Texas Water at the Century's turn — perspectives, reflections and a comfort bag

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Water for Texas: 2000 and Beyond*
Texas A&M University
College Station

23-25 September 2000

ABSTRACT

A précis is presented of the status of the water resources of Texas at the turn of the century, both 1900 and 2000. The purpose is to assess the similarities maintained, and the changes wrought in water problems and their management over the intervening century. Then, as now, the state exhibits a wide range of hydroclimatology, the greatest of any of the contiguous states. Runoff derives mainly from deep convection, largely associated with equinoctial midlatitude storms and landfalling tropical depressions, so the resulting streamflow is flashy. There is a near balance between rainfall and evapotranspiration, making their difference—the water source for both runoff and recharge—susceptible to slight variations in either. These two facts, instability of and flashiness in runoff and recharge, together comprise the fundamental problem of Texas water supply.

The close of both centuries showed Texans reeling from droughts and floods. Population growth in the state over the last decade of both centuries was over 30%. In the Twentieth Century, Texas population has multiplied by an order of magnitude and has shifted from rural to urban. Then, as now, the predominant consumption of water was for irrigation, but the volumes of this consumption grew substantially during the 20th Century. A ubiquitous pattern in Texas water use is a shift from reliance on groundwater to surface water, and the Twentieth Century has seen the development of practically the entirety of Texas reservoir system. During the first decade of the century, rice irrigation grew to be the predominant demand for surface water irrigation, and in the closing decade it still is but is in decline. There has been an almost total shift from hydroelectric power to steam-electric generation, though the latter also has a substantial water requirement, often overlooked in water planning.

The greatest difference between 2000 and 1900 is the sense that Texas water supply development may be approaching its feasible limit. Groundwater supplies have declined due to increasing drafts and decreasing recharge: hundreds of artesian springs across Texas no longer flow, the great Ogallala aquifer has been substantially depleted, and municipal and agricultural pumping can now draw down the entire spring recharge of the Edwards aquifer. The ability of reservoirs to be maintained by a "critical-mass" of feeding watershed area, together with the political opposition to such projects, limits present reservoir development. Around 1970 a pronounced reversal in the trend of reservoir storage per capita occurred (coinciding with the defeat of the Texas Water Plan). Looking ahead, interbasin transfer from the eastern water-surplus region of the state will increase, as will re-use strategies, and conversion of irrigation rights to municipal/industrial, resulting in further decline of irrigated agriculture. This writer worries about the consequences of a major statewide drought, and attempts to spread his worries.

Introduction

This conference is inspired by the approaching occasion of the passage of a whole number of centuries, as reckoned in the present Gregorian calendar system. While the cosmic import of this event is open to debate, it does afford a convenient benchmark for the appraisal of water resources, their utilization and management, in the State of Texas.

Consider, then, the state of things at the turn of the century. After weathering major recessions in the 80's, Texas is in an economic boom, its population having increased by a staggering 35% in the closing decade of the century. The past several years have been unusually warm, with many record high temperatures, and large regions of the state have suffered from drought. On the national scale, after a harrowing century, the United States has emerged in a new position of world leadership, and is enjoying relative peace and prosperity. Our last war, with an

* Conference manuscript published after expurgation in Norwine et al. (2004).

old-world power, which occurred within the closing decade of the century, was swift and decisive, and while popular at the time, its motivations have subsequently been called into question. Politically, the country is in one of its periodic slides to the right, both houses of Congress controlled by Republicans, the leadership of the House being practically reactionary. However, the business climate is healthy, despite consolidations of huge corporations motivating widespread concern about trusts and monopolies. American society is undergoing a revolution driven by the explosion of technology, not the least of which is telecommunication that has created capacity for exchange of information on unprecedented scales. Texas especially is benefiting from technological advancement, notably in the urban areas, where electricity has largely replaced gas lighting, and the telephone now permits instantaneous communication within and between cities.

This is, of course, the year 1900, the turn of the Twentieth Century. There are tantalizing parallels between Texas in 1900 and Texas in 2000, some of which may have occurred to the reader of the preceding paragraph. One of the most basic parallels (in this writer's view, *the* most basic) is the effect of climate. The backdrop to the growth of population and development of commerce, both in 1900 and in 2000, is the vagaries of Texas climate. These plagued Texans throughout the Nineteenth Century, and were destined to continue through the Twentieth. Numbing blizzards, searing heat, deadly floods, and fearful windstorms were endemic. However, these were episodes, widely scattered in time and space. The climate component that remorselessly stressed the state was water supply. To echo Fehrenbach in his *Seven keys to Texas*, "…the dominant feature of Texas is water, or rather, its scarcity."

Texas hydroclimate

On the broadest scale, the climates of the North American continent are determined predominantly by the relative interplay among four factors:

(1) the belt of westerlies and their synoptic-scale perturbations,
(2) the influx of water vapor from the Gulf of Mexico carried by the easterly limb of the Bermuda High circulation
(3) the physiography of the continent, notably the barrier of the Rocky Mountain cordillera to the west and the relief-free plain in their lee
(4) the receipt of solar radiation at the surface

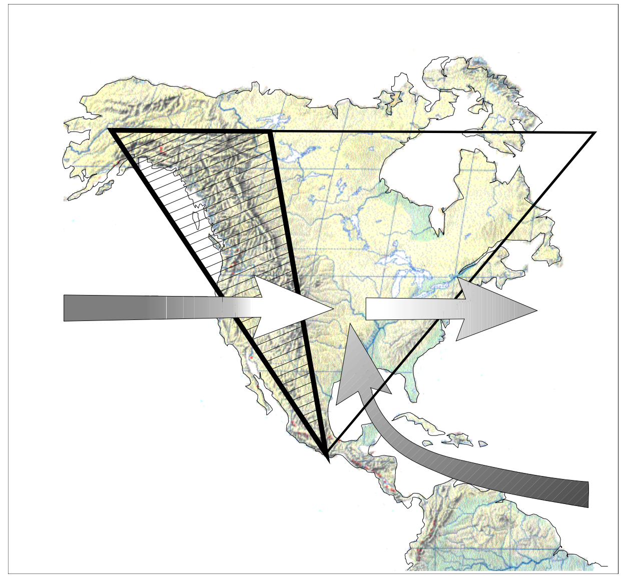

Figure 1 - Principal determinants of North American climate. Note the position of Texas at the apex of the indicated triangle.

The westerlies impinge on the mountains, are forced up and over, releasing their moisture in the process, then descend to the lee plain as warmed dried air establishing a semi-arid climate, the familiar "rain-shadow" effect. Onshore flow from the tropical Gulf carries water vapor northward into the lee plain to be entrained back into the air stream. The rate of entrainment is governed by the synoptic-scale disturbances in the westerlies. Surface heating and cooling are controlled by insolation, which reinforces synoptic disturbances by inducing or suppressing convection. If one steps back and squints at the North American continent, as suggested in Fig. 1, its general morphology is seen to be that of an inverted triangle, with the Rocky Mountain cordillera converging from the west and the moisture source of the Gulf of Mexico converging from the east. At the apex of this triangle lies the state of Texas. This geographical fact accounts for one of the dramatic features of the climate of Texas, namely its pronounced geographical variation, which includes the first of several maxims of Texas water:

(I) Precipitation and river flow decline markedly from east to west across the state.

There is a six-to-seven-fold variation in annual precipitation across Texas, the largest range of variation of the contiguous states (tying California). The humid eastern sections of the state are heavily forested, the westward extension, in fact, of the great

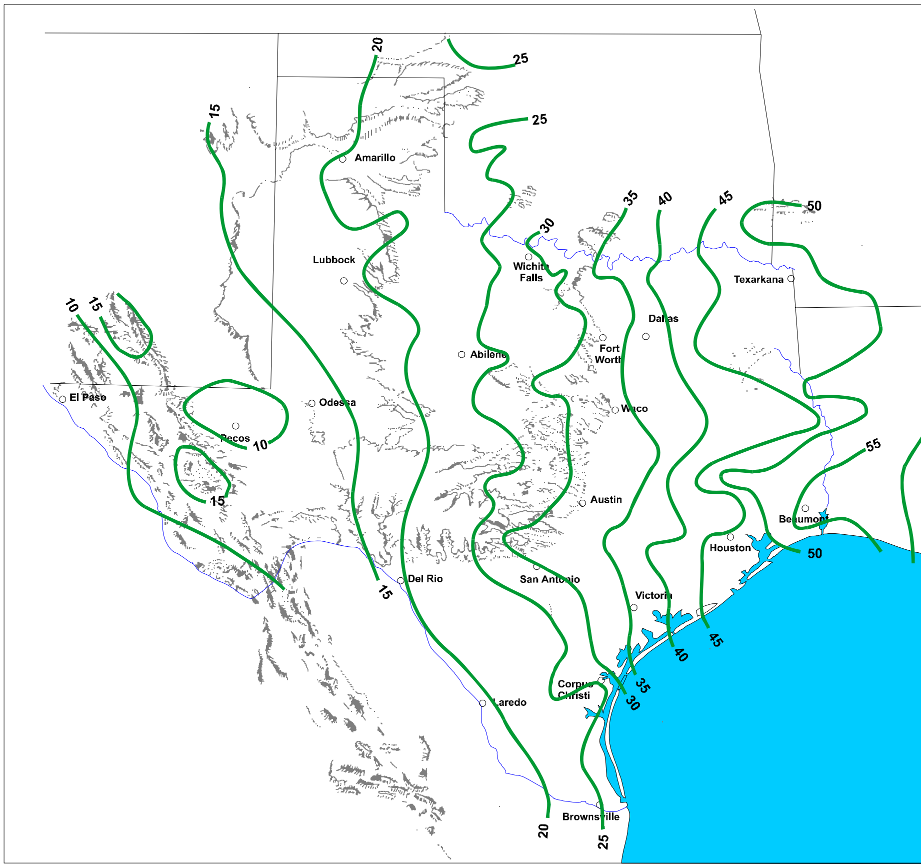

Figure 2 - Annual precipitation in Texas (contours in inches per year).

eastern forest, while the western sections of the state are desert, the northward extension of Mexico's *Tierra Caliente*. Between these extremes, the majority of Texas is semi-arid. Benedict and Lomax (1916) observed, with tongues-in-cheek, "Irrespective of the prohibition issue, Texas is permanently divided into wet and dry." This is exemplified by the patterns of annual precipitation[1] shown in Fig. 2. The isohyets generally lie along meridians of longitude. Isotherms, in contrast, align mainly along parallels of latitude, see Fig. 3, evidencing the role of southward increasing insolation as well as the diminishing effect of synoptic disturbances in the westerlies (the two being interrelated, of course). Another defining characteristic of Texas water is the source of precipitation, *viz*.

(II) Precipitation is almost entirely rainfall derived from deep convection.

The implications are that runoff is closely keyed to the occurrence of storms and the resulting streamflow is flashy. In contrast to other regions of the country, Texas is not routinely visited by large-scale stratiform systems that deliver widespread rainfall at a slow rate over extended periods, nor is there storage of precipitation in its solid form to slowly melt with the onset of spring.[2]

This also implies that the seasonal pattern of rainfall is governed by the synoptic processes that trigger thunderstorms. Figure 4 displays the occurrence of seasonal monthly rainfall maxima in Texas. The spring maximum results from the interplay between midlatitude systems in the westerlies and the increasing influx of moist, unstable air from the Gulf of Mexico, an interplay that is maximized in the late spring months. A fall maximum results from a similar interaction, as the summer trades weaken in the early fall and low-pressure systems with their associated surface fronts penetrate more readily to these latitudes. The fall maximum also reflects the occurrence of tropical disturbances entering Texas mainly from the Atlantic and Gulf. A large segment of Central Texas has a bimodal rainfall distribution, with maxima in both fall and spring. Airmass thunderstorms and disturbances developing along the

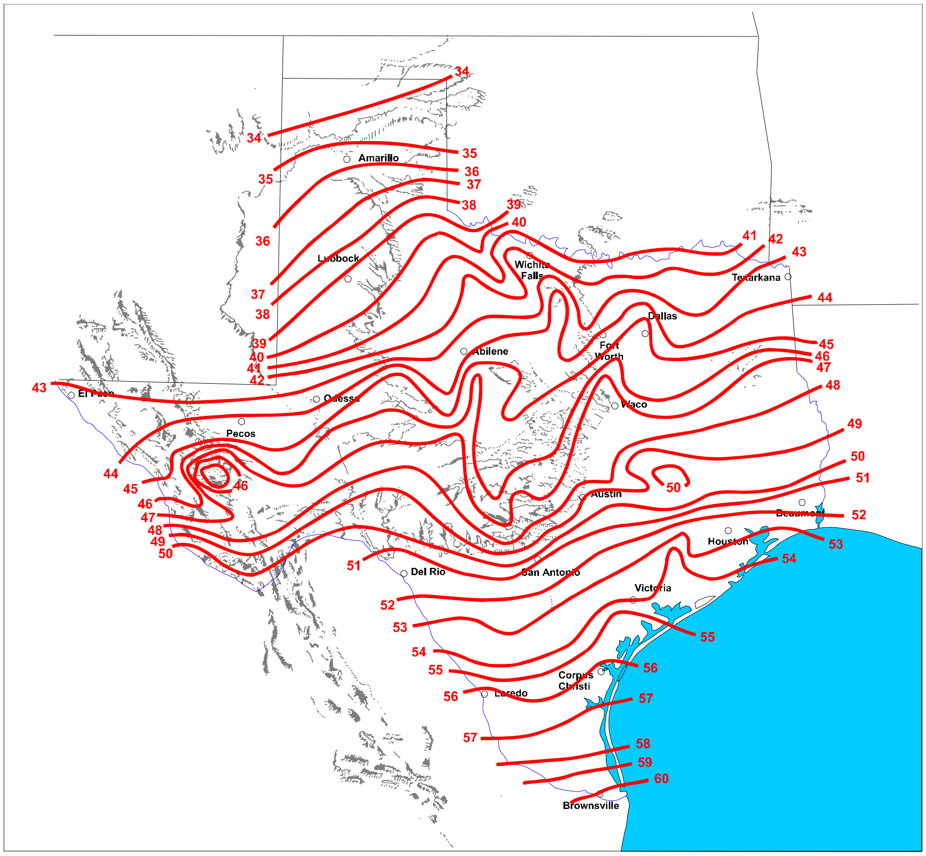

Figure 3 - Average January temperatures (degrees F)

dryline are the primary source of rainfall in West Texas, the maximum for which occurs in summer.

Monthly rainfall values upon which Fig. 4 is based are in one respect misleading, because the rainfall is actually delivered as isolated storm events of short duration, in effect spikes (or impulses) of rainfall. Figure 5 is a rather famous compilation of magnitude-duration data, originally presented by the U.S. Weather Bureau (Jennings, 1942, revised 1963), and appearing in several standard textbooks on engineering hydrology (e.g., Linsley and Franzini, 1964). This plots the largest storm event in the entire U.S. for each duration value, based upon measurements through 1961. It is worth noting that of the 20 data points plotted, 45% are from Texas.[3]

Data on Texas hydroclimate and water supply were presented by Ward (1993), who analyzed this data by considering the state to comprise four broad hydroclimatic zones, as shown in Fig. 6. The surface

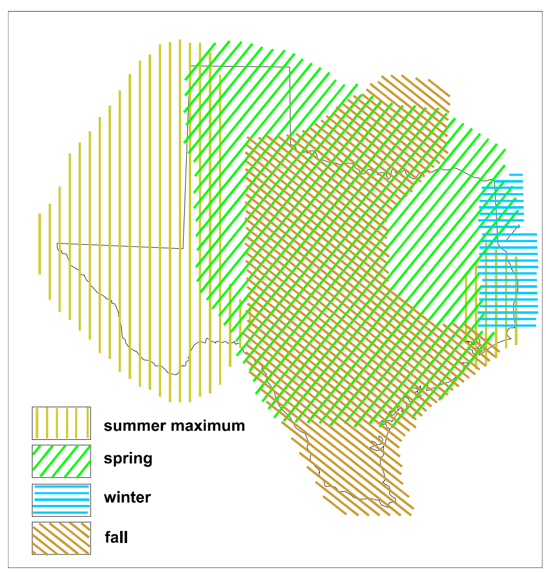

Figure 4 - Regions of seasonal rainfall maxima

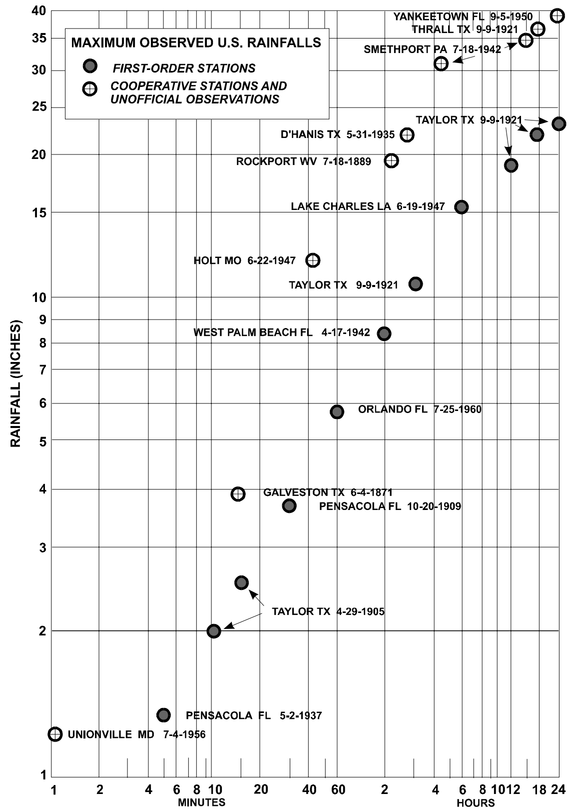

Figure 5 - Greatest rainfall volumes for specified duration in contiguous United States, data of U.S. Weather Bureau (Jennings, 1942 revised 1963)

water budgets for the state as a whole and for these four component regions are tabulated in Table 1. Inspection of these data disclose:

(III) On both a statewide and a regional basis, apart from the extreme humid eastern section of the state, there is a near balance between precipitation at the land surface and evapotranspiration.

The distribution of the ratio of runoff to rainfall across the state is depicted in Fig. 7. Even in the humid eastern portions of the state, only a fraction of the rainfall, about 20% on average, appears in the drainageways as streamflow. Farther west, this fraction dwindles to only a few percent.

The two sources for water supply, namely runoff and recharge, are therefore the difference between two large, nearly equal parameters, precipitation (P) and evapotranspiration (E). This is a prescription for instability: only a slight change in either is capable of producing a great change in their difference, e.g. in runoff.[4] This consequence of Maxim (III) is so important to Texas water supply that it warrants separate identification:

(IV) Rainfall and runoff are subject to long-period vacillations

It was remarked above that much of Texas is semi-arid. This term, in the present context, does not mean an intermediate stage between arid and humid, but rather that some years are humid and some years are arid. This alternation between extended periods of high and low rainfall is in many respects the *central* feature of Texas water, because it determines the limits of natural water supply for use by humans. When he visited San Antonio in 1854 Frederick Law Olmsted (1857) noted the existence of irrigation ditches and aqueducts that had been indispensable 10 years before but now were unused and in disrepair. This was due to a steady increase in moisture during that period. Apparently unaware of Maxim (IV), he opined, "By common Mexican report the commencement of this change is coincident with American occupation. It is certainly, if well attested, a remarkable scientific phenomenon. In the settled districts of Western Texas, the evidence seems to have been so palpable as to have become a matter of common allusion." A similar vacillation in the Great Plains climate later in the century would lead to the incorrect precept that "rain follows the plow."

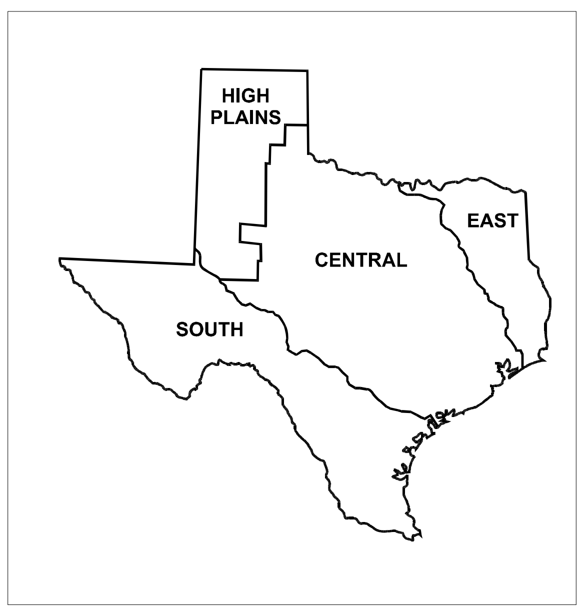

Figure 6 - Texas regions used in hydrological data compilation, Ward (1993)

Table 1
Regional and statewide water budgets for Texas, normal conditions ca. 1980, rounded to 3 significant digits, 10^3 acre-feet per year, after Ward (1993)

	Region (see Fig. 6)				
	EAST	CENTRAL	SOUTH	HIGH PLAINS	TEXAS
Surface water budget:					
Inflow from upstream:	4070	912		10	1530
from:	Central (2550) Louisiana (1520)	High Plains		NM	NM & LA
Precipitation	68300	193000	79400	38400	379000
Evapotranspiration	49800	167000	75400	36900	329000
Runoff	17500	24800	3720	1180	47200
Recharge	1090	2600	1090	343	5130
Downstream flow to:					
other regions/states	8380	2550		912	9330
Texas coast	12600	21100	973		34700
Human activities:					
Ground water withdrawal	246	2100	1100	7190	10600
Surface water diversion	6250	17000	3380	150	26800
Surface water return	5740	15900	1500	89	23200
Consumption	752	3190	2990	7250	14200
Spills/uncaptured	21000	23200	973	1010	42700

Floods and droughts

Since the Nineteenth Century, the wide range of flows exhibited by any given Texas river had been noted by travelers and settlers, from “insignificant,” as Olmsted (1857) described the Neches when he crossed it in 1854, barely “three rods in width,” to “bluff to bluff” flows, a roaring roiling froth of brown water. These freshets are of course produced by intense rainfall events, and the time base of the storm is often so short compared to the response of the watershed that the rainfall event appears like an impulse function. The time variation of the resulting streamflow hydrograph is typically a classical impulse-response function (which can be nicely modeled by a two-parameter gamma distribution, see Dooge, 1979). The spring freshet on the major rivers in the east of the state is a merger of such responses, both in time and with distance down the river channel. With distance to the south or to the west, into the more arid sections of the state, the seasonal freshet becomes resolved into a series of such impulse-responses, such as the freshet on the Trinity shown in Fig. 8. Particularly intense rainfall events produce hydrographs that exceed the capacity of the channel resulting in floods, which have plagued Texans since the first settlements along rivers.

In 1900, stream gauging was in its infancy, and the only record of Nineteenth Century floods were the recollections of amateur observers, usually in the form of high-water marks. Thus, floods were noted on the Colorado in 1843, 1852 and 1870 (Baker, 1875), but the greatest of the Nineteenth Century occurred in 1869. By interviewing old-timers, and sifting through newspaper records and similar reports, Taylor (1930) reconstructed the high-water profile and determined that the flood reached a stage of 43 ft relative to the USGS gauge datum at Austin, at least 7 ft higher than the other floods. At Dallas, the Trinity flooded in 1844, 1866, 1871, 1899 and 1908, all reaching stages around 50 ft (Kimball,

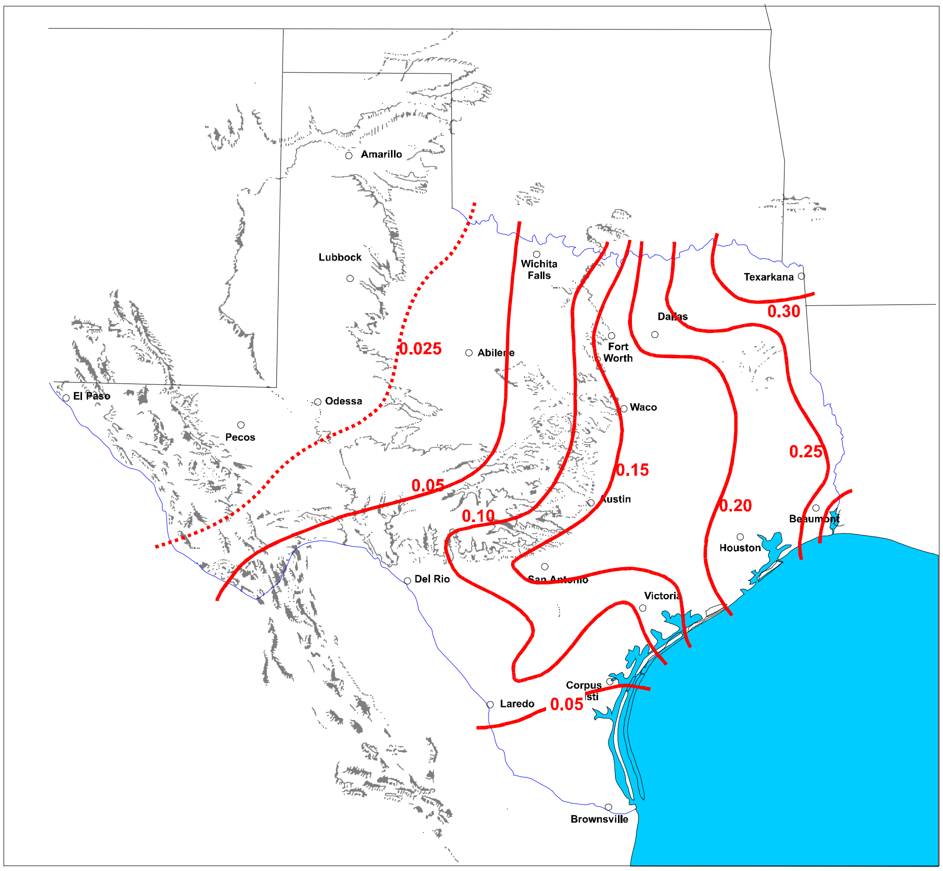

Figure 7 - Runoff as a proportion of rainfall

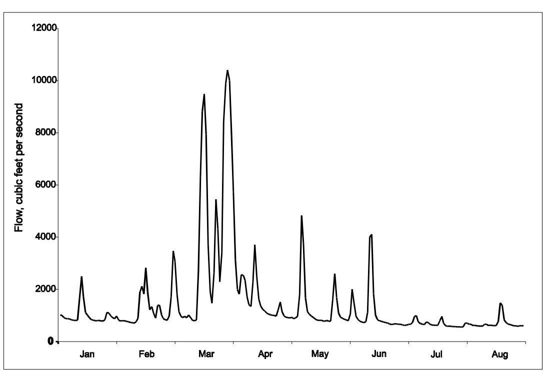

Figure 8 - Freshet of spring 1984 on Trinity River at Trinidad, resolved as a series of impulse responses to individual storm events

1927): the 1866 flood may have been the largest, as one estimate puts the high water at 56.5 ft

The operation of stream gauges and archiving of the data are indispensable in the engineering and management of state water resources. Not only do these data provide objective, consistent quantification of such events, but they also allow rigorous statistical evaluation. It is ironical, therefore, that in the closing years of the Twentieth Century, there is a move afoot in USGS to reduce the number of operating stream gauges to save money (USGS, 1998). Table 2 summarizes the record floods on the major rivers of Texas within the gauged record. Of these record floods, we observe that 50% have occurred within the last fifteen years. The October 1994 event in Southeast Texas is especially noteworthy. This event, whose meteorology is not well-understood but included the ingredients of an open Gulf, a long Trade-Wind fetch (with dew points in the high 70's!),

Table 2
Record floods on principal Texas rivers
Data of U.S. Geological Survey and International Boundary and Water Commission

river/gauge	*agency number*	*reliable gauge record begins:*	*stage (ft)*	*date*		*estimated max before period of record*	
USGS:							
Wichita/Wichita Falls	07312500	1938	24.0	Oct	1941		Jun 1915*
Red/Terral, OK	07315500	1938	33.6	Oct	1983	27.2	May 1935**
Red/Index, AK	07337000	1936	32.3	May	1990		
Sabine/Beckville	08022040	1938	38.9	Mar	1989	33.8	Apr 1945
Sabine/Bon Wier	08028500	1923	37.9	Jul	1989	43.5	Apr 1913
Neches/Evadale	08041000	1921	20.8	Jul	1989	26.2	May 1884
Trinity/Dallas	08057000	1931	47.1	May	1990	52.6	May 1908
Trinity/Romayor	08066500	1924	45.8	May	1942†		
San Jacinto/Sheldon	08072050	1970	27.1	Oct	1994††		
Brazos/Glen Rose	08091000	1923	35.8	Apr	1990	29.5	May 1922
Brazos/Richmond	08114000	1922	50.3	Oct	1994	61.2	Dec 1913
Colorado/San Saba	08147000	1915	62.2	Jul	1938		
Colorado/Columbus	08161000	1916	48.5	Jun	1935	51.6	Dec 1913
Lavaca/Edna	08164000	1938	35.5	Oct	1994	33.8	May 1936
San Antonio/Falls City	08183500	1925	33.8	Sep	1946‡		
San Antonio/Goliad	08188500	1924	53.7	Sep	1967		1869‡‡
Guadalupe/Victoria	08176500	1934	34.0	Oct	1998		
Nueces/Three Rivers	08210000	1915	37.3	Jun	1987¶	46.0	Sep 1919
Nueces/Mathis	08211000	1939	48.7	Sep	1967		
IBWC:							
Pecos/Langtry	08-4474.10	1898	>100	Jun	1954		
Conchos/Ojinaga	08-3730.00	1896	n/a	Sep	1904¶¶		
Rio Grande/Brownsville	08-4749.00	1934	31.5	Oct	1945		

* 1941 peak flow: 17,800 cfs; 1915 peak est 50,000 cfs
** max daily flow Jun 95
† max daily 117,000 cfs & instantaneous flow 122,000 cfs Oct 94
†† 356,000 cfs Oct 94 *measured* near flood peak
‡ max daily 63,600 cfs and instantaneous 70,000 cfs Oct 1998
‡‡ exceeded 1967 stage by "several feet"
¶ max for 1949-pres post-regulation
¶¶ max flow of 162,000 cfs

an approaching surface front, and a Pacific hurricane that jumped the continental divide into northeastern Mexico, produced phenomenal rainfall from the Guadalupe to the Calcasieu basins. The precipitation was exceptional in its combination of intensity and duration: in terms of average rainfall on the San Jacinto basin, the maximum daily rainfall during the October 1994 storm was a one in two-hundred-year event, but the maximum five-day rainfall had a return period of 1,300 years. The peak flow at the US 90 gauge (Table 2) had a return period of 2,100 years, and the five-day cumulative flow was off the scale at more than 10,000 years.

However, we are presently concerned with the opposite end of the flow spectrum. It has been said that the same river cannot be crossed twice. But this wasn't said by a Texan, who became accustomed to the stagnant or even bone-dry streambeds of the state. In his *Seven keys to Texas*, Fehrenbach (1983) observes, "Although the annual rains across most of central Texas equal those of London in total measure, the moisture tends to fall at scattered periods, long dry spells broken by heavy rains, rainy seasons interspersed by months of extreme aridity." This is the obverse face of convection-derived precipitation. Everywhere in the state, there is a low-flow season, which often amounts to a "no-flow" season. Baker (1875) refers to this in Central Texas as the "usual summer drought." This regular annual drought is inconvenient enough, but when it stretches for months or years, the results are catastrophic.

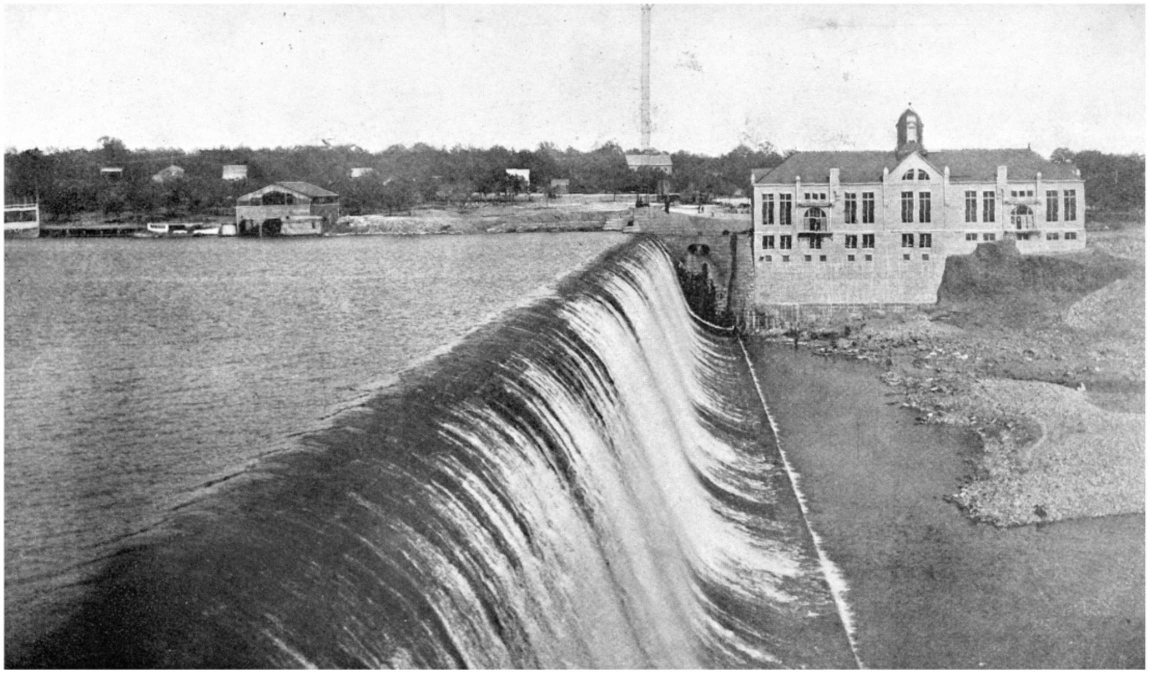

Figure 9 - Austin Dam on Colorado, looking north toward powerhouse, from Hutson (1898). Note moonlight tower in background.

In the Nineteenth Century, *the* drought was that of the 1880's, which reached its absolute nadir in South Texas in 1886, but intensified and lingered in Central and West Texas through the early 90's. The Panhandle and Rolling Plains regions of the State were subjected to repeated occurrences of the infamous Texas "dusters." Farming was devastated statewide, and farmers defaulted in record numbers. (A summary of the effects on Texas farmers of this drought by King, 1965, is sardonically titled *Wagons East*.) To attempt farming west of the Brazos, one reporter wrote, "… is folly of the very worst sort" (King, 1965). In the cattle industry, this was known as the Great Die-off. Many ranchers cashed in. The beef packeries at Fulton and Rockport turned to canning sea turtles. The Red Cross was called to Texas in 1887, and its president Clara Barton made a visit. Through her offices, clothes and food were shipped to the state, and the Red Cross became active in motivating additional aid, from private sources and from the federal government.

During the Twentieth Century several devastating droughts have occurred. The drought of the 1930's is the famous Dust Bowl, and at the time seemed to be the worst possible drought conditions that could be inflicted upon the state. For most areas of the state the drought of record, however, is that of the 1950's. This was a 6-9 year drought (depending upon the region), which created havoc statewide. President Eisenhower visited San Angelo, where the Bureau of Reclamation made a presentation showing the problems with the groundwater supply and the need for surface storage (Bureau of Reclamation, 1957). While the 1950's are the drought of record for most basins, for the Nueces Basin an even more intense drought occurred in the 1961-64 period, which is its drought of record (Ward and Proesmans, 1996).

Compared to droughts, floods are easy to analyze: they are sharp, well-defined events, they can be unequivocally linked to specific rainfall events, their occurrence in time is precisely defined in terms of maximum stage or peak flow. Droughts are insidious, unfocussed, shadowy, like silent vampires flitting in the darkness to suck the lifeblood from the state. Their beginnings and ends are indistinct (Karl, 1983), and their very existence may be controversial (see, e.g., Riggio et al., 1987).[5] The contrast between a flood and a drought, from the standpoint of hydrological analysis, is analogous to that between a gunshot wound and consumption. Riggio et al. (1987) examined shorter-term droughts in Texas, and concluded from an extensive and careful analysis of meteorological data that "the occurrence of 6-month and year-long drought has a greater probability of occurring than either a near-normal or wet-weather spell for the same time frames."

Dendrochronology has provided one means of reconstructing much longer records of drought by employing proxy measures of tree-ring growth. One of the more rigorous such studies is reported by Stahle and Cleaveland (1988), who used post oak to re-construct the June Palmer index for the past 283 years. They found the driest decades to be 1855-64 (immediately after Olmsted's visit), 1950-59 and 1772-81, noting that the proxy Palmer index underestimated the actual intensity of the 1950's drought. They also discovered that of the most severe June droughts, since 1917 five out of six had occurred in north Texas and five out of seven in south Texas. A long-term positive trend in Palmer index (i.e., increasing drought severity) was disclosed. For present purposes, the most important conclusion relating to Texas water is that there is no evidence that the great drought of the 1950's was in any way unique to the Twentieth Century or is unlikely to be repeated (or exceeded) in the future.

Water supply

In 1900, the population of Texas stood at 3,050,000, a spectacular increase from its 1890 value of 2,240,000, and people continued to pour into the state. Droughts only temporarily staunched the influx of population. Benedict and Lomax (1916) commented, "The population flows westward after good seasons and ebbs eastward after bad, each ebb tide leaving increased numbers." In 1900, about 66% of the population was rural and 33% urban (Benedict and Lomax, 1916). By 1940, these proportions had reversed (Steen, 1942), with 33% of the state population now rural, and after another 30 years, in 1970, only 20% was rural (Rodriguez, 1978). These same proportions obtained in 1990 (Sharp, 1992), and with the boom in high-tech jobs in the past decade, the shift to urban predominance has no doubt continued to the turn of the century.

The major source of domestic water supply in the early part of the Twentieth Century was groundwater. For a dispersed, largely isolated rural populace with low-volume needs, this made perfect sense: groundwater was widely available and could be had by digging straight down, the water thereby being supplied largely where it was needed without the requirement of infrastructure. The advent of the windmill provided an accessible source of energy (a device, along with the Colt revolver and barbwire, to which Webb, 1931, credits the habitation of the Great Plains). Even the majority of the cities relied on groundwater: an "aerial" photograph of Plainview taken from the dome of the courthouse after 1900 shows a small city bristling with windmills. However, windmills are capable of producing only several hundred gallons of water a day under optimum conditions, and soon after the turn of the century began to be replaced by gasoline or electric pumps.

There is a short-term limit to the flow that can be economically produced from groundwater, however. An even more basic long-term limitation is the rate of recharge of the aquifer. Once withdrawal exceeds the rate of recharge, the volume in storage in the aquifer will begin to be depleted. As the water table drops, further withdrawal becomes more difficult, until it is either technologically or economically infeasible. This became a familiar pattern of water usage in Texas: what was at first a reliable groundwater supply is subjected to increasing withdrawal until the aquifer can no longer meet the demand. At this point, the second aspect of the water usage pattern occurs: adoption of a surface supply. In many respects, the defining feature of Texas water in the past century has been this consistent usage pattern:

(V) The water supply paradigm is an increasing overdraft of a groundwater source followed by a shift to surface water.

This pattern was repeated across the state, differing only in the volume of withdrawals and the time that passed before the demand exceeded the yield of the aquifer, motivating the change to a surface supply. In Dallas in the Nineteenth Century "many springs" furnished the water supply, and "…water could be found almost everywhere by the mere digging of a well" (Brown, 1930). The first artesian well in Dallas was drilled in 1876, and by 1900 Dallas and Fort Worth had artesian wells distributed in and around each city (Brown, 1930, Taylor, 1931). Following the loss of artesian pressure, the cost of pumping became so great that by then both cities were already shifting to a surface supply. Dallas completed White Rock Lake around 1910, and Fort Worth completed a dam on the West Fork in 1915. By 1877, due to a combination of increasing population and a severe drought, Austin was considering construction of a dam on the Colorado, and completed Lake McDonald in 1893 (Taylor, 1910). The Austin dam, Fig. 9, "one of the largest hydraulic works of the country" (Hutson, 1898), noted by Taylor (1901) for its "immense importance

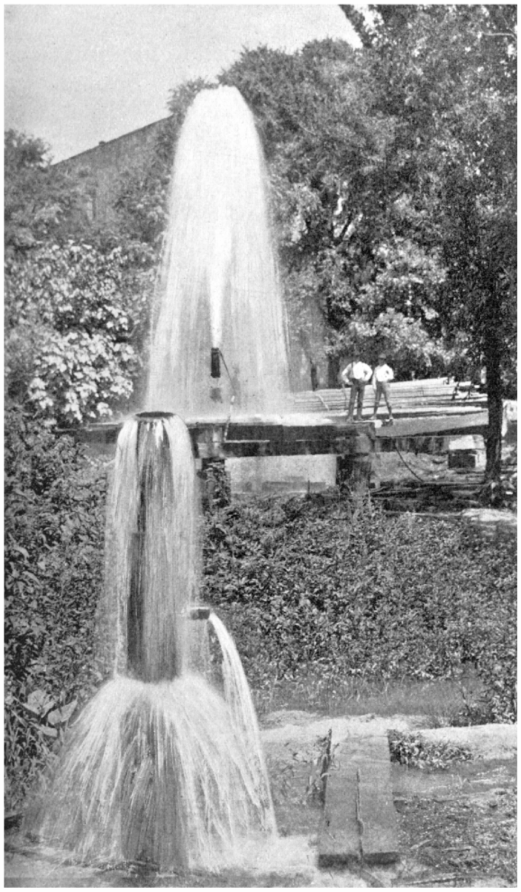

Figure 10 - Artesian wells at the San Antonio waterworks around 1895, from Hill and Vaughan (1897). One well drilled 4-5 miles from these rose 85 ft above the surface.

… as an engineering structure — it being the largest in the world across a flowing stream," did not last into the Twentieth Century, being carried away by high flows in April 1900. Lakes were built to supply Abilene, Sweetwater, Stamford and Wichita Falls (Dowell and Breeding, 1967). Houston's artesian wells were frequently unreliable, and since 1879, Buffalo Bayou water was used as a back-up supply, being stored in a small reservoir (Burke, 1879).

The most spectacular groundwater source for municipal supply in the state is the Edwards aquifer, a complex of water-bearing limestone strata that lies beneath the Balcones escarpment and is recharged on the Edwards plateau. The limestone formations are porous, being fractured and fissured, so groundwater moves readily into and through the aquifer. The aquifer is also leaky, with numerous springs along the Balcones fault zone, most important of which are Comal and San Marcos, which together produced on the order of 350,000 ac-ft/yr, discharging to the Guadalupe River, until about 1930. The artesian zone of this aquifer has been tapped for municipal, industrial and agricultural uses since the Nineteenth Century, Fig. 10. Through the Twentieth Century, it has served as the sole water supply for the city of San Antonio. The monthly elevation of the water table at the Bexar index well J-17 is plotted in Figs. 11-12. The effect of the 1950's drought in combination with pumpage from the aquifer is clear in the depression of the water table. During this drought, Comal Springs ceased flowing for about 5 months in 1956. The pumpage was about 321,000 ac-ft during that year. In the last two decades, it has nearly doubled this 1956 value, mainly due to the increasing usage of San Antonio. The much greater excursions in water level during the 1960-90 period evidence the effects of the higher pumpage rates. It is now possible for the withdrawals to approach the annual recharge.

For farming and ranching, enterprises which entailed much greater spatial extents than cities, water supply was far more aleatory. A strategy was needed for moving water "from where it is to where it ain't," which involves the practice of irrigation, i.e. the use of canals, laterals and ditches for the transport of water. Irrigation is considered separately in the next section.

The temporal variability in water supply, especially a surface-water supply, is dealt with by the construction of storage facilities, *viz*. reservoirs. Reservoirs also serve as flood control facilities, and in power generation, which will be addressed later. At the beginning of the Twentieth Century, dam construction was limited mainly to small structures (see Dowell and Breeding, 1967, and the following section). As noted above several cities constructed reservoirs to ameliorate water supply difficulties, one of which was the ill-fated Austin dam. The first major reservoir constructed in the Twentieth Century[6] was Lake Medina, capacity 254,000 ac-ft, completed in 1913 on the Medina River about 40 mi northwest of San Antonio (Taylor, 1930). This was a privately funded reservoir intended for irrigation supply.

Around 1910 a Board of Water Engineers and a Reclamation Department were created at the state level. In August 1922, Gov. Neff convened the "largest body of engineers ever congregated in Texas" who adopted resolutions for appropriations from the State and Federal governments to gather data needed to design works for dams, reservoir & levees (Hughes, 1937). Motivated by the State Reclamation Engineer, major reservoirs were later proposed for construction on the Colorado and the Brazos. The 43rd Legislature in 1933-34 wrestled

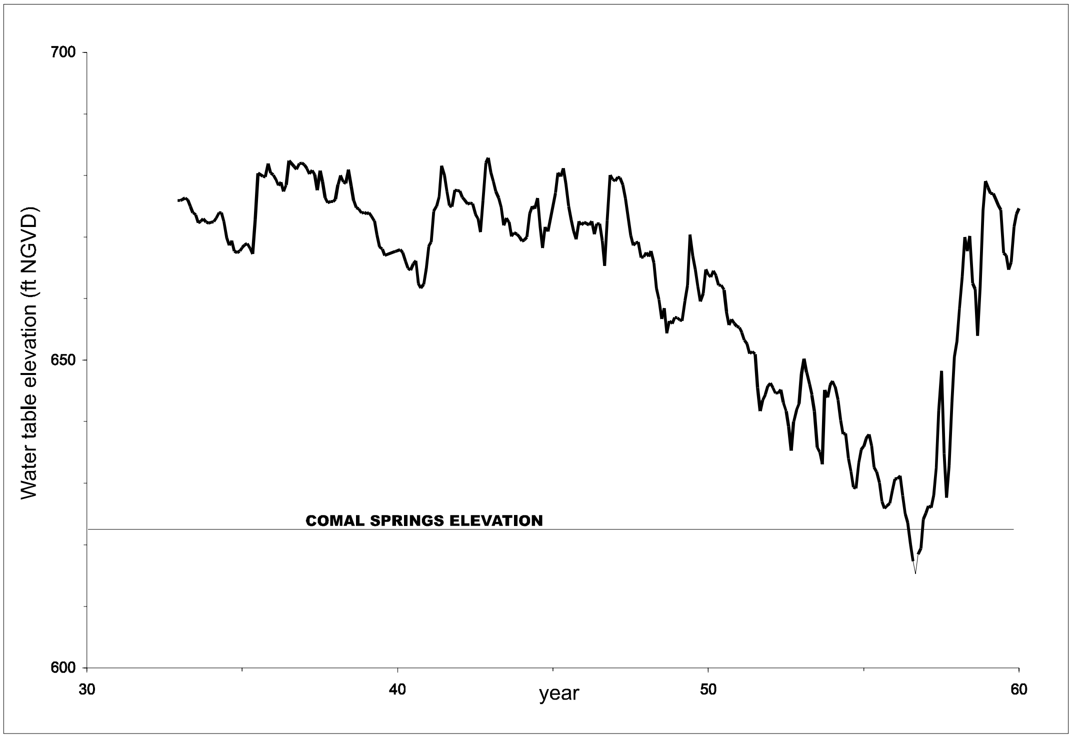

Figure 11 - Average monthly water elevation at Edwards Aquifer Bexar index well J-17, 1930-1960

with the need to create a public agency in order to obtain federal funds—and the presence of the Bureau of Reclamation in the state—to build Hamilton Dam (i.e., Lake Buchanan) on the Colorado, and in the fourth called session created the Lower Colorado River Authority (see Adams, 1990).

The construction of reservoirs during the Twentieth Century is depicted in Fig. 13, from data of the Texas Water Development Board. Buchanan inaugurated the heyday of dam construction in Texas, which extended roughly over the period 1940-70. As shown in Fig. 13, about half of the state reservoir capacity is allocated to flood control, and this is rather consistent over time (although the proportion on a given river varies substantially depending upon the exposure to flooding). As of the close of the Twentieth Century, the state has about 84.3×10^6 ac-ft of combined reservoir capacity, of which 38.8×10^6 ac-ft is allocated to flood control. There are also some 1500 SCS sediment control reservoirs and perhaps 300,000 stock tanks, farm ponds, and recreational reservoirs (e.g., Lowry, 1958, TSPE, 1974) impounding about 3 maf.

This brief survey cannot overlook pluviculture. The drought of the 1880's motivated the first wide-scale attempts at rainmaking in Texas. These were based upon a theory current at the time that loud continuous noise could stimulate rain, forwarded by an engineer, Edward Powers, who wrote an 1871 book demonstrating a relation of rainfall to battles (Powers, 1871). In 1891, under the auspices of the Department of Agriculture, an array of cannons was fired on the prairie near Midland, and later El Paso. The results were at best equivocal.[7] Desperate ranchers in the Coastal Bend area tried similar cannonades near Corpus Christi and later San Diego, again with equivocal results. But the most elaborate such exercises began in 1911, those of C.W. Post near Post City, now Post (the first planned community in Texas), who drove in mule trains of dynamite from DuPont and staged full-scale "rain battles" (Eaves and Hutchinson, 1952). Sometimes lit dynamite sticks were carried aloft by kites, but usually Post's men lined for a mile or more along the rim of the Caprock setting off hundreds of rounds of explosions. At first, these experiments seemed successful, but this was apparently due to a few fluke thunderstorms. As time wore on, and the experiments continued, it became apparent that these would not solve the water-supply problem of Post.

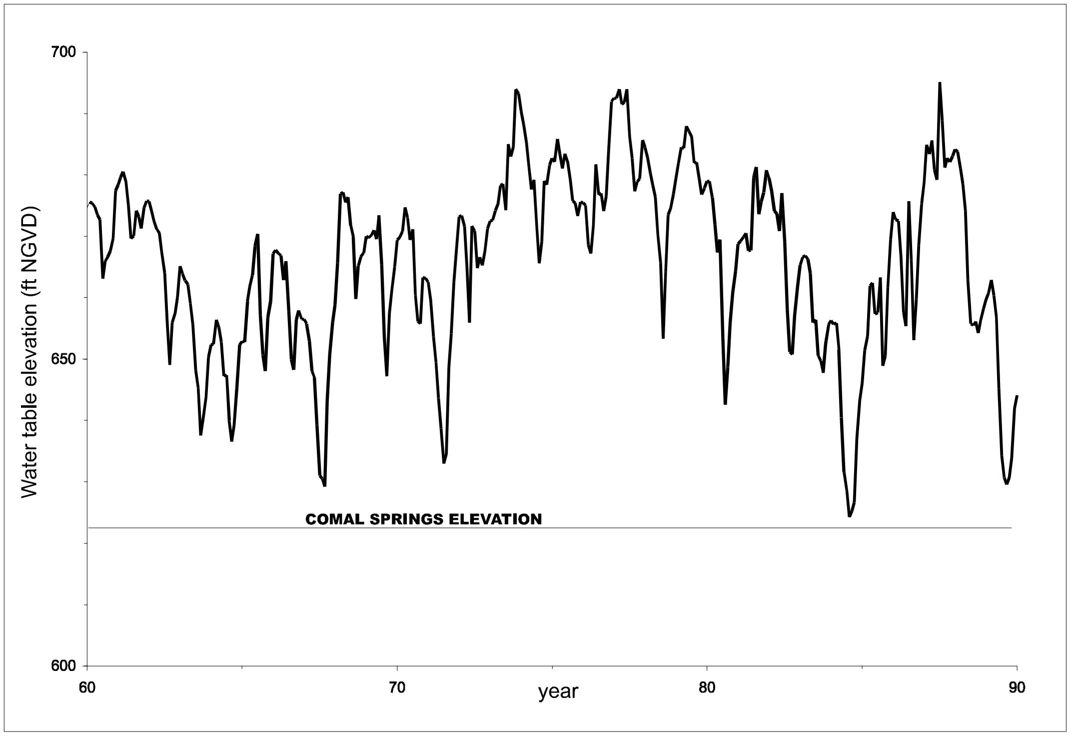

Figure 12 - Average monthly water elevation at Edwards Aquifer Bexar index well J-17, 1960-1990

During the Twentieth Century, after WWII, the more soundly based strategy of cloud seeding became the basis for extensive experimentation in West Texas, and such projects have been underway for the past half-century. The experimental region has ranged from the Edwards Plateau to the High Plains, the objectives have ranged from rainfall stimulation to hail suppression, and the financial support has ranged from local, through state, to federal (notably the Bureau of Reclamation). At the close of the century, some form of cloud seeding experiment is underway in over 75 counties in Texas, extending from the northern Panhandle to the Rio Grande. While there is a potential scientific value to these experiments, in the spin-off information about Texas meteorological processes, it is difficult to document any substantive impact on the Texas surface water budget, beyond the contribution of a variety of acronyms to the water-resources lexicon.

Irrigation

The beginning of modern irrigation (by which is meant large-scale farming with permanent aqueducts) in Texas is sometimes marked as 1869 at Del Rio (e.g., Taylor, 1901, 1902a; Benedict and Lomax, 1916), where San Felipe springs served as a water source, and an extensive system of canals was constructed, Fig.14. Other copious springs in the state later served as irrigation supplies for similar canal systems, including Comanche Springs near Fort Stockton (Hutson, 1898; Taylor, 1901), and those of the Pecos Valley (whose springs were described by the 1912 *Texas Almanac* as "inexhaustible", Galveston-Dallas News, 1912). Such natural artesian sources were rare, however.

In the closing decade of the Nineteenth Century, the prospects for large-scale irrigation in the western states had been growing upon the success of the Spanish and the Mormons (Baker and Conkling, 1930), and culminated in passage of the Newlands Act in 1902, which inaugurated the national "reclamation" program of the federal government. Texas did not immediately benefit from the federal initiative for the simple reason that there were no federal lands in Texas, the state having retained ownership of its public lands when admitted to statehood. But the attitude engendered by the federal

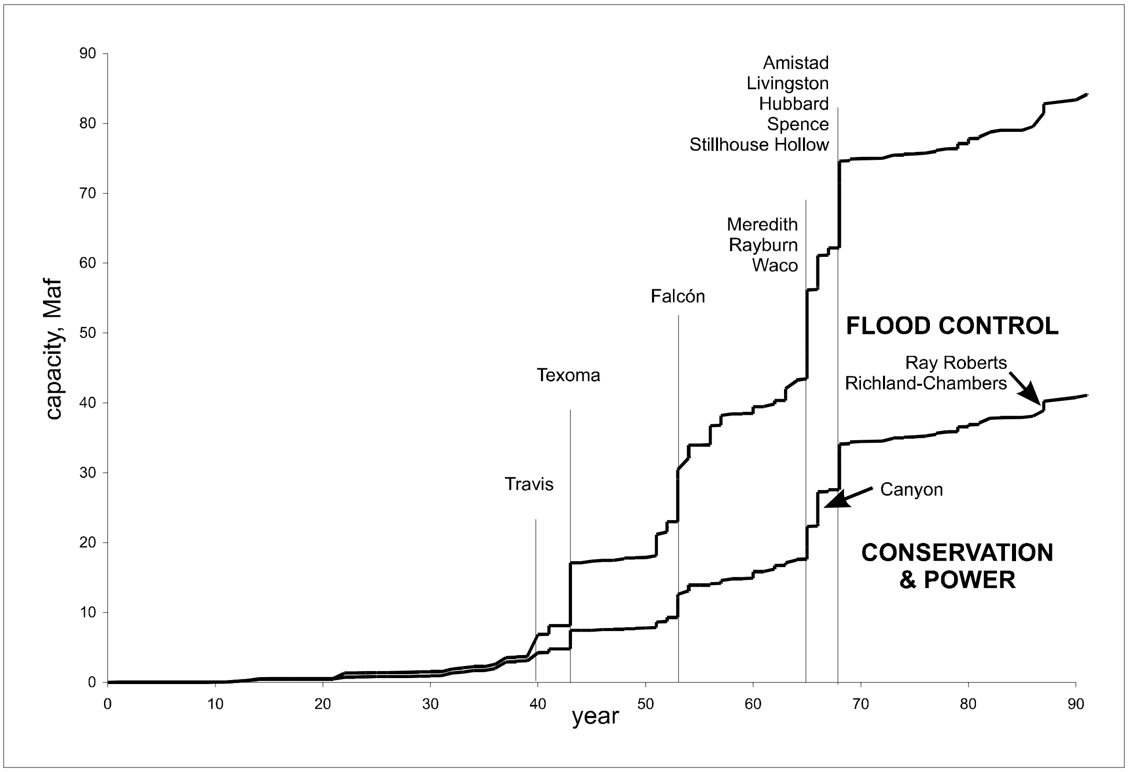

Figure 13 - Cumulative reservoir capacity (ac-ft) in Texas

reclamation program proved an intangible benefit to Texas, the philosophy that water supply could be engineered by large-scale reservoir construction. (The federal government became directly involved in Texas after the first third of the century.)

On a parallel track, other developments were underway to have profound effects on Texas irrigation: the centrifugal pump, drilling technology, and the low-compression internal combustion engine. All of these came together in East Texas at the start of the Twentieth Century. By 1900, the 150-year old centrifugal pump had undergone improvements to become at last efficient and reliable. Rotary drilling technology was stimulated by the Beaumont oil boom, and coincidentally such drillers were in the East Texas area when the Dingley protective tariff passed (by the Republicans who had returned to power in the 1896 election) and Latin American markets opened after the Spanish-American war, both of which created a demand for rice, and an opportunity for Texas production. At first, Texas rice irrigation used ground-water supplies. The exigencies of maintaining a pump pit in East Texas gumbo soil, and clambering in and out of the pit to operate the pump, led to the creation in 1902 of a "pit-less" pump that could be placed in a drilled well casing. The first such pump was installed at El Campo, and a company was created for its manufacture, the Layne and Bowler Company of Houston. Finally, the low-compression oil-burning engine, the "hot-ball" diesel, began to be widely manufactured in the United States by 1895, providing an economical autonomous power plant for pumping.

Rice was first planted in Beaumont in 1862-63 (Benedict and Lomax, 1916, Scanlon, 1954) for domestic consumption. (For many years before, Cajuns had planted in freshwater "pockets," Phillips, 1951.) Commercial production began when the first rice mill was constructed in Beaumont in 1892, and irrigation *per se*, pumping water to rice (a method "peculiar to Texas and Louisiana" according to Benedict and Lomax, 1916) began in 1893. Both subsurface and surface water was used, but the latter became predominant as the industry grew. The first pumping plants were built on Taylor and Hillebrandt Bayous (Scanlon, 1954). At the beginning of the century, Taylor (1902a, 1902b) described the coastal plain from Sabine Pass to the Rio Grande as the "rice

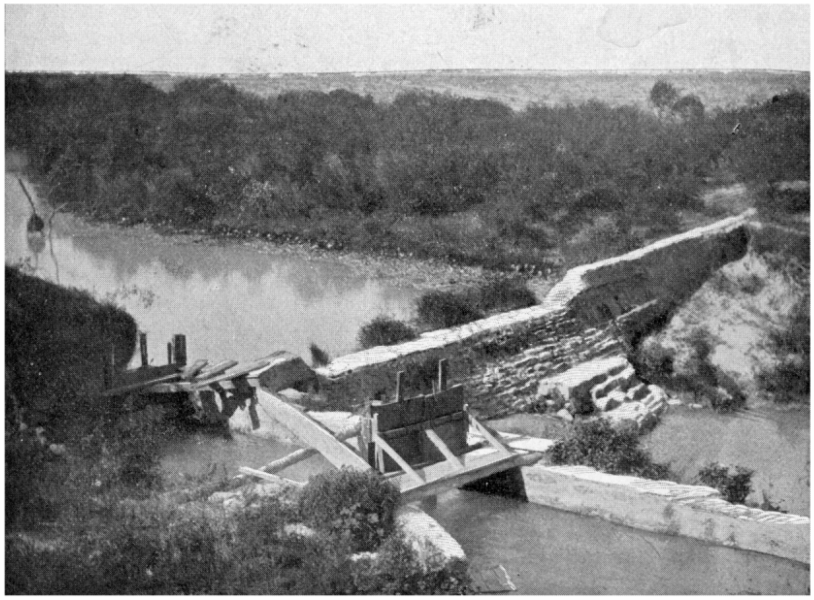

Figure 14 - San Felipe ditch and damworks, near Del Rio, from Hutson (1898)

belt" of the state, noting that there are two well-developed zones, the Beaumont section including Liberty, Orange, Jasper and Chambers counties, and the Colorado valley extending from Columbus to the coast, which together accounted for 75% of the Texas crop. Figure 15 shows the time history of the Texas rice industry. Between 1900 and 1906 the rice industry exploded from 9,000 ac to 200,000 ac. As of 1910, there were about 250,000 ac planted, primarily on the Sabine near Orange, the Neches near Beaumont, and on the Colorado from Eagle Lake down to Bay City. By mid-century, rice irrigation water was pumped from the Colorado, Brazos, San Jacinto, Trinity, Neches, Sabine and Guadalupe Rivers (Scanlon, 1954). The rice industry peaked in the 1970's. In the mid-1980's about 60% of the Texas rice irrigation water came from surface sources, and about 40% from groundwater (Webb, 1990).

The Sabine and Neches were capable of a reliable water supply for rice irrigation due to the high runoff in this part of the state. The low flow of the Colorado, in contrast, could not supply the requirements for its rice industry. That a rice industry could be built here in the early part of the century is due to a fluke of nature, a huge log raft that extended from just upstream of Matagorda to Bay City (Clay, 1949; Wadsworth, 1966). The earliest detailed survey of the log raft was made in 1894, at that time covering a distance of 15-20 miles. The main raft was described to be 300 ft wide, 25-50 ft thick, and practically solid, though of course permitting percolation of water. Trees with 2-ft diameters were noted to be growing on its surface. The raft functioned as a natural dam for the lower Colorado (Taylor, 1902b), providing storage and a pumping head, until it was eliminated in the 1930's by a combination of snagging and dynamiting.

The importance of the rice industry in Texas water is that it is the single greatest use of surface water for irrigation. Timing of the growth of the industry is important. In the Nineteenth Century, since 1840, the use of water was governed according to the riparian doctrine, devolving to the landowner or grantee adjacent to the watercourse, a doctrine that had been imported from the water-rich eastern seaboard, and thence from English common law. As the semi-arid regions of the state were settled, the inadequacy of the riparian doctrine in a water-stressed climate became evident, and the state began evolving the notion of ownership of surface water as a separate right. A major step was taken in 1895 when the 24th Legislature enacted a law establishing the prior appropriative system (Hutson, 1898), founded upon the concept of seniority in time, i.e. "first in time is first in right." In 1913, the Board of Water Engineers established a formal permitting system. Between these years of 1895 and 1913, by sheer coincidence

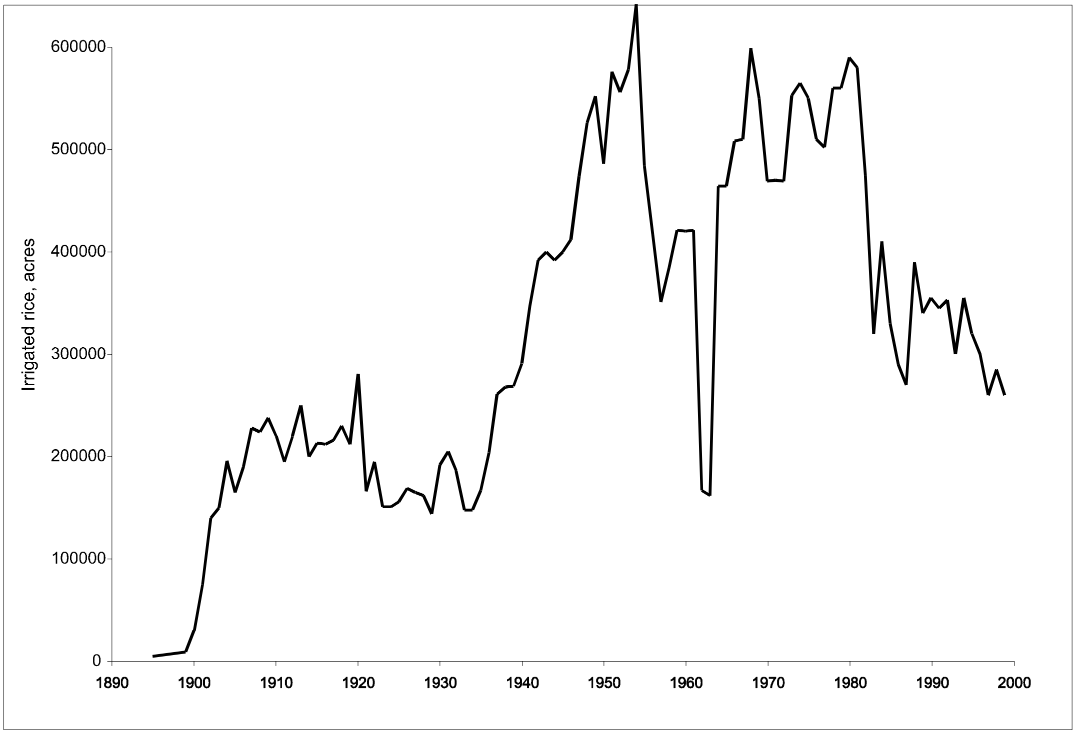

Figure 15 - Irrigated rice acreage in Texas during 20th Century

the rice industry grew from nonexistence to a major industry, and in the process established senior water rights from the Colorado to the Sabine.

At the opposite corner of the state, on the Texas High Plains, these same developments in pump technology were used to tap the groundwater resource of that region, the vast Ogallala. By 1900, the existence of substantial groundwater in the High Plains was established through surveys and reports of the U.S. Geological Survey (Green, 1973). *The Earth*, a magazine published by the Santa Fe Railroad, stated in 1904 that this water was "inexhaustible" (Green, 1973). The problem was lifting the water to the surface. The first successful wells were completed by McDonald near Hereford in 1910 and Green on the Slaton farm at Plainview in 1911. Irrigation was mainly promoted by land speculators, one of whom dubbed the region the "land of the underground rain." From 1913-17, visitors to the Santa Fe depot in Plainview were astonished to see a 30-acre lake lying across the railroad tracks to the north, Lake Plainview, created by the operation of a single well by the Texas Land and Development Company. The lake provided boating and fishing in the summer and ice-skating in winter (Brunson, 1970). A combination of climate and economics, however, prevented widespread growth of irrigation on the High Plains until the drought of the 1930's. Improved technology, reduced capital costs, New Deal financing, and—especially—a market for cotton and wheat produced an acceleration in irrigation. The number of operating wells increased by an order of magnitude between 1930 and 1940, by when a quarter of a million acres on the High Plains were "under ditch." This would further increase by another order of magnitude over the next two decades.

At the southern tip of Texas, around 1900 there was an initial impetus in irrigation from the Rio Grande, primarily in the Lower Rio Grande Valley. At first truck crops were raised, but by 1910 most of these had converted to field crops. Some of the largest irrigation plants in the world were built in this area at the time, with enormous pump stations on the river and hundreds of miles of canals and laterals (Benedict and Lomax, 1916). Two canals measured 200 ft wide by 18-20 ft deep (Galveston-Dallas News, 1912). "Under present regulations and with proper conservation, the water supply is practically assured," wrote the *Texas Almanac* (Galveston-Dallas News, 1912). This proved to be overly optimistic. Irrigators turned to groundwater to supplement the unreliable Rio Grande flow, but the groundwater supply suffered from the same limitation on economics of pumping and rate of recharge as other regions of the state.[8] The complete potential for agriculture was not realized in the Lower Rio Grande Valley until surface water became available from the international reservoirs Falcón (1953) and Amistad (1968). Less than 1% of the irrigation water now comes from groundwater sources (TDWR, 1981).

The two reservoirs are operated in tandem, releases being made from the lowermost Falcón to meet demands in the Lower Valley. Diversions are made to both the U.S. and Mexico to supply the municipal and industrial requirements of the cities below Falcón and to meet the heavy irrigation requirements of the extensive agricultural areas in both countries. The strategy of diversion is different for the two countries. Mexico diverts its share of the water mainly at a single point, the Anzalduas canal, which then routes the water to various agricultural areas, principally District 26, and to several cities. The U.S. water, in contrast, is diverted at numerous pump stations distributed along the river channel from Falcón to Brownsville. The Valley is extensively plumbed with canals and siphons to effect the transport of this water over a four-county agricultural area. Over the 1972-90 period the total U.S. diversions averaged 171,000 ac-ft/mo (Ward, 1999).[9]

Water and power

There is an intimate relation between water and electric power generation, fundamentally that the generation of electric power requires the availability of an enormous amount of water.

Water has been a source of power in Texas since the Nineteenth Century. At the beginning of the Twentieth Century, Taylor (1901, 1904) surveyed the use of water power on the principal Texas rivers,and determined that these facilities were largely concentrated in the Guadalupe, Brazos and Colorado basins. These fell into categories of mechanical power (mills and sawmills) and electrical power (including turbine-driven sawmills), and with rare exceptions entailed the construction of a small dam to provide power head. Taylor inventoried nearly 70 dams, with 14 on the Brazos, 17 on the Colorado (including 10 on the Concho alone), and 28 on the Guadalupe. The Guadalupe was favored because of its stable, spring-driven flow. The dam at Del Rio on San Felipe Creek included one power plant, which ran an electric light plant and an ice plant. San Antonio had separated the San Antonio River into two canals, with a powerhouse built on each, and operated two more dams on the upper river. The river became so low in 1896 that waterpower was

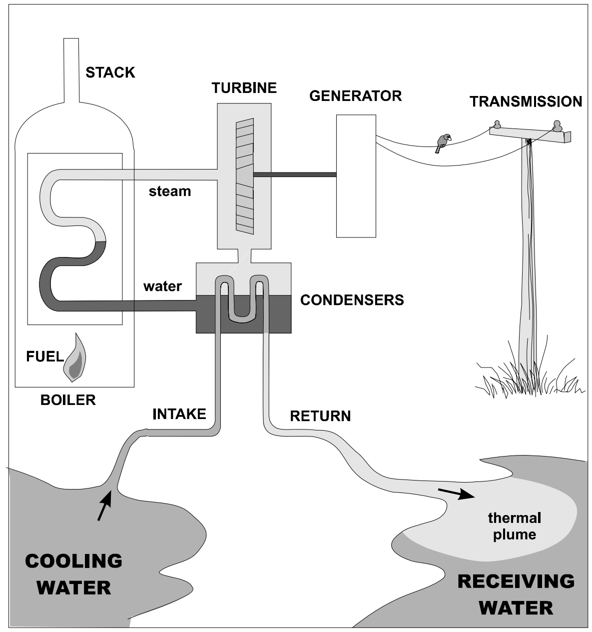

Figure 16 - Schematic of the operation of a steam-electric station using once-through cooling, after Ward and Huston (1984)

abandoned. The largest single power plant was that on the doomed Austin dam.

Many of the large dams in Texas include provision for hydroelectric generation, beginning with Buchanan in 1937. However, hydroelectric generation represents less than 5% of the present electric generation capability in Texas. The combination of stable river flow, suitable dam site, and adequate bed slope is rare in Texas. Benedict and Lomax (1916) summed it up nicely, “Water-power in Texas is scanty, because where there is plenty of water the country is too flat to make a fall, and where there is plenty of fall there is no water.” Electrical power in Texas depends, instead, upon steam-electric generation. The generation process is diagrammed in Fig. 16. The high-pressure steam, produced from pure water in a boiler, spins a turbine that turns a generator, producing electricity. The steam cycle is completed by re-condensing the spent steam and feeding the resultant water back into the boiler. Power plants differ in their fuels (natural gas, coal, lignite, fuel oil, nuclear reactions) and in the stack emissions, but are equivalent insofar as the steam-generation cycle is concerned. The key is the condenser stage, which requires passing great volumes of ambient water in thermal contact with the spent steam, thereby cooling the steam so that it recondenses. In the process the cooling water is heated, and is then rejected to the external environment. Figure 16 shows a once-through cooling circuit, in which the heated water is returned to a receiving water body, into which it is mixed. Most steam-electric plants in Texas employ once-through cooling.

From the opening of the Twentieth Century, steam-electric generation has been a major source of the state's power, increasing in proportion to the growth of population. At present, steam-electric generation represents about 95% of the state's generating capacity. Of 177 major reservoirs in the state (i.e., greater than 5,000 ac-ft capacity), 44 have power plants situated on them, collectively representing 65% of the state's steam-electric capacity.[10] These reservoirs serve both as the source of cooling water and as the receiving water for the thermal effluent. The trick is to site the plant so that the discharge canal is sufficiently far from the intake that the excess heat is dissipated to the atmosphere before the water circulates back to the power-plant intake. More than half of these plants are located on cooling reservoirs, small lakes constructed for the express purpose of serving as a cooling water source for the power plant (though most also provide recreational amenities as well). These cooling reservoirs are generally located on minor tributaries off the main stem of rivers, and have insufficient watershed to ensure maintenance of water level, so they have to be made up from some nearby water source.

Surveying the century

Texas was already undergoing change when the Twentieth Century opened. The buffalo were gone, and their bones had been stacked on the plains, whitening in the summer sun. But even the bones were being gathered in 1900 and shipped off to sugar refineries (Philips, 1942). In a few years there was nothing at all left of the great Southern Herd. Much of the native forests had been cleared and the effects on turbidity of Texas rivers were evident (Benedict and Lomax, 1916). Tarpons—"the greatest in the world"— and sea turtles were still plentiful on the coast: they would be eliminated during the Twentieth Century. The mesquite was now well established over much of Texas, having spread into the state during the last half of the Nineteenth Century (Olmsted, 1857, encountered dense growths west of San Antonio in 1854), covering the central prairies and even pushing onto the High Plains. The boll weevil, the armadillo and the inca dove were spreading their range into Texas. However, these were benign; fire ants and killer bees still lay in the future.

The population in 1900 was about 3 million. As of this writing, a nose count is underway to census the state's 2000 population. Lacking these results, we can make an estimate from the 1990 census of 16,986,510, with a judicious use of the data of Sharp (1992)[11], of 23 M. This represents an order of magnitude increase in population over the span of the Twentieth Century, and a population growth of 35% over the past decade, the same rate of growth experienced by Texas in the closing decade of the Nineteenth Century.

The Twentieth Century encompasses the development (some might say exploitation) of the state's water resources. The century opened with a drought, particularly severe in South Texas, where extensive irrigation from the Rio Grande and from groundwater sources in the Valley was already in operation. The main water supply statewide was groundwater at this time, but at some point in time the demand exceeded the aquifer yield, as expressed by Maxim (V), and surface supplies were sought. For many of the major cities in Texas, this point occurred early in the century. For a few, reliance on groundwater was able to serve the city well into the century. Groundwater was an important part of the municipal source for Houston until past mid-century.[12] For San Antonio, the Edwards remains the water supply for the city as of 2000, but the limits of that supply have become apparent, and the city is seeking surface supplies.

A prominent example of the continued reliance upon groundwater is the High Plains, for which the Ogallala supplied the extensive irrigated agriculture that developed after the 1930's. The growth of this industry is evident from the following magnitudes of irrigated acreage (Stockton and Arbingast, 1952; Texas Department of Water Resources, 1981):

1935	0.080	10^6 ac
1940	0.25	
1950	2.0	
1980	5.6	

The withdrawals for this aquifer far exceed its recharge, so the term "water mining" is appropriate. By 1960, the water table in the region identified as the "shallow water belt" at the beginning of the century (Green, 1973) had declined markedly, about 60 ft average but with pockets of decline of 100-120 ft (Cronin, 1969). By 1979, the decline continued, these areas logging an additional 20 ft or more depletion since 1960. There is no alternative surface source capable of yielding the volumes of usage of High Plains agriculture[13], so when the groundwater is

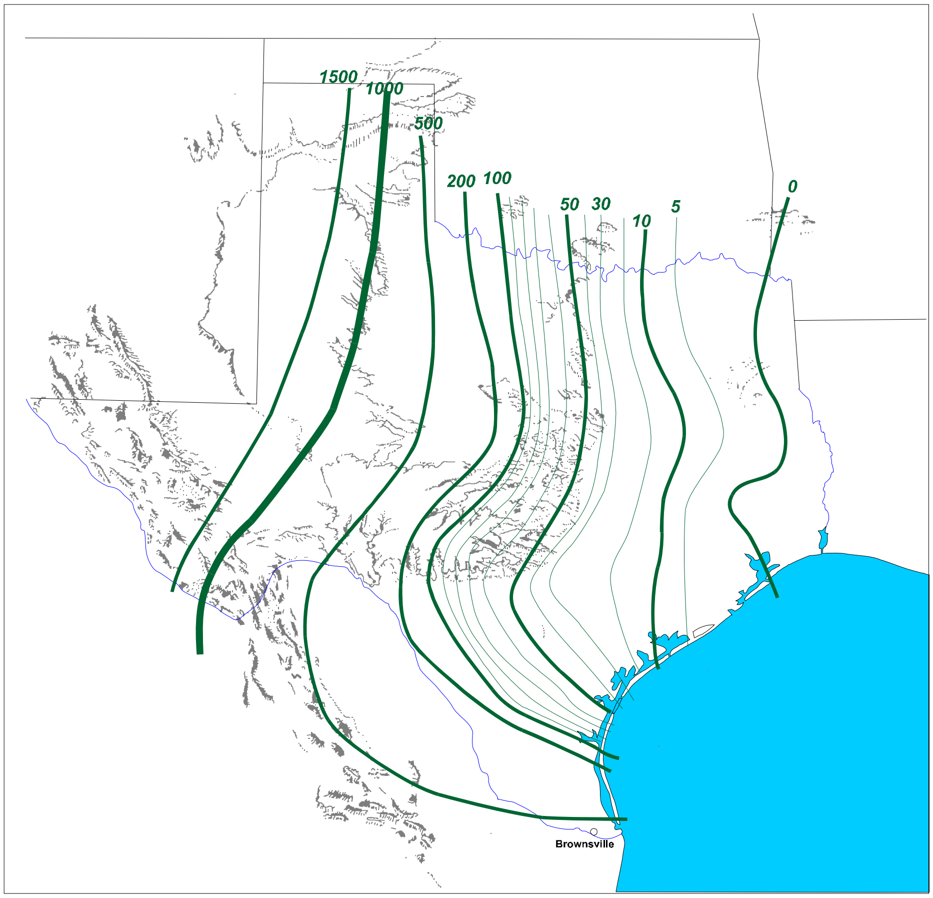

Figure 17 - Variation of the ratio of watershed area to reservoir surface area, necessary to maintain average volume against evaporation and yield assumed equal to three times evaporation

depleted in a region or becomes uneconomical to lift, the region reverts to dryland farming. By the end of the century, this in fact has occurred in many regions of the High Plains.

Although beyond the scope of this brief review, we note in passing that groundwater in Texas is governed by the old riparian right of "capture." Since its inception and throughout the century, groundwater authorities have called for an appropriative doctrine (Hutson, 1898; Benedict and Lomax, 1916, Texas Society of Professional Engineers, 1956, Hughes and Harman, 1969; TSPE, 1974), but the riparian mentality seems ingrained, perhaps because of the central role of petroleum in the state's economy. Hughes and Harman (1969) suggested that the lack of regulation leads to a "use it or lose it" mentality, "The landowner has little choice with respect to the time of use. If he elects to defer use for more propitious times, a large part of his water supply is likely to be drained off and used by his more current-income conscious neighbors. The pressure for income and the lack of area-wide water use restrictions combined with the fixed nature of assets invested in irrigation facilities virtually dictate that a farm operator extract all the water he can gainfully use each year." What they describe is known as the "tragedy of the commons" in ecology (Hardin, 1968). No clearer example could be cited than the Ogallala.

In 1960, the pumpage from the Ogallala was estimated at 5 maf/yr (Hughes and Harman, 1969). In 1979, a rare wet year, the reported pumpage was 5.7 maf/yr, but the following year was 7.1 maf/yr (TDWR, 1981). The next decade was unusually wet, reducing the irrigation demand and increasing recharge, so that in 1989, the pumpage was reduced to 4.7 maf (Peckham and Ashworth, 1993). At the close of the century, over the past several decades there has been improvement in efficiency of water use achieved by various methods of conservation, but there have been corresponding increases in irrigated acreage due to large-scale mechanized farming: the present irrigated water usage is reported as 5.4 maf/yr (TWDB, 1997).

The effect of groundwater pumpage statewide on the subsurface resource is demonstrated by the behavior of springs. Throughout the state, hundreds of springs that were flowing under artesian pressure at the beginning of the century are dry at its end.[14] A sampling of the historical springs that have ceased flowing or flow at best intermittently includes: Big Spring (Howard County), Carrizo Springs on El Camino Real (Dimmit County), Cherokee Spring and Tyler Springs (Smith County), Comanche Springs (Pecos County), Fort Elliott Springs (Wheeler County), Leon Springs on the Chisolm Trail (Bell County), Mill Spring and Kickapoo Spring (Tom Green County), Nacogdoches and Shawnee Springs on El Camino Real (Nacogdoches County), San Pedro Springs and San Antonio Springs in San Antonio (Bexar County), Santo Rosa Spring (Pecos County), Smith Springs (Galveston County), Sulphur Springs and Mustang Spring on the Comanche Indian trail (Martin County), Walnut Springs in Seguin (Guadalupe County), Willow Springs (Winkler County), XIT Springs on the XIT Ranch headquarters (Hartley County). Extensive inventories of Texas springs are presented by Brune (1975, 1981).

The Twentieth Century also encompassed the growth of the USGS stream-gauging network, an enterprise of inestimable value to the hydrologist, the water manager, the planner and the public at large. The Texas network began to be implemented in earnest around 1915, through a cooperative program between the State Board of Water Engineers and the USGS. At mid-century, TSPE (1954) pleaded for more gauges, noting only 266 stations existed, and "no less than 160" additional stations would be needed. It is sobering to realize that this network reached its zenith around 1970, and as of the close of the century continues to decline. A recent report to Congress (USGS, 1998; Lanfear and Hirsch, 1999) indicates "more than 100" stations with over 30 years of data are discontinued nationwide *each year* due to lack of funding. An inspection of the data in the report reveals that it is worse than that: in the data analyzed (through 1996) the rate of discontinuation has increased exponentially[15] to 170 discontinuations in 1996. Specific statistics are not available to this writer for Texas (though he can personally attest to the frustration of encountering discontinued stations), but of the Hydroclimatic Data Network stations in Texas (Slack and Landwehr, 1983), as of 1996, 68% had been discontinued.

The need for reservoirs became apparent early in the century. As noted earlier, only minor dams existed in 1900, mainly for waterpower (Taylor, 1904). Several municipalities constructed water-supply dams in the first couple of decades of the century, including Dallas and Fort Worth. Major droughts occurred in 1915-18 and 1925-32, the latter once again requiring the services of the Red Cross. The Dust Bowl years of the mid-1930's seemed as bad as it could get, but in fact drought conditions were mainly concentrated in the northern regions of the state. The drought of the 1950's demonstrated how bad water shortages can be in Texas.

Large-scale dam building coincided with the Bureau of Reclamation involvement in the late 1930's. The majority of dams in the state were completed in the period 1940-70 (Fig. 13). The better, more economical, higher yield, dam sites were built first, so with the passage of time, availability of suitable sites has diminished. The increasing aridity with distance westward (and southward) in Texas conspires against successful reservoir construction. Surface storage is constrained on both sides of the surface water budget: decreasing runoff (Fig. 7) and increasing lake-surface evaporation. The more constrained this water budget becomes, the greater the watershed area needed to achieve a desired yield. (Or, conversely, for a fixed watershed area, the more constrained the water budget the smaller the yield.) But as one proceeds westward in Texas, the watershed areas decrease. It follows that there is a westward limit for an operational reservoir in any particular basin. Some suggestion of how severe this may be is indicated by Fig. 17, showing the watershed area necessary to maintain the surface water balance of a given area, assuming an average yield of three times the evaporative loss.[16] The 100:1 line serves as a general boundary of practicality.[17] (We hasten to observe that establishing feasibility of a reservoir is a site-specific matter, and yield may not be an issue, e.g. in flood control or power cooling reservoirs. Also, the relation of reservoir surface area to volume, not considered in Fig. 17, is an important determinant in the actual operation of the project.[18])

This century has also experienced reversal in the public perception of dams and reservoirs. This is exemplified by the most recent major dam to be completed, the Wallisville project on the Trinity. In its re-design around 1990, this reservoir would have had a surface area of 5600 acres and a mean depth of 4.4 ft with the conservation pool elevation at 4.0 NGVD.[19] By the time construction began, its conservation pool elevation had been reduced to one-third of this.

Table 3
Present regional and statewide water uses for Texas, after Ward (1993), rounded to 3 significant digits, 10^3 acre-feet per year

	Region (see Fig. 6)				
	EAST	CENTRAL	SOUTH	HIGH PLAINS	TEXAS
Surface water diversion	1070	3380	2080	132	6650
M&I	615	1800	274	110	2790
Agr	452	1580	1810	22	3860
Ground water withdrawal	246	2100	1100	7190	10600
M&I	215	995	178	154	1540
Agr	24	1080	905	7030	9040
Electric	7	27	14	8	56
Return flows	624	2390	210	89	3310
M&I	468	1780	154	89	2490
Agr	156	606	56	0	818
Consumption					
M&I	362	1020	298	175	1840
Agr	320	2050	2660	7050	12080
Steam-electric, surface-water					
Diversion	5181	13601	1300	15	20088
Return	5120	13500	1290	0	19900
Consumption	61	101	10	15	188

The general distribution of water use among various human activities representative of the close of the century is summarized in Table 3. This table expands the "human activities" entries of Table 1. Groundwater withdrawal is dominated by the High Plains pumpage from the Ogallala, the agricultural pumpage from the Carrizo and Edwards (in both Central and South regions, Fig. 6), and the municipal usage by the City of San Antonio from the Edwards (Central region). If these three activities are deleted from Table 3, it will be seen that at the close of the century water use in Texas has become predominantly surface-water. Rice irrigation dominates the surface-water diversion for agriculture in the East and Central regions, and irrigation in the Lower Rio Grande Valley (and to a much lesser extent, the Maverick Canal area) dominates the surface-diversion for agriculture in South Texas.

The establishment of the Texas rice industry almost exactly coincides with the beginning of the Twentieth Century, reached its apex after mid-century, and now is in decline (Fig. 15). Though economic forces are at work, water has also been a part of this, because the senior water rights held by rice irrigators are becoming more valuable to upstream users, especially for municipal supplies, than the economic yield these water rights represent in a rice crop. The price paid by the Lower Colorado River Authority in its recent (1998) acquisition of 133,000 ac-ft/yr from the Garwood Irrigation Company of $75 M would have been unthinkable only a few years ago.[20]

Conversion of irrigation supply to municipal supplies is also underway in the Lower Rio Grande Valley (LRGV). This is partly due to the ability of municipalities to pay top dollar for the water, but also to the increased water-supply shortages in the Valley. It is difficult to perform an accurate accounting of water uses in the LRGV because the diversions from the various pump stations serve multiple uses. In a recently completed binational study (the first such

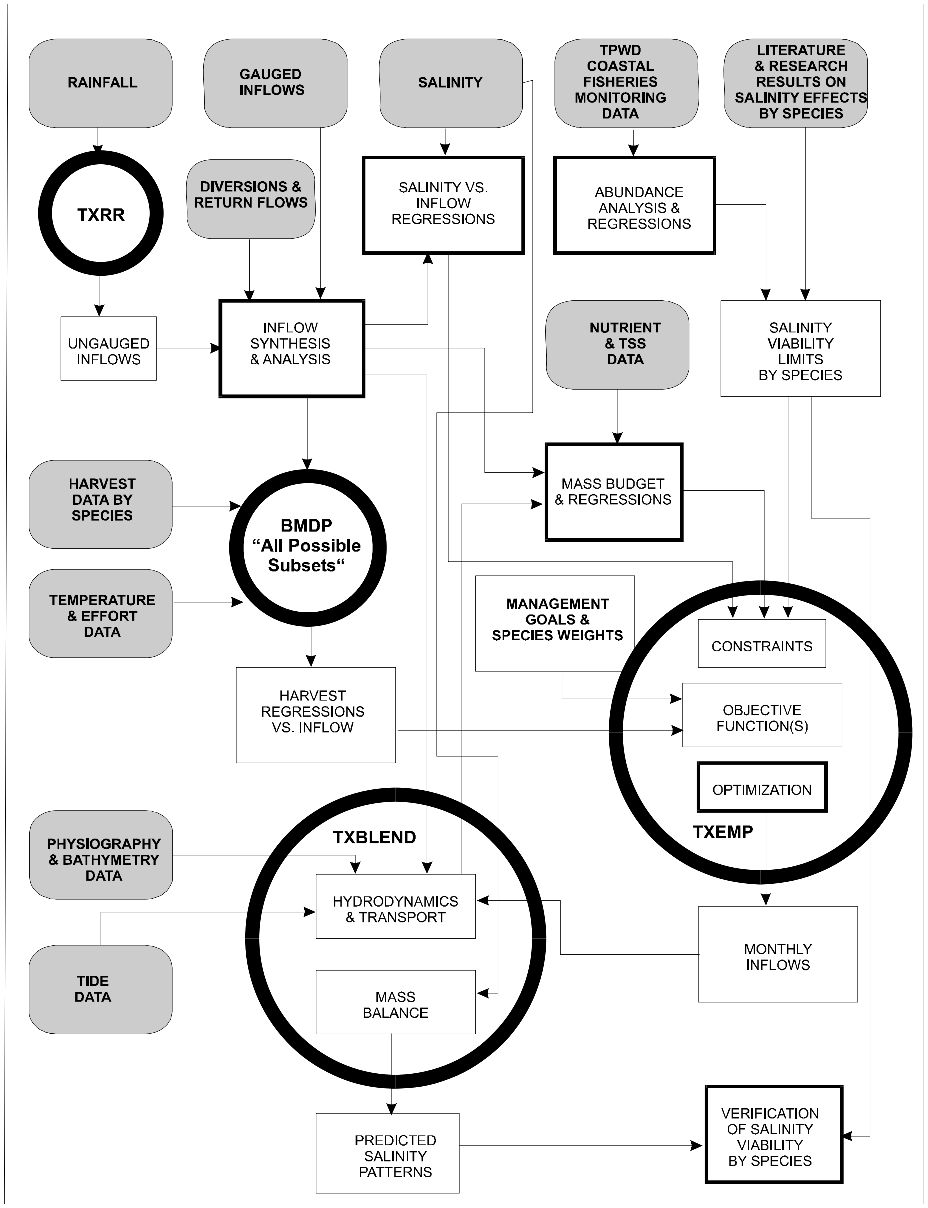

Figure 18 - Schematic of State methodology for establishing beneficial inflows to estuary (Longley, 1994). Bold circles represent models, shaded oblongs represent external data analysis

study with balanced expertise from both sides of the border), Schmandt et al. (2000) disaggregated the municipal & industrial usage from the total diversions on both sides of the river to infer the irrigation components. At present, the Valley is practically fully developed for agriculture, in that all available land is in production. Based upon the highest five values in the 1980-93 data record, when uncurtailed deliveries were made to agricultural interests, an annual combined U.S. and Mexico usage of 3,000 Mm^3/yr (2.4 maf/yr) was judged by Schmandt et al. (2000) to represent the potential feasible irrigation usage for the Lower Rio Grande.

Under drought conditions, when this demand cannot be met, there will of course be a corresponding shortfall. The Schmandt (2000) study was based upon hydrometeorological and socioeconomic data through about 1993, up to when no serious curtailment of water deliveries from the international reservoirs had ever occurred. The study investigated various stressed-supply scenarios, one of which was the recurrence of a drought similar to that of the 1950's (which occurred before construction of the two tandem reservoirs). The analysis and conclusions regarding this scenario proved to be portentive, because since 1993 the LRGV has been experiencing the most intensive drought in many years, with catastrophic impacts on the agriculture of both countries, as anticipated by the Schmandt et al. (2000) analyses.

Another scenario investigated by the Schmandt (2000) team may be of particular significance as the new century unfolds. The Twentieth Century conveniently coincides, almost exactly, with the development of riparian diplomacy between the U.S. and Mexico. The Convention of 1906 established the distribution of river waters above Fort Quitman between Mexico and the U.S. (Jetton and Kirby, 1970). International management of the waters in the Rio Grande from Fort Quitman to the Gulf of Mexico was formalized by the Treaty of 1944 (U.S. Dept. of State, 1946). Among other actions, this treaty authorized construction of international reservoirs for water supply, flood control and power generation, and established a quantitative division of the waters of the river between the two countries. Development of the treaty rules has been consummated by a roomful of minutes and memoranda, to which the present drought is contributing more.

External to this process, an engineering company has recently accused Mexico of failing to meet its obligated delivery to the Rio Grande system, as mandated by the 1944 Treaty (R.J. Brandes Company, 2000). The furor raised among Texas water users, who apparently would like to fix blame for the drought conditions somewhere other than Nature, has (inadvertently) raised an important issue that was already addressed by Schmandt et al. (2000). The obligated delivery by Mexico under the conditions of the Treaty is 350,000 ac-ft/yr. Since 1924, and also since the tandem operation of the two reservoirs began in 1972, the average inflow from the Mexican tributaries is nearly five times the Treaty-mandated minimum flow. Put another way, on average 80% of the past inflow from Mexico is not obligated under the terms of the Treaty. Most of the Mexican inflow to the Rio Grande comes from the Rio Conchos. The Schmandt (2000) team evaluated a scenario in which reservoir construction diverted most of this flow, while meeting the Treaty-mandated volume. The net result would be a reduction in yield from the international reservoirs of more than 25% (which implicitly assumes optimum management of the available water, a feat that can occur only with perfect predictive ability over the duration of a drought).

From Table 3, the greatest single statewide diversion of surface water is for steam-electric generation. However, as a *consumer* of water, power generation is minor, being less even than municipal consumption. The reason, of course, is that the diverted water is returned to the water resource, albeit heated somewhat (which accounts for the consumption, because the elevated temperature increases the evaporation slightly over what would have occurred naturally).

In the early part of this century the notion was prevalent in Texas that water allowed to escape to the Gulf of Mexico (i.e., "uncaptured" water) represented a waste, e.g. Benedict and Lomax (1916), TSPE (1954). It is now recognized that the resources downstream from dams have a minimum flow requirement that should be met. Most important is the inflow needed for the Texas bays. These are estuarine systems that serve as spawning or nursery areas for a variety of marine species, including most of the major *Gulf* fisheries. Freshwater inflow into these systems provides nutrients and sediments, and maintains a salinity gradient across the bays, all of which are necessary for the estuaries to maintain their ecological function. At the close of the century, the concept of "beneficial inflows" has now been incorporated into the Texas Water Code (by the 69th,

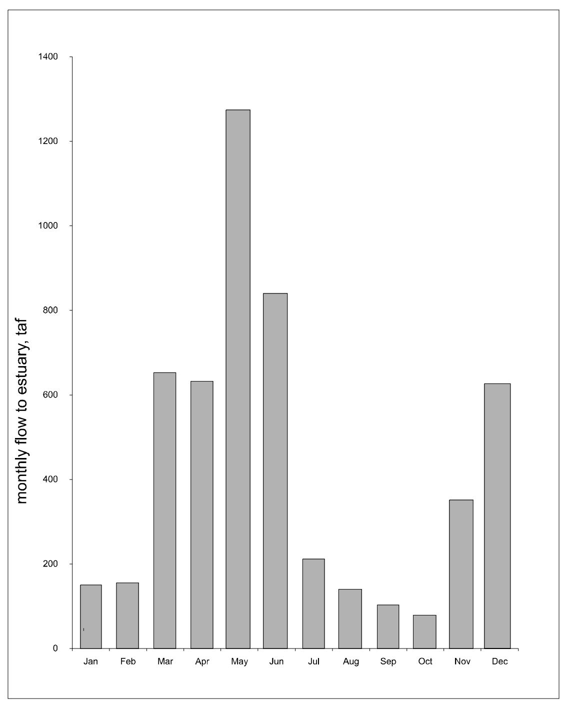

Figure 19 - Monthly beneficial inflows (10^3 ac-ft/mo) recommended for Galveston Bay developed from State methodology (TPWD, 1998)

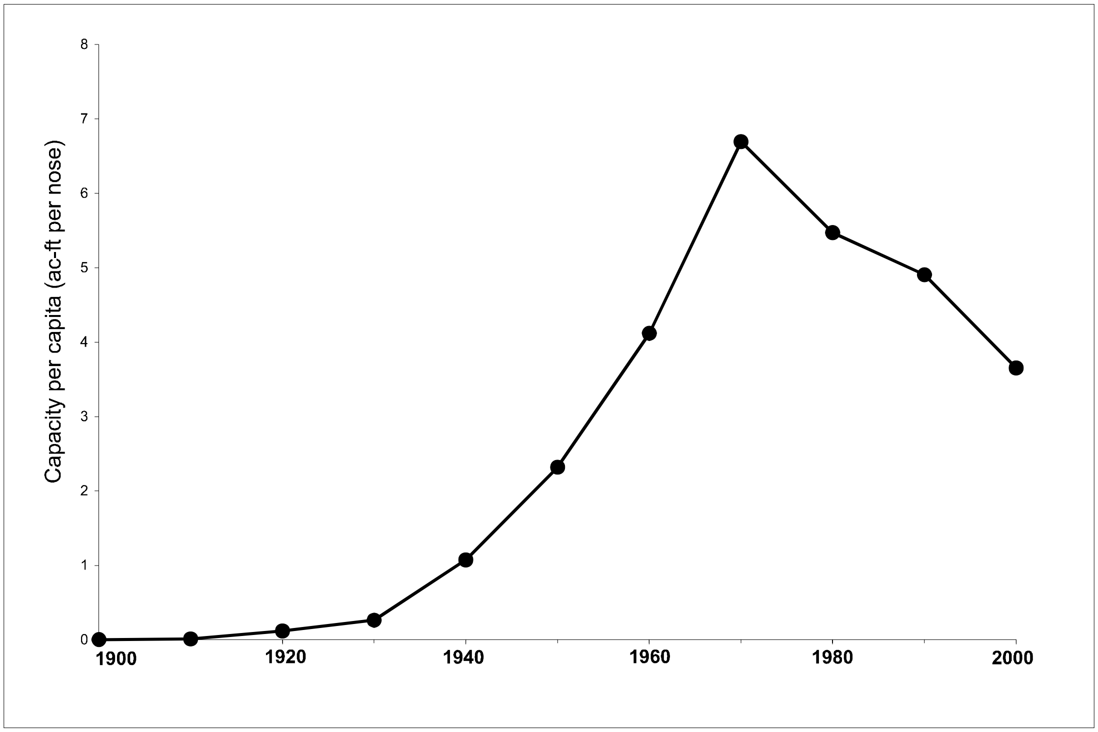

Figure 20 - Variation of reservoir capacity per capita during Twentieth Century

1985, Legislature), and environmental water needs have become a part of project planning (TWDB, 1997). A comprehensive methodology for establishing the necessary level of inflows to the Texas estuaries is under development by the Texas Water Development Board and Texas Parks and Wildlife Department, presented in Longley (1994). This methodology is diagrammed in Fig. 18, and involves application of several sophisticated models and the use of extensive hydrological, hydrographic, chemical and biological data. An example of the results of this methodology is the pattern of beneficial inflows recommended for Galveston Bay, depicted in Fig. 19. Apart from the complexity of the methodology (from which, it will be noted in the flow chart of Fig. 18, there is no escape), there are outstanding questions on how it can be implemented operationally, and how it will affect existing water uses in a basin.

Summary

In summary (at last), the hydrometeorological features of Texas, as expressed in Maxims (I) through (IV), that vexed the state at the beginning of the century are still with us and dictate the natural water supply. The instability of runoff and recharge, implied by Maxim (III), results in the recurrence of drought (among other results, Maxim IV). The major feature of water supply in Texas in the Twentieth Century is an inexorable shift from groundwater to surface water, as expressed in Maxim (V) above. Apart from that, the uses of water in 2000 are very much like those in 1900. They have changed quantitatively, however. Many of the features of Texas water have described a parabolic trajectory[21] over the past century, rising from practically zero at the outset to a maximum, and by the close of the century, falling. These include groundwater use, reservoir development, and large-scale irrigation, though the point in time at which the high point of the trajectory was attained is variable. The glaring exception is population, which continues to grow exponentially and at a rate greater than that of the country as a whole. The ratio of reservoir capacity to population underwent a sharp reversal in trend after 1970, see Fig. 20 (the 2000 point is estimated). The difficulty of new reservoir construction—both hydrological and political—ensures that this trend will continue. No better symbol of this is the fact that at the close of the century, the Bureau of Reclamation has only a single water-supply-related project active in Texas. This project involves the diversion of the Nueces River into its tidal marsh, the frequency of natural overbank flows being substantially reduced due to construction of the reservoirs on the Nueces River.

The most prolific sites for reservoirs in the state, from Maxim (I), are in the east, Fig. 17, and indeed there is excess water in many of the reservoirs extant in this region. It is a good bet that this water will be transported westward, primarily to supply municipal/ industrial requirements. The Texas Water Plan of 1968 (TWDB, 1968) included major conveyances to bring this water westward through DFW into the South Plains, and southward along the Texas coast. Though the Water Plan on its grand scale was defeated by the voters (at just about the point in Fig. 20 that the trend in *per capita* ratio turned negative), the westward interbasin transfer is taking place, albeit via isolated, uncoordinated, *ad hoc* conveyances (e.g., the Mary Rhodes Memorial Pipeline from Lake Texana to Corpus Christi).

The relatively modest requirements of cities and industries (compared to irrigated agriculture) also allow other alternatives that, though expensive, can be important additional sources. Prominent among these are desalination and water re-use. With respect to the latter, this brief survey has completely avoided the issue of water quality, which also circumscribes the use of a watercourse as supply. Suffice it to note that the improvements in treatment technology now allow recovery and reuse of effluent water as a viable process.

One aspect of Texas water seems clear: that irrigated agriculture will become increasingly difficult to sustain, both in terms of supply and in terms of economic competition for water. As noted earlier, the conversion of irrigation surface rights to municipal supply is underway on the coast and in the Lower Rio Grande Valley, and will no doubt continue. On the Edwards, San Antonio competes effectively with irrigation for the groundwater by its pumping capacity, in lieu of a structure of water-rights law. On the High Plains, the Ogallala resource is limited and continues to be depleted, the advances in conservation and efficiency notwithstanding.

With the decline in reservoir construction there seems to be an associated decline in monitoring and research enterprises, which are the foundation of water management. Stream gauging has followed a parabolic trajectory during the Twentieth Century, also, and is now declining. Maxim (III) expresses the fact that the ultimate source of water supply is the difference between two large, nearly equal fluxes: precipitation and evapotranspiration. Of all of the elements of the Texas water balance, it is this difference, recharge and runoff, about which we know the least. We have been able to get by because direct measurements of streamflow can be used as a surrogate in reservoir engineering.

Although droughts have occurred in the latter half of the century, thus far there has been no repetition of the great 1950's drought, but this is merely a matter of time. It is noteworthy that of the major reservoirs in Texas, two-thirds were built after the drought of the 1950's. Though water planning in Texas *is* drought planning, the system has not been truly tested in a major drought. (There have been critical droughts in certain areas, e.g. North Texas in the 1980's, Corpus Christi in the 1990's, and the Lower Rio Grande Valley at present, but nothing of the spatial scale of the droughts of the 1930's and 1950's.)

Moreover, almost all of the steam-electric cooling lakes were built after the 1950's drought. The dependency of Texas electric generation on the maintenance of water level in the State's reservoirs does not seem to be given adequate consideration in water planning. Though power generation is a minor consumer of water, a minimum water elevation is necessary, both to allow pumping of the cooling water, and to prevent heating of the reservoir and reduced efficiency of generation. In the last two decades several power plants have been forced off-line because of either low water levels or high intake temperatures, but these have been spasmodic and easily accommodated with the redundancy of the grid. A large-scale drought with widespread reduction in reservoir levels would endanger the State's generating capacity.

There is one other aspect of Texas water that has not changed since 1900. This is the promotion mentality, which expands on the many attributes of the state, but disregards the water-supply problem. The term in 1900 was "booster," in 2000 it is "developer." Benedict and Lomax (1916) observed, "Boosters frequently say two things: 'rainfall is increasing' and 'this drought is unusual.'" After a century, the availability of water is still widely ignored in municipal planning and land development. The effectiveness of the State's water districts and river authorities in planning and brokering its water supply is no small factor in this: they make a difficult task look easy. However, there are hydrological limits, and the attitude that somehow the water will be there is no longer tenable. To use an expression current in the year 2000, after a century, it is time to get real.

Notes

1. All climatological data presented in this paper are derived from the 1941-70 normals. This normal time period coincides most closely to the time periods for which the statistics on streamflow and water demand were computed.

2. One noteworthy exception to this statement is the Rio Grande, which in 1900 derived a substantial amount of its flow from the snowpack in the Rockies. With the completion of Elephant Butte dam, and the diversion of the entirety of the normal flow above El Paso for water supply and irrigation, the statement in the text is true of the Texas reach of the river.

3. It is also worth noting that of the 9 data points from Texas, 8 are from stations lying along the Balcones escarpment. This abrupt rise in topography is frequently a favored region for the development of thunderstorms, particularly associated with strong inland flow of moist, convectively unstable air from the Gulf of Mexico.

4. The statewide-average rainfall for the period of the 1950's drought, 1950-56, was only 20% below normal, see, e.g., Lowry (1958).

5. At this writing (June 2000), the cumulative rainfall in Austin is exactly at its long-term average value for this point in the calendar, but Lake Travis on the Colorado is over 30 ft below conservation pool, its lowest such level in 20 years.

6. The 1912 state almanac lists one (1) major reservoir in the state as of 1910, unnamed but with a stated capacity of 91,000 ac-ft (Galveston-Dallas News, 1912). This is erroneous.

7. The officer in charge, one General Dyrenforth from Fort Bliss, was dubbed "General Dryhenceforth."

8. In recent years, another problem has emerged with the groundwater supply, salination due to leaching in the arid environment of the Valley.

9. Tandem operation is considered to begin when both reservoirs reach conservation pool, which occurred in 1972.

10. Of the remaining 35% of steam-electric capacity, 15% is situated on bays or estuaries, and 20% employ cooling towers.

11. Sharp (1992) estimates an average annual growth of 2.0%, which would project the 1990 value of 17 M to a 2000 population of 20.7 M. But this growth rate reflects the recession of the 1980's and could not anticipate the present economy-driven growth. To accommodate the activity of the past five years, this estimate was bumped by an additional 10% to yield an estimate of 2000 population of 23 million.

12. In Houston a separate problem limited continued groundwater withdrawal, namely the resulting subsidence of the land, and the consequent encroachment of the sea.

13. No alternative surface sources in the High Plains area, that is. The Texas Water Plan of the 1960's (TWDB, 1968) included a proposal to move surface waters from East Texas and from the Mississippi.

14. On a personal note, this writer grew up about 100 yds from a desiccated gully with the paradoxical name of Running Water Draw. On no less authority than his seventh-grade history teacher, Mrs. A.B.Cox, this in fact was a perennial flowing stream fed by many springs from the shallow water belt of the Ogallala from prehistoric times until the 1930's when the springs and the Draw went dry.

15. Approximately as $\exp\{0.05\ T\}$ where T is the elapsed time in years since 1921.

16. SCS (1971) presented data on the variation of "drainage area per unit volume of storage," as a means of estimating reservoir feasibility. This measure, which does not consider yield, appears to be more than it is, because it in fact is simply the reciprocal of runoff.

17. As an example, the surface area of the Lake Corpus Christi/Choke Canyon system is 45000 ac. From Fig. 17, about 50 times this area is required for a viable project, or 3500 sq mi. The actual watershed is 17,000 sq mis.

18. The Texas Water Rights Commission in 1972 attempted empirically to determine a relation between reservoir capacity and yield, based upon permitted withdrawals. It proved noisy ranging from 0.5 to 10, but this relation reflects a variety of water uses, and, moreover, the permitted withdrawal may bear no relation to the reservoir yield. Ward and Proesmans (1996) surveyed Reclamation reservoirs to determine such a relation, but actual yield numbers proved to be largely nonexistent.

19. These are not misprints.

20. The purchase price was for not only the water rights but also the physical assets of the Garwood company, including a low-water dam, two pump stations, and 170 miles of canal. But the purpose of the acquisition was to obtain the water rights, so the total price paid is a measure of their value.

21. The intended metaphor is a ballistic.

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