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ABSTRACT

Fuel shortages and resultant rising fuel costs as well as federal policies prompting energy independence have served to encourage power companies to exploit available lignite deposits of the western states as a viable fuel source. Large reserves of lignite found in a northeasterly trending belt through Texas have been only partially tapped. To develop this natural resource, large volumes of water will be required for mining, handling, processing, cooling, power generation, and land reclamation.

Throughout the Texas lignite belt, physical characteristics vary widely depending mainly upon the amount of water present in any form. Research into the potential impact of the development of the Texas lignite resources on both the surface and groundwater resources of Texas has produced three separate areas within the lignite belt which have varying capabilities of supporting lignite development. The northeastern section of the lignite belt has sufficient surface water resources and backup groundwater resources to allow extensive development of lignite. The central section will support mining and development, but care must be taken to conserve and regulate water use. The southwestern section of the lignite belt does not possess sufficient ground or surface water resources for much, if any, lignite development. The most water thrifty methods of production would have to be employed for even limited development.

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*In pocket in rear.

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INTRODUCTION

Objective

The primary objective of this research is to evaluate the potential impact of the development of the Texas lignite resources for electrical energy production on both the surface and groundwater resources of Texas.

The Switch to Lignite

The energy crisis of 1973, rising fuel oil costs, and federal policies promoting energy independence have served to encourage power companies to exploit avilable lignite deposits of the western states for use as a fuel source in the generation of electricity. Texas has been a leading supplier of fossil energy in the form of oil and gas and her large lignite resources have been only partially tapped. Eighty-one Texas counties (Fig. 1) have some deposits of lignite with principal deposits located in the counties listed in Table 1. Estimated reserves by county are found in Table 2. Recent estimates indicate that the total near surface deposits (within 200 feet of the ground surface) are approximately 12.2 billion short tons (Kaiser, 1978) and deep-basin deposits (between 20 and 5000 feet below ground surface) equal to 112 billion short tons (Kaiser, 1974). Because a continued need for fossil energy can be expected to partially provide for the energy needs of our nation, Texas will benefit from the utilization of the lignite reserves within the state.

Lignite is a low-rank coal, thus greater quantities of lignite are needed to produce as much heat energy as the higher ranking bituminous and anthracite coals. For example, two pounds of Texas lignite are needed to

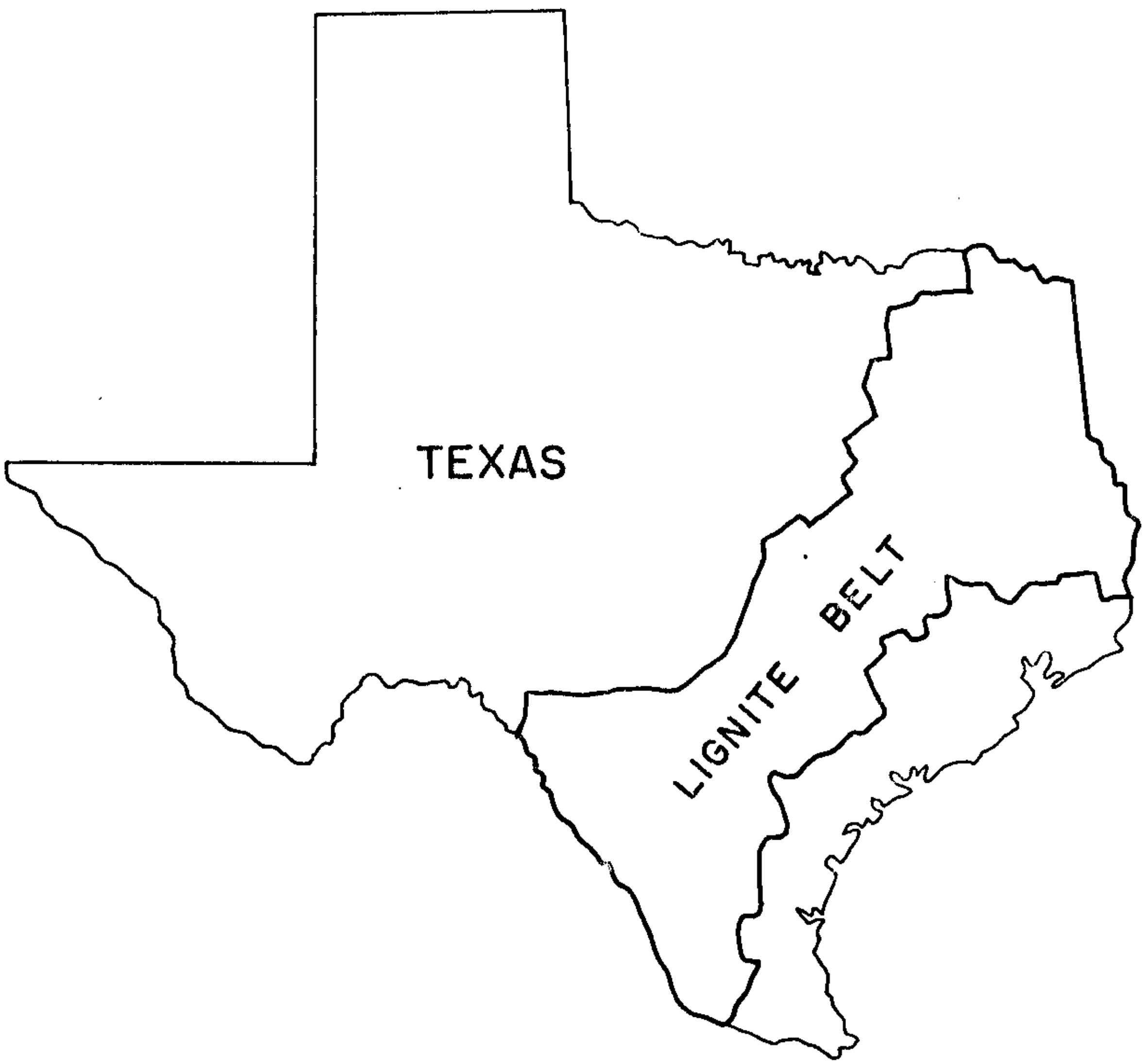

Figure 1. Location of the Texas lignite belt.

TABLE 1. Counties in the Texas lignite belt.

Anderson	Harrison	Panola
Angelina	Hays	Polk
Atascosa	Henderson	Rains
Bastrop	Hopkins	Red River
Bell	Houston	Robertson
Bexar	Hunt	Rusk
Bowie	Jasper	Sabine
Brazos	Jim Hogg	San Augustine
Burleson	Karnes	San Jacinto
Caldwell	Kaufman	Shelby
Camp	Kinney	Smith
Cass	LaSalle	Stan
Cherokee	Lavaca	Titus
Comal	Lee	Travis
Delta	Leon	Trinity
De Witt	Limestone	Tyler
Dimmit	Live Oak	Upshur
Duval	McMullen	Uvalde
Falls	Madison	Van Zandt
Fayette	Marion	Walker
Franklin	Maverick	Washington
Freestone	Medina	Webb
Frio	Milam	Williamson
Gonzales	Morris	Wilson
Gregg	Nacogdoches	Wood
Grimes	Navarro	Zapata
Guadalupe	Newton	Zavala

TABLE 2. Estimated reserves of lignites in the Texas lignite belt by county; figures in millions of short tons.

County	Measured Reserves Overburden* Thin	Measured Reserves Overburden* Thick	Indicated Reserves Overburden* Thin	Indicated Reserves Overburden* Thick
WILCOX LIGNITES				
Anderson	21.4	55.2	64.2	165.6
Bastrop	54.8	86.4	153.9	348.2
Bexar	15.5	28.6	46.5	85.8
Bowie	47.4	2.0	10.2	6.0
Caldwell	38.0	59.2	114.0	177.6
Camp	6.8	2.0	20.4	6.0
Cass	17.9	21.6	53.7	64.0
Cherokee	11.0	34.6	33.0	67.8
Franklin	3.0	4.0	9.0	12.0
Freestone	25.5	23.8	76.5	71.4
Gregg	4.1	32.0	12.3	96.0
Harrison	46.8	17.8	76.8	53.4
Henderson	37.8	33.0	113.4	99.0
Hopkins	24.1	6.0	61.8	18.0
Lee	6.2	11.2	18.6	33.6
Leon	24.4	18.0	73.8	54.0
Limestone	---	6.2	---	18.6
Marion	11.1	16.0	33.0	48.0
Milam	254.6	2.0	163.8	6.0
Morris	5.5	3.4	16.5	10.2
Panola	35.1	17.0	105.3	51.0
Rains	3.6	5.6	10.8	16.8
Robertson	28.1	26.0	84.3	78.0
Rusk	41.6	104.4	124.8	313.2
Shelby	18.6	10.0	55.8	30.0
Titus	36.5	10.0	109.5	30.0
Van Zandt	69.3	34.4	207.9	103.2
Wood	38.5	33.6	94.5	100.8
YEGUA AND JACKSON LIGNITES				
Angelina	5.1	7.6	15.3	22.8
Brazos	2.8	6.0	8.4	18.0
Burleson	4.0	17.8	12.0	53.4
Fayette	27.0	5.4	81.0	16.2
Grimes	12.8	19.8	38.4	59.4
Houston	16.9	29.2	50.7	87.6
Madison	7.6	5.0	22.8	15.0
Nacogdoches	4.5	16.2	13.5	348.6
San Augustine	---	1.0	---	3.0
Trinity	6.1	13.8	18.3	41.4
Walker	7.9	11.0	23.7	33.0
Washington	5.4	22.0	16.2	66.0

*Thin overburden, less than 90 feet; thick overburden, greater than 90 feet.

(Computed by J.M. Perkins; data on file at Bureau of Economic Geology.)

produce 14,000 Btu's while one pound of bituminous will produce the same amount (Fig. 2). To economically employ lignite as a fuel source in the generation of electricity, it is important that mining costs not be excessive relative to the end use. The regional geology of the Texas lignite belt, with a flat to gently rolling topography, contributes significantly to both the practicality and economic feasibility of strip mining Texas lignite.

Transferring energy production from natural gas and fuel oil to lignite will have a significant technical, environmental, and social impact in Texas. Mine-mouth power plant operations, located throughout the lignite belt, with high voltage power transmission lines going to consumer, may replace the oil and gas fired plants now in operation and located near the user.

Large volumes of water are required in the process of strip mining as well as in the handling of lignite and the generation of power in steam-turbine power plants. Water is essential for mine haul road maintenance, dust control, retention of the moisture content of the lignite during transportation, boiler stock cooling, and other facets of the production of electrical energy.

In addition, there are water requirements for mined land reclamation which will vary according to the climatic conditions of the mining area. For example, reclamation of the East Texas lands will have less of an impact on the existing water budget than reclamation endeavors in the central and West Texas regions because of the differences in climate conditions.

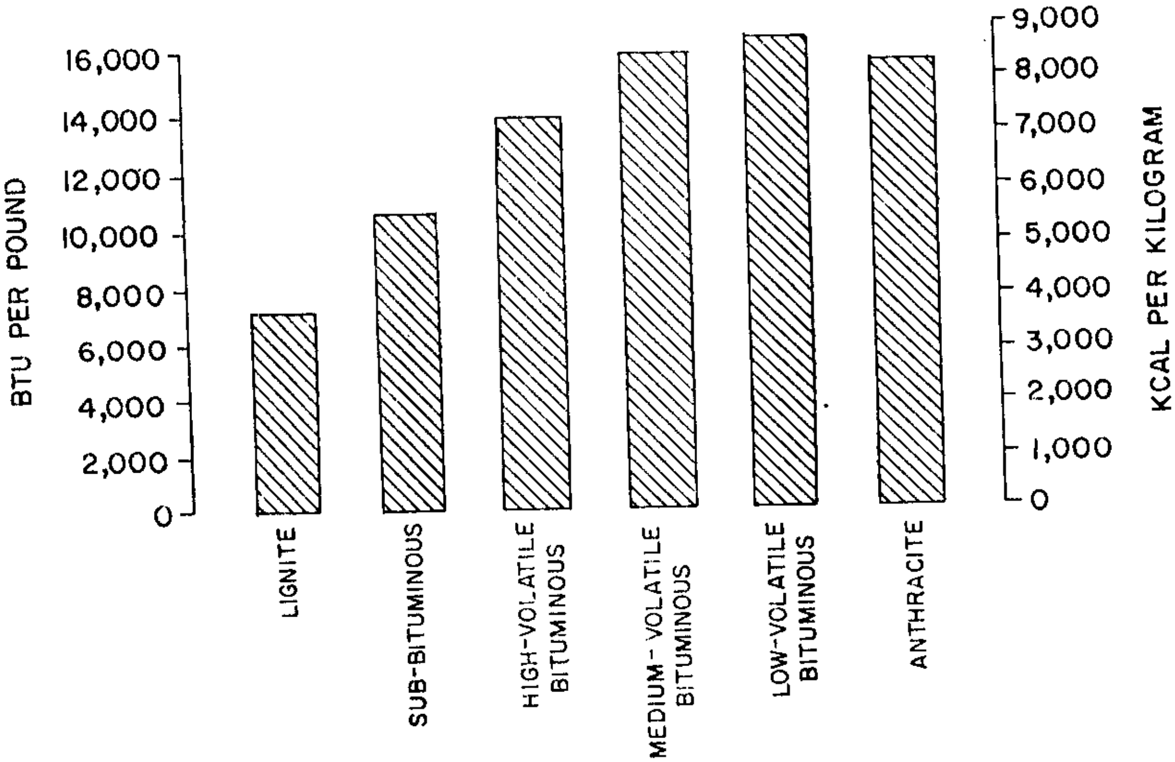

Figure 2. Heat content of various ranks of coal.

A surface mine operations requires 2-6 gallons of water per million Btu's of lignite mined (1200-4000 acre-feet per year) including water used for dust control and reclamation. Electric power generation requires more water than other synthetic fuel technologies. To produce 3000 megawatts of electricity, 23,000-29,000 acre-feet of water per year are consumed (Energy Resource Development Associates). The City of Bryan, Texas, consumes 0.75 gallons of water to generate 1 kwh of electricity in a gas fired 125 megawatt steam turbine power plant (Jack Bayer, personal communication). While some data exists, the quantity of water actually used in mine-mouth conversion processes along with reclamation requirements has not been fully determined. Therefore, the total effects of developing Texas lignite to generate electricity is not known. The question of water resource capacity to meet all needs becomes even more complex when variables such as population increases, industrial expansion, and urbanization resulting from non-energy related growh patterns such as Texas is now experiencing, are considered in addition to the development of lignite.

Lignite Mining in Texas

History

Lignite mining in Texas was documented as early as 1819 when L'Heriter, a Frenchman, located a "mine de charbon de Terre" in east Texas on a map accompanying a report published in Paris. Lignite was used by many of the early settlers as a fuel source, and, prior to the impact of the discovery of oil and gas, there were as many as 100 small lignite mines operating in east Texas (Fisher and Kaiser, 1979). Early production of lignite was minimal and conducted locally with many of the mines operating underground. "From an annual production of about 20,000 tons in the late 1880's, lignite gradually increased to as much as 1.4 million short tons in 1914. Yearly production averaged about 1 million tons from 1915 through 1930. From 1930 to 1940 annual production dropped to slightly more than 0.5 million tons, and by 1950 it has practically ceased" (Fisher and Kaiser, 1974). Figure 3 graphically illustrates lignite production in Texas from 1885 to 1950.

In 1954, the Industrial Generating Company (ICG) opened a lignite mine near Rockdale, Milam County, for use in generating power for the Aluminum Company of America (ALCOA) to process aluminum. This power plant became Texas' first major mine-mouth operation. Imperial Chemical Industries, Ltd., operates another mine near Marshall, Harrison County. Texas Utilities also has mine-mouth operations at Martin Lake near Tatum in Panola County and at Monticello near Mt. Pleasant in Hopkins and Titus Counties. Basic Resources of Texas Utilities has recently been granted a permit by the Texas Railroad Commission for an in situ lignite gasification test facility in Palestine, Anderson County. Other mining permits approved by the Texas Railroad Commission include: Amistad Fuel Company of San Antonio for Little Bull Creek in Coleman County; Texas Municipal Power Associates for operations in Grimes County; Shell Oil Company for Milam Mine in Milam County; and an in situ gasification facility outside Rockdale to Texas A&M University. Operations of these facilities are pending posting of performance bonds.

Extensive lignite exploration programs are being carried out by utility companies, private industry and mineral investors. Plans are in the formation stages for development and construction of new lignite fired power generation facilities throughout the entire lignite belt of Texas. Exploration activities are being conducted by Phillips Petroleum in Hopkins County, Sabine River Authority of Texas in Hopkins, Woods and

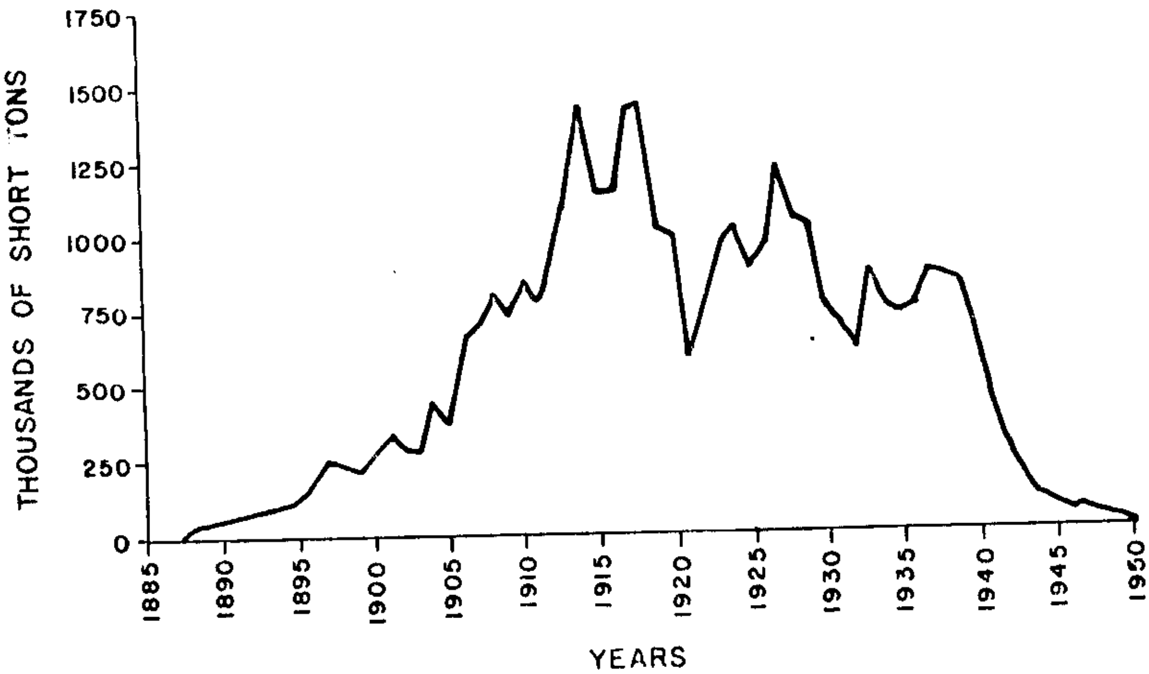

Figure 3. Lignite production in Texas, 1885-1950.

Rains Counties, Texas Power Pool, Inc. in Grimes County, Dow Chemical in Freestone County, Sunoco Energy Development Company in Angelina County, Carter Oil Company in Rusk County, Southwestern Electric Power Company and Texas Lignite Products Corporation in Harrison County, Duval and Associates Consulting and Construction Company in Young and Erath Counties, Dahlstrom Industries, Inc. in Maverick County and Enserch Exploration, Inc. who are test hole drilling in various locations.

Mining and Reclamation

Until 1944, the shaft, room and pillar method of underground coal mining was used. Less than 50% of the coal seam could be recovered by this method, thus proving to be inefficient if other methods of extraction are available.

Strip mining has been the only type of lignite mining in Texas since 1950. Surface mining allows large deposits of lignite occurring at shallow depths and underlying soft, unconsolidated rocks to be profitably mined in large volumes. The average recovery rate of lignite for this type of operation is approximately 75% (Fisher, 1963).

Strip mining for lignite in Texas is an operation in which no net volume is lost because the deposit to be mined is considerably thinner than the overburden. Mining consists of removing the overburden with a drag line and placing it in the previously mined-out trench. The lignite is removed with a power shovel and placed in large haul trucks for transportation over special haul roads to the nearby power plant. Reclamation begins with backfilling the mined-out trench. The spoil piles are then leveled and the whole area regraded to natural contours, fertilized, and planted (Fig. 4).

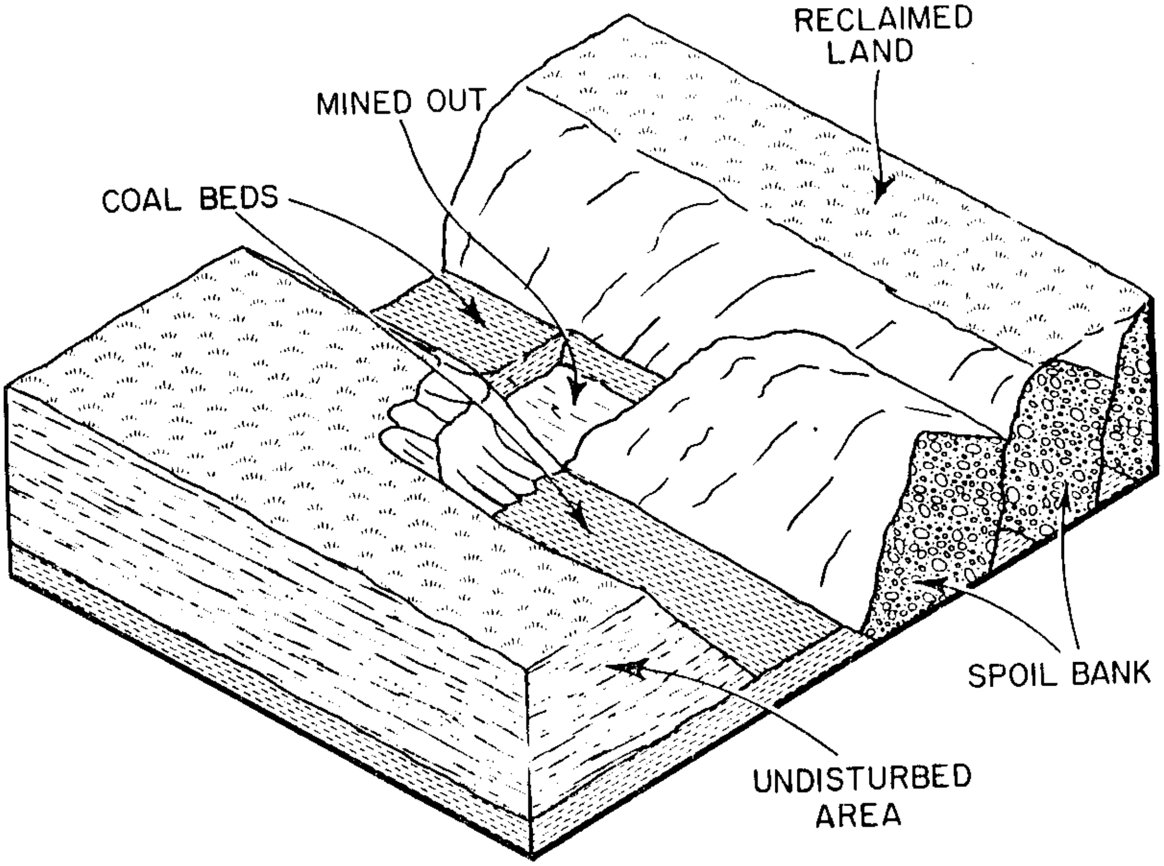

Figure 4. Schematic block diagram of lignite strip mining and reclamation.

CHARACTERISTICS OF THE LIGNITE BELT

Physiography

Texas has a total area of 267,339 square miles or one-fourteenth of the land and inland water area of the nation. Generally, the state is a vast plain sloping gently southeasterly to the Gulf of Mexico. Texas contains parts of five of the natural regions in the United States. Of these, two are found in the lignite belt (Fig. 5): the Gulf Coastal Plain and the Great Plain (Chambers and Kennamer, 1963).

The Gulf Coastal Plain

The Gulf Coastal Plain along the Texas shoreline is located between the lower course of the Sabine River and the southern shore of Corpus Christi Bay and extends inland to the pine and post oak belts. The low almost level prairie is covered with grasses, wild flowers, and trees. Closest to shore, the land is low, flat, and somewhat marshy. Barrier islands, sand bars, and spits enclose broad shallow bays and lagoons along most of the coast. Moving inland, drainage becomes better developed as the land surface gradually increases above sea level. Rivers and streams have created shallow, level valleys in this part of the plain. From 75 to 100 miles inland, the land surface increases in elevation and becomes gently rolling to hilly due to deeper cutting of river and stream valleys. Most of the plain area is less than 100 feet above sea level (Chambers and Kennamer, 1963).

The Great Plain

The Great Plain region extends from the South Texas Plain and the Rio Grande River northward across the United States into Canada. The

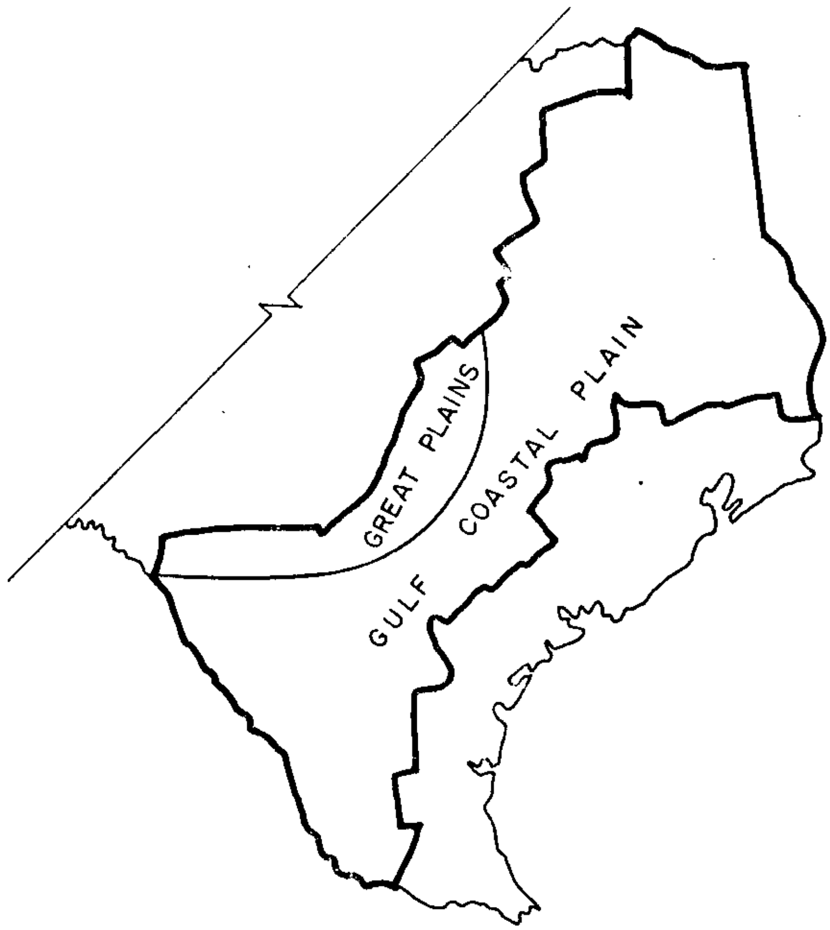

Figure 5. Physiographic regions of the Texas Lignite belt.

portion found within the Texas lignite belt is a limestone highland with thin, flaggy soils covered with grasses, brush, and small trees. Streams flowing across this high plateau have created canyons, gorges, and valleys, making this area hilly or even mountainous. Relief reaches several hundred feet from mountain tops to the bottom of nearby valleys (Chambers and Kennamer, 1963).

Soils

One of Texas' most important natural resources is her soil, which supports several industries, crops, pastureland, and forestland. Nearly 500 different soil types are recognized within the state, but these can be narrowed to seven dominant soil orders (Fig. 6) within the Texas lignite belt.

Soils form as a result of "interaction of climate and organisms on geologic materials as conditioned by topography over a period of time" (Fisher, 1972). Variety in type, number, and degree of development of natural layers (horizons) differentiates soil orders. Following is a desciption of the soil orders within the lignite belt:

Entisols

Entisols are recent soils without well-developed horizons. They are variable in texture and develop under many climatic conditions, usually on young geomorphic surfaces. Characteristic are deep sandy soils of coastal terraces.

Vertisols

These dark soils are characterized by shrink-swell properties due to high clay content. They hold water and nutrients well but resist further permeation by air and water when moist. The dark clay soils of the uplands and stream terraces of the Blackland Prairie are vertisols.

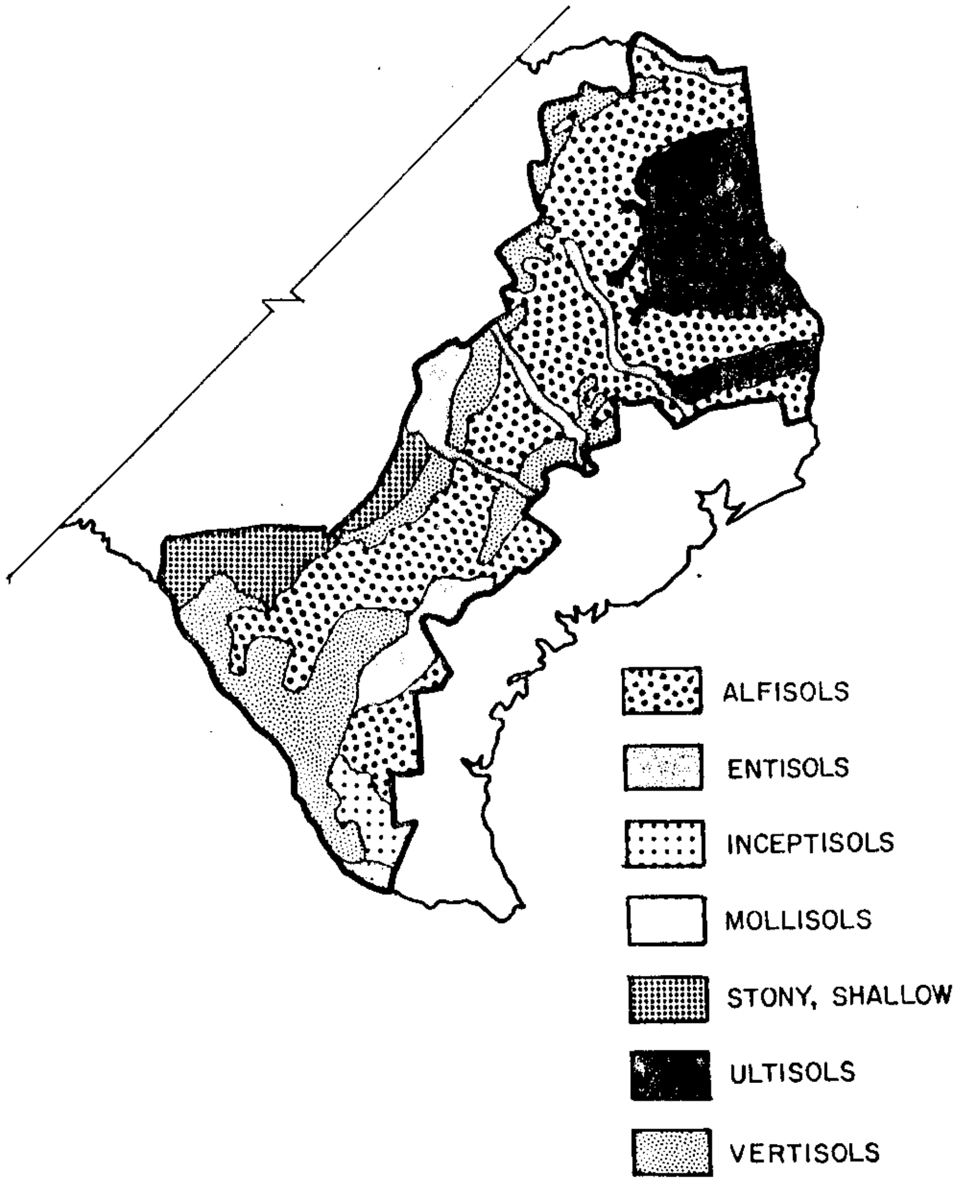

Figure 6. Soil orders within the Texas lignite belt.

Alfisols

Alfisols have a grayish-brown loamy surface horizon with a clayey subsurface horizon that has a low permeability. These are good agricultural soils and are found throughout much of the lignite belt.

Inceptisols

Variable soils with limited horizon development due to lack of extreme weathering are inceptisols. In this case, alteration of parent material and erosion are in equilibrium. Characteristic are the red loamy soils of the South Texas Plain.

Mollisols

Mollisols are thick, soft, dark soils formed in moderate climatic regions high in calcium. Much decomposing organic matter is usually present within rather than on the soil layer. They generally develop from calcareous water-laid parent material. Mollisols may also be somewhat thinner with flags or stones of the parent rock on the surface.

Ultisols

Ultisols form in warm, humid climatic regions and are commonly light reddish-colored, loamy, sandy, and acidic. They have well-developed horizons due to a high degree of weathering. Stratified sand and clay sediments of the East Texas Timberlands produce ultisols (Fisher, 1972 and Mathewson, 1980).

Geology

Description

Certain physical and biochemical processes act on accumulated plant material to form coal. Its nature and form depend on the original composition of the plant material and the length of time during which these processes acted. Coalification, or the gradual transition from plant material to coal resulting from these processes, produces different levels of maturation of coal. All coals can be ranked in ascending order by carbon content as follows: peat, lignite, subbituminous, bituminous, and anthracite (Berkowitz, 1979). Lignite has been described as a low rank, brownish-black coal with a high moisture and volatile matter content and a heating value of less than 8,300 Btu's per pound, that is intermediate in coalification between peat and subbituminous coal (ASTM, 1979). Lignite contains separable pieces of plant material and is soft, friable, and porous with a low specific gravity. At present, international classification of soft, or low rank, coal is based on bed moisture content and tar yield.

Lignite in Texas is formed in three facies: fluvial, deltaic, or lagoonal. Fluvial lignite has a high percentage of wood and low percentages of sulfur and ash. If formed as backswamp peats or in broad flood plains along ancient meandering rivers. Deltaic lignite is non-woody with little ash, and moderate amounts of sulfur. It has a wide, tabular shape and formed in marshes on ancient deltas. Lagoonal lignite has a high ash content which indicates frequent introduction of clastic materials and a high sulfur content suggesting it formed in salt marshes associated with ancient lagoons (Kaiser, 1974).

Stratigraphy

There are abundant deposits of lignite among the Eocene rocks in Texas (Fig. 7). Table 3 shows the stratigraphic occurrence of these lignite deposits. Primarily they are found in the Wilcox Group and locally in the Yegua and Manning Formations. Potential reserves include about 41% of the outcrop area of the Wilcox aquifer. Figure 8 indi-

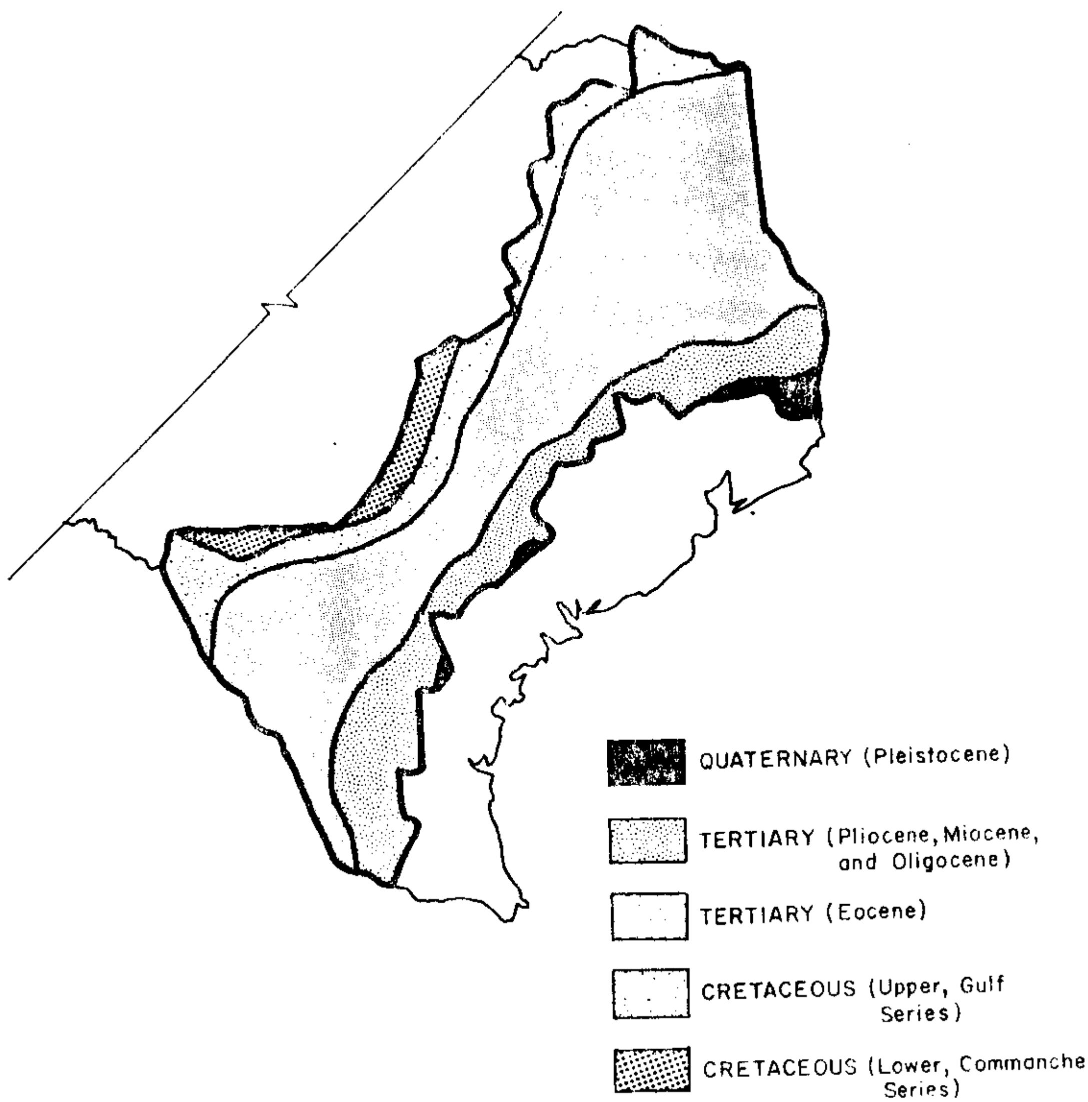

Figure 7. Principal surface geologic formations in the Texas lignite belt.

TABLE 3. Stratigraphic occurrence of principal lignite deposits in Texas.

Period	Series	Group and Formation		
Neogene	Pliocene			
	Miocene			
	Oligocene			
		Jackson	Whitsett	
			* Manning	
			Wellborn	
			Caddell	
		Claiborne	* Yegua	
			Cook Mountain	
			(NE Texas)	(S Texas)
			Stone City	Mt. Selman
			Sparta	
			Weches	
			Queen City	Bigford
			Reklaw	
			Carrizo	
		* Wilcox		
	Paleocene	Midway		

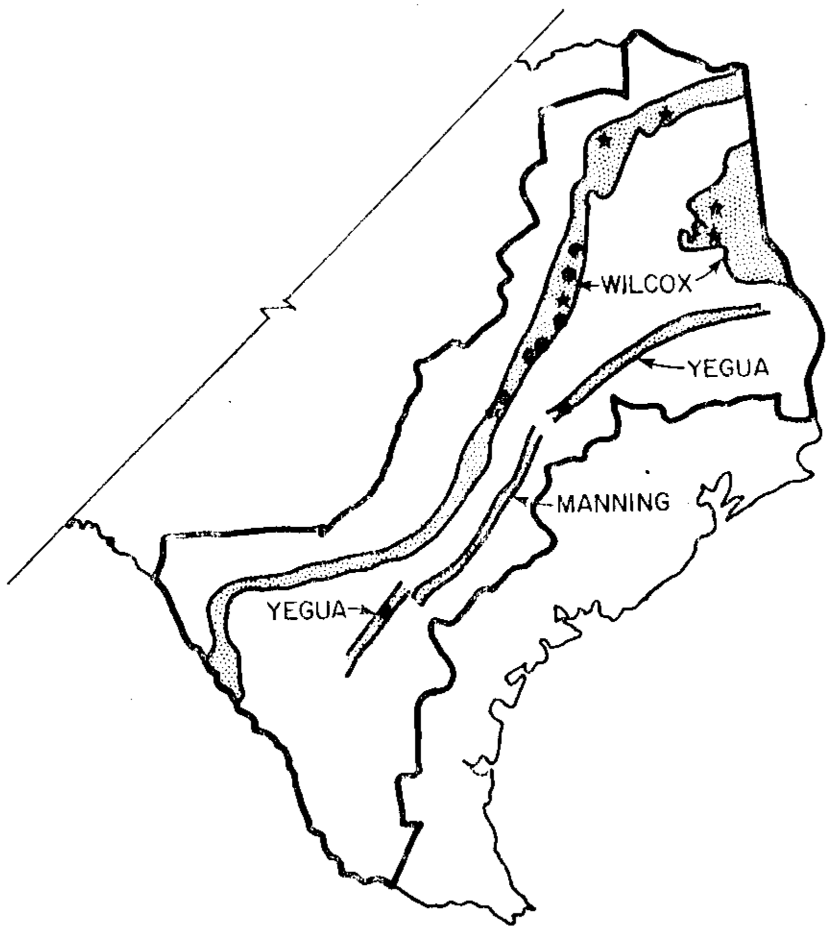

Figure 8. Distribution of lignite bearing rocks in Texas.

✶ Existing mine sites.

● Proposed mine sites.

cates the distribution of lignite-bearing rocks in Texas. These near surface lignite deposits occur in two elongated bands stretching from the Angelina River in Angelina County and the Red River in Bowie County to the Rio Grande River in Webb and Starr Counties. Approximately one million acres are possibly underlain by recoverable lignite. Recoverable lignite refers to the lignite located within 200 feet of ground surface, removable by strip mining methods.

Regional Variation

In general, the strata which contain the lignite dip towards the Gulf of Mexico. Southwest along the outcrop, the ash and sulfur content increases, while the content of volatile matter and fixed carbon and caloric value decreases. Average ash content of Texas lignite (Fig. 9) is approximately 17%, but can vary between 10% and 40%. North of the Colorado River, Wilcox lignites contain the lowest percentage of ash (less than 15%), while south of the Colorado River the ash content increases. A similar southward increase in ash content occurs in the Upper Eocene lignites. Sulfur content increases southward from less than 1% in much of the area north of the Colorado to 2% south of the Colorado. Some of the lignite between the Brazos and Trinity Rivers contains 1% to 1.5% sulfur locally (Fig. 10). The most desirable lignite for fuel use is one having low percentages of both ash and sulfur. Lignites containing high percentages of ash or sulfur present waste management and pollution problems.

Regional variations reflect differences in both source material and formation processes (Fisher, 1963). Fluvial lignite occurs in east-central Texas, deltaic in southeast Texas, and lagoonal in south Texas. Deltaic is the highest grade lignite and is found primarily in the Wilcox Group with smaller occurrences in the Yegua and Manning

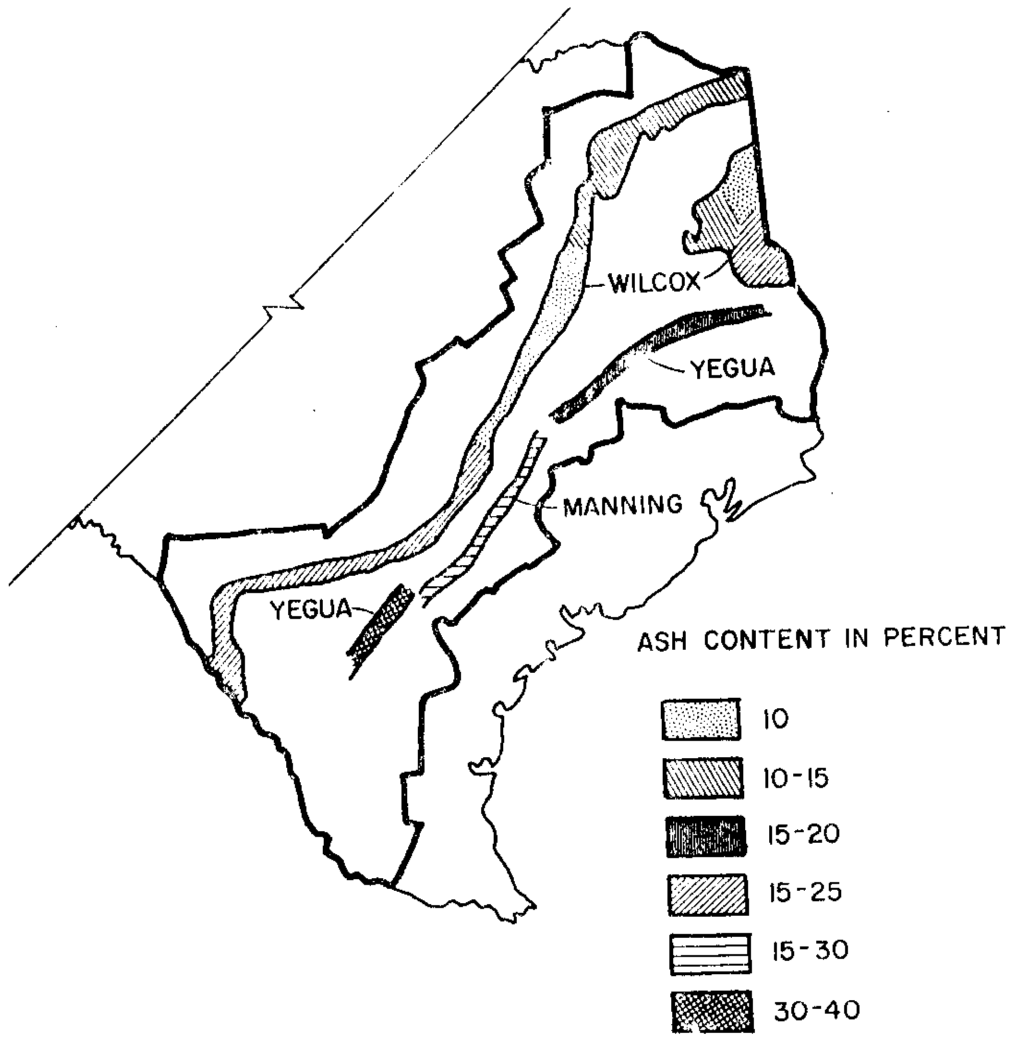

Figure 9. Regional variation in ash content of Texas lignite (as-received basis).

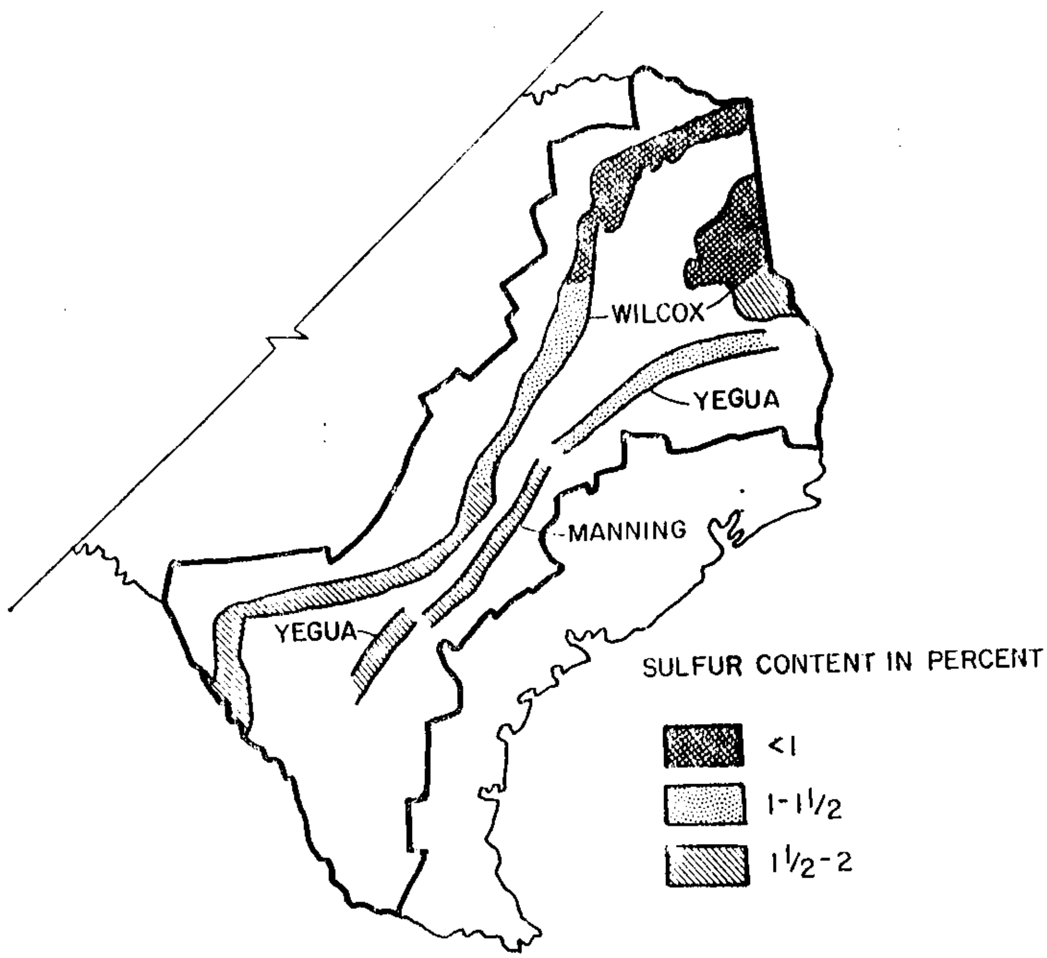

Figure 10. Regional variation in sulfur content of Texas lignite (as received basis).

Formations. Lagoonal lignite occurs with equal abundance in the Wilcox, Yegua, and Manning while fluvial lignite has been found only in the Wilcox Group. The highest quality and largest recoverable deposits are found in the Wilcox Group north of the Colorado River in east and central Texas where individual seams are thicker, more uniform in quality and more persistent. Of secondary importance are deposits of the Yegua Formation north of the Brazos River. There are, however, certain local deposits of the Yegua Formation such as those found in Fayette and Grimes Counties and of the Manning Formation in Grimes County which may have commercial importance. Table 4 lists the principal lignite deposits by county and facies.

Hydrology

To assess water availability for lignite development, the magnitude of the water resource and the total demand placed on it must be taken into consideration. The stream-electric power generation industry alone will consume approximately 1.5 million acre-feet (maf) of water by the year 2000 to generate 1.1 billion megawatt hours of electricity, if present and planned cooling practices are continued (Texas Water Development Board, T.W.D.B., Report, 1974). In addition, it has been noted that strip mining requires 1200-1400 acre-feet of water per year for dust control, fire protection, cooling, and reclamation of mined lands. Public water consumption has increased as a result of energy related population increases. Water is also needed by municipalities for domestic consumption and waste disposal, by industries, by agriculture where regional demands have already exceeded renewable supply, and for environmental maintenance.

According to the Texas Department of Water Resources, Texas has an annual supply of fresh water from surface and ground sources of 14.1

TABLE 4. Principal lignite deposits by facies and county.

County	Group or Formation	Location	Thickness[1] (feet)	Facies
Anderson	Calvert Bluff	concentrically around the Palestine salt dome 5 miles west-southwest of Palestine	7.5	deltaic
Atascosa	lower Wilcox	northern part; vicinity of Lytle	5.5	lagoonal
Bastrop	Calvert Bluff	vicinity of Butler, divide area between Big Sandy and Piney Creeks from Sayersville to Bastrop, and Cedar Creek east of FM 20	4 - 10	deltaic
Bexar	lower Wilcox	Medina-Atascosa line to Somerset area	4.5 - 6	deltaic
Bowie	Wilcox	south-central part in Carbondale area; Sulphur River	3 - 13	fluvial
Freestone	Wilcox	southern corner and belt 3x12 miles trending northeast from Fairfield (Big Brown steam plant and strip mine)	5 - 12	deltaic
Grimes	Manning	central portion, belt 2x15 miles trending northeast between Carlos, Singleton, and Piedmont	5 - 8	deltaic
Harrison	Wilcox	astride the Sabine River from State Hwy. 43 to Eight Mile Creek (Darco area)	5 - 10	fluvial
Henderson	Wilcox	north and east of Malakoff within 6.5 mile radius; Caney Creek (site of T.P.&L. Forest Grove steam plant, 6 miles northwest of Athens)	7 - 12	fluvial
Hopkins	Wilcox	southeastern part; vicinity of Como	5.5 - 8.5	fluvial
Houston	Yegua	southwest part from Lovelady area to Trinity Rivers; Wooters Station	2 - 6	deltaic

TABLE 4. (cont.)

County	Group or Formation	Location	Thickness[1] (feet)	Facies
Lee	Calvert Bluff	extreme northeastern part in vicinity of Hicks	4 - 6	deltaic
McMullen	Yegua-Jackson	north-central part, San Miguel Creek area, 8 miles north of Tilden	5 - 8	lagoonal
Medina	lower Wilcox	just west of Lytle at the old community of Coal Mine	5 - 8	lagoonal
Milam	Calvert Bluff	from the southern corner northeast to the Brazos River; Alcoa (Industrial Generating Co. active strip mine), and Rockdale vicinities	7 - 16	deltaic
Nacogdoches	Wilcox	extreme northeastern part in Garrison area	4.5	lagoonal
Panola	Wilcox	northwestern part; Beckville area (site of Industrial Generating Co. strip mine)	5 - 15	fluvial
Rains	upper Wilcox	southeastern part; vicinity of Ginger	3 - 10	fluvial
Robertson	Calvert Bluff	west-central part north of Calvert in general area of Brazos River; Little Brazos River and Walnut Creek	3 - 12	deltaic
Shelby	Wilcox	vicinity of Timpson and Stockman	4 - 6.5	lagoonal
Titus	Wilcox	southern half; vicinity of Winfield (site of Industrial Generating Co. strip mine), Mt. Pleasant, Cookville	4 - 11	fluvial
Uvalde	Indio	southeastern part; east of Leona River to west of Nueces River	5 - 10	lagoonal
Van Zandt	Wilcox	Canton and Edgewood areas	5 - 12	fluvial

TABLE 4. (cont.)

County	Group or Formation	Location	Thickness[1] (feet)	Facies
Wood	Wilcox	extreme western edge; Alba-Hoyt district	8 - 13	fluvial
Zavala	Indio	northwestern part; astride the Nueces River	3 - 10	lagoonal

[1]Maximum expected thickness of individual seams.

(Kaiser, 1974)

maf. Of this, 5.1 maf is defined as the "quantity of average, annual, recoverable recharge to groundwater aquifer" or "safe groundwater yield" (McNeely and Lacewell, 1978). The other 9.0 maf is found as firm surface water yield or "the quantity of water that can be withdrawn or released from reservoirs continuously, on an annual basis, over periods of time of sufficient length so as to span the most severe period of drought in the reservoir catchment areas" (T.W.D.B., 1977). Groundwater use in Texas in 1974 exceeded the annual safe groundwater yield by 7.1 maf, which lowered groundwater tables, increased pumping costs, and changed the physical characteristics of individual aquifers. Actual surface water use in 1974 was estimated at 5.1 maf, somewhat below the firm surface water yield.

Surface Water

One of the most dramatic extremes in Texas climate is in the amount and timing of annual precipitation, which varies from 8 inches or less in far west Texas to more than 56 inches in far east Texas (Fig. 11). Precipitation rates may vary as much as 50% from year to year and periods of drought are quite common. High summer temperatures and constant wind raise evapotranspiration rates substantially. Runoff rates increase from west to east (Fig. 12), with three-fourths of the annual runoff in Texas occurring in the eastern one-fourth of the state (T.W.D.B., 1968).

Surface water may be in the form of diffused surface water or water within a watercourse. Diffused surface water results from rain, sleet, hail, or snow and is classified as such until it reaches a defined watercourse. When it reaches the watercourse it becomes part of the streamflow and is therefore property of the State, subject to landowner and appropriated rights. A watercourse is an "identifiable natural stream having a definite natural channel originating from a definite

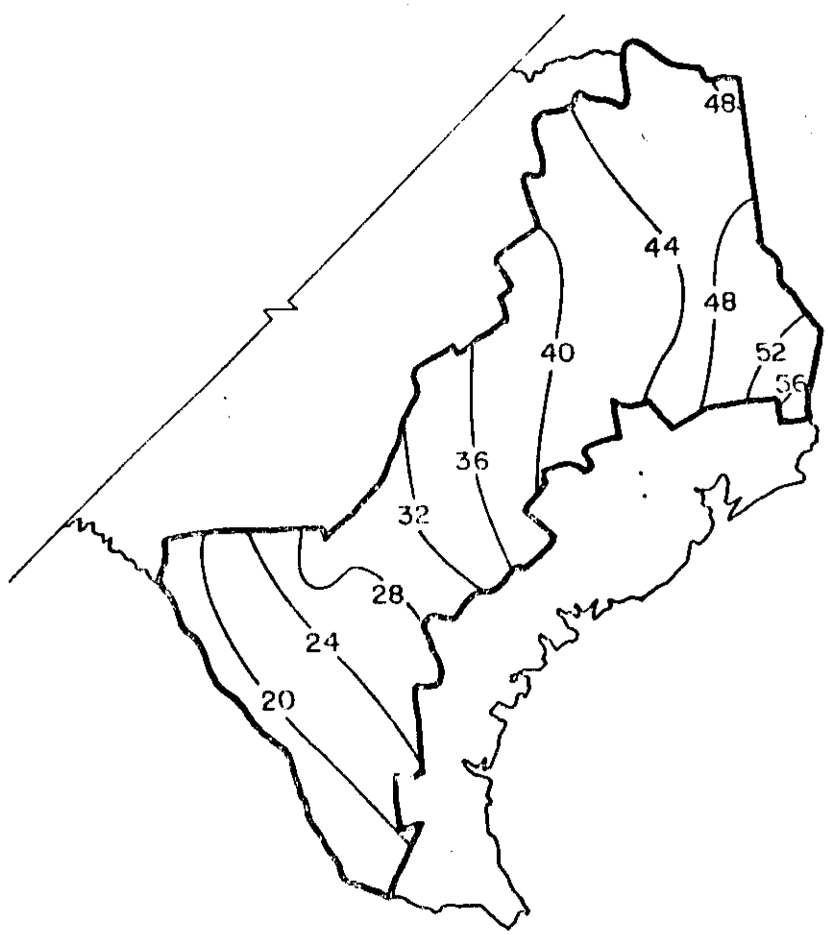

Figure 11. Mean annual precipitation in inches.

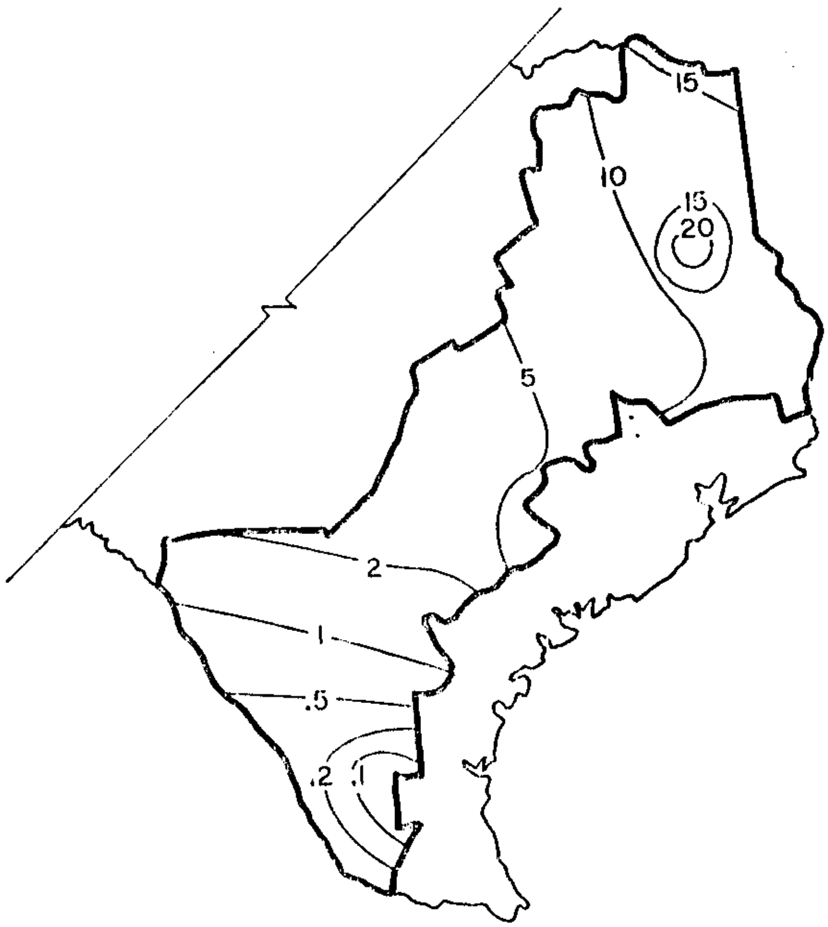

Figure 12. Mean annual runoff in inches.

source of supply" (McNeely and Lacewell, 1977).

In Texas, landowners have the right to intercept and impound up to 200 acre-feet of diffused surface water before it reaches a watercourse without obtaining a permit. Surface water in Texas is also regulated by the riparian and prior appropriation water rights systems. The riparian doctrine allows landowners with land containing or abutting a watercourse to reasonably use water for irrigation or other purposes. Under prior appropriation doctrine water rights on a stream may be acquired from the State, however, riparian rights to the stream are recognized as superior. The Texas Water Rights Commission had granted claims to 53.7 million acre-feet by the middle of 1975 (McNeely and Lacewell, 1977). Table 5 shows the number and extent of claims to basins within the lignite belt as of July 1980.

Drainage Basins. Texas is drained by twelve principal drainage basins, three minor river basins, and eight coastal basins (Fig. 13). Of these, fifteen basins drain all or part of the lignite belt. Following are descriptions of each basin within or partly within the Texas lignite belt. Included is information on size of drainage area, soils, reservoirs, and some general geology. Following the descriptions, Table 6 contains water availability data on selected streams within the lignite belt.

The Red River basin is bounded on the north by the Canadian River basin and on the south by the Trininty, Brazos, and Sulphur River Basins. The total basin drainage area is 48,030 square miles, of which only 24,463 square miles is in Texas. Of the basin's area that is within the state, only the southeastern portion is included in the Texas lignite belt. Most of the soils in this area are reddish brown to dark gray,

TABLE 5. Appropriation claims to basins in the Texas lignite belt.

Basin	Number of Claims	Water Claimed (acre-feet)
Rio Grande River	1346	7,084,812
Nueces River	333	922,251
San Antonio River	249	248,982
Guadalupe River	453	10,513,136
Lavaca River	35	120,342
Colorado River	1575	9,028,560
Brazos River	1707	4,796,057
San Jacinto River	96	3,551,993
Trinity River	652	5,827,352
Neches River	460	2,501,547
Sabine River	311	2,043,452
Cypress Creek	154	382,304
Sulphur River	78	358,510
Red River	399	665,182
Rio Grande-Nueces Coastal	86	2,201,797

(Texas Department of Water Resources, 1980)

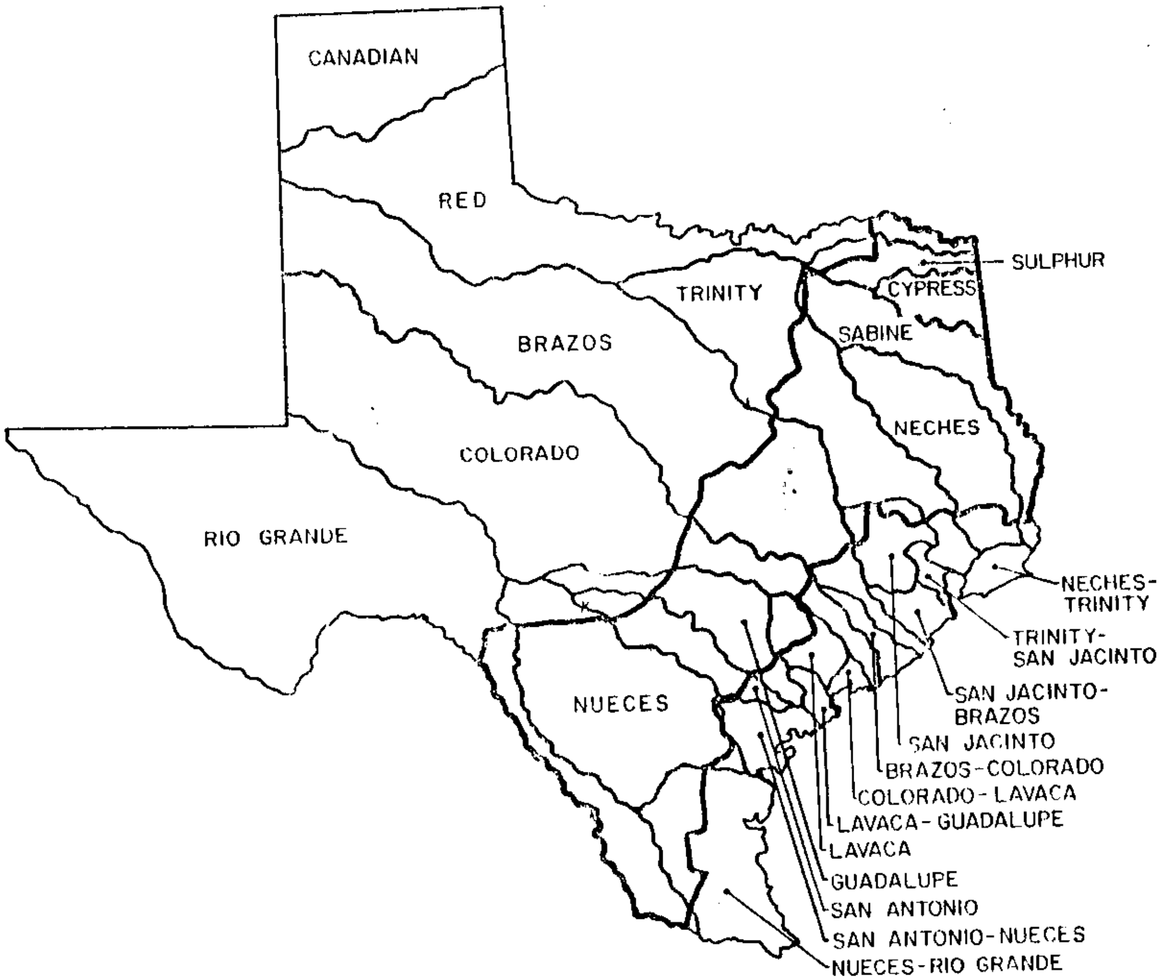

Figure 13. Drainage basins of Texas.

calcareous, alluvial soils, that are underlain by Cretaceous limestone, clay, chalk, and sand. The annual runoff in the basin from 1941 to 1970 averaged 203 acre-feet per square mile of contributing drainage area, and about 156 acre-feet per square mile of total drainage area. There are 22 major reservoirs in this basin. Of these, eight are located within or near the Lignite Belt.

In Texas, the Sulphur River basin is bounded on the north by the Red River basin, on the west by the Trinity River basin, and on the south by the Sabine and Cypress Creek basins. The total drainage basin area within Texas is 3,588 square miles. Soils in the uplands are mostly light to red, acid sandy loams and sands. Bottomland soils are light brown to dark gray, acid to calcareous, alluvial deposits. The upper Sulphur River asin is underlain by southeasterly dipping clay and limestone beds of Cretaceous age. Most of the basin is underlain by clay and sand of the Midway Group, which are overlain by sand, clay, silt, and lignite of the Wilcox Group (Calvert Bluff Formation). Average runoff of this basin during the 1941-1970 period varied from approximately 600 acre-feet per square mile in the western part to 1000 acre-feet per square mile in the eastermost part. There are three major reservoirs in the area today and one, the Cooper Lake and Channels Project, is awaiting renewed construction pending the approval of a new environmental impact statement.

The Cypress Creek basin is bounded on the north by the Sulphur River basin, on the west and south by the Sabine River basin, and on the east by the Texas-Arkansas and Texas-Louisiana boundaries. In Texas, the total drainage area of the basin is 2,812 square miles, all within the lignite belt. The soils are similar to those of the Sulphur River basin.

This basin is underlain by southeasterly dipping sand, clay, glauconite, and lignite of the Wilcox and Claiborne Groups of Tertiary Age and most of the iron ore produced in Texas came from formations within the Cypress Creek asin. During the 1941 to 1970 measured period, the average runoff in this basin was 696 acre-feet per square mile. There are seven major reservoirs in the Cypress Creek basin: Cypress Springs, Lake O' The Pines, Monticello, Welsh, Ellison Creek, Johnson Creek, and Caddo Lake (shared with Louisiana). One other reservoir, Lake Bob Sandin, is currently under construction.

The Sabine River basin is bounded on the north by the Sulphur River and Cypress Creek basins, on the west by the Trinity and Nueces River basins, and on the east by the Texas-Louisiana boundary. Maximum basin width is about 45 miles. The total basin drainage area is about 9,756 square miles, of which 7,426 square miles is in Texas (76.1%). In the northern portion, upland areas have dark calcareous, clayey soils which change gradually with depth to light marls or chalks. Bottomland soils are reddish brown to dark gray, slightly acid to calcareous, alluvial soils. Soils in the southern part of the Sabine River basin are similar to those in the Sulphur and Cypress Creek basins. Average runoff within about 97 percent of the Sabine River basin during the 1941-1967 period was about 640 acre-feet per square mile. In the southern-most part near Buna, average runoff in the 1953-1970 period was 687 acre-feet per square mile. There are 10 major reservoirs in this basin, nine of which are in the northern section, and one currently under construction (also in the north).

The Neches River basin is bounded on the north and east by the the Sabine River basin, on the west by the Trinity River basin, and on the south by the Neches-Trinity Coastal basin. The total drainage area is roughly 15,000 square miles. Light grayish brown to red, acid sandy loams and sands overlying gray, yellow, red sandy clay subsoils are characteristic of the upland areas. In the bottomlands, light brown to dark gray, acid to calcareous, alluvial soils occur. In the north, this basin is underlain by a thick sequence of southeasterly dipping beds of sand, clay, glauconite, and lignite of the Tertiary Wilcox and Claiborne Groups. These are overlain by sand, clay, silt, lignite, and volcanic ash beds of the Jackson and Catahoula Formations. The middle and lower reaches are underlain by a thick sequence of sedimentary rocks comprising the Fleming Formation. Also present are Pliocene and Pleistocene sequences as well as recent alluvium along streams. The average annual runoff during the 1941-1970 period was 522 acre-feet per square mile, and ranged from 930 acre-feet per square mile near the mouth of the Neches to about 400 acre-feet per square mile in the northwestern part of the basin. There are ten major existing or under-construction reservoirs located in the Neches River basin, seven in the north and three in the southern part.

The Trinity River basin is bounded on the north by the Red River basin, on the east by the Sabine and Neches River basins and the Neches-Trinity Coastal basin, and on the west by the Brazos and San Jacinto River basins and the Trinity-San Jacinto Coastal basin. The total basin drainage area is 17,969 square miles and approximately the central one-third lies within the Texas lignite belt. Land resource areas within thie basin include the North Blackland Prairies, East Texas Timberland, and Coastal Prairies and their associated soil and vegetation characteristics. The upper portions of the Trininty River basin are underlain by westerly dipping rocks of Permian and Pennsylvanian Age and are characterized by mudstone, claystone, limestone, and conglomerate. These Pennsylvania and Permian strata are unconformably overlain by southeasterly dipping Cretaceous rocks. The lower Cretaceous strata are fine-grained sands with small amounts of clay, silt, and limestone which grade upward into alternating clay and limestone layers. The upper Cretaceous rocks are primarily basal sand with some silty clay lenses, glauconite and carbonaceous material which grades upward into alternating clay and limestone layers. These rocks are overlain by Tertiary strata consisting of alternating sand and clay layers, with some iron cement, limestone, lignite, volcanic ash, glauconite and gravel. Above these are Pliocene and Pleistocene layers and Quaternary age alluvium in the streams. Average runoff for the 1941-1970 period was 310 acre-feet per square mile for the entire basin and ranged from 153 to 606 acre-feet per square mile from the upper to lower basin, respectively. There are 26 major reservoirs and two additional projects under construction in the Trinity River basin. Only three are within the lignite belt (Navarro Mills Lake, Cedar Creek Reservoir, and Lake Livingston).

The San Jacinto River basin plays a very small part in surface water availability for the Texas lignite belt. Of this 3,834 square mile drainage basin only portions of three important counties for lignite development--Grimes, Walker, and San Jacinto--are included in the San Jacinto River basin. This northern part of the basin is underlain by the Catahoula Formation, a south-easterly-dipping sandstone interbedded with volcanic ash and clay deposited during Oligocene times. Over this is a Miocene clay of the Fleming Formation and its overlying Pliocene and Pleistocene deposits. Recent alluvium occurs along streams. From 1941-1970, the average annual runoff for the entire area was about

440 acre-feet per square mile. There are no major reservoirs within the lignite belt counties.

The Brazos River basin is bounded on the north by the Red River basin, on the east by the Trininty and San Jacinto River basins, and the San Jacinto-Brazos Coastal basin and on the south and west by the Colorado River basin and the Brazos-Colorado Coastal basin. The total drainage basin area is 45,573 square mile of which about 43,000 square miles is in Texas (94.3%). Approximately 9,556 square miles (21%) of drainage area is non-contributing (no runoff). The south central portion of the Brazos River basin is important to lignite development. Here Pennsylvanian formations are overlain by a broad area of southeasterly dipping, Cretaceous limestone, clay and sandstone that are transected by the Balcones and the Luling-Mexia Fault Zones. The Cretaceous rocks are overlain by a thick sequence of southeasterly dipping clay, silt, sand, glauconite, and lignite beds of Tertiary Age. Above these are Pliocene and Pleistocene deposits and Recent alluvium occurs along streams and in some upland areas. Here soils range from dark, deep to shallow, stoney, calcareous clays to dark, neutral to slightly acid clay loams and clays. The average annual runoff for the 1941-70 period for the Brazos River basin was 156 acre-feet per square mile of contributing area and about 119 acre-feet per square mile for the total area. Most of the area in the High Plains is non-contributing. The average runoff ranged from about 530 acre-feet per square mile near the rivers' mouth to less than 50 acre-feet per year near the escarpment of the High Plains. There are 34 major reservoirs in the Brazos River basin and five more currently under construction. Of these, there are several within the lignite belt (Belton Lake, Stillhouse Hollow Lake, and Lake

Somerville).

The Colorado River basin is bounded on the north and east by the Brazos River basin and the Brazos-Colorado Coastal basin, and on the south and west by the Lavaca, Guadalupe, Nueces, and Rio Grande basins, and the Colorado-Lavaca Coastal basin. The total basin drainage area is 41,763 square miles, of which 39,893 square miles is in Texas. Only the southern portion of the Colorado River Basin is within the lignite belt and includes Travis, Bastrop, Fayette, and part of Hays counties. Soils in the Colorado River basin are similar to those in the Brazos River basin. The Cretaceous strata of this portion of the Colorado River basin grade from limestone and chalk to shale and clay. The Cretaceous rocks are transected by the Balcones Fault Zone and are overlain by Pliocene and Pleistocene layers and Recent alluvium is common along the streams. The average annual runoff from 1941 to 1970 was about 80 acre-feet per square mile in the contributing area. The average annual runoff ranges from about 350 acre-feet per square mile near the mouth of the Colorado to less than 50 acre-feet per square mile in the northern part of the basin. The Colorado River basin has 23 major reservoirs and two reservoirs currently under construction. Many of these are located in the southern third of the basin and are as such located near the lignite development area.

The Lavaca River basin is bounded on the north and east by the Colorado River basin, on the west by the Guadalupe River basin, on the southeast by the Colorado-Lavaca Coastal basin, and on the southwest by the Lavaca-Guadalupe Coastal basin. Drainage area of the basin is 2,309 square miles. Upland soils in the area of the basin included in the lignite belt are dark, calcareous, clay soils, changing gradually with depth to light marls or chalks. Bottomland soils are reddish-brown to dark gray, slightly acid to calcareous, alluvial deposits. This portion of the basin is underlain by gray clay of the Fleming Formation (Tertiary) which dips toward the Gulf. Overlying the Fleming are gravel, sand, silt, and clay of Pleistocene age. Recent alluvium occurs along the streams. Average annual runoff during the 1941-1970 period in the western and eastern parts of the Lavaca River basin was 236 and 325 acre-feet per square mile, respectively. Palmetto Bend I Reservoir, presently under construction by the Bureau of Reclamation, is the only major reservoir project of the Lavaca River basin.

The Guadalupe River basin is bounded on the north by the Colorado River basin, on the east by the Lavaca River basin and the Lavaca-Guadalupe Coastal basin, and on the west and south by the Nueces and San Antonio River basins. Total basin drainage area is 6,070 square miles and its central portion is included in the Texas lignite belt. Soils in the northern part of the basin vary from dark, calcareous clays and clayey loams in the uplands to dark, calcareous, clayey alluvial soils in the bottomlands. The central area's upland soils are either dark, calcareous, clayey soils or neutral to slightly acid clays to dandy loams, both of which change gradually with depth to marls or chalks. Bottomland soils in this area are reddish brown to dark gray, slightly acid to calcareous, loamy to clayey alluvial soils. The upper reach of the Guadalupe River basin is underlain by Cretaceous age limestone which forms the Edwards Plateau. East and south of the plateau are Upper Cretaceous chalk, limestone and clay. The Balcones Fault Zone distinguishes the Edwards Plateau from the Gulf Coast Plain. Cretaceous strata are overlain by a sequence of south-easterly dipping sand, silt, clay, glauconite, volcanic ash, and lignite of Tertiary age. These are, in turn, overlain by clay, silt, and sand of the Beaumont Formation (Pleistocene). Recent alluvium is common along streams within the basin and caps some upland areas. The average annual runoff in the southern part of the basin during the 1941-1970 period was 178 acre-feet per square mile. In the northeastern part of the basin the average annual runoff from 1960 to 1971 was 236 acre-feet per square mile. Canyon Lake, located on Comal County (part of the lignite belt) on the Guadalupe, is the only existing major reservoir in the basin containing conservation storage.

The San Antonio River basin is bounded on the north and east by the Guadalupe River basin and on the south and west by the Nueces River basin and the San Antonio-Nueces Coastal basin. The Total drainage area of the basin is 4,180 square miles. Soil types and general geology of the San Antonio River basin are the same as those of the Guadalupe River basin. The average annual runoff from 1955 to 1970 was about 150 acre-feet per square mile in the lower part of the basin, and from 1963-1970 it was about 185 acre-feet per square mile in the northern part of the basin near Boerne. Much of the runoff in the upper part of the basin enters the Edwards and associated limestones of the Balcones Fault Zone. Major reservoirs occur only in the northern part of the San Antonio River basin and these include: Medina Lake, Olmos Reservoir, Victor Braunig Lake, Calaveras Creek Reservoir, and Mitchell Lake.

The Nueces River basin is bounded on the north and east by the Colorado, Guadalupe, and San Antonio River basins and the San Antonio-Nueces Coastal basin, and on the west and south by the Rio Grande River basin and the Nueces-Rio Grande Coastal basin. Almost the entire Nueces River basin is included in the Texas lignite belt. The total basin drainage area is 16,950 square miles. The upland soils are dark, calcareous to slightly acid clays, loams, and sands. Bottomlands have brown to gray, calcareous, alluvial soils. The upper reach of the Nueces River basin is underlain by Cretaceous limestone which forms the Edwards Plateau. South of the plateau are younger Cretaceous chalk, clay and limestone beds. The entire sequence gently dips to the southeast. Much of the basin is underlain by a Tertiary sequence of southeasterly dipping sand, clay, silt, glauconite, volcanic ash, and lignite beds; and sand, clay, and gravel of the Goliad Formation. Overlying these are Pleistocene deposits and Recent alluvium is again common along the streams. In the Edwards Plateau area north of the Balcones Fault Zone, the average annual runoff during the 1941-1970 period was 118 acre-feet per square mile. In the eastern portion is was 88 acre-feet per square mile during the same time span. In the southwestern part of the basin the average annual runoff (1962-1970) was 74 acre-feet per square mile. The Balcones Fault Zone crosses this basin along an east-west line from San Antonio to Del Rio and a substantial part of the flows of the Nueces and its tributaries enter the fractured and cavernous limestone formations as they cross the fault zone. The only major reservoir in the Nueces River basin is Lake Corpus Christi and it is of little use as a source of water for lignite development.

The Nueces-Rio Grande Coastal basin is bounded on the north by the Nueces River basin and Corpus Christi Bay, on the west by the Rio Grande basin, and on the south by the Rio Grande River. The total drainage area is 10,442 square miles. Soils in this area vary from calcareous to neutral and clayey to sandy. Bottomlands have brown to gray, calcareous, alluvial soils. The regions of this coastal basin that are part of the Texas lignite belt are underlain by Tertiary sediments of the Fleming Formation and clay, sand, and gravel of the Goliad Formation. Average annual runoff during the 1968-1974 period was 23 acre-feet per square mile within the 480 square mile drainage area west of Falfurrias. The runoff declines in the area west of Alice and increases toward the north and east, but in all areas is less than 50 acre-feet per square mile. The nearest reservoir is Alice Terminal Reservoir near Alice in Jim Wells county (east of Duval county).

The Rio Grande River originates in southern Colorado, flows across New Mexico, and eventually forms the international boundary between the United States and Mexico. The total drainage area of the Rio Grande River basin is 182,215 square miles of which 88,968 square miles is in Texas. Soils common in the uplands range from light, reddish-brown to brown sands, clay loams and clays, to dark, calcareous stoney clays. The bottomlands have dark grayish-brown to reddish-brown, calcareous clay loams and clays. From Big Bend to the Gulf of Mexico the basin is underlain by a series of easterly dipping Cretaceous (limestone, clay, and sand), Tertiary (sand, silt, clay, lignite, and channel coal near Laredo), and Quaternary age formations. The average annual runoff from 1941 to 1970 was approximately 20 acre-feet per square miles in Mexico and Texas. However, amounts and rates vary greatly throughout the Rio Grande basin. Reservoirs, numerous diversions, and substantial return flows also modify the flow of the main channel. Furthermore upstream development has progressively reduced the flow of the Rio Grande as it enters Texas. Allocation of surface waters of the Rio Grande basin is governed by two interstate compacts and two international treaties. There are no major reservoirs in the northwestern portion of the Rio Grande basin; however, there are two in the northeastern area (Red Bluff Reservoir and Lake Balmorhea) and four further

TABLE 6. Water availability data on selected Texas streams in the lignite belt.

River	Locale	Average Discharge (cfs)	Average Discharge (ac-ft/yr)	Maximum Discharge (cfs)	Minimum Discharge (cfs)
N. Sulphur	Cooper, Delta-Lamar County line	252	182,600	15,000	0
S. Sulphur	Cooper, Hopkins-Delta County line	417	302,100	22,000	1
Sulphur	Talco, Red River-Titus County line	1520	1,101,000	37,100	2
Sabine	Wills Point, Van Zandt County	556	402,800	7130	0
Sabine	Ruliff, Newton County	7969	5,774,000	14,210	774
Kickapoo Creek (Neches)	Brownsboro, Henderson	143	103,600	2490	0
E.Fork Angelina	Cushing, Nacogdoches	105	76,070	2430	15
Neches	Evadale, Jasper-Hardin County line	5184	3,756,300	19,800	1780
E.Fork Trinity	Grandall, Kaufman County	645	567,300	9050	41
Trinity	Rosser, Ellis-Kaufman County line	2634	1,008,000	43,400	323
San Gabriel	Circleville, Williamson County	196	142,000	18,600	56
Navasota	Groesbeck, Limestone County	198	143,500	20,900	3
Colorado	Austin, Travis County	2071	1,500,400	24,000	4198
Lavaca	Halletsville, Lavaca County	48	34,630	5280	4
Navidad	Halletsville, Lavaca County	159	115,200	12,600	15
Comal	New Braunfels, Comal County	291	210,800	2890	360
San Marcos	San Marcos, Hays County	165	119,500	316	167
San Antonio	San Antonio, Bexar County	53	38,040	930	26
San Antonio	Falls City, Karnes County	359	260,100	7350	297
W. Nueces	Bracketville, Kinney County	33	26,950	12	0
Frio	Uvalde, Uvalde County	25	18,690	317	0
Atascosa	Whitsett, Live Oak County	135	97,810	9500	5

(Texas Water Development Board Reports and United States Geological Survey Reports) downstream including San Estaban Lake, International Amistad Reservoir, Casa Blanca Lake, and International Falcon Reservoir.

Reservoirs. Storage of surface water in reservoirs allows some control of allocation over periods of time. During a year or several years, excess water from wet periods can be held for use in dry period. The "firm yield" of a reservoir is the "maximum amount of water that can be supplied continuously by a reservoir under conditions of the driest and most severe drought period known to have occurred at that site" (McNeely and Lacewell, 1978). Evaporation, leakage, infiltration, and evapotranspiration decrease the firm yield as storage capacity is decreased by sedimentation.

The ratio of storage capacity to firm yield varies widely throughout the state of Texas. In west Texas, storage capacity may be ten to thirteen times the firm yield while the humid climate in east Texas allows firm yield to equal or surpass storage capabilities of a reservoirs.

Sixty-three major reservoirs represent 95% of Texas reservoirs with over 5000 acre-feet storage capacity. Twenty-nine of these either lie within or closely border the lignite belt (Fig. 14). Estimates of storage conservation capacity and flood control storage capacity as well as the owner and/or operator are provided in Table 7.

Groundwater

The Texas Water Code defines groundwater as "water percolating below the surface of the earth and that is suitable for agricultural, gardening, domestic, or stock raising purposes but does not include defined subterranean streams or the under flow of rivers." Groundwater is one of Texas' major natural resources, however, heavy pumping has caused many problems throughout the state: land subsidence, saltwater encroachment, rapid depletion of groundwater in the driest areas, and increased pumping costs.

1. Pat Mayse Lake
2. Lake Sulphur Springs
3. Wright Patman Lake
4. Lake Cypress Springs
5. Lake O' the Pines
6. Lake Tawakoni
7. Toledo Bend Reservoir
8. Lake Palestine
9. Lake Tyler
10. Sam Rayburn Reservoir
11. B. A. Steinhagen Lake
12. Lavon Lake
13. Lake Ray Hubbard
14. Cedar Creek Reservoir
15. Navarro Mills Lake
16. Bardwell Lake
17. Lake Livingston
18. Lake Conroe
19. Whitney Lake
20. Belton Lake
21. Stillhouse Hollow Lake
22. Somerville Lake
23. Lake Buchanan
24. Lake Travis
25. Canyon Lake
26. Medina Lake
27. Lake Corpus Christi
28. Intl. Amistad Reservoir
29. Intl. Falcon Reservoir

Figure 14. Reservoirs within or bordering the Texas lignite belt (storage capacity 5000+ acre-feet).

TABLE 7. Storage capacities, flood control storage capacities, and owner/operators of reservoirs within or bordering the Texas lignite belt.

Basin	Reservoir	Owner and/or Operator	Storage Capacity (acre-feet)	Flood Control Storage Capacity (acre-feet)
Red River	Pat Mayse Lake	Corps of Engineers	124,500	64,600
Sulphur River	Lake Sulphur Springs	Sulphur Springs Water District	13,250	0
	Wright Patman Lake	Corps of Engineers	142,700	2,506,000
Cypress Creek	Lake Cypress Springs	Franklin Co. Water Dist.-48.4%, Texas Water Dev. Board-51.6%	66,800	0
	Lake O'the Pines	Corps of Engineers	252,000	587,200
Sabine River	Lake Tawakoni	Sabine River Authority	936,200	0
	Toledo Bend Reservoir	Sabine River Authority of Texas and Louisiana	4,472,900	0
Neches River	Lake Palestine	Upper Neches River Municipal Authority	411,300	0
	Lake Tyler	City of Tyler	73,700	0
	Sam Rayburn Reservoir	Corps of Engineers	2,876,300	1,145,000
	B.A. Steinhagen Lake	Corps of Engineers	94,200	0
Trinity River	Lake Ray Hubbard	City of Dallas	490,000	0
	Cedar Creek Reservoir	Tarrant Co. Water Control and Improvement Dist. No. 1	679,200	0
	Lake Livingston	City of Houston and Trinity River Authority	1,750,000	0
Trinity River	Lavon Lake	Corps of Engineers	129,300	279,800
	Navarro Mills Lake	Corps of Engineers	60,900	148,900
	Bardwell Lake	Corps of Engineers	53,580	85,100
San Jacinto River	Lake Conroe	San Jacinto River Authority-13.15%, City of Houston-66.67%, Texas Water Dev. Board-20.18%	429,900	0
Brazos River	Lake Buchanan	Lower Colorado River Authority	955,200	0
	Whitney Lake	Corps of Engineers	622,800	1,620,400
	Belton Lake	Corps of Engineers	457,300	887,000
	Stillhouse Hollow Lake	Corps of Engineers	234,900	394,700
	Somerville Lake	Corps of Engineers	160,100	347,400

TABLE 7. (cont.)

Basin	Reservoir	Owner and/or Operator	Storage Capacity (acre-feet)	Flood Control Storage Capacity (acre-feet)
Colorado River	Lake Travis	Lower Colorado River Authority	1,144,100	778,000
San Antonio River	Medina Lake	Bexar-Medina-Atascosa Counties Water Improvement Dist. No. 1	254,000	0
Guadalupe River	Canyon Lake	Corps of Engineers	385,600	354,700
Nueces River	Lake Corpus Christi	Lower Nueces River Water Supply District	269,900	0
Rio Grande River	International Amistad Reservoir	Owner-U.S. and Mexico. Operator-International Boundary and Water Commission	1,563,200	613,100
	International Falcon Reservoir	Owner-U.S. and Mexico. Operator-International Boundary and Water Commission	1,563,200	613,100
TOTAL			21,069,600	11,556,200

(Texas Water Development Board, Water for Texas, Vol. 6, No. 4, April 1976)

Presently, management of groundwater resources occurs on a local basis for local objectives and this has been supported by Texas state law. The effects of groundwater depletion occur slowly and do not affect all users at one time, therefore action to regulate use statewide all but stands still. State agencies merely study the situation and collect data because they have no regulatory control. In 1979, the Texas legislature created the Underground Water Conservation District plan which would, if the district voted to adopt it, be able to regulate consumption of groundwater within that district. Only five regions adopted the plan and of those, none regulates production of water from wells directly.

Aquifers. Most of the groundwater in Texas is located in relatively few aquifers. Within the lignite belt are located all or part of four major aquifers: the Trinity Group, the Carrizo-Wilcox, the Gulf Coast, and the Edwards (Balcones Fault Zone); and three minor aquifers: the Woodbine, the Queen City, and the Sparta (Figs. 15 and 16). Following is a general description of these aquifers, their water-bearing properties, and the amounts of water available.

The Trinity Group aquifer is made up of the Paluxy, Glen Rose, and Travis Peak Formations of Cretaceous age. These rocks extend over a large area of north and central Texas, but are only found along the upper northwest edge of the lignite belt. They are composed of sand with interbedded clays, limestone, dolomite, gravel, and conglomerates. The aquifer dips toward the southeast and reaches a thickness of 1000-1200 feet where it is found within the lignite belt. Wells in this part of the aquifer can produce up to 2000 gallons per minute. Infiltration of precipitation, seepage of surface water, and return flows of irrigation water are the main forms of recharge to the aquifer. Artesian

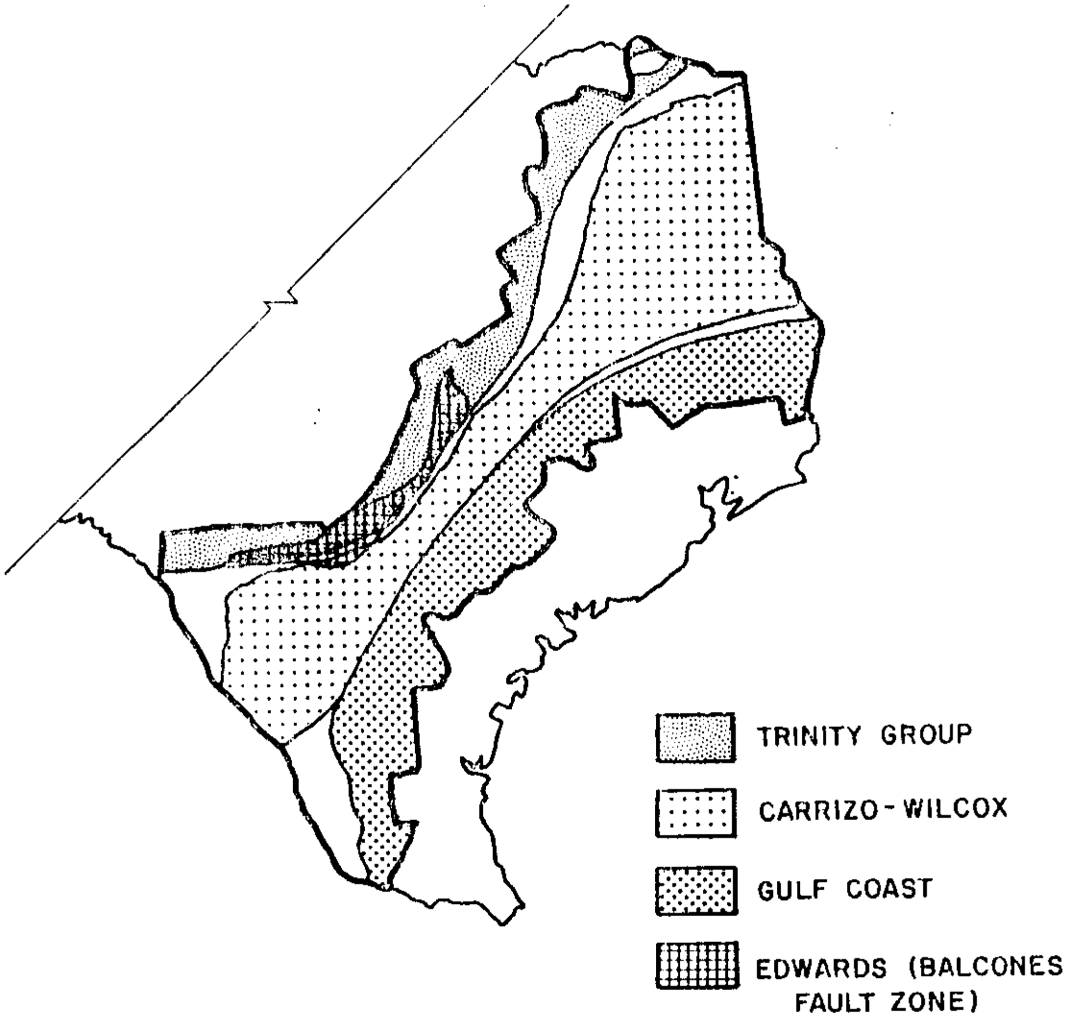

Figure 15. Major aquifers within the Texas lignite belt.

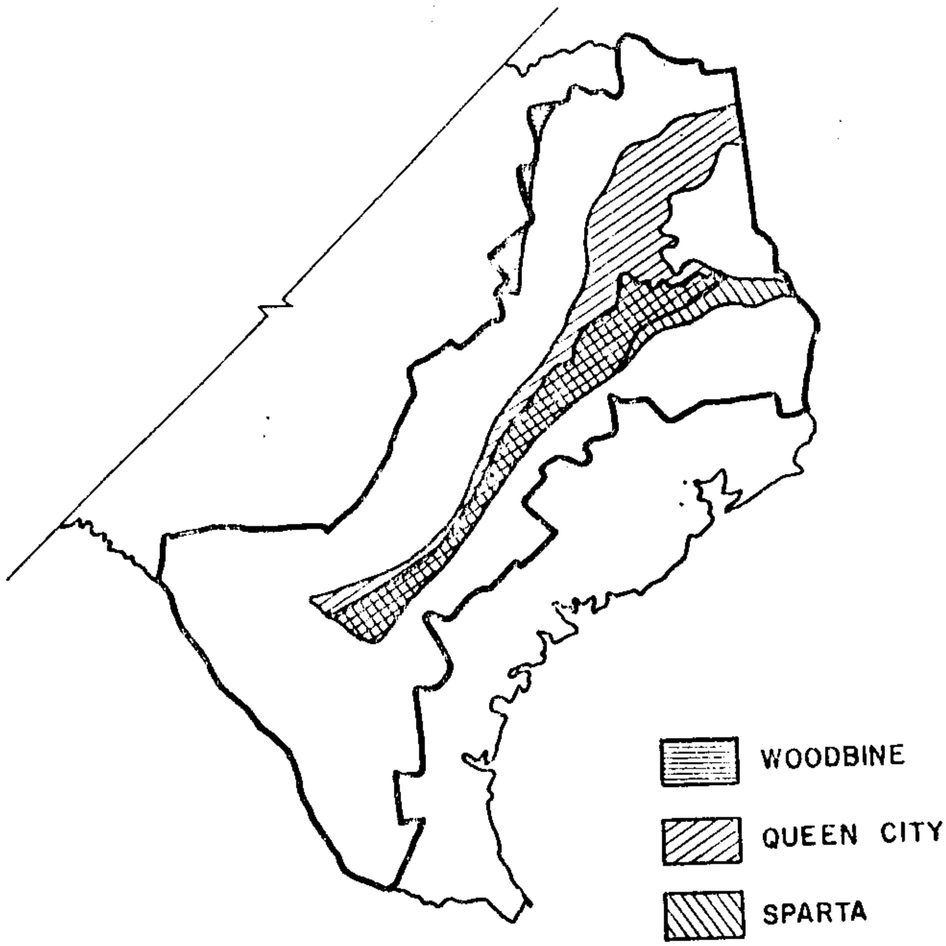

Figure 16. Minor aquifers within the Texas lignite belt.

pressure conditions exist in the downdip area and water quality is acceptable with the exception of excess fluoride at shallower depths.

The Trinity Group aquifer has been severely overdrawn in some areas and water levels overall are declining because withdrawal exceeds effective recharge. Low transmissibility further limits recharge rates. The declining water levels cause encroachment at the salt-fresh interface and increased pumping costs.

Total average groundwater availability for the aquifer has been estimated at 114,000 acre-feet, including volume of water recoverable from storage and annual effective recharge. The annual effective recharge was estimated at 95,100 acre-feet (Muller and Price, 1979).

The Carrizo-Wilcox aquifer forms a wide, northeast trending band extending from the the Rio Grande River the full length of the lignite belt into Arkansas and Louisiana. It is made up of cross-bedded sands with clay, silt, lignite, and gravel of the Wilcox Group and Carrizo Formation of Eocene age. Recharge comes mainly from precipitation and streams that cross the outcrop. The aquifer dips to the southeast except in far east Texas where it dips away from the structural high of the Sabine Uplift; it ranges in thickness from 150 to 3000 feet. Downdip wells are artesian and may yield up to 3000 gallons per minute.

Large withdrawals on the aquifer have lowered water levels and artesian pressure, resulting in leakage between beds and encroachment of poorer quality water. Saline water from the overlying Bigford Formation is contaminating the aquifer through old boreholes. In some areas, reversal of hydraulic gradient has caused a shift in the salt-fresh interface.

The overall quality of Carrizo-Wilcox water is acceptable and fresh to slightly saline. It ranges from hard water, low in dissolved solids on the outcrop, to soft, warmer water, with more dissolved solids in the downdip area. High iron content, hydrogen sulfide, and methane gas are found locally.

The Carrizo-Wilcox has an estimated average annual availability of groundwater of 847,600 acre-feet. Total annual effective recharge is estimated at 644,900 acre-feet (Muller and Price, 1979).

The Gulf Coast aquifer includes the eastern lowermost edge of the lignite belt. The Miocene to Holocene formations making up the aquifer are beds of clay, silt, sand, and gravel which alternate to form a leaky, artesian system. Water quality in this part of the aquifer is better than further south, with 500 mg/l being common for dissolved solids. High quality water can be found to depths of 3200 feet. The aquifer sediments reach 1300 feet thick in this area and wells may produce up to 1600 gal/min.

Unique problems exist relating to excessive withdrawal of water from the Gulf Coast aquifer; a) subsidence of the land surface due to compaction of water bearing clays, b) increase in chloride content to the southwest, and c) encroachment of salt water at the coastline. Two minor aquifers, within the Gulf Coast aquifer, the Chicot and Evangeline, are located in the lignite belt. Pumpage from these two aquifers has been directly related to land-surface subsidence in Houston, Texas, with water derived from clay compaction being nearly equal to the amount of subsidence (Jorgensen, 1975).

A digital computer model was developed by Muller and Price to evaluate long-term supply capabilities of the Gulf Coast aquifer based on simulations of pumpage, water level declines, and land-surface subsidence. From this, a perpetual annual effective recharge of 1.23 million acre-feet was estimated. Approximately 4% of the mean annual rainfall on the outcrop would be needed to support this amount of recharge (Muller and Price, 1979).

The Cretaceous-age Edwards (Balcones Fault Zone) aquifer consists of massive to thin-bedded, cherty, nodular, argillaceous grayish-white limestones and dolomites of the Georgetown, Edwards, and Comanche Peak Formations. It is found in the uppermost western half of the lignite belt and ranges from 200-600 feet thick. Yielding large amounts of fresh water, the Edwards Limestone is extensively honeycombed and cavernous due to solution channeling. This aquifer produces wells yielding up to 16,000 gal/min.

The Edwards aquifer is recharged by infiltration of precipitation and stream water on the outcrop mainly through crevices and faults in the Balcones Fault Zone. Some groundwater enters the aquifer laterally from the Glen Rose Formation. Water within the aquifer is discharged through natural springs in addition to hundreds of wells. It moves rapidly through the aquifer where volume and flow rate respond quickly to precipitation. Water quality is good overall.

A digital computer model was also developed for the Edwards aquifer which included simulations of pumpage, recharge, areal distribution of water levels, and major spring flows. Average annual groundwater availability for the aquifer was estimated to be 438,700 acre-feet (Muller and Price, 1979).

The sands of the Woodbine aquifer cover a small area on the northern edge of the lignite belt where they are 600 feet thick at 2000 feet of depth. Wells yield from 100 to 700 gal/min and water is mainly a sodium bicarbonate type, high in dissolved solids, sulfate, fluoride, and chloride. Groundwater availability is estimated to be about 26,100 acre-feet annual (Muller and Price, 1979).

Located in the northeastern part of the lignite belt, the Eocene-age Queen City aquifer is made up of sand, loosely cemented sandstone, and clays. Although it dips slightly southeast, most of the aquifer is exposed at the surface. It reaches a thickness of 500 feet, but due to low transmissibility does not transmit large quantities of water. Wells usually produce less than 400 gal/min. Quantities of dissolved solids are usually low, while acidity, iron concentrations, and hydrogen sulfide may be locally high. Average annual groundwater availability is approximately 682,000 acre-feet (Muller and Price, 1979).

The Eocene-age Sparta aquifer is also located in the northeastern part of the lignite belt slightly south of the Queen City aquifer. Over thicknesses of 100 to 300 feet, the aquifer consists of sands and interbedded clays which dip south and southeast. Large wells yield 400 to 500 gal/min; water is slightly saline, low in dissolved solids, and locally high in iron content. Groundwater availability is estimated to be 163,800 acre-feet per year (McMullen and Price, 1979).

In Table 8 are found estimates of groundwater availability for aquifers within the Texas lignite belt by river basin. Also listed are projected availability through 2030 and estimated remaining recoverable storage as of 2031. Totals for each aquifer are computed at the end of the table.

In order to contour the groundwater hydrology of the lignite belt, the area encompassed by both major and minor aquifers was drawn onto a large base map. Then the water availability values for each county as determined by the Texas Water Development Board studies were added (Table 9). Since groundwater availability values represented a county-wide average, the center of aquifer extent in each county was used as the contour point. In counties with two aquifers, one overlying the other,

TABLE 8. Estimates of groundwater availability in the Texas lignite belt by basin.

Basin	Aquifer	Groundwater Availability: Effective Recharge (acre-feet)	Groundwater Availability: 1974 Recoverable (acre-feet)	Projected Average Annual Groundwater Availability (storage, depletion, and effective recharge) in acre-feet: 1980 - 2029	Projected Average Annual Groundwater Availability (storage, depletion, and effective recharge) in acre-feet: 2030	Remaining Recoverable Storage, 2031 (acre-feet)
Red River	Trinity Group	3700	57,200(2)	4800	3700	0(3)
	Woodbine	14,000	(1)	14,000	14,000	---
Sulphur River	Trinity Group	0(4)	68,400	1300	0(4)	0(3)
	Carrizo-Wilcox	4000	3000(5)	4100	4000	0(3)
	Woodbine	(1)	(1)	---	---	---
	Queen City	7000(6)	(1)	7000	7000	---
Cypress Creek	Carrizo-Wilcox	15,000	42,400(5)	15,800	15,800	0(3)
	Queen City	234,500(6)	(1)	234,500	234,500	---
Sabine River	Trinity Group	0(4)	23,200(5)	400	0(4)	0(3)
	Carrizo-Wilcox	44,000	75,500(5)	45,400	44,100	0(3)
	Gulf Coast	54,000	(1)	54,000	54,000	---
	Queen City	137,800(6)	(1)	137,800	137,800	---
	Sparta	7400(7)	(1)	7400	7400	---
Neches River	Carrizo-Wilcox	150,000	237,700(2)	154,500	150,000	0(3)
	Gulf Coast	101,000	(1)	101,000	101,000	---
	Queen City	261,300(6)	(1)	261,300	261,300	---
	Sparta	54,400(7)	(1)	54,400	54,400	---
Trinity River	Trinity Group	45,500	466,200	54,300	45,500	0(3)

TABLE 8. (cont.)

	Carrizo-Wilcox	79,000	217,600	83,000	79,000	0(3)
	Gulf Coast	61,400	(1)	61,400	61,400	---
	Woodbine	11,100	(1)	11,100	11,100	---
	Queen City	15,000	(1)	15,000	15,000	---
	Sparta	35,000	(1)	35,000	35,000	---
San Jacinto River	Gulf Coast	337,000	(1)	337,000	337,000	---
Brazos River	Trinity Group	32,600	340,300(2)	39,000	32,600	---
	Carrizo-Wilcox	129,300	184,400(2)	132,800	129,300	0(3)
	Gulf Coast	51,400	(1)	51,400	51,400	---
	Edwards	5000	(1)	5000	5000	---
	Woodbine	1000	(1)	1000	1000	---
	Queen City	2700	(1)	2700	2700	---
Colorado River	Trinity Group	13,300	52,600(2)	14,300	13,300	0(3)
	Carrizo-Wilcox	49,200	46,900(2)	50,100	50,100	0(3)
	Gulf Coast	26,000	(1)	26,000	26,000	---
	Edwards	8700	(1)	8700	8700	---
	Queen City	3700	(1)	3700	3700	---
	Sparta	10,000	(1)	10,000	10,000	---
Lavaca River	Gulf Coast	86,000	(1)	86,000	86,000	---
Guadalupe River	Trinity Group	20,000(9)	(1)	---	---	---
	Carrizo-Wilcox	38,600	476,400(10)	46,500	38,600	0(3)

TABLE 8. (cont.)

	Gulf Coast	21,000	(1)	21,000	21,000	---
	Edwards	38,200(13)	(1, 8)	38,200	38,200	---
	Queen City	8000	(1)	8000	8000	---
	Sparta	20,000	(1)	20,000	20,000	---
San Antonio River	Trinity Group	1100(9)	(1)	---	---	---
	Carrizo-Wilcox	43,400	1,035,500(11)	60,700	43,400	0(3)
	Gulf Coast	13,000	(1)	13,000	13,000	---
	Edwards	285,100	(1, 8)	285,100	285,100	---
	Queen City	3600	(1)	3600	3600	---
	Sparta	10,000	(1)	10,000	10,000	---
Nueces River	Trinity Group	(1, 9)	(1)	---	---	---
	Carrizo-Wilcox	78,700	9,573,500(11)	238,300	78,700	0
	Gulf Coast	14,000	(1)	14,000	14,000	---
	Edwards	101,700	(1, 8)	101,700	101,700	---
	Queen City	8500	(1)	8500	8500	---
	Sparta	20,000	(1)	20,000	20,000	---
Rio Grande River	Carrizo-Wilcox	13,700	160,300(12)	16,400	13,700	0(3)
	Gulf Coast	114,000	(1)	114,000	114,000	---
Nueces-Rio Grande Coastal	Gulf Coast	115,000	(1)	115,000	115,000	---

(1) Not determined.
(2) Confined storage.
(3) An undetermined amount will be in artesian storage in January 2031.
(4) All of the average annual availability is from artesian storage.

TABLE 8. (cont.)

(5) Recoverable artesian storage in 1976.
(6) Groundwater is corrosive (low pH), has high iron concentrations, generally exceeding 0.3 mg/liter.
(7) Groundwater has very high iron concentrations, locally exceeding several mg/liter.
(8) Pumpage from aquifer directly depletes surface supplies.
(9) Extensive development of the natural recharge or storage of the aquifer in the zone or basin would cause a decrease in the base flow of streams and underflow to the Edwards (Balcones Fault Zone) aquifer, thus affecting the natural recharge to that aquifer.
(10) Recoverable artesian storage available from 1970 to 2030.
(11) Recoverable storage for 1970.
(12) Recoverable artesian storage in 1970.
(13) An additional 34,000 acre-feet would be available as annual effective recharge had not constraints been used to provide minimum spring flow at San Marcos Springs to maintain the environment of that area.

(Muller and Price, 1979)

TABLE 9. Groundwater availability by county, 1976.

County	Report or Bulletin	Millions of Gallons Per Day
Anderson, Cherokee, Freestone Henderson	R. 150	68
Angelina, Nacogdoches	R. 110	54
Atascosa, Frio	R. 32	no data
Bastrop	R. 109	no data
Bell	B. 5902	no data
Bexar	B. 5911	210
Brazos, Burleson	R. 185	57
Caldwell	R. 12	50
Camp, Franklin, Morris, Titus	B. 6517	8 - 9
Cass, Marion	R. 135	15
Comal	B. 5610	no data
De Witt	B. 6518	55 - 90
Dimmit	B. 6002	22
Duval	R. 181	23
Falls	R. 41	no data
Fayette	R. 56	49
Gonzales	R. 4	150
Gregg, Upshur	R. 101	6.8
Grimes	R. 186	52
Guadalupe	R. 19	40 at least
Harrison	R. 27	49 at least
	B. 6004	no data
Houston	R. 18	46
Jasper, Newton	R. 59	500
Karnes	B. 6007	1.7 at least
Kinney	B. 6216	no data
LaSalle, McMullen	B. 6520	80
Lee	R. 20	12 - 40
Leon	B. 6513	76
Live Oak	B. 6105, 6301	2.15 at least
Medina	B. 5601	80
Milam	R. 41	no data
Navarro	R. 160	1.3 at least
Polk	R. 82	46
Rains, Van Zandt	R. 169	4.5
Robertson	R. 41	no data
Sabine, San Augustine	R. 37	44 - 165
San Jacinto	R. 80	35
Smith	B. 6302	52
Starr	B. 5209	no data
Travis	B. 5612, 5708	no data
Tyler	R. 74	62
Uvalde	B. 6212	178
Walker	B. 5003	no data
Washington	R. 162	27.3 at least
Webb	R. 70	no data

TABLE 9. (cont.)

County	Report or Bulletin	Millions of Gallons Per Day
Williamson	B. 5612	no data
Wilson	B. 5610	4 at least
Wood	R. 79	47
Zavala	R. 70	no data

(Texas Water Development Board Publications) the center of the area of overlap was assigned the water availability value. Thus it was possible to contour groundwater hydrology in accordance with aquifer geology and to obtain reasonable estimates of water availability in counties that have not as yet been surveyed by the Texas Water Development Board (Fig. 17 - in pocket).

Climate

Climatic conditions affect local water tables as well as water availability and future domestic, industrial and agricultural needs. Texas has a variety of climates ranging from humid in the east to arid in the west. While the climatic conditions of the eastern sector of the state generally support ample water supplies for present needs, the western sector has little or no water reserves.

Precipitation

Most of the water used in Texas comes from the Gulf of Mexico and includes the sum of rainfall, sleet, hail and snow in one year expressed in inches of water (Texas Natural Resources, 1959). The mean annual precipitation for the state was 28.04 inches for the period 1941-1970, however, the distribution is not even. The far Trans-Pecos region of the west received 8 inches while far east Texas received over 56 inches (average annual rainfall can also be measured in acre-feet which is equivalent to 325,851 gallons). Measured average annual rainfall over Texas for the period 1924-1956 was 360 million acre-feet (1370 acre-feet per square mile). An annual average of 413 million acre-feet was reported in 1968 by the Texas Water Development Board. Figure 18 contours mean annual precipitation rates for the Texas Lignite Belt in acre-feet per square mile. Precipitation varies approximately one inch per 15.5 miles with a decrease from east to west.

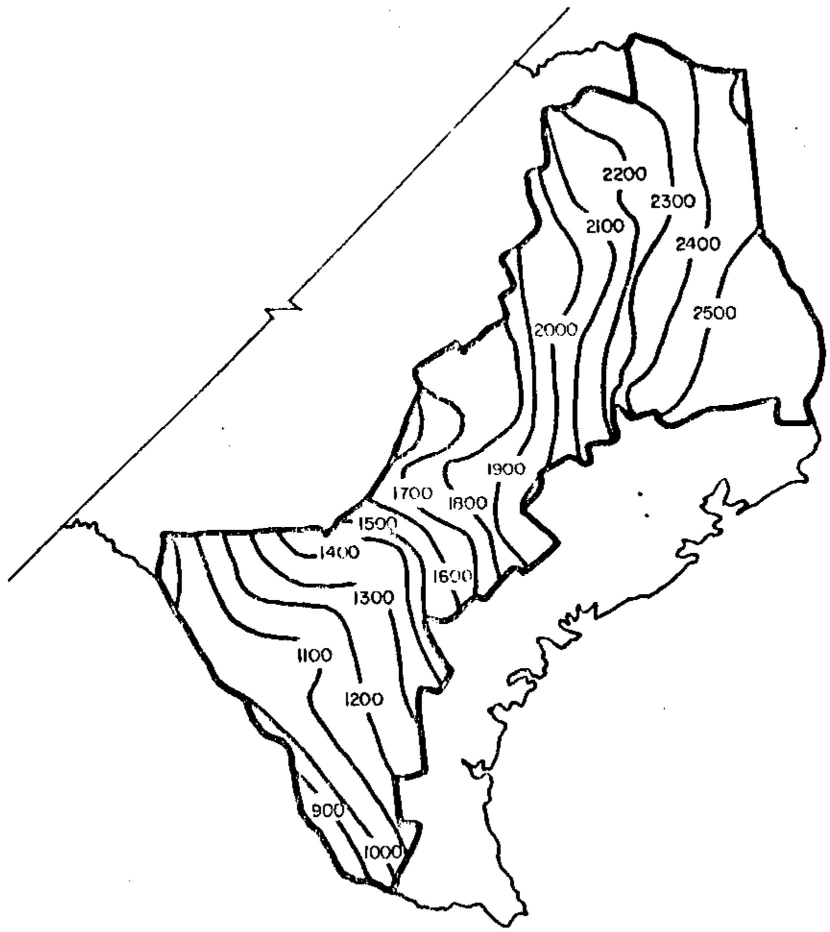

Figure 18. Mean annual precipitation in acre-feet per square mile.

"Average" rainfall seldom actually occurs. The nation's greatest short period storm rainfall was recorded in Texas. A long wet period lasting seven years occurred between 1940-1946. During this seven year period measured average rainfall of 33 inches annually exceeded the long term average by nearly 20%. In one year a total of 556 million acre-feet fell - 154% of the long-term average. Twelve drought periods have been recorded since 1891 with the 1950-56 drought averaging only 22 inches of rainfall per year - 80% of the long term average. In essence, shift in short-period climate had occurred causing a 200 mile displacement in which the humid climatic region was partially replaced by a semi-arid climate and a semi-arid climatic region was partially replaced by an arid one (Lowry, 1958)

Using average rainfall figures can also be misleading without the specifications of time and place. Annual rainfall in extreme west Texas is less than 10 inches while extreme portions of east Texas register more than 50 inches annually. Figures 11 and 18 show lines of equal rainfall trending in a north - south direction with precipitation increasing in the east. Table 10 gives annual precipitation rates for the climatic regions of the Texas lignite belt for the years 1941-1970. Figure 19 graphically depicts average monthly precipitation for the years 1931-1960 (Carr, 1967).

<u>Movement of Air Masses</u>

The interaction of two major air masses controls moisture distribution in Texas. Warm, moist air from the Gulf of Mexico moves in a northerly direction, while cold air masses move from the northwest of Texas (Fig. 20). Cold air movements dominate during winter months and contribute to the seasonal moisture variations in Texas. The major

TABLE 10. Mean precipitation in Texas by climatological divisions.[1]

Climatological	Average Annual Precipitation	Wettest Month		Driest Month	
North Central	32.94	May	4.65	January	1.93
East	45.37	May	5.34	August	2.81
Edwards Plateau	23.94	September	3.22	December	1.18
South Central	33.03	September	4.32	March	1.84
Southern	21.95	September	3.56	March	0.80

[1]Precipitation, in inches, is based upon average monthly precipitation totals observed for the period 1941-1970 for each climatological division of Texas.

(U.S. Department of Commerce, Climatology of the United States No. 81)

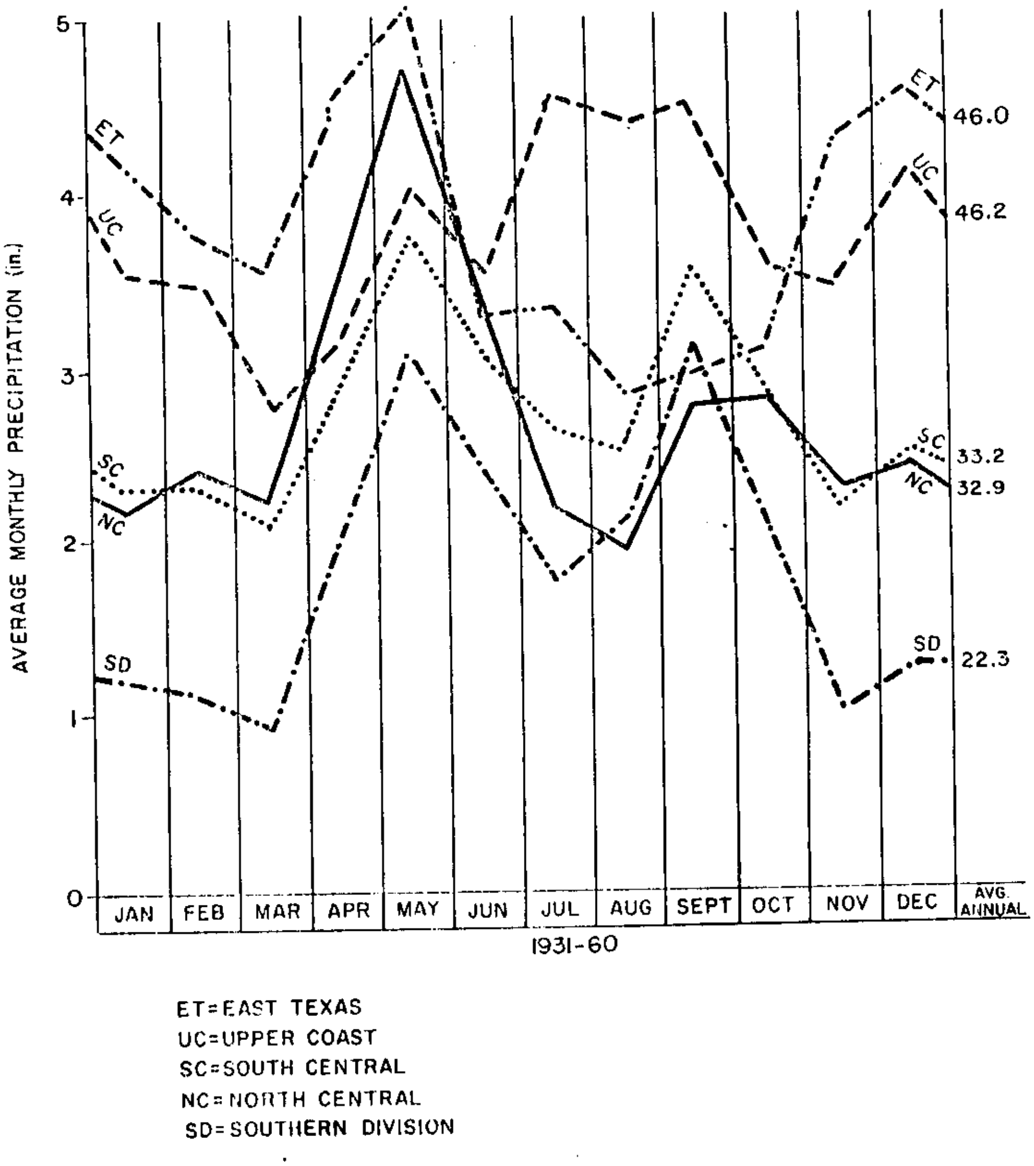

Figure 19. Average monthly precipitation in selected areas of Texas, 1931-1960.

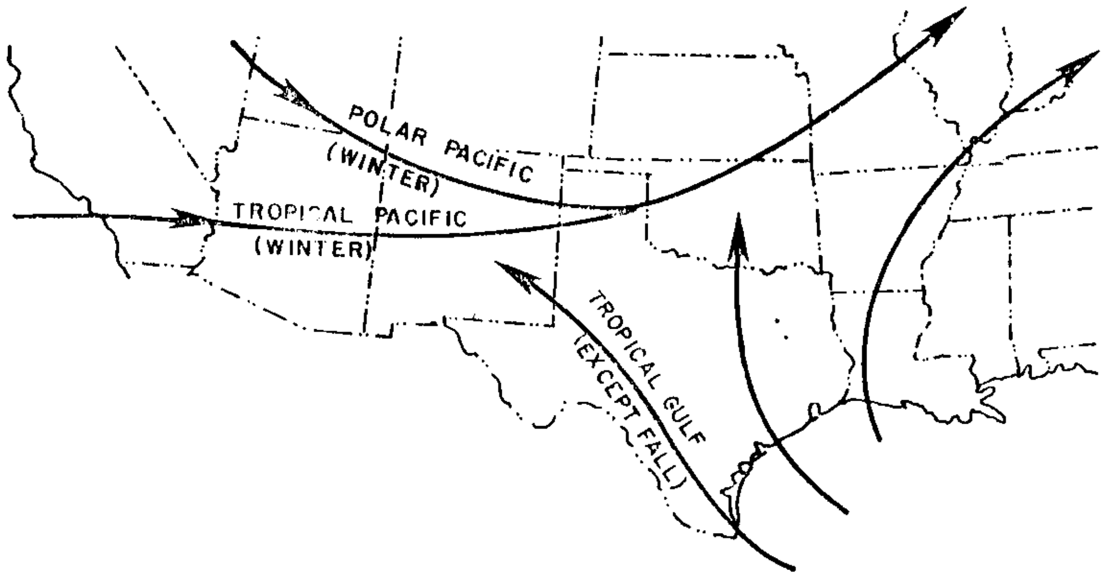

Figure 20. Movement of air masses in Texas.

precipitation producing mechanisms along the Texas Gulf Coast are seasonal and include: fronts, troughs in westerly winds, waves in easterly winds, tropical storms and thunderstorms (Carr, 1967). South Texas tends to be dry due to its distance from the interaction of the two air masses. East Texas, on the other hand, is moist because of its proximity to a moisture source as well as the interaction of the two air masses.

Temperature

Average January and July temperatures for the climatic regions of the Texas lignite belt are listed in Table 11. The range between daily maximum and minimum temperatures and temperature spread between the coldest and warmest months generally increase with distance from the Gulf of Mexico and with latitude. Mean annual temperature is shown in Figure 21.

Evaporation and Transpiration

Evaporation is "the climatic process by which moisture is picked up from any source and transported as vapor to other locations by wind movement" (Kane, 1967). Water evaporates from open bodies of water such as a reservoir, lake, or stream and also from the soil. The evaporation rate of a saturated soil is nearly equal to that of an adjacent body of water. Evaporation, which is inversely proportional to rainfall, will occur at a faster rate during dry periods and therefore significantly affect water supplies. Contours of net lake surface evaporation are shown in Figure 22. Net lake surface evaporation is actual evaporation loss calculated by subtracting effective rainfall from gross lake surface evaporation.

Transpiration is the process through which water vapor is transferred

TABLE 11. Ranges in temperature, in degrees Fahrenheit, at selected Texas cities.[1]

City	January			July		
	Average Minimum	Average Maximum	Average	Average Minimum	Average Maximum	Average
Dallas-Fort Worth	33.9	55.7	44.8	74.0	95.5	84.8
Denison	31.5	53.3	42.3	72.3	94.6	83.5
Jacksboro	32.5	57.7	45.2	72.6	96.9	84.8
Waco	36.6	57.4	47.0	75.0	96.2	85.6
Longview	35.2	56.9	46.2	72.4	94.4	83.5
Lufkin	38.2	60.0	48.8	71.9	94.3	83.0
Palestine	37.0	56.8	46.8	72.3	93.9	83.0
Del Rio	38.1	63.4	50.8	74.2	99.2	86.7
Llano	33.1	60.0	46.6	72.4	97.9	85.4
San Angelo	33.6	59.1	46.4	72.4	96.9	84.7
Austin	39.3	60.0	49.7	73.7	95.4	84.6
Corpus Christi	46.1	66.5	56.3	75.2	94.4	84.8
San Antonio	39.8	61.6	50.7	73.8	95.6	84.7
Smithville	38.0	62.1	50.7	72.6	96.3	84.5
Eagle Pass	38.2	64.3	51.3	74.9	100.4	87.8

[1]Average temperatures are the arithmetic means of daily minimum and maximum temperatures observed during the respective months for the period 1941-1970.

(Environmental Data Service, Climatological Data: Texas)

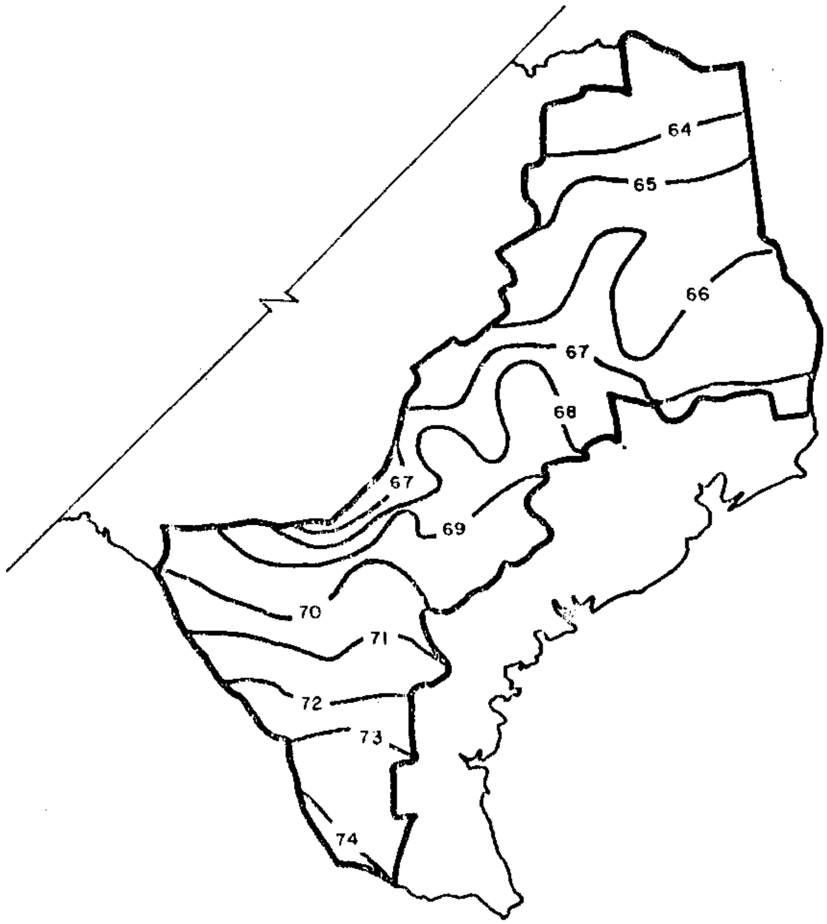

Figure 21. Mean annual temperature in degrees fahrenheit in the Texas lignite belt.

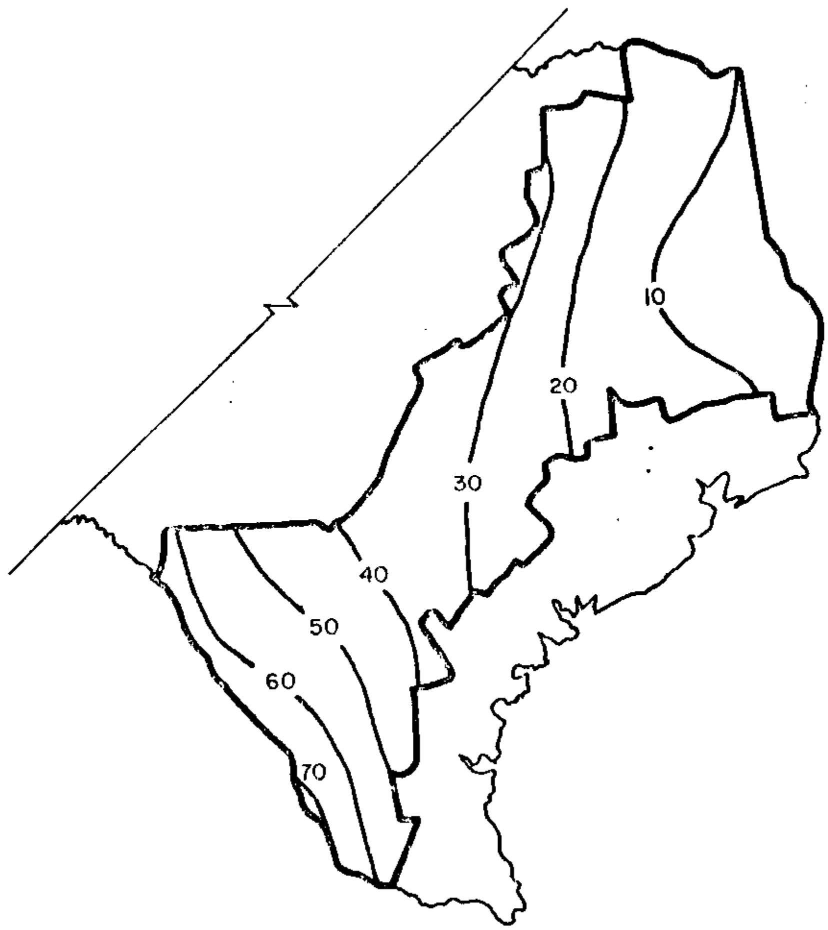

Figure 22. Net lake surface evaporation in inches.

into the atmosphere by plants. The amount of water lost through transpiration depends upon the character and density of the vegetation and atmospheric conditions (Thornthwaite, 1942). The amount of water removed from a field by transpiration will depend on the water requirements of the vegetation and growth which, in turn, may be limited by the availability of water. Vegetation bulk increases as some power of the annual precipitation. In addition, vegetation changes from desert shrub to grassland to forest with increased precipitation.

Total evaporation or the combination of evaporation and transpiration is important when considering the hydrologic balance of an area. Thornthwaite (1942) introduced the concept of potential evapotranspiration on the assumption that any reduction in evapotranspiration brought about by a deficiency of soil moisture is independent of meteorological conditions. Potential evapotranspiration is the amount of water that would evaporate and transpire were it available rather than the quantity of water that actually does evaporate and transpire (Fig. 23).

Thornthwaite (1948) developed a classification system to determine climatic boundaries rationally rather than empirically by comparing precipitation and potential evaporation and formulated a moisture index for the United States based on indices of humidity and aridity.

Thornthwaite's moisture index is:

$$I_m = I_n - .6Ia$$

where:

$$I_n = \frac{100s}{n}, \quad I_a = \frac{100d}{d}$$

and

s = water surplus

d = water deficiency

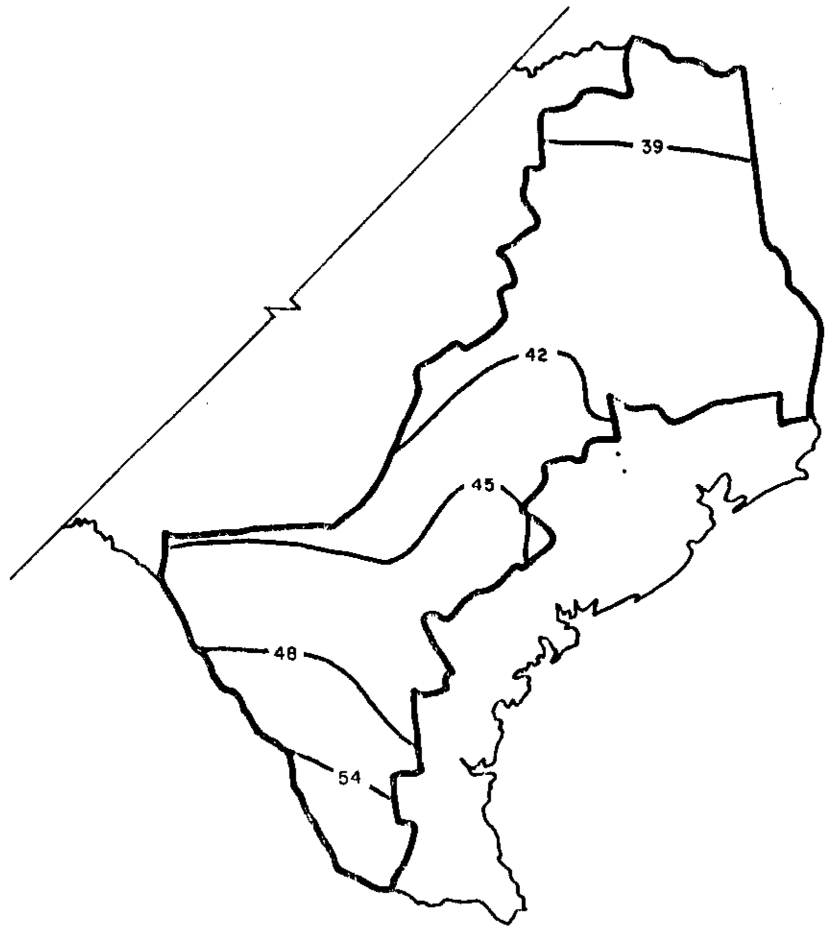

Figure 23. Average annual potential evapotranspiration in inches in the lignite belt.

n = water needed

I_m = moisture index

This formula corrects for fluctuating moisture levels and those due to seasonal variation. Thornthwaite assigned variables to indicate the degree of seasonal variation in moisture and which season, summer or winter, is drier. Thornthwaite's Moisture Index is given in Figure 24 (in pocket) for the Texas lignite belt.

Major climatic regions of Texas based on common seasonal rainfall characteristics are (Carr, 1967):

1. Interior and Lower Coast - maximum precipitation period during late spring and early fall

2. Upper Coast and Trans-Pecos - maximum precipitation period during summer (coastal areas also receive considerable precipitation during winter months)

3. East Texas - maximum precipitation period during winter months.

Figure 25 outlines the climatic regions included in the lignite belt as designated by Carr and the National Weather Service which also classifies its climatic regions on similar rainfall. Figures 26 and 27 indicate moisture regions and seasonal moisture variation.

Vegetation

Climatic factors, especially temperature and moisture conditions, influence both the vegetation and land use in an area. Soil characteristics are determined by climate and parent rock of the area. A parent rock that is coarse and siliceous weathers to a material that leaches rapidly and is low in nutrients. Leaching and weathering will occur faster in areas of heavy rainfall or where the climate is hot and moist. The average rate of decomposition doubles with every 18°F increase in temperature (Eyre, 1963).

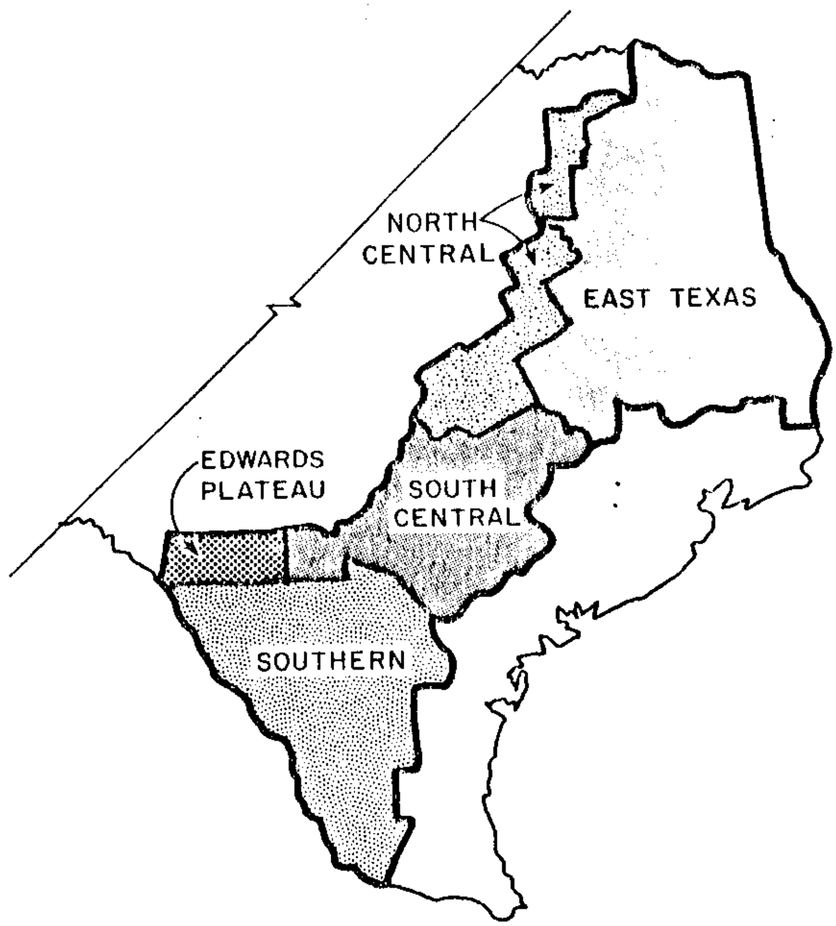

Figure 25. Climatic regions within the Texas lignite belt.

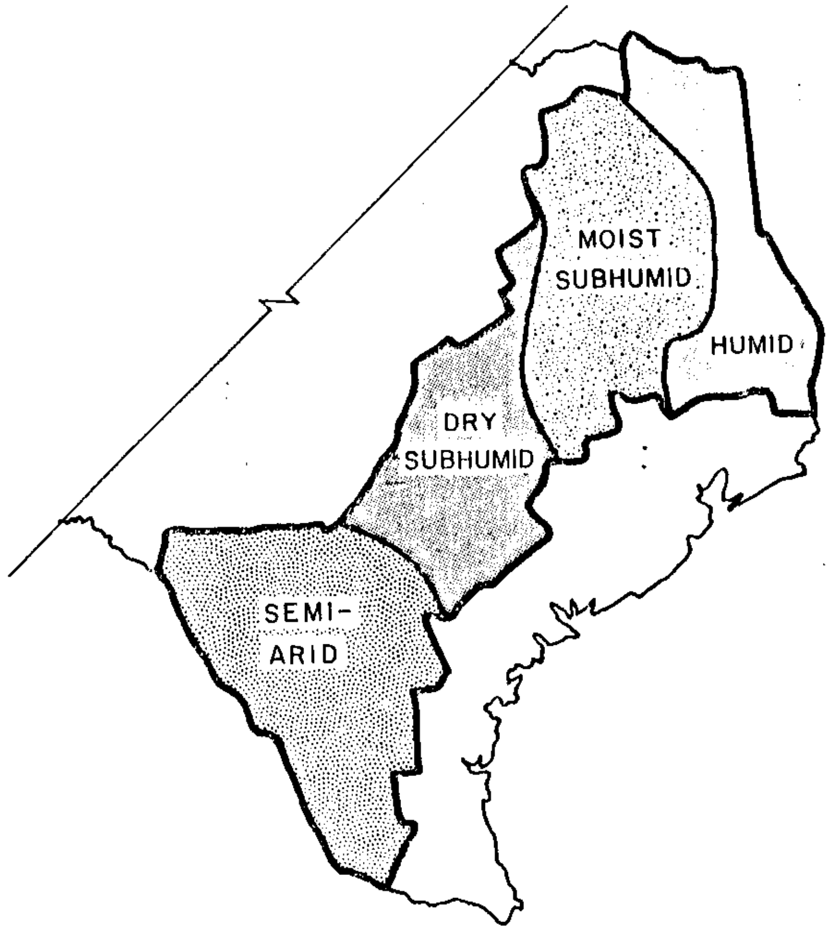

Figure 26. Moisture regions within the Texas lignite belt.

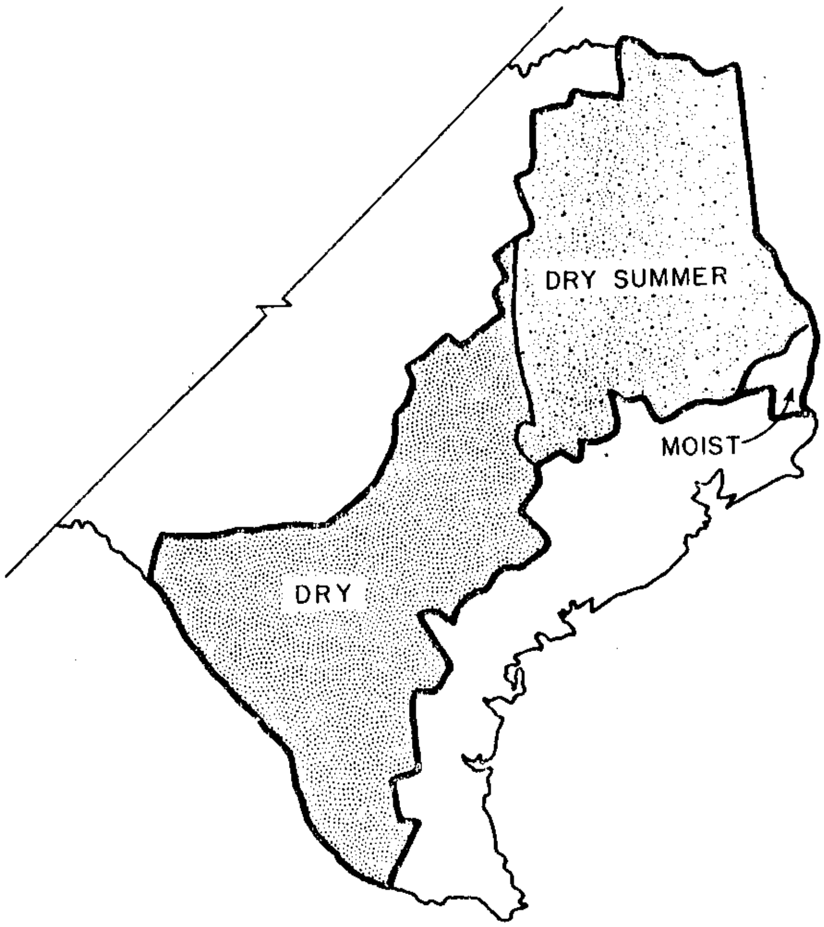

Figure 27. Seasonal variation of effective moisture in the Texas lignite belt.

The microclimate in the air layer nearest the soil is directly affected by the soil and vegetation (Walter, 1973). Therefore, climate as modified by soil cover, directly influences the distribution of plant species. However, plants are capable of exiting beyond their normal areas of distribution when not competing with other species. This indicates that physiological requirements cannot always be determined simply from plant distribution.

Vegetative cover consists of: a) stems and leaves, living or dead, which lie above the soil; b) decaying plant remains found on or in the soil; and c) roots and stems which penetrate the soil (Colman, 1953). These stems, leaves, and decaying plant remains act as a barrier between the soil and the atmosphere to restrict the amount of precipitation that enters the soil and serve as insulators for temperature regulation and wind erosion. This prevents water from evaporating from the soil as rapidly. The vegetative cover partially obstructs water flow and soil erosion by trapping and filtering out sediment from flowing water.

Hence, vegetation is the first line of defense in water yield control. However, certain factors such as soil texture, structure, and depth can limit the effectiveness of the vegetation. For example, a limestone or sandstone outcrop may support only a thin forest in a region where, on other types of rock, a rich forest might have developed. Relief also has an effect on vegetative distribution. A hillside could be so steep that soil would not accumulate, or, on the other hand, a plain near sea level might have marshy conditions where large trees cannot exist (Eyre, 1963). Where shallow water tables exist, vegetation is not as effective in reducing evapotranspiration (Colman, 1953), and in cultivated areas, the extent of water yield control by vegetation depends on agricultural practices.

In general, evapotranspiration losses from vegetation and watershed soils offset much of each year's precipitation. The rate of evaporation is reduced by vegetative cover and thus, the management of vegetation is the only way to reduce this loss.

Vegetative Regions

Seven vegetative regions exist within the lignite belt (Fig. 28). Of these, the Southeastern Evergreen Forest, Oak Pine Forest, Post-Oak Savanna, Blackland Prairies, and the South Texas Plains are significant. The Cross Timbers and Edwards Plateau regions occur along the northern and western boundary of the lignite belt.

East Texas Timberlands. The 16 million acres included in the East Texas Timberland contains the Southeastern Evergreen Forest and the Oak-Pine Forest regions. These regions receive the highest annual precipitation measuring an annual average of 40-56 inches. This is a nearly level, locally hilly, area with an elevation of 200-700 feet. 235-265 days out of the year are frost-free. Uplands soils are light-colored, acid, sandy loams and sands, with some red soils. The bottomlands are light-brown to dark-gray, acid, sandy loams, clay loams and some clays. These soils overlie Tertiary sandstones and shales.

The Southeastern Evergreen Forest is found in Tyler, Jasper, and Newton counties and parts of Sabine, San Augustine, Angelina, Polk, Hardin and Orange counties. Its dominant vegetation includes the loblolly pine (Pinus taido), longleaf pine (Pinus palustris, Magonlia sp.), and the American holly (Ilex opaca). The bald cypress (Taxodium distichum) is common in swamps and on stream banks.

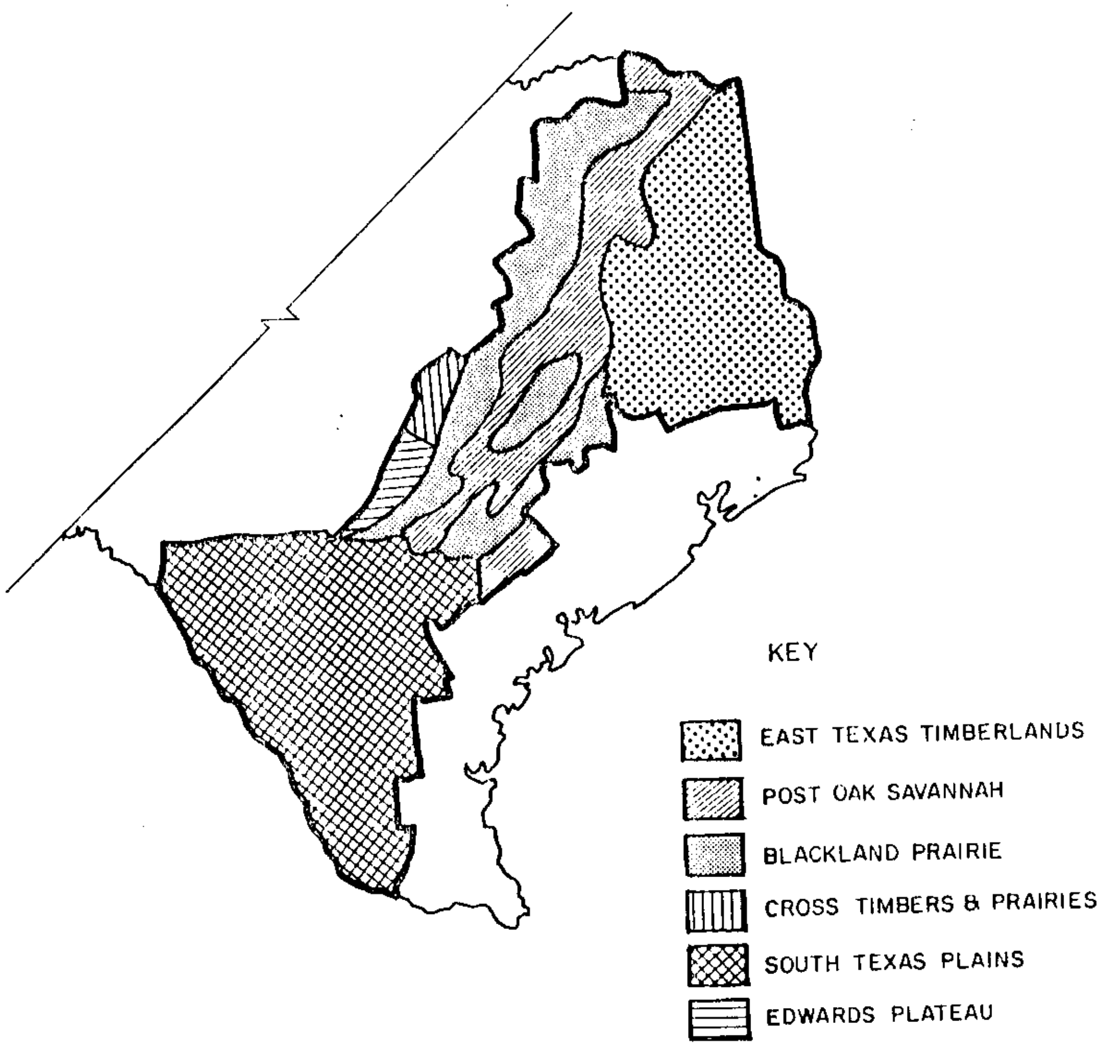

Figure 28. Vegetative regions in the Texas lignite belt.

Dominant species of the Oak-Pine Forest include the loblolly pine (*Pinus taeda*), the shortleaf pine (*Pinus echinata*), eastern red cedar (*Juniperus virginiana*), red oak (*Quercus falcata*), white oak (*Q. alba*), water oak (*Q. nigra*), willow oak (*Q. phellos*), post oak (*Q. stellata*), sweetgum (*Liquidambar styraciflua*), beech (*Fagus grandigolia*), hickory (*Carya* sp.), maple (*Acer* sp.), and elms (*Ulmus* sp.), and in the bottomlands, willow (*Salix nigra*) and bald cypress (*Taxodium distichym*) occur.

Post Oak Savanna. This region is also referred to as the Claypan Area, and covers 6,900,000 acres of nearly level to gently rolling savannah to brushy area with moderate drainage. At an elevation of 200-500 feet, the annual rainfall is 30-45 inches and 235-280 days of the year are frost-free. The soils of the uplands are gray, slightly acid, sandy loams. In the bottomlands reddish-brown to dark gray, slightly acid to calcareous, loamy to clayey alluvial soils predominate. These soils lie above Tertiary sandstones and shales.

The climax community of the area is composed of post oak (*Quercus stellata*) and the blackjack oak (*Quercus marilandica*). Undercover grasses include little bluestem (*Schizachyrium scoparium*), switch grass (*Panicum virgatum*), purpletop (*Tridens falvus*), and silver bluestem (*Bothriochloa saccharoides*). Other woody species are the eastern red cedar (*Juniperus virginiana*), yaupon (*Ilex vomitoria*), and possumhaw (*Ilex decidua*). Due to overgrazing, thickets have formed in many areas.

Blackland Prairie. This nearly level to gently rolling prairie contains 13 million acres and begins at a point below San Antonio and extends northeastward in a widening strip. It is an area with moderate to rapid surface drainage and is divided by the Eastern Cross Timbers which grow on the outcrop of the Woodbine Sand separating the eastern marly clays of Upper Cretaceous from the western rolling hills of Lower Cretaceous. The elevation varies from 250-700 feet with annual rainfall of 30-45 inches and annual frost-free period of 230-280 days. Uplands soils are dark-colored calcareous clays and bottom-land soils are dark-gray to reddish-brown calcareous clay loams and clays. Upper Cretaceous shales and limestone generally underlie these soils.

The climax grasslands are complsed chiefly of big bluestem (Andropogon gerardii), sideoats gramma (Bouteloua curtipendula), hairy gramma (Bouteloua hirsuta), and tall dropseed (Sporobolus asper). Woody species such as mesquite (Prosopis glandulosa), post oak (Quercus stellata) and blackjack oak (Q. miralandica) are invading the prairies.

South Texas Plains. 20,500,000 acres of nearly level to rolling brushy plain is found in this area. Its elevation varies from sea level to 1000 feet. Surface drainage is slow to rapid. Annual rainfall is 18-30 inches and annual frost-free period is 260-340 days. Soils in the uplands are dark calcareous to neutral clays and clay loams; reddish-brown, neutral to slightly acid sandy loams; or grayish-brown, neutral sandy loams and clay loams; with some saline soils near the coast. Bottomlands soils are brown to dark-gray, calcareous clay loams and clays with some saline soils. These soils overlie Quaternary and Tertiary sandstones and shales.

Overgrazing on the original savannah grassland of the South Texas Plains has caused a severe brush problem. The most common species of vegetation include mesquite (Prosopis glandulosa), live oak (Quercus frutescens), prickly pear (Opuntia spp.), tasajillo (Opuntia leptocaulis), silver bluestem (Bothriochloa saccharoides),and seacoast bluestem

(Schizachrium scoparium Setaria spp., Paspalum spp., and Chloris spp.).

East Cross Timbers. This narrow strip occupies one million acres of gently rolling area ranging from open savannah to dense thickets of scrub oak woodlands. At an elevation of 500-700 feet, it has a moderate to rapid surface drainage with an annual rainfall of approximately 35 inches and an annual frost-free period of 230 to 250 days. Lying on the outcrop of the Woodbine Sand, the soils are consequently light-colored, acid-loamy sands and sandy loams.

The post oak (Quercus stellata), blackjack oak (Quercus marilandica), mesquite (Prosopis glandulosa), little bluestem grass (Schizachrium scoparium), big bluestem grass (Andropogon gerardii), switch grass (Panicum virgatum), hairy gramma (Bouteloua hirsuta), sideoats gramma (Bouteloua curtipendula), and the Canada Wildrye (Elumus canadensis) are common.

Edwards Plateau. The 24 million acres of the Edwards Plateau is a broad, flat stony plain broken by undulating divides and is deeply dissected and rapidly drained. At an elevation of 1200-3000 feet, the annual rainfall is 12-32 inches with a frost-free period of 220-260 days annually. Soils are dark, calcareous stony clays and some clay loams. Cretaceous limestone of the Washita and Fredericksburg Groups is found in the underlying bedrock.

Common trees are live oak (Quercus virginiana), ash juniper (Junperus asheri), Texas persimmon (Diospyros texana), and Texas oak (Tuercus shummardii var. texana). Bald cypress, sycamores and native pecans can be found along stream banks. Cacti include the prickly pear (Opuntia spp.), tasajillo (Opuntia leptocaulis) and thorny shrubs like agarita

(*Berberis trifoliolata*). Common grasses include bluestems (*Andropogon* spp.) and wildryes (*Elymus* spp.).

Land Use

The Texas lignite belt is made up of parts of five land resource areas - the East Texas Timberlands, Blackland Prairies, Grand Prairie, Edwards Plateau, and Rio Grand Plain (Fig. 29). Land use in each area is generally governed by precipitation.

The East Texas Timberlands and Blackland Prairies are a portion of the low, level, and fertile Gulf Coast Plain. The most significant difference between the two areas is the dominant presence of dark calcareous clays in the Blackland Prairies and sandy loams and sands in the Timberlands. This part of the state receives the most rainfall annually. However, over wide areas the land is flat and drainage is poor and excessive ground moisture discourages cultivation. Thus, pasture acreage far outnumbers acres of cropland. Mild climate and availability of moisture allow grasses to grow year round and support a large cattle-raising industry. Another advantage for livestock producers is the case with which water can be obtained from wells on the low plain. To the southwest towards the Rio Grande Plain, the land becomes drier and farming more prevalent. Leading crops are cotton, grain sorghum and corn. In the east where abundant water is available for irrigation, rice is an important grain crop.

The Grand Prairie takes up only a small portion of the lignite belt but a sharp increase in elevation makes it easily distinguishable. The increase in elevation as well as the thin, stony soils of this region result from the hard limestone bedrock. Rivers flow rapidly down the

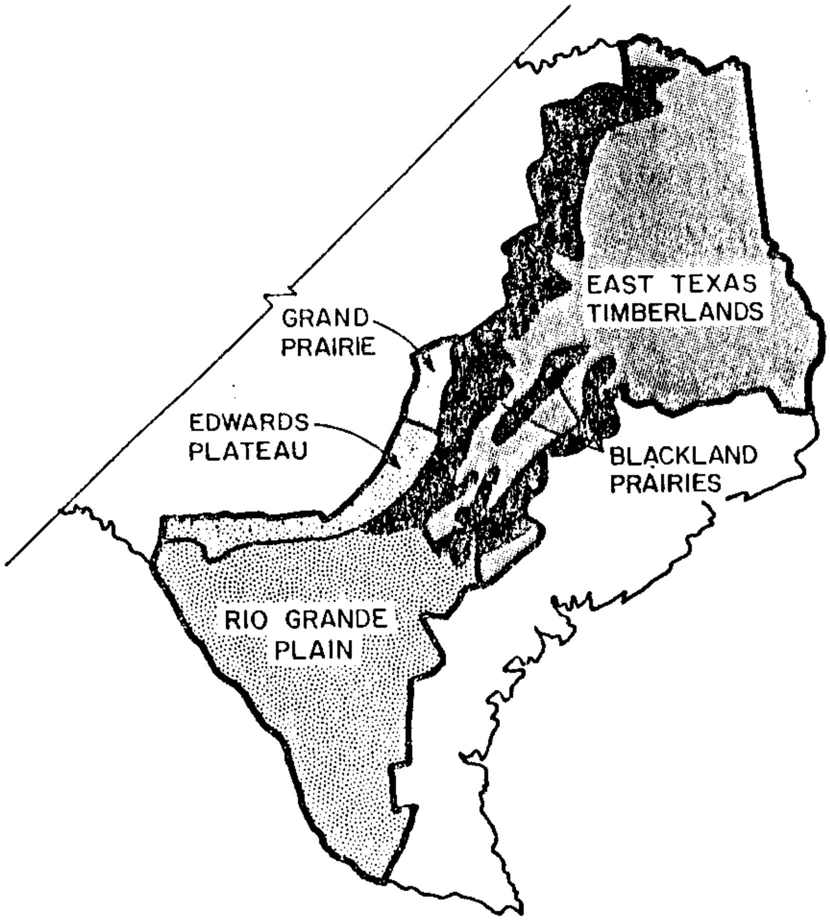

Figure 29. Land resource areas in the Texas lignite belt.

northwest to southeast slope of the Grand Prairie and carry away accumulating sediments. There are some large fertile areas, however, which have soils a few feet thick. Nearly three times as much land is in pasture as is cultivated; moisture and soils available allow brush, cedar trees, and dense pastures to thrive. Approximately one-fifth of the land is used for growing crops - principally oats, sorghum, and corn - of which most goes for livestock feed. Water can easily be ponded in the grasslands for use by livestock, and its high lime and phosphate content eliminates the need for some mineral supplements.

The upper southwest edge of the lignite belt lies within the Edwards Plateau, a rocky, brush-covered highland section of the Great Plains of Texas. Streams in the areas have washed out canyons and valleys to create a hilly to mountainous relief and limestone bedrock has produced a sticky, clay soil with chunks of rock scattered throughout. Rainfall comes mainly in the form of thunderstorms and runoff is much higher than absorption. Many of Texas' largest springs occur in this part of the Edwards Plateau. As the stony soils support mainly grasses, weeds, brush, and clumps of trees, pastureland equals about sixty-two times the amount of cultivated land. Numerous stock tanks and natural springs provide water for livestock. The minor amount of farming which does take place generally provides feed crops such as grain sorghum. A few small areas are under irrigation and produce alfalfa, vegetables, and fruits.

The Rio Grande Plain includes one of the largest portions of the lignite belt in southwest Texas. A wide variety of bedrock results in several soil types throughout the region and elevation and relief increasing away from the coastline. Brush, grasses, and mesquite trees are common throughout the area, providing good rangeland for raising livestock. Tanks and deep artesian wells provide water for livestock throughout frequent drought periods. Only ten percent of the Rio Grande Plain is cultivated due to lack of rainfall and the need for irrigation. Corn and grain sorghum are grown as feed crops, while cotton, vegetables, and fruit are grown farther south (Chambers and Kennamer, 1963).

Table 12 describes land use for counties within the Texas lignite belt and Figure 30 generalizes the distribution of irrigated acreage.

Water Use

Water is consumed by both natural and man-related processes. In the humid climatic regions of east Texas water consumption by natural vegetation exceeds that consumed by plants in the semi-arid regions to the west. Higher rainfall and lower evapotranspiration rates provide for greater quantities of available water, thus supporting higher densities of high water-demand vegetation.

In 1931, the Texas legislature passed the Wagstaff Act as a guideline for granting future water permits. The act provided that for a given water supply the following priority would hold for use: domestic and municipal needs, industry, irrigation, mining, hydro-electric, navigation, and recreation and pleasure.

Domestic and Municipal Use

As the population in Texas increases so does the size of her metropolitan areas, thus increasing domestic and municipal water requirements. Daily per capita use by urban residents has increased from 100 gallons in 1950 to over 150 gallons at present and the figure continues to grow (Van Dyke, 1974). The three basic water services: water

TABLE 12. Land use for counties in the Texas lignite belt.

County	Total Acreage[1]	Total Farmland[1] (acres)	Pasture & Rangeland[1] (acres)	Total Woodland[1] (acres)	Irrigated Acreage[1]	Federal Forest Acreage[2]	Urban Area, % of Total	Major Crops[3]
Anderson	686,336	345,138	85,390	113,962	730	---	4.1	Peanuts/Vegetables
Angelina	472,320	110,972	23,999	32,197	221	365,729	4.0	Corn/Vegetables
Atascosa	771,776	656,620	360,542	50,631	31,179	---	2.6	Peanuts/Sorghum
Bastrop	569,728	407,602	146,304	89,121	1065	---	4.8	Sorghum/Cotton
Bell	670,080	481,701	168,927	34,791	891	---	5.5	Sorghum/Cotton
Bexar	797,440	487,605	179,434	56,697	20,135	---	19.5	Soybeans/Cotton
Bowie	570,304	278,793	91,053	43,263	1649	---	4.6	Cotton/Sorghum
Brazos	374,720	261,086	114,118	40,589	7409	---	4.9	Cotton/Sorghum
Burleson	428,800	293,563	91,871	40,011	6809	---	2.4	Sorghum/Cotton
Caldwell	348,160	255,287	90,584	32,306	200	---	2.6	Sorghum/Cotton
Camp	123,008	66,904	14,500	11,823	---	---	5.4	Vegetables/Soybeans
Cass	602,496	201,339	43,060	65,872	165	---	2.1	Corn/Vegetables
Cherokee	671,552	270,629	67,363	65,620	2820	---	4.0	Vegetables/Peanuts
Comal	362,880	218,277	108,437	38,011	621	---	7.5	Sorghum/Sm. Grains
Delta	176,640	145,378	40,308	8147	24	---	3.3	Cotton/Sorghum
De Witt	582,336	512,523	264,926	59,650	1173	---	2.2	Corn/Sorghum
Dimmit	860,096	832,836	777,838	1312	13,294	---	1.5	Sorghum/Vegetables
Duval	1,161,024	971,506	758,151	37,299	6898	---	0.8	Sorghum/Vegetables
Falls	488,960	396,687	114,586	22,188	5855	---	4.0	Cotton/Sorghum
Fayette	597,696	472,474	148,032	75,128	1082	---	1.1	Corn/Cotton
Franklin	187,264	127,602	49,009	13,348	425	---	3.4	Corn/Cotton
Freestone	553,792	379,849	162,181	67,582	134	---	2.7	Sm. Grains/Cotton
Frio	714,240	595,898	386,084	12,061	52,330	---	1.2	Sorghum/Peanuts
Gonzales	676,032	691,250	385,301	104,526	3739	---	1.3	Sorghum/Corn
Gregg	180,160	84,675	27,298	22,094	269	---	22.1	Cotton/Corn
Grimes	512,704	339,505	159,177	41,376	887	---	2.5	Cotton/Sorghum
Guadalupe	457,024	362,309	90,786	34,945	3535	---	4.2	Sorghum/Cotton
Harrison	572,352	221,827	54,120	61,968	567	---	4.2	Vegetables/Wheat
Hays	416,000	293,508	189,038	14,976	743	---	2.7	Sorghum/Cotton
Henderson	603,264	336,389	134,134	55,493	367	---	3.4	Vegetables/Corn
Hopkins	507,584	365,197	128,824	34,762	797	---	3.2	Cotton/Sorghum
Houston	791,936	451,351	136,424	109,157	1523	443,963	2.1	Cotton/Peanuts

TABLE 12. (cont.)

County	Total Acreage[1]	Total Farmland[1] (acres)	Pasture & Rangeland[1] (acres)	Total Woodland[1] (acres)	Irrigated Acreage[1]	Federal Forest Acreage[2]	Urban Area, % of Total	Major Crops[3]
Hunt	528,640	371,685	81,490	20,470	235	---	5.7	Cotton/Sorghum
Jasper	580,480	129,911	19,945	65,947	4	---	0.9	Corn/Sorghum
Jim Hogg	731,584	842,375	792,002	2628	510	517,316	0.7	Vegetables/Cotton
Karnes	484,992	404,227	165,336	30,073	1084	---	2.4	Sm. Grains/Sorghum
Kaufman	521,344	420,830	187,811	20,102	---	---	4.4	Cotton/Sm. Grains
Kinney	891,520	714,124	677,490	(D)	(D)	---	0.4	Sorghum/Wheat
LaSalle	960,128	878,483	770,060	27,916	6618	---	0.8	Vegetables/Sorghum
Lavaca	624,000	477,202	190,288	64,746	8896	---	2.9	Corn/Sorghum
Lee	407,680	296,245	108,277	56,859	1313	---	1.6	Peanuts/Corn
Leon	705,088	409,540	145,537	107,268	410	---	1.4	Cotton/Vegetables
Limestone	495,520	431,771	164,534	39,377	117	---	3.1	Cotton/Sorghum
Live Oak	675,456	547,807	309,413	54,656	2297	---	1.1	Sorghum/Corn
McMullen	741,504	579,036	490,277	28,400	169	---	0.5	Sorghum/Corn
Madison	307,200	235,967	110,628	22,605	70	---	2.8	Sorghum/Corn
Marion	242,880	53,496	11,003	23,395	180	---	3.0	Vegetables/Corn
Maverick	824,960	892,744	855,698	1128	22,041	---	1.4	Sorghum/Wheat
Medina	865,088	754,969	397,489	84,106	25,112	---	1.7	Sorghum/Corn
Milam	658,112	451,869	144,059	53,902	573	---	2.3	Sorghum/Cotton
Morris	166,208	114,832	40,163	35,170	126	---	616	Peanuts/Corn
Nacogdoches	577,280	256,437	67,484	67,455	16	381,661	4.7	Vegetables/Corn
Navarro	684,800	570,928	210,939	34,865	112	---	3.3	Cotton/Sorghum
Newton	607,360	113,597	19,051	73,563	662	---	1.2	Sm. Grains/Corn
Panola	556,160	228,209	55,861	69,205	15	---	2.7	Corn/Vegetables
Polk	703,744	163,720	35,845	91,459	36	---	1.5	Corn/Cotton
Rains	134,400	99,250	34,844	11,817	14	---	2.1	Cotton/Sm. Grains
Red River	661,184	443,138	173,031	82,898	486	---	1.8	Cotton/Soybeans
Robertson	561,216	380,628	148,669	64,355	17,143	---	2.0	Cotton/Sorghum
Rusk	600,768	273,381	56,766	65,267	614	---	2.8	Vegetables/Cotton
Sabine	291,840	36,569	5139	12,640	40	280,112	3.4	Corn/Vegetables
San Augustine	302,720	72,589	12,808	18,969	6	286,481	3.1	Vegetables/Corn
San Jacinto	399,360	79,239	17,693	36,086	1	316,725	0.8	Corn/Vegetables

TABLE 12. (cont.)

County	Total Acreage[1]	Total Farmland[1] (acres)	Pasture & Rangeland[1] (acres)	Total Woodland[1] (acres)	Irrigated Acreage[1]	Federal Forest Acreage[2]	Urban Area, % of Total	Major Crops[3]
Shelby	497,920	212,252	35,412	70,685	5	346,910	3.4	Vegetables/Corn
Smith	597,952	281,416	90,806	46,459	1239	---	6.1	Vegetables/Corn
Starr	774,720	486,420	299,818	35,844	14,385	---	1.3	Sorghum/Vegetables
Titus	267,392	150,301	41,567	20,490	571	---	4.7	Sorghum/Vegetables
Travis	647,488	390,436	185,932	43,774	1330	---	8.3	Sorghum/Cotton
Trinity	452,608	141,239	35,515	53,341	15	345,883	1.8	Corn/Sm. Grains
Tyler	588,096	89,736	11,900	51,418	17	---	0.9	Corn/Vegetables
Upshur	373,440	164,350	31,026	48,918	20	---	3.5	Vegetables/Corn
Uvalde	1,016,320	808,182	573,833	68,956	31,672	---	0.9	Sorghum/Corn
Van Zandt	540,300	354,198	106,948	34,604	782	---	3.0	Cotton/Sm. Grains
Walker	505,472	274,908	100,005	78,678	354	361,661	2.2	Sm. Grains/Cotton
Washington	380,160	281,191	85,487	27,496	609	---	3.7	Corn/Cotton
Webb	2,115,584	1,943,304	1,831,282	11,586	9343	---	1.0	Vegetables/Sorghum
Williamson	706,560	605,994	166,879	59,295	1095	---	3.1	Sorghum/Cotton
Wilson	513,344	401,287	125,594	47,278	20,464	---	2.8	Sorghum/Peanuts
Wood	461,312	215,759	56,622	46,410	145	---	4.6	Vegetables/Potatoes
Zapata	612,480	5.9,523	445,738	4367	3866	---	0.6	Vegetables/Cotton
Zavala	826,496	794,095	655,885	22,674	47,024	---	0.8	Sorghum/Vegetables

[1]From 1974 Census of Agriculture.
[2]From Texas Almanac, 1976-1977.
[3]Major crops by acreage grown per county with the dominant crop listed first. From 1974 Census of Agriculture.
(D) - Data withheld to avoid disclosing information for individual farms.

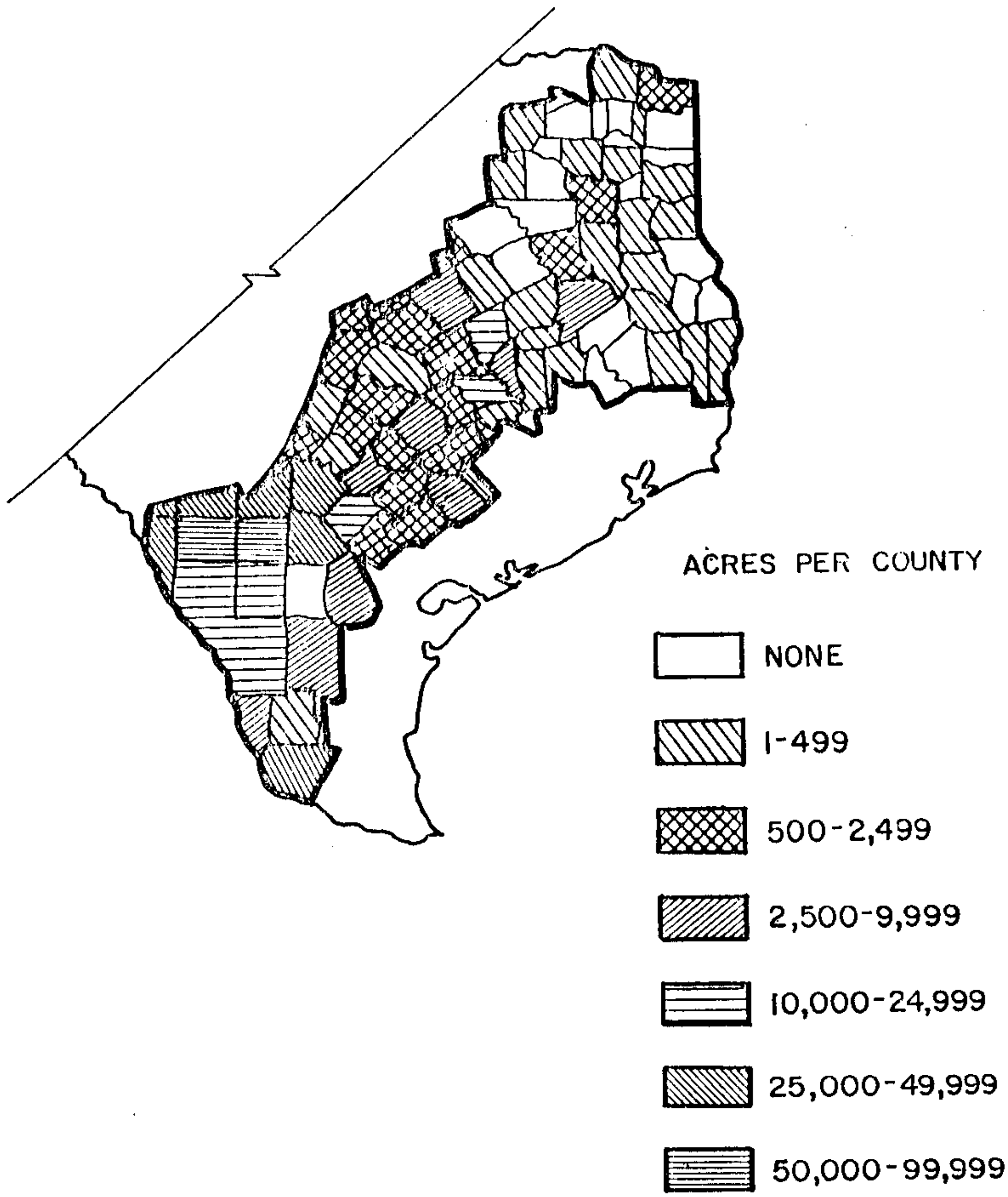

Figure 30. Distribution of irrigated acreage within the Texas lignite belt.

supply, wastewater collection and treatment, and storm water management - account for most urban needs. Uses include: domestic purposes, commercial uses, fire protection, street flushing, lawn and garden irrigation, and some municipal industry. Some water is lost through leakage from systems.

Industrial Water

Five major industries require a majority of the water used for industrial purposes - food, paper, chemicals, petroleum, and metals (National Water Commission, 1973). Industrial water is largely reusable so there is less net loss of availability. Cooling towers equipped for multiple recycling are common, and coagulation, sedimentation, and softening are practiced to cleanse waste water. Industry faces increasingly strict regulations regarding amount, quality, and environmental implications of water used even though it accounts for only a small portion of water use in Texas.

Irrigation

Agricultural needs place a heavy demand on water resources in Texas. Most of this water is consumed with less return flow and with less available for reuse. In some areas of Texas, crops are completely dependent upon irrigation while rain falls on unsuitable croplands elsewhere. Both surface and groundwater sources are used for irrigation, however, decline in groundwater levels is projected to cause a major decline in irrigation (T.W.D.B., 1977).

Recent data on irrigation in Texas is found in a report compiled by the Texas Water Development Board published in October, 1975 with the cooperation of the United States Soil Conservation Service, area district conservationists, and engineering field specialists. Data from this report for the counties of the Texas lignite belt are contained in Table 13. Accuracy of inventory data differs from county to county according to the quantity and accuracy of data available, assigned personnel's degree of familiarity with the surveyed area, and the amount of field observation that could be made. Generally the Soil Conservation Service teams considered their estimates within a 5 to 10 percent range of accuracy. A knowledge of irrigation requirements for the various counties of the Texas lignite belt will be essential in estimating water requirements for counties with proposed mines.

Figures 31 and 32 show diagramatically the average acre-feet of surface and groundwater used for irrigation per county in the lignite belt.

Mining Use

Fuels, metals, and nonmetals are mined in Texas. The petroleum and natural gas industries alone consumed 163,572 acre-feet of water in 1972 while the metal industry used 3683 acre-feet. Mining of nonmetals such as salt, sand, clay, etc. required much less water by comparison.

Mineral fuel development directly depends upon availability of water. Vast amounts of water are needed to mine lignite, coal, and uranium as well as for processing and land reclamation. Until very recently, water availability has had little effect on the mining industry in Texas.

Electric Power Production

Because surface water in Texas is fairly limited, only a small amount of power is produced by hydroelectric plants and this is generally during peak use times or emergencies. Electric power generation creates

TABLE 13. Irrigation in the Texas lignite belt, 1974.

County	Total Acreage	Surface Water (acre-feet)	Ground Water (acre-feet)	Combined Sources (acre-feet)	All Irrigation (acre-feet)	Irrigated Acres % of Total
Anderson	686,272	470	90	183	734	0.25
Angelina	514,368	0	462	0	462	0.04
Atascosa	771,712	134	56,962	0	57,096	4.50
Bastrop	569,728	1920	515	580	3015	0.56
Bell	682,176	7053	10,311	17,170	1802	4.28
Bexar	795,820	13,953	13,699	0	27,652	3.32
Bowie	570,304	1733	1296	0	3029	0.30
Brazos	374,720	0	1975	3933	5908	2.32
Burleson	436,992	1369	8393	0	9762	3.34
Caldwell	348,160	1563	97	0	1660	0.50
Camp	123,008	0	0	0	0	0
Cass	603,386	0	0	0	0	0
Cherokee	671,488	3	13	54	70	0.009
Comal	362,880	20	172	0	192	0.09
Delta	176,640	0	0	0	0	0
De Witt	582,336	166	821	0	987	0.21
Dimmit	859,260	394	18,781	14,347	33,576	2.74
Duval	1,160,414	0	2909	0	2909	0.33
Falls	488,960	2129	0	0	6970	1.56
Fayette	497,652	139	90	72	301	0.12
Franklin	187,264	0	0	0	0	0
Freestone	553,792	0	0	0	0	0
Frio	714,240	27	72,767	0	72,794	8.6
Gonzales	676,032	527	1538	42	2107	0.34
Gregg	180,160	0	0	0	0	0
Grimes	512,704	0	115	0	115	0.04
Guadalupe	457,024	1645	1080	0	2725	0.79
Harrison	572,352	45	2	0	47	0.01
Hays	428,800	822	903	0	1725	0.40
Henderson	603,264	0	0	0	0	0

TABLE 13. (cont.)

County	Total Acreage	Surface Water (acre-feet)	Ground Water (acre-feet)	Combined Sources (acre-feet)	All Irrigation (acre-feet)	Irrigated Acres % of Total
Hopkins	507,584	0	0	0	0	0
Houston	791,936	1378	0	509	1887	0.55
Hunt	532,696	7	0	0	7	0.002
Jasper	593,536	40	0	0	20	0.02
Jim Hogg	731,584	0	129	0	129	0.05
Karnes	484,992	1986	2677	0	4663	0.31
Kaufman	411,916	42	0	0	42	0.02
Kinney	891,520	3497	10820	0	14,317	0.96
LaSalle	960,128	703	10,900	1282	12,885	1.28
Lavaca	624,000	50	23,965	310	24,325	1.31
Lee	410,269	349	334	0	683	0.21
Leon	705,012	0	34	0	34	0.006
Limestone	595,520	0	40	0	40	0.006
Live Oak	670,391	433	1742	0	2157	0.55
McMullen	741,504	0	0	0	0	0
Madison	307,150	0	40	0	40	0.01
Marion	242,880	0	0	0	0	0
Maverick	818,560	97,600	3,330	0	100,930	5.20
Medina	865,088	28,638	41,033	0	69,667	3.98
Milam	658,112	1001	123	192	1316	0.31
Morris	166,108	265	0	8	273	0.28
Nacogdoches	597,354	21	0	0	21	0.004
Navarro	695,488	0	0	0	0	0
Newton	607,265	0	750	17	767	0.09
Panola	551,635	0	3	0	3	0.002
Polk	703,744	0	0	0	0	0
Rains	140,032	0	0	0	0	0
Red River	661,184	0	40	0	40	0.01
Robertson	561,152	3592	15,547	925	20,295	3.97
Rusk	600,640	0	0	0	0	0
Sabine	304,803	0	0	0	0	0

TABLE 13. (cont.)

San Augustine	348,608	0	0	0	0	0
San Jacinto	399,360	0	0	0	0	0
Shelby	497,874	0	0	0	0	0
Smith	597,952	167	0	100	267	0.12
Stan	774,784	26,155	0	0	26,155	3.30
Titus	267,392	0	0	0	0	0
Travis	647,552	804	74	100	978	0.19
Trinity	452,608	0	0	0	0	0
Tyler	583,160	9	0	0	9	0.006
Upshur	373,504	7	0	0	7	0.003
Uvalde	1,016,320	1633	67,312	1367	70,312	3.89
Van Zandt	544,230	0	0	0	0	0
Walker	505,472	273	0	0	273	0.08
Washington	391,744	30	75	0	105	0.04
Webb	2,115,584	14,934	0	0	14,934	0.59
Williamson	720,640	237	30	0	267	0.05
Wilson	513,280	2848	13,750	1109	17,707	3.61
Wood	461,312	10	3	0	13	0.01
Zapata	655,872	4588	0	0	4588	0.70
Zavala	826,496	1479	114,723	30,113	146,314	9.85

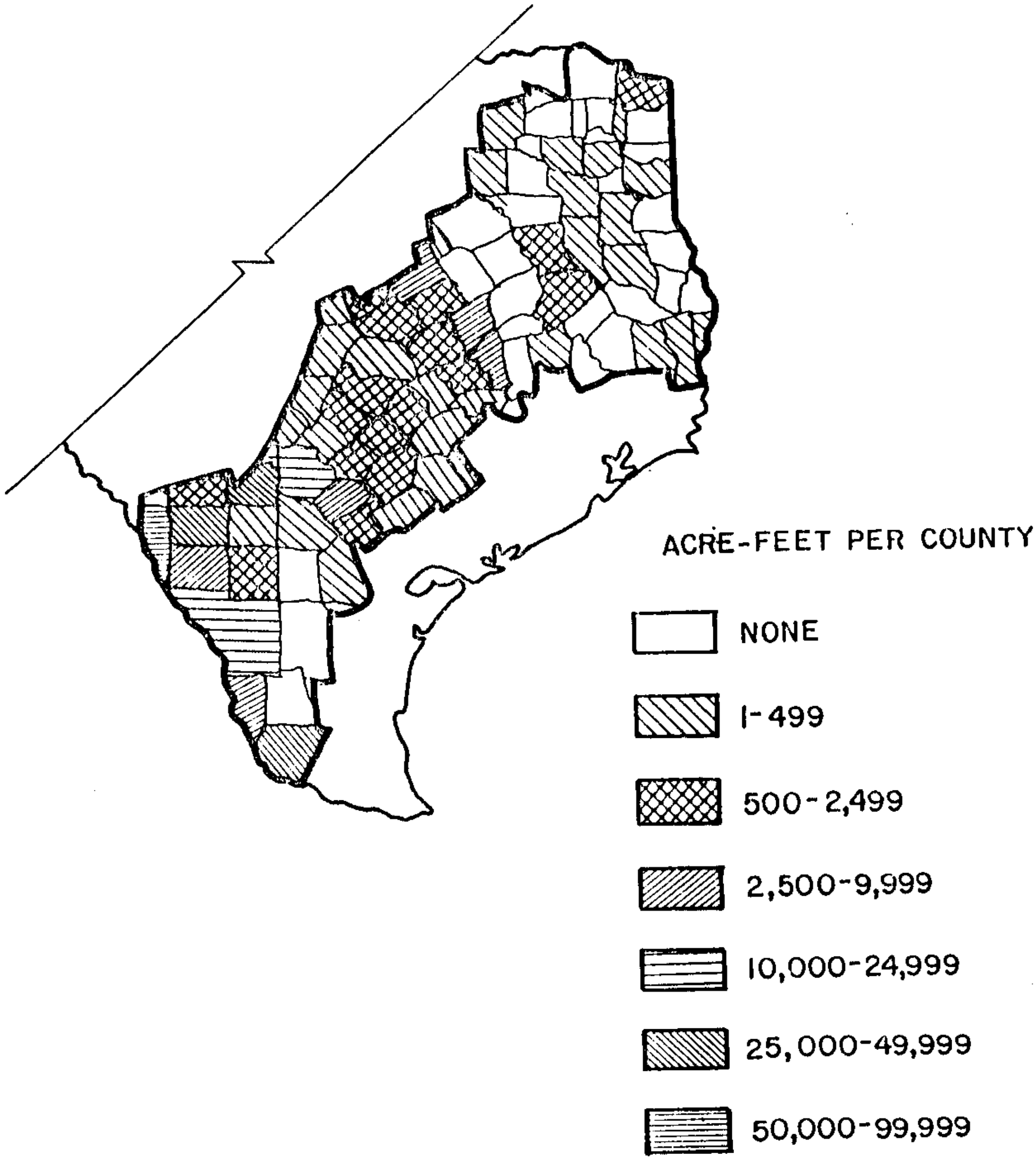

Figure 31. Average acre-feet of surface water used for irrigation by county in the Texas lignite belt.

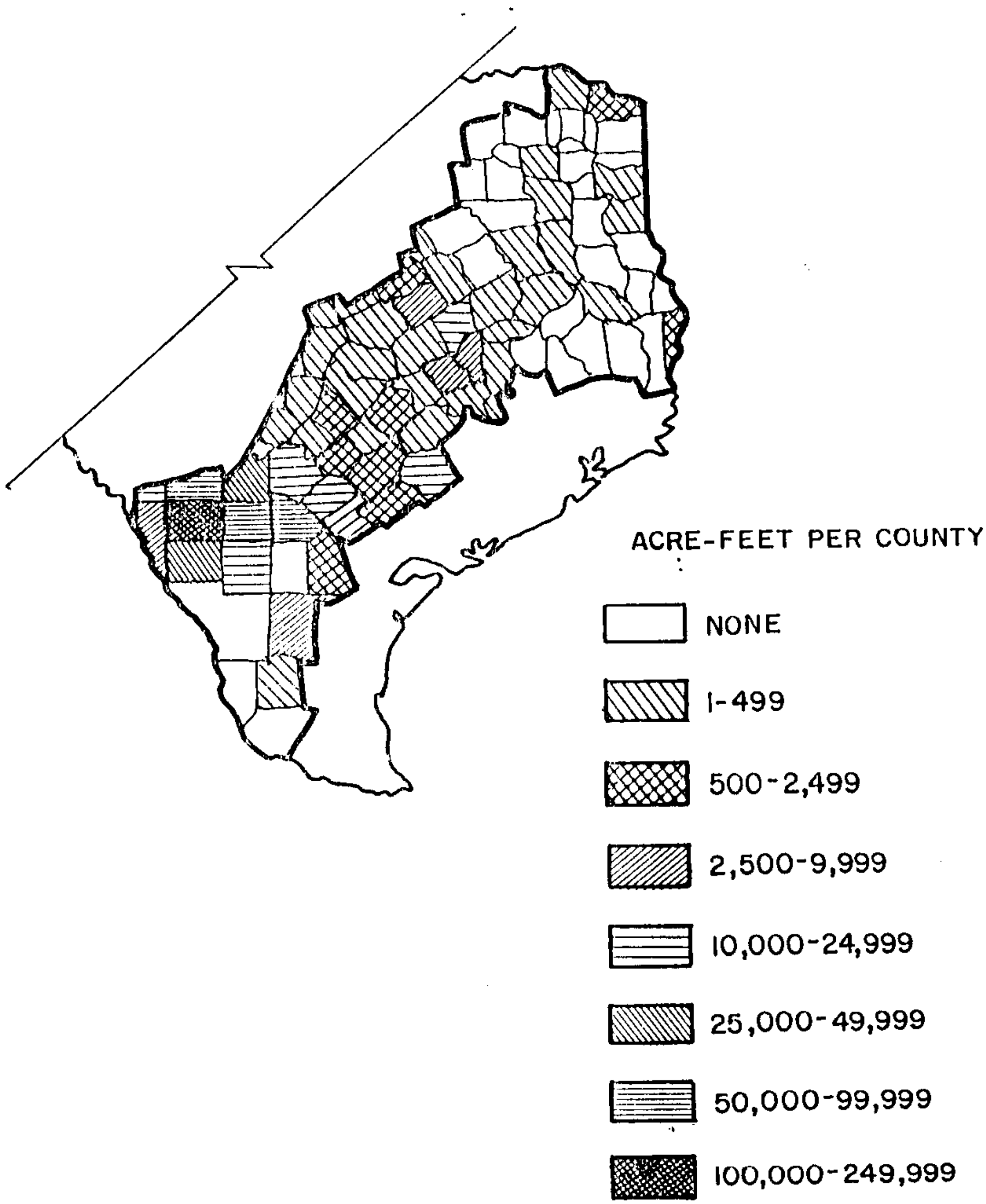

Figure 32. Average acre-feet of groundwater used for irrigation by county in the Texas lignite belt.

a water loss resulting from the method of cooling employed for water heated in the process of power production. Cooling towers and tanks lose water to evaporation and seepage from tanks further reduces reusability.

Navigation and Recreation

Navagational and recreational water uses are considered to be nonconsumptive. Usually water resource storage areas and watercourses developed for other uses also provide for the needs of navigation and recreation (McNeely and Lacewell, 1978).

Tables 14 and 15 estimate use of ground and surface water sources for several different areas by river basin.

TABLE 14. Water use by surface water sources, by basins, 1974.

Basin	Municipal	Manu-facturing	Steam-Electric	Irrigation	Mining	Livestock	Total
	1000's acre-feet						
Red River	42.5	4.4	7.8	37.3	1.0	20.0	113.0
Sulphur River	14.2	28.5	0.2	0	(1)	7.9	50.8
Cypress Creek	3.2	153.1	10.6	0.3	0.1	4.0	171.3
Sabine River	17.8	65.6	3.7	8.1	0.3	9 9	105.4
Neches River	17.9	108.8	6.3	26.3	1.1	9.8	170.2
Trinity River	366.1	115.7	31.4	68.1	10.5	25.0	616.8
San Jacinto River	65.9	91.5	2.6	0.4	0	3.5	163.9
Brazos River	129.2	214.2	37.6	68.0	10.6	45.3	504.9
Colorado River	119.9	14.0	19.7	134.3	12.9	15.0	315.8
Lavaca River	0	0	0	80.3	0	317	84.0
Guadalupe River	4.2	31.0	2.0	4.9	0.5	6.0	48.6
San Antonio River	0	0.3	16.9	21.3	0	212	40.7
Nueces River	1.5	0.7	3.2	68.8	0	1.6	75.8
Nueces-Rio Grande Coastal	94.6	32.2	4.3	997.6	0.1	1.0	1129.8
Rio Grande River	42.0	0.8	2.0	438.8	0.3	0.4	484.3
Total	919.0	860.8	148.3	1954.5	37.4	155.3	3075.3

(1)Less than 50 acre-feet.

(Texas Water Development Board, 1977)

MINING AND PROCESSING LIGNITE: WATER DEMANDS

Water requirements for the conversion of lignite into a useful power source may be a major factor limiting full potential development of lignite resources in Texas (Hoffman, 1976). Mine operations by pre-agrarian man were primitive. Throughout the Stone Age the demand for flint made it an important trade item. From the beginning of the New Stone Age shallow mining pits with a ramified network of tunnels to extract the flints were used. During the Bronze Age man mined other metals such as copper and tin and made alloys such as bronze from them. The Iron Age man extracted iron ores and produced metallic iron (Stoces, 1954).

Texans are presently becoming more involved with shallow surface mines or, as they are more commonly called, strip mines. Comparatively uniform shallow, flat coal beds are mined in open pits where the overburden is not exceedingly thick. For strip mining to be practical, the area to be mined must be flat to gently rolling. During mining (Fig. 4) the overburden is removed in successive strips that vary in width and in backfilled into the area from which the coal has been removed (Young, 1946).

Water needs for these processes vary substantially according to tye type of utilization and conversion processes employed (Table 16). The amounts of water required for each of these processes are included in five categories: 1) mining, 2) processing, 3) cooling, 4) those water requirements of area population increase that would result from plant construction and operation, and 5) miscellaneous.

Hoffman (1976) makes a distinction between "water intake" and "water consumption" which have differing effects in lignite water needs. Water intake refers to the total amount of water withdrawn from a lake, stream,

TABLE 16. Water needs for lignite conversion and utilization processes (theoretical plant using 25,000 tons of lignite per day).

Process	Output (billion Btu's/day)	Water Intake (1000 acre-feet/year)		Water Consumption (1000 acre-feet/year)	
		Minimum	Maximum	Minimum	Maximum
Steam Electric Power Plant[1]	120	23.3	1,503.0	13.2	25.3
Gasification	230-300	6.6	1,506.0	5.2	19.2
Liquification	130-230	6.4	752.0	4.0	19.0
In-Situ Gasification[2]	70	12.0	7.8	6.6	11.6
Pipeline Slurry	360	5.8	63.9	0.08[3]	7.8
Solvent Refined Coal[4]	280	2.5	---	1.7	---

[1]This includes mining, processins, cooling, miscellaneous, and associated population requirements.

[2]This assumes that in-situ gasification recovers 50% of the heating value of the lignite and that gas is used on location to power a 1000 megawatt power plant. Therefore, water use figures reflect power plant water requirements.

[3]5000 acre-feet per year is exported from the mine site.

[4]Information for the SRC process water requirements is scanty; thus, these projections should be used with caution.

(Hoffman, 1976)

estuary, or aquifer while water consumption refers to that amount of the water intake which is lost through evaporation, chemical conversion, or other means.

Mining Requirements

Water is needed for dust control in the mining area, on the haul roads, and for land reclamation. A 25,000 ton per day lignite strip mine requires approximately 500 acre-feet of water per year for dust control. Land reclamation and revegetation of a stripped area could require up to an additional two acre-feet of water per acre of land that is surface mined and reclaimed. Therefore for a 25,000 ton per day mine with a mining rate of 12,500 tons per acre, total water requirements can exceed 4000 acre-feet per year (Hoffman, 1976).

Rainfall is an important factor in estimating the amounts of water actually needed. For example, east Texas and much of central Texas receive sufficient rainfall to preclude or reduce irrigation needs, but further to the south periodic irrigation will probably be necessary for the reestablishment and maintenance of vegetation. In determining water needs, Hoffman (1976) assumes that there will be no water requirements for land reclamation using irrigation in the east Texas area west to Freestone County, but estimates irrigation water needs in the central and southern climatic regions of Texas would range from 500 acre-feet to 2000 acre-feet per year for a 25,000 ton per day mining operation. No return flows are assumed; thus water intake equals water consumption. Other processes, such as underground mining dust control and in-situ gasification operations have minimal water requirements (Table 17).

TABLE 17. Water for lignite development in Texas.

	Estimates for a 25,000 ton/day Operation
MINING	
Strip	500 acre-feet/year
Dust control - mine area and land reclamation	2 acre-feet per acre of land
Underground	small
In-Situ Gasification	small, but may affect aquifers
PROCESSING	
Steam Electric Power Plants	
Boiler makeup, ash handling	200 acre-feet/year
Stack gas scrubbing (if used to control emissions)[1]	2000 acre-feet/year
Lignite Gasification and Liquification	(varies with process used)
Gasification in general	1000 acre-feet/year
Liquification in general	800 acre-feet/year
Solvent refined coal[2] - gasification	300 - 3000 acre-feet/year
liquification	300 acre-feet/year
In-Situ Gasification	minimal[3]
Lignite Washing	usually not practiced but, if so, it would be small
Pipeline Slurry	500 acre-feet/year
COOLING	
Air Cooling	minimal
Wet Cooling	
Once through cooling - consumption	10,000 acre-feet/year
Cooling ponds or towers	20,000 acre-feet/year
Gasification and liquification - consumptive	3000-5000 acre-feet/year (depends on process and amount air cooled)
Total waste heat removal - intake	20,000-45,000 acre-feet/year
With air cooling to remove 75% heat in gasification and liquification processes	4000 acre-feet/year
Once through cooling - intake	1.5 million acre-feet/year
SECONDARY POPULATION REQUIREMENTS	2000-6000 new people[3]
Local Municipal Water - intake	increase 300-900 acre-feet/year
Municipal - consumption	increase 150-450 acre-feet/year
MISCELLANEOUS	varies with each report
Intake	500-1000 acre-feet/year
Consumption	250-400 acre-feet/year

[1]Water requirements for all types of stack gas scrubbers (wet limestone, double alkali, magnesia, etc.) are about the same.

TABLE 17. (cont.)

[2] SRC process requires the least amount of water because total gasification or hydrogeneration is not accomplished.

[3] However, gas will probably be used on site for steam electric power production so the water requirements for this method will be associated with those for electric power generation.

(Hoffman, 1976)

Process Requirements

Process water requirements vary with the type of lignite conversion process used (Table 17). A steam electric power plant using 25,000 tons of lignite per day needs 200 acre-feet per year for boiler feed make up and ash handling, and approximately 2000 acre-feet per year for stack gas scrubbing (Hoffman, 1976). Since much of this water is lost through evaporation, intake and consumption are therefore equal.

Process water requirements for lignite gasification and liquification also vary with the process employed. A substantial volume of the water used in these operations is chemically consumed in the conversion reactions to produce hydrogen (Hoffman, 1976). Plants that produce high Btu gas usually consume more water than low Btu gas plants because they use shift conversion and methanization[1] (Table 18). Since the process water is actually consumed, intake is equal to consumption. Liquification methods such as the Synthoil process require less water than gasification processes because the molar ratio of carbon to hydrogen in the lignite is not significantly changed (Hoffman, 1976). The solvent refined coal (SRC) process uses the least amount of water because total gasification or hydrogeneration is not carried out. Hoffman (1976) estimates process water requirements for these operations range from approximately 300 to 3000 acre-feet per year. For most gasification processes, consumption rates are generally 1000 acre-feet per year. Liquification processes normally require about 800 acre-feet per year and SRC processes only about 300 acre-feet per year, or less if it is assumed that the ratio of process water to cooling water for these SRC plants is the same as that for liquification plants (Hoffman, 1976). The actual water

[1] Methanization - the process of producing methane gas from lignite coal.

TABLE 18. Energy output of various lignite conversion processes using 25,000 tons of lignite per day.

Process	Billion Btu's per day	Plant Output per day	Units
Steam Electric Power Plant	120	36,000,000	KWH[1]
High Btu Gas	230	280,000,000	SCF[2]
Low Btu Gas	300	830,000,000	SCF[3]
Fischer-Tropsch	130	26,000	Barrels
Synthoil & Others	230	45,000	Barrels[4]
Solvent Refined Coal	280	38,000	Barrels
Pipeline Slurry	360	25,000	Tons

[1]KWH - Kilowatt hours and is equivalent to a 2,000 megawatt power plant operating at 80% of capacity.

[2]SCF - Standard cubic feet.

[3]A heat value of 300 Btu's per SCF is assumed.

[4]Direct catalytic hydrogeneration and hydrocarbonization have similar conversion efficiencies.

(Hoffman, 1976)

requirements can be affected by the moisture content of the lignite.

Water requirements for in-situ gasification of existing deep-basin lignite in Texas will be minimal (Hoffman, 1976). However, the gas produced will most likely be used at that site for steam electric power production and therefore water needs for in-situ gasification will be associated primarily with electric power generation. Lignite washing, while generally not practiced due to the large amounts of fines produced, if employed, would require small amounts of water in comparison with other lignite conversion process requirements (Hoffman, 1976). Transporting Texas lignite via slurry pipeline is an unlikely alternative because lignite tends to disintegrate, when slurried, into a fine powder which drains poorly and is difficult to handle. However, if used, a pipeline slurry system transporting 25,000 tons of lignite per day would require about 5000 acre-feet of water per year (Hoffman, 1976). This water is not actually consumed, but would be removed from the lignite producing area.

Cooling Requirements

Cooling water intake and consumption rates are dependent upon the type of cooling system used (Table 17). Both air and water cooling systems are available. In air-cooled operations little water is used, but in wet cooling systems water needs are substantial. Air cooling systems are proving useful for many gasification and liquification operations because of the extremely high temperatures involved in processing. Some gasification plants have plans to employ air cooling for nearly 75% of their cooling needs to reduce water requirements. Steam electric power plants, however, generally do not use air cooling systems for the following reasons: 1) relative cost is excessive compared to wet cooling systems, 2) power plant efficiency is reduced by 12%, and 3) from 3% to 8% of the electric power output of a plant is required for operation (Hoffman, 1976).

Available wet cooling systems include wet cooling towers, recirculating cooling ponds, and once-through cooling systems from multipurpose reservoirs, streams, or estuaries. Once-through systems consume far less water than cooling towers and cooling ponds.

Consumptive water requirements for a steam electric power plant using 25,000 tons of Texas lignite per day would total about 10,000 acre-feet per year if once-through cooling is used, but would be as much as 20,000 acre-feet per year if cooling ponds or towers are used (Hoffman, 1976). Water consumption for gasification and liquification plants of the same size would range from 3000 to 15,000 acre-feet per year, Hoffman says, depending on the specific process and the amount of air cooling used.

Water intake rates also depend on the process used. If wet cooling towers or cooling ponds are used for total waste heat removal in either steam electric power plants or gasification or liquification plants using 25,000 tons of lignite every day, water intake requirements will be around 20,000 to 45,000 acre-feet per year (Hoffman, 1976). This equals the volume of water needed to replace that lost through evaporation and blowdown from the cooling system. Hoffman points out that if air cooling is used to remove as much as 75% of the waste heat from the latter two conversion processes, intake requirements can be reduced to as little as 4000 acre-feet per year.

Once-through cooling systems withdraw water, circulate it through a condenser and heat exchanger, then discharge it to receiving water (Hoffman, 1976). For either steam electric power plants or lignite conversion plants intake rates can exceed 1.5 million acre-feet per year. Such large requirements generally preclude use of groundwater. If located on a surface water source, the water should be immediately returned to that body of water and not represent an actual depletion of the water source. However, the widely varying flow rates on most Texas streams limit the feasibility of using such cooling systems. A different situation exists if the plants are located on multi-purpose reservoirs. Since this system merely circulates the lake water, the only requirements are that: 1) sufficient water is impounded at any one time to provide enough water surface area for heat dissipation, 2) the lake's water level remains above the water intake structure of the plant, and 3) sufficient water is released from the reservoir to control the levels of dissolved solid concentrations (Hoffman, 1976). Single purpose cooling reservoirs should be used only when absolutely necessary. Such impoundments may preclude the statewide water resource planning and development.

Secondary Population Requirements

Steam electric plants that require 25,000 tons of lignite per day will require 200 to over 800 new employees for operation. If it is assumed that 75% of these employees are married, then the total direct population increase, including workers and their families, could range from 400 to 2000 people (Hoffman, 1976). These employees and their families would also create new demands for goods and services thus requiring more people. For most installations these related population requirements would be on the order of 600 acre-feet per year for intake and 300 acre-feet per year for consumption (Hoffman, 1976).

Miscellaneous Requirements

Miscellaneous requirements include water used for sanitary purposes, watering the lawn around the plant, washing and maintenance, utilities, air conditioning, and other needs (Hoffman, 1976). Hoffman estimates that for a 25,000 ton per day plant intake rates of 500 to 1000 acre-feet per year and consumption rates of 250 to 500 acre-feet per year would be more than sufficient for miscellaneous needs.

Summary

To fully comprehend water requirements the total water needs of the various lignite utilization and conversion processes must be examined (Table 17). Table 19 shows the consumptive water requirements of the various processes on a "gallons per million Btu's" basis so that relative water use efficiencies can be compared. As Table 19 shows, steam electric power plants are the most "water intensive" while slurry pipeline and solvent refined coal processes are the least water intensive (Hoffman, 1976). However, Hoffman points out, slurry pipelines are for transportation and the lignite will be used at its destination. So in many ways slurry pipelines may merely transport the water use needs from the mining location to the point of use. The same may be true for the SRC processes since the product is a solid substance with a heating value of 16,000 Btu's per pound (Hoffman, 1976). This product can be burned in the power plant boilers or liquified by hydrogeneration -- both processes will require additional water.

TABLE 19. Water consumption rates for lignite utilization and conversion[1].

Process	Water Consumption (Gallons per million Btu's)
Steam Electric Power Plant	98 - 188
Gasification	15 - 74
Liquefication	16 - 130
In-Situ Gasification[2]	84 - 148
Pipeline Slurry	0.2 - 19
Solvent Refined Coal[3]	5.4 - 8

[1]This includes mining, processing, cooling, miscellaneous, and associated population requirements.

[2]This assumes that in-situ gasification recovers 50% of the heating value of the lignite and that gas is used on location to power a 1000 megawatt power plant. Therefore, water use figures reflect power plant water requirements.

[3]Information for the SRC process water requirements is scanty; thus, these projections should be used with caution.

(Hoffman, 1976)

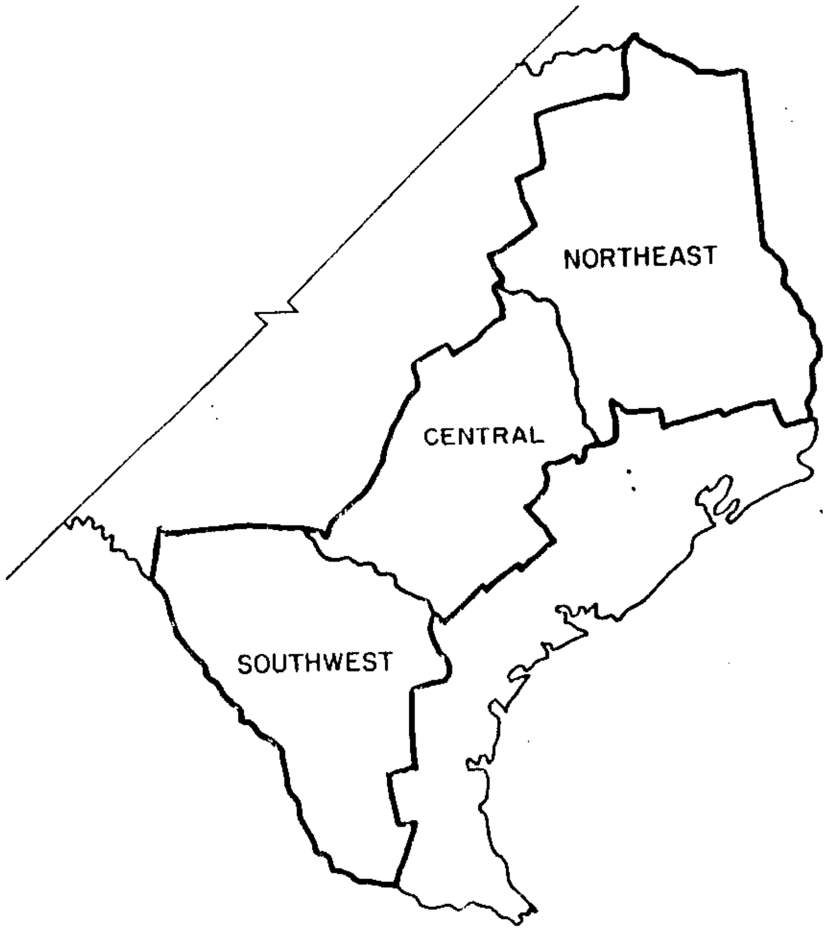

Figure 33. Impact evaluation divisions in the Texas lignite belt.

TABLE 20. Impact evaluation figures for the Texas lignite belt.

	Northeast	Central	Southwest
Available Groundwater (acre-feet per year)	4,690,700	6,469,500	1.975,600
Groundwater Use (acre-feet per year)	2,996,200	5,525,700	1,347,700
Remaining Groundwater (acre-feet per year)	1,694,500	943,800	627,900
Available Surface Water (acre-feet per year)	69,700,311	58,042,783	3,769,974
Surface Water Use (acre-feet per year)	1,391,400	994,000	1,689,900
Remaining Surface Water (acre-feet per year)	68,308,911	57,048,783	2,080,074
Precipitation, Annual (acre-feet per year)	2000-2500	1400-2000	900-1400
Runoff, Annual (acre-feet per mi^2)	150-1000	50-530	30-120
Net Lake Surface Evaporation (inches per year)	5-25	20-40	40-70
Evapotranspiration (inches per year)	39-42	42-45.5	45.5-54.5
Reservoirs (5000+ acre-feet)	17	9	3

Total average water requirements were computed for lignite mining operations with air-cooled and water-cooled processing systems (Fig. 33). Since air-cooling is less commonly used, the water-cooled figures are at present more realistic. For an air-cooled processing system, water needs for a mining operation might be 2000 - 6500 acre-feet per year, with in-situ gasification requiring the least amount of water. A wet-cooled processing system would cause mining water requirements to be 500 - 25,000 acre-feet per year, with cooling ponds or towers consuming the maximum amount.

Within all three sections available groundwater would play only a minor role, if any, in providing for mining water needs. Groundwater use throughout the state has reduced available supplies in storage to dangerously low levels. Therefore, water resources for mining use would be limited to surface water and precipitation.

The northeastern area of the lignite belt is lush and forested with fertile soils and moderate temperatures. Precipitation and runoff rates are high while net lake surface evaporation and evapotranspiration are low. Along with seventeen major reservoirs, available surface water as watercourse discharge reaches nearly 70 million acre-feet per year. This section will not be water limited in the future as far as extensive lignite resource development is concerned. Less water will be required for dust control and reclamation while abundant runoff will provide water for cooling ponds or once-through cooling. Thirty million acre-feet of surface water per year would support 1200 25,000-ton-per-day mining operations with maximum water requirements. Some groundwater will be available for mining needs if necessary.

The central section of the lignite belt will be somewhat water limited for lignite development. The climate is warmer and drier than

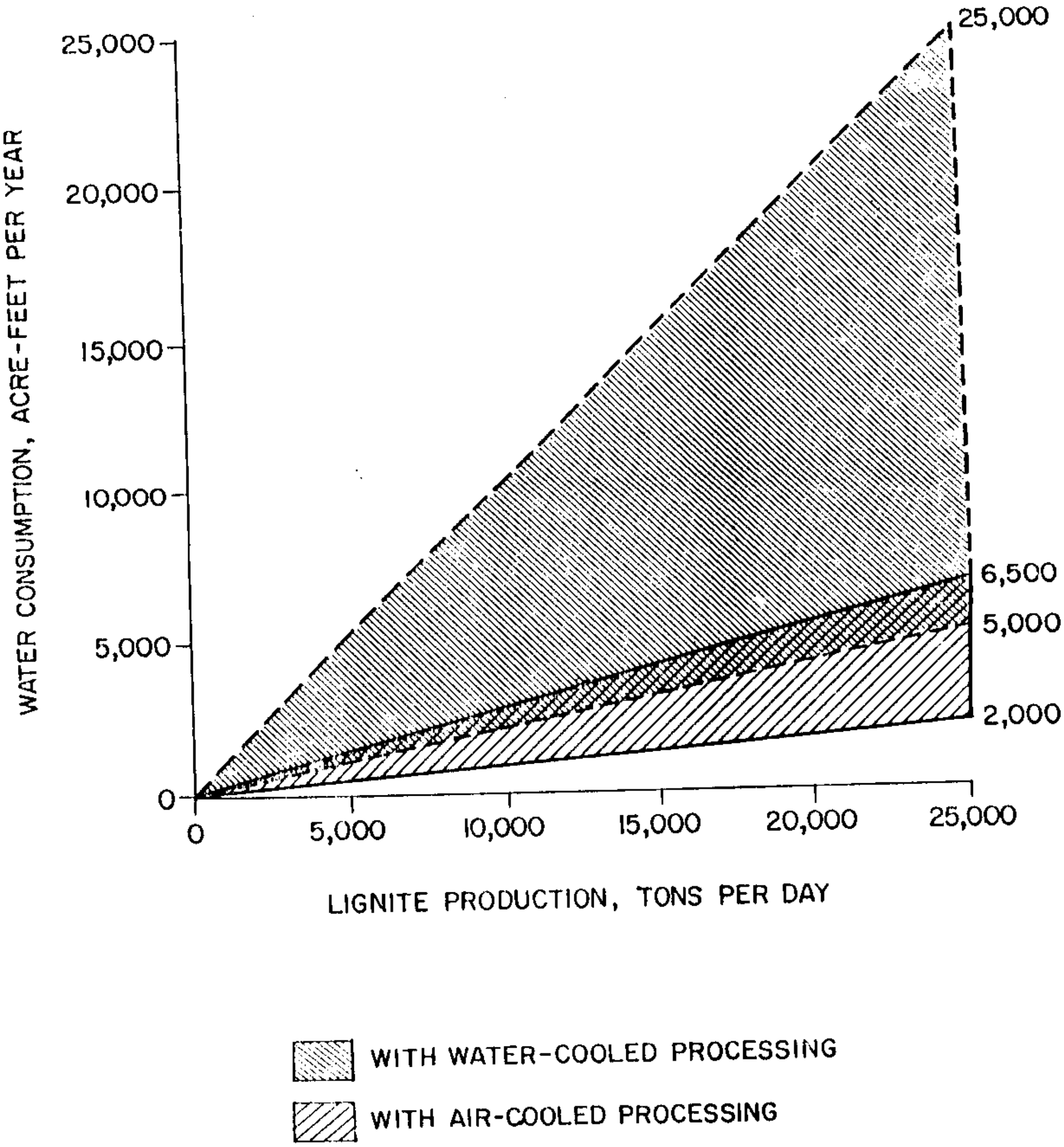

Figure 34. Total average water requirements for lignite production.

in the northeastern section and water needs for agriculture are higher. Surface water availability is estimated at 58 million acre-feet per year but precipitation and runoff rates are considerably lower than in the northeast. Evaporation and evapotranspiration rates are higher, creating an elevated water requirement for some mining operations. Nine major reservoirs serve this section. Water conservation-oriented mining methods will have to be implemented in order to retain the equilibrium of water use in this area.

The southern section of the lignite belt is and will be severly water limited for any resource development. Precipitation and runoff rates are extremely low and surface water availability barely reaches 2 million acre-feet per year. The extremely hot, dry climate raises net lake surface evaporation to three times that of the northeastern section. Evapotranspiration averages thirteen inches more than in the northeast. Only three reservoirs are available for use in this area and two of these are international reservoirs shared with Mexico. Water resources in this section will support only minimal development of lignite resources and then only with mining methods consuming minimum quantities of water.

The conclusion remains that the northeastern section of the lignite belt is the most suited to lignite development. Extensive rainfall provides natural dust control and irrigation water while runoff can be used to create cooling ponds or used in once-through cooling systems. If conservation and careful regulation are practiced, lignite mining should not affect water resources in this area adversely. In the central section more care will be needed to conserve the natural water resources. Mining operations and systems will have to be designed to use less water because more water will have to be alotted to things such as dust control and reclamation and less water is available overall. If necessary, limited mining could be practiced in the southern section with systems consuming the minimum amount of water. Evaporation and dust control will be major problems behind the basic extreme lack of water itself.

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