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Inaugural Issue

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Climate Change Impacts on Texas Water: A White Paper Assessment of the Past, Present and Future and Recommendations for Action

Jay L. Banner[1*], Charles S. Jackson[1], Zong-Liang Yang[1], Katharine Hayhoe[2], Connie Woodhouse[3], Lindsey Gulden[1], Kathy Jacobs[4], Gerald North[5], Ruby Leung[6], Warren Washington[7], Xiaoyan Jiang[1], and Richard Casteel[1]

Abstract: Texas comprises the eastern portion of the Southwest region, where the convergence of climatological and geopolitical forces has the potential to put extreme stress on water resources. Geologic records indicate that Texas experienced large climate changes on millennial time scales in the past, and over the last thousand years, tree-ring records indicate that there were significant periods of drought in Texas. These droughts were of longer duration than the 1950s "drought of record" that is commonly used in planning, and they occurred independently of human-induced global climate change. Although there has been a negligible net temperature increase in Texas over the past century, temperatures have increased more significantly over the past three decades. Under essentially all climate model projections, Texas is susceptible to significant climate change in the future. Most projections for the 21st century show that with increasing atmospheric greenhouse gas concentrations, there will be an increase in temperatures across Texas and a shift to a more arid average climate. Studies agree that Texas will likely become significantly warmer and drier, yet the magnitude, timing, and regional distribution of these changes are uncertain. There is a large uncertainty in the projected changes in precipitation for Texas for the 21st century. In contrast, the more robust projected increase in temperature with its effect on evaporation, which is a dominant component in the region's hydrologic cycle, is consistent with model projections of frequent and extended droughts throughout the state.

For these reasons, we recommend that Texas invest resources to investigate and anticipate the impacts of climate change on Texas' water resources, with the goal of providing data to inform resource planning. This investment should support development of 1) research programs that provide policy-relevant science; 2) education programs to engage future researchers and policymakers; and 3) connections between policy-makers, scientists, water resource managers, and other stakeholders. It is proposed that these goals may be achieved through the establishment of a Texas Climate Consortium, consisting of representatives from academia, industry, government agencies, water authorities, and other stakeholders. The mission of this consortium would be to develop the capacity to provide decision makers with the information needed to develop adaptation strategies in the face of future climate change and uncertainty.

Keywords: climate change, drought, paleoclimate

1. Jackson School of Geosciences, University of Texas, Austin, TX 78712 2. Department of Geosciences, Texas Tech University, Lubbock, TX 79409-1053 3. Department of Geography & Regional Development, University of Arizona, Tucson, AZ 85721-0076 4. Department of Soil, Water and Environmental Science, University of Arizona, Tucson, AZ 85721 5. Department of Atmospheric Sciences and Department of Oceanography, Texas A&M University, College Station, TX 77843-3148 6. Pacific Northwest National Laboratory, Richland, WA 99352 7. National Center for Atmospheric Research, Boulder, CO 80307-3000
*Corresponding author: banner@mail.utexas.edu

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FOREWORD

"Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems."

These words, from the *Intergovernmental Panel on Climate Change Technical Paper VI: Climate Change and Water* (Bates et al. 2008), sound a sufficiently sobering call for more research, more deliberation, and more informed actions in efforts to mitigate predicted climate change impacts on Texas' water resources. And now, bolstering the vital importance of serious and timely attention to these matters, a report issued in December 2008 by the U.S. Climate Change Science Program suggests that earlier projections may have underestimated the climatic changes that could take place by 2100 and that the United States faces the possibility of much more rapid climate change by the end of the century than previous studies have suggested (Clark and Weaver 2008).

"Climate Change Impacts on Texas Water," produced by the Environmental Science Institute and the Jackson School of Geosciences at the University of Texas at Austin, focuses on the impacts and uncertainties of climate change on Texas and its water resources. Understanding climate change impacts on water resources is critical because of the implications of these impacts for many other important sectors, including agriculture, energy, ecosystems, and public health. The paper provides an excellent presentation of potential global climate change effects on Texas' water resources; identifies future scientific research efforts deemed necessary to develop more reliable climate projections; and proposes recommendations designed to enhance further collaborations between research scientists, regional and state water managers, policy-makers, consultants, and the public. If implemented, these recommendations can lead to potential policy changes and resource management decisions that may help prepare Texas for climate change impacts on its water resources.

Almost all climate model projections show that Texas is extremely susceptible to significant future climate variability and has the strong potential of extreme stress on its water resources. This fact, coupled with a rapid and concurrent population growth, will likely push water supply and demand issues in the state, especially in the urban areas, to the "breaking point." Texas has one of the world's most robust economies, but if sound, scientifically based water infrastructure and water management strategies are not implemented, Texas could face serious social, economic, and environmental consequences.

Given the possibilities that perfectly legitimate, science-based scenarios present or imply, Texas must act now to develop and implement feasible and effective measures to mitigate climate change impacts on its water resources. Texas has the world's greatest concentration of experts in energy research, finance, law, science, engineering, and business development. All this knowledge and all these skills can be applied to make Texas a world leader in addressing climate change and its predictable impacts. *Climate Change Impacts on Texas Water* is an excellent example of the application of such knowledge and expertise.

Larry R. Soward, Former Commissioner
Texas Commission on Environmental Quality

SUMMARY OF RECOMMENDATIONS

Based on our study, we find that climate change may have significant impact on the future of Texas' water resources and that large uncertainties exist regarding the nature and extent of the changes and impacts. Understanding the changes in climate, the impacts, and the uncertainties will require new initiatives to conduct policy-relevant scientific research. As a guide to this research process, we make the following series of recommendations:

1. Establish a Texas Climate Consortium (TCC), consisting of representatives from academia, industry, federal, state and local agencies, water resource managers, and other stakeholders. The proposed TCC will be administered by the Texas Water Development Board (TWDB). The proposed mission of the consortium includes: a) to serve as a state-level equivalent to the Intergovernmental Panel on Climate Change (IPCC) to bring together experts and stakeholders to investigate and report on the latest climate science to help inform policy and management, b) to identify high-priority science and policy topics related to Texas' climate change and water resources, and c) to identify resources needed for research and education.
2. Incorporate large droughts of the past into water planning. Whereas the current use of the 1950s drought as the drought of record has provided a baseline for water resource planning, paleoclimate studies indicate that longer-term "megadroughts" occurred in the past. An investment in research to improve the temporal and spatial resolution and accuracy of proxies for paleoclimate reconstructions will provide a more extended and accurate drought history for Texas. This research can be used to determine whether droughts that better represent the extremes documented in the 13th and 16th century should be considered in water planning.
3. Develop a statewide, real-time monitoring network of climate and hydrologic variability so that the response of water resources to extreme climate events can be determined.
4. Improve the applicability of climate models for the Texas region by supporting research to improve methods

to use global climate model results for "downscaling" to model projections for regions in Texas and assess the sources of uncertainty in climate model projections to determine how well models can simulate observed climate variability at diurnal to decadal time scales and how well they can replicate processes that control Texas climate (e.g., generation of tropical storms, winter cold fronts).

5. Continue to advance the use of adaptive management strategies for Texas' water resources.
6. Determine the impacts and calculate the costs of projected climate change to the state's economy, including the long-term costs of not planning for changes in water availability due to climate change.
7. Advance research on the relationship between Texas' water supply and energy use and incorporate the findings into water planning.
8. Encourage and support development of K-12 and university-level education programs on the science and policy of climate change and water resources to inform and inspire future researchers, policy-makers, and citizens.

INTRODUCTION

In April 2008, the conference *Forecast: Climate Change Impacts on Texas Water 2008* was held at the State Capitol in Austin, Texas. It was cosponsored by the Environmental Science Institute and the Jackson School of Geosciences at The University of Texas at Austin, the River Systems Institute at Texas State University, and the Texas Water Resources Institute at Texas A&M University. The conference focused on what we know and what we need to gain knowledge about regarding the effect of climate change on Texas' water availability and on the Texas communities and ecosystems that depend on reliable sources of water. The conference featured presentations by scientists who study climate change and who investigate how climate change may affect Texas and our water resources.

The future of Texas' water supplies is difficult to predict with confidence because of the large number of factors that influence precipitation and water storage. At the same time, state-of-the-art research is currently available to help inform policy decisions, but more research is needed to fully address policy and planning needs. This white paper first reviews what is known about how global climate change may affect Texas' water resources. We then outline research steps necessary to build more reliable regional climate projections. We conclude by providing a set of recommendations for research that may be useful for guiding potential policy changes and resource management decisions.

Our intention in writing this white paper is to further interactions between research scientists, regional and state water managers, policy-makers, consultants, and the public, as they pertain to assessing the impacts of climate change on Texas' water resources. The goal of the recommendations is to help the state build resilience in the face of an uncertain future, a future where the only certainty is that future climate conditions in Texas will not resemble those experienced over the past century. By acknowledging this uncertainty and developing robust, relevant tools capable of quantifying future uncertainty, we believe it is possible to prepare the state of Texas for successful adaptation to future climate change and its impacts on water resources.

We recognize that the problems associated with climate change impacts on Texas' water resources go beyond the subjects considered in this white paper. For example, steps to mitigate climate change, such as energy conservation, developing alternative energy and carbon sequestration, and efforts to increase water conservation, are only generally treated here. These are all considered in detail in other available and well-referenced reports (e.g., IPCC 2007c; US EPA 2008; Bates et al. 2008). The focus of this white paper is the impacts of climate change in Texas on the state's water resources.

CURRENT UNDERSTANDING OF CLIMATE CHANGE IMPACTS ON WATER RESOURCES

Water resources around the world are already stressed by rapid population increases, rising demand, and limited supply. In many regions, climate change will exacerbate existing stresses, leading to increased competition for water resources and raising the specter of water shortages. Exactly how climate change will affect a specific region's water resources is dependent on physical and social characteristics unique to each region. The Southwest has been characterized as one of seven geopolitical "danger zones" in the world, due to both vulnerability to significant future climate change and rapidly growing populations and cities (Sachs 2008). Using Seager et al.'s (2007) definition, the "Southwest" is all land between 125°W and 95°W and 25°N and 40°N. This includes most of Texas. Here we summarize the current understanding of principal climate change impacts on water at the global and national scale. We then build on this discussion to provide a more detailed discussion of Texas-specific impacts.

General impacts of climate change on water resources

The potential impacts of climate change on water resources at the global and national scale have been described in recent reports by the Intergovernmental Panel on Climate Change and the U.S. Global Change Research Program (IPCC 2007b; Bates et al. 2008; USGCRP 2009). At the global scale, a number of projected impacts of climate change on freshwater resources include (Bates et al. 2008):

- Changes in the availability of drinking water, resulting from shifting patterns of precipitation and evaporation, rapidly shrinking glaciers and snowpack that provide water to over half of the world's population, and changing water demands
- More frequent and intense extreme events, including floods and droughts
- Increased risk to coastal areas due to rising sea level, storm surge floods, and increasing ocean temperatures
- Increases in water pollution and shifts in aquatic biology resulting from increased water temperatures
- Both growth and shrinkage in water boundaries resulting from rising sea level, changing precipitation patterns, and changing flow to lakes and streams

Climate change impacts specific to Texas water: Past, present, and future

Texas climate

Texas is located in climate zones that transition from the humid Southeast United States to the arid Southwest United States. The state's climate is characterized by a north-south gradient in minimum annual temperature and a strong east-to-west moisture gradient, from 145 cm of rainfall per year (57 inches/yr) in the east to less than 25 cm/yr (10 inches/yr) in the west (Fig. 1). The climate of Texas is influenced by a complex range of atmospheric processes, physiographic features, and moisture sources (Fig. 2). The North American Cordillera funnels cold air southward into Texas, whereas the Gulf of Mexico serves as Texas' main moisture source and a moderating influence on temperature on the land surface (Nielsen-Gammon 2010). The Pacific Ocean is a less frequent moisture source for the region. Along the region's coast to the southeast, tropical storms and hurricanes are infrequent but important weather systems. Texas experiences great extremes in rainfall, and large rainfall events may be triggered by a variety of mechanisms, including synoptic-scale and coastal fronts, topography, and large-scale ascent (Nielsen-Gammon et al. 2005). This range of sources and interacting processes produces significant variability in the intra- and interannual patterns of rainfall in Texas, making the prediction of recharge to aquifers and runoff to streams challenging. Texas spans 26 to 37 °N latitude, and as a result, the state's climate is influenced by the descending limb of the Hadley atmospheric circulation cell. This is one of several factors that produce semi-arid conditions in the western part of the state (Griffiths and Ainsworth 1981; Bomar 1995). In addition to these regional factors, Texas' climate is also influenced by more remote connections with other regions such as the tropical Pacific Ocean, where sea surface temperatures control El Niño-Southern Oscillation climate phenomena that influence rainfall and temperature in Texas. El Niño episodes typically bring higher than average rainfall to Texas, whereas La Niña episodes typically bring below average rainfall.

Among the factors that make Texas susceptible to drought are the aridity caused by high pressure associated with Hadley circulation, variations in the strength and position of the Bermuda High, and the influence of La Niña events (Fig. 1). Failure of the Southwest Monsoon, which brings warm moist air in July and August from the Pacific Ocean to northwest Mexico, Arizona, and New Mexico, can also result in drought in Far West Texas (Nielsen-Gammon 2010).

Past climate change in Texas

Climate change that is driven by natural processes occurs over many time scales. According to the IPCC (2007a), atmospheric warming over the 20th and 21st centuries is "unequivocal," and is "very likely" (greater than 90% probability) to have been driven by a combination of natural and anthropogenic processes. To place this warming into a broader context, geologic materials are analyzed that preserve information about past climate and can thus serve as "proxies" for time periods prior to instrumental measurement of temperature and rainfall. These paleoclimate proxies indicate that Texas experienced large changes in the past, on millennial time scales that in some cases follow global-scale glacial to interglacial cycles. These inferred changes are based on the analysis of sedimentary deposits, fossils, cave mineral formations, and other proxies (Toomey et al. 1993; Musgrove et al. 2001; Cooke et al. 2003). These studies produce a consistent reconstruction of central Texas as a much wetter and cooler region, covered by thicker soils, during the late Pleistocene time period, between approximately 25,000 and 15,000 years before present.

Instrumental records document variations in climate and hydrology based on observations, using devices such as thermometers and rain gauges. These records are generally limited to little more than a century and have formed a basis for water resource management and planning. The 1950s drought is commonly used as the worst-case-scenario for drought planning. Climate records have been extended further back in time using proxies such as tree rings, which can track annual variations in climate, and have been used to reconstruct precipitation, drought, and streamflow for past centuries to several millennia. These proxy records, which have been generated for many areas of the United States including Texas, place the 20th century events, such as the 1950s drought, into a long-term context. It can be concluded from these studies that the 20th century contains only a subset of the climatic variability that is evident over past centuries.

The magnitude of the 1950s drought is not unprecedented, and reconstructions show that more severe and sustained droughts occurred prior to the 20th century. For example, a reconstruction of Rio Grande headwaters flow using tree rings documents a drought in the late 1800s with 11 consecutive years of below-average flows (Woodhouse and Lukas 2006). Central and west Texas tree-ring reconstructions provide evidence for the occurrence of droughts that rivaled or exceeded the drought of the 1950s in this region. The most severe of these droughts occurred in west Texas during much of the 13th century (Fig. 3A), and in central Texas during the last half of the 16th century and at the turn of the 18th century (Cleaveland 2006). The 16th century included a period of "megadrought" that was nearly continental in scale (Stahle et al. 2000; Cleaveland 2006). Climate reconstructions in combination with climate model results suggest cool sea surface temperatures (SSTs) in the eastern equatorial Pacific Ocean as a driving mechanism for these megadroughts (Cook et al. 2008). An observational and model analysis of the major North American droughts in the Great Plains of the 20th century indicates that there is a regional sensitivity in the apparent driving mechanisms for these droughts (Hoerling et al. 2009). 20th century drought severity in the southern portion of the Great Plains (i.e., Texas) is strongly linked to Pacific equatorial SSTs, whereas drought severity in the northern portion is not. These climate observations and proxy records indicate that significant variability in water availability has occurred even in the absence of anthropogenic climate change.

In addition to multiyear droughts, the reconstructions of past climate discussed above also document slow, multidecadal variations in climate. This low-frequency variability is a challenge for water management approaches that consider climate as relatively stationary. Superimposed over the natural low-frequency variability will be trends in climate due to anthro-

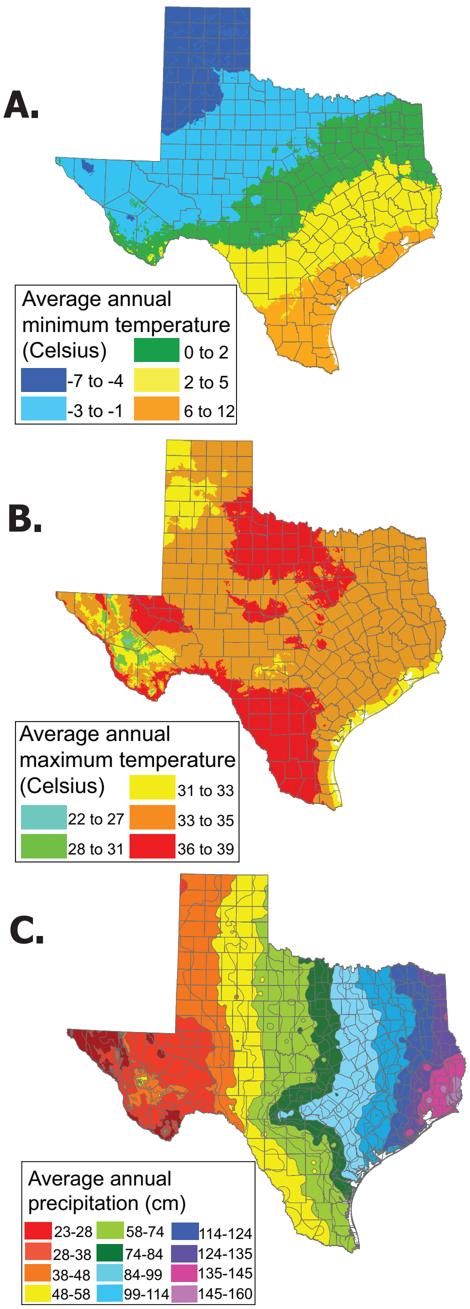

Fig. 1. A. Average annual minimum temperature; B. Average annual maximum temperature; C. Average annual rainfall (cm) for Texas. Data are from USDA National Resources Conservation Service for the time period 1971 to 2000 (USDA NRCS 2006).

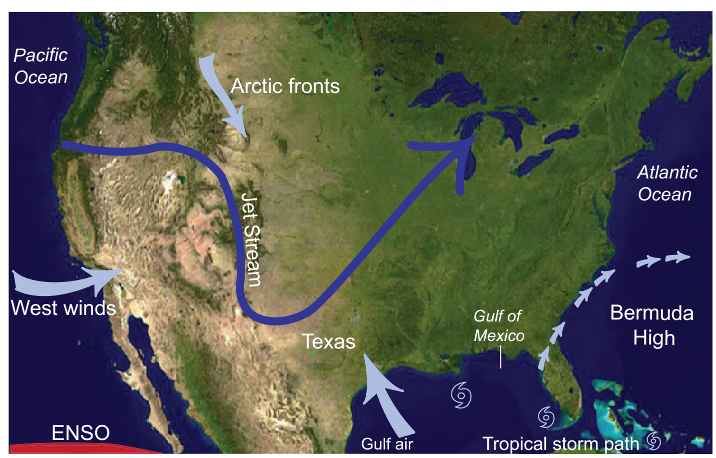

Fig. 2. Atmospheric processes in North America that influence the variability of Texas climate. Red 'ENSO' region schematically represents the northeast extent of the El Nino–Southern Oscillation climate phenomenon, which drives changes in sea-surface temperature in the tropical Pacific Ocean and which can influence rainfall and temperature variability in Texas. Modified from TWDB (2007).

pogenic influences that are expected to contribute to future changes in Texas' climate (Fig. 3). We therefore recommend that planning take into account a broader range of scenarios by considering both the natural variability of the extended records of paleoclimate data, along with 20th century records and 21st century projections. This recommendation necessitates reassessment of the use of the most severe drought in the instrumental record, which is the 1950s drought for most of Texas, as the worst-case scenario. Research collaboration among scientists, planners, and decision makers should be conducted to determine how best to incorporate the information from the paleoclimatic data into future planning. Such research should assess the need for improving the temporal and spatial resolution, temporal extent, and accuracy of proxies for paleoclimate reconstruction. More accurately determining such paleoclimate information from such proxies will allow the development of a more comprehensive climate history for Texas.

Recent temperature trends

During the last 130 years, measurements of observed surface temperatures of the Earth have shown warming globally and regionally, with increases in global mean temperature of almost one degree C (almost 2 °F). This warming is less than the 4–7 °C warming that occurred since the Last Glacial Maximum (around 21,000 years before present) to the pre-industrial era, but it has occurred at a rate that is ten times faster (IPCC 2007a, Chap. 6). The IPCC supported its 2007 announcement that global warming was unequivocal by showing that state-

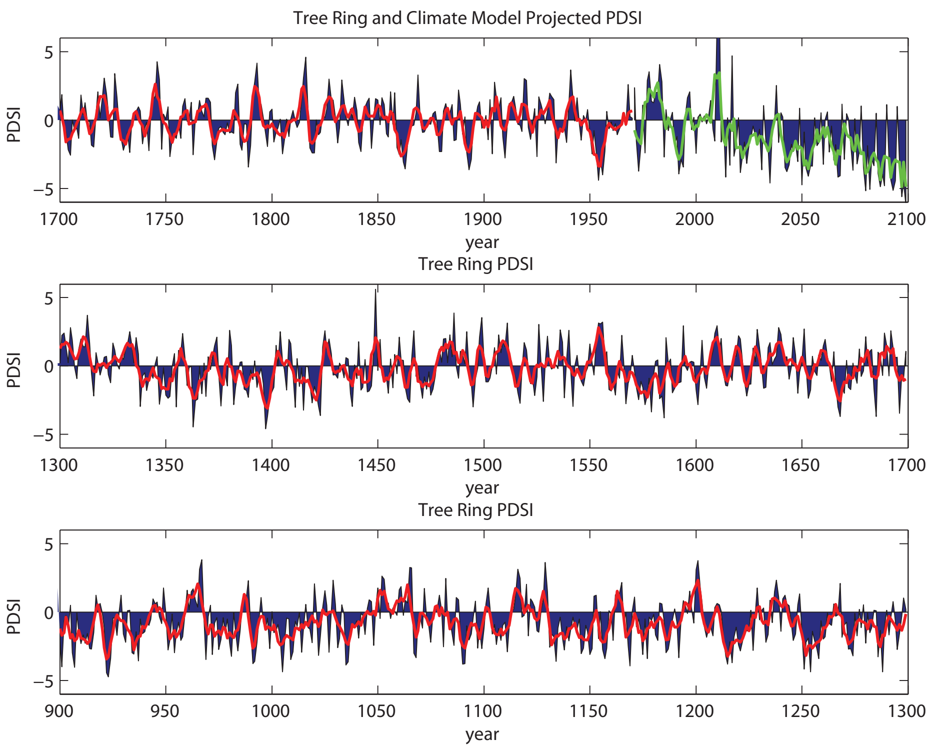

Fig. 3A. Drought history for the time period 900-1970 (red time series, based on tree-ring data), and one possible drought projection for the 21st century (green time series, based on climate model results) for west Texas. The Palmer Drought Severity Index (PDSI) is a measure of drought that incorporates rainfall and temperature information (Palmer 1965; Wells et al. 2004). The utility of the PDSI and other indices for drought is evaluated by the IPCC (2007a, Chap. 3). The PDSI tree-ring reconstruction is from the North American Drought Atlas (Cook and Krusic, 2004). Climate model data are from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 multi-model dataset. The model data are from downscaled regional climate projections from coarser-scale global climate model results, as described in Maurer et al. (2007). The featured projection is for IPCC emissions scenario A2, using the Canadian Global Climate Model (CGCM) projections of monthly mean temperature and precipitation and converted to PDSI using the self-calibrating algorithm of Wells et al. (2004). The red and green curves are 4-year running means of the PDSI index given in dark blue. The IPCC emissions scenarios involve a range of projected rates of economic growth, population growth, and balances between fossil and alternative fuels, as described in IPCC (2000). The A2 group of scenarios involves high-population growth and slow technological change in terms of energy use, and is also referred to as the "business as usual" group of scenarios.

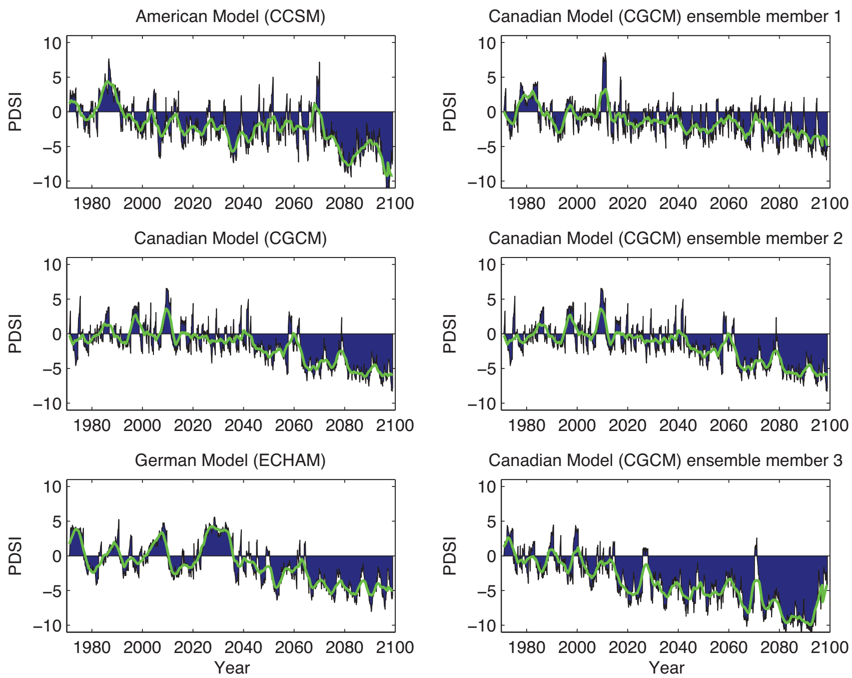

Fig. 3B. Climate model projections of the PDSI for west Texas over the next 100 years under emissions scenario A2 for three different climate models: the American CCSM model (top left), Canadian CGCM model (middle left), and German ECHAM model (bottom left); and for three different runs of the Canadian model for different initial conditions (three panels in right column). There is uncertainty in the severity of the drying as indicated by the spread in predictions among the American, Canadian, and German models. It is important to note that climate models do not provide information about the precise timing of particular drought or flooding events. This is illustrated by the right column, which presents three ensemble members (a kind of repeat experiment) from the Canadian model that were initialized with different starting conditions. Taking into account the range of uncertainties associated with the different models, the results indicate that west Texas has the potential to become much drier than it is at present.

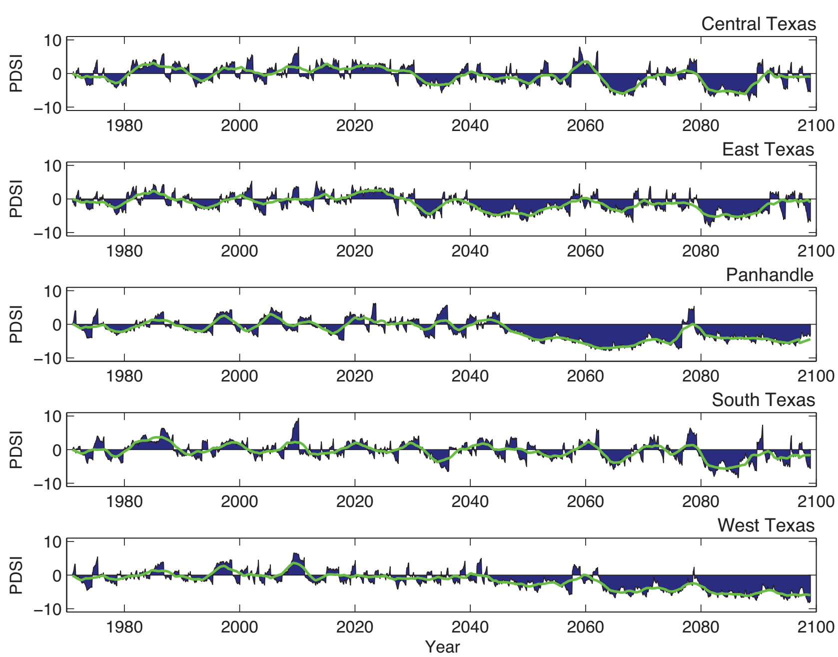

Fig. 3C. Climate model projections of the PDSI, based on the Canadian CGCM model for each of five regions in Texas.

of-the-art climate models were able to reproduce the observed temperature trends only when they included natural solar and volcanic forcings together with the anthropogenic increase of greenhouse gases (Fig. 4). This inability of the models that lack anthropogenic forcings to reproduce observed temperature trends is largest over the past three decades. Although the average change in surface temperature has been only 1 °C, the warming across the globe has not been evenly distributed. Larger warming is concentrated at the poles and over the continents, so that local climate change may be significantly different from the global average change. Similarly, surface temperature is projected to increase unevenly, with larger changes over land than over the ocean. In Texas, there has been relatively rapid warming over the past three decades, yet over the past century, there has been a negligible temperature change (Fig. 5, TWDB 2007). Warming similar to the global average has occurred over the past century in the subtropical, southern part of the state (Yu et al. 2006).

Climate change projections

Global and regional climate models are improving rapidly, both in terms of geographic resolution and in terms of representing the physical processes of climate. A larger number of model simulations produced for different scenarios exist than in the past, which gives us a greater basis for estimation and assessment of probable future climate conditions. Model projections for the coming century for the interior west of the United States, including west Texas, project up to four times the global average warming that occurred over the 20th century (NRC 2007). Results of climate models from the IPCC

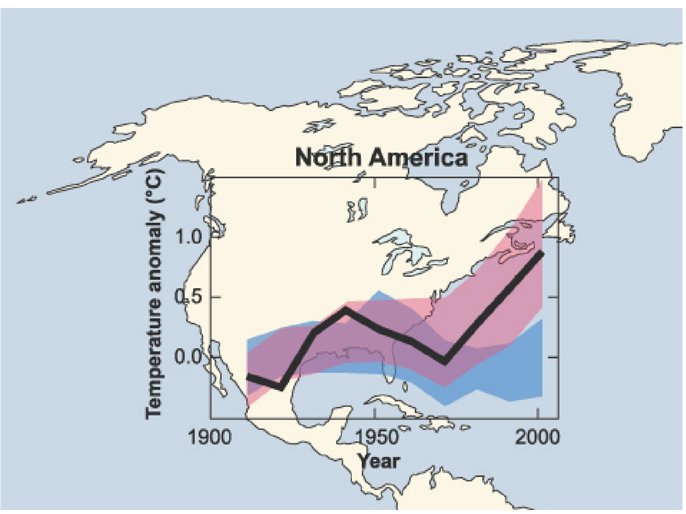

Fig. 4. Twentieth century temperature trend for North America. The black line is the observational trend, the blue band encompasses the range of climate model results that use only natural forcings, and the pink band is the range of model results that use both natural and anthropogenic forcings (Fig. SPM4, IPCC 2007a).

(2007a) project that average surface air temperature for Texas will increase by 2-5 °C over the 21st century (Fig. 5). Another manifestation of the projected warming is the larger number of days per year that a given region of Texas will experience temperatures over 100 °F. While in the recent past, approximately 10-20 days per year have been above 100 °F in some regions in Texas, climate models project more than 100 such 100 °F days per year by the end of the century under a high emissions scenario (Fig. 6). The projected temperatures for Texas are dependent on which emissions scenario is ultimately achieved by our society, as illustrated by the range in temperature produced using the A2, A1B, and B1 scenarios (Fig. 5).

The IPCC concluded in 2007 that the Southwest is likely to experience reduced precipitation in addition to higher temperatures. This conclusion is consistent with projected changes in the large-scale circulation, including an expansion and strengthening of the subtropical high and the associated subsiding motion and retreat of the jet stream and winter storm tracks toward the poles. Observations over the last three decades, as well as climate model simulations, indicate that the descending branch of the Hadley cell has expanded northward. This expansion of Earth's tropics is hypothesized to continue with global warming, which would lead to increased aridity in the Southwest (Hu and Fu 2007; Lu et al. 2007; Frierson et al. 2007; Seidel et al. 2008). Based on an analysis of a series of global climate modeling studies, Texas has been identified as one of three significant climate "hot spots" in North America, in terms of the region's susceptibility to projected changes (Koster et al. 2004; Diffenbaugh et al. 2008).

Several global analyses of climate model results provide projected temperature, precipitation, and runoff information for the Southwest region, which as defined here includes Texas at its eastern end. The analyses compare model results for periods in the 21st century with observations for the 20th century. These include the following:

1. An analysis comparing modeled precipitation minus evaporation for the period 2021–2040 with observations of precipitation minus evaporation for the period 1950–2000 projects pronounced drying of the Southwest (Seager et al. 2007).
2. An analysis comparing modeled runoff for the period 2041–2060 with observed runoff for the period 1900–1970 projects pronounced drying of Southwest, with west Texas experiencing more drying than east Texas (Milly et al. 2005). This study also demonstrated stronger agreement among the different models for the projected results for the western portion of the Southwest than the eastern portion.
3. An analysis comparing modeled temperature and precipitation for the period 2080–2099 relative to observations for the period 1980–1999 projects warmer

temperatures for the Southwest, with strong agreement across different model simulations (Meehl et al. 2007a). For the same periods and model comparisons, precipitation is projected to be lower in the Southwest. These models do not project a pronounced west-east gradient in drying across Texas, and there is more agreement among different model simulations for the result of lower winter precipitation in the western portion of the Southwest than for the result of lower winter precipitation in the eastern portion. Agreement among the different model simulations is significantly weaker for precipitation than for temperature (Meehl et al. 2007a).

In summary, the implications for Texas of these global climate model and observation analyses are that 1) compared with the 20th century, Texas is projected to be warmer and drier for the three different 21st century time periods investigated: 2021–2040, 2041–2060, and 2080–2099; 2) there is stronger agreement among the models regarding the predictions of increasing temperature than for the predictions of decreasing precipitation; and 3) there is not strong consensus regarding 21st century differences across the state in terms of the extent of decreasing precipitation and runoff.

We further focus here on constraining future aridity in Texas by considering projections for the Palmer Drought Severity Index (PDSI) for different climate models and for five different parts of the state (Fig. 3). Future aridity in Texas appears to be significant and comparable to the megadroughts of the past. For example, model projections for west Texas show that nearly every decade from 2040 to 2100 includes a drought of similar or longer duration than the drought of the 1950s (Fig.s 3A, 3B). There are considerable uncertainties in the timing and magnitude of the model projections, illustrated by the differences in results among different climate modeling research groups, and among repeat model runs with different starting conditions within the same research group (Fig. 3B). Climate models are not capable of predicting timing and magnitude of individual drought events. Given these limitations in the models and the differences in their results, some notable similarities among all of the model results exist for the projected increases in aridity (Fig. 3B). While some parts of the state may receive more annual precipitation (Jiang and Yang sub-

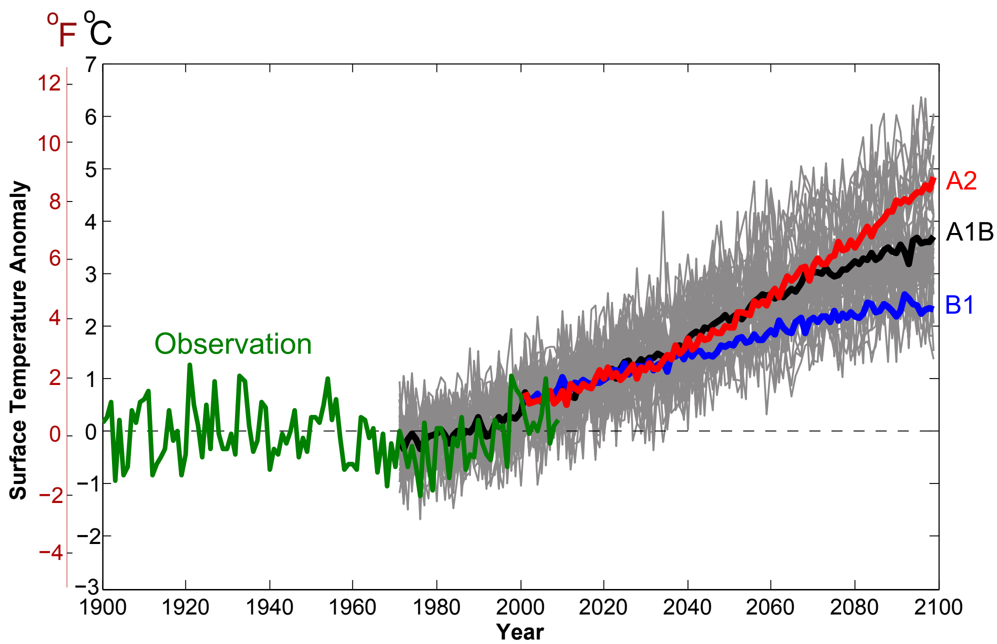

Fig. 5. Observed and modeled surface temperature anomalies for Texas. The observed anomalies are yearly observed departures from the 30-year observed mean climatology from 1971 to 2000. Modeled changes in annual mean surface temperature are averaged over ensemble members for each of the 16 models (and 39 total simulations) that participated in the IPCC Fourth Assessment Report (2007a). The future climate projections are based on three different emissions scenarios, A2, A1B, and B1. For the A1B scenario (balanced energy use) the gray trend represents all model results and the black trend denotes the average. For the B1 (purple trend, rapid economic change and clean and resource efficient technology) and A2 (red trend, business as usual scenario as described in Fig. 3) only the averages are shown. Emissions scenarios described in IPCC (2000). Anomalies for each model are shown relative to that model's mean climatology from 1971–2000. The model data are from downscaled regional outputs from models that participated in the World Climate Research Programme as described in Fig. 3. The source of the observations is the National Climatic Data Center dataset (Guttman and Quayle 1996). From Jiang and Yang (submitted).

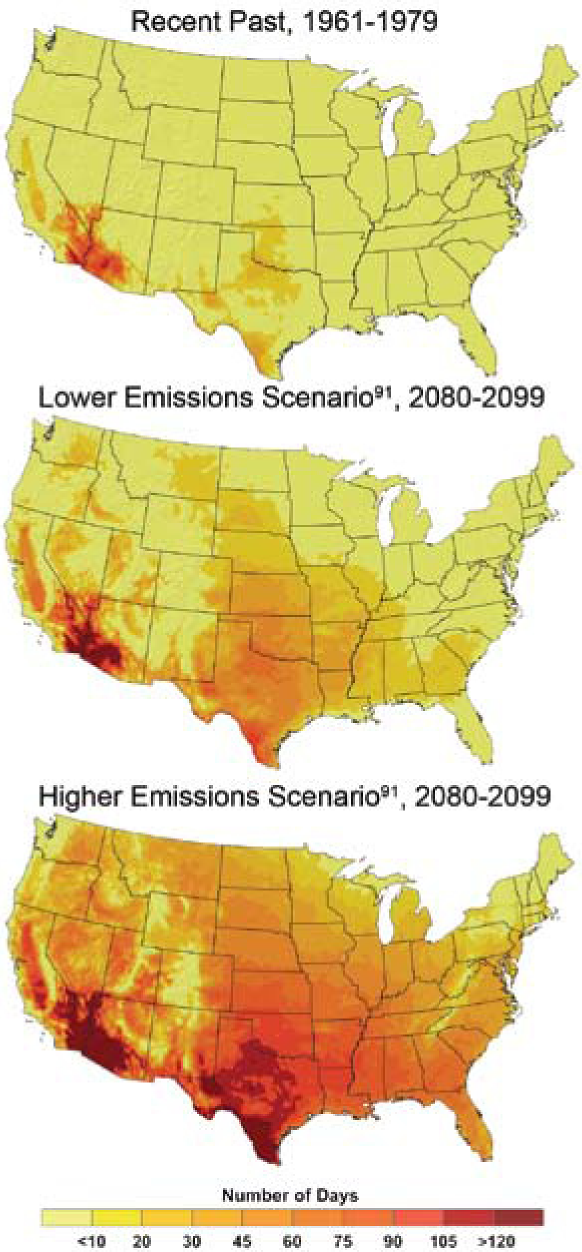

Fig. 6. Recent (1961-1979) and projected future (2080-2099) temperature changes in the US for two emissions scenarios (B1 and A1). Temperature changes expressed as the number of days per year with temperatures above 100 °F. In the higher emissions scenario A1, some regions of Texas will shift from 10-20 days in the recent past to more than 100 days per year in which the temperature exceeds 100 °F. From U.S. Global Change Research Program (2009), following approach of Hayhoe et al. (2004, 2008). Emissions scenarios described in IPCC (2000).

mitted), the net result of projected increased temperatures is proposed to be drier conditions moving eastward relative to today (Yu et al. 2006). A projected increase in aridity through the 21st century is common to the model results for all regions in Texas (Fig. 3C). It is proposed that on the time scale of years to decades the normal climate of the Southwest may resemble that of the drought of the 1950s (Seager et al. 2007).

The high variability and uncertainty in the precipitation forecasts for Texas over the 21st century (Tebaldi et al. 2006; Meehl et al. 2007a; Jiang and Yang submitted) suggest that climate change impacts on water availability would be difficult to project. Two factors, however, indicate that evaporation may be a more important and more predictable determinant in projections of water availability in Texas. First, there is much stronger agreement between model forecasts of temperature increase and less variability in the forecasted temperature increases (Fig. 5) compared with precipitation projections (Tebaldi et al. 2006; Meehl et al. 2007a). Second, evaporation plays a large role in Texas' hydrologic cycle, as evidenced by Nexrad estimates of precipitation and streamflow data that indicate that nine out of every 10 drops of rain that fall on Texas leave Texas as evaporation rather than as runoff to streams (C. David and others, UT Austin, personal communication). This is based on the assumption that submarine discharge of fresh groundwater is minor relative to streamflow and evaporation, and this assumption is in agreement with global-scale estimates (Burnett et al. 2003). These two factors are consistent with evaporation dominating over precipitation in governing future dryness indices such as expressed by the PDSI.

Different mechanisms are attributed to the proposed future and recorded past droughts in the Southwest. The projected future drying in this region is consistent with the expansion of the Hadley circulation and a poleward shift of the westerlies and storm tracks driven by greenhouse gas forcing (Hu and Fu 2007; Frierson et al. 2007; Lu et al. 2007; Seidel et al. 2008, Cook et al. 2008). The droughts of the past, in contrast, appear to be associated with changes in SSTs in the eastern equatorial Pacific Ocean associated with La Niña episodes and solar forcing (Cook et al. 2007, 2008; Hoerling et al. 2009). As such, the paleorecord is not an ideal analog for future droughts. As noted by Cook et al. (2008), "It is thus disquieting to consider the possibility that drought-inducing La Niña-like conditions may become more frequent and persistent in the future as greenhouse warming increases." Thus, key research areas include improved coverage of regional and temporal variability of past droughts in Texas, downscaled model projections for regional climate change, and an improved understanding of the driving mechanisms of both past and potential future droughts.

Research is also needed regarding the changes in soil moisture and runoff that will accompany these climatic changes. The relatively few studies that have been conducted on the projected impacts of climate change on Texas water resources have significant uncertainties associated with the projections (Muttiah and Wurbs 2002; Wurbs et al. 2005; CH2M HILL 2008). These studies provide estimates of the impacts of changes in temperature and precipitation on the San Jacinto, Brazos, and Colorado River drainage basins. Each estimate is based on assumptions that need to be validated concerning the use of climate-model information on the long-term mean and variability in changes in precipitation and temperature and resulting impacts on streamflows. The San Jacinto River Basin evaluation was the only study to find an increase in streamflow. A 20% increase in flow and 30% increase in variability in a 50-year model projection come from increased flood flows in spring and fall (Muttiah and Wurbs 2002). For the Brazos River Basin, a 50-year model projection finds reduced streamflow and a 5% reduction in reliability of this resource (Wurbs et al. 2005). Multiple climate model projections for 2050 for the Colorado River Basin yield estimates of significantly decreased runoff in the basin in central Texas, with estimates of future streamflow to the Colorado River to decrease by 13% to 34% (CH2M HILL 2008). Water-demand projections for 2100 for Travis, Hays, and Williamson counties in central Texas are 170% to 400% larger than for 2010 (LCRA 2010). Combining the impacts of increased demand on water due to population growth and projections in climate change by 2050, first-order water budget calculations indicate that, under drought conditions, Texas' surface water supply will fail to meet the state's water-use demands (Ward 2010).

SIGNIFICANT UNKNOWNS REGARDING CLIMATE CHANGE IMPACTS ON TEXAS WATER

In this section we consider the main impacts and uncertainties regarding climate change in Texas, with particular emphasis on water resources and more general consideration of impacts on public health and the state's economy. The following are the principal areas of uncertainty regarding the scientific community's understanding of climate change impacts on Texas water resources.

1. Climate models are better at predicting mean climate than climate variability and climate extremes. Climate change projections are based on global circulation models that are best at replicating and projecting global scale climate. Although projections of future temperature are relatively robust in that there is good agreement between different climate models for most regions of the world, projections for precipitation at regional scales contain a higher degree of uncertainty (Meehl et al. 2007a; Deng et al. 2007). The applicability of such projections will be enhanced by an improved understanding of the sources of uncertainty through evaluation of the ability of different models to reproduce observed (e.g., 20th century) climate. Understanding how well physical and dynamic processes are represented and understanding climate feedbacks (i.e., links between processes that can enhance or diminish effects) are important, especially for the regions that influence climate in Texas (Tebaldi and Knutti 2007).
2. In general, there is less confidence in regional scale predictions than those at larger scales. For Texas relative to other regions, there is little agreement on the magnitude of changes in precipitation in the 21st century (Nielsen-Gammon 2010), although pronounced drying trends characterize most model results for the Southwest (Fig. 3; Milly et al. 2005; Seager et al. 2007; Meehl et al. 2007a). Whereas there are uncertainties and approximations in hydrologic models used for watershed management in Texas, larger uncertainties for such management lie in the use of global climate models for predicting regional climate change (Wurbs et al. 2005).
3. Texas is affected by short-term climate phenomena driven by changes in tropical SSTs, such as the El Niño–Southern Oscillation (ENSO). El Niño and its counterpart, La Niña, are not well predicted by global climate models, but they do have a strong correlation to specific climate patterns across the Southwest and in Texas (Wurbs et al. 2005; Kurtzman and Scanlon 2007; Cook et al. 2007; Meehl et al. 2007b; Hoerling et al. 2009). The Pacific Decadal Oscillation is another periodic climate phenomenon associated with the Pacific Ocean and ENSO (Newman et al. 2003) that also shows some correlation with Texas climate patterns, but to a lesser degree than ENSO (Kurtzman and Scanlon 2007).
4. Texas' vulnerability to severe weather from tropical storms and hurricanes is well established, yet there is only limited knowledge for predicting the impact of future climate change on the intensity and frequency of such events for Texas (Deng et al. 2007), as well as the response of water resources to such events. An increase in the frequency of such storms may serve to increase recharge to aquifers and runoff to streams. Negative consequences of such storm activity include damage to water resource infrastructure from flooding and winds, soil erosion, and contamination of aquifers from runoff and coastal storm surges. Although there have been recent advances in our understanding

of the relationship between global warming and tropical storm intensity and frequency, the specifics of this relationship and its potential impact on water resources have large uncertainties associated with them (e.g., Emanuel 2005; Webster et al. 2005; Knutson and Tuleya 2004; Pielke et al. 2005; Emanuel et al. 2008).

5. Local factors such as land-use change can significantly affect local climate, yet the role of these factors in climate change in Texas has not been examined in detail (Yang 2004; Scanlon et al. 2005). Feedbacks between climate change and land-use change in this region may be significant, as indicated by analysis of the 1950s and 21st century droughts in Mexico (Stahle et al. 2009).

Unique aspects of Texas water resources and unknowns regarding impacts of climate change

Unique aspects of Texas' groundwater and surface water resources add to the uncertainty associated with the impact of climate change on Texas water. Climate change will likely intensify a number of existing stresses on water supplies in the state.

Across the state, highly variable conditions exist for rates of recharge and storage, and flow regimes. All rivers cross Texas from west to east, discharging in the Gulf of Mexico, and most are not snow-fed. At a state level, Texas precipitation is relatively unique in the strong east-to-west decrease in rainfall (Fig. 1C). Consequently, water supply needs in west Texas are strikingly different from those in east Texas. At one extreme, arid regions in north Texas receive little rainfall and are highly dependent upon groundwater supplies via aquifers that recharge through playa lakes. For example, much of the recharge to the regionally extensive Ogallala Aquifer likely occurred during the last ice age, creating a challenge to this resource's sustainability in the face of increasing usage, changing climate, and slow, persistent decreases in availability over time (Scanlon et al. 2005). At the other extreme, the Edwards Aquifer is recharged by more frequent rainfall with runoff to small rivers, such as Barton Creek, and a fast-moving groundwater system. The resultant conditions of water resource availability can fluctuate rapidly in the Edwards, with the potential to exhibit very low flow and then shift quickly to normal levels (Mahler and Massei 2007). Such karst aquifers that recharge rapidly, as well as shallow, highly permeable clastic aquifers that are responsive to precipitation and drought (such as the Seymour and Lipan-Kickapoo aquifers) will be more susceptible to the impacts of climate change (Mace and Wade 2008; Chen et al. 2001).

Competition for resources, particularly water resources, is aggravated by the growth of the state's population. While population growth alone increases water resource needs, the basic services provided to support the burgeoning populations can compound the overall level of demand. For example, many Texans get electric power from traditional forms of energy generation, which are often water-intensive when compared to emerging energy generation technologies.

Climate change is likely to exacerbate a number of existing stresses in the state. Detailed projections of the impacts of climate change on south Texas agriculture, ecosystems, air quality, and water supply are provided in Norwine and John (2008). The implications of climate change for Texas' unique water resource conditions include the following:

1. With projected warming of Texas' climate, rivers and reservoirs will lose increasing amounts of water to evaporation.
2. The Rio Grande and other rivers are essential for irrigation but could experience a drastic reduction in streamflow or dry up if, as the balance of evidence indicates, droughts become more common. Significantly decreased river flow will damage agriculture, aquatic ecosystems, and the estuaries that depend on fresh–salt water balances for cash crops such as shrimp.
3. A global analysis using observational and model results suggests that more intense rainfall events are associated with global warming (IPCC 2007a, Chap. 3). For the period 2080–2099 relative to 1980–1999, the Southwest is projected to experience both an increase in precipitation intensity (with relatively weak agreement among models) and longer dry periods in between rain events and more heat waves (with relatively strong model agreement; Tebaldi et al. 2006). Implications of such projections for Texas include the potential to increase runoff and lessen the amount of water that infiltrates into the ground and recharges aquifers. Both increased runoff of rainfall and decreased infiltration of rain into soil have the potential to exacerbate water quality problems.
4. Agricultural productivity, already water-limited in much of the state, is vulnerable to an increased frequency of drought and to potential shifts in the locations of optimal growing zones for typical crops. Land-use change driven by agriculture in the High Plains of Texas has been shown to impact recharge and groundwater quality (Scanlon et al. 2005). Groundwater-irrigated agriculture may also be affected by dropping aquifer levels and rising electricity costs for pumping water.
5. Many forms of traditional energy generation require water that, due to climate-induced and other stresses, will be under demand in other sectors. Cooling water for coal-fired, natural gas, and nuclear power plants, for example, represents 40% of freshwater extraction

in the United States (King et al. 2008). The interdependence of energy and water is also evident in the significant amounts of energy expended for purifying and pumping freshwater. Severe drought could cause water-intensive energy generation to shut down, with cascading effects on the economy and health if brownouts or blackouts follow.

Population growth in Texas

Under any of several likely projections, Texas will have a population that is at least twice as large (at 35.8 million projected for 2040) as in 1990 (when it was 17.0 million) and may be more than three times as large, at 51.7 million (OSD 2006). Another projection has the state's population more than doubling between 2000 and 2060 from 20.9 to 45.6 million people, whereby 297 Texas cities are expected to more than double their population during this period (TWDB 2007). A rural-to-urban population shift is projected, with greatest growth in regions encompassing the Dallas, Houston, San Antonio, Austin, and McAllen areas. Such rapid population changes concurrent with climate change would exacerbate water demand and supply problems, particularly in urban areas.

Potential economic and human health impacts of climate change in Texas

Given the projections for warmer temperatures, more extremes (duration, time between occurrences, and intensity) in drought and rainfall, and rising sea level, there are potential economic and human health impacts for Texas. If temperatures rise as projected, human health will likely be affected by more heat-related illnesses, water quality impacts, and the northward spread of tropical diseases and pests. Rising temperatures also suggest that more regions in Texas will not attain EPA ground-level ozone standards (US EPA 2009). Many human health impacts of global climate change are also projected to occur via climate change impacts on water (Shea et al. 2007; Frumkin et al. 2008).

Projected climate changes also have the potential to negatively affect Texas' economy. The state's economy and land-use patterns will likely shift to adjust from traditional energy and agriculture to renewable sources and dryland agriculture (Norwood and Dumler 2002). Under a scenario of increasing aridity, Texas' second largest industry, agriculture, would be significantly impacted and the state's ability to meet electric power demands would be challenged. Rising sea level and changes in stream discharge into Gulf of Mexico estuaries would threaten coastal freshwater aquifers, and the coast's $2.5 billion economic benefit derived from tourism, recreation, and fishing (TWDB 2007). The Texas coast has experienced among the greatest sea level rises in the United States over the past 50 years, and is projected by the end of the century to experience among the greatest rises, including a projected 3.5-foot rise in Galveston (USGCRP 2009). The protection provided by barrier islands and coastal wetlands against storm surges would be significantly reduced or lost. Costs of replacement or replenishment of beaches, bays, and marshes and coastal development and infrastructure will likely be staggering. Developing a funding plan for the anticipated costs of water development and conservation efforts is another significant challenge (Texas Comptroller 2009). As noted by the TWDB (TWDB 2007):

> *"Not only is Texas' population rapidly growing, but it also has one of the world's most robust economies. If Texas were an independent nation, its economy would rank eighth in the world when measured by gross national product. Rapid growth, combined with Texas' susceptibility to severe drought, makes water supply a crucial issue. If water infrastructure and water management strategies are not implemented, Texas could face serious social, economic, and environmental consequences."*

The state of Texas already has a significant stake in, and could further benefit economically from, an expansion of climate-mitigating efforts, including the development of renewable energy resources, such as wind and solar power; underground sequestration of carbon dioxide from coal fired power plants; and energy trading systems. A significant unknown involves determining what the cost to the state will be if no action is taken. If no further climate mitigation efforts are undertaken, if major research programs into the climate change impacts on Texas water resources are not developed, and if no policy changes based on such research are enacted, what will the economic costs to Texas be in 10, 20, or 50 years?

There have been few attempts at determining the economic costs of climate change. A comprehensive analysis of the global economic costs of global climate change was undertaken by the United Kingdom (Stern 2006). This analysis includes costs of "business as usual" (i.e., assuming no mitigation actions are taken) and mitigation scenarios, and it applies the following three methods: 1) a consideration of the physical impacts of climate change on the economy, human life, and the environment; 2) application of integrated assessment models to estimate economic costs of climate change, and macro-economic models to estimate economic costs of the transition to low-emission energy systems; and 3) a comparison of the costs of social impacts of increased emissions with the costs of achieving emissions reductions. The costs of climate change impacts under a business as usual scenario are a reduction in global consumption per head (the value of goods and services bought by people) in the upper part of the range of 5% to 20%, whereas the costs of emissions mitigation are on the order of

1% of global GDP. The consensus conclusion based on the range of analytical methods is that the benefits of significant and early action will considerably outweigh the costs of no action (Stern 2006).

On a national scale, from 1980 to 2003, there were ten droughts estimated to have cost more than $1 billion dollars each (Ross and Lott 2003, Cook et al. 2007). The TWDB estimates the costs to Texas businesses and workers of a future water shortage similar to the drought of the 1950s, with no change in supply infrastructure or management strategies, to be $9.1 billion in 2010 and $98.4 billion by 2060 (TWDB 2007). Associated lost business taxes are $466 million in 2010 and $5.4 billion in 2060. Given our analysis that the proxy records and model projections indicate that the 1950s drought is not an appropriate worst-case scenario, these estimated costs should be taken as minima. Incorporation of the Stern approach into the TWDB economic models is an important next step in weighing the economic costs of no action for Texas. Integration of expertise from the communities of climate change, hydrology and hydrogeology, land-use change, water resource engineering, and socioeconomics will be essential for a comprehensive understanding of the future of global water resources in general (Vorosmarty et al. 2000) and Texas' water future in particular.

RECOMMENDATIONS

Based on our analysis of the current state of knowledge regarding global climate change, Texas climate change, and the sensitivity of the state's water resources to these changes, we make the following series of recommendations.

1. **Establish a Texas Climate Consortium (TCC).** This proposed consortium will periodically bring together scientists, engineers, policy-makers, and consultants from industry, academia, and government agencies to assess current knowledge of climate change impacts on Texas water. Proposed missions for the TCC are to serve as a state-level IPCC-like resource for investigating and reporting state-of-the-art climate science to help inform policy and management; identify the highest priority science topics and make recommendations for essential research needed, and identify resources needed for research and education. The proposed TCC would be implemented by and report its findings to the TWDB. There are similar organizations in other regions of the United States, such as National Oceanic and Atmospheric Administration's Regional Integrated Sciences and Assessments (http://www.climate.noaa.gov/cpo_pa/risa/), but there is no such organization with a focus on Texas. The proposed TCC will develop the means to engage the science research community with the communities of regional water management, state agencies, industry, and other stakeholders on issues of climate change impacts on Texas water resources. It is proposed that an overarching consortium such as a TCC can best direct progress on the key recommendations below.
2. **Incorporate large droughts of the past into water planning.** Given the evidence for more intense and extended droughts in proxy records of Texas climate relative to the drought of the 1950s, research should be advanced to improve the accuracy, temporal range, and geographic coverage of such proxy records, as well as to improve our understanding of the driving mechanisms of such phenomena. Through improved paleoclimate reconstructions, a more comprehensive drought history can be developed and applied in Texas water planning. Although the climate of the past will not be an exact analogue for the future, natural variability as preserved in paleoclimatic data can be used to help plan for the future, as it will underlie anthropogenic trends. In particular, an understanding of natural, low-frequency climatic variability is essential for future water resource planning.
3. **Establish a statewide, real-time monitoring network of climate and hydrologic variability.** Extensive observations of Texas climate and water will allow scientists and planners to better apply leading-edge scientific understanding to Texas' needs. An extensive network that includes and advances present monitoring systems will allow researchers to better understand the detailed response of hydrologic systems to the onset and nature of extreme climate events. Such a network would be similar to those proposed by The Consortium of Universities for the Advancement of Hydrologic Science (http://www.cuahsi.org/) and The National Ecological Observatory Network (http://www.neoninc.org/).
4. **Improve the applicability of climate models for the Texas region.** This recommendation can be achieved by supporting research in developing methods for using results from global climate models to make predictions for different parts of Texas; and determining how well such models a) simulate the observed variability of Texas climate across time scales (hourly to decadal); b) replicate climate processes that control Texas climate (e.g., tropical storms, winter cold fronts), and c) translate the interactions of the climate system with land surface to produce resultant streamflow, which is a key variable used in water resource planning. Such assessments and improvements are necessary if projections of future climate are to be useful for Texas planners

and policy-makers. An unmet basic research need is to learn which of the many global climate models used are most accurate at representing Texas climate and its variability, and to determine the optimal approach to downscaling from global to regional climate modeling. We must also identify what is most uncertain about current climate predictions for Texas so that resources can be invested toward minimizing that uncertainty. Paleoclimate records should also be improved as means to assess climate models for future projections.

5. **Continue to advance the use of adaptive management strategies for Texas' water resources.** Although many scientific uncertainties remain regarding the details of the extent and rate of climate change and its impact on Texas water resources, we have enough knowledge to act now. The TWDB's adaptive water planning framework is well positioned to incorporate adjustments to respond to climate change. Adaptive management needs include improved, strategic monitoring of climate in operational real-time. Water quality changes resulting from climate change impacts should be anticipated, including the impacts of increased water temperatures, reduced base flows, more intense storms, fire, dust, and sediment. With regard to water quantity, adaptive strategies must maximize options, such as conservation, that have double benefits—from both an energy and water perspective—and fewer environmental impacts. The complexity of climate change processes in Texas and the resulting impacts indicate that the development of effective adaptive strategies would require resource managers and decision makers to work closely with scientists from across many disciplines.
6. **Determine the impact and calculate the costs of projected climate change to the state's economy, including the costs of taking no action.** If we continue with a business as usual approach, and do not develop new research and management programs regarding the climate change impacts described in this white paper, what are the potential costs to Texas' economy? Potential costs of water shortage impacts for Texas include those to businesses and workers estimated to be $9.1 billion in 2010 and $98.4 billion by 2060. Following the approach of the United Kingdom (i.e., Stern 2006) and the TWDB (2007), an integrated assessment should be undertaken to determine costs of no action if water shortages on the order of the most significant historical and projected droughts occur (Fig. 3).
7. **Advance research on the connection of water supply and energy use.** There is a continuing need for connecting water and energy in a water management context. Significant volumes of water are required to generate energy by most conventional means, mostly for cooling, as well as by many alternative means, such as biofuels. Additionally, energy is required to pump, treat, and deliver water, and to treat and reuse wastewater. In fact, water and wastewater management are two of the largest users of energy in most states (approximately 30% of the total energy produced by power plants in California). Impacts on the available freshwater supply have immediate bearing on our ability to generate electricity from hydropower, coal, nuclear, and gas. Many water supply options being discussed as technology fixes for the future are energy-intensive, including interbasin transfers, desalination, cloud seeding, dry cooling, and expanded groundwater pumping. The large potential for solar power in the Southwest will be maximized by developing technologies that do not require significant amounts of water for cooling (King and Webber 2010). Therefore, capital (infrastructure) and water rights decisions need to be evaluated regarding short- and long-term energy and emissions impacts. Texas should continue to be a leader in pursuing alternative energy sources such as wind and solar, as well as improving existing energy technologies, to gain the multiple benefits of conserving water and reducing emissions.
8. **Encourage and support development of K-12 and university-level education programs.** Innovative educational programs focused on the science and policy of climate change and water resources are needed to train and inspire future researchers and policy-makers. In a comparison among 17 nations of the percentage of 24-year-olds who earn degrees in natural sciences or engineering vs. other majors, the United States ranks 16th (NA 2007). This nationwide trend of fewer students choosing careers in science, combined with the need for new interdisciplinary approaches to training future water resource scientists, managers, and policy-makers, indicates that new and innovative educational efforts are essential. New interdisciplinary degree programs are needed to integrate traditional disciplinary strengths of Texas universities in climate science, water science and engineering, and public policy (Banner and Guda 2004). Scholarships for university students and engaging K-12 curricula on these topics would provide incentives for young learners to follow such programs.

The investments that we make today in such recommendations to anticipate and adapt to these impacts of climate changes may not be visible in our lifetimes, but they will improve the lives of our children and grandchildren.

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Condensing Water Availability Models to Focus on Specific Water Management Systems

Ralph A. Wurbs[1] and Tae Jin Kim[2]

Abstract: The Texas Water Availability Modeling System is routinely applied in administration of the water rights permit system, regional and statewide planning, and an expanding variety of other endeavors. Modeling water management in the 23 river basins of the state reflects about 8,000 water right permits and 3,400 reservoirs. Datasets are necessarily large and complex to provide the decision-support capabilities for which the modeling system was developed. New modeling features are being added, and the different types of applications are growing. Certain applications are enhanced by simplifying the simulation input datasets to focus on particular water management systems. A methodology is presented for developing a condensed dataset for a selected reservoir system that reflects the impacts of all the water rights and accompanying reservoirs removed from the original complete dataset. A set of streamflows is developed that represents flows available to the selected system considering the effects of all the other water rights in the river basin contained in the original complete model input dataset that are not included in the condensed dataset. The methodology is applied to develop a condensed model of the Brazos River Authority reservoir system based on modifying the Texas Water Availability Modeling System dataset for the Brazos River Basin.

Key words: reservoirs, rivers, water supply reliability

INTRODUCTION

The Texas Commission on Environmental Quality (TCEQ), in collaboration with the Texas water management community, maintains a Water Availability Modeling (WAM) System used in the administration of the state's water rights permit system, regional and statewide planning, and other activities (Alexander Martin and Chenoweth 2009). The WAM System is routinely applied by applicants in preparation of water right permit applications and by TCEQ staff in evaluating the applications. The Texas Water Development Board (TWDB) is the lead agency for regional and statewide planning studies, which represent another major application of the modeling system. River authorities and other water management agencies and their consultants also apply the WAM System in other endeavors not directly mandated by either the TCEQ water rights permitting or TWDB planning programs. The WAM System supports a broad range of water management activities and contributes to the integration of those activities. Modeling capabilities continue to be expanded and the range of applications continues to grow.

WAM System datasets for the larger river basins are complex with numerous reservoirs, water supply diversions, and instream flow requirements. These large, complex models are essential for the water rights permitting applications for which the WAM System was originally developed. However, simplification of datasets is beneficial for other applications that focus on a particular water management system while still considering interactions between that system and other water management entities in the river basin.

This paper presents a methodology for condensing WAM datasets, which has been applied to the Brazos River Basin (Wurbs and Kim 2008). The original Brazos WAM has about 3,750 control points, 670 reservoirs, and 1,700 water rights (HDR Engineering 2001). A much easier-to-use condensed

[1]Professor, Zachry Department of Civil Engineering, Texas A&M University, College Station, Texas 77843, r-wurbs@tamu.edu
[2]Senior Research Associate, Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas 76402, kimtae@tiaer.tarleton.edu

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dataset with 48 control points and 15 reservoirs is focused on a reservoir system operated by the Brazos River Authority (BRA) and associated water rights. The effects of the numerous other reservoirs and water rights in the river basin are incorporated in the streamflow inflows at the 48 selected control points while properly maintaining the priority system reflected in the water right permits.

The paper begins by describing the TCEQ WAM System, including major new features currently being added as well as basic modeling capabilities that have been routinely applied for several years. The recently developed methodology for condensing input datasets to focus on a particular reservoir system is then presented. The procedure is illustrated by the development and application of a BRA condensed dataset.

TEXAS WATER AVAILABILITY MODELING (WAM) SYSTEM

The TCEQ WAM System consists of the generalized Water Rights Analysis Package (WRAP) river/reservoir system water management model, WRAP hydrology and water rights input files for all of the river basins of Texas, geographic information system tools, and other supporting databases (Wurbs 2005). The WRAP modeling system is generalized for application to river/reservoir systems located anywhere in the world, with input datasets being developed for the particular river basin of concern. For simulation studies in Texas, WRAP input files from the TCEQ WAM System are altered as appropriate to reflect proposed water management plans of interest, which

Table 1. Texas WAM System Models

Fig. 1 Map ID	Major River Basin or Coastal Basin	Period of Analysis	Number of Primary Control Points	Number of Total Control Points	Number of Model Water Rights	Number of Instream Flow Rights	Number of Model Reservoirs
1	Canadian River Basin	1948-98	12	85	56	0	47
2	Red River Basin	1948-98	47	447	489	103	245
3	Sulphur River Basin	1940-96	8	83	85	5	53
4	Cypress Bayou Basin	1948-98	10	189	163	1	91
5	Rio Grande Basin	1940-00	55	957	2,584	4	113
6	Colorado River Basin and Brazos-Colorado Coastal	1940-98	45	2,395	1,922	86	511
7	Brazos River and San Jacinto-Brazos Coastal	1940-97	77	3,830	1,634	122	670
8	Trinity River Basin	1940-96	40	1,334	1,169	23	703
9	Neches River Basin	1940-96	20	318	333	17	176
10	Sabine River Basin	1940-98	27	376	310	21	207
11	Nueces River Basin	1934-96	41	542	373	30	121
12	Guadalupe and San Antonio River Basins	1934-89	46	1,349	860	184	237
13	Lavaca River Basin	1940-96	7	185	71	30	22
14	San Jacinto River Basin	1940-96	16	411	148	13	114
15	Lower Nueces-Rio Grande	1948-98	16	119	70	6	42
16	Upper Nueces-Rio Grande	1948-98	13	81	34	2	22
17	San Antonio-Nueces	1948-98	9	53	12	2	9
18	Lavaca-Guadalupe Coast	1940-96	2	68	10	0	0
19	Colorado-Lavaca Coastal	1940-96	1	111	27	4	8
20	Trinity-San Jacinto	1940-96	2	94	24	0	13
21	Neches-Trinity Coastal	1940-96	4	245	138	9	31

could involve changes in water use or reservoir/river system operating practices, construction of new facilities, or other water management strategies.

WAM System input datasets

The Texas Legislature authorized development of a water availability modeling system in the comprehensive water management legislation enacted as its 1997 Senate Bill 1. The TCEQ and its partner agencies and contractors implemented the WAM System during 1997–2003. Consulting engineering firms and university researchers under contract with the TCEQ performed much of the technical work. Consulting firms developed WRAP input datasets and modeled specified water management scenarios for each of the river basins. The water rights in the datasets are updated by the TCEQ as applications for new permits or revisions to existing permits are approved. Other aspects of the datasets also continue to be refined. The river basin datasets and an array of information regarding the WAM System are available at the TCEQ WAM website.

The 21 WRAP input datasets as of 2008 covering 23 river basins are listed in Table 1 (Wurbs 2010a). The river basins are delineated in Fig. 1. Three of the 21 WAM datasets combine two river basins, and one basin is divided into two datasets. Each dataset includes water rights information in a file with filename extension DAT (called a DAT file) and hydrology data in streamflow (FLO), net reservoir evaporation (EVA), and flow distribution (DIS) files.

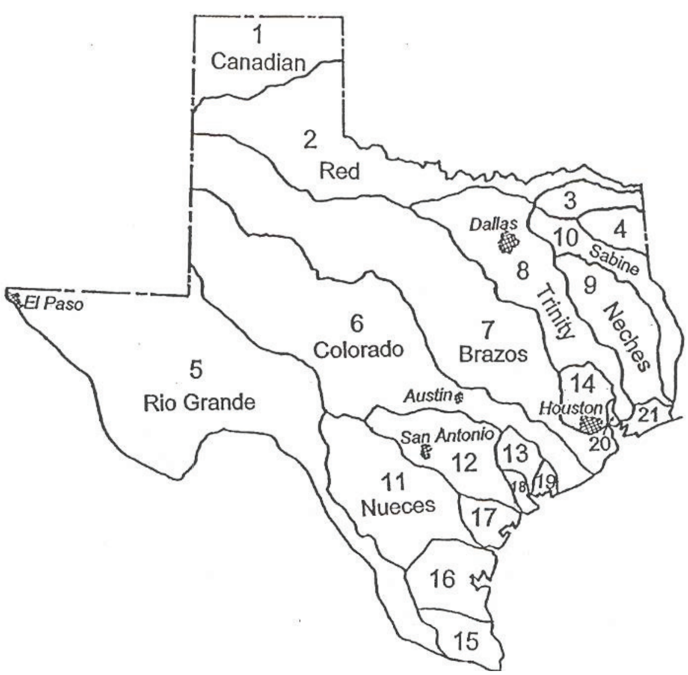

Fig. 1. Texas WAM System River Basins

Authorized use and current use versions of the water rights (DAT) files model two alternative scenarios, reflecting different combinations of premises regarding water use, return flows, and reservoir sedimentation. The authorized use scenario water rights input files are based on the following premises:

- Water use targets are the full amounts authorized by the water right permits.
- Full reuse with no return flow is assumed.
- Reservoir storage capacities are those specified in the permits, which typically reflect no sediment accumulation.
- Term permits are not included.

The current use scenario water rights input files are based on the following premises:

- The water use target for each right is based on the maximum annual amount used in any year during a selected 10-year period.
- Best estimates of actual return flows are adopted.
- Reservoir storage capacities and elevation-area-volume relations for major reservoirs reflect year 2000 conditions of sedimentation.
- Term permits are included.

The TCEQ applies the authorized use scenario in evaluating regular water right permit applications and the current use scenario in evaluating applications for term permits. The holder of a regular water right permit is entitled to continue to use the water forever, though permits may be cancelled if water is not actually used during a 10-year period. A term permit is issued for a set period, usually ranging from one to 10 years, and is generally based on other water rights holders not using their full permitted amounts.

The authorized use versions of the 21 datasets as of January 2008 contained 10,512 water right (WR) records and 662 instream flow (IF) records for 11,174 total model water rights representing almost 8,000 water right permits (Wurbs 2010a). Multiple water rights in the model may represent a single permit. The datasets model the approximately 3,435 reservoirs for which a water right permit has been issued. More than 90% of the total storage capacity of the 3,435 reservoirs is contained in the approximately 210 reservoirs that have conservation capacities exceeding 5,000 acre-feet (ac-ft). The TCEQ continues to periodically update the datasets.

In WRAP terminology, water use requirements, water control infrastructure, and reservoir/river system operating strategies are called water rights. Required and optional features for defining water use requirements and management practices in a DAT file include:

- locations of system components by control point
- priority specifications
- water supply diversion, environmental instream flow,

and hydroelectric energy targets for each of the 12 months of the year and specifications for varying the water use targets as a function of reservoir storage contents or streamflow
- seasonal or annual limits on diversions, reservoir releases, or flow depletions
- return flow specifications in various optional formats
- conveyance of flow through pipelines and canals
- reservoir/river system operating rules including multiple-reservoir system operations, multiple-purpose operations, multiple-owner reservoirs, off-channel storage, and constraints on depleting streamflows
- reservoir storage volume versus surface area and elevation relationships

Several of the river systems shown in Fig. 2 are shared with neighboring states. The Rio Grande is shared with Mexico. For the interstate and international river basins, hydrology and water management in neighboring states and Mexico are considered to the extent necessary to assess water availability in Texas. The models reflect two international treaties and five interstate compacts as well as the two Texas water rights systems administered by the TCEQ. The water rights system allocating the Texas share of the waters of the lower Rio Grande is significantly different from the water rights system for the rest of Texas (Wurbs 2004).

The spatial configuration of a river system is defined in WRAP by a set of control points, with the next downstream control point being specified for each control point. All reservoirs, diversions, return flows, hydropower plants, environmental instream flow requirements, and other system components are assigned control point locations. The 21 datasets contain approximately 13,300 control points (Table 1). About 500 primary control points, most representing gaging stations, have naturalized flows included in WAM System hydrology input files. Hydrology input for a WRAP simulation consists of sequences of monthly naturalized streamflows at all control points and net evaporation less precipitation rates for all reservoirs for the hydrologic period-of-analysis shown in Table 1.

Primary control points are locations, usually gaging stations, for which naturalized flows are provided in a WRAP simulation input FLO file. Naturalized flows at ungaged secondary control points are computed during a simulation. The model includes several alternative methods for transferring naturalized flows from gaged to ungaged sites. Flows may be distributed in proportion to drainage area with or without considering channel losses. SIM also includes an option based on the relationship between precipitation and runoff determined by the Natural Resource Conservation Service. The WAM System datasets include watershed parameters required for these methods in a DIS file.

Water Rights Analysis Package (WRAP)

WRAP simulates water resources development, management, regulation, and use in a river basin or multiple-basin region under a priority-based water allocation system. The model facilitates assessments of hydrologic and institutional water availability and reliability in satisfying requirements for environmental instream flows; municipal, industrial, and agricultural water supply; hydroelectric energy generation; and

Fig. 2. Major Rivers of Texas

reservoir storage. Basinwide impacts of water resources development projects and management practices are modeled. The public domain software and documentation (Wurbs 2009, 2010a, 2010b, 2010c, and Wurbs et al. 2010a) are available at the following website: http://ceprofs.tamu.edu/rwurbs/wrap.htm.

WRAP computer programs

WRAP is a set of executable programs developed in Fortran. WinWRAP is a user interface for executing the programs on microcomputers within Microsoft Windows®. WinWRAP provides the model-user an environment in which to manage data files and WRAP programs and connect with other software.

Program HYD is a set of routines for converting sequences of monthly gaged streamflows to naturalized flows and compiling sets of monthly net reservoir evaporation less precipitation depths. HYD output consists of hydrology input for SIM. Recently added HYD features are designed to apply procedures, discussed later, for developing condensed datasets.

Program SIM performs the conventional river/reservoir/use system water allocation simulation using a monthly time step. SIMD (D for daily) is a recently expanded version of SIM with submonthly time step, flow forecasting, routing, and flood control simulation features. Program SALT reads a SIM output file and salinity input file and tracks salt loads and concentrations through a river/reservoir system.

Program TABLES organizes the SIM, SIMD, and SALT simulation results and develops frequency relationships, reliability indices, and summary statistics. TABLES organizes simulation results into a variety of user-defined tables and also provides convenient export to Microsoft Excel® or HEC-DSS-Vue (USACE 2005). WRAP Display is an ArcGIS®-based tool for spatially displaying simulation results (CRWR 2007).

WRAP simulation

WRAP-SIM simulation computations are performed in a water rights priority loop that is embedded within a monthly time-step loop. The WAM System input datasets reflect a monthly interval though the new SIMD also allows a daily or other submonthly computational time step. SIM model execution begins with reading and organizing input data. Water rights are sorted into priority order based on priority numbers and/or other user-defined options. The simulation steps through time. Naturalized flows for primary control points and net evaporation rates for reservoirs are read from the FLO and EVA files. Flows are distributed from primary control points to all other sites based on watershed parameters read from the DIS file. Within each sequential month, water accounting computations are performed as each set of water use requirements (water right) from the DAT file is considered in priority order.

Water allocation and management are modeled by accounting procedures within the water rights priority sequence. An array is maintained of streamflow available for appropriation at all control points. The following tasks are performed as each water right is considered in priority order:

- The diversion, instream flow, or hydropower target is set starting with an annual amount and set of 12 monthly distribution factors provided as input. The target may be further modified as a function of the storage content in any number of specified reservoirs and naturalized, regulated, or unappropriated flow at any control point.
- The amount of water available to the water right from streamflow is determined based on the available streamflow array considering the control point of the water right and all downstream control points.
- Water use requirements are met subject to water availability following specified system operating rules. Water accounting computations are performed to determine the diversion, diversion shortage, end-of-month storage, and related quantities. Reservoirs and hydropower plants necessitate an iterative algorithm since evaporation and hydropower releases are a function of both beginning-of-month and end-of-month storage.
- The available streamflow array is adjusted for that location and all downstream sites to reflect the effects of the water right. Channel loss factors are applied in translating adjustments for streamflow depletions and return flows to flows at downstream sites. Within the priority sequence, the available flow array is used to determine the amount of water available to each individual right. At the end of the month, the available flow array is used to determine regulated and unappropriated flows.

Simulation results consist of time series of the variables computed in the simulation covering the period-of-analysis. The model-user selects the control points, water rights, and reservoirs for which simulation results are recorded. Variables written to the main output file include but are not limited to

- naturalized, regulated, and unappropriated flows, streamflow depletions, and return flows for each selected control point
- channel losses and channel loss credits for each selected control point representing the reach below the control point
- storage, net evaporation, inflows, releases, diversions, and hydroelectric energy at each selected reservoir
- diversion targets and shortages, return flows, available streamflows, streamflow depletions, and storage for each selected water supply right
- hydropower targets, firm energy produced, secondary energy produced, energy shortages, and storage for each

selected hydroelectric power right
- instream flow target and shortage for each selected instream flow right

WRAP includes the post-simulation program TABLES that organizes simulation results in various user-specified formats, including time series of selected variables, water budgets, statistical summaries, and various types of frequency relationships, statistics, and reliability indices. Tables may be created in a format for incorporation in reports. Alternatively, data may be organized in formats convenient for export to Microsoft Excel or HEC-DSSVue.

Forms of streamflow in WRAP

The WRAP modeling process consists of a series of adjustments to streamflow sequences covering the hydrologic period-of-analysis. The Texas WAM System reflects simulation periods that range from 50 to 60 years for the various river basins listed in Table 1 and a monthly time step. The procedure for converting a WAM dataset to a condensed dataset adds another set of flow adjustments. In a condensed dataset, an adjusted set of inflows replaces the naturalized flows described below. The distinction between regulated and unappropriated flow is important in the development and application of condensed datasets.

A WRAP-SIM simulation begins with naturalized flows. In general, the terms *naturalized* or *unregulated* refer to sequences of past streamflows adjusted to represent a specified condition of river basin development that includes either no human impact or some defined level of development. For the Texas WAM System, naturalized flows ideally are river flows that would have occurred historically, in the absence of the water management activities reflected in the water rights input data, but with all other aspects of the river basin reflecting constant present conditions.

Regulated and unappropriated flows computed by SIM reflect adjustments to naturalized flows for water right requirements representing a specified scenario of water resources development and use. Regulated flows are physical flows considering all water rights in the input dataset. Unappropriated flows are available for further appropriation after all the water rights receive their allocated share. Regulated flow in a particular month at a particular control point is never less than the corresponding unappropriated flow but may be greater than the unappropriated flow due to instream flow requirements at the site or commitments to other water rights at downstream control points.

The adjustments that convert naturalized flows to regulated flows include both streamflow depletions and return flows. Streamflow depletions are the quantities of water appropriated to meet water supply diversion requirements and refill reservoir storage. Return flows are added back to streamflows. Channel losses are considered as SIM streamflow adjustments are cascaded downstream.

New WRAP modeling capabilities

The WRAP modeling capabilities that are routinely applied with the TCEQ WAM System consist of using a hydrologic period-of-analysis of about 50 to 60 years and a monthly computational time step to perform water availability and reliability analyses for municipal, industrial, and agricultural water supply; environmental instream flow; hydroelectric power generation; and reservoir storage requirements. The modeling capabilities currently being routinely applied are documented by Wurbs (2010a, 2010b, and 2010c). Work has been underway for several years on the following new and expanded WRAP modeling capabilities that are becoming operational during 2009 and 2010 (Wurbs 2009, Wurbs et al. 2010a):

- features incorporated in the WRAP programs HYD and SIM for developing and applying condensed datasets as described by this paper
- features incorporated in HYD for extending the hydrologic period-of-analysis
- short-term conditional reliability modeling, which provides estimates of the likelihood of meeting water right requirements and maintaining reservoir storage levels during time periods of one month to several months to a year or perhaps longer into the future, given preceding reservoir storage contents
- daily time-step modeling capabilities that include flow forecasting, flow routing methods, disaggregation of monthly water supply and instream flow targets to daily targets, and disaggregation of monthly naturalized flows to daily flows
- simulation of flood control reservoir system operations
- salinity simulation motivated by natural salt pollution in several Texas river basins

METHODOLOGY FOR DEVELOPING A CONDENSED DATASET

Wurbs and Kim (2008) document the development and application of procedures for (1) extending WAM datasets to cover a longer hydrologic period-of-analysis and (2) condensing WAM datasets to focus on a particular water management system while reflecting the effects of all other water rights in the streamflow inflows. Both of these two very different tasks are based on new features in which the program HYD develops a program SIM streamflow input file based on SIM simulation results. The procedures were applied to the WRAP input dataset for the Brazos River Basin from the TCEQ WAM System. The modeling methods developed are applicable to other river basins as well.

The WAM System datasets for the larger river basins listed in Table 1 contain hundreds of water rights, control points, and reservoirs. These voluminous datasets are necessary to support administration of the water rights permit system by the TCEQ and planning studies conducted by the TWDB and regional planning groups. The datasets are necessarily complex to serve the original purposes for which the WAM System was developed. However, the modeling system is being used in an expanding range of different types of applications. Condensed datasets are advantageous for certain types of applications.

A methodology is presented by Wurbs and Kim (2008) for simplifying WAM System datasets to focus on management of a particular river/reservoir system. Selected water rights, control points, and reservoirs are removed with their effects retained in the adopted stream inflow input data for the condensed dataset. A much simpler dataset is developed for purposes of studying or providing decision support for a particular reservoir/river water management system. WRAP input datasets and corresponding simulation results with dramatically fewer control points, water rights, and reservoirs are much more manageable to use in modeling studies. However, the interactions between numerous water users and water control facilities in a river basin should be preserved in the model. The condensed model allows alternative operating plans for the primary water management system to be simulated based on the premise of assuring appropriate protection of all other water rights.

Development of a condensed dataset serves two purposes. Firstly, the condensed dataset is much easier to apply in certain types of studies focused on a particular water management entity. Secondly, the entity of interest can be segregated and managed in various ways in the WRAP-SIM simulation model while allowing the entity access to only river flows legally available to it considering all other water right permit holders in the river basin.

The accuracy achieved in the development of a condensed dataset is checked by comparing SIM simulation results with the condensed versus original complete dataset. The water supply reliabilities computed for the diversions included in the condensed model should be the same as in the simulation with the original complete dataset. Likewise, the sequences of monthly storage volumes at the common reservoirs and unappropriated streamflows at the common control points will be the same. Near perfect correspondence between simulation results with the condensed versus complete datasets should be expected.

The selected water rights and reservoirs from the complete TCEQ WAM System DAT file that are retained in the condensed DAT file are called the primary system. After creating a condensed dataset, comparing complete TCEQ WAM System versus condensed model simulation results for the primary system reservoirs and water rights requires minimal time and effort. Verifying the condensed dataset is easy and precise. After the development and verification of the condensed WRAP input dataset, then applications of the condensed model may include any number of alternative simulations that reflect different water demands, modified reservoir system operating plans, and other changes in water management strategies associated with the primary system.

Water Rights (DAT) and Hydrology (FLO and EVA) files

A condensed WRAP-SIM input dataset (DAT, FLO, and EVA files) is created by reducing the number of control points, water rights, and reservoirs in a TCEQ WAM System dataset and thus simplifying the modeling system for certain applications. A SIM water rights DAT file for the particular river/reservoir water management and use system of interest, called the primary system, is developed along with a FLO file containing river system inflows that have been adjusted to reflect all other water rights in the original complete WAM dataset, which are referred to as secondary water rights. The effects of the water rights, control points, and reservoirs that are removed from the original WAM DAT file are maintained in the stream inflow input data (FLO file) for the condensed dataset. The condensed dataset also includes an EVA file containing the same net reservoir evaporation-precipitation rates as used with the complete WAM dataset with the same adjustments.

The methodology for creating a condensed WRAP input dataset from a TCEQ WAM System dataset is based on developing flows at selected control points that represent stream inflow amounts available to the selected primary system. These river flows recorded in the condensed dataset FLO file represent flows available to the primary system modeled in the water right DAT file considering the effects of all the other water rights in the river basin contained in the original complete DAT file that are not included in the condensed DAT file.

The river system inflows in the FLO file for a condensed dataset include streamflow depletions made for the selected water rights less return flows plus unappropriated flows. Hydropower releases and reservoir releases made specifically to meet instream flow requirements are also properly incorporated in the flows. Summation and cascading operations, including channel losses, are applied in developing the FLO input file.

The primary system in the condensed DAT file has access only to the flows in the condensed FLO file, which consist of the monthly streamflows that the primary system appropriated in the complete TCEQ WAM System model plus unappropriated flows. Thus, all reservoir storage, water supply diversions, return flows, instream flow requirements, subordination agreements, and other water allocation, control, management, and use associated with the secondary system are reflected in the streamflows incorporated in the FLO file of the condensed dataset.

The methodology for developing the sequences of monthly streamflow volumes and net evaporation-precipitation depths (FLO and EVA files) for a condensed dataset is outlined as follows:

1. The WRAP simulation program SIM is executed with the original complete dataset.
2. Program HYD is used to retrieve the adjusted net evaporation-precipitation depths from the SIM output file and store them in an EVA file for the condensed dataset.
3. HYD is applied to read streamflow depletions, return flows, unappropriated flows, and other pertinent variables from the SIM output file and combine these variables as required to develop the streamflow FLO file for the condensed dataset. Combining the time sequences of flow volumes includes summations and cascading operations that may include channel losses.

The accuracy of the procedure is confirmed by reproducing the sequences of monthly water supply diversions, reservoir storage contents, unappropriated flows, and other pertinent variables contained in the SIM simulation results associated with the primary system reservoirs, diversions, and control points. These SIM simulation results should be same with the condensed dataset versus the original complete dataset. The primary system reservoirs and diversions must be operated the same in both the condensed and complete datasets for the comparison simulations. After completing the comparison to confirm that the dataset is correct, the condensed dataset can be used to simulate alternative river/reservoir system operating rules and water management and use scenarios for the primary system.

Regulated-Unappropriated Flow (RUF) File

With the exception of naturalized and regulated flows, all the variables in the SIM input and simulation results are defined the same in condensed and complete models. However, the regulated flows computed by SIM are defined differently. The optional RUF file described below is needed only for those applications in which knowing the actual regulated flows is important.

The unappropriated streamflows computed by SIM are the

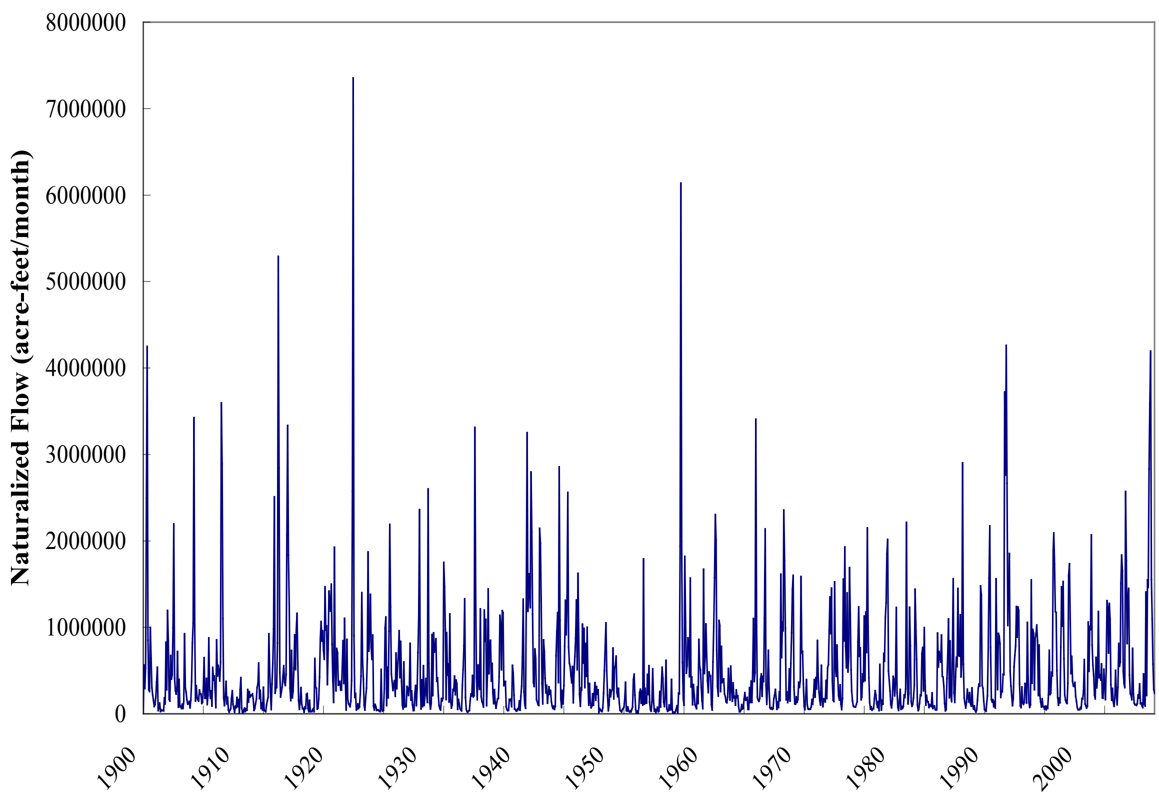

Fig. 3. Naturalized Flows at the Richmond Gage on the Brazos River

same with either a condensed or a complete WAM input dataset. However, the naturalized and regulated flows are defined differently. The streamflows in the FLO file of the original WAM dataset are naturalized flows. However, the streamflows in the FLO file of the condensed dataset are flows reflecting the effects of all of the water rights in the river basin that are not included in the DAT file of the condensed dataset. With a complete dataset, the regulated flows computed by SIM represent the actual flows at a site on a river. With a condensed input dataset, the regulated flows computed by SIM represent the flows that remain unaffected by the water rights omitted from the DAT file.

The basic condensed dataset methodology focuses on unappropriated river flows rather than regulated flows. However, a regulated-unappropriated flow (RUF) file with filename extension RUF may be created using program HYD. A RUF file contains deviations between regulated and unappropriated flows from the simulation results for the original dataset that are used within a SIM simulation with a condensed dataset to estimate regulated flows based on adjusting unappropriated flows.

The RUF file and accompanying flow adjustment options are not needed in various applications in which regulated flows are not of concern. However, the estimates of regulated flows provided by the RUF options may be required in applications for which environmental instream flow requirements or flood control operations are included in the condensed DAT file. A RUF file is not necessarily required if all instream flow requirements and flood control operations are associated with only the secondary system. Salinity simulations require a RUF file. Also, a RUF file may be useful simply to provide general information regarding river flows.

The regulated-unappropriated flow RUF file contains the differences between the regulated flows less unappropriated flows from the simulation results of the original complete dataset. These data are used to perform flow adjustments that allow conventionally defined regulated flows to be included in the SIM simulation results for the condensed dataset.

Incorporation of regulated flows, as normally defined in WRAP-SIM simulations, into a condensed model using the RUF file feature is complicated by the differences between regulated and unappropriated flows being caused by both secondary (FLO file) and primary system (DAT file) water rights. The RUF file feature is necessarily approximate in certain situations because of the combined effects of secondary and primary water rights on river flows. SIM includes a set of options for creating and applying the RUF file adjustments in different situations.

Condensed WRAP input dataset

A condensed dataset consists of required DAT, FLO, and EVA files and an optional RUF file. The DAT file contains the information that describes the primary system water rights including reservoirs, water supply diversions, return flows, instream flow requirements, and other features of water rights. The DAT file water rights may be modified in various ways during studies that apply the condensed dataset. However, only the streamflows recorded in the FLO file are available to the primary system described in the DAT file. The optional RUF file contains adjustments used by SIM to estimate regulated flows based on simulated unappropriated flows. Reservoir surface net evaporation less evaporation rates are contained in the EVA file.

BRAZOS RIVER AUTHORITY SYSTEM CONDENSED MODEL

The BRA sponsored development of the Brazos River Authority Condensed (BRAC) datasets designed to provide a much simpler model that facilitates operational planning studies and other decision support endeavors for the BRA reservoir system (Wurbs and Kim 2008). Alternative versions of the BRAC model were developed for the authorized use and current use scenarios with hydrologic periods-of-analysis of 1900–2007 and 1940–2007 by condensing the TCEQ WAM System authorized use and current use datasets for the Brazos River Basin and San Jacinto-Brazos Coastal Basin, referred

Table 2. Size of Brazos WAM and Condensed Datasets

Complete WAM versus Condensed	Brazos WAM		Condensed	
Water Use Scenario	Authorized	Current	Authorized	Current
Number of primary control points	77	77	48	48
Number of secondary control points	3,753	3,757	0	0
Number of WR record water rights	1,634	1,725	114	112
Number of instream flow rights	122	144	0	0
Number of reservoirs	670	711	15	14

to here as the Brazos WAM. The Brazos WAM has a hydrologic period-of-analysis of 1940–1997, which was extended to 1900–2007 by Wurbs and Kim (2008). The 1900–2007 monthly naturalized flows at the U.S. Geological Survey (USGS) gaging station on the lower Brazos River near Richmond are plotted in Fig. 3.

The condensed datasets are useful for a broad spectrum of different types of WRAP-based studies and decision-support activities. For example, Wurbs and Lee (2009) applied the BRAC datasets in a study of the effects of natural salt pollution in the Brazos River Basin. Unlike the application noted below, the salinity study required the use of the RUF file.

The BRA is currently sponsoring conditional reliability modeling studies that use the BRAC datasets to develop storage frequency statistics for individual reservoirs and groups of reservoirs for storage at various times over the period of a year, given specified initial preceding storage levels (Wurbs et al. 2010b). One of the several variations of the model used in these analyses consists of a version of the BRAC dataset described as follows. The BRAC DAT file developed based on the TCEQ WAM System current use scenario dataset is further adjusted to reflect actual water use and system operations during the relatively dry year 2008. The resulting DAT file is combined with condensed FLO and EVA files developed from the TCEQ WAM System authorized use scenario dataset. Thus, the primary system is operated based on year 2008 water demands based on the premise that all water rights included in the secondary system appropriates the full amounts authorized in their water right permits. With the focus on developing storage statistics, the RUF file was not needed for this particular application.

Brazos River Basin

The 45,600-square-mile Brazos River Basin extends from New Mexico southeasterly across Texas to the Gulf of Mexico as shown in Fig.s 1 and 2. The upper extreme end of the basin in and near New Mexico is an arid flat region that rarely contributes to streamflow. Climate, vegetation, topography, land use, and water use vary greatly across the basin. Mean annual precipitation varies from 16 inches in the upper basin in the High Plains to over 50 inches in the lower basin in the Gulf Coast Region.

More than 1,000 water districts, cities, companies, and individuals hold water right permits to use the waters of the Brazos River and its tributaries. Based on the Brazos WAM, water rights associated with the 13 reservoirs shown in Fig. 4 account for 74% of the conservation storage capacity of the 711 permitted reservoirs and 33% of the permitted annual water supply diversion volume in the basin. The BRA owns and operates Possum Kingdom, Granbury, and Limestone reservoirs and has contracted with the U.S. Army Corps of Engineers for the conservation storage capacity of nine federal multiple-purpose reservoirs. A significant portion of the water diverted from the Brazos River is actually used in the adjoining San Jacinto-Brazos Coastal between the City of Houston and Galveston Bay.

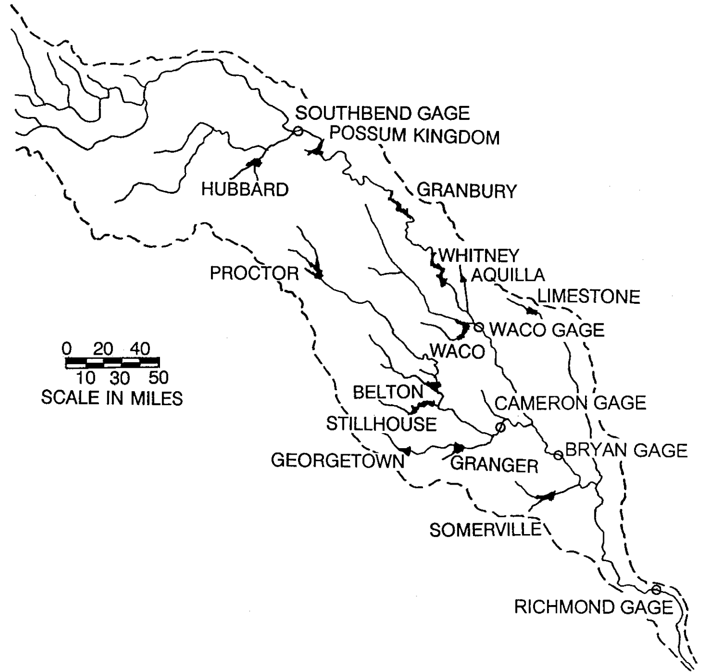

Fig. 4. Brazos River Basin

Brazos River Authority Condensed (BRAC) Datasets

The large complex Brazos WAM dataset is necessary for the planning and water right permitting applications for which the WAM System was developed. However, a much simpler model focused on the BRA reservoir system facilitates BRA operational planning studies. Wurbs and Kim (2008) developed and applied a methodology for simplifying WAM System datasets to focus on management of a particular reservoir system. Selected water rights, control points, and reservoirs are removed with their effects retained in the adopted stream inflow input data file for the condensed dataset. The BRAC datasets developed based on modifying the Brazos WAM authorized use scenario and current use scenario datasets contain 48 primary control points and no secondary control points. BRAC authorized use and current use scenario datasets contain 15 and 14 reservoirs, respectively, with a permitted but not constructed project included in the authorized but not the current scenario. The stream inflows at the 48 control points reflect the effects of the numerous water rights, reservoirs, and control points removed from the Brazos WAM dataset.

The relative size of the Brazos WAM versus BRAC datasets is compared in Table 2. The Brazos WAM authorized use scenario dataset contained 1,634 water right *WR* records, 122 instream flow records, 670 reservoirs, and 3,830 control points, as of 2009. The Brazos WAM current use dataset is slightly larger. Naturalized flows are input in a FLO file for 77 primary control points and distributed within SIM to the other ungaged secondary control points as specified by 3,138 flow distribution records in a DIS file.

The condensed datasets designed to focus on operation of the BRA reservoir system include the 15 largest reservoirs in the river basin and associated water rights (Wurbs and Kim 2008). The 15 reservoirs include one proposed (Allen's Creek Reservoir), 12 existing BRA reservoirs, and two other reservoirs (Hubbard Creek and Squaw Creek reservoirs). The proposed Allen's Creek Reservoir is included in the authorized use scenario but is not included in the current use scenario. The 12 BRA reservoirs shown in Fig. 4 include Possum Kingdom, Granbury, and Limestone reservoirs owned by the BRA and nine federal multiple-purpose reservoirs owned by the U.S. Army Corps of Engineers for which the BRA has contracted for the water supply storage capacity. The condensed dataset has 48 primary control points and no secondary control points. With no secondary control points, there is no flow distribution DIS file. The impacts of the 655 reservoirs and numerous water rights removed from the Brazos WAM dataset are reflected in the FLO file river flows developed for the condensed SIM input dataset.

The condensed datasets were developed using the WRAP programs SIM and HYD as outlined earlier in this paper. The resulting BRAC datasets consist of SIM input files with filename extensions DAT, FLO, EVA, and RUF. Four versions of the condensed datasets were initially developed representing authorized use and current use scenarios of water resources development and management and 1900–2007 and 1940–2007 hydrologic periods-of-analysis. The condensed dataset DAT files continue to be modified for particular studies as previously noted. The SIM input files comprising the basic condensed datasets are described as follows:

- The authorized use and current use DAT files contain water rights and related information for 15 and 14 reservoirs, respectively, and associated water supply diversions. This information was excerpted from the Brazos WAM DAT files. All but 48 of the original 3,800 control point records are omitted. Thus, the next downstream control point identifiers and channel loss factors are modified for the adopted 48 control points.
- FLO files with alternative 1940–2007 and 1900–2007 sets of monthly flows at 48 control points represent conditions of river system development that include all of the water rights and associated reservoirs in the original complete Brazos WAM DAT files except the 15 reservoirs and associated diversions contained in the condensed DAT files.
- EVA files contain alternative 1940–2007 and 1900–2007 sets of monthly net evaporation-precipitation depths for the 15 reservoirs. Adjusted net evaporation-precipitation depths are obtained from the SIM output OUT file.
- RUF files contain alternative 1940–2007 and 1900–2007 sets of differences between the regulated flows less unappropriated flows from the SIM output file for complete Brazos WAM simulation. The optional RUF files allow conventionally defined regulated flows to be included in the BRAC simulation results.

The DAT files for the condensed datasets are developed by excerpting pertinent water rights and associated data records from the original DAT file, excerpting pertinent records providing reservoir data, and modifying remaining control point records to reflect removal of many of the control points. With removal of control points, channel loss factors for the stream reaches removed are aggregated for the combined longer reaches between the remaining control points. Various other organizational refinements have no effect on simulation results.

A number of the water rights included in the BRAC datasets have diversion return flows that are returned back to the river in the Brazos WAM dataset at control points that have been removed in the BRAC datasets. The return flows are returned in the BRAC dataset at the next downstream control point that was not removed. Channel losses associated with the return flows may be affected. The decrease in channel loss could be offset by increasing the return flow factor. However, this ploy was not applied for the Brazos since the impacts on channel losses of reassigning return flow locations were negligible.

The condensed dataset should adopt the same net evaporation-precipitation depths for the 15 reservoirs as used in the original complete dataset SIM simulation. SIM includes a routine for adjusting net evaporation-precipitation depths for the precipitation runoff from the portion of the watershed inundated by the reservoir. Therefore, net evaporation-precipitation depths are obtained from the output file for the complete simulation rather than using the original evaporation-precipitation depth input dataset.

River flows developed for the 48 BRAC control points consist of 1940–2007 or 1900–2007 sequences of monthly volumes of the following variables obtained from the simulation results output file created by SIM with the original complete input dataset. The computations are performed with HYD.

- Streamflow depletions made by each of the water rights associated with the 15 reservoirs are included in the flows being developed. These flow volumes are placed at the control point of the streamflow depletion and at all downstream control points. Channel losses are con-

Table 3. Comparison of Means of Flows in FLO Input

USGS Gaging Station	Brazos WAM	Condensed Datasets	
		Authorized	Current Use
	(ac-ft/yr)		
Cameron gage on Little River	1,318,302	81.5%	83.9%
Waco gage on Brazos River	1,942,324	85.6%	87.5%
Richmond gage on Brazos River	5,850,224	77.8%	78.2%

sidered in cascading the streamflow depletions downstream.

- Return flows from the diversion component of the streamflow depletions are subtracted from the flows. These flow volumes are placed at the control point at which the return flow is returned to the stream and at all downstream control points. Channel losses are considered in cascading the return flows downstream.
- Unappropriated flows at each of the control points are added to the flows. Since unappropriated flows are cumulative total flows, these flows are not cascaded downstream.
- Any releases from the 15 selected reservoirs made specifically for instream flow requirements are subtracted at the control point of the reservoir and cascaded downstream in the normal manner, which includes consideration of channel losses.

The BRAC inflows are the portion of the naturalized flows still available to the primary system water rights after the secondary water rights have appropriated their appropriate quantities of the streamflow. Naturalized flows are the same in the authorized use and current use scenario versions of the complete WAM dataset but differ in the condensed datasets. The 1940–1997 means are compared in Table 3 for three of the gaging station locations shown in Fig. 4. The 1940–1997 means of the Brazos WAM naturalized flows at the three control points are tabulated in ac-ft/yr. The corresponding 1940–1997 means of the inflows in the FLO files of the condensed inflows are shown in Table 3 as a percentage of the Brazos WAM naturalized flows. At the Richmond gage control point, the mean FLO file inflows for the authorized use and current use scenarios are 77.8% and 78.2% of naturalized flows.

SUMMARY AND CONCLUSIONS

The TCEQ Water Availability Modeling (WAM) System has significantly contributed to water management in Texas over the past several years. Capabilities are provided for assessing institutional as well as hydrologic water availability and supply reliability. The modeling system supports preparation and evaluation of water right permit applications, regional and statewide planning studies, and various other water management activities.

The primary reason for developing condensed datasets is to provide a much simpler model that can be conveniently and effectively applied in studies dealing with a particular river/reservoir water management system. Condensed datasets also provide a mechanism for allocating water between a primary system of concern and all of the other water rights in the river basin that can be useful in certain types of modeling applications.

The control points, reservoirs, and water rights included in a condensed dataset are called the primary system. The control points, reservoirs, and water rights that are not included in the primary system comprise the secondary system. The effects of all secondary water rights on river flows available to primary water rights are reflected in the inflow streamflows. The inflows provided in the flow input file of a WAM System dataset are naturalized flows. The inflows contained in the flow file of a condensed dataset represent the river flows available to the primary system considering all the other secondary water rights.

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Desalination and Long-Haul Water Transfer as a Water Supply for Dallas, Texas: A Case Study of the Energy-Water Nexus in Texas

Ashlynn S. Stillwell[1*], Carey W. King[2], Michael E. Webber[3]

Abstract: As existing water supplies become increasingly strained in some locations, water planners turn to alternative options to quench cities' thirst. Among these options for inland cities is desalination of seawater or brackish groundwater with long-haul water transfer. Desalination using reverse osmosis membranes is the most common technology in use, yet high pressures required for operation make desalination an energy-intensive water supply option. The subsequent conveyance of desalinated water through long-haul pipelines also requires large amounts of energy. To analyze desalination and long-haul transfer as a drinking water supply, Dallas, Texas, was chosen as a test-bed with two scenarios: seawater desalination near Houston and brackish groundwater desalination near Abilene, both with long-haul transfer of desalinated water to Dallas. Combining the energy requirements for long-distance pumping with the energy demands for desalination, we estimate that desalination and long-haul transfer is nine to 23 times more energy-intensive per unit of water than conventional treatment of local surface water sources, an increase of 230 to 630 MWh/d for 20 million gal (75,700 m^3). These results suggest that desalination and long-haul transfer as a water supply for Dallas is less sustainable, based on energy consumption, than use of local surface water sources or water conservation.

Keywords: desalination, long-haul transfer, energy, water

INTRODUCTION

Desalination is a water treatment technology that produces potable water from brackish groundwater or seawater. Though many desalination technologies exist, including thermal processes such as multieffect distillation and multistage flash, the most popular is reverse osmosis (Van der Bruggen and Vandecasteele 2002). Most reverse osmosis treatment operations use a staged or cascade layout like that shown in Fig. 1 to improve recovery—the ratio of permeate (product water) to feed water.

Historically, commercial desalination plants operated using thermal processes in locations where energy was plentiful or inexpensive and freshwater was scarce. For example, desalination provides substantial volumes of drinking water in areas of the Middle East with abundant energy resources. Emerging reverse osmosis technology has enabled the construction of new and larger desalination plants, yet estimated worldwide capacity totals only 15.8 billion gal/d (59.9 million m^3/d), or 0.5% of global freshwater use (Desalination & Water Reuse 2009). Public resistance to desalination plants in the United States stems from both environmental and energy sustainability issues. Seawater intake structures can harm marine wildlife and excessive brackish groundwater withdrawal can contribute to land subsidence (Galloway et al.1999; Lattemann and Hopner 2008). Furthermore, the large energy requirement for desalination—more than 10 times the traditional surface water treatment—contributes to greenhouse gas emissions when using fossil fuel-generated electricity (CEC 2005; EPRI 2002b). As an alternative, wind-generated electricity can be used to power a desalination plant, as has been demonstrated in Perth, Australia, which switched from coal to wind power after protests, and produces 36 million gal/d (mgd) (136,000 m^3/d) of potable water without emissions (Barta 2008). Sydney Water, the water utility of Sydney, Australia, has also laid plans for wind-powered desalination (Tadros and Robins 2008).

Since desalination makes use of water normally considered

[1] The University of Texas at Austin, 1 University Station C1786, Austin, TX 78712,[2] The University of Texas at Austin, P.O. Box B, Austin, TX 78713, [3] The University of Texas at Austin, 1 University Station C2200, Austin, TX 78712
*Corresponding author: ashlynn.stillwell@mail.utexas.edu

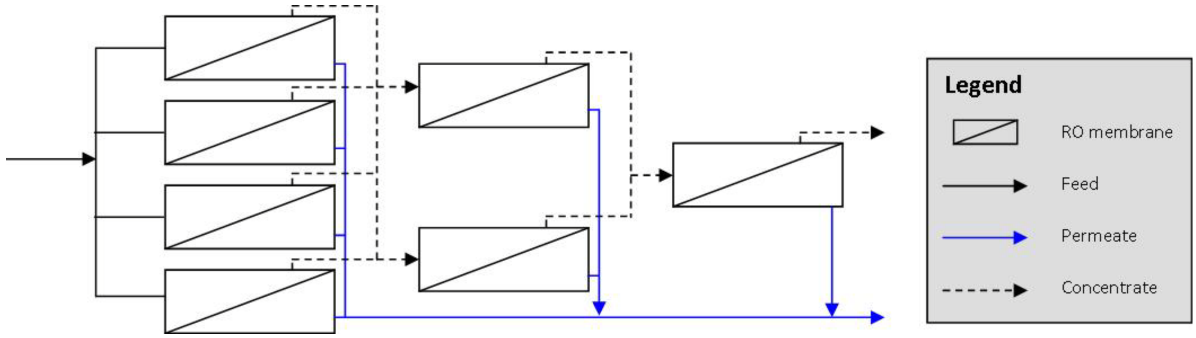

Fig. 1. Typical reverse osmosis units are configured in a cascade layout to improve water recovery, which typically ranges from 35% to 50% for seawater and 60% to 85% for brackish groundwater (Lawler and Benjamin 2008; Zander et al. 2008).

unusable, many turn to desalination as an alternative water resource when existing supplies become strained. Due to the abundance of saline ocean water and brackish groundwater, desalination—and the subsequent transfer of treated water—can provide a reliable water supply that is generally plentiful and resistant to droughts. This reliability comes with a price; desalination is an energy-intensive water treatment technology. Despite that price, historical trends show a near-exponential increase in installed desalination capacity in the United States (Gleick et al. 2006).

DALLAS, TEXAS, AS A CASE STUDY

Strained water supplies and growing populations often cause cities to pursue alternative water sources. Dallas, Texas, is no exception. In 2003, the Dallas-Fort Worth metropolitan statistical area population totaled 5.6 million people, which has increased annually by 2%, on average. Per capita water use, as reported by the Texas Water Development Board (TWDB) from Water Use Survey data, for Dallas and Fort Worth is 238 and 177 gal/person/ (0.90 and 0.67 m^3/person/d), respectively (Ward et al. 2007). This large water use in the Dallas area—the third largest in Texas based on TWDB estimates—and others throughout the state has led water resource planners to pursue alternative water supplies for the future, with desalination among those options (Herring et al. 2008; Office of Governor [cited 2009]; Texas Comptroller of Public Accounts [cited 2009]).

One drought-resistant water supply option is seawater desalination. For example, Corpus Christi, Texas, is currently evaluating three desalination opportunities for incremental water supply; additional water supply was added in 1998 via a 101-mi (163-km) long-haul transfer pipeline from Lake Texana (City of Corpus Christi 2009). For inland cities, desalination must be coupled with long-haul transfer to become a usable water supply. This analysis considers such a scenario for Dallas. In the situation modeled here, seawater from the Gulf of Mexico is desalinated near Houston, transferred via pipeline to a central distribution point in Dallas, and then distributed to water users, as necessary. As an alternative comparison, a brackish groundwater source was analyzed for desalination near Abilene and long-haul transfer to Dallas. Dallas was selected for this case study as an inland population center with potentially increasing water needs. While a project such as this would likely be both capital- and energy-intensive and is not currently being considered, this analysis focuses only on the energy aspects of two possible desalination and long-haul transfer scenarios and not life-cycle economic costs. Competing options for increasing water supply to Dallas include development of new reservoirs, construction of pipelines to connect Dallas to Lake Palestine, fostering relationships with Oklahoma Water, and conservation coupled with direct and indirect water reuse (Dallas Water Utilities Department 2009).

DATA AND ASSUMPTIONS

Analysis of this desalination and long-haul water transfer scenario was completed by integrating a variety of geographic, water, and energy datasets with models for energy consumption (for pumping, treatment, and conveyance). ArcGIS software from ESRI was used for the spatial analysis and standard fluid mechanics equations were used for the pipeline analysis. To simulate the desalination and long-haul transfer scenario, certain data and assumptions were necessary. Our analysis relied on a variety of datasets for the simulation, including the following:

- Global 30 Arc-Second Elevation Dataset (USGS [mod 2009]) – This 1-km digital elevation model (DEM) was used to determine elevation changes between the desalination plants near Houston and Abilene and the cen-

Fig. 2. Major Texas roads and highways were used to determine the right-of-way long-haul pipeline routes such that the routes follow existing easements. The brackish groundwater pipeline is shown traveling west to east and the seawater pipeline is shown traveling southeast to northwest.

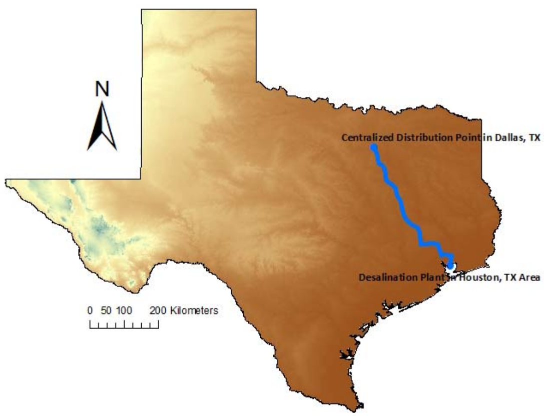

Fig. 3. A map of the right-of-way water pipeline for long-haul transfer illustrates a more practical pipeline route from a property rights perspective.

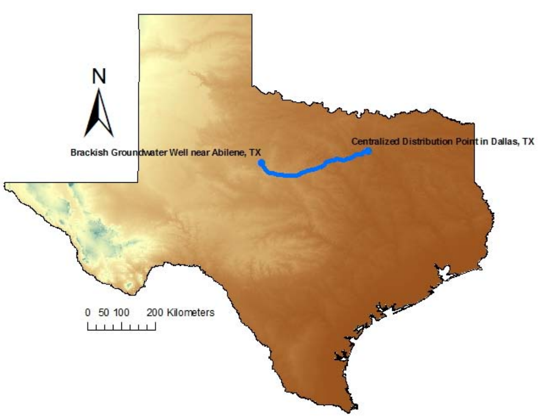

Fig. 4. An alternative desalination and long-haul transfer water supply for Dallas analyzed here is brackish groundwater desalination near Abilene with a long-haul pipeline following existing road right-of-ways.

tralized distribution point in Dallas. The 1-km DEM was appropriate for this analysis to represent topographic variability at sufficient scale.

- Roads/Highways of Texas (Texas GLO [cited 2008]) – This U.S. Department of Transportation dataset showing major roads and highways in Texas was used to determine state-owned right-of-ways as a possible water pipeline route.
- Major Texas River Basins (TWDB [cited 2008]) – This dataset from the TWDB was used to analyze which river basins were crossed by the long-haul pipeline.
- Google Earth Latitude and Longitude – Google Earth was used to estimate latitude and longitude of the potential desalination plants and centralized distribution point.
- Existing Brackish Groundwater Wells (TWDB 2009) – This dataset from the TWDB was used to determine locations and water quality of existing brackish groundwater wells near Abilene.
- Energy for Desalination (CEC 2005) – Reported ranges of energy for desalination of seawater and brackish groundwater were used to determine energy consumption for water treatment.

The following assumptions provide the basis for scenario evaluation:

- Desalination capacity of 20 mgd (75,700 m^3/d) – This treatment capacity is sufficient for 100,000 people at a mid-range current water use of 200 gal/person/d (0.76 m^3/person/d). This mid-range estimate is based on current per capita water use of 238 and 177 gal/person/day (0.90 and 0.67 m^3/person/d) in Dallas and Fort Worth, respectively, as calculated by the TWDB (Ward et al. 2007).
- Real estate available for desalination – Though demand for coastal property is high, this simulation assumes land is available for the seawater desalination facility.

While the data described above were generally reported in consistent formats, energy analysis is not a built-in function of the elevation capabilities of ArcGIS. As a result, raw elevation data exported to a spreadsheet were used for the pipeline simulation.

METHODOLOGY

DEM and facility locations

To begin the desalination with long-haul transfer to Dallas simulation, a 1-km DEM was used to represent elevation changes along the water pipeline route. The DEM and all other ArcGIS layers were projected using the North American

Datum 1983 Texas Statewide Mapping System projection. This DEM for the state of Texas was extracted from the U.S. Geological Survey 30 arc-second DEM using the raster calculator function in ArcGIS 9.3.

Pipeline routing

To simulate the long-haul water pipeline in ArcGIS, routes were drawn between the two facility points. A shortest-distance, straight-line approach was initially considered due to the possibility that is would be the lowest energy consumption option, but such a pipeline is impractical from a property rights perspective; thus a straight-line pipeline was excluded from the final analysis. If a long-haul project such as this were to be implemented, the pipeline would likely follow existing right-of-ways. Possible routes for the seawater and brackish groundwater long-haul pipelines might follow existing right-of-ways of major state roads, shown in Fig. 2, where easements could be used as pipeline routes. Adding the seawater right-of-way pipeline route shown in Fig. 2 to the DEM creates the pipeline route illustrated in Fig. 3. The brackish groundwater right-of-way pipeline, combined with the DEM, is shown in Fig. 4.

As additional analysis, a layer for major river basins in Texas was added to the DEM and simulated pipelines. Illustrated in Fig. 5, the seawater right-of-way pipeline begins in the Trinity-San Jacinto River Basin at the desalination plant, then passes into the Trinity and San Jacinto basins, returns to the Trinity basin, and then passes briefly into the Brazos River Basin before returning to the Trinity basin at the distribution point. The brackish groundwater right-of-way pipeline, shown in Fig. 6, begins in the Brazos basin and then passes into the Colorado River Basin before returning to the Brazos basin and ending in the Trinity basin.

While this case study considers two possible pipeline routes, many routes are possible between the desalination plants and distribution point.

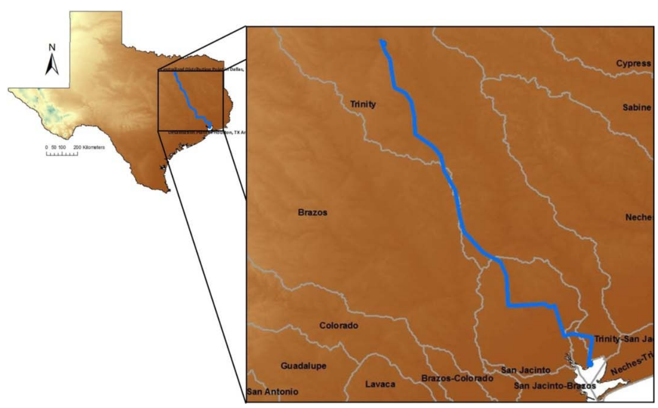

Fig. 5. The seawater right-of-way long-haul transfer pipeline passes back and forth between major river basins: Trinity-San Jacinto, Trinity, San Jacinto, and Brazos, before ending in the Trinity basin.

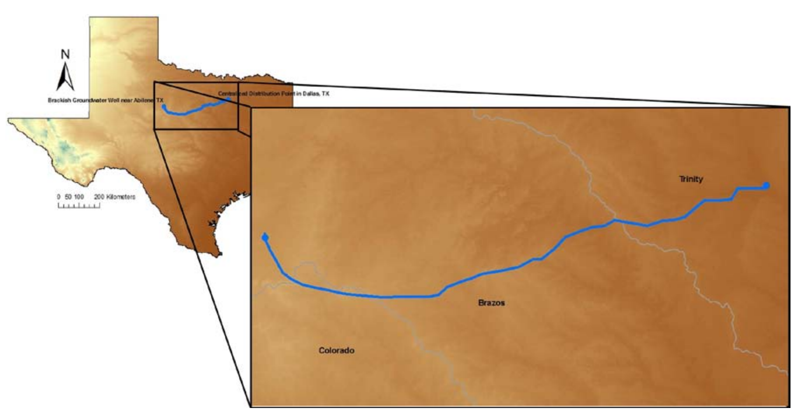

Fig. 6. The brackish groundwater right-of-way long-haul transfer pipeline begins in the Brazos basin and moves into the Colorado, before returning to the Brazos and ending in the Trinity basin.

Table 1. Pipeline length and cumulative elevation change for the long-haul pipeline routes were used to determine total energy consumed for long-haul transfer.

	Net Elevation Change (m)	Pipeline Length (km)	Cumulative Elevation Change (m)
Seawater Right-of-Way Pipeline	125	434	939
Brackish Groundwater Right-of-Way Pipeline	-385	325	1,010

Elevation change using 3D analyst

To determine the elevation change over the route of the right-of-way long-haul water pipelines, the 3D Analyst capabilities of ArcGIS were used to measure elevation changes along the route. Following the pipeline routes, the profile graph shown in Fig. 7 was generated, providing a snapshot of the elevation cross section for the seawater and brackish groundwater pipelines, respectively.

The net elevation change between the proposed seawater desalination plant in the Houston area and Dallas was measured as 125 m. Since the elevation decreases between the proposed brackish groundwater desalination plant in Abilene and the distribution point in Dallas, the net elevation change is negative at -385 m. Additionally, the cumulative elevation was measured as the summation of elevation increases measured in the direction of flow. While it is possible to generate energy during downward flows (similar to what is done in California, where water from the Owens Valley generates electricity with in-line turbines on its way downhill to Los Angeles) elevation decreases in the direction of flow are ignored to provide a high estimate of energy consumption. This high energy-consumption estimate represents a worst-case scenario, which could be used to determine whether in-line turbines or other energy-recovery devices are necessary. Complete energy recovery on downhill runs—that is, using only the net elevation change between the desalination plant and the distribution point—was used as a low estimate of energy consumption. The net elevation change, cumulative elevation change, and pipeline distance from Fig. 7 are provided in the data shown in Table 1. These data were then used to calculate energy needed for long-haul water transfer.

Table 2. Estimated and measured parameters for calculations in the long-haul transfer pipeline were used to determine energy consumption of water transfer.

Parameter	Value	Units
Acceleration due to gravity, g	9.81	m/s^2
Density, ρ	997.08	kg/m^3
Flow rate, Q	20 (0.8763)	mgd (m^3/s)
Friction factor, f (Bertin 1987)	0.0115	unitless
Height, Δh	See Table 1	m
Length, ΔL	See Table 1	m
Pipe diameter, D	3.66	m
Velocity, v	0.305	m/s
Viscosity, μ	8.94E-04	kg/m·s

RESULTS

To calculate the energy required by the desalination and long-haul transfer scenarios discussed above, the desalination treatment and long-haul transfer were considered separately. Seawater desalination requires 9,780 to 16,500 kWh/10^6 gal, while brackish groundwater requires 3,900 to 9,750 kWh/10^6 gal (CEC 2005). For treatment of 20 mgd (75,700 m^3/d), the energy requirements for seawater desalination using reverse osmosis total 196 to 330 MWh/d, while brackish groundwater desalination consumes 78 to 195 MWh/d.

To calculate the energy requirements for long-haul transfer, both the elevation change and pipeline distance were considered. The power for overcoming the potential energy of raising the elevation of the water is:

$$\frac{\Delta E_p}{\Delta t} = \rho Q g \Delta h \qquad (1)$$

In Equation 1, $\frac{\Delta E_p}{\Delta t}$ is the change in potential energy per time, ρ is the fluid density, Q is the flow rate, g is acceleration due to gravity, and Δh is the net or cumulative change in height.

For the flow rate of 20 mgd (75,700 m^3/d), overcoming net elevation changes in the seawater pipeline (a low estimate of energy consumption for elevation changes, assuming complete energy recovery on downhill runs) requires approximately 26 MWh/d; overcoming cumulative elevation changes (a high estimate of energy consumption for elevation changes with no energy recovery on downhill runs) requires 193 MWh/d for right-of-way water transfer. Since the net elevation change of the brackish groundwater pipeline is negative, no energy is required to overcome net elevation changes; power generation might be possible, depending on sharp elevation increases along the route, but zero is used here as an approximation. For cumulative elevation changes, the brackish groundwater long-haul transfer requires 208 MWh/d. Note that although the net elevation change of the brackish groundwater scenario is negative, the cumulative elevation change of the downhill brackish groundwater pipeline is greater than that of the uphill seawater pipeline. Thus, these scenarios illustrate that a pipeline with an overall downhill route does not necessarily require less energy than an uphill route due to cumulative elevation changes along the pipeline.

Additional energy is required to overcome friction within the pipeline. For turbulent flow in the pipeline, the Darcy-Weisbach equation can be used to estimate head loss due to friction:

$$h_f = f\frac{v^2}{2g}\frac{\Delta L}{D} \qquad (2)$$

In Equation 2, h_f is the head loss due to friction, f is the friction factor, ΔL is the pipe length, v is the average fluid velocity, and D is the inside pipe diameter. The friction factor f was estimated using a Moody diagram (Bertin 1987). Using the head loss calculated from the parameters in Table 2 and Equation 2, the additional energy requirement to overcome pipe friction is 1.3 MWh/d and 1.0 MWh/d for seawater and brackish groundwater right-of-way transfer, respectively.

Factoring in high-flow pump efficiencies of 65% (CAT 2009) and additional distribution from the centralized point in Dallas to consumer homes at 1.2 MWh/10^6 gal, estimated total energy consumption is 261 to 653 MWh/d for seawater desalination and 423 to 540 MWh/d for brackish groundwater desalination, both with right-of-way transfer. Energy requirements for the two water supply options are shown in Table 3, showing energy for treatment and distribution with long-haul transfer for desalination.

Based on estimated energy consumption totals compared to conventional local surface water treatment, the total energy use of 261 to 653 MWh/d is nine to 23 times more energy-intensive than conventional water treatment from local surface sources at 28.5 MWh/d for 20 mgd (75,700 m3/d). Note that here conventional local surface water treatment is based on national average values of energy consumption for water treatment and distribution. Energy-consumption data for water collection, treatment, and distribution are not directly mea-

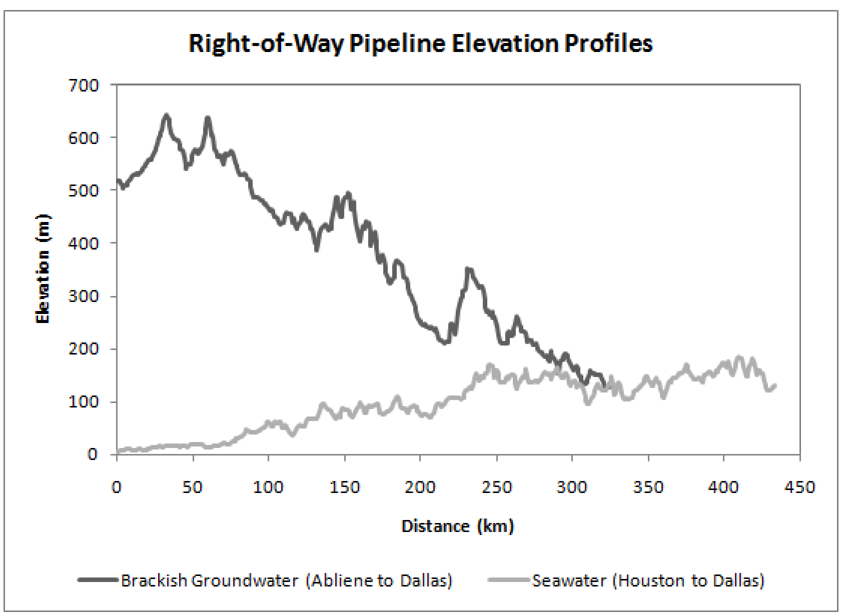

Fig. 7. Elevation profiles for the seawater and brackish groundwater pipelines show a general uphill route for seawater and downhill route for brackish groundwater. Despite these trends, elevation increases along the brackish groundwater pipeline are larger than those increases of the seawater pipeline.

sured and reported in Texas, thus this comparison to national average values of energy consumption serves as the baseline for our analysis.

IMPLICATIONS

The desalination and long-haul transfer simulation presented above represents a highly energy-intensive water supply for Dallas. For the 100,000 people served by this scenario, the energy requirements total approximately 2.61 to 6.53 kWh per person per day. On average, Texans used 39.1 kWh of electricity per person per day in 2008 (EIA 2010; U.S. Census Bureau [cited 2010]). Implementation of this desalination and long-haul transfer project causes a 7% to 17% average increase in daily energy consumption per person that uses the desalinated water.

Additional electricity generation releases additional air emissions, depending on the fuel source for power generation. For coal and natural gas, which generate much of the electricity consumed in Texas, the daily air emissions for 653 MWh, the high estimate of a desalination and long-haul transfer scenario, are shown in Table 4.

Thermoelectric power generation using coal or natural gas combined-cycle power plants also requires water for cooling. Generation of 653 MWh would withdraw 150,000 and 359,000 gal and consume 118,000 and 313,000 gal for natural gas combined-cycle and coal power generation, respectively, both using cooling towers (EPRI 2002a; Stillwell et al. 2009). While nuclear power would not directly produce air emissions like coal and natural gas, generation of 653 MWh with nuclear power would withdraw 620,000 gal and consume 470,000 gal using cooling towers (EPRI 2002a; Stillwell et al. 2009). For seawater desalination (with 50% recovery) and long-haul transfer, total water withdrawals for desalination and power generation could reach 40.6 million gal (154,000 m^3) for delivery of 20 million gal (75,700 m^3) of desalinated water. Similarly, brackish groundwater desalination (with 90% recovery) and long-haul transfer could total 22.8 million gal (86,500 m^3) of water withdrawn to deliver 20 million gal (75,700 m^3) of desalinated water. This feedback loop of alternative water supplies requiring additional energy, which requires water for power generation, might become increasingly more important

Table 3. A comparison of the energy consumption for the cases with conventional surface water treatment shows a much larger energy requirement for desalination and long-haul transfer (EPRI 2002b).

	Treatment (MWh/d)	Long-Haul Transfer (MWh/d)	Distribution (MWh/d)	Total (MWh/d)
Seawater Desalination + Long-Haul Transfer	196-330	41.4-299	24.1	261-653
Brackish Groundwater Desalination + Long-Haul Transfer	78-195	321	24.1	423-540
Conventional Surface Water	4.4	0	24.1	28.5

Table 4. Daily air emissions from electricity generation of 653 MWh using coal and natural gas show the desalination and long-haul transfer scenario to produce large quantities of greenhouse gases (CO_2) and criteria pollutants (SO_2 and NO_x) compared to conventional surface water treatment (EPA [mod 2010]).

	Desalination with Long-Haul Transfer and Distribution		Conventional Surface Water Treatment with Distribution	
	Coal	Natural Gas	Coal	Natural Gas
CO_2 (kg/d)	679,000	340,000	25,100	12,500
SO_2 (kg/d)	2,020	296	74	11
NO_x (kg/d)	1,480	8.9	55	0.3

as water managers seek the next increment of water supply.

While a desalination and long-haul transfer project would provide a plentiful source of water for Dallas, additional electricity consumption and increased air emissions are trade-offs for securing water. Notably, if nuclear, wind, or solar power were used, the emissions would be zero.

Analysis of the elevation profiles of the seawater and brackish groundwater long-haul pipelines shows that cumulative elevation changes along the route are important for energy consumption for pumping. While the brackish groundwater pipeline has a general downhill trend, the cumulative elevation changes along the route are greater than that of the uphill seawater pipeline. Thus, we cannot assume that downhill long-haul water transfer consumes less energy than uphill transfer consumes, depending on whether energy capture via in-line turbines is deployed. Elevation analysis becomes necessary to evaluate energy consumption from moving water long distances.

Additional reliability concerns might arise in response to a desalination and long-haul water transfer scenario. While reverse osmosis technology is reliable, external factors can affect the consistency of the seawater supply. The selected location of the seawater desalination plant is close to Trinity Bay as a source of seawater. Though a location near the shore minimizes raw seawater pumping distance, such a location is also susceptible to inclement weather during hurricane season. Additionally, recreational and commercial activity in Trinity Bay may degrade influent water quality by increasing suspended sediment, as was observed during pilot-scale testing for a seawater desalination plant in Brownsville, Texas (Herring et al. 2008). Discharge of seawater reverse osmosis concentrate can also harm marine life due to elevated levels of salinity (Lattemann and Hopner 2008).

Multiple factors regarding human behavior figure into such an alternative water supply option as desalination and long-haul water transfer. Quantity of water consumption is not constant and might increase or decrease over time. Additionally, lower cost options such as conservation and redistribution to high-valued water applications may replace or reduce pursuit of new water supplies (Zander et al. 2008).

Another option for providing the next increment of water supply is implementation of desalination in coastal communities in Texas, eliminating the need for long-haul water transfer. As coastal communities move to seawater or brackish water sources, holding surface water rights in these communities might no longer be necessary, opening up the possibility for inland cities to negotiate contracts for local surface water sources. While transfer of existing surface water rights would require complex legal negotiations, such a redistribution of water sources, would likely decrease energy consumption for water pumping over long distances.

CONCLUSIONS

While desalination and long-haul transfer of treated water might improve the resiliency of water supply to Dallas, this water comes with a large cost of additional energy consumption and attendant emissions. Such a water treatment and supply system is nine to 23 times more energy-intensive than conventional surface water treatment of local sources for drinking water.

Sustainability of a water supply includes all aspects of the water system: collection, treatment, disinfection, and distribution. Seawater desalination near Houston, Texas, or brackish groundwater desalination near Abilene, Texas, with subsequent long-haul water transfer to Dallas, Texas, requires additional energy over local surface water sources for both treatment and distribution. However, desalination and long-haul transfer might be appropriate as a back-up water supply during times of drought. The increased energy requirement, along with reliability concerns due to weather and influent water quality, might make desalination and long-haul transfer as a water supply scenario less sustainable than other alternatives, including conservation and end-use transfer.

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