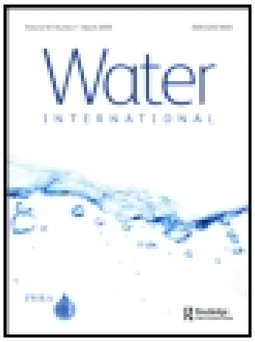

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Modeling the Impacts of Climate Change on Water Supply Reliabilities

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Abstract: *A strategy is presented for predicting impacts of future climate change on water supply capabilities, which is based on using output from a general circulation model (GCM) developed by the Canadian Center for Climate Modeling and Analysis (CCCma) with a watershed hydrology model and a river/reservoir system management model. The GCM output was used to adjust input to a watershed hydrology model in order to predict the corresponding impacts on streamflows. Output from the watershed model was used to adjust naturalized streamflows in a river/reservoir system management model in order to determine the corresponding impacts on water supply reliabilities. The methodology was applied in an investigation of capabilities for supplying water to the City of Houston and other users in the San Jacinto River Basin of Texas. Historical versus 2040 to 2059 climate scenarios were compared. Study results indicate that long-term mean streamflows under 2040 to 2059 climate conditions were higher than under historical climate due to significant increases in floods and other high flows. However, flows were lower for the future climate scenario during periods of normal and low flows. Seasonal variations in flows were greater with the future climate scenario than the historical climate. Reservoir storage fluctuations increase under future climate. Due to relatively large storage capacities, reliabilities for water supply diversions were improved somewhat under future climate conditions.*

Keywords*: Climate change, water supply, reliability, modeling.*

Introduction

Effective water management requires an understanding of the capabilities of river basin management systems to supply municipal, industrial, and agricultural water users and to maintain streamflows for ecosystem and other instream flow needs. Water availability for meeting reservoir storage, water supply diversion, and environmental instream flow requirements must be assessed based on various premises regarding future water management/use and climatic and hydrologic conditions. Texas has recently developed a Water Availability Modeling (WAM) System to support regulatory and planning activities throughout the state. This paper outlines a strategy for incorporating climate change into the WAM System by coupling it with climate and watershed hydrology models. An application to the coastal San Jacinto River Basin is presented to illustrate the analysis approach.

The modeling strategy provides a general framework for evaluating the impacts of climate change on water management. The three component models and the interconnections between them are subject to continued refinements and improvements. Although the work was motivated by the development of the Texas WAM System, the simulation models and strategies for combining them may be applied to river/reservoir/use systems located anywhere.

Global Climate Change and Impacts on Hydrology

In recent years, human-induced impacts on global warming associated with greenhouse gases have received much attention in the scientific research community (IPCC, 2001). The impacts of climate change on hydrology and water resources management has been addressed by various research programs and global, regional, and national assessments (Marshall et al., 1994; Mimikou, 1995; van Dam, 1999; Frederick et al., 1997; Lettenmaier et al., 1999; Gleick, 2000; Arora and Boer, 2001). All these assessments are nearly universal in suggesting that changes to the hydrology on the landscape will mainly follow changes to precipitation patterns. Throughout the 20th century, the average temperature of the United States has risen by about 0.6^{O} Celsius, and precipitation has increased by about 5 to 10 percent, mostly due to increases in intense rain storms (National Assessment Team, 2000). These trends are most apparent over the past few decades. The National Assessment Synthesis Team (2000) of the U.S. Global Change Research Program concluded that, assuming no interventions to reduce continued growth of world greenhouse gas emissions, average temperatures in the U.S. will rise by about 3 to 5^{O} C during the 21st century. This temperature rise is likely to be accompanied by more extreme precipitation and faster evaporation, leading to greater frequency of both very wet and very dry conditions. The IPCC (2001) estimates that increased temperatures are likely to lead to reduced lake levels and outflows potentially requiring conjunctive use of ground and surface water sources to meet municipal and other water demands. Coastal basins are especially important since they may play a role at the millennial time scale through dilution of the ocean salinity conveyor belts via continental runoff (Kerr, 1998).

Various General Circulation Models (GCMs) modeling global climate processes have been linked offline to hydrologic models representing watershed precipitation-runoff processes to predict the effects of climate change on streamflows in various regions of the world (van Dam, 1999). For example, Matondo and Msibi (2001) coupled the WatBall water balance model with three alternative GCMs developed by the United Kingdom Meteorological Office, Geophysical Fluid Dynamics Laboratory in the USA, and Goddard Institute of Space Studies in the USA to assess the impact of climate change on the Usutu River Basin in Swaziland. Their results indicate that future climate change will increase summer streamflows and decrease winter flows in that particular region. Arora and Boer (2001) used the CCCma model to investigate routed flows world wide and found decreased flow amplitudes and advancement in the phase of annual flow cycles in mid to high latitude regions due to increased fraction of precipitation falling as rain and the early onset of spring runoff maximum. Miller and Russell (1992) from un-routed flows found that 25 of the 33 major river basins in the world had increased runoff under future climate. A contribution made by this paper is examination of human water consumption and reservoir level changes under climate change in a U.S. coastal basin.

Overview of the Modeling Strategy

The objective of the study reported here was to incorporate the effects of climate change in water supply assessments. A GCM, watershed model, and river/reservoir system model were applied sequentially. A number of alternative climate (van Dam, 1999), watershed hydrology (Singh, 1995), and river/reservoir system (Wurbs, 1996) models are available. Development of the approach outlined here included selecting models for each of the three component tasks and devising methodologies for coupling them. The models adopted were:

- Global Circulation Model (GCM) developed by the Canadian Center for Climate Modeling and Analysis (CCCma), http://www.cccma.bc.ec.gc.ca;
- Soil and Water Assessment Tool (SWAT) watershed model developed by the Agricultural Research Service of the U.S. Department of Agriculture, http://www.brc.tamus.edu/swat/;
- Water Rights Analysis Package (WRAP) model developed by the Texas Water Resources Institute and Texas Natural Resource Conservation Commission, http://twri.tamu.edu and http://tnrcc.state.tx.us.

The general framework for incorporating the effects of climate change in assessing water availability included the following tasks:

- Temperature, precipitation, evaporation, and other climatic data for a particular climate scenario were provided by the CCCma GCM or optionally another GCM. Simulation results from a global-scaled climate model were downscaled for input to the SWAT model for the river basin of concern.
- Given climatic input data representing a particular climate scenario and parameters representing watershed characteristics, the SWAT model transformed precipitation to streamflow. SWAT simulation results were used to adjust WRAP naturalized streamflows for the effects of climate change.
- The WRAP model allocated sequences of naturalized streamflows to meet reservoir storage, water supply diversion, and instream flow requirements throughout the river basin and computed water supply reliability indices, flow frequency statistics, and other measures of water availability.

The SWAT and WRAP models are public domain and generalized for use anywhere. The web sites cited above provide information for those interested in obtaining the software and documentation. The models and methodologies for coupling them are described next, followed by a discussion of the San Jacinto River Basin investigation.

Modeling River/Reservoir/ Use System Management

The Texas Natural Resource Conservation Commission (TNRCC), its partner agencies, and contractors have developed a statewide Water Availability Modeling (WAM) System pursuant to comprehensive water management legislation enacted by the Texas Legislature in 1997 (Wurbs, 2001a). The WAM System consists of the generalized WRAP simulation model, WRAP input data sets for each of the 23 river basins of the state, user interfaces and utility programs, a geographic information system, and other data management systems. The WAM System is used by water management entities and their consultants in planning studies and preparation of water right permit applications and used by the TNRCC in evaluating permit applications.

The TNRCC administers a water rights permit system that allocates water resources among the numerous water users of the state. About 7,000 water use permits are held by river authorities, municipal water districts, cities, irrigation districts, other governmental entities, private companies, and individual citizens. Any significant change in water management or use requires TNRCC approval based on reliability evaluations of capabilities of proposed projects or management strategies in meeting proposed new water demands and impacts on all other existing water users.

Water Rights Analysis Package (WRAP) Model

WRAP is a river/reservoir/use system water allocation model designed for assessing hydrologic and institutional water availability and reliability (Wurbs, 2001b). WRAP is generalized for application to essentially any river basin or multiple-basin region. Input data files for each of the 23 river basins of Texas, including the San Jacinto Basin discussed later, are available through the TNRCC WAM System. Application of WRAP to river basins outside of Texas requires compilation of hydrologic and water use data sets for the river basin of concern. In WRAP terminology, water resources management and use requirements, policies, practices, and facilities are described in terms of water rights. The model provides considerable flexibility in modeling complex system configurations and operations.

A typical WRAP simulation study involves assessing capabilities for meeting specified water management and use requirements during a hypothetical repetition of historical hydrology. In the San Jacinto River Basin case study, capabilities for supplying present and projected future water needs are analyzed with basin hydrology represented by sequences of monthly naturalized streamflows and reservoir net evaporation-precipitation rates at all pertinent locations for each of the 684 months of a 1940 to 1996 hydrologic period-of-analysis. The model allocates water to meet the specified water use requirements during each sequential month of the 684-month simulation.

A monthly time step is used with no limit on the number of years in the hydrologic period-of-analysis. Water use targets vary seasonally over the 12 months of the year and may also vary as a function of reservoir storage or streamflow. Water use requirements (water rights) include reservoir storage, water supply diversions, return flows, environmental instream flow needs, and hydroelectric power generation. In each sequential month of the hydrologic period-of-analysis, volume accounting computations are performed for each water right in priority order.

The spatial configuration of a river/reservoir/use system is represented in WRAP as a set of control points. Essentially any configuration of stream tributaries and man-made storage and conveyance facilities may be modeled. In the Texas WAM Project, the number of control points has ranged from less than 100 for small basins to over 2,000 for the larger basins.

The WRAP simulation process for a river basin consists of the following tasks:

- Complete sequences of monthly naturalized flows covering the specified period-of-analysis at selected gauging stations are developed.
- Naturalized flows are distributed from gauged to all pertinent ungauged locations.
- The water management system is simulated, with water being allocated to each water right in priority order each month.
- Reliability indices, flow frequency relationships, and other summary statistics are computed, and the simulation results are organized in various optional formats.

River Basin Hydrology

River basin hydrology is represented in WRAP by naturalized streamflows and reservoir net evaporation-precipitation depths for each month of the hydrologic period-of-analysis at each pertinent location. The objective of the streamflow naturalization process is to develop a homogeneous set of flows representing a specified condition of river basin development. Naturalized streamflows represent the natural flows that would have occurred in the absence of the water users and water management facilities and practices reflected in the WRAP water rights input data set. The extent to which observed historical flows are naturalized is based largely on judgment. In extensively developed river basins, quantifying and removing all effects of human activities is not possible. For sites with relatively undeveloped watersheds, little or no adjustments may be necessary. Sequences of monthly flows representing natural hydrology are typically developed by adjusting recorded flows at gauging stations to remove the impacts of upstream reservoirs, water supply diversions, return flows from surface and ground water sources, and possibly other factors.

Naturalized streamflows may be distributed from gauged locations to ungauged sites using several alternative methods (Wurbs and Sisson, 1999). Most applications of WRAP have used either the simple drainage area ratio method or an option based on an adaptation of the Natural Resource Conservation Service curve number (CN) method. The CN is a watershed parameter reflecting land cover and soil type. If the CN and mean annual precipitation are the same for the gauged and ungauged watersheds, this method reduces to simply distributing streamflow in proportion to drainage area.

WRAP allocates naturalized streamflows to meet specified water right requirements subject to losses or gains associated with evaporation from and precipitation onto reservoir water surfaces and channel losses. A simulation starts with naturalized flows and computes regulated flows and unappropriated flows at all pertinent locations. Naturalized flows represent natural basin conditions without the effects of human water development and use. Regulated and unappropriated flows reflect the effects of reservoir storage and water use associated with the water right requirements. Unappropriated flows at a location are the amounts of streamflow still uncommitted after all water users have received their allocated share of the naturalized flow. Regulated flows represent actual physical flows and may be greater than unappropriated flows because some or all of the flow may be committed to meet instream flow requirements at that location and/or other water use requirements at downstream locations.

Water Supply Reliabilities

Simulation results may be organized in various formats including: the entire time series of monthly or annual values of various variables, water budgets, frequency statistics, and reliability indices. The results of a WRAP simulation are typically viewed from the perspectives of frequency, probability, percent-of-time, or reliability of meeting water supply, instream flow, hydropower, and/or reservoir storage requirements.

Reliabilities may be computed for either water supply diversion or hydroelectric energy generation targets for individual water users or the aggregation of selected groups of users. Volume reliability (R_V) is the ratio of the water volume supplied or energy generated (v) to the amount demanded (V), expressed as a percentage

$$R_V = \frac{v}{V}(100\%) \tag{1}$$

or equivalently the ratio of the mean actual rate supplied to mean target rate. Period reliability (R_p) is the percentage of months in the simulation for which a specified demand target is fully met without shortage

$$R_P = \frac{n}{N}(100\%) \tag{2}$$

where n denotes the number of months during the simulation for which the demand is fully supplied, and N is the total number of months in the simulation. A reliability table is also created that includes tabulations of both the percentage of months and the percentage of years during the simulation during which the amounts supplied equal or exceed specified magnitudes expressed as a percentage of the target demand.

Exceedance frequency relationships may be developed for naturalized flow, regulated flow, unappropriated flow, instream flow shortages, and reservoir storage. Exceedance frequency is defined as

$$Frequency = \frac{e}{N}(100\%) \tag{3}$$

where e is the number of months during the simulation that a particular flow or storage amount is equaled or exceeded, and N is the total number of months in the simulation.

Incorporating the Impacts of Climate Change

The purpose of a WRAP simulation is to assess capabilities for satisfying water supply, hydropower, instream flow, and reservoir storage needs. The amount of water available for a proposed new or modified water right permit and the impacts on other water users are typically of concern. Since future hydrology is unknown, naturalized streamflows computed by adjusting gauged historical flows to remove the effects of historical human water management/use are adopted as being representative of the hydrologic characteristics of a river basin. Thus, for most typical applications, the model simulates capabilities for meeting specified water management and use requirements during an assumed hypothetical repetition of historical hydrology.

However, due to climate change, historical hydrology may not be representative of future hydrologic characteristics of the river basin. This paper outlines a methodology developed to incorporate the effects of climate change in a WRAP simulation. The sequences of naturalized historical streamflows were adjusted to reflect future climate change. In performing WRAP simulation studies, alternative future climate change scenarios were reflected in the adjusted naturalized streamflows. SWAT coupled with the GCM was used to adjust the WRAP naturalized streamflows to reflect future climate conditions. Multiple WRAP simulations with alternative sets of adjusted naturalized streamflows to provide a comparison of water availability for alternative premises regarding climate change.

Modeling Watershed Hydrology

The Soil and Water Assessment Tool **(**SWAT) was used to adjust WRAP naturalized streamflows to reflect the impacts of future climate change. SWAT is a comprehensive watershed modeling package developed and maintained by the Grassland, Soil and Water Research Laboratory of the USDA Agricultural Research Service (ARS), and the Blackland Research Center of the Texas Agricultural Experiment Station (TAES), which are colocated in Temple, Texas, USA (Neitsch et al., 2001a; 2001b; http://www.brc.tamus.edu/swat/). The SWAT model was developed during the 1990s, incorporating features of several earlier ARS models, and continues to be expanded and improved.

SWAT is a daily time step watershed hydrology model generally using as input measured precipitation, maximum and minimum temperatures (Arnold et al., 1993), and generating other variables such as relative humidity, solar radiation, and wind speed (Richardson and Wright, 1984). SWAT simulates hydrologic processes and performs water balance accounting for 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 or watershed may be divided into any number of subwatersheds. The precipitation-runoff model has two major components: land surface water balance and in-stream reach routing. Inputs on land use, soils, land management practices, topography, hydrogeology, and weather are required to run the model. For agricultural lands, inputs must be specified regarding type of crop grown, planting and harvest dates, and management practices. SWAT outputs consist of the watershed water balance components (runoff, evapotranspiration, soilwater storage, and deep percolation) and stream routed hydrographs.

Application of SWAT to watersheds in the U.S. was facilitated by the Hydrologic Modeling of the United States (HUMUS) database of climate, land use, and weather. This database was developed in the previous HUMUS project, which involved applying SWAT to all of the river basins of the contiguous United States subdivided by hydrologic cataloging units (Srinivasan et al., 1995; Arnold et al., 1998). The HUMUS database was used for the San Jacinto River Basin.

WRAP naturalized streamflow data sets for the 23 river basins in Texas, including the San Jacinto Basin, were developed during 1997 to 2002, in conjunction with the TNRCC WAM Project, by adjusting gauged flows to remove the impacts of historical water management and use. In the present investigation, these flows were further adjusted to reflect climate change, based on two alternative runs of SWAT representing historical and future climate, as follows:

- Streamflows at pertinent locations in the river basin were generated by SWAT with temperature and precipitation data representing historical climatic conditions.
- With all other input held constant, the streamflows were generated again with SWAT with temperature and precipitation data representing specified future climatic conditions.
- Multiplication factors to relate the two sets of flows representing historical and future climate conditions were generated from the two alternative executions of SWAT.
- The resulting multiplication factors were used to convert WRAP naturalized streamflows from historical to future climate conditions.

The temperature and precipitation input to SWAT for future climate conditions were obtained from the output of a GCM. GCM results made publicly available by the CCCma were used for the San Jacinto Basin study.

CCCma GCMs

The Canadian Center for Climate Modeling and Analysis (CCCma) global circulation model (GCM) is a coupled atmosphere-ocean dynamics model (Flato et al., 2000). The terrestrial portions of the CCCma model have ten vertical levels discretized by rectangular finite elements. The land resolution is 3.75^o x 3.75^o, and oceans are modeled on a 1.875^o x 1.875^o grid with 29 vertical levels. The soils on the land are modeled using a one-layer bucket model soil while accounting for runoff and soil water storage with depth that is spatially variable depending 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.

The modeled and observed climate means, and variability over a 96 year period from 1900 to 1995 significantly agree at the 95 percent confidence level for North America for land surface temperature and land precipitation (Flato et al., 2000). Daily time series observation of precipitation, maximum, and minimum temperatures were obtained from the Canadian Climate Center for the First Generation Coupled Model (CGCM1), and only monthly data were supplied for the Second Generation Coupled Model (CGCM2). The CGCM1 models vertical and horizontal diffusion in oceans and CGCM2 models eddy stirring (Gent and McWilliams, 1990). The two different ocean mixing routines are different ways of modeling sea surface temperatures. Globally, the difference between the CGCM1 and CGCM2 model predictions for 2041 to 2060 climate compared to 1971 to 1990 climate is the more uniform warming of the southern hemisphere in CGCM2. Over the Texas Gulf region, the difference in model predictions for temperature are nearly the same with annual mean warming of air over the Gulf of about 2˚C, and over land of about 3°C. The CCCma models assume a CO_2 concentration increase of one percent per year (called IS92a).

Climate forcing to estimate naturalized streamflows for the San Jacinto River Basin under future climate conditions during 2040 to 2059 was generated from the coarse grid (3.75 x 3.75 degree grids) CCCma GCM. Reasons for use of the CCCma GCM was its acceptance in the climate modeling and assessment community (Zweirs, 1996), and daily and monthly CCCma GCM output data were readily available over the internet (http://www.cccma.bc.ec.gc.ca).

The Vegetative/Ecosystem Modeling and Analysis Project (VEMAP) could provide another alternative source of climate data (Kittel et al., 1995; 1998). While finer grid (0.5 x 0.5 degree grids) downscaled climate from the VEMAP are available, (at present only monthly precipitation downscales can be obtained from the public database requiring, as yet unreliable, daily precipitation generation from monthly values), when consistency between downscaled daily VEMAP climate and global scale climate has been determined, use of VEMAP weather in the GCM/SWAT coupling procedure outlined here will be investigated in the future.

San Jacinto River Basin Study

The 7,300 km^2 San Jacinto River Basin shown in Figure 1 drains into Galveston Bay on the Gulf of Mexico. The Texas Water Development Board (1997) projects that the 1990 basin population of 2,771,000 will more than double to 5,782,000 people in 2050. Houston, with a 1990 population of 1,741,000 people, is the largest city in the basin. Most of the remaining basin population is concentrated in smaller cities located near Houston. About 95 percent of the water use in the basin is for municipal and industrial purposes. Irrigated agriculture accounts for most of the remaining 5 percent. Instream flows and freshwater inflows to Galveston bay to support fisheries and ecosystems have in recent years become major concerns in managing water resources.

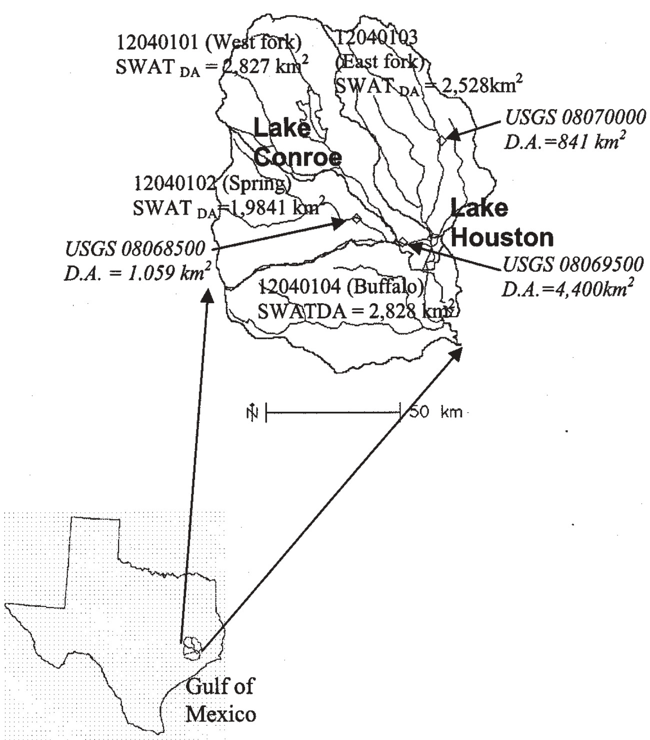

Figure 1. San Jacinto river basin; $SWAT_{DA}$ is the drainage area estimated by the Soil and Water Assessment Tool (SWAT) model using GIS data.

Groundwater supplied about 59 percent of the total water use in the basin in 2000 with surface water supplying the remaining 41 percent. Subsidence due to decades of overdrafting groundwater is a major problem in the area. The ground surface has been lowered as much as four meters during the past 50 years in some places. Motivated by severe ground subsidence problems, government entities have mandated a major shift away from ground water use, with a goal of 80 to 90 percent of the total water use being from surface water by about 2020.

Most of the water supplied by the San Jacinto River and its tributaries is stored and regulated by Lake Houston owned and operated by the City of Houston and Lake Conroe owned jointly by the San Jacinto River Authority (SJRA) and City of Houston and operated by the SJRA. About 20 percent of the total water used in the San Jacinto Basin in 2000 was imported from the Trinity River Basin, and interbasin imports are expected to increase greatly in the future.

Scope of the Water Supply Reliability Study

The San Jacinto River Basin was modeled with WRAP in 1998 to 2001 by a team of consultants for the TNRCC WAM Project. Historical 1940 to 1996 hydrology was combined with year 2000 water rights. The WRAP input data files developed for the TNRCC WAM Project were used for the study reported here. However, additional alternative modeling scenarios were developed to investigate the effects of climate change. Following the procedure outlined by this paper, an alternative set of naturalized streamflows was developed based on 2040 to 2059 climate projections to represent 2050 climate conditions. A hypothetical set of projected 2050 water use requirements was developed based on Texas Water Development Board (1997) water use projections. Modeling results for the following scenarios are presented later in this paper.

- Present (year 2000) water right permits combined with historical (1940-1996) hydrology
- Future (year 2050) projected water use combined with historical (1940-1996) hydrology
- Present (year 2000) water right permits combined with historical (1940-1996) naturalized flows adjusted to reflect 2040 to 2059 (simply labeled from here on as year 2050) climate.
- Future (year 2050) projected water use combined with historical (1940-1996) hydrology adjusted to reflect 2050 climate.

The WRAP naturalized streamflow data set from the TNRCC WAM System consists of 1940 to 1996 sequences of monthly flows developed based on adjusting gauged flows following the conventional WAM procedures outlined by Wurbs (2001a; 2001b). These flows represent natural 1940 to 1996 historical hydrology. Further adjustments to these flows to convert them to 2050 climate conditions were accomplished using the CCCma GCM output with SWAT as follows.

Adjusting Climate and Hydrology with SWAT and the CCCma GCM

The SWAT input data for the San Jacinto Basin were generated from the Hydrologic Unit Modeling of the United States (HUMUS) data set involving climate, land use, and weather from 1960-1989 (Srinivasan et al., 1995). The SWAT model was calibrated for watershed parameters such as curve numbers, evaporation compensation factor, and shallow groundwater storage by matching SWAT predicted monthly hydrographs during 1960 to 1989 against available U.S. Geological Survey (USGS) gauged flows at the outlets of the San Jacinto Basin hydrologic cataloging units (HCUs) shown in Figure 1. When flow observations during 1960 to 1989 were not recorded by the USGS, all pre-1960 monthly averaged flows were used for calibration of SWAT parameters.

National Weather Service (NWS) weather data (daily observations during 1960-1989) available within the HUMUS database for each pertinent hydrologic cataloging unit (HCU) were weighted by Theissen polygon areas to generate a standard weather record by HCU. The 30 years of data were assumed adequate for calibration of the hydrology model and modeling of flows during climate change. The future climate during 2040 to 2059 from the CCCma models CGCM1/M2 models were "downscaled" to HCUs via two methods: D1) assuming recurrence of historical 1970-1989 climate, with fluctuations dictated by 2040 to 2059 climate; and D2) assuming homogeneous climate across watershed, by directly using daily CGCM2 model outputs. Scenario D1 captures the spatial variability of historical climate while scenario D2 captures the temporal variability of predicted climate. Conservatively, the minimum predicted stream multiplication factors from either of D1 and D2 were selected to adjust the naturalized flows of the San Jacinto Basin WRAP model. The downscale D1 was performed by weighting the historical daily precipitation during each month by

$$\ddot{a}_P = \frac{P_{2040\text{-}2059} \text{ w/greenhouse gases and aerosol}}{P_{post\text{-}1995} \text{ w/o greenhouse gases and aerosol}}$$

Temperatures were added to daily maximum and minimum temperatures using:

$$\ddot{a}_T = \frac{T_{max/min} \text{ w/greenhouse gases and aerosol}}{T_{max/min} \text{ w/o greenhouse gases and aerosol}}$$

where P is the average monthly precipitation and T is the average monthly max/min temperatures.

The averages from the CCCma model output were given in units of millimeters/day for precipitation, and degrees Celsius/day for temperatures.

After calibration of the SWAT model against historical flow observations, the SWAT model was run using climate data generated by downscale methods D1 and D2. The SWAT predicted average monthly streamflows during 2040 to 2059 were divided by historical average monthly flows during 1970 to 1989 for D1, and for (scenario) method D2 SWAT flows due to CGCM1 daily weather during 2040 to 2059 were divided by flows during 1970 to 1989 to generate multiplication factors for naturalized streamflows by HCU for use in the WRAP input data. Monthly lake precipitation-evaporation rates were generated directly from CGCM2 assuming spatial homogeneity for water vapor demand by the atmosphere.

Discussion of Results of Hydrologic Modeling

Figures 2a through 2c show the match between USGS observed and SWAT predicted flows after calibration of subbasin parameters. Since contemporaneous USGS records with SWAT simulations during 1960 to 1989 for the West Fork of the San Jacinto River were not available, historical average annual flows from 1929 to 1954 were used. No stream gauges were available on the main stem of Buffalo Bayou. The SWAT calibration curves were significantly (p=0.05) similar to USGS observations. Because the USGS and SWAT drainage areas were different, the difference between SWAT and USGS measured amplitudes of flow is not surprising. The calibration parameters in the subbasins are shown in Table 1. Since no USGS flows were used for calibration of the Buffalo Bayou subbasin, these parameters were adjusted based on the other subbasins. The initial curve numbers were based on soil drainage class and land use within the subbasin (USDA-NRCS, 1985). Default curve numbers were used for the Buffalo Bayou subbasin. The canopy interception parameters for the brush cover in Texas were based on previous

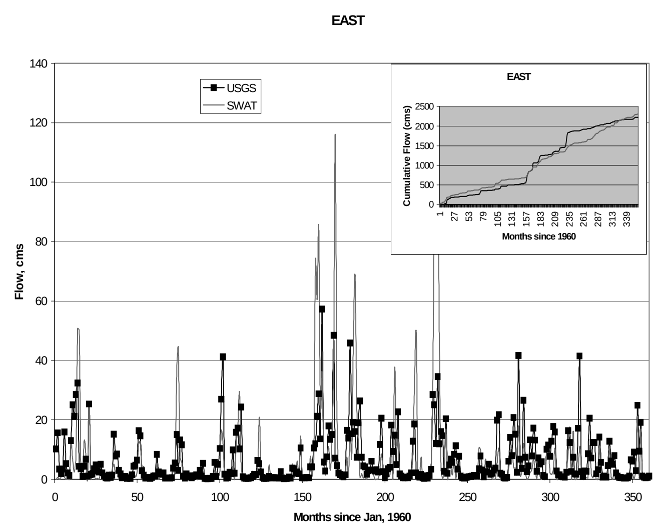

Figure 2a. Monthly SWAT and U.S. Geological Survey (USGS) measued flows after calibration for the East Fork (12040103). Inset is comparison of cumulative flows.

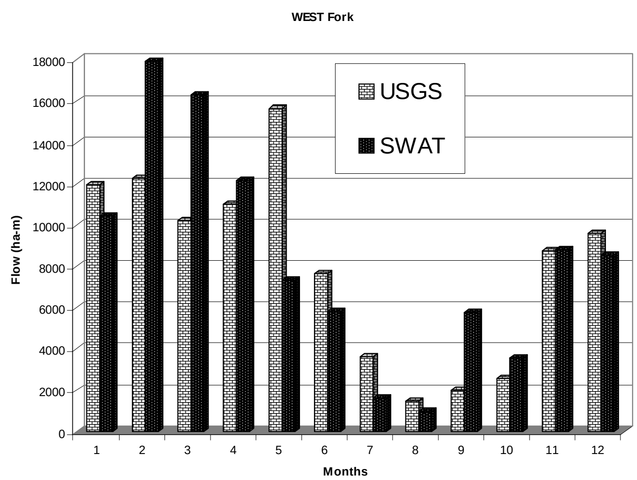

Figure 2b. Bar chart of averaged flows (in units of hectare-meters/month) of SWAT and USGS (id=8069500) flows based on monthlies during 1929 to 1954 after calibration of SWAT parameters on the West Fork of San Jacinto (12040101).

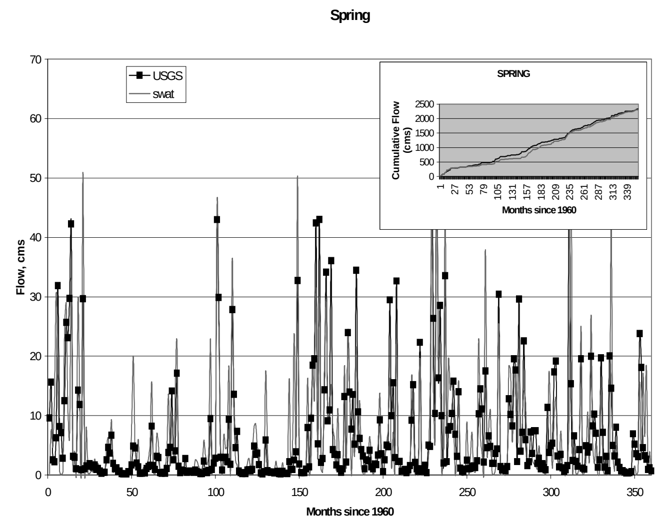

Figure 2c. The SWT predicted and USGS (measured flows on the Spring (12040102) sub-basin of San Jacinto. Inset is cumulative flow.

Table 1. Final SWAT Parameters by HCU after Calibration of SWAT Streamflows against USGS Observation

HCU	*Maximum Canopy Interception (mm)*	*Curve Numbers*	*Dominate Soil Types by % Area of HCU*	*Shallow Aq. and Min. Storage (mm)*
12040101	Shrub/brush = 15 Herbaceous = 5 Mixed woods = 10	Herbaceous = 84 Deciduous = 83 Evergreen shrubs = 55	Depcor (53%)-Loam fine sand Frelsburg (17%)-Clay Sorter (6%)-Silty loam Falba (4%)-Fine sandy loam	Quartz sand muddy sand & granite 125
12040102	Shrub/brush = 15 Herbaceous = 5 Mixed woods = 10	Herbaceous = 79 Deciduous shrubs = 72 Evergreen shrubs = 50 Mixed shrubs/grass = 55	Conroe (51%)-Granular loamy sand Wockley (47%)-Fine sandy loam Katy (2%)-Fine sandy loam	Quartz sand, muddy sand, and granite 125
12040103	Shrub/brush = 15 Herbaceous = 5 Mixed woods = 10	Herbaceous = 62 Deciduous shrub = 71 Evergreen shrubs = 71 Mixed shrub/grass = 54	Conroe (77%)-Granular loamy sand Sorter (13%)-Silty loam Wiergate (6%)-Clay	Quartz sand 175
12040104	Shrub/brush = 15 Herbaceous = 5 Mixed woods = 10	Grassland = 79 Deciduous shrub = 83 Evergreen shrubs = 83 Mixed shrub/grass = 79	Clodine (41%)-Loam Lake Charles (36%)-Clay	Quartz sand, muddy sand, and granite 125

work by Thurow and Taylor (1995) and brush management in Texas (Bednarz et al., 2000). The shallow aquifer materials for San Jacinto were obtained from the land resources map developed by Kier et al. (1977). During calibration, the curve numbers, and shallow aquifer storage volume in SWAT were altered until a best match was obotained with USGS flows. As shown in the table, the shallow aquifer storage for secondary aquifers consisting of quartz sand, muddy sand, and granite were found to be 125 mm, and for areas with recharge sand (quartz sand), 175 mm. Loamy sand is the dominant soil type in the San Jacinto Basin.

Figures 3a through 3d show the multiplication factors (flows during 2040 to 2059 divided by flows during 1970 to 1989) generated from downscale methods D1 and D2. The largest changes to flows were simulated in the east fork of the San Jacinto River, likely due to increased shallow groundwater storage and porous soils leading to relatively higher evaporation of water from soil-water storage during dry historical periods compared to the wetter future climate. In general, there are increased streamflows during fall and early spring, and decreased flows during summer under future 2040 to 2059 climate. Subak (2000) found a similar change to the phase in stream flow cycles in the U.K. under future climate.

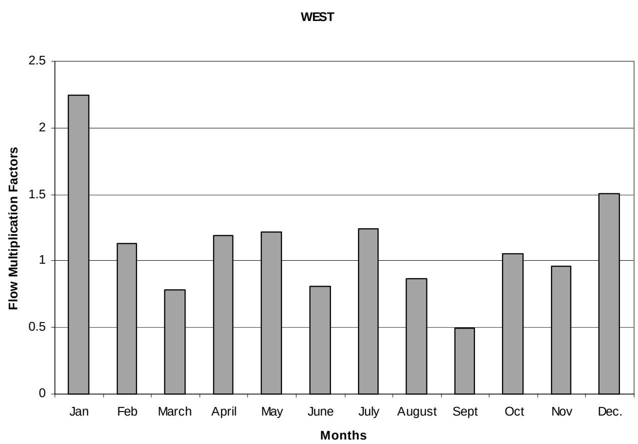

Figure 3a. Multiplication factors for Hydrologic Cataloging Unit (HCU) West.

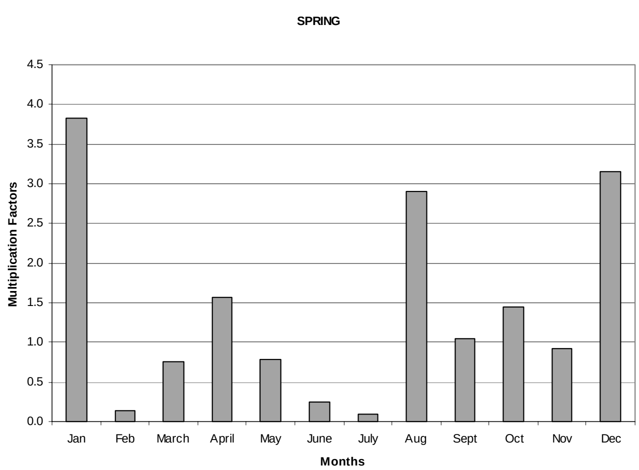

Figure 3b. Monthly multiplication factors for HCU Spring.

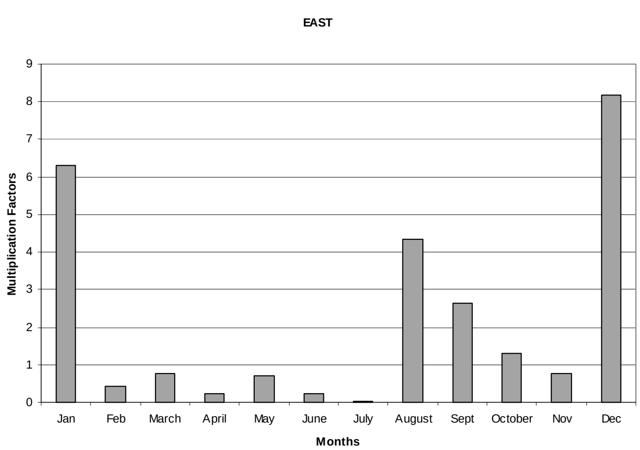

Figure 3c. Multiplication factors for HCU East.

WRAP-Based Assessment of Water Availability

Management and use of the waters of the San Jacinto River and its tributaries are controlled by 235 water right permits that include storage in 103 reservoirs. The WRAP model of the river basin includes 372 control points repre-

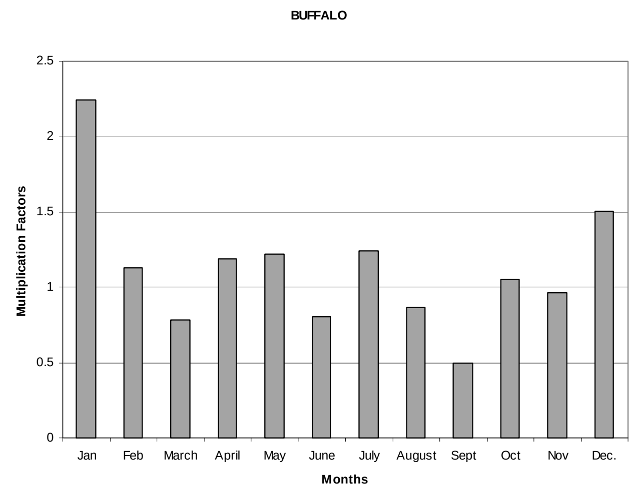

Figure 3d. Multiplication factors for HCU Buffalo.

senting locations of diversions, return flows, reservoirs, and other pertinent system features. The City of Houston and San Jacinto River Authority hold 49 percent and 45 percent, respectively, of the total diversion rights of 427 million m^3/year. The city operates Lake Houston and the River Authority operates Lake Conroe, which contain 25 percent and 68 percent of the 786 million m^3 of total reservoir storage capacity in the basin. Over 200 other entities hold permits for smaller diversions and 101 small reservoirs and lakes accounting for the remaining 7 percent of the total basin storage capacity. The WRAP model also includes the contributions to flows in the San Jacinto River and its tributaries attributable to wastewater treatment plant effluent and other return flows from water supply diversions from groundwater and interbasin transfer sources.

Climate and Water Management Scenarios

Four alternative WRAP simulations are presented, representing present (2000) and future (2050) water use combined with historical (1940 to 1996) and future (2050) climate scenarios. Future (2050) climate conditions are reflected in adjustments to 1940 to 1996 naturalized streamflows and net rates of reservoir surface evaporation less precipitation. The first simulation is directly from the TNRCC WAM System. The other three simulations reflect modifications to the WRAP hydrology (naturalized streamflow and net reservoir evaporation) and/or water rights (water management and use) data files.

The present (2000) water use scenario was based on the premise that all water users use the full amounts allowed in their water right permits that were effective in 2000, subject to water availability. The future (2050) water use scenario includes increasing municipal and industrial water use targets by 287 percent and decreasing agricultural water use by 20 percent. These 2050 water use requirements were adopted based on the following considerations.

- Texas Water Development Board (1997) projections indicate that municipal and industrial water use in the San Jacinto River Basin will increase by 47 percent between 2000 and 2050. Agricultural water use is projected by the TWDB to decrease about 20 percent.
- In 2000, 59 percent of the water supplied from sources within the basin was from groundwater. A stated goal of the TWDB and regional water management agencies is to reduce the groundwater contribution to 10 to 20 percent of total water use by 2020. For this modeling study, the groundwater contribution in 2050 was assumed to be 20 percent.
- In 2000, about 20 percent of the water demand in the San Jacinto Basin was met by supplies imported from the Trinity River Basin. For this modeling study, the contribution in 2050 from interbasin imports is assumed to remain constant with the same amounts as in 2000.

The 2050 water use scenario adopted for the study demonstrates the effects of climate change on water supply reliability in an extreme scenario of demands greatly exceeding supplies. The TWDB (1997) and other studies have recognized that increasing water demands in the Houston area will necessitate greatly increased import of water from the Trinity and Sabine Rivers. The contribution from interbasin transports is expected to be much greater than reflected in the model for the 2050 water use scenario. The modeling results presented here assess water supply capabilities in 2050 hypothetically assuming additional interbasin transfer projects are not implemented in the future.

Simulation Results

Simulation results are summarized in Tables 2 through 5. Streamflows at the basin outlet are inflows to Galveston Bay. Statistical characteristics of flows at the basin outlet are presented in Table 2. The naturalized flows are 1940 to 1996 gauged monthly streamflows adjusted to remove the impacts of reservoirs and human water management and use. For the 2050 climate scenario, the 1940 to 1996 monthly naturalized flows are further adjusted to reflect 2040 to 2059 climate conditions. As indicated by Table 2, the climate change adjustments increase the mean of the 57-year sequence of monthly flows by 20 percent from 0.599 m^3/s to 0.717 m^3/s. The standard deviation increases from 0.784 to 1.049 m^3/s. The flow-frequency relationships in Table 2 are presented in terms of the mean monthly flow that is exceeded during a specified percentage of the 684 months in the 1940 to 1996 hydrologic period-of-analyses. The future climate scenario is characterized by increases in flood flows and decreases in flow magnitudes in the more frequent lower-flow range of the flow-frequency relationship. In this region of Texas, high precipitation and streamflows tend to occur in Spring and Fall. The hot drier summers are characterized by low flows. The impacts of climate change vary seasonally as well as with wet-dry conditions.

Table 2. Flow-Frequency Relationships for Streamflows at the Basin Outlet

Water Use	*Naturalized*		*2000*	*2000*	*2050*	*2050*
Climate	*Historical*	*2050*	*Historical*	*2050*	*Historical*	*2050*
Mean (m^3/s)	0.599	0.717	0.786	0.908	0.776	0.890
St.Dev.(m^3/s)	0.784	1.049	0.747	1.018	0.683	0.933
Exceedance Frequency %	*Mean Monthly Streamflow at Outlet into Bay (m^3/s)*					
100	0.017	0.011	0.052	0.065	0.052	0.046
99	0.024	0.019	0.258	0.257	0.253	0.250
98	0.029	0.025	0.264	0.267	0.273	0.272
95	0.042	0.038	0.281	0.279	0.316	0.320
90	0.057	0.057	0.296	0.301	0.342	0.355
75	0.120	0.112	0.343	0.339	0.395	0.400
60	0.193	0.198	0.399	0.413	0.441	0.447
50	0.279	0.297	0.471	0.491	0.484	0.510
40	0.421	0.438	0.601	0.632	0.579	0.615
25	0.787	0.925	0.951	1.075	0.879	1.039
10	1.674	1.793	1.793	1.967	1.731	1.858
Maximum	7.189	7.552	7.161	7.724	6.359	6.723

Table 3. Summary of 57-Year Simulation Results for Lake Conroe

Water Use	*2000*	*2000*	*2050*	*2050*
Climate	*Historical*	*2050*	*Historical*	*2050*
Water Balance				
Stream inflow to reservoir (m^3/s)	7.28	10.26	7.33	10.27
Outflow to river (m^3/s)	2.80	5.91	0.99	2.21
Water supply diversions (m^3/s)	3.88	3.91	6.48	8.07
Evaporation-precipitation (m^3/s)	0.69	0.47	0.16	0.24
Change in reservoir storage (m^3/s)	0.09	0.03	0.30	0.25
Mean storage over 57 years:				
(million m^3)	409	471	64	166
(percent of capacity)	77.1	88.7	12.0	31.2

Table 4. Summary of 57-Year Simulation Results for Lake Houston

Water Use	*2000*	*2000*	*2050*	*2050*
Climate	*Historical*	*2050*	*Historical*	*2050*
Water Balance				
Stream inflow to reservoir (m^3/s)	52.16	65.61	51.46	62.84
Outflow to river (m^3/s)	43.21	56.55	31.75	43.21
Water supply diversions (m^3/s)	8.49	8.72	19.31	19.54
Evaporation-precipitation (m^3/s)	0.46	0.33	0.41	0.09
Change in reservoir storage (m^3/s)	0.00	0.00	0.01	0.00
Mean storage over 57 years:				
(million m^3)	192	196	131	155
(percent of capacity)	97.3	99.1	66.6	78.8

Table 5. Reliabilities for Water Supply Diversions

Diversion Requirements	*2000 Water Use*				*2050 Water Use*			
Water Supply Source	*Lake Houston*	*Lake Conroe*	*All Others*	*Basin Total*	*Lake Houston*	*Lake Conroe*	*All Others*	*Basin Total*
Mean diversion target (m^3/s)	8.72	3.91	0.91	13.55	20.98	11.21	1.31	33.50
Mean shortage (m^3/s)								
Historical hydrology	0.23	0.03	0.06	0.33	1.68	4.73	0.42	6.83
2050 adjusted hydrology	0.17	0.00	0.05	0.22	1.45	3.14	0.28	4.86
Volume reliability (percent)								
Historical hydrology	97.4	99.2	93.0	97.6	92.0	57.8	67.8	79.6
2050 adjusted hydrology	98.0	100.0	94.6	98.4	93.1	72.0	79.0	85.5
Period reliability (percent)								
Historical hydrology	84.2	99.0	29.5	-	54.8	52.3	7.2	-
2050 adjusted hydrlogy	87.6	100.0	48.0	-	52.1	69.2	24.3	-

Lake Houston on the San Jacinto River is located downstream of Lake Conroe on the West Fork of the San Jacinto River. With storage capacities of 531 and 197 million m^3, respectively, Lakes Conroe and Houston account for 93 percent of the reservoir storage capacity in the basin. Water balances for the 57-year simulation are presented in Tables 2 and 3. The streamflow flowing into the reservoirs plus the decrease in storage from the beginning to end of the 57-year simulation is accounted for in Tables 3 and 4 as the sum of: (1) outflow released to the river below the dam; (2) water supply diversions; and (3) reservoir surface evaporation less precipitation. The mean storage during the 57-year simulation is also shown for each of the four alternative combinations of climate and water use scenarios. The mean storage as a percentage of capacity for each of the 12 months of the year is shown in Figures 4a and 4b for three of the simulations. It might be expected that the larger lake (Conroe) would sustain higher percent of capacities under increased flows in the 2050 climate. However, this is not the case. Because Lake Conroe is forced to meet the down stream demands by Lake Houston and other water users by formal agreements, Lake Conroe has lower capacities than Houston. The higher regulation of Conroe compared to Houston under 2050 climate is evidenced in the larger change in reservoir storage. Overall, the 2050 water use is forecasted to have a dramatic impact on lake water levels which may be ameliorated to varying degrees in Lake Conroe and Houston by increased stream flows under future climate.

The many water supply diversions from the San Jacinto River and its tributaries reflected in the legal water rights permits administered by the TNRCC are divided into three groups in Table 5: (1) withdrawals from Lake Houston based on permits held by the City of Houston; (2) withdrawals from Lake Conroe authorized by permits held by the City of Houston and the San Jacinto River Authority; and (3) all other diversions. The City of Houston sells water to neighboring cities and industries as well as supplying its own citizens. The San Jacinto River Authority sells water to a number of entities including the City of Houston. Reliabilities for the aggregate of all water supply diversions from the San Jacinto River and its tributaries and lakes are also included in Table 4. During the 57-year simulation, 97.6 percent of the total target demand is met for 2000 water use requirements combined with historical hydrology. This volume reliability increases to 98.4 percent when the naturalized monthly streamflow sequences and net reservoir evaporation-precipitation sequences are adjusted to reflect 2050 climate. Volume reliabilities for the basin diversion targets are 79.6 and 85.5, respectively, for historical and 2050 climate.

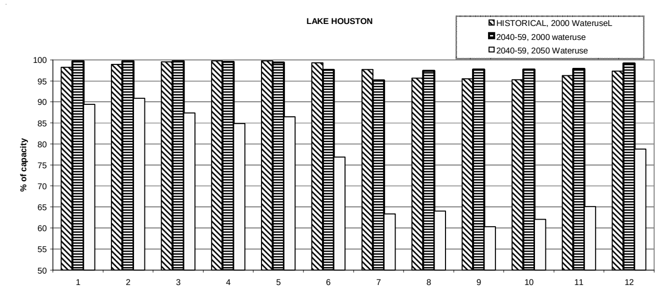

Figure 4a. Monthly average percent of capacity (19,784 ha-m) for water levels in Lake Houston.

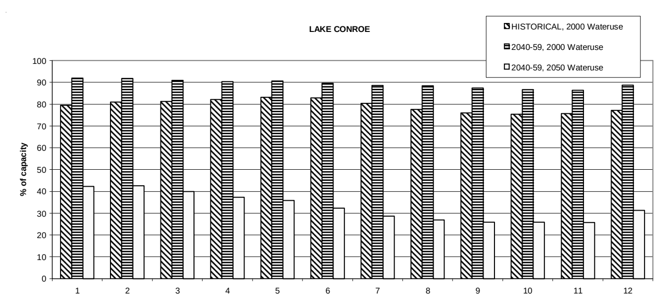

Figure 4b. Average monthly percent of storage capacity (53,068 ha-m) of Lake Conroe.

Summary and Conclusions

Output from a general circulation global climate model was used with a watershed hydrology model combined with a river/reservoir system management model to assess the impacts of potential future climate change on water supply capabilities. The CCCma GCM, SWAT, and WRAP models were adopted, and methodologies for using them together were developed. Other alternative models could be incorporated into the general modeling strategy instead of the selected models. Research is continuing on improving methods for combining general circulation, watershed, and water rights models. The general modeling approach presented here can provide a general assessment of the role of climate change in water supply reliability assessments.

Future climate change was found to slightly improve water supply reliabilities in the San Jacinto River Basin. Stream flows naturally exhibit great seasonal and random variations. Reservoir storage is necessary to develop dependable water supplies. For the range of stream flows that reflect normal and dry hydrologic conditions, predicted future climate change was found to result in a decrease in flow magnitudes (Table 2). Conversely, floods and other high flows were increased by climate change. Seasonal differences were greater under the future climate scenario. Climate change was characterized by an increase in long-term mean flows and a wider variation in extremes. Due to the significant reservoir storage in the San Jacinto River Basin, water supply reliabilities are a little better under the future climate scenario as compared to historical hydrology.

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