos River Basin. Mean precipitation and mean maximum and minimum daily temperatures for each of the 12 months of the year during the GCM period 2040–2060 were compiled for the base and IS92a scenarios. The corresponding data from the two alternative CCCMA data sets that represented scenarios without and with climate change were used to develop multiplication and addition factors for each of the 12 grid cells.

Precipitation ratios for each of the 12 grid cells were computed for each of the 12 months of the year as

$$\text{Ratio} = \frac{\text{2040 - 2060 mean monthly precipitation with climate change}}{\text{2040 - 2060 mean monthly precipitation without climate change}}$$

Table 3. Adjustment Factors for Water Rights Analysis Package Input

Month	Naturalized streamflow multipliers				Net reservoir evaporation added (mm)			
	Aquilla gauge	Waco gauge	Cameron gauge	Hempstead gauge	Aquilla gauge	Waco gauge	Cameron gauge	Hempstead gauge
January	0.79	1.10	0.95	0.76	1.6	2.0	3.2	4.2
February	0.71	0.90	1.08	0.66	5.8	5.8	7.5	9.3
March	0.61	0.43	0.41	0.42	24.5	23.4	27.3	31.4
April	0.59	0.66	0.72	0.51	22.1	21.6	26.1	30.8
May	0.37	0.54	0.57	0.38	19.5	19.1	23.7	28.6
June	0.30	0.39	0.34	0.27	22.4	22.4	26.6	30.0
July	0.35	0.68	0.94	0.53	13.8	15.5	18.9	19.1
August	0.34	1.00	0.88	0.42	3.8	6.3	8.6	7.4
September	1.42	2.66	2.84	1.58	−27.4	−22.7	−22.8	−27.2
October	1.56	2.18	2.27	1.88	−18.7	−15.3	−15.0	−17.6
November	1.06	0.96	1.43	1.29	6.6	7.0	9.1	10.7
December	0.94	1.65	1.77	1.13	−7.7	−6.4	−6.1	−6.5
Average	0.75	1.10	1.18	0.82	5.5	6.6	8.9	10.0

The means for the 12 grid cells are shown in Table 2, along with the range of values for the 12 individual grid cells.

Maximum and minimum temperature factors from the 2040–2060 data for each of the 12 grid cells were computed for each of the 12 months of the year as

$$\text{Factor} = \text{mean with climate change} - \text{mean without climate change}$$

Table 2 also shows the means of the maximum and minimum temperatures for each of the 12 months for the 12 grid cells, along with the range of values for the 12 grid cells.

Observed daily climatic data for 1971–1990 were adopted as SWAT input representing historical climate. The 2050 climate was modeled by applying the 12 monthly multiplier ratios to the 1971–1990 daily precipitation. Maximum and minimum temperatures were obtained by adding the previously discussed factors. All other climatic input were generated within SWAT and were held constant, except as affected by precipitation and temperature.

Adjustments to Historical Hydrology Input to Water-Rights Analysis Package to Reflect 2050 Climate

The naturalized flows in WRAP were adjusted to reflect climate change, on the basis of two alternative runs of SWAT that represented historical and 2050 climate, as follows:

1. SWAT was calibrated by adjusting parameters to reproduce the naturalized monthly flows at selected locations, given historical weather observations during selected periods.
2. A SWAT simulation with daily temperature and precipitation data representing historical 1971–1990 climatic conditions was performed to generate streamflows at pertinent locations.
3. With all other input held constant, 1971–1990 streamflows were generated again with SWAT, with temperature and precipitation data representing future conditions developed by using the previously discussed adjustment factors.
4. Daily flows were aggregated to months. Multiplication factors for the 12 months of the year were computed as the ratios of the two sets of mean-monthly streamflows.
5. The resulting multiplication factors were used to convert WRAP naturalized 1940–1997 monthly streamflow sequences from historical to 2050 climate conditions.

Streamflow adjustment factors were developed for 18 locations. Table 3 tabulates the multipliers used to convert naturalized flows from historical to the 2050 climate scenario for the four gauging stations shown in Fig. 1. Pertinent data for these stations are given in Table 4. Annual streamflows are reduced more than the average of the 12 monthly ratios because the wet high-flow months of April to June have smaller multiplier ratios than the drier winter months.

Table 5 compares the 1940–1997 monthly naturalized flows for the 2020 climate scenario with the corresponding flows for historical conditions. Means, standard deviations, and flow-frequency relationships are tabulated. At the Hempstead gauge, with the climate-change adjustments, the 1940–1997 mean flow of 146.5 m^3/s is 69.9% of the corresponding mean flow of 209.5 m^3/s for historical conditions. Most of the reduction in runoff occurs in the upper half of the basin above the Aquilla gauge. Under historical natural conditions, a mean-monthly flow

Table 4. Stream Gauging Stations Cited in Fig. 1 and Tables 3–7

Nearest city	Stream	U.S. Geological Survey gauge number	Drainage area (km^2)	Mean naturalized streamflow	
				(m^3/s)	(mm/year)
Aquilla	Brazos River	08093100	70,600	1,310	0.066
Waco	Bosque River	08095600	4,290	340	0.282
Cameron	Little River	08106500	18,300	1,260	0.244
Hempstead	Brazos River	08111500	113,600	5,100	0.159

Table 5. Comparison of Naturalized Streamflows with Historical and 2050 Climate

	Aquilla gauge			Waco gauge			Cameron gauge			Hempstead gauge		
	Historical (m^3/s)	2050 (m^3/s)	2050/H (%)	Historical (m^3/s)	2050 (m^3/s)	2050/H (%)	Historical (m^3/s)	2050 (m^3/s)	2050/H (%)	Historical (m^3/s)	2050 (m^3/s)	2050/H (%)
Mean	53.9	36.6	67.9	14.0	12.2	87.6	51.6	49.8	96.7	209.5	146.5	69.9
Standard deviation	96.1	69.7	72.6	25.0	69.7	279.3	80.0	88.5	110.6	276.1	213.6	77.4
Exceedance frequency												
100%	0.0	0.0	—	0.0	0.0	—	0.0	0.0	—	0.0	0.4	—
98%	0.8	0.4	49.6	0.0	0.0	—	0.6	0.6	109.0	8.2	5.9	72.4
90%	3.3	2.4	73.2	0.2	0.2	97.8	2.6	2.9	115.1	21.2	13.7	64.6
75%	7.8	5.2	66.1	1.3	1.2	97.8	7.1	6.7	94.6	42.2	30.4	72.1
50%	21.7	12.6	58.2	4.7	4.3	91.6	21.0	19.2	91.4	107.6	71.8	66.8
25%	61.8	37.9	61.2	16.2	12.4	76.5	61.2	58.9	96.3	273.0	186.9	68.5
10%	131.9	92.6	70.2	37.6	30.3	80.6	136.3	123.6	90.7	541.2	347.4	64.2

of 21.2 m^3/s is equaled or exceeded during 90% of the months of the 1940–1997 flow sequence at the Hempstead gauge. With the flows adjusted for the 2050 climate scenario, 13.7 m^3/s is equaled or exceeded during 90% of the months in the 1940–1997 flow sequence.

Net reservoir evaporation–precipitation rate (mm/month) adjustments to be added to historical depths to reflect the future climate were developed by combining separate precipitation and evaporation adjustments for each of the 12 months of the year at pertinent locations. Table 4 also tabulates the monthly net evaporation depths added to historical 1940–1997 depths to obtain values for the 2050 climate scenario for reservoirs near the four locations.

Water-Rights Analysis Package Simulation Results

WRAP models the capabilities for meeting specified water-use requirements with specified water-management facilities and practices during a hydrologic simulation period. It represents river-basin hydrology by sequences of naturalized flows and net reservoir surface evaporation–precipitation depths. The water-rights scenario adopted for the simulation results presented here is based on all water users appropriating the full amounts authorized by their permits, as summarized in Table 1, with current reservoir system management practices in effect. This scenario is the basic one adopted by the TCEQ in evaluating water-right permit applications.

A WRAP simulation converts naturalized flows to regulated and unappropriated flows, as previously defined. Tables 5, 6, and 7 compare naturalized, regulated, and unappropriated flows at four locations, without and with climate change. Since available water is used to meet water-supply diversion targets and refill reservoirs to the extent possible, climate change decreases regulated and unappropriated flows significantly more than naturalized flows.

WRAP computes reservoir storage and diversion amounts for each individual water right. However, Tables 8 and 9 aggregate the more than 1,200 water rights into two groups: those held by the BRA and those held by entities other than the BRA.

The impacts of potential climate change on storage contents of reservoirs are illustrated in Table 8. The total conservation storage capacity of the 590 reservoirs in the basin is 5,428 million m^3. The mean storage contents during the 1940–1997 simulation are 4,185 million m^3 for the 2050 climate scenario, or 87% of the corresponding mean storage of 4,810 million m^3 for historical climate conditions. The relationships between storage as a percentage of capacity and the frequency of being equaled or exceeded

Table 6. Comparison of Regulated Streamflows with Historical and 2050 Climate

	Aquilla gauge			Waco gauge			Cameron gauge			Hempstead gauge		
	Historical (m^3/s)	2050 (m^3/s)	2050/H (%)	Historical (m^3/s)	2050 (m^3/s)	2050/H (%)	Historical (m^3/s)	2050 (m^3/s)	2050/H (%)	Historical (m^3/s)	2050 (m^3/s)	2050/H (%)
Mean	22.9	10.8	47.0	11.3	9.5	84.7	44.7	43.4	97.2	176.5	116.6	66.1
Standard deviation	78.7	37.4	47.6	24.5	25.2	102.7	73.6	80.8	109.8	248.9	175.1	70.3
Exceedance frequency												
100%	0.0	0.0	—	0.0	0.0	—	0.0	0.0	—	2.4	11.7	486.6
98%	0.0	0.0	—	0.0	0.0	—	4.1	1.3	32.2	19.5	20.8	106.6
90%	0.0	0.0	—	0.0	0.0	—	6.0	5.8	96.4	29.5	26.9	91.3
75%	0.0	0.0	—	0.0	0.0	—	8.5	9.8	114.2	43.0	35.7	83.0
50%	0.0	1.0	—	0.4	0.5	136.7	15.5	17.6	114.0	71.9	56.6	78.8
25%	9.5	6.7	70.6	11.8	8.7	73.8	47.4	41.3	87.2	205.4	126.3	61.5
10%	64.5	22.6	35.0	34.5	26.4	76.4	114.3	103.8	90.9	450.3	257.8	57.3

Table 7. Comparison of Unappropriated Streamflows with Historical and 2050 Climate

	Aquilla gauge			Waco gauge			Cameron gauge			Hempstead gauge		
	Historical (m^3/s)	2050 (m^3/s)	2050/H (%)	Historical (m^3/s)	2050 (m^3/s)	2050/H (%)	Historical (m^3/s)	2050 (m^3/s)	2050/H (%)	Historical (m^3/s)	2050 (m^3/s)	2050/H (%)
Mean	20.3	7.3	35.9	11.0	8.6	78.4	42.3	36.3	86.0	153.7	77.6	50.5
Standard deviation	78.4	37.0	47.1	24.6	24.9	101.2	74.6	80.9	108.4	249.6	152.4	61.1
Exceedance frequency												
90%	0.0	0.0	—	0.0	0.0	—	0.0	0.0	—	0.0	0.0	—
75%	0.0	0.0	—	0.0	0.0	—	5.8	0.0	—	12.7	0.0	—
50%	0.0	0.0	—	0.0	0.0	—	12.5	10.1	—	50.7	23.6	46.6
25%	2.9	0.0	0.0	10.9	7.5	69.0	46.6	37.2	79.8	198.7	86.7	43.6
10%	56.8	4.9	8.6	33.9	24.7	72.8	114.3	99.0	86.6	437.3	212.8	48.6

are also compared in Table 8 for the two climate scenarios. With historical climate conditions, the minimum basinwide storage is 58.4% of the storage capacity of the 590 reservoirs. Under the 2050 climate scenario, the minimum storage content is 33.2 percent of capacity. For 50% of the time, the aggregate basinwide storage is at or above 90.4 and 80.2% of capacity for the historical and 2050 climate scenarios. Since the BRA operates its multiple reservoirs as a system and makes releases to meet water needs along the lower Brazos River, storage depletions tend to be somewhat balanced among the reservoirs. The effects of climate change and the risk of severe drawdowns are shared among the reservoirs.

Water-supply diversion targets vary over the 12 months of the year, and the seasonality in water use varies with different types of use. Mean-annual diversion targets total 89.4 m^3/s, as indicated in Table 9. The actual diversions during the 1940–1997 simulation constrained by water-availability total 85.4 m^3/s, with a shortage of 4.0 m^3/s, under the historical climate scenario, resulting in a volume reliability (R_V) of

$$R_V = \frac{85.4\ \text{m}^3/\text{s}}{89.4\ \text{m}^3/\text{s}}(100\%) = 95.5\%$$

Table 8. Comparison of Reservoir Storage with Historical and 2050 Climate

	Total 590 reservoirs		12 Brazos River Authority reservoirs		578 other reservoirs	
	Historical	2050	Historical	2050	Historical	2050
Capacity (Mm^3)	5,428	5,428	3,437	3,437	1,990	1,990
Mean (Mm^3)	4,810	4,185	3,011	2,711	1,799	1,474
Exceedance frequency	Storage as a percent of storage capacity					
100%	58.4	33.2	51.1	23.4	71.0	47.4
98%	63.6	37.1	57.1	31.1	74.8	50.2
90%	75.2	55.4	71.3	52.0	82.0	61.3
75%	83.4	69.9	81.2	71.5	87.3	67.0
50%	90.4	80.2	89.8	82.6	91.3	76.1
25%	96.3	87.1	97.4	91.1	94.5	80.1
10%	99.0	93.6	99.9	97.6	97.3	86.6

The corresponding reliability under the 2050 climate scenario is 90.0%. As shown in Table 9, climate change reduces the R_V for the total BRA diversions from 99.4 to 97.3%. The R_V for the aggregate of all non-BRA diversions is reduced from 94.1 to 87.3%. The impacts of climate change on BRA diversion rights are less severe than on other diversion rights because the BRA has a large amount of reservoir storage capacity relative to water-supply demands.

Summary and Conclusions

The Texas WAM system hydrology data sets are representative of a homogeneous constant twentieth-century climate condition. No long-term trends were detected in the statistical analyses of 1900–1997 naturalized flows. Hidden several-year streamflow cycles were detected and found to have significant correlation with ENSO events. These multiple-year cycles do not affect conventional applications of the WAM system in estimating long-term water-supply reliabilities. However, the cycles may have implications for further research in improving short-term reliability estimates for water-management decision support during droughts. Methods could possibly be developed that allow information regarding the current timing of ENSO-related cycles to be used to

Table 9. Comparison of water-supply Diversions with Historical and 2050 Climate

	Historical climate			2050 climate		
	Total	Brazos River Authority	Other	Total	Brazos River Authority	Other
Target diversions (m^3/s)	89.4	24.1	65.3	89.4	24.1	65.3
Actual diversions (m^3/s)	85.4	23.9	61.4	80.4	23.4	57.0
Shortage (m^3/s)	4.0	0.1	3.8	8.9	0.7	8.3
Volume reliability (%)	95.5	99.4	94.1	90.0	97.3	87.3

improve estimates of reliabilities in meeting water-use requirements over the next several months or perhaps the next several years.

With the CCCMA IS92a climate-change scenario reflecting a CO_2 concentration increase of 1% per year, the modeling approach adopted for the Brazos River Basin case study indicates that water-supply capabilities change significantly under 2050 climate conditions. The projected 2050 climate scenario resulted generally in a decrease in mean flows of the Brazos River and tributaries. This decrease was caused by decreases in precipitation and greater watershed evapotranspiration associated with increases in temperature. The scenario indicates increased temperatures and resulting evapotranspiration throughout the basin for all seasons. The changes in precipitation vary spatially and temporally and include both increases and decreases. Most of the decrease in runoff attributable to climate change occurs in the contributing portion of the upper half of the basin in the dry high plains. The upper basin area lying in and near New Mexico contributes essentially no runoff with or without climate change.

Because of human water use and regulation of streamflow by reservoirs, climate change affects regulated and unappropriated flows differently than naturalized flows. In general, reliability estimates for supplying water from the Brazos River and its tributaries are adversely affected by the projected climate-change scenario. However, the effects on water-supply capabilities are highly dependent on the reservoir storage capacity available to various water users for dealing with fluctuations in streamflows. Water resources are extremely variable regardless of future climate change. Water management in Texas is influenced greatly by the need for reservoir storage and demand-management strategies to deal with infrequent severe droughts. The prospect of future climate change significantly increases the uncertainties and risks already inherent in managing highly stochastic water resources.

The modeling strategy that is based on combining climate, watershed hydrology, and water-management models provides a general framework for evaluating the effects of possible future climate-change scenarios on water-supply capabilities. The component models and the interconnections among them are subject to continued refinements and improvements. Although uncertainties and approximations are also inherent in the WRAP and SWAT models, the greatest uncertainties are in the use of a global circulation model to predict future climate change. The challenge is to obtain better predictions of future climate change at the river-basin and subbasin scale. However, the general modeling strategy presented allows a predicted climate-change scenario to be translated to impacts on streamflows and water-supply reliabilities.

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