3. Water Resources and Water Supply

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Of all of the elements of the Texas economy, society, and environment considered in this book, water is most closely coupled with climate. It is also the quintessential limiting factor for human development of the state. Simply put, “…the dominant feature of Texas is water, or rather, its scarcity” (Fehrenbach, 1983). The present chapter focuses on availability of fresh water, i.e., water with sufficiently low dissolved solids that it can be used for human and animal consumption, for various agricultural and industrial enterprises, and for the wide suite of biological processes that require water of this quality. Specifically, this chapter addresses the question of whether there is a realistic potential for global warming, and associated climatological changes, to impact the availability of water in the state, and seeks an answer by a rudimentary accounting of the sources and uses of water and their responses to meteorological variables.

Texas hydrology

The ultimate source of fresh water in the state is precipitation, almost entirely rainfall. To understand the challenge of water management in the state, and to anticipate the effect that a greenhouse-warmed climate may have, it is necessary to trace the disposition of water after its delivery as rainfall onto the landscape of the state. This disposition is illustrated schematically in Figure 1. Rainfall impingent upon the surface immediately begins infiltrating into the soil. If the rainfall rate exceeds the infiltration rate, the excess ponds on the surface. Once this ponding suffices to establish continuity across the surface, the excess water can flow downslope. This downslope flow is runoff, and becomes organized into the network of drainageways incised into the landscape surface that collect and convey water, viz. streams and rivers. On a longer time period, some of the water infiltrated into the near-surface layer of the soil is evaporated, some is
Figure 1 - Schematic cross section showing water transfers in the landscape

taken up by plant roots and ultimately transpired back to the atmosphere, some moves laterally and emerges down-gradient at the surface (as seeps and interflow), and some percolates downward into aquifers, deep water-bearing formations.

There are two components of this hydrological network in which water volume is sufficiently and reliably concentrated to serve as managed water supply, namely the river systems of the state and the aquifers, referred to respectively as surface water and groundwater. Surface water encompasses all of the watercourses on the surface of the land in which water flows or is accumulated, including rivers and their tributaries, lakes and reservoirs. The principal rivers and their associated basins are shown in Figure 2. A river basin is its watershed (technically, the watershed at the river mouth), the geographical region that supplies runoff to the stream channels of the river system. Groundwater is the water contained in permeable rock formations, of which nine major and twenty minor aquifers provide important water-supply sources in Texas. The major aquifers of the state are shown in Figure 3. The influx of water to an aquifer, percolating down from the surface, is referred to as recharge. The extent to which an aquifer is recharged is
strongly dependent upon the overlying strata, the nature of the land surface and soils, the hydroclimatology of the recharge area, and the geological properties of the formation itself.

In Texas, runoff is usually produced during and immediately after thunderstorm events, which are characteristically brief and intense, but infrequent. Rainfall, and therefore runoff, exhibit long-term patterns in time and space that emerge when data are appropriately averaged. The frequency and intensity of storm events have a definite seasonality, with maxima in spring and fall in most areas of the state. There is also a pronounced variation in annual rainfall across the state. As summarized in Chapter 2, annual rainfall declines precipitously from east to
west across the state, by a factor of six to seven (depending upon the time period of averaging). The proportion of rainfall that appears as runoff (the runoff:rainfall ratio) similarly declines by more than an order of magnitude, as shown in Figure 4. The product of these, runoff, and hence streamflow, declines by nearly two orders of magnitude from east to west. The contrast between the geographical distribution of surface water in the state and the geographical distribution of the demands for water is a defining feature of the challenge of water management in Texas.
The convective nature of precipitation in Texas has profound consequences on water availability and water use. Texas does not accumulate a winter mass of snow, which slowly melts in the spring, feeding lakes and rivers, nor is Texas subjected to stationary stratiform weather systems that sustain moderate, prolonged rainfall over large regions. Rather, Texas’ precipitation is derived from deep-convecting storm systems and individual thunderstorm cells. Precipitation, consequently, is locally intense but short-lived: rainfall is intense when it occurs, but of brief duration. As this precipitation falls on the surface and is organized into stream and river channels, the corresponding river flows are “flashy,” with pronounced peaks in flow and rapid rise and recession. Flow in a Texas stream may be characterized as a small base flow upon
which are superposed these occasional storm hydrographs, whose frequency and intensity vary seasonally, and which are often separated by long periods of low flow.

This variability means river flows are not dependable as a source, and poses a major problem in using surface water for water supply. Most of the time in most of the state, there will be too little river flow to meet the needs of water supply. This problem is dealt with through the construction of dams, which impound reservoirs that capture some of the higher flows of the rivers and hold this water for use during dry periods. The reservoir is the cornerstone of surface-water management in Texas. Nowhere in the state is there any significant use of uncontrolled, run-of-the-river flow as water supply. According to data of the Texas Water Development Board (TWDB), there are presently 195 major reservoirs in Texas (by which is meant a capacity exceeding 5,000 acre-feet). They have a total storage capacity of 38.7 million acre-feet (maf) allocated for conservation, i.e. water supply. (Many of these reservoirs have additional capacity allocated for flood control, but that is not used for conservation storage and therefore is not considered here.) In addition there are some 1500 SCS flood and erosion control reservoirs (PL-566), and perhaps 300,000 smaller reservoirs, private lakes, farm ponds and stock tanks. Clearly, the surface of Texas is extensively plumbed, see, e.g., the PL-566 reservoirs on a small subwatershed of the Bosque, Figure 5. Information about the history of water-resource development in the state, as well as more discussion of state hydroclimatology, is given in Ward (2004) and citations therein.

Water Budgeting

A valuable technique for analyzing the availability of water is a water budget. As the name implies, this is an accounting of water transfers, analogous in many respects to financial transactions, in which the sources and dispersion of money are identified. A water budget similarly analyzes the different compartments or accounts of water and the transfers among them. A water budget is carried out for some well-defined region in space and integrated over some definite period of time. Clearly, water budgets can be performed for smaller and smaller
units, e.g., a river basin, a county, a city, or even an agricultural field, or house and lot, depending upon
the purposes of the analysis. In the present context, we will present water budgets closed over the entire state or in large subregions of the state. We will also average the water budget over periods of many years. For the hydroclimatological components, this period will typically be 30 years, the conventional averaging period of a climatological norm (see Chapter 2).

Unlike a financial budget, there is little documentation of the transfers of water, nor are there records of the balances in the different water accounts. These must be discovered by direct measurement, by inference from meteorological or hydrological principles, or by posing and
testing alternative assumptions. Closing a water budget can become a challenging scientific endeavor, and the results are frequently unexpected.

An approximate water budget for Texas is shown in Figure 6. The upper part of this diagram formalizes the transfers of water indicated in Figure 1. The transfer of water from one compartment to another is indicated in Figure 6 by the arrows, and the magnitude of that transfer
is shown by the number attached to the arrow. The units are millions of acre-feet per year, but the units are less important for this discussion than the relative size of the transfers. To emphasize this, the larger transfers are shown by larger and bolder numerals.

While the results of this water budget are presented for the entire state, they were not computed this way. Instead, the state was subdivided into four large regions, shown in Figure 7, representing broadly distinct hydroclimatologies, and a water budget analogous to Fig. 6 developed for each region (results from which are given below). These were then combined to determine the statewide budget of Fig. 6. Though each of these regions is far from homogeneous in climate, vegetation, and hydrology, as a group they generally characterize the range in hydroclimatology of the state. (The names of the regions apply only in the present context and only poorly approximate the usual geographic terminologies.)
The details of the water-budget methodology follow those presented in Ward (1993), with the following exceptions: (1) more recent data are employed, as described below; (2) runoff was directly computed from rainfall using the regression relations of the U.S. Geological Survey (Lanning-Rush, 2000); (3) data on electrical generation and associated water uses are taken from King et al. (2008), rather than data of the Public Utilities Commission; (4) the budget includes computation of runoff from adjacent states (using the nearest regional USGS relation); (5) inflow from Mexico into the Rio Grande, which was not considered in the Ward (1993) budget, is a specified input variable; (6) recharge is based upon TWDB data (Muller and Price, 1979), statistically related to rainfall (rather than to runoff); (7) rather than incorporate measured streamflow into the elements of the water budget, as done in Ward (1993), the present approach directly computes all elements of the budget (other than water uses and the inflow from Mexico, which are inputs) and validates the predicted streamflow against measurements of USGS. As in Ward (1993), all of the reservoirs within each region are lumped as a single element at the site of the lowermost dam in the basin. Thus their combined effect is modeled as a reservoir with surface area and conservation storage equal to the totals for the region.

Meteorological data for the water budget of Fig. 6 are taken from the National Climatological Data Center 1971-2000 climatological norms for NCDC divisions of Texas, New Mexico, Oklahoma, Arkansas and Louisiana. Lake evaporation data compiled monthly and aggregated by the Texas Water Development Board (TWDB) were averaged over the same period. Streamflow data of the U.S. Geological Survey averaged over the 1971-2000 period were used to validate the computed runoff for each of the regions. Unfortunately, we do not have a 30-year record of water use data to similarly average, so instead water-use data for the year 2000 from the TWDB are used. Reservoir status as of the year 2000 was used to characterize area and volume of the conservation and power reservoirs of the state, based upon data compilations of TWDB. The conditions depicted in Figure 6, which we refer to as “Present Normal” for simplicity, are therefore a sort of mongrel: more-or-less current water uses imposed upon a 30-year average hydroclimatology.
Water uses

In discussing human water use, we distinguish between withdrawal and consumption. *Withdrawal* means the removal of water from a surface water or groundwater resource for some purpose (the term *diversion* is synonymous). Once water is withdrawn and used, it may be returned to the water resource as a *return flow*. For example, municipal water use entails a withdrawal for water supply and a return flow of treated wastewater. Of course, the quality of the two may be very different, and contamination can delimit further use of the water. This discussion views water supply in Texas from a broad perspective with the focus on water *quantity*; we therefore disregard water *quality* issues and consider a return flow to be a credit to the available water resource. (This will be qualified further in discussion of specific uses.) *Water consumption* means that the water is permanently removed from the water resource. The difference between withdrawal and return flow for a specific use is the water consumption of that use. Water that is consumed generally is eventually emitted back to the atmosphere in some form and may find its way back into the water supply through precipitation. But the accounting of a water budget disregards such consumed water for the simple reason that it is no longer available for water supply.

Many human activities require the use of water in large volumes. For present purposes, these are treated in three broad categories: municipal and industrial, agriculture, and electric. These are shown in Figure 6 by the circles within the “Water Uses” compartment. The first, municipal and industrial uses, are combined because the two are generally associated with large population centers in Texas. This category includes personal water consumption and domestic use, as well as water used as part of an industrial process. The principal return flow is treated wastewater. Advancements in wastewater treatment technology have resulted in significant improvements in the quality of such return flows.

The second broad category is agriculture, including crop and livestock production. The dominant water use in this category on a statewide basis is irrigation, which involves the diversion of large volumes of water for placement on soil. Some of this returns to the surface water system through the runoff process, but much of it ends up in the atmosphere, evaporating...
directly from the soil or being transpired as a byproduct of plant metabolism. (Some of Texas’ most insidious water quality problems are associated with agricultural return flows, which contain elevated nutrient and pesticide levels.)

The third category of water use is electric-power generation, or more specifically, steam-electric generation. Steam-electric generation is the dominant form of power generation in Texas and involves exploiting the thermodynamics of evaporation and condensation of pure water to create high-pressure steam for spinning turbines. In the process, this steam is recondensed by the use of large volumes of cooling water drawn from the surface water supply. Cooling water is returned to the surface resource altered only by an increase in temperature. This excess heat is quickly dissipated to the atmosphere, and the water can be reused for cooling. In fact, many of the steam-electric plants in Texas are situated on a dedicated reservoir, continuously reusing the water for cooling.

There are, of course, other uses of water, such as mining and recreation, but the three categories listed above dominate water use in Texas. We also note that these categories refer strictly to water used by people and their enterprises. The maintenance of natural ecosystems, notably the streams and rivers in the interior of the state and the estuaries along the Texas coast, requires a dependable flow of water. Maintaining the integrity of these ecosystems is also important for the economy of the state. This is why a category is included in the water budget for downstream flows, which ultimately leave the state, either as a transfer into neighboring states or as a flow into the Gulf of Mexico.

An inspection of the water budget of Fig. 6, crude as it is, reveals several, perhaps surprising facts about water use in Texas. First, of the total runoff flowing into the reservoirs, less than 10 percent is removed for all human uses (a net 2.6 maf per year withdrawn, compared to 47 maf/yr runoff). This is mainly because the reservoirs are able to capture only a fraction of the higher flows of the rivers; the rest flows through (or over) the dams and, ultimately, to the Gulf of Mexico. Next, we note that municipal (and industrial) surface withdrawals are offset by a return flow of 70 percent of the volume withdrawn. Such a high proportion is due to the additional return flows from groundwater withdrawal. We also note that there is an enormous withdrawal
required for steam-electric generation (nearly 19 maf per year). This is, in fact, the largest single
diverter of water in the state, but this water is almost entirely returned to the surface water
resource. This is indicated in Fig. 6 by the closed loop of withdrawal and return flow for steam-
electric. Thus, while the actual consumption of water for power generation is minuscule in
comparison to total consumption, electric power requires the availability of a large volume of
throughflow. The next largest category of withdrawal is for agricultural purposes. This is the
dominant consumer of water in the state, over three times the consumption of all other uses
combined.

As part of the planning process, the Texas Water Development Board compiles projections of
future water use for decadal planning horizons, based upon population projections, and scenarios
of industry and agriculture development, as detailed in TWDB (2007). In this chapter we
employ the TWDB 2050 projected water uses, to correspond to the 50-year changed climate
scenario.

**Regional water budgets, present and projected normal conditions**

Over the 30-year averaging period of Fig. 6, rainfall supplies roughly 417 maf of water to Texas
per year. Less than 1 percent of this falls directly on lakes and rivers. The remainder of the
influx to the lakes and rivers of the state must traverse the land surface. In the present context,
we regard the land surface as a “processor” of rainfall. As shown in Figs. 1 and 4, most of the
precipitation falling on the land surface—nearly 90 percent statewide—does not make it to a
surface water body but is intercepted by a complex of processes, most importantly
evapotranspiration, i.e. direct evaporation back into the atmosphere or uptake by plants and
subsequent transpiration. The efficiency of the runoff process is very low, therefore, and is a
strong function of terrain, soils and near-surface geology, and vegetation. Antecedent conditions
are particularly important: the runoff produced from a rainstorm is greatly reduced if the surface
is desiccated, a characteristic of arid regions and of drought conditions when there are long
intervals separating storm events.
Table 1
Regional hydroclimatology (see Figure 7) and water budget inflows, 1971-2000
millions of acre-feet per year except where indicated otherwise

<table>
<thead>
<tr>
<th>Hydroclimatological Region</th>
<th>High Plains</th>
<th>Central</th>
<th>East</th>
<th>South</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean temperature (°F)</td>
<td>59.0</td>
<td>65.4</td>
<td>65.4</td>
<td>67.1</td>
<td>64.9</td>
</tr>
<tr>
<td>Precipitation</td>
<td>44.8</td>
<td>211.7</td>
<td>69.5</td>
<td>90.6</td>
<td>416.7</td>
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<tr>
<td>Evapotranspiration</td>
<td>43.7</td>
<td>182.9</td>
<td>43.8</td>
<td>86.3</td>
<td>356.8</td>
</tr>
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<td>Runoff</td>
<td>0.4</td>
<td>22.9</td>
<td>22.3</td>
<td>2.2</td>
<td>47.7</td>
</tr>
<tr>
<td>Recharge</td>
<td>0.5</td>
<td>2.4</td>
<td>1.2</td>
<td>1.3</td>
<td>5.5</td>
</tr>
<tr>
<td>Lake evaporation</td>
<td>0.1</td>
<td>3.5</td>
<td>2.2</td>
<td>0.8</td>
<td>6.6</td>
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<tr>
<td>Inflow from upstream:</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Mexico</td>
<td>0.1</td>
<td></td>
<td>0.4</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Oklahoma</td>
<td>5.0</td>
<td>0.3</td>
<td></td>
<td>5.3</td>
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</tr>
<tr>
<td>Louisiana</td>
<td>3.8</td>
<td></td>
<td>3.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mexico</td>
<td>2.2</td>
<td></td>
<td></td>
<td>2.2</td>
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</tbody>
</table>

Two of the most significant inferences to be drawn from the statewide water budget of Fig. 6 merit special comment. The first is that, from a water supply viewpoint, Texas is primarily a groundwater state: in terms of net withdrawals (i.e., with credit for agricultural, municipal, and industrial return flows), the groundwater withdrawal is nearly four times that from surface supplies. The second is that runoff is more than ample to meet the surface water requirements of the state, being well over three times the present total water demand. Both inferences are misleading. The problem is the geographical variation in the elements of the water budget. This is demonstrated by examining the water budgets for the four hydroclimatological regions shown in Fig. 7. The separate water budgets for each of these regions are presented in Tables 1 and 2. Table 1 details those components of the water budget driven by hydroclimatology, in this case the 1971-2000 means, but unaffected by human activities. Table 2 presents the various water uses, from the TWDB 2000 data compilation, and the resulting downstream flows. The flow to the Texas coast should be especially noted. A water-budget diagram analogous to Fig. 6 could be displayed for each of the four regions of Fig. 7 using the entries of Tables 1 and 2.
Table 2
2000 water uses by Region (Figure 7) and water-budget flows based on 1971-2000 regional hydroclimatology (Table 1), millions of acre-feet per year

<table>
<thead>
<tr>
<th>Hydroclimatological Region</th>
<th>High Plains</th>
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<th>East</th>
<th>South</th>
<th>State</th>
</tr>
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<tr>
<td>Surface water use</td>
<td></td>
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</tr>
<tr>
<td>M&amp;I</td>
<td>0.09</td>
<td>2.54</td>
<td>0.65</td>
<td>0.39</td>
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<td>agriculture</td>
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<td>0.82</td>
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<td>2.0</td>
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<td>electric</td>
<td>0.02</td>
<td>0.24</td>
<td>0.06</td>
<td>0.00</td>
<td>0.3</td>
</tr>
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<td>Groundwater use</td>
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<td></td>
</tr>
<tr>
<td>M&amp;I</td>
<td>0.13</td>
<td>1.27</td>
<td>0.21</td>
<td>0.21</td>
<td>1.8</td>
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<td>agriculture</td>
<td>6.52</td>
<td>0.78</td>
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<td>0.09</td>
<td>0.01</td>
<td>0.02</td>
<td>0.1</td>
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</tr>
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<td>M&amp;I</td>
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<td>1.99</td>
<td>0.48</td>
<td>0.21</td>
<td>2.7</td>
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<td>agriculture</td>
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<td>0.61</td>
<td>0.05</td>
<td>0.04</td>
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<tr>
<td>Steam-electric circulation</td>
<td>0.0</td>
<td>12.3</td>
<td>6.3</td>
<td>0.0</td>
<td>18.6</td>
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<td>Downstream flow to:</td>
<td>Oklahoma</td>
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<tr>
<td>Arkansas</td>
<td>0.2</td>
<td>10.7</td>
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</tr>
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<td>Louisiana</td>
<td>1.8</td>
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<td></td>
<td>1.8</td>
</tr>
<tr>
<td>Texas coast</td>
<td>17.0</td>
<td>17.8</td>
<td>2.7</td>
<td></td>
<td>37.5</td>
</tr>
</tbody>
</table>

The High Plains region accounts for 70 percent of the groundwater withdrawal of the entire state, predominantly for agriculture. With only 4 percent of the population, the other uses in this region are minor at best. The source for this enormous volume of groundwater withdrawal is a single remarkable resource, the Ogallala formation. Its recharge is only about 5 percent of the withdrawal. Thus, from a water-supply viewpoint, the Ogallala is a finite resource, which can only decline monotonically until depleted. There are also reservoirs in the High Plains, but runoff is quite low as a consequence of the arid climate. The reservoirs principally supply some of the municipal demands of the region. Clearly, the available runoff, even if totally captured (probably a physical impossibility), cannot begin to replace the Ogallala. The High Plains region is virtually isolated from the rest of the state’s water budget, both as a source and a sink of water, but its inclusion in the state averages of Fig. 6 greatly distorts the interpretation of that water
budget. If the High Plains groundwater withdrawal is deleted from Fig. 6, then Texas appears to be about equally dependent upon surface water and groundwater.

At the other extreme of the spectrum, the East region is also sparsely populated with about 8 percent of the state’s population, but has little groundwater usage, and receives about half of the runoff of the state. Indeed, on an areal basis, this region has the greatest runoff rate of the state by about a factor of four, and is therefore the most water-rich. Some of the water captured in reservoirs, and most of the electric power, is exported to the more populous regions of the state. The central concern, amounting to a fixation, of water-supply engineering in Texas for at least four decades has been devising a means of transporting water from this water-rich region to areas where demand exceeds supply (Ward, 2004).

The Central region contains the principal population centers of the state and most of its industrial capacity. While the runoff in total volume equals that of the East Texas region, the runoff per unit area is considerably less. The groundwater withdrawal for agricultural and municipal use is dominated by one formation: the Edwards aquifer in south-central Texas. (The Edwards is the sole municipal water supply for the city of San Antonio, a fact that has erupted as a political issue in recent years because of competing demands for this water, both for agricultural irrigation farther west and for maintenance of spring and river flow, see Ward, 2004, and citations therein.) In addition to the Ogallala, the Edwards also distorts the statewide picture of water supply. If it is also deleted from the water-budget of Table 2, it will be seen that Texas is predominantly a surface-water state.

Finally, the South Texas region includes the vast semitropical areas of the Nueces and Rio Grande basins and is the most arid region of the state, with substantial areas of desert in the west. Groundwater usage for agriculture is dominated by withdrawals in the Winter Garden. Agricultural irrigation in the Rio Grande Valley is the dominant use of surface water, supplied mainly from the Rio Grande international reservoir system of Falcon and Amistad. The most significant feature of this region’s water budget is the high ratio of reservoir supply to runoff. In other regions, this ratio is at least an order of magnitude, e.g. somewhat more than ten percent in the Central region. In the South region, net surface water withdrawal is over 50 percent of the
runoff. Unlike the other regional water budgets, this one cannot be closed reliably for influxes from out of state. Most of the watershed is located in Mexico, and the majority of the flow of the Rio Grande is from the Rio Conchos. For the scenarios evaluated here, there are two candidates for the Mexican inflow: the average measured inflow based upon gauged data of the International Boundary and Water Commission, which was 2.2 maf/yr over the 1971-2000 period, and the minimum delivery mandated by the Treaty of 1944, viz. 0.35 maf/yr. The former is used in Table 2.

The TWDB (2007) population projection to 2050 is a nearly doubled 2000 population (a factor of 1.97 to be precise), and the associated ratios of projected 2050 water uses relative to 2000 are:

<table>
<thead>
<tr>
<th></th>
<th>surface</th>
<th>ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>municipal &amp; industrial</td>
<td>1.87</td>
<td>1.66</td>
</tr>
<tr>
<td>agriculture</td>
<td>1.37</td>
<td>0.81</td>
</tr>
<tr>
<td>steam electric</td>
<td>2.69</td>
<td>3.18</td>
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</tbody>
</table>

These are substantial increases (except for the large decline in withdrawals for agriculture from the Ogallala). Regional data and the projected downstream flows from the water-budget model are given in Table 3. Since this water budget is for average 1971-2000 conditions, the data of Table 1 apply to this scenario as well.

**Drought**

The focus in water planning and management in Texas is the drought. Water supply is predicated on what can be dependably available during the “worst-case” drought condition. The volume of water that can be removed from a water-supply source without failure during such drought conditions is its *firm yield*, and water in Texas has been historically allocated on a firm-yield basis. The key notion of the worst-case drought in present practice is defined as the most intense drought that has occurred during the period for which hydrometeorological data are available, i.e., the *drought of record*. From an engineering and water-management viewpoint, this has the considerable advantage of basing water management on real events—for which meteorological and hydrological measurements are available, and whose effects have been actually demonstrated—rather than on a theoretical construct. Using an historical event for
Table 3

2050 projected water uses from TWDB (2007) by Hydroclimatological Region (Figure 7) and resulting water-budget flows, based on 1971-2000 regional hydroclimatology (Table 1), millions of acre-feet per year

<table>
<thead>
<tr>
<th>Hydroclimatological Region</th>
<th>High Plains</th>
<th>Central</th>
<th>East</th>
<th>South</th>
<th>State</th>
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<td>Surface water use</td>
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</tr>
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<td>M&amp;I</td>
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<td>0.03</td>
<td>0.9</td>
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<td>17.5</td>
<td>2.2</td>
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</table>

planning purposes is particularly advantageous from a policy standpoint. Water development is highly political, involving large public expenditures and the sacrifice of land for the creation of reservoirs and pipelines. It is far easier to argue such actions based upon a real drought event rather than an abstract possibility.

Use of the drought of record also presents an important disadvantage: we are effectively assuming that the most intense drought to have occurred in our period of data collection (which climatologically is relatively short, about 50 years for most rivers in Texas—at most, 100 years) is the very worst that nature can inflict upon us. If our assumption is correct and we design our reservoirs and water supplies to accommodate that level of drought severity, then we will be all right. However, given the variability of climate on time scales longer than our data record, this assumption is most likely untrustworthy (see Ward, 2004, and citations therein).
Moreover, climate change may well increase the severity of extreme drought. For most of Texas, the drought of record is in the 1950’s. During this decade, especially during the first 6–7 years, rainfall events were sparse in time and limited in magnitude, leading to a cumulative surface-water shortage that was an economic disaster for the state (Ward, 2004). The severity of a drought is measured by the combination of its intensity (i.e., the deficit below normal of rainfall) and its duration (the period over which the rainfall deficit is prolonged). The 1950’s drought was especially severe because of both its intensity and its duration of nearly seven years.

Because of the central importance of the 1950’s drought in Texas water planning, a separate water-budget analysis was performed for this event. Hydrological and meteorological data were compiled for the 1950-56 period, as summarized in Table 4. These data should be compared to those of Table 1, for the 1971-2000 normal conditions. Most notable is the disproportionate reduction in runoff, from 47.7 to 19.7 maf/yr, a reduction of 60% compared to the more modest reduction in rainfall of 25%. This is an example of how the landscape operates as an amplifier of changes in rainfall on the resulting runoff.

<table>
<thead>
<tr>
<th>Hydroclimatological Region</th>
<th>High Plains</th>
<th>Central</th>
<th>East</th>
<th>South</th>
<th>State</th>
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</thead>
<tbody>
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<td>65.9</td>
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<td>170.1</td>
<td>52.4</td>
<td>64.0</td>
<td>317.1</td>
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<td>0.9</td>
<td>1.0</td>
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<td>0.2</td>
<td>0.4</td>
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<td>0.0</td>
<td>1.6</td>
<td>1.6</td>
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<tr>
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<td>2.3</td>
<td>0.2</td>
<td>2.4</td>
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<td>2.6</td>
<td>2.6</td>
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</tr>
<tr>
<td>Mexico</td>
<td>1.6</td>
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</tr>
</tbody>
</table>

Moreover, climate change may well increase the severity of extreme drought. For most of Texas, the drought of record is in the 1950’s. During this decade, especially during the first 6–7 years, rainfall events were sparse in time and limited in magnitude, leading to a cumulative surface-water shortage that was an economic disaster for the state (Ward, 2004). The severity of a drought is measured by the combination of its intensity (i.e., the deficit below normal of rainfall) and its duration (the period over which the rainfall deficit is prolonged). The 1950’s drought was especially severe because of both its intensity and its duration of nearly seven years.

Because of the central importance of the 1950’s drought in Texas water planning, a separate water-budget analysis was performed for this event. Hydrological and meteorological data were compiled for the 1950-56 period, as summarized in Table 4. These data should be compared to those of Table 1, for the 1971-2000 normal conditions. Most notable is the disproportionate reduction in runoff, from 47.7 to 19.7 maf/yr, a reduction of 60% compared to the more modest reduction in rainfall of 25%. This is an example of how the landscape operates as an amplifier of changes in rainfall on the resulting runoff.
While water-use data were evaluated for the 1950-56 period, it was more useful in the present context of estimating climate-change impacts to create a synthetic scenario in which current (i.e., 2000) water uses were coupled with 1950’s climatology. (The reduction in lake evaporation, for example, in Table 4 is due to the considerably smaller reservoir development in the late 1950’s compared to 2000. With 2000 reservoir development, this evaporation would increase from that of Table 1.) For this synthetic scenario, it is further assumed that the contribution of runoff from the Mexican portion of the Rio Grande watershed is limited to the minimum delivery of the 1944 Treaty. These results are presented, along with the changed-climate scenario, in the following section.

Potential impacts of climate change

While hydrologists readily acknowledge that the ultimate controls on the surface-water budget are atmospheric, it is far easier, and in many respects more precise, to measure the manifestations of these controls in streamflow and to extend these results statistically, than to measure and calculate the direct effect of atmospheric processes on hydrology. So long as climate is stable over the long term, this is certainly a valid and fruitful approach to hydrology. Indeed, the lower portion of the diagram of Fig. 6 depicts rather well the conventional hydrological model employed in engineering and water planning, as represented, for example, by the Water Availability Model of Texas (e.g., Wurbs et al., 2005). The information transfers from the upper part of Fig. 6, i.e., the atmosphere and landscape components, into the lower part of the diagram, i.e. surface-water and groundwater supply sources, are replaced by actual observations, suitably analyzed. Without the resource of long-term hydrological measurements, viz. lake evaporation rates, water-table elevations, and—most importantly—streamflows, accurate water planning would be impossible.

This method is, however, poorly equipped to address the impact of climate change, because this would require the explicit incorporation of dependencies upon atmospheric conditions. In other words, the changed-climate analysis must restore the upper part of the diagram of Fig. 6, and specify in addition dependencies upon atmospheric variables. With the water-budget constructed
here, in which runoff is explicitly based upon rainfall (Lanning-Rush, 2000), a first approximation of potential climate effects can be explored. We assume that the entirety of climate effects are driven by atmospheric temperature and precipitation, and employ the same dependencies upon these two variables as in Ward (1993), viz. Dalton-law dependency of evaporation and steam-electric forced evaporation on air temperature, regional regressions of municipal and industrial water demand on air temperature, and electric power demand on air temperature. In addition, the increase in agricultural water demand with air temperature is modeled by the dependency given in Table 5 of Chapter 5, acknowledging that this table is limited to the Edwards aquifer and specific crops, whereas we apply it statewide to the entirety of the agricultural demand.

Global warming is expected to increase the intensity of the global hydrologic cycle (e.g., Mitchell 1989; IPCC 2007, and Chapter 1 of this book). The impacts are quantified by application of global climate models (GCMs) and by reasoning from historical and prehistorical associations between climate indicators, as summarized in Chapter 1. There is considerable uncertainty in any such quantitative climate forecast, especially as applied to the hydrological cycle, which is the end product of a chain of complex physical processes (and, therefore in the GCM, assumptions and approximations). This is no better exemplified than in the range of predicted future temperature and precipitation climates generated by the twenty-one GCMs used for such simulation in the IPCC (2007). Generally, an increase in temperature is indicated for the entire south-central U.S., with reduced precipitation and drier soil conditions for the Texas area, but the range about this prediction is considerable, especially for precipitation. The estimated 2050 climate for the Texas area model-averaged predicted results for air temperature and precipitation for scenarios A2 and A1B at the 2050 time point (at which these two scenarios are virtually indistinguishable) were obtained from IPCC (2007). These prove to be about a +2°C (+3.6°F) increment in temperature and 5 percent decrease in precipitation (which, coincidently—or perhaps not—are exactly the same estimates from the 1990 IPCC assessment used in Ward, 1993, and in the first edition of this book).
Table 5
Statewide water budget components for various scenarios, as fraction (per cent) of present normal conditions, Tables 1 and 2

<table>
<thead>
<tr>
<th></th>
<th>Normal climate</th>
<th>Greenhouse-warmed normal</th>
<th>Drought</th>
<th>Greenhouse drought</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>100</td>
<td>95</td>
<td>76</td>
<td>72</td>
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<tr>
<td>Evapotranspiration</td>
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<td>Runoff</td>
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<td>Recharge</td>
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<td>95</td>
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<td>72</td>
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<td>Lake evaporation</td>
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Water-use scenario year

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<th>2050</th>
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<tr>
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<td></td>
</tr>
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<td></td>
</tr>
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<td>M&amp;I</td>
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<td>106</td>
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<td>286</td>
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<td>278</td>
<td>289</td>
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The resulting water-budget analyses are given in Table 5 for the entire state, and in Tables 6-9 for the four hydroclimatological regions of Fig. 7, for normal and drought conditions with 2000 and 2050-projected water uses, with and without additional effects of greenhouse warming. In these tables, the results are presented as a ratio (in per cent) relative to the 2000 normal values. Results are included for the 50-year climate projection in concert with 2000 water uses, to facilitate separating the effect of future increased water use, driven by growth, from the effects of climate change. Although the postulated alterations in temperature and precipitation for the
### Table 6
High Plains Region water budget components for various scenarios, as fraction (per cent) of present normal

<table>
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<tr>
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<th>Normal climate</th>
<th>Greenhouse-warmed normal</th>
<th>Drought</th>
<th>Greenhouse drought</th>
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<tbody>
<tr>
<td>Precipitation</td>
<td>100</td>
<td>95</td>
<td>68</td>
<td>65</td>
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<tr>
<td>Evapotranspiration</td>
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<td>95</td>
<td>69</td>
<td>65</td>
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<td>Runoff</td>
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<td>Recharge</td>
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<td>95</td>
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<td>65</td>
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<td>Lake evaporation</td>
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**Water-use scenario year**

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<td>Groundwater</td>
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</tr>
<tr>
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<td>Return flows</td>
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<tr>
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### Table 7
East Region water budget components for various scenarios, as fraction (per cent) of present normal

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<th>Greenhouse-warmed normal</th>
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**Water-use scenario year**

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<tr>
<td>agriculture</td>
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<tr>
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<td>Return flows</td>
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**Downstream flow to:**

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24
### Table 8
Central Region water budget components for various scenarios, as fraction (per cent) of present normal

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<th>Normal climate</th>
<th>Greenhouse-warmed normal</th>
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<th>Greenhouse drought</th>
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</tr>
<tr>
<td>Surface-water</td>
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<td></td>
</tr>
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### Table 9
South Region water budget components for various scenarios, as fraction (per cent) of present normal

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<tr>
<th></th>
<th>Normal climate</th>
<th>Greenhouse-warmed normal</th>
<th>Drought</th>
<th>Greenhouse drought</th>
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Table 10
Reservoir surfeit flows for Hydroclimatological Regions of Fig. 7 and statewide totals, negative numbers indicating a shortfall (millions of acre-feet per year)

<table>
<thead>
<tr>
<th>Region:</th>
<th>Normal climate</th>
<th>Greenhouse-warmed normal</th>
<th>Drought</th>
<th>Greenhouse drought</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Plains</td>
<td>0.0 -0.1</td>
<td>-0.1 -0.2</td>
<td>-0.2 -0.3</td>
<td>-0.4</td>
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<tr>
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<td>11.4 8.0</td>
<td>2.4 -0.7</td>
<td>-3.9</td>
</tr>
<tr>
<td>East</td>
<td>15.1 14.5</td>
<td>12.1 11.3</td>
<td>5.5 4.8</td>
<td>3.0</td>
</tr>
<tr>
<td>South</td>
<td>2.3 1.5</td>
<td>1.4 0.5</td>
<td>-1.6 -2.4</td>
<td>-3.2</td>
</tr>
<tr>
<td>State</td>
<td>34.4 29.9</td>
<td>24.7 19.5</td>
<td>6.1 1.4</td>
<td>-4.4</td>
</tr>
</tbody>
</table>

climate change scenario are modest, their effect on the state water resources is dramatic: a reduction of 17 percent in runoff and 26 percent in flows to the coast under normal conditions at year 2050 demands. Under drought conditions, the 2000 runoff and flows to the coast are reduced to 41% and 32% of normal, resp., i.e., reductions of 59% and 68% from normal, and under the greenhouse-warmed 2050 conditions are reduced further to 35% and 27%, resp., i.e. additional reductions of 15% and 10%.

But this is only part of the impact. In the above water budgets, no indication is given whether the water-use demands are in fact met. If reservoir volume is never driven to zero, then there is a surfeit of water above the total demand, and the water-use demands are provided. These surfeits, by region and statewide, are summarized in Table 10. A negative surfeit (deficit) indicates a shortfall, i.e., the extent to which the surface water supply fails to meet the water-use demands. Under both normal and greenhouse-warmed conditions for both 2000 and 2050 levels of water use, there is not significant shortfall in the state. Under drought conditions, however, the situation is worse. The 2000 water uses will result in a substantial shortfall in the South Region, which is primarily associated with the overallocation of the Lower Rio Grande, a statement which accords well with the experience of the recent drought in the Rio Grande Valley. Under
Table 11
Flows to the Texas coast in Central Region and statewide, assuming that the deficits (Table 10) are met with new supplies in the East and Central Regions, see text

<table>
<thead>
<tr>
<th>Region</th>
<th>Normal climate water-uses year:</th>
<th>Greenhouse-warmed normal</th>
<th>Drought</th>
<th>Greenhouse drought</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2000</td>
<td>2050</td>
<td>2000</td>
<td>2050</td>
</tr>
</tbody>
</table>
| a. Flows in millions of acre-feet per year
| Central       | 17.0  | 16.0  | 12.1  | 10.9  | 4.2   | 3.1   | 0.5   |
| East          | 17.7  | 17.4  | 14.5  | 14.0  | 7.1   | 6.8   | 5.0   |
| South         | 2.7   | 2.2   | 1.8   | 1.1   | 0.0   | 0.0   | 0.0   |
| State         | 37.5  | 35.6  | 28.4  | 26.1  | 11.3  | 9.9   | 5.5   |
| b. Flows as a fraction (%) of 2000 normal
| Central       | 100   | 94    | 71    | 64    | 24    | 18    | 3     |
| East          | 100   | 98    | 81    | 79    | 40    | 38    | 28    |
| South         | 100   | 80    | 67    | 41    | 0     | 0     | 0     |
| State         | 100   | 95    | 76    | 69    | 30    | 26    | 15    |

2050 water uses, shortfalls occur in each region except the East, and these are further exacerbated under the greenhouse-warmed condition.

These water budgets assume the same level of reservoir development in 2050 as existing in 2000. This assumption and the indicated water-use shortfalls (Table 10) explain the paradoxical result above that the greenhouse scenario has more impact to flows to the coast under normal conditions (26%) than under drought conditions (10%). This is unrealistic, because additional surface supplies will be mandated by the doubled population. While future reservoir development cannot be projected within any confidence, because this will most likely entail multiple reservoir sites with extensive interbasin transfers, we can impose on the water budget the least-development assumption: that new supplies are created to meet only and exactly the water-use shortfalls of Table 10 (in which the High Plains shortfalls are met in the East Region). Under this scenario, the resulting flows to the Texas coast are given in Table 11. At 2050
projected water uses under drought conditions, the effect of greenhouse climate change is to reduce flows to the coast by an additional 42% statewide, to a level 15% of the 2000 normal.

**Discussion and conclusions**

The water budgets presented here are rudimentary and approximate, and are proffered as a means of addressing the question stated at the outset, whether Texas water supply is potentially vulnerable to climate changes on the order of those projected for a greenhouse-warmed scenario. The answer is clearly affirmative. Taking flows to the coast as a measure of river-basin impact, the net effect statewide of the assumed greenhouse climate change, a 3.6°F increase in air temperature and a 5% decrease in precipitation, is to reduce these flows by about 25% under normal conditions and by 42% under drought conditions, relative to the already reduced flows under 2050-projected water-use demands. The 2050 projected flows to the coast are 70% of the 2000 normal values under normal conditions with the effect of a greenhouse climate imposed, and 15% of 2000 normal under drought conditions. In general, the effect of climate on water demands and watershed processing of rainfall is to amplify the changed-climate signal, because the causal connections are nonlinear and reinforcing.

It is important to observe that nearly every assumption or approximation in this argument is imposed to *minimize* the estimated effect of climate change. The first such assumption is the estimated changed-climate condition itself, a uniform statewide increase in average temperature and decrease in average precipitation that is a long-term (10-20 years centered on the 2050 forecast) average of model results averaged over 21 models of varying skill in depicting meteorology in the Texas area. Most of the model simulations indicate greater temperature rises and less rainfall in the interior and western areas of the southcentral U.S., which becomes more exaggerated with distance south into Mexico (IPCC, 2007). This would imply less runoff into those reservoirs in the upland reaches of Texas basins, and a reduced capture efficiency. Additionally, the intra-annual variation in temperature would have a nonlinear effect on evaporation, hence reservoir drawdown, that is not depicted by a long-term change in annual value.
The second major assumption is to treat the surface water budget by aggregating hydrometeorology and water uses over four large hydroclimatological regions of the state, shown in Fig. 7. The reservoirs in each region are taken to be lumped together in terms of area and storage, and placed at the downstreammost damsite in the region. This maximizes the efficiency of that hypothetical reservoir, i.e., it captures the greatest amount of runoff feasible for its size. The reality is that reservoirs are distributed throughout the basin, each with a limited effectiveness in the amount of runoff it can intercept and store. Moreover, the actual runoff in a basin is skewed to the east, so that a higher proportion is unavailable for human storage and use. The water budget is carried out for transfers only, and does not consider the volume of water in each compartment. Notably, storage and drawdown of reservoirs are not modeled; spills are therefore the net of runoff less evaporative losses and withdrawals. Thus the ability of the reservoirs to meet the demands is optimistic.

The third major assumption underlies the central feature of the water-budget model presented here, the set of runoff-versus-precipitation regressions developed by USGS (Lanning-Rush, 2000). While these equations capture, in part, the decrease of the ratio runoff:rainfall with decreasing rainfall, the fact that they are annual runoff based upon annual precipitation means that much of the effect of correlated high flows with wet conditions and low flows with dry is averaged out of the data before the regressions are determined. Much more runoff (per unit rainfall) occurs when the watershed is saturated during the wet season, and much less runoff (per unit rainfall) occurs when the watershed is desiccated during the dry season than reflected in the equations. It is this intra-annual variation that is expected to be particularly exacerbated by climate change. This will also have a strong geographical variation within the four hydroclimatological regions of Fig. 7. None of this is depicted in the water-budget model; instead the extremes of runoff as a function of rainfall are diminished and the climate-change response muted.

The fourth assumption is the set of specific causal pathways by which climate change affects the water budget represented in this model, viz: (1) reduced runoff due to decreased rainfall; (2) increased evaporation, forced evaporation (power generation), and municipal and industrial demands as a function of increasing temperature; (3) increased agriculture demand with
increasing temperature. There are other relations driven by these two variables, e.g., reduced precipitation forcing increased demands and increased temperature driving increased evapotranspiration hence reduced runoff, and there are other climate-change variables not considered, e.g. decreased clouds, increased CO₂ concentration, most of which will further augment the changed-climate response.

Some of the above weaknesses can be repaired by the more complex procedure of carrying out a water-budget analysis on a regional scale with more refined time resolution. Schmandt and Ward (1991) reported such an analysis for three river basins in Texas, the Trinity, Colorado, and Rio Grande, and later Schmandt et al. (2000) reported a more detailed evaluation of the Rio Grande. For all of these basins, severe reservoir drawdowns were determined, in most cases the storage being depleted before the end of the drought of record. Wurbs et al. (2005) report an analysis of the Brazos basin achieved by coupling a detailed watershed model (SWAT) to the state WAM model, thereby allowing monthly simulations and detailed reservoir operation. The results are generally consistent with those presented here (though the predicted changed-climate scenarios were based upon only a single GCM, and the relations between atmospheric parameters and watershed response are not clear).

These data demonstrate the extent to which Texas is vulnerable to changes in climate. The drought of the 1950’s is within living memory, and yet it is evident that population growth alone would make it extremely difficult to cope with a similar drought under the 2050 scenario, during which many water uses would have to be curtailed. When the consequences of global warming for Texas climate are included in the analysis, the situation is even more serious, a conclusion that is even more robust in light of the minimal responses assumed for the water-budget components in this analysis.
References


King, C., I. Duncan, and M. Webber, 2008: Water demand projections for power generation in Texas. Report to Texas Water Development Board (Contract 0704830756), Bureau of Economic Geology, University of Texas at Austin.


