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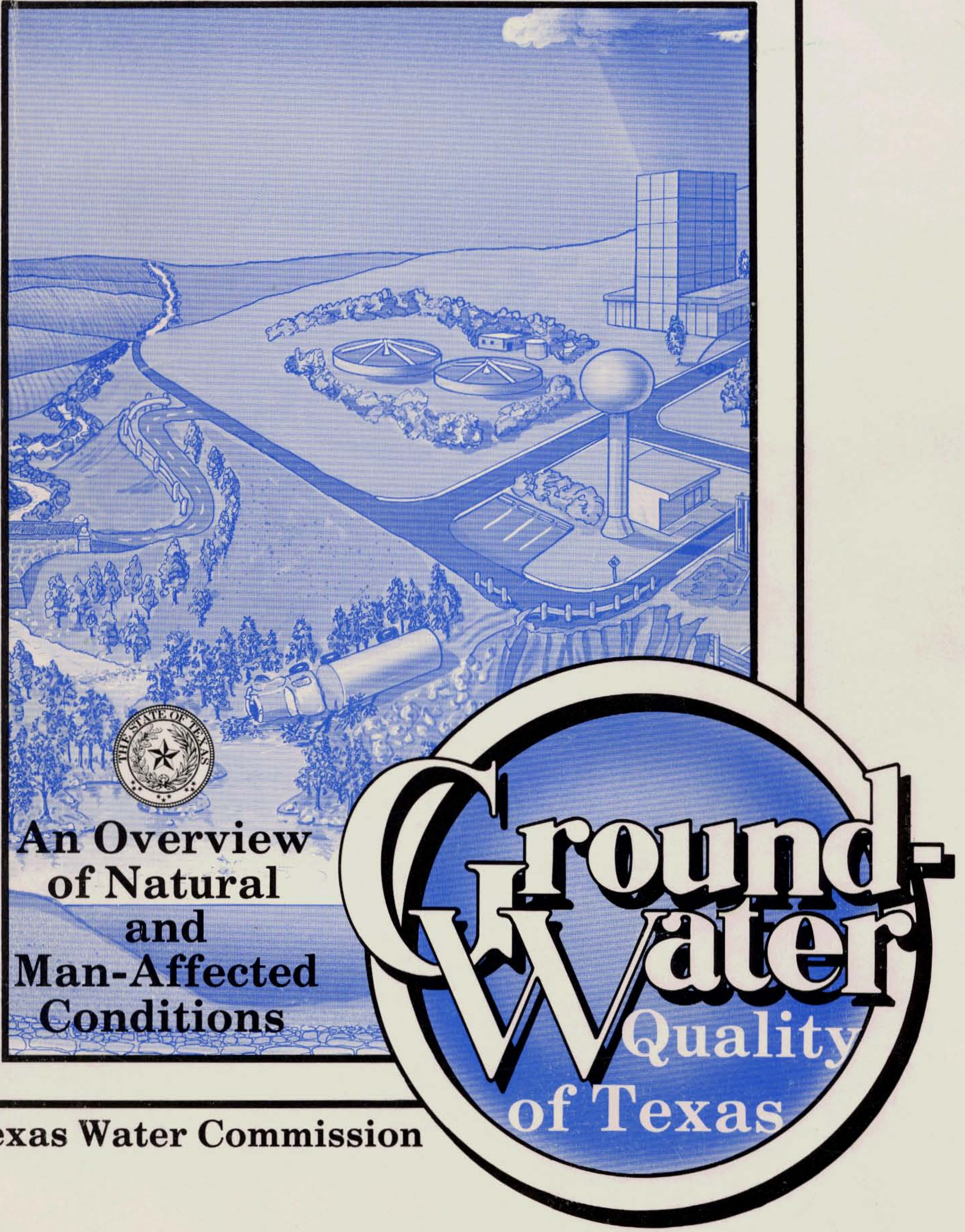

Ground-Water Quality of Texas

An Overview of Natural and Man-Affected Conditions

Texas Water Commission

THE STATE OF TEXAS

TEXAS WATER COMMISSION

Report 89-01

GROUND-WATER QUALITY OF TEXAS—AN OVERVIEW OF NATURAL AND MAN-AFFECTED CONDITIONS

COMPILED BY
GROUND WATER PROTECTION UNIT STAFF

March 1989

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SUMMARY OF RESULTS

Ground water is an important resource in Texas, and provides a major source of usable water. During 1984, the major and minor aquifers furnished about 57 percent the total state water requirements, or about 8.9 million acre-feet of the total annual need of 15.6 million acre-feet. These aquifers crop out or underlie approximately 76 percent of the state's surface area of about 276,300 square miles. As the ground-water stewards, it is essential that the responsible state agencies, as well as the public, exert every effort to preserve this valuable resource for future generations.

Data availability, time, funding, and cooperation from numerous people and organizations, will insure that the state has clean water. To accomplish this task, the Texas Water Commission has established close working relationships with the federal government, responsible state agencies, and local entities. Through these groups, a statewide ground-water protection strategy was developed.

During the development of the strategy, it was recognized that statewide definition of natural verses man-induced regional quality changes, ground-water pollution problems, and identification of known and potential sources of pollution was needed. This report is designed to outline the existing natural ground-water quality in the major and minor aquifers of the state, identify areas which are hydrologically sensitive to man-induced contamination, and delineate known or potential sources of natural and man-induced ground-water contamination.

Ground-water chemical composition changes along its flow path from recharge to discharge. Natural ground-water quality within an aquifer is dependent upon many factors including reactions which take place between the water and aquifer matrix; aquifer waters mixing with water containing a high percentage of ions, either through interaquifer exchange, inflow of basinal waters, or diffusion of marine connate water into the fresher water zones from muddier facies; and the flow velocity, distance along the flow path, and residence time of the ground water in the aquifer. The environment under which the aquifer sediments were deposited will influence the chemical character of the water, due to permeability variations; orientation of thicker, more permeable units; and chemical composition of the lithologic units. Ground-water chemical quality between individual aquifers within the state will vary, due to the difference in lithologic and hydrologic conditions.

Natural contamination probably affects the quality of more ground water in the state than all other sources of contamination combined. Leaching is the result of the interaction between water and the aquifer matrix, substances tied up in the soil zone, and/or minerals in the watershed. Discharge from deeper, more saline, aquifers can contribute additional mineralization to ground water, increasing its salinity. Natural contamination can take many forms including increased mineralization; the addition of toxic substances including metals, nitrates, and radioactivity; and the addition of excessive nuisance minerals such as iron, sulfate, or chloride which may give the water an undesirable color, odor, or taste.

Suitability of ground water for municipal, industrial, rural, irrigation, and other uses is determined by the amount and type of minerals present in the water. One of the main factors which limits the use of ground water is the total dissolved solids (TDS) concentration. Most aquifers contain water which ranges from fresh, less than 1000 ppm (parts per million) TDS, to brine, greater than 35,000 ppm TDS. Waters for irrigation use of less than 480 mg/L (milligrams per liter) TDS are considered to pose no problem under ordinary conditions, however, universal standards have not been formulated. High TDS is usually avoided for industrial water supplies. TDS concentrations were mapped for all major and select minor aquifers. Generally, TDS concentration increases downgradient from recharge areas. Topography, surface drainage pattern, and faults have visible effects on the mapped regional water quality trends within an aquifer and may be responsible for some identified areas of natural contamination.

Individual discussions of natural pollutants, such as sulfate, chloride, iron, nitrate, and radium, include natural sources, recommended limits in drinking water, known health effects (if any), and limits based on health or esthetic reasons such as taste, color, odor, staining, and scaling. Because 78 percent of all the ground-water pumped in Texas in 1984 was used for irrigation, and the nuisance of high concentrations when present in drinking water, areas that exceed the secondary drinking water standard of 300 mg/L for sulfate and chloride were mapped for the major aquifers. Excessive amounts of iron forms a red precipitate which stains laundry and plumbing fixtures, gives water an irony taste, and can clog pipes and well screens. Areas where the secondary drinking water standard of 0.3 mg/L for iron were exceeded are mapped for the Carrizo-Wilcox aquifer.

Nitrate, the most common contaminate of ground water, is very mobile and does not absorb onto the aquifer material or precipitate as a mineral. Natural processes which may add nitrate to the ground water include precipitation, mineral weathering, and decay of organic matter. Nitrate (as N) in concentrations greater than 10 mg/L can produce anoxemia and even death by asphyxia in infants under three months of age and in the human fetuses. Although determining the exact source and relative contribution between man-induced and natural causes of nitrate contamination was not feasible for this report, maps showing the locations of wells or areas where the primary drinking water standard for nitrate has been exceeded were made for the High Plains (Ogallala), Edwards (Balcones Fault Zone), and Alluvium and Bolson Deposits aquifers.

Radium is a naturally occurring radioactive nuclide, and the most abundant isotope, radium-226, is the most toxic of all inorganic material, and decays into radon-222, a water soluble gas. Radium is absorbed by the bone tissue, with bone cancer being the greatest health risk. Exposure to radon gas can cause lung cancer. Locations of counties where the limit for radium has been exceeded in the public drinking water supplies, and the location of geologic trends, statewide, that contain potentially radioactive waters were mapped. Gulf Coast and Hickory aquifer discussions contain additional information on specific areas and sources of high radium concentration.

Pollution potential mapping was carried out with the objectives of delineating areas of the state sensitive to contamination of ground water and developing tools for decision-making. Two maps illustrating ground-water pollution potential for general and agricultural sources of pollution were constructed. In addition, the relative ranking of both major and minor aquifers in the state according to their potential for contamination from the land surface was determined. Finally, areas of the state which received high pollution potential indices were compared with known contamination incidents to test the validity of DRASTIC in predicting the potential for aquifer contamination.

DRASTIC mapping can be used as a tool in combination with other information sources for developing ground-water management and protection plans. Ground-water protection programs can utilize these maps to delineate priority areas for program action. Regional and local planners can also use the maps to provide guidance for zoning, community action, and water resource planning.

This particular methodology (DRASTIC), while presenting a means for identifying areas sensitive to ground-water pollution, does not take into account certain aspects of the hydrologic cycle. Interpretation of pollution potential maps depends upon an understanding of just how the methodology works and what is and is not considered during a DRASTIC evaluation. Information relating to human use, water quality, or existing features which affect the aquifer is not considered here. It is important to understand that DRASTIC does not stand alone as an interpretive tool, however, it can be concluded that pollution potential mapping, when viewed in the light of its inherent limitations, can be an effective tool for setting priorities and decision-making.

The quality of ground water in the state is generally good; however, localized areas have been impacted by sources of contamination which are not located at a specific point, or noncompliant waste disposal activities. This has caused pockets of pollution immediately around the source, but no resulting aquifer-wide quality problems. The susceptibility of a facility site to ground-water contamination depends in part on the hydrogeologic setting. If ground water does become contaminated, it is extremely difficult to clean up. Therefore, the regulatory philosophy is to prevent contamination from occurring in the first place.

Man induced ground-water contamination usually involves substances released on or slightly below land surface and, therefore, shallow aquifers are normally considered more susceptible to pollution than the deeper aquifers. Current data suggests that, for the most part, pollution is regionally confined to the most heavily populated and industrialized areas of Texas. However, isolated local cases of ground-water contamination have been found in many other parts of the state. At this time, it is not thought that the usefulness of ground water has been appreciably reduced statewide. Probably less than one percent of the state's ground water has been contaminated by man. However, due to the sparsity of data, "only the tip of the iceberg" may have been assessed.

Contamination found in the ground water ranged in degree from slight degradation, in the case of septic tanks, to the presence of toxic concentrations of contaminants, such as heavy metals, organics, and inorganics (including pesticides), which were present in abandoned hazardous waste facilities. Additionally, minor amounts of pesticides, related to agricultural activities, have been detected in the state's ground waters. In most cases, ground-water contamination was discovered only after a drinking water source had been affected. There are several known cases where municipal water supply wells have become unusable due to contamination. Numerous instances of private wells being affected were noted during the investigation.

Based on this statewide assessment of potential and actual ground-water contaminants, waste disposal practices being employed, and existing regulations which are available for contamination detection and mitigation, it was concluded that there are still conditions which exist or practices being used which are a cause for concern. For the most part, the state presently has in place regulations which will effectively reduce future pollution, however, past practices may return to haunt us. It is difficult to prioritize areas or practices of concern, however, based on best professional judgement, the following are considered to be of major concern.

Improperly completed and abandoned water wells are possibly of greatest concern. These wells allow direct access from the surface to ground-water aquifers by permitting vertical leakage from the surface. Most pesticides presently found in ground water are believed to have moved to aquifers through wells of this type. Interaquifer transfer of high TDS water is also believed to be occurring between different water-bearing zones encountered by these wells. Additionally, a safety hazard to humans and animals is posed by this category of wells. It is conservatively estimated that statewide there may be at least 600,000 total wells, of which about 150,000 are believed to be abandoned. Shallow wells which are used for agricultural drainage, stormwater runoff disposal, heat pump / air conditioning exchange, sewage disposal, mine backfill spoil disposal, automobile service station disposal, and artificial recharge purposes may also provide avenues for possible contaminants to reach the underlying aquifer.

Septic tanks, used for disposal of human waste, discharge large volumes of effluent directly to water-bearing units. If these septic systems are not properly sited, constructed, or employed, this waste disposal practice becomes a threat to ground water. There are more than one million older tanks scattered throughout the state. It is these older tanks which are of primary concern. Newly constructed tanks will be adequately controlled under revised regulations.

Industrial waste-water impoundments are used to handle large volumes of waste in a concentrated area. In the past, all types of industrial impoundments have locally polluted ground water and almost every county of the state could possibly have been affected by these disposal units. Until 1969, thousands were used for disposal of salt water associated with oil and gas production. With the exception of previously abandoned salt water disposal impoundments, regulations for the cleanup of pollution are in place. Chemical quality maps included in this report, indicate that a plume of salt water may be present below many of these now abandoned salt water pits. Since there are so many of these, it is not known if it would be economically or technically feasible to attempt to mitigate these ground-water problems. Possibly contamination should be addressed on a case-by-case basis as it becomes a problem. → WHEN IT BECOMES A PROBLEM [illegible]

Underground storage tanks often lie within the vadose zone or where continually saturated conditions exist at shallow depths. Therefore, when they leak, high concentrations of contaminants may reach the ground water. Underground storage tanks are considered to be one of the principal contributing sources of ground-water pollution, placing a significant loading on the state's aquifers, due to their regional distribution and high number which are estimated to be leaking. Statewide, there should be about 154,000 tanks which will ultimately be registered. It is now estimated that about 38,500 could eventually leak. As of July 12, 1988, there were about 1000 confirmed leakers. At that time, the Texas Water Commission was receiving notice of confirmed leakers at the rate of about 50 per month. Leakers, which have contaminated ground water, are being actively mitigated.

Based on a recent study, past disposal practices associated with municipal sanitary landfills may have already resulted in, or ultimately will contribute significantly to ground-water pollution. Historically, this contamination has been caused by siting these facilities in areas where the bottom of the landfill encountered the water table. Additionally, almost all of the older operations lacked proper liners, leachate collection systems, and/or did not have ground-water monitoring wells. The Environmental Protection Agency is now in the process of developing new rules related to the operation of municipal solid waste landfills.

Within agricultural producing areas, located primarily in north-central Texas, there are localities where excessively high nitrate content is present in ground water. Much of this is believed to be naturally occurring, however, over fertilization and seepage from barnyards and/or septic tanks may also be causes. Recently, pesticides have also been documented in ground water in these and other agricultural areas. Both high nitrates and pesticides in ground water are problems which require additional attention. To address these problems, a statewide agricultural chemical (fertilizer and pesticide) ground-water strategy will be developed in the immediate future. Additionally, since high nitrate-bearing materials and waste waters are used in land spreading operations, there should be a revaluation of the use of these wastes within the affected areas.

INTRODUCTION

One of Texas' most treasured natural resources is its surface and ground water. The general public has come to expect an abundance of inexpensive, clean, and environmentally safe water at the turn of the tap. Ground water provides the major source of usable water within Texas. During 1984, the major and minor aquifers furnished about 57 percent of the state's total water requirements or about 8.9 million acre-feet of the total annual need of 15.6 million acre-feet (Texas Water Development Board, 1988).

Almost daily, the public reads or hears of numerous ground-water conditions or water-related issues which are a cause of concern, such as declining water levels, land-surface subsidence, and saline-water encroachment as well as ground-water pollution which has resulted from many of man's activities. These concerns and other hydrologic events have raised numerous questions about the status of the state's ground-water resources. What is the natural ground-water quality? What changes to the natural quality are taking place? What type of contamination is occurring? How does man contaminate ground water? How extensive is ground-water contamination? How sensitive is the ground water to contamination? What is being done to combat quality changes which are taking place?

To answer these questions and many others, it is necessary to assess, analyze, and evaluate existing hydrologic data, as well as evaluate waste disposal and chemical use practices that are currently being employed. A periodic evaluation of statewide ground-water conditions, both natural and man-induced, can aid in the identification of deficiencies in the type of water-related information being gathered, waste disposal practices being employed, and present regulatory practices, and it also can serve as a tool for developing future water-policy options, including the formation of underground water conservation districts, the establishment of wellhead protection areas, and development of future regulations, if deemed necessary. As the lead agency in Texas with the responsibility for protecting and restoring the quality of surface and ground water, the Texas Water Commission is responsible for making such an evaluation and for coordinating the state's efforts to develop and implement a comprehensive ground-water protection strategy.

This report is intended to describe and analyze the conditions which affect the quality of the state's ground-water resources. It is organized into the following four parts, each of which is independent, but related to the others:

General hydrologic principles of ground water and definition of terms, which provides a synopsis of hydrologic processes including short discussions on the hydrologic cycle, how ground-water occurs, the interrelationship between surface and ground water, hydrochemical evolution of ground water, how ground water becomes contaminated, and the general chemical quality of ground water. This section provides background information for aquifer chemical quality, pollution potential estimates, and man-induced contamination hazards discussed in subsequent parts of this report.

Chemical quality of the major and minor aquifers, which discusses the naturally occurring ground-water quality within the seven major and seventeen minor aquifers of the state. Aquifer specific data is presented on naturally occurring hydrologic processes, such as mineralization due to aquifer matrix - water interactions and interaquifer exchange (both of which are considered for this report to be sources of natural contamination). Total dissolved solids, sulfate, and chloride concentration maps are included in each major aquifer section and, where there is a recognized problem, areas and possible causes of excessive concentrations of nitrate, radium, or iron are examined. General water quality is discussed for all minor aquifers, with total dissolved solids concentration trends and quality problems provided for selected minor aquifers.

DRASTIC - a systematic approach to ground-water pollution potential mapping, which identifies statewide areas which are hydrologically sensitive to man-induced contamination. The DRASTIC methodology is explained through a discussion of the underlying principles and the difference between general and agricultural DRASTIC mapping is highlighted. Statewide pollution potential maps are presented and the use of pollution potential mapping as a tool is discussed.

An assessment of known and potential sources of man-induced ground-water contamination within Texas, which summarizes brief assessments of many categories of pollution, caused by man, which may degrade the aquifers of the state. Major categories addressed are land disposal of waste materials; water wells; sewage and waste-water disposal systems and municipal sewage collection lines; leaks and spills; oil and gas production and other mining; agricultural practices; class V injection wells; stormwater runoff; other possible ground-water pollution sources; and ground-water withdrawals. Each of these contain numerous subcategories with discussions of potential contaminants, nationwide problems, a statewide assessment, the responsible state agency, and the existing regulatory programs employed to prevent or mitigate pollution.

Purpose and Scope

The primary purpose of this investigation was to expeditiously determine the existing water quality of the major and minor aquifers of the state, identify areas which are hydrologically sensitive to man-induced contamination, and delineate known or potential sources of ground-water contamination. The general scope of this investigation included the evaluation, synthesis, and mapping (on an aquifer by aquifer basis) of both previously compiled hydrochemical data in the published literature and data available in the Commission computer data base files; generation of state wide maps illustrating ground-water pollution potential; and synthesis and evaluation, on a statewide basis, of man-induced ground-water pollution.

Methods of Study and Limitations

Principal objectives of this investigation were to establish a base line profile of current water quality of the state, to identify and rank areas which are sensitive to ground-water contamination, and to assess and evaluate man-induced ground-water pollution. To accomplish the first objective, it was necessary to review previous water-quality reports and investigations covering major and minor aquifers of the state. The most recent information was reviewed with emphasis placed on regional reports. Sources of information were found in the libraries, files, and reports of the Texas Water Commission, Texas Water Development Board, U.S. Geological Survey, and the University of Texas Bureau of Economic Geology. Where insufficient compiled data exist, the computerized statewide water quality data base was utilized.

Based on the available data, major and minor aquifer water-quality maps were either modified from existing work or constructed from the data in the computerized system. Data acquired from the existing computerized data base required filtering before the maps were constructed, with only the most recent analysis for an individual well being utilized. Maps were constructed for all major and specific minor aquifers, illustrating total dissolved solids (TDS) concentrations using 500, 1000, 3000, and 10,000 TDS contour intervals. Generally, the boundaries of the aquifers as delineated in December, 1982, by the Texas Department of Water Resources were used, however, some of the areas have been revised and/or extended to reflect more recent work. Specific problem constituents, that occur in some aquifers, were delineated on separate aquifer inset maps, such as high sulfate and chloride concentrations which exceed the recommended drinking water standards, or known areas of high constituent concentrations, such as high iron in the Sabine Uplift area, high nitrates in North Central Texas, high arsenic in the High Plains, or high radium. All water-quality maps presented in this report represent a regional estimate of quality trends. Local quality may vary from the regional trends and caution should be exercised if the maps are used to predict specific water quality in an area.

The second objective of this investigation was accomplished through the creation of maps which depict statewide hydrologic sensitivity to surface contamination, using the DRASTIC methodology. DRASTIC uses a relatively straightforward process of data collection and evaluation to create maps which represent vulnerability to pollutants in the ground water. Readers interested in a more detailed explanation of the DRASTIC methodology are referred to the EPA Report entitled "DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings," (Aller and others, 1987).

The assessment of known and potential sources of man-induced ground-water contamination, the third objective, was severely restricted by: the fact that most land disposal practices being assessed lacked ground-water monitoring facilities; most data found did not indicate the condition of ground-water quality, and there was an acute shortage of data which located potential or known pollution problems. This assessment, which is limited in scope, was made using easily accessible existing data, which in some cases, was far from complete. Sources included questionnaires obtained from personnel of the Texas Water Commission district field offices and the Commission's extensive water related library which contained data from multi-state agencies, the U.S. Geological Survey, ground-water consultants, some underground water conservations districts, and numerous state universities including the University of Texas Bureau of Economic Geology.

Additionally, technical and assessment data generated by the U.S. Environmental Protection Agency were used extensively. Also included were categories of pollution related to nonpoint sources. These data were provided by members of a Task Force composed of members selected by participating agencies which make up the statewide Ground Water Protection Committee. Agencies represented by this Task Force were the Texas Water Commission (lead agency), the Texas Water Development Board, Railroad Commission of Texas, Texas Department of Health, Texas Department of Agriculture, the Texas State Soil and Water Conservation Board, and the Texas Agricultural Extension Service.

Background

Texas is a very large and diversified state. Compared to other states, it is second in size only to Alaska. With a total area of 267,338 square miles (about 171 million acres), approximately 167.8 million acres consist of land area and about 3.3 million acres are covered by inland water (Kingston and Harris, 1983).

The climate of the state is varied. Mountainous conditions prevail in parts of the Trans-Pecos Region of West Texas contrasted by a subtropical arid climate in the surrounding lowlands. Humid subtropical conditions occur in the Coastal Plain. Average annual precipitation ranges from eight inches in El Paso County to 56 inches in eastern counties (Beaumont area). Temperatures also vary widely with average monthly lows during January ranging from 18° Fahrenheit(F) in the northwest corner to 51°F in the extreme southern part. The hottest temperatures of the summer months occur during July when average monthly highs vary from 91°F in the state's northwest corner to 100°F or greater in the south-southwest part of the state (Larkin and Bomar, 1983).

Geologically, the state is also varied. Its surface geology consists of igneous, metamorphic, and sedimentary rocks; however, sedimentary units are the dominant type. Major physiographical subdivisions consist of the Rocky Mountain Region (foothills of) in the west-southwest, the Great Western High Plains, the Great Western Lower Plains, and the Gulf Coastal Forested Plains. These features and favorable soils enable Texas to be one of the most prominent agricultural states in the nation and to rank highly in nearly every phase of agricultural production.

Texas has a varied topography with its surface elevations ranging from 8751 feet at Guadalupe Mountain, located in Culberson County in the western part of the state, to sea level along the Gulf Coast on the southeast. This elevation differential results in all of the state's major streams flowing to the east-southeast.

Industry within Texas differs greatly by region; however, major statewide industries are: hydrocarbon production, energy related services, and processing; agribusiness; manufacturing; mining and related activities; forest products; finance, banking, and trade; commerce and shipping; and fishing. Both agribusiness and energy production in Texas are currently suffering serious economic problems.

In addition, the following background information is made available to the reader to aid in the assessment of data contained in this report:

State population: 14,229,191 (1980 Texas Water Development Board (TWDB) data); 16,369,586 (1985 TWDB data)

Rural population: 3,080,544 (1980 TWDB data); 3,752,992 (1985 TWDB data)

Population density: 54.3 persons per square mile (one of lowest densely populated states in the nation, 1980)

Breakdown of land use: (January 1, 1983—Kingston and Harris, 1983)

Use	Acres
Cropland	30,430,000
Pastureland	18,773,000
Rangeland	95,401,000
Forestland	9,240,000
Urban and Transportation	7,310,000
Other land	3,725,000
Federal	2,887,000
Total land area	167,766,000

Number of river or coastal basins: 23 basins (Figures 1 and 2)

Total streambed miles: 80,000 stream miles

Classified stream miles: 15,942 stream miles

Total stream segments: 311 segments

Number of major lakes or reservoirs with capacity greater than 5000 acre-feet (January 1, 1983): 189 lakes or reservoirs

Total lake or reservoir capacity: 58.6 million acre-feet

Total area of lakes or reservoirs with capacity greater than 5000 acre-feet: Greater than 1,616,781 acres (for 186 lakes or reservoirs)

Area of marsh and wetlands: 400,000 acres

Area of bays and estuaries adjacent to coast: 2350 square miles

Miles of coast bordering Gulf of Mexico: 367 miles

Names and mileage of border rivers:

Sabine River	180 miles
Red River	480 miles
Rio Grande	1200 miles

Average annual runoff (streamflow): 49 million acre-feet

A total of seven major and seventeen minor aquifers have been delineated within Texas (Figures 1 and 2). Based on data supplied by the U. S. Geological Survey, it is conservatively estimated that there is a total of approximately nine billion acre-feet of potable ground water in storage within Texas (West and Broadhurst, 1975; Baker and Wall, 1976; and Bedinger and Sniegocki, 1976). At present, it is not known how much of this can be considered as recoverable storage without causing irreparable damage to the states aquifers.

The estimated average annual quantity of ground water available from the state's aquifers was 12.9 million acre-feet in 1980 and is expected to decrease to 9.6 million acre-feet in 2030 based on current and projected rates of water use (Texas Water Development Board, 1988). In 1984, Texans used 8,854,470 acre-feet of ground water, with pumpage for irrigation supply in the High Plains accounting for 60 percent and other significant pumpage occurring in the Houston and San Antonio areas (Texas Water Development Board, 1988). Of the total ground water pumped in the state in 1984, approximately 78 percent was used for irrigation supply, 17 percent for municipal supply, 2 percent for manufacturing supply, and 1 percent each for livestock, electric, and mining supplies (Texas Water Development Board, 1988).

GENERAL HYDROLOGIC PRINCIPLES OF GROUND WATER AND DEFINITION OF TERMS

Hydrologic Cycle

For the benefit of the general reader, this section is included for familiarization with some basic ground-water hydrologic principles and terms. Portions of the following discussion borrow heavily from Muller and Price (1979, p. 3 - 8).

Water is constantly moving between the ocean, atmosphere, and land. Water available for use by man - whether as rain, water from wells, or stream flow - is captured in transit, and after its use and reuse, is returned to the hydrologic cycle from which it came. **Ground water** is part of the returning water which has entered the subsurface and filled the void spaces of the porous rocks which are within the zone of saturation. The primary source of ground water is precipitation. Only a small percentage of precipitation actually reaches the ground water by the process of recharge.

Figure 3 graphically illustrates the continuing movement of ground water from infiltrating rainfall to movement down gradient through the aquifer to disposition either by evapotranspiration (evaporation and plant transpiration) or discharge to wells, rivers,

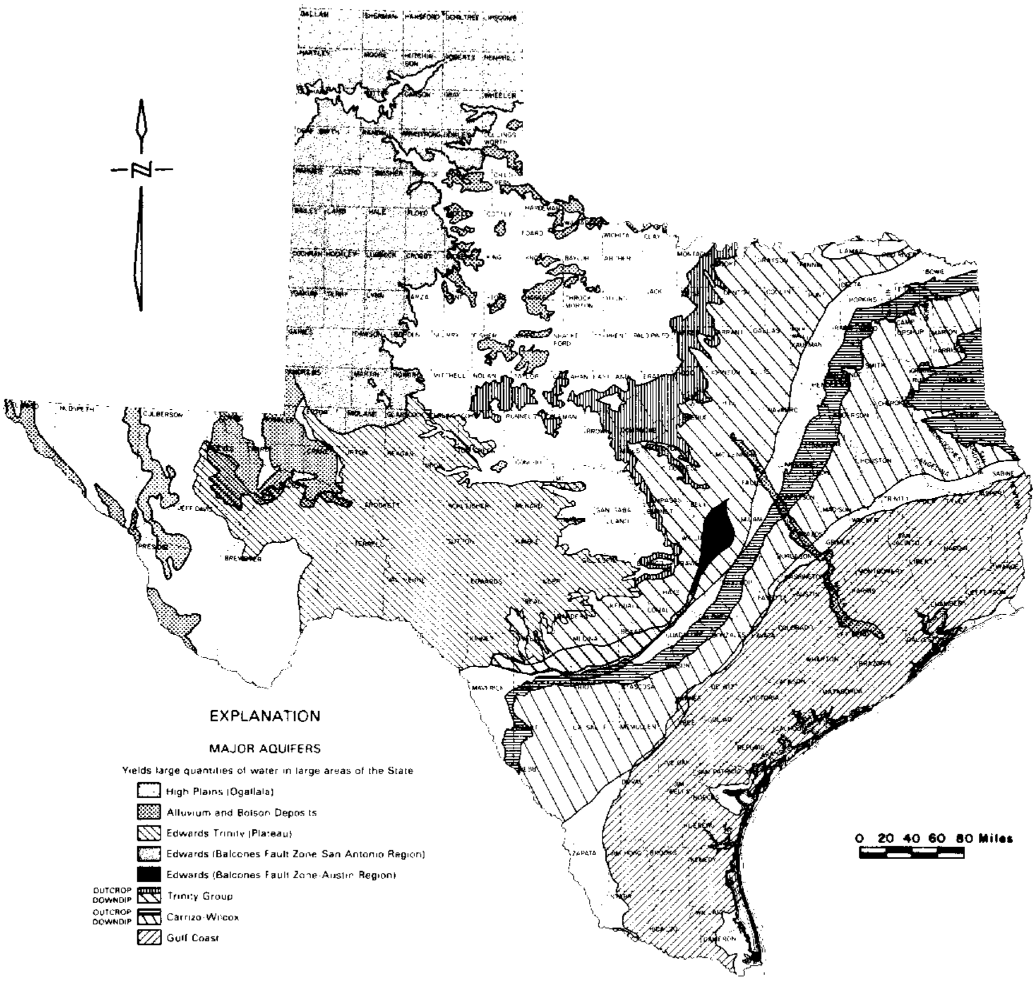


Figure 1

Major Aquifers of Texas

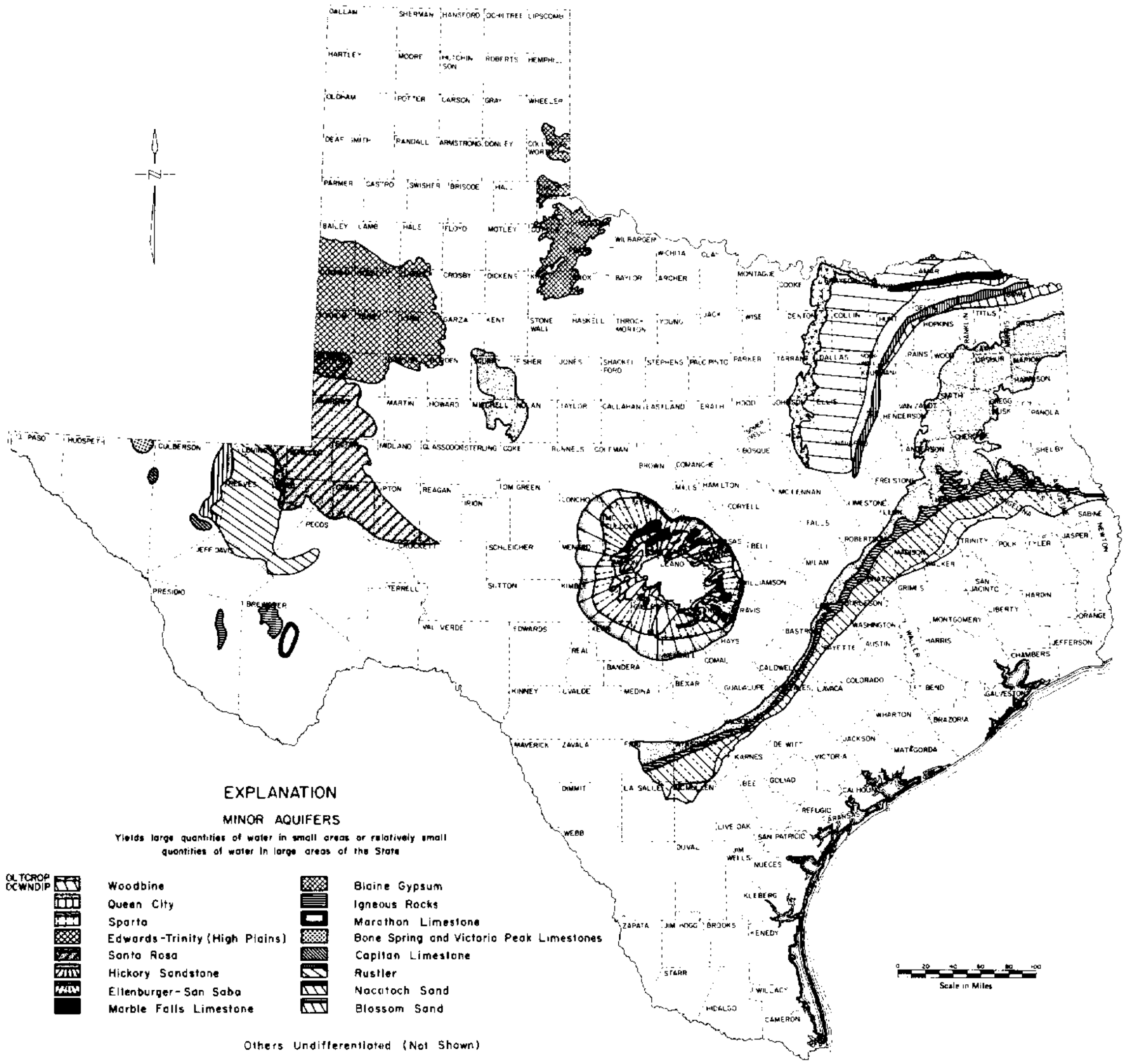


Figure 2
Minor Aquifers of Texas

streams, and ultimately the ocean. **Recharge** is the addition of water to an aquifer and may be absorbed from precipitation, streams, and lakes, either directly into a formation or indirectly by way of another formation. Also, it may mean the quantity of water which is added to the zone of saturation (Meinzer, 1923). **Effective recharge** is the amount of water that enters an aquifer and is available for development. Among the factors which influence the amount of recharge received by an aquifer are: the amount and frequency of precipitation; the aerial extent of the outcrop or intake area; topography, type, and amount of vegetation, and the condition of soil cover in the outcrop area; and the ability of the aquifer to accept recharge and transmit it to areas of discharge.

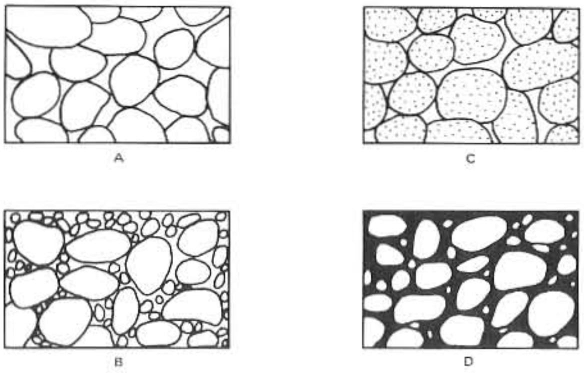
Ground water moves from areas of recharge to areas of discharge or from points of higher water level to points of lower water level. Movement is in the direction of the hydraulic gradient just as in the case of surface-water flow. Under normal artesian conditions, movement of ground water usually is in the direction of the aquifer's regional dip. Under water-table conditions, the slope of the water table and consequently the direction of ground-water movement usually is closely related to the slope of the land surface. However, in the case of both artesian and water-table conditions, local anomalies are developed in areas of pumping and some water moves toward the center of artificial discharge.

Discharge is the loss of water from an aquifer. Discharge may be either artificial or natural. Artificial discharge takes place from flowing and pumped water wells, drainage ditches, gravel pits, and other excavations which intersect the water table. Natural discharge occurs as effluent seepage, springs, evaporation, transpiration, and interformational leakage (Peckham, 1965).

Occurrence

The quantity of water an aquifer receives as recharge and the ability of the aquifer to transmit water to the areas of discharge are the principal factors that must be considered in determining the amount of water available for withdrawal on a sustained basis. The following discussion of how and where water occurs within aquifers borrows heavily from Muller and Price (1979, p. 3 - 8).

Ground water is contained in the interstices or void spaces of rocks. Two rock characteristics of fundamental importance related to the occurrence of ground water are **porosity**, which is the amount of open space contained in the rock; and **permeability**, the ability of the porous material to allow fluids to move through it. In sedimentary rocks, such as sandstone, gravel, clay, and silt, the porosity is a function of the size, shape, sorting, and degree of cementation of the grains (Figure 4). In limestone and evaporites (other types of sedimentary rocks) porosity is a function of openings such as cracks, crevices, caverns, and vugs caused in part by dissolution of the rock matrix by ground water.



A. Well sorted sedimentary deposit having high porosity.

B. Poorly sorted sedimentary deposit having low porosity.

C. Well sorted sedimentary deposit consisting of pebbles that are themselves porous, so that the deposit as a whole has a very high porosity.

D. Well sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter (cementation) in the interstices.

Figure 4.—Relationship of Rock Texture to Porosity (Adapted From Meinzer, 1923, p. 3).

Fine-grained sediments, such as clay and silt, usually have high porosity, but due to the small size of the voids, the permeability is low and these formations do not readily yield or transmit water. Therefore, in order for a geologic formation to be an aquifer it must be porous, permeable, and water-bearing. An **aquifer** is made up of saturated permeable rocks of a geologic formation, group of formations, or part of a formation that is water-bearing (Meinzer, 1923). In general, to be an aquifer, the water-bearing formation should yield water in sufficient quantities to provide a useable supply; otherwise, the formation may be termed either an aquitard or aquiclude. Figure 5 depicts areas within the state in which no major or minor aquifer is present. An **aquitard** is a semipermeable, semiconfining geologic formation adjacent to or between aquifers and partially restricts the movement of ground water. Clay lenses interbedded with sands are characteristic of "leaky" aquitards. Where clay is sufficiently thick and widespread, it is called an **aquiclude** and is usually impervious, an impediment to ground-water movement, and acts as a confining layer to the aquifer. Considerable quantities of ground water can be stored in the clay interstices.

When precipitation falls on the outcrop of an aquifer, it may take one of many courses in completing the hydrologic cycle. A large portion of it returns to the atmosphere by evaporation. Vegetation utilizes a part of the water and returns moisture to the atmosphere by transpiration. Some of the precipitation will run off the land surface into streams and return to the sea. A small percentage will percolate downward through the soil zone by the force of gravity to the **zone of saturation** in which the hydrostatic pressure in the water-filled interstices of the permeable rocks of the aquifer is equal to or greater than atmospheric pressure (Meinzer, 1923). The upper surface of this zone is called the **water table**. Water entering the zone of saturation moves to lower elevations where it is discharged naturally, for example, by springs or artificially by wells. Above the zone of saturation, the rock interstices are partially filled by moisture and partially by air, and is known as the **zone of aeration, unsaturated zone, or vadose zone**. Occasionally, a local impermeable layer is present in this zone above the water table, and it will intercept the downward percolating water, creating a perched saturated zone above the main water table causing a **perched water table** of limited aerial extent.

An aquifer is considered to be under **water-table conditions** or **unconfined** when the ground water is in direct contact vertically with the atmosphere. The water surface fluctuates with atmospheric pressure and in response to a change in the volume of water in storage within the aquifer. In an unconfined aquifer, the zone of saturation extends from the water table to the underlying confining bed. The aquifer is **confined** when the ground water contained in it is separated from the atmosphere by impermeable material of a confining bed and the water is under sufficient pressure to rise above the level at which it is encountered by a well. In this case, the water is under **artesian conditions**, whether it flows at the land surface or not, and the level to which the water will rise in a borehole defines an imaginary surface called the **piezometric surface**. For a confined aquifer, the zone of saturation represents complete saturation of the water-bearing unit and is equal to its thickness. The term **potentiometric surface** applies both to the piezometric surface of a confined aquifer and the water-table surface of an unconfined aquifer, coinciding with the hydrostatic pressure level of the water in the aquifer (Todd, 1959).

The **hydraulic gradient** or **pressure gradient** of an aquifer is exemplified by the slope of the potentiometric surface. It is the rate of change of the hydrostatic pressure per unit distance in a given direction. If the rate of change is uniform between two points, the hydraulic gradient between these points is the ratio of the difference in static level between the points to the horizontal distance between them (Meinzer, 1923). The **hydrostatic pressure** is the pressure exerted by the water at any given point in a body of water at rest. Hydrostatic pressure of ground water is generally due to the weight of the water at higher levels in the zone of saturation (Meinzer, 1923).

The water-producing capability of an aquifer depends upon its ability to store and transmit water. Although the porosity of a rock is a measure of its capacity to store water, not all of this water in storage may be recovered by pumping. Some of the water stored in the interstices is retained because of the molecular attraction between the rock particles and the water. The **coefficient of storage** is the volume of water an aquifer releases from or takes in to storage per unit surface area of the aquifer per unit change in the component of hydrostatic pressure normal to that surface (Ferris and others, 1962). In confined or artesian aquifers, it is the result of two elastic effects–compression of the aquifer and expansion of the contained water–when the hydrostatic pressure is reduced by pumping. The value of the coefficient of storage is small, and is dimensionless. In the unconfined case, the storage coefficient is also dimensionless and is assumed equal to the specific yield of the material. The **specific yield** measures the water removed from an aquifer by the force of gravity. It has been defined as the ratio of the volume of water which an aquifer, after being saturated, will yield by gravity to the volume of the aquifer drained. The ratio is usually expressed as a percentage (Meinzer, 1923).

Interrelationship Between Surface and Ground Water

An understanding of the interrelationship between surface water and ground water is important in the interpretation of both regional and local hydrologic conditions. In humid and semiarid areas such as those found in most of Texas, an aquifer's water table, in outcrop, normally conforms to the surface topography. Usually, the water table is high beneath topographically high areas and its hydraulic gradient slopes away from the divides (recharge areas) toward the low areas which serve as ground-water discharge zones (U.S. Environmental Protection Agency, 1987b, p. 56-58). Ground water may eventually flow into a stream or body of surface water. Approximately thirty percent of the nation's surface-water flow is provided by ground water (Feliciano, 1985).

Under normal conditions, ground-water discharge may account for a stream's entire flow, during dry weather. During flood stages, the hydraulic gradient may develop a higher potential than that of ground water. When this happens, a reversal of flow occurs and any contaminants in the surface water may enter the ground-water system (U.S. Environmental Protection Agency, 1987b, p. 4). When ground-water pumpage near a stream lowers the water level sufficiently, a reversal of flow may also occur which induces vertical leakage from a nearby stream or lake. Under these conditions, contamination of the most permeable shallow aquifers can easily occur.

When ground-water discharges to a surface-water body, it can affect the surface-water quality. Most ground-water aquifers contain water which ranges from fresh, less than 1000 milligrams per liter (mg/L) or parts per million (ppm) total dissolved solids (TDS), to brine, greater than 35,000 ppm TDS. In general, the quality and availability of ground water degrades or diminishes from east to west across Texas. Natural surface-water quality varies widely within the state. Total dissolved solids concentrations of streamflows range from less than 100 mg/L in the extreme eastern part of the state to 3000 mg/L or greater in the upper reaches of the Red, Brazos, and Pecos Rivers, as well as within the San Antonio–Nueces and Nueces-Rio Grande Coastal basins. In general, surface-water quality improves from west to east across the state, reflecting an improvement in ground-water quality and increased average precipitation amounts.

Volumetric importance of ground water when compared with surface water is illustrated in Table 1. Freeze and Cherry (1979) gave a breakdown of the available volume of water worldwide and estimated residence time of each category. Water residing in the ground accounts for four percent of the total world water balance. If water containing high levels of salinity, the oceans and seas, is removed from the total budget, ground water then represents about 66 percent of the total available fresh water. If only utilizable fresh-water resources are considered (minus the icecaps and glaciers), then ground water accounts for almost the total volume of fresh water available for man's use. They estimate that the fresh-water budget breakdown is: ground water, 95 percent; lakes, swamps, reservoirs, and river channels, 3.5 percent; and soil moisture, 1.5 percent.

Residence times and rate of water movement vary greatly between different phases of the hydrologic cycle. Surface water has a residence time of about two weeks, while ground water may reside within an aquifer from two weeks to 10,000 years depending on the flow velocity (Freeze and Cherry, 1979). However, the average residence time of ground water is on the order of 200 years (Miller, 1980, p. 103). Ground water moves relatively slowly through the aquifer, as little as a few feet per year, and in distinct paths with little mixing. In contrast, surface water flow is turbulent and often fast (Feliciano, 1985). Due to its high visibility, contamination of surface water is relatively easier to detect than ground-water contamination. Because contamination in ground water occurs in distinct plumes, almost every known instance of ground-water contamination has been discovered only after a drinking-water source has been affected (Miller, 1980).

Table 1.–Estimate of the Water Balance of the World

Parameter	Volume (km^3)x10^6	Volume (km^3)x10^6	Residence time
Oceans and seas	1370	94	~4000 years
Lakes and reservoirs	0.13	<0.01	~10 years
Swamps	<0.01	<0.01	1-10 years
River channels	<0.01	<0.01	~2 weeks
Soil moisture	0.07	<0.01	~2 weeks-1 year
Ground water	60	4	2 weeks-10,000 years
Icecaps and glaciers	30	2	10-1000 years
Atmospheric water	0.01	<0.01	~10 days
Biospheric water	<0.01	<0.01	~1 week

Source: Freeze and Cherry, 1979

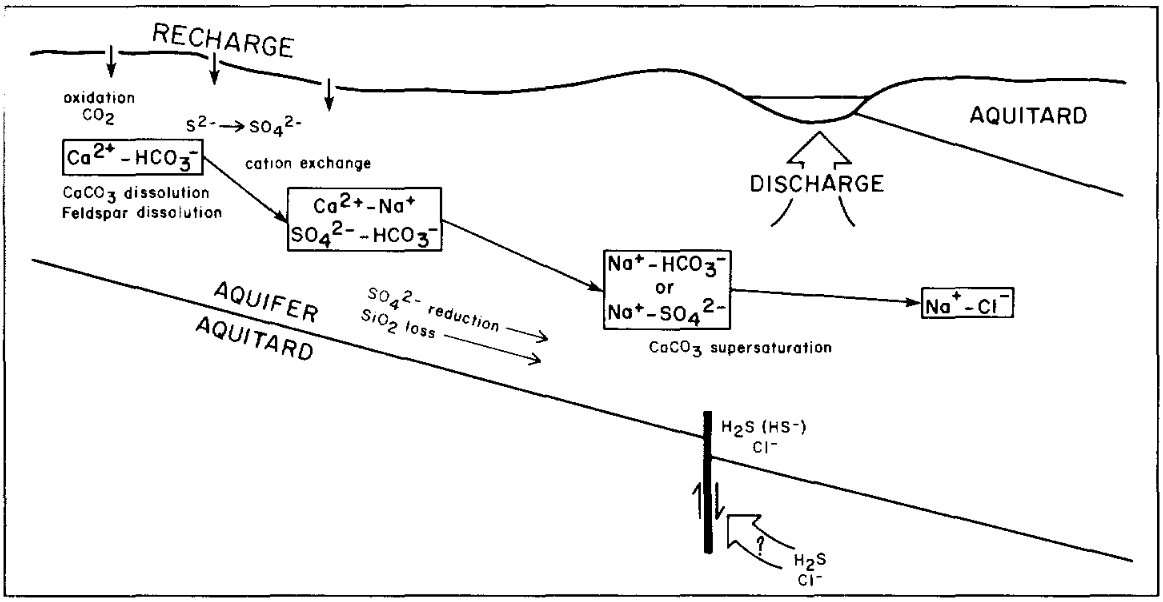


Figure 6.—Schematic Diagram Illustrating Ground-Water Hydrochemical Evolution From Calcium-Bicarbonate to Sodium-Chloride Type. Major controls are bulk rock composition (or mineralogy), water rock interaction, flow velocity, distance along flow path, residence time, and mixing (Modified from Kaiser and Ambrose, 1986.)

Hydrochemical Evolution

Ground-water quality within an aquifer is dependent upon reactions which take place between water and the aquifer bulk-mineral composition. Ground-water chemical composition evolves along the flow path, from recharge to discharge areas, or with increasing depth. Total dissolved ions in the ground water, or total dissolved solids (TDS), increase along the flow path as the ground water, an excellent solvent, reacts with the bulk rock that composes the aquifer (Figure 6).

Generally, ground water starts as precipitation which moves through the soil zone to the underlying aquifer materials. The soil zone contains organic matter that generates carbonic acid through plant respiration and decay. In recharge areas, mineral matter such as calcite and feldspar is dissolved by the low pH waters, releasing calcium and bicarbonate ions. Calcium can be removed from the system when it exchanges for sodium on clay mineral surfaces. As more calcite is dissolved, more calcium is released to exchange for sodium on the clays, resulting in a net increase in both sodium and bicarbonate concentrations in the ground water (Kaiser and Ambrose, 1986).

Increased sulfate and chloride concentrations may be derived from several different sources. Along the flow path, the dissolution of minerals which contain these ions (such as gypsum, pyrite, anhydrite, or halite) or the mixing of aquifer waters with waters that contain a high percentage of these ions either through interaquifer exchange, mixing with basinal waters, or diffusion of marine connate water into the fresher water zones from muddier facies, may occur. As the ground water becomes either supersaturated with respect to certain ions, or as the water becomes chemically reduced, minerals will precipitate onto the surface of aquifer materials, in a process known as cementation. In deep basinal systems or in areas where ground-water movement is almost static, a chloride brine may evolve (Freeze and Cherry, 1979).

Chemical composition of individual aquifers within the state will vary, due to differences in bulk rock composition (i.e. minerals which are available for reaction with the ground water). Total ground-water chemical composition is controlled by the amount of soluble minerals available and the opportunity for the ground water to react with the minerals (Table 2). Therefore, the chemical character of ground water mirrors the general mineral composition of the media through which it has passed. Flow velocity, distance along the flow path, and residence time of the ground water in the aquifer are additional controlling factors on hydrochemical evolution (Kaiser and others, in progress). A more detailed discussion of the hydrochemical evolution process can be found in Freeze and Cherry (1979).

Table 2.–Source, Significance, and Concentration of Dissolved Mineral Constituents and Properties of Water (Adapted from Doll and others, 1963, p. 39-43)

Constituent or Property	Source or Cause	Significance
Silica (SiO_2)	Dissolved from practically all rocks and soils, commonly less than 30 mg/L. High concentrations, as much as 100 mg/L, generally occur in highly alkaline waters.	Forms hard scale in pipes and boilers. Carried over in steam of high pressure boilers to form deposits on blades of turbines. Inhibits deterioration of zeolite-type water softeners.
Iron (Fe)	Dissolved from practically all rocks and soils. May also be derived from iron pipes, pumps, and other equipment.	On exposure to air, iron in ground water oxidizes to reddish-brown precipitate. More than about 0.3 mg/L stains laundry and utensils reddish-brown. Objectionable for food processing, textile processing, beverages, ice manufacture, brewing, and other processes. Texas Department of Health (1988) drinking water standards recommend that iron should not exceed 0.3 mg/L. Larger quantities cause unpleasant taste and favor growth of iron bacteria.
Calcium (Ca) and Magnesium (Mg)	Dissolved from practically all soils and rocks, but especially from limestone, dolomite, and gypsum. Calcium and magnesium are found in large quantities in some brines. Magnesium is present in large quantities in sea water.	Causes most of the hardness and scale-forming properties of water; soap consuming (see hardness). Waters low in calcium and magnesium desired in electroplating, tanning, dyeing, and in textile manufacturing.
Sodium (Na) and Potassium (K)	Dissolved from practically all soils and rocks. Also found in oil-field brines, sea water, industrial brines, and sewage.	Large amounts, in combination with chloride, give a salty taste. Moderate quantities have little effect on the usefulness of water for most purposes. Sodium salts may cause foaming in steam boilers and a high sodium content may limit the use of water for irrigation.
Bicarbonate (HCO_3) and Carbonate (CO_3)	Action of carbon dioxide in water on carbonate rocks such as limestone and dolomite.	Bicarbonate and carbonate produce alkalinity. Bicarbonates of calcium and magnesium decompose in steam boilers and hot water facilities to form scale and release corrosive carbon-dioxide gas. In combination with calcium and magnesium, cause carbonate hardness.
Sulfate (SO_4)	Dissolved from rocks and soils containing gypsum, iron sulfides, and other sulfur compounds. Commonly present in some industrial wastes.	Sulfate in water containing calcium forms hard scale in steam boilers. In large amounts, sulfate in combination with other ions gives bitter taste to water. Can have a laxative effect. Texas Department of Health (1988) drinking water standards recommend that the sulfate content should not exceed 300 mg/L.
Chloride (Cl)	Dissolved from rocks and soils. Present in sewage and found in large amounts in oil-field brines, sea water, and industrial brines.	In large amounts in combination with sodium, gives salty taste to drinking water. In large quantities, increases the corrosiveness of water. Texas Department of Health (1988) drinking water standards recommend that the chloride content should not exceed 300 mg/L.
Fluoride (F)	Dissolved in small to minute quantities from most rocks and soils. Added to many municipal water supplies.	Fluoride in drinking water reduces the incidence of tooth decay when the water is consumed during the period of enamel calcification. However, it may cause mottling of the teeth, depending on the concentration of fluoride, the age of the child, amount of drinking water consumed, and the susceptibility of the individual (Maier, 1950, p. 1120-1132). Texas Department of Health (1988) recommends a primary drinking water standard for fluoride content of 4.0 mg/L for all community type systems and a secondary standard of 2.0 mg/L for all public water systems.

Table 2.–Source, Significance, and Concentration of Dissolved Mineral Constituents and Properties of Water–Continued (Adapted from Doll and others, 1963, p. 39-43)

Constituent or Property	Source or Cause	Significance
Nitrate (NO_3) or Nitrate (as N)	Decaying organic matter, sewage, fertilizers, run off from barnyards and/or concentrated feeding operations, and nitrates in soil.	May give water a bitter taste. Concentration much greater than the local average may suggest pollution. Texas Department of Health (1988) drinking water standards suggest a limit of 45 mg/L (as NO_3) or 10 mg/L (as N) in community water systems. At the discretion of the Texas Department of Health, nitrate (as N) levels not to exceed 20 mg/L may be allowed if the water will not be available to children under six months of age, the system will continuously post the fact that the nitrate (as N) levels exceed 10 mg/L, local and state public health authorities are notified, and no adverse health effects result. Waters of high nitrate content (greater than 10 mg/L) have been reported to be the cause of methemoglobinemia (an often fatal disease in infants) and therefore should not be used in infant feeding (Maxcy, 1950, p. 271). Nitrate shown to be helpful in reducing inter-crystalline cracking of boiler steel. It encourages growth of algae and other organisms which produce undesirable tastes and odors.
Boron (B)	A minor constituent of rocks and of natural waters. Also found in evaporite deposits and sea water.	An excessive boron content will make water unsuitable for irrigation. Wilcox (1955, p. 11) indicated that a boron concentration of as much as 1.0 mg/L is permissible for irrigating sensitive crops; as much as 2.0 mg/L for semitolerant crops. Crops sensitive to boron include most deciduous fruit and nut trees and navy beans; semitolerant crops include most small grains, potatoes and some other vegetables, and cotton; and tolerant crops include alfalfa, most root vegetables, and date palm.
Dissolved solids	Chiefly mineral constituents dissolved from rocks and soils.	Texas Department of Health (1988) drinking water standards recommended that waters containing more than 1000 mg/L dissolved solids not be used if other less mineralized supplies are available. For many purposes the dissolved-solids content is a major limitation on the use of waters. A general classification of water based on dissolved-solids content, in ppm, is as follows (Winslow and Kister, 1956, p. 5): Water containing less than 1000 of dissolved solids are considered fresh; 1000 to 3000, slightly saline; 3000 to 10,000, moderately saline; 10,000 to 35,000, very saline; and more than 35,000, brine.
Hardness as $CaCO_3$	In most waters, nearly all the hardness is due to calcium and magnesium. All of the metallic cations other than the alkali metals also cause hardness.	Consumes soap before a lather will form. Deposits soap curd on bathtubs. Hard water forms scale in boilers, water heaters, and pipes. Hardness equivalent to the bicarbonate and carbonate is called carbonate hardness. Any hardness is excess of this is called non-carbonate hardness. Waters of hardness up to 60 mg/L are considered soft; 61 to 120 mg/L, moderately hard; 121 to 180 mg/L, hard; more than 180 mg/L, very hard.
Percent Sodium (% Na)	Sodium in water.	A ratio (using milliequivalents per liter) of sodium ions to the total sodium, calcium, and magnesium ions. A sodium percentage exceeding 60 percent is a warning of a sodium hazard. Continued irrigation with this type of water will impair the tilth and permeability of the soil.

Table 2.–Source, Significance, and Concentration of Dissolved Mineral Constituents and Properties of Water–Continued (Adapted from Doll and others, 1963, p. 39-43)

Constituent or Property	Source or Cause	Significance
Sodium-adsorption ratio (SAR)	Sodium in water.	A ratio for soil extracts and irrigation waters used to express the relative activity of sodium ions in exchange reactions with soil (U.S. Salinity Laboratory Staff, 1954, p. 72, 156). The SAR is defined by the following equation, all ions are expressed in milliequivalents per liter (me/L): $\mathrm{SAR} = \mathrm{Na}^{+} / \sqrt{(\mathrm{Ca}^{+} + \mathrm{Mg}^{2+}) / 2}$.
Residual sodium carbonate (RSC)	Sodium and carbonate or bicarbonate in water.	As calcium and magnesium precipitate as carbonates in the soil, the relative proportion of sodium in the water is increased (Eaton, 1950, p. 123-133). Defined by the following equation, all ions are expressed in milliequivalents per liter (me/L): $\mathrm{RSC} = (\mathrm{CO}_3^{2-} + \mathrm{HCO}_3^{-}) - (\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+})$.
Specific conductance (micromhos at 25°C)	Mineral content of the water.	Indicates degree of mineralization. Specific conductance is a measure of the capacity of the water to conduct an electric current. Varies with concentration and degree of ionization of the constituents.
Hydrogen ion concentration (pH)	Acids, acid generating salts, and free carbon dioxide lower the pH. Carbonates, bicarbonates, hydroxides, phosphates, silicates, and borates raise the pH.	A pH of 7.0 indicates neutrality of a solution. Values higher than 7.0 denote increasing alkalinity; values lower than 7.0 indicate increasing acidity. pH is a measure of the activity of the hydrogen ions. Corrosiveness of water generally increases with decreasing pH. However, excessively alkaline waters may also attack metals. The Texas Department of Health (1988) recommends a pH greater than 7.

Contamination

Natural contamination probably affects the quality of more ground water in the state than all other sources of contamination combined (Scalf and others, 1973). Natural leaching of minerals to the ground water is the result of the interaction between water and either the aquifer matrix, substances tied up in the soil zone, or minerals in the watershed (Scalf and others, 1973). Natural discharge from deeper, more saline, aquifers can contribute additional mineralization to an aquifer, increasing its salinity. Natural contamination can take many forms including increased salinity; the addition of toxic substances including metals, nitrates, and radioactivity; and addition of excessive nuisance minerals such as fluoride, iron, or sulfate which may give the water an undesirable color or taste.

Man-induced ground-water contamination usually involves substances released on or slightly below land surface and, therefore, shallow aquifers are normally considered more susceptible to pollution than the deeper aquifers. Ground-water pollution occurs by infiltration, direct migration, interaquifer exchange, and recharge from surface water (U.S. Environmental Protection Agency, 1987b, p. 2-4). Various human induced impacts on the ground-water quality are exhibited on Figure 3. Contamination from specific activities is discussed in the section which assesses the known and potential sources of man-induced ground-water contamination within Texas.

Ground-water contamination begins with a source of pollutants or with waste disposal practices. These sources have a wide range, including anything from landfill leachates to the excessive amounts of salts in oil-field brines. Contaminants may be retained in the soil profile, leaked to, percolated to, discharged to, or injected into the aquifers of the state (Miller, 1980a and 1980b). Eventually, they may be discharged to the surface-drainage network.

A small portion of surface water moves downward under the influence of gravity, and slowly infiltrates the soil through pore spaces in the soil matrix. This downward percolating water may carry pollution with it, or may move through a contaminated zone dissolving material and/or picking up additional contaminants (leachate). Leachate may continue to migrate downward and eventually reach the saturated zone. When this happens, horizontal and vertical spreading of contaminants will occur, and usually moves in the direction of ground-water flow.

The soil profile plays a significant role in governing the behavior of chemical contaminants. Important soil properties are texture, permeability, and organic matter content. Soil acts as a complicated buffer system. Its composition determines if a chemical leaches to the water table as well as determining the concentration of the pollutants which reach an aquifer. Downward movement of a chemical is determined by the interaction between the processes of degradation and leaching. Normally, downward movement of a chemical under the influence of infiltrating water, is unlikely when a chemical degrades rapidly in soil. A chemical which is tightly bound to the soil is also unlikely to move downward no matter how long it remains in the soil. Therefore, the two dominant characteristics of chemicals which determines their potential to leach to ground water are their relative persistence in soil and the lack of binding to the soil (U.S. Environmental Protection Agency, 1987d, p. 31-35). More detailed information related to this subject may be found in Dragun (1988a and 1988b).

Not all chemicals have equal ability to reach ground water. There are great variations in the properties of chemicals which control their tendency to leach. The interaction of several independent properties governs leaching behavior. These are: 1) water solubility, 2) hydrolysis, 3) soil adsorption, 4) volatility, and 5) soil degradation (U. S. Environmental Protection Agency, 1987d, p. 34). **Water solubility** is the ability of a chemical to dissolve in water. **Hydrolysis** is the rate at which the degradation of a chemical takes place in water when no other process is occurring. **Soil adsorption** is the ability of a chemical to bind to soil. Highly volatile chemicals are easily lost to the atmosphere through evaporation. **Soil degradation** is a simplified measure of a chemical's persistence in soil, normally measured as the time required for the disappearance of one-half of the residue present. A pollutant with a high leaching potential, indicated by a half-life of greater than about three weeks, has a soil persistence sufficient to allow migration to the ground water (U.S. Environmental Protection Agency, 1987d, p. 34).

Once a pollutant has moved through the vertical soil profile above the water table and entered ground water, it flows in a linear path in a downdip direction at right angles to contours which denote the potentiometric surface. The rate at which a contaminant moves is dependent upon the aquifer's permeability. Along the course of its travel, the contaminant may be modified by attenuation processes such as biological, physical, and chemical reactions which operate to depress or reduce the chemical concentration in water by mixing it with native ground water. Some toxic substances are highly mobile, however, in most instances, a pollutant will move extremely slowly along a very distinct path. A contaminant undergoes very little mixing since movement of ground water typically ranges from about three feet per year to slightly over 3300 feet per year. The most common ground-water velocities range between 33 and 328 feet per year (U. S. Environmental Protection Agency, 1987d, p. 17). This results, in most cases, in ground-water pollutants moving very slowly in concentrated slugs called plumes which will not likely be diluted and/or dispersed through mixing. By contrast, surface water flow is turbulent, often fast, frequently causing contaminants to be well mixed and dispersed throughout the water system (Feliciano, 1985, p. 5).

Site conditions also determine the vulnerability of ground water to pollution from chemicals or pesticides. Important considerations of the site are: 1) depth to ground water, 2) geologic conditions, and 3) climate. Since soil acts as a filter, the shallower the depth to ground water, the shorter transit time in the vadose zone results in fewer opportunities for degradation or adsorption of the chemicals. The permeability of the lithologic layers present, between the soil surface and the water table, determines the downward rate at which a chemical moves. Ground water is more vulnerable to contamination when the permeabilities of the overlying layers are higher or when they contain less clay. Lastly, chemicals are more likely to leach to the water table when there are greater amounts of water moving through the soil profile. This occurs when high rainfall or a large volume of water, due to irrigation, is percolating downward in areas with a shallow water table and the soil profile contains highly permeable materials.

Under some conditions, contaminants can migrate directly into ground water from below-ground sources which lie within the saturated zone. Examples of these sources are pipelines, septic tanks, waste-water disposal ponds, landfills, and underground storage tanks. Since "continually saturated conditions" usually exist below these sources and degradation in the soil zone does not take place, much greater concentrations of contaminants may enter the water. Ground-water contamination may also result from vertical leakage through the seals around well casings of improperly abandoned wells, or through deteriorated or improperly constructed water wells (U.S. Environmental Protection Agency, 1987b, p. 3).

The process known as **interaquifer exchange** occurs when one water-bearing unit is in hydraulic communication with another water-bearing zone. This is most common in wells which penetrate more than one water-bearing unit to provide an increased yield. When the well is not being pumped, water will move from the formation with the greatest potential head to the formation with lesser potential. If the formation with the greater potential contains contaminated or poor quality water, the water in the other unit can be degraded. Vertical movement may also be induced by pumping, or may occur under normal gradients, in old and improperly abandoned wells with deteriorated casings (U.S. Environmental Protection Agency, 1987b, p. 3).

All ground-water systems constantly undergo recharge at varying rates. Even though movement through an aquifer may be only a few feet per year, eventually ground water will discharge to the surface. An estimate of the amount of time involved has been postulated by Freeze and Cherry (1979) who stated that the residence time of ground water within an aquifer, may vary from two weeks to 10,000 years (Table 1). Ground-water discharge rates vary depending on climatic and aquifer conditions. Miller (1980) postulates that the average residence time of ground water is on the order of 200 years. In arid areas, recharge and discharge are extremely small and infrequent. In humid regions, discharge of pollutants is relatively rapid in shallow water-table aquifers. However, discharge from artesian aquifers is limited. Points of discharge of contaminated ground water (either natural or man-induced) may be to wells and springs used for water supply, and to surface-water bodies such as streams and lakes. During low flow periods, the base flow of many streams is supported almost entirely by ground-water discharge. Therefore, sampling of surface water stream flow during these times may give an indication of ground-water problems.

General Chemical Quality

Suitability of ground water for municipal, industrial, rural, irrigation, and other uses is determined by the amount and type of minerals present in the water (Muller and Price, 1979). Several criteria for water-quality requirements have been developed through the years (Table 2), and serve as guidelines in determining the suitability of ground water for various uses. The Texas Department of Health (1988) has established chemical quality standards, for inorganic and organic constituents (Table 3) for drinking water, which comply with the requirements of Public Law 93-523, the Federal "Safe Drinking Water Act", and the "Interim Primary Drinking Water Regulations" which have been promulgated by the Environmental Pro-

Table 3.–Maximum Acceptable Concentration Levels in Drinking Water

(25 Texas Administrative Code, Chapter 337, Water Hygiene, Section 337.1-337.18,
Drinking Water Standards Governing Drinking Water Quality and Reporting
Requirements for Public Water Supply Systems)

Maximum constituent level (for Community Type Systems):

Constituent	Level in mg/L
Arsenic	0.05
Barium	1.0
Cadmium	0.010
Chromium	0.05
Lead	0.05
Mercury	0.002
Nitrate (as N)*	10.0
Selenium	0.01
Silver	0.05
Fluoride	4.0

*Also applicable to noncommunity water systems.

Maximum contaminant levels for organic chemicals (for Community Water Systems):

Constituent	Level in mg/L	Micrograms/L
Chlorinated hydrocarbons	0.0002	0.2
Lindane	0.004	4.0
Methoxychlor	0.1	100.0
Toxaphene	0.005	5.0
Chlorophenoxys	0.1	100.0
2,4,5-TP Silvex	0.01	10.0

Maximum contaminant levels for organics (for Community Water Systems and Nontransient Noncommunity Water Systems):

Constituent	Level in mg/L	Micrograms/L
Benzene	0.005	5
Vinyl Chloride	0.002	2
Carbon Tetrachloride	0.005	5
1,2-Dichloroethane	0.005	5
Trichloroethylene	0.005	5
1,1-Dichloroethylene	0.007	7
1,1,1-Trichloroethane	0.20	200
para-Dichlorobenzene	0.075	75

Table 3.–Maximum Acceptable Concentration Levels in Drinking Water–Continued

(25 Texas Administrative Code, Chapter 337, Water Hygiene, Sections 337.1-337.18,
Drinking Water Standards Governing Drinking Water Quality and Reporting
Requirements for Public Water Supply Systems)

Maximum radiological contaminant level (for Community Systems):

Constituent	Radiation Level
Combined radium-226 and radium-228	5 pCi/L
Gross alpha particle	15 pCi/L
Average annual concentration for beta particle and photon radioactivity from man-made radionuclides	4 (mrem)/year

Recommended Secondary Constituent Levels (for all Public Water Systems):

Constituent	Level
Chloride	300 mg/L
Color	5 color units
Copper	1.0 mg/L
Corrosivity	Non-corrosive
Fluoride	2.0 mg/L
Foaming agents	0.5 mg/L
Hydrogen sulfide	0.05 mg/L
Iron	0.3 mg/L
Manganese	0.05 mg/L
Odor	3 Threshold Odor Number
pH	> 7.0
Sulfate	300 mg/L
Total Dissolved Solids	1000 mg/L
Zinc	5.0 mg/l

tection Agency (EPA). The maximum contaminant level for a pollutant that is allowed in drinking water is the established maximum limit for that contaminant which will cause no adverse effects on human health. Secondary levels, usually based on esthetic reasons such as taste, color, odor, staining, and scaling, are recommended limits, except for water systems which were not in existence as of the effective date for that standard. If no other alternate source of water supply of acceptable chemical quality is available, then the Texas Department of Health may give written approval to exceed the secondary standards.

Total Dissolved Solids

One of the main factors which limits the use of ground water is the total dissolved-solids concentration (TDS). TDS trends were mapped for all the major aquifers and for selected high-use minor aquifers. Winslow and Kister (1956) developed a general classification of waters based on the TDS in parts per million (ppm). Fresh water is defined as having less than 1000 ppm; slightly saline ranges from 1000 to 3000 ppm; moderately saline ranges from 3000 to 10,000 ppm; very saline ranges from 10,000 to 35,000;

and brine is defined as greater than 35,000 ppm. Analyses are usually reported either in milligrams per liter (mg/L) or ppm. Below 7000 units (either ppm or mg/L) there is little significant difference between these two units of measure. In more highly mineralized waters, the following density correction factor should be used (Price and others, 1983):

$$\text{Parts per million} = \frac{\text{milligrams per liter}}{\text{specific gravity of water.}}$$

Agricultural Use

According to Bouwer (1978), waters for irrigation use, of less than 480 mg/L TDS are considered to pose no problem under ordinary conditions of climate and soil, even for sensitive plants. Waters ranging between 480 and 1920 mg/L will cause increasing problems, with greater than 1920 mg/L TDS causing severe problems (Table 4). Quality standards for irrigation water are based on the total salt concentration in the water as it affects crop yield through osmotic effects, the concentration of specific ions which may be toxic to plants or have an unfavorable effect on crop quality, and the concentrations of cations that can cause deflocculation of the clay in the soil (resulting in damage to soil structure and declines in infiltration rates) (Bouwer, 1978). Universal standards for irrigation water cannot be formulated, because ground-water quality which would be poor for irrigation in one soil and climatic regime could be acceptable somewhere else. For example, alfalfa grown in sandy soil can tolerate concentrations of dissolved constituents many times greater than citrus trees grown in clayey soil (Davis and DeWiest, 1966).

Caution should be used when watering stock with high TDS water. As the TDS level increases above 7000 mg/L, the risk to farm animals increases. An upper limit of about 5000 mg/L TDS for use by livestock is recommended for best growth and development of animals, with an upper TDS limit for the following stock (Hem, 1985): poultry - 2860 mg/L, pigs - 4290 mg/L, horses - 6435 mg/L, cattle (dairy) - 7150 mg/L, cattle (beef) - 10,100 mg/L, and sheep (adult) - 12,900 mg/L. Young animals and pregnant

Table 4.–Guidelines for Interpretation of Water Quality for Irrigation

Problems and quality parameters	No Problems	Increasing Problems	Severe Problems
Salinity effects on crop yield:			
Total dissolved-solids concentration (mg/L)	<480	480-1920	>1920
Deflocculation of clay and reduction in K and infiltration rate:			
Total dissolved-solids concentration (mg/L)	>320	<320	<128
Adjusted sodium adsorption ratio (SAR)	<6	6-9	>9
Specific ion toxicity:			
Boron (mg/L)	<0.5	0.5-2	2-10
Sodium (as SAR) if water is absorbed by roots only	<3	3-9	>9
Sodium (mg/L) if water is also absorbed by leaves	<69	>69	
Chloride (mg/L) if water is absorbed by roots only	<142	142-355	>355
Chloride (mg/L) if water is also absorbed by leaves	<106	>106	
Quality effects:			
Nitrogen in mg/L (excess N may delay harvest time and adversely affect yield or quality of sugar beets, grapes, citrus, avocados, apricots, etc.)	<5	5-30	>30
Bicarbonate as HCO_3 in mg/L (when water is applied with sprinklers, bicarbonate may cause white carbonate deposits on fruits and leaves)	<90	90-520	>520

From: Bouwer, 1978

or lactating animals are less resistant to high TDS levels than older animals (Bouwer, 1978).

Industrial Use

High total dissolved solids content is usually avoided for industrial water supplies, although the specific water-quality requirements are generally determined by the type of industry (Muller and Price, 1979). Of main concern to many industries, is that the supply does not contain corrosive or scale-forming constituents (Table 2). Both magnesium and calcium affect the water hardness, and are of concern in boiler use. Excessive amounts of silica and iron cause scale deposits which reduce the efficiency of many industrial processes. Water quality is of concern in food processing due to possible taste or vegetable hardness problems.

Sulfate

Sulfate is the most common form of sulfur found in normal pH waters (Hem, 1985), however, hydrogen sulfide gas (H_2S), with its associated "rotten egg" odor, is found in ground water in many parts of the state. Areas which exceed the secondary drinking water standard of 300 mg/L for sulfate (Table 3) were mapped for all the major aquifers. Water having more than 500 mg/L sulfate has a bitter taste and, when sodium and magnesium are present, can have a laxative effect on persons when first used as drinking water due to the formation of salts. Humans can tolerate up to 2000 mg/L sulfate in their drinking water after becoming acclimated (Anderson, 1981). Water that contains sulfate along with calcium and magnesium will contribute to the formation of non-carbonate water hardness which can form hard scale in boilers and is not suitable for some industrial uses (Table 2).

Sulfates are considered beneficial in irrigation waters, especially in the presence of calcium (Bouwer, 1978). The addition of gypsum (calcium sulfate) to irrigation waters is a common practice with the excess calcium used to counteract high sodium content. Calcium may prevent the formation of, or restore, deflocculated soil clays that have become impermeable to water and therefore difficult to cultivate (Bouwer, 1978).

Chloride

Chloride is the most common form of chlorine found in water (Hem, 1985). Areas which exceed the secondary drinking water standard of 300 mg/L for chloride (Table 3) were mapped for all the major aquifers. Water that contains a chloride concentration greater than 400 mg/L will have a noticeable salty taste for most people (Hem, 1985). Humans can tolerate up to 1500 mg/L chloride in their drinking water (Anderson, 1981), however, large quantities will increase the corrosivity of the water (Table 2), causing problems with piping.

According to Bouwer (1978), waters for irrigation use which contain less than 142 mg/L chloride are considered to pose no problem under ordinary conditions of climate and soil, if water is absorbed by roots only (Table 4). If water is also absorbed by the leaves, 106 mg/L is considered safe. Waters ranging between 142 and 355 mg/L will cause increasing problems, with greater than 355 mg/L chloride causing severe problems. Irrigation water, absorbed by the leaves, greater than 106 mg/L chloride will cause increasing problems.

Nitrate

Although igneous rocks contain small amounts of soluble nitrate or ammonia, most nitrate in ground water is derived from organic sources or from industrial and agricultural chemicals (Davis and DeWiest, 1966). Nitrate, the most common contaminant of ground water, is very mobile, does not adsorb onto aquifer matrix materials, and does not precipitate as a mineral (Hendry, 1988). Natural processes that may add nitrate to the ground water include precipitation, mineral weathering, and decay of organic matter. Certain plants, such as alfalfa and other legumes, have bacteria living on root nodules which fix nitrogen gas from the atmosphere and these nitrates are commonly in excess of the plant's needs, leaving a surplus available for leaching into the ground water (Davis and DeWiest, 1966). Another natural source of nitrates which may leach to ground water is the accumulated guano from large numbers of bats living in limestone caves (Hem, 1985). Man's activities which contribute to nitrate contamination of the ground water include runoff from barnyards, pastures, and livestock feed yards; effluent from sewage lagoons, privies, and septic systems; sanitary landfills; excessive nitrogen fertilization; deforestation; and the change in the soil organic matter regime resulting from crop rotation (Hendry, 1988).

In 1982, the U.S. Office of Drinking Water estimated that more than a half-million households in the United States were using water with high nitrate levels (McFarland, 1988). Maps showing locations of wells with analysis and/or areas which exceed the primary drinking water standard of 10 mg/L nitrate (as N) or 45 mg/L nitrate (as NO_3) (Tables 2 and 3) for the High Plains (Ogallala), Edwards (Balcones Fault Zone), and the Alluvium and Bolson Deposits aquifers were made, although the exact source and the relative contribution between man-induced contamination and naturally large concentrations in ground water is not known. Detailed sampling using sophisticated analysis would be necessary to determine the source or sources of nitrate to the ground water. One such study in Runnels County indicated that sources of nitrate in the ground water were natural soil nitrogen and, to a much lesser extent, animal waste nitrogen (Kreitler, 1975). It was concluded that high nitrate concentrations in the ground water were due to cultivation practices that oxidized the soil humus, which was naturally high in nitrate due to the previous cover of buffalo grass. Subsequent migration of the nitrate from the soil zone to the ground water followed extensive terracing in the 1950's which resulted in a rise in the water table.

Water which contains a nitrate concentration greater than 10 mg/L nitrate (as N) or ~45 mg/L nitrate (as NO_3) has been proven to be a health hazard to human fetuses and infants under three months of age (Fetter, 1980). At these and higher levels, young infants could die from methemoglobinemia or blue-baby disease. Infants can be poisoned by the water itself, by their mother's milk if she drinks the water, or by the milk from cows drinking the water (ReVelle and ReVelle, 1974). Since gastric juices of infants lack sufficient acidity, nitrate reducing bacteria can grow in their upper intestinal tracts. When they ingest high nitrate levels, it is reduced by the bacteria to nitrite. Nitrite is then absorbed directly into the blood stream, where it reacts with the hemoglobin to form methemoglobin, an ineffective oxygen carrier (Bouwer, 1978). This can produce anoxemia, and can cause death by asphyxia.

Older infants and adults can consume higher nitrate levels in drinking water and food because their stomach is acid enough to prevent the growth of nitrate reducing bacteria (Bouwer, 1978). However, nitrate may play a role in the production of nitrosamines in the stomach, which are known carcinogens (Bouwer, 1978) that may cause birth defects and genetic damage (ReVelle and ReVelle, 1974). High nitrates in drinking water have been linked with cancer of the stomach and esophagus (Bouwer, 1978; McFarland, 1988).

Waters for irrigation use which contain less than 5 mg/L nitrate (as N) are considered to pose no problem under ordinary conditions of climate and soil (Bouwer, 1978, Table 4). Waters ranging between 5 and 30 mg/L nitrate (as N) will cause increasing problems, with greater than 30 mg/L nitrate (as N) causing severe problems. Excess nitrogen may delay harvest time, and adversely affect crop yield (Bouwer, 1978).

Radium

Radium is a naturally occurring radioactive nuclide with a half-life of 1620 years (Hem, 1985). The most abundant isotope of radium, 226, is the most toxic of all inorganic material (Davis and DeWiest, 1966) and is a decay product of uranium-238. A review by Hem (1985) gives the following relevant data: 1) isotopes of radium and radon are the main alpha-emitting substances in natural water; 2) the radioactivity of water is usually expressed in terms of an equivalent quantity of radium, or in terms of the rate of radioactive disintegration (curies) per liter of water; 3) one curie (Ci) is defined as 3.7×10^{10} disintegrations per second; and 4) ground-water analysis are generally expressed in picocuries (curies $\times 10^{-12}$, or pCi).

Radiation harms tissue through the ionization of body cells, and as radium (which is absorbed into the bone tissue) decays, the radiation exposure may result in bone cancer (Aieta and others, 1987). The maximum allowable radiological contaminant level for community public water supply systems is 5 pCi/L for radium-226 and radium-228 combined (Table 3) based on the carcinogenic potential of these ions. Radium-226 will decay into radon-222 (Hem, 1985), a water soluble gas which has recently received notoriety. Cothern (1987) estimates that between 5000 and 20,000 lung cancer fatalities occur every year in the United States because of the existence of radon in indoor air, with approximately one to seven percent of these fatalities being the result of radon released from water. Exposure occurs through inhalation of natural radon released from water during showering, bathing, flushing toilets, cooking, and washing clothes and dishes.

Figure 7 illustrates the locations of counties where the limit for radium has been exceeded in public drinking water supplies, and the location of geologic trends where potentially radioactive ground waters may occur. Relatively high concentrations of radium and associated radon gas are most likely to occur in water from deep aquifers, or in areas of uranium or phosphate mining (Hem, 1985). Potential areas were delineated on the basis of the presence of uranium bearing strata or radioactive anomalies. A study by Cech and others (1987 and 1988) indicated that low levels of radium and radon had been found in ground water from wells completed in northern part of the High Plains (Ogallala) aquifer. They reported high levels in water from aquifers situated adjacent to the Llano Uplift in West-Central Texas and from the Gulf Coast aquifer in parts of northwest Harris County and Fort Bend County. A more detailed discussion of the location and natural source of radium in the Hickory and Gulf Coast aquifers can be found in the ground-water quality discussion for those aquifers.

Iron

Iron is necessary for metabolism in animals and plants, however, when present in excessive amounts in water, it forms a red precipitate which stains laundry and plumbing fixtures (Hem, 1995), gives water an irony taste, and can clog pipes and well screens (Broom, 1966). Large amounts of iron pose a nuisance, and cause problems for many domestic, municipal, and industrial users of ground water in parts of east Texas (Broom, 1966). Analyses that exceed the secondary drinking water standard of 0.3 mg/L for iron (Tables 2 and 3) were mapped for the Carrizo-Wilcox aquifer, a major aquifer where excess iron is a recognized problem.

CHEMICAL QUALITY OF THE MAJOR AND MINOR AQUIFERS

A **major aquifer** is defined as one which yields large quantities of useable quality water in a comparatively large area of the state (Muller and Price, 1979). The major aquifers (Figure 1), as described by the Texas Department of Water Resources (1984), are the High Plains (Ogallala), Carrizo-Wilcox, Edwards (Balcones Fault Zone), Trinity Group, Alluvium and Bolson Deposits, Gulf Coast, and Edwards-Trinity (Plateau). Approximately 96 percent of the ground water used in Texas in 1984 was produced from the major aquifers (Texas Water Development Board, 1988). **Minor aquifers** (Figure 2) are defined as those which yield large quantities of useable quality water in small areas or relatively small quantities of water in large areas of the state (Muller and Price, 1979) and consist of the Woodbine, Queen City, Sparta, Edwards-Trinity (High Plains), Santa Rosa, Hickory Sandstone, Ellenburger-San Saba, Marble Falls Limestone, Blaine Gypsum, Igneous Rocks, Marathon Limestone, Bone Spring and Victorio Peak Limestones, Capitan Limestone, Rustler, Nacatoch Sand, Blossom Sand, and other undifferentiated aquifers. The minor aquifers are important locally, and may be the only source of fresh water available in some areas. Individual aquifer ground-water quality is discussed in detail later in this chapter.

Major and minor aquifers either occur at the surface, or underlie about 76 percent of the state's total area (Figure 5). They are composed of many rock types, including limestones, dolomites, sandstones, gypsum, and alluvial gravels (Muller and Price, 1979). In some parts of the state, ground waters are also found in igneous rocks. In 1984, Texans used about 15.6 million acre-feet of water, of which 8.9 million acre-feet, or 57 percent, was derived from ground-water sources (Texas Water Development Board, 1988). The remaining 43 percent or about 7.05 million acre-feet was derived from surface sources. About 78 percent of all ground water is used for irrigation, with the remainder being utilized for public supplies, rural and domestic consumption, rural livestock, electric utility, and other industries (Texas Water Development Board, 1988). About 50 percent of municipal water is obtained from ground-water sources (Texas Department of Water Resources, 1984). The High Plains (Ogallala) aquifer is intensively developed and primarily used to supply water for irrigation (Strause, 1987). The Gulf Coast, Carrizo-Wilcox, Edwards (Balcones Fault Zone), and Trinity Group aquifers are intensively developed around population centers and are also utilized for irrigation supply (Strause, 1987).

Major Aquifers

High Plains (Ogallala)

The High Plains (Ogallala) aquifer, located in the Panhandle of Texas (Figure 1), covers approximately 35,000 square miles in all or part of 46 counties and consists primarily of the Ogallala Formation of Tertiary age and associated hydraulically connected water-bearing units in underlying Cretaceous and Triassic sediments (Knowles and others, 1984). Most of the water from the aquifer is used for irrigation, however, many public water supply systems are dependent upon ground water as their sole production source (Strause, 1987).

With a maximum of almost 900 feet of thickness in Ochiltree County, the aquifer is composed of unconsolidated, fine- to coarse-grained, gray to red sand, clay, and silt with interbedded cemented zones of calcium carbonate (i.e. caliche) (Gutentag and others, 1984). These sediments were deposited by overlapping low-gradient alluvial fans (aprons of sediment along a mountain front) which were sourced in the mountains to the west (Seni, 1980). As discussed in the "Hydrochemical Evolution" section, bulk rock mineral composition controls water quality and ground water flow velocity. A detailed sedimentological study of the Ogallala Formation by Seni (1980) concluded that three lobes of medial- (middle) and distal- (farthest from the source area) fan facies are present in Texas. Medial-fan facies occur in the north and northwest part of the Panhandle and are thick sand and gravel layers of high permeability which were deposited by braided-stream processes. To the south and southeast, the medial-fan facies grade into distal-fan facies which were deposited by narrow channel systems resulting in distinct sand lenses with a net thickness range of 100 to 300 feet. Areas between the channel deposits are predominately composed of mud and silt sediments of lower permeability. Seni also stated that aquifer thickness and composition was controlled by pre-Ogallala topography (valleys) and depressions caused by dissolution of the underlying salt beds.

Water-bearing areas of the aquifer are hydraulically connected except where the Canadian River has eroded partially or totally through in Oldham, Potter, Moore, and Hutchinson Counties (Muller and Price, 1979). This division is considered to be the separation between the North Plains and South Plains. In general, the greatest saturated thickness lies in the North Plains. South of Lubbock, to Midland County, the saturated thickness varies from less than 20 to 200 feet. Depth to water below land surface reaches almost 400 feet in parts of the North Plains. Much of the South Plains has a depth to water of 100 to 200 feet. Wells yields vary from 100 to 2000 gallons per minute (gal/min) with an average of 500 gal/min.

An average of less than 0.2 inches per year (in/yr) of effective recharge actually reaches the water table from precipitation on the surface (Klemt, 1981). Knowles and others (1984) report that recharge rates are affected by a combination of small annual precipitation, high evaporation rate, and low infiltration rate controlled by vegetative cover, soil type, and the presence of clay or caliche aquicludes. Recharge due to underflow from the part of the aquifer in New Mexico also occurs (Knowles and others, 1984). Ground water moves through the aquifer in a southeastward direction toward the caprock edge or eastern escarpment of the High Plains (Figure 8). The majority of ground-water discharge from the High Plains (Ogallala) aquifer occurs artificially through wells, with natural discharge being minimal, and primarily through seeps and springs along the eastern edge of the escarpment and the Canadian River (Knowles and others, 1984).

General quality of ground water in the High Plains (Ogallala) aquifer is illustrated in Figure 8. In general, total dissolved solids (TDS), chloride, sulfate, and nitrate concentrations increase from north to south. TDS concentrations range from 200 to 9000 mg/L (Knowles and other, 1984). The North Plains area generally contains lower TDS waters (less than 500 mg/L or ppm) with the exception of Ochiltree and Roberts Counties. The northern half of the South Plains also contains lower TDS waters. Greater aquifer thickness and more permeable medial-fan sediments (Seni, 1980) contribute to the higher quality of ground water found in these areas.

As the aquifer thins to the south, higher concentrations of all mapped constituents occur. The south and southeast portion of the High Plains (Ogallala) aquifer is underlain by, and in hydrologic contact with, lower Cretaceous rocks (as defined by Gutentag and others, 1984), and is composed of lower permeability (i.e. higher clay content) distal-fan facies (Seni, 1980). Water with TDS values which exceed 3000 mg/L or ppm and high chloride and sulfate values are associated with alkali lake basins where Cretaceous rocks are very shallow or crop out in Lamb, Hockley, Terry, Lynn, eastern Gaines, and Martin Counties. Possible reasons for the elevated concentrations are deep discharge from the underlying Cretaceous rocks, declining water levels and thinner saturated thickness of the aquifer, local contamination from industrial activities such as petroleum production and animal feed lots, and dissolution of underlying Permian salt beds with discharge to these areas (Knowles and others, 1984). Higher TDS, sulfate, and chloride areas in the South Plains also occur along natural discharge areas such as springs and incised streams.

Most High Plains (Ogallala) aquifer wells that have analyses which exceed the drinking water standard for nitrate occur in the South Plains area. Strause (1988) indicated that 25 percent of all the analyses from wells throughout the High Plains (Ogallala) aquifer exceeded 10 mg/L nitrate as N, the drinking water standard for nitrate. Reeves and Miller (1978) attribute the source of nitrates present in the ground water to leaching of nitrogen-based fertilizers applied to intensively cultivated sandy soils and subsequent vertical migration to the shallow ground-water table. Other possible causes for natural nitrate concentrations are discussed in the preceding section on that constituent.

Water analyses which exceed the drinking water standard for fluoride occur throughout the High Plains (Ogallala) aquifer (Knowles and others, 1984). Analyses which exceeded the primary drinking water standard of 4.0 mg/L for fluoride (Table 3) occurred in almost 20 percent of the samples studied by Strause (1987). Fluoride in smaller quantities in drinking water can reduce the incidence of tooth decay when consumed during enamel calcification in childhood (Table 2).

When fluoride concentration in the drinking water is excessive, discoloration and mottling of the teeth may occur. High natural concentrations in the High Plains (Ogallala) aquifer are attributed by Gutentag and others (1984) to the leaching of volcanic-ash deposits within the aquifer or to discharge from the underlying Cretaceous rocks. A smaller portion of the fluoride is attributed to dissolution of fluoride minerals in the sand and gravel that comprise the aquifer.

Within the High Plains (Ogallala) aquifer, arsenic concentrations in some areas exceed the primary drinking water standard of 0.05 mg/L (Table 3 and Figure 50). The majority of the arsenic contamination in this area is considered by many authors to be agriculturally related, although arsenic can occur naturally, and leaching of arsenic-containing rocks or discharge of arsenic-bearing ground waters are considered to be possible sources for part of the arsenic content found within the High Plains (Ogallala) aquifer. Nativ (1988) indicates that high concentrations of arsenic, which exceed the drinking water standard of 0.05 mg/L, exist where the High Plains (Ogallala) aquifer water table is generally less than 40 feet below land surface and where there is a potential for upward movement of Dockum Group ground water. Arsenic in the ground water has been found to be associated with natural uranium mineralization in the High Plains (Nichols and others, 1977). Areas with arsenic concentrations which exceed the drinking water standard (Figure 50) are located basinward of outcrop of uranium bearing strata (Figure 7) indicating that a natural contribution to the arsenic problem is possible.

Carrizo-Wilcox

The Carrizo-Wilcox aquifer of Paleogene (early Tertiary) age is one of the most extensive aquifers in Texas, furnishing water to wells in a wide belt extending from the Rio Grande to the Arkansas and Louisiana border (Figure 1). The aquifer provides irrigation and public supplies throughout much of central and southern Texas (Strause, 1987). The eastern part of the aquifer provides water for public supplies and industry. Covering all or part of 61 counties, the aquifer consists of hydrologically connected ferruginous, cross-bedded sand with clay, sandstone, silt, lignite, and gravel of the Wilcox Group and overlying Carrizo Sand Formation (Muller and Price, 1979). These sediments were deposited by large, fluvial-deltaic river systems which were sourced in the Rocky Mountain foreland region and, to a minor extent for the eastern part of the aquifer, the Ouachita-Arbuckle Mountains (Ayers and Lewis, 1985).

Sediments that make up the aquifer in the south and central regions crop out in a band which is subparallel to the coast and then dip beneath the land surface, thickening toward the Gulf (Figures 1, 9A, 9B, and 9C). The arc in the outcrop, shown on Figure 9A in Zavala County, is a surface expression of the Rio Grande Embayment, a structural low area that received Carrizo-Wilcox sediment fill from both the north and south (Ayers and Lewis, 1985). The eastern part of the aquifer is more complex structurally as indicated on Figure 9D by the two distinct bands of outcrop, one in Van Zandt, Rains, Wood, Hopkins, Franklin, Titus, Morris, Cass, and Bowie Counties; the other, caused by the Sabine Uplift, in Marion, Harrison, Gregg, Rusk, Panola, Shelby, Nacogdoches, San Augustine, and Sabine Counties. Between these two outcrops lies the East Texas Basin, a structural trough into which sediments of the aquifer dip from both sides, allowing recharge to occur from both directions. South of Nacogdoches, San Augustine, and Sabine Counties, the aquifer dips beneath the land surface and thickens toward the Gulf (Figure 9C and 9D). The thickness of the aquifer in the downdip, artesian areas ranges from 150 feet in Dimmit County to more than 3000 feet in Atascosa County in the southern part of the aquifer (Muller and Price, 1979); from less than 1000 to more than 3500 feet in the downdip portion of the aquifer in the central and eastern areas (Ayers and Lewis, 1985).Structural and lithologic features are hydrologically important in this aquifer and affect water quality. Faults in the outcrop and subsurface throughout the aquifer, may act like baffles, and cut off recharge to downgradient portions of the aquifer by disconnecting the more permeable sand units, which may result in ground water flow being redirected around the hydrologic barriers. Faults can also expose sediments at the surface, providing additional surface area for recharge to the aquifer. Salt domes, in the East Texas Basin area, provide conduits for vertical groundwater flow both from deeper units, as discussed later in the Gulf Coast aquifer section, and through recharge at aquifer outcrop exposed at the surface.

The San Marcos Arch, which lies parallel to the Guadalupe and Caldwell County line, is a positive structural feature which affected the deposition of the Carrizo-Wilcox, acting as a division between the southern (Figure 9A) and central areas (Figures 9B and 9C). The aquifer thins over the arch and thickens to either side. South of the arch, sediments of the Carrizo Sand are the dominant source of ground water. North of the arch, sediments of both the Wilcox Group and Carrizo Sand are utilized for ground-water production. In the eastern part of the aquifer (Figure 9D), the Carrizo Sand Formation thins and is undifferentiated from the sediments of the Wilcox Group. These natural separations within the aquifer were utilized in mapping water quality.

The Carrizo-Wilcox aquifer yields fresh to slightly saline water which is acceptable for most irrigation, public supply, and industrial purposes along most of its extent (Muller and Price, 1979). Surface topography exerts a strong control on ground-water movement within the aquifer, with recharge occurring in outcrop along drainage divides and moving down gradient into the aquifer and/or discharging to topographic lows along river basins. Bulk rock mineral composition controls water quality and ground-water flow velocity as discussed in the "Hydrochemical Evolution" section. In outcrop, the aquifer contains hard water that is usually low in dissolved solids content. Downdip, the water becomes softer due to carbonate loss through clay cation exchange, has a higher temperature, and contains more dissolved solids. Throughout the aquifer, nitrate and fluoride do not exceed drinking water standards (Strause, 1987). Hydrogen sulfide and methane gas may be found locally within the aquifer (Muller and Price, 1979). Lignite beds in the Wilcox Group may impart an undesirable color to the water in some areas (Scalf and others, 1973). Excessive pumpage in certain areas, such as Angelina and Nacogdoches Counties (W. F. Guyton & Associates, 1970), is causing a reversal of the hydraulic gradient in the aquifer, resulting in an encroachment of poorer quality water into these areas, either through cross formational flow (poorer water coming from the surrounding strata) or from deeper more basinal waters being drawn up into the aquifer (Muller and Price, 1979).

Excessively corrosive water, with a high iron content, occurs in many parts of the aquifer, however, it is most common throughout much of the northeastern part of the aquifer. Dissolution of iron containing minerals (present in all sediments) by oxidizing, acidic waters provides the source of iron in the ground water (Hem, 1985). Iron ore deposits which overlie the Carrizo-Wilcox aquifer in East Texas provide an additional source of iron. In a study of this area, Broom (1966) found that hematite and limonite, stable in oxidizing conditions, were generally present at and near the land surface, with siderite and pyrite, stable in reducing conditions, found at depths below sixty feet. Shallow ground waters, in recharge areas, were found to be relatively free of iron, probably due to prior removal of available iron by oxidizing waters. Deep, reduced ground waters were also relatively free of iron, probably due to removal of free iron by precipitation of pyrite. Within the transition zone between oxidizing and reducing conditions, iron dissolved in the ground water was stable and water wells which intersected this zone were postulated to produce iron bearing waters.

Ground-water quality in the southern part of the aquifer (Figure 9A) is characterized by low TDS concentrations near outcrop, increasing down dip into the basin. Chloride and sulfate concentrations which exceed drinking water standards are small in geographic extent. One possible explanation for the distribution of these local areas, especially in Dimmit County, may be that saline water from the overlying Bigford Formation is leaking through old well bores and contaminating the aquifer (Muller and Price, 1979). Iron content is high in some wells which are located in and near the Carrizo outcrop in Guadalupe, western Gonzales, northern Atascosa, and parts of Frio Counties.

Water quality in the Carrizo Sand Formation portion of the Carrizo-Wilcox aquifer in Central Texas displays a strong correlation with topography (Figure 9B). Low TDS waters (less than 500 mg/L) occur in recharge areas in outcrop. Higher TDS waters occur downdip of outcrop and in natural discharge valley areas, such as the Brazos and Little Brazos Rivers between the Milam-Robertson and Burleson-Brazos County lines and the Trinity River between Freestone-Anderson and Leon-Houston County lines. Higher TDS waters also occur in the middle of the East Texas Basin in south-central Cherokee and eastern Houston Counties. The width of the band of ground water which contains less than 1000 mg/L TDS water, increases in a northeast direction (as the dip of the aquifer decreases). Only isolated areas exceed drinking water standards for chloride and sulfate. Iron problem areas occur in and near outcrop and appear to decrease with distance from the outcrop or in discharge (chemically reduced) areas.

The lithology in the Wilcox Group portion of the Carrizo-Wilcox aquifer in Central Texas is different from the Carrizo Sand Formation. Containing a thicker sequence of sediments with a higher percentage of less permeable sediment layers within the aquifer and an overall higher clay fraction within the aquifer (Ayers and Lewis, 1985), the Wilcox Group is less hydrologically conductive than the Carrizo Sand. As illustrated on the previous map, topography has a high correlation with TDS concentration in the Wilcox part of the aquifer (Figure 9C). Drainage divides (topographic highs) in outcrop, such as the area around Rockdale in Milam County, can cause discharge from the aquifer to occur into topographically lower areas, to the northwest, down stratigraphic section within the outcrop. Deepest penetration of less than 500 mg/L TDS waters (recharging waters) occurs in Burleson, Robertson, and Leon Counties, along major depositional channel-sand axes mapped by Ayers and Lewis, 1985. Higher TDS waters again correlate with discharge areas such as river basins. In contrast to the Carrizo Sand map, there are larger and more numerous areas that exceed drinking water standards for chloride and sulfate in the outcrop. This difference may be due to the higher clay fraction of the sediments and/or the more marine depositional origin of the aquifer matrix. Highest iron concentrations appear to correlate with recharge waters of less than 500 mg/L TDS. A more detailed discussion of the ground-water chemistry in both the Carrizo and Wilcox portions of the aquifer in the Central Texas area can be found in Fogg and others (in press).

Ground-water quality in the eastern part of the aquifer (Figure 9D) is variable, but generally characterized by low TDS (less than 1000 mg/L) concentrations in and near outcrop, increasing downdip. As discussed earlier, this area contains two outcrop belts, with recharge to the aquifer occurring from both the east and the west into a trough of sediments. TDS concentrations increase basinward, with increasing depth, in both the East Texas Basin and the Gulf Coast Basin in southern Cherokee, Angelina, San Augustine, and Sabine Counties. Higher TDS values (greater than 500 mg/L) are coincident with discharge along rivers, for example: southwest Van Zandt County (again, due to topography, discharge occurs opposite from the the dip of the sediments); along the Sabine River in outcrop areas along the Van Zandt-Rains, Harrison-Gregg, Harrison-Rusk, and Harrison-Panola County lines; along the Sulphur River in northern Titus, Morris, and Cass-Bowie County lines; Big Cypress Bayou in southern Marion County; and Attoyac Bayou along the Nacogdoches-Shelby County line. Higher TDS areas occur on the northern (down thrown) side of the Mount Enterprise Fault Zone in central Cherokee, southwest Rusk, and westernmost Shelby Counties.

Isolated areas with ground-water concentrations that exceed drinking water standards for sulfate occur in the outcrop of the eastern section of the Carrizo-Wilcox aquifer (Figure 9D). Wells with high iron concentrations are found in or near outcrop, near recharging areas, and decrease in number down gradient, deeper into the basins. Areas with high chloride concentrations are generally isolated in outcrop, however, large areas occur along the Sulphur River in Cass, Morris, and Titus Counties; in Marion County, east of a fault which runs through Jefferson and extends northward into an oil producing area; and in southern Upshur and eastern Gregg Counties, extending along the Sabine River. The latter area has been attributed by Kaiser and others, in preparation, to natural deep discharge from underlying Cretaceous sediments in the area of the East Texas Oil Field. A more detailed discussion of the ground-water chemistry in this area can be found in Kaiser and Ambrose (1986).

Edwards (Balcones Fault Zone)

Located in central and south-central Texas, the Edwards (Balcones Fault Zone) aquifer (Figure 1) covers approximately 4350 square miles and is bounded by ground-water divides in Kinney County on the west, by faulted outcrop on the north and northwest, by the interface between fresh and saline water to the south and southeast, and by extreme thinning of the aquifer near the Leon River in Bell County (Baker and others, 1986; Maclay and Small, 1986; and Senger and Kreitler, 1984). The aquifer consists of the Edwards and associated Georgetown and Comanche Peak Formations in the north and the Edwards Group in the south (Muller and Price, 1979). Composed of evaporitic, tidal flat, and reef deposits of Cretaceous age (Maclay and Small, 1983); the aquifer provides water primarily for public supply, although some water is pumped for irrigation, industry, domestic, and livestock use.

The uneroded thickness of massive to thin-bedded, nodular, cherty, gypsiferous, clayey, white to gray limestones and dolomites which are in hydraulic continuity (Muller and Price, 1979), increases from northeast to southwest along strike and expands down dip from the outcrop. In Kinney County, the aquifer thickness is greater than 1000 feet and diminishes northward to about 500 feet in Hays County to 225 feet in southern Bell County (Baker and others, 1986). The Edwards Limestone is the primary water-bearing formation, and yields moderate to large quantities of fresh water (Muller and Price, 1979). Over wide areas, the aquifer produces water from several layers of highly permeable and porous honeycombed rocks (karst) caused by ground-water dissolution (Maclay and Small, 1983). Due to the extremely high permeability of these layers, wells pumping from this aquifer are among the most prolific in the world, with some yielding more than 16,000 gal/min (Muller and Price, 1979).

Recharge occurs by downward percolation of surface water from rivers and streams crossing the aquifer outcrop and/or infiltration zone (Figure 10) and secondarily by direct infiltration of precipitation on the outcrop (Muller and Price, 1979). Some streams crossing the outcrop flow only during floods because of the high rate of surface-water seepage into the underlying strata. Recharge waters reach the aquifer mainly through solution crevices and faults within the

Balcones Fault Zone. Small amounts of ground water enter the aquifer from the underlying Glen Rose Formation as either lateral underflow or upward leakage along faults. Water moves regionally from recharge areas, through highly permeable solution zones, to discharge at wells and naturally at numerous small and large springs including Leona Springs near Uvalde, San Antonio and San Pedro Springs in San Antonio, Comal Springs in New Braunfels, San Marcos Springs in San Marcos, Barton Springs in Austin, and Salado Springs in Salado (Muller and Price, 1979).

Discussions by Maclay and Small (1983) and Maclay and others (1985) on lithology and fault barriers within the Edwards (Balcones Fault Zone) aquifer indicate that the direction of ground-water flow is controlled by the presence and continuity of permeable strata within the aquifer and by faults which abruptly disrupt the lateral continuity of these permeable zones. High angle normal faults within the aquifer can place rocks of very high permeability adjacent to rocks of very low permeability. They concluded that as ground water moves downgradient, the displacement of high permeable layers can cause a partial to complete barrier to flow within the aquifer, and can result in a redirection of flow parallel to the fault. The "bad water line," defined for this report as the down gradient boundary of less than 1000 mg/L TDS water (Figure 10), in the southern portion of the aquifer is partially caused by ground water not crossing faults with a vertical displacement of greater than 50 percent of the thickness of the aquifer (Maclay and Small, 1983). Also, the aquifer permeability is less downdip from the "bad water line," with the rock matrix in the saline water zone having undergone relatively little change since burial by late Cretaceous deposits. The permeability of this part of the aquifer is less, due to the small size of the interconnecting channels between the pores within the rock matrix (Maclay and Small, 1983).

In the southern part of the aquifer, in Medina County, the width of the aquifer which contains fresh water (TDS of 1000 mg/L or less) is greatest, and thins to the east and northeast towards Austin in Travis County (Figure 10). The fresh water zone widens in the Round Rock and Georgetown area and then thins in Bell County. The narrow zone of low TDS water in the Austin area is associated with intensive faulting which retards ground-water recharge and flow in an easterly (downgradient) direction (Baker and others, 1986). North of Pflugerville, where faulting is less intense, a tongue of recharging water containing less than 500 mg/L TDS has penetrated downgradient between fault blocks. In Williamson and Bell Counties where faulting and the resultant displacement of the aquifer is less severe, ground water with a TDS concentration of less than 1000 mg/L extends a greater distance downdip (Baker and others, 1986).

The same quality trends are evident for chloride and sulfate, with concentrations that exceed drinking water standards generally occurring downgradient of the "bad water line" (Figure 10). Clement and Sharp (1987) attribute the increase of chloride and sulfate to either the long residence time of the water in the aquifer, which allows the water to react with the natural evaporite deposits within the rock matrix, or upward movement along faults of more saline waters into the aquifer. The latter may be responsible for isolated spots of highly mineralized ground water which occur upgradient of the "bad water line."

High nitrate concentrations in the ground water are considered to be a man-induced problem (Kreitler and others, 1987). A review of published data did not indicate a problem with high nitrate concentrations in wells completed in the southern section of the aquifer (Browning, 1977), possibly due to dilution by the high recharge volumes entering the aquifer. However, high values have been recorded in one well northeast of the city of Uvalde. In the northern section of the aquifer in the Pflugerville and Georgetown area, wells with high nitrate concentrations occur (Figure 10). Concentrations that exceed the drinking water standard are associated with low TDS (less than 500 mg/L) recharging waters, and may be the result of direct recharge to the aquifer from leaking septic systems (Kreitler and others, 1987).

Trinity Group

Providing public, domestic, and industrial supplies in densely populated areas in North, Central, and South-Central Texas and irrigation supply throughout much of northern and central Texas (Muller and Price, 1979), the Trinity Group aquifer serves all or part of 56 Texas counties (Figure 1). The aquifer is composed of the Paluxy, Glen Rose, and Travis Peak (Twin Mountains) Formations. The Glen Rose Formation normally separates the Paluxy and Travis Peak, however, west of a line which runs through Eastland, Comanche, and Brown Counties and north of Decatur in Wise County, the Glen Rose Formation thins or is missing, and the Paluxy and Travis Peak Formations merge and are termed the Antlers Formation (Muller and Price, 1979). These lower Cretaceous-age strata were deposited in fluvial, deltaic, strandplain, and shallow marine environments (Mosteller, 1970; Hobday and others, 1981) and are composed primarily of sand with interbedded clays, limestone, dolomite, gravel, and conglomerates with evaporite deposits present in the upper Glen Rose Formation. Saturated thickness ranges from approximately 100 feet in the outcrop area to about 1200 feet near the downdip limit of fresh to slightly saline water (Muller and Price, 1979).

General quality of the ground water in the Trinity aquifer is illustrated in Figure 11. Recharge, infiltration, lithology, environment of deposition, and structure exert natural controls on the water quality. Recharge through the unconfined portion of the aquifer is primarily in the form of infiltration of precipitation and seepage of surface water from lakes, unlined earthen ponds, streams, and return flows of water used to irrigate crops; and substantial recharge to the confined portion of the aquifer is derived by leakage from the overlying water-bearing strata (Ashworth, 1983; Rapp, 1988). During dry periods, recharge is relatively small, and large water level declines can occur. Water entering the Trinity Group aquifer generally moves basinward to the south and southeast as reflected in the increasing TDS, sulfate, and chloride concentrations along the flow path. Discharge occurs in areas of continuous pumpage and naturally through spring flow to drainage areas. Topography controls the local flow direction more directly than structural dip in the unconfined portion of the aquifer (Ashworth, 1983) with higher TDS concentrations occurring in major drainage basins.

Structural features, including the Balcones and Luling-Mexia-Talco Fault Zones and the ridges and valleys of the eroded pre-Cretaceous depositional surface such as the McGregor High, affect the direction and rate of regional ground-water flow (Klemt and others, 1975). The Balcones Fault Zone extends from Kinney to Bell Counties (Figure 11). The Luling-Mexia-Talco Fault Zone parallels the Balcones in the northeastern part of the aquifer. These fault zones may completely block or severely restrict the movement of water into the basin, and may allow undesirable saline water to enter the aquifer along the fault planes. The western boundary of the Luling-Mexia-Talco Fault Zone may control the downdip limit of fresh to slightly saline water (Klemt and others, 1975). Control on accumulated thickness of the aquifer was exerted by the paleotopography which existed prior to the deposition of the Cretaceous sands, resulting in thicker accumulations of sand occurring in the paleovalleys and thinner (less permeable) accumulations occurring on the ridges (Klemt and others, 1975).

The environment under which the aquifer sediments were deposited influences the chemical character of the water due to permeability variations; orientation of thicker, more permeable units; and chemical composition of the lithologic units. There is a rapid increase in TDS, chloride, and sulfate concentration at the boundary between the dip-elongate more permeable fluvial-deltaic systems and the less permeable strike-elongate prodelta, lagoon, and shelf system in Falls, McLennan, and Hill Counties (Woodruff and McBride, 1979). Strike-elongate sand thicks correlate with deep penetration of less than 1000 mg/L TDS waters in the central part of the aquifer. Recharge by infiltration through the overlying Glen Rose Formation may result in an increase in sodium sulfate and chloride by dissolution of the evaporite deposits (Rapp, 1988). High TDS and associated high sulfate and chloride concentrations also correspond to a mapped lithologic change of less permeable calcareous cemented facies south of Killeen (Klemt and others, 1975). Higher constituent concentrations in northern Lamar, Fannin, and Red River Counties may be due to a lithologic pinch out of aquifer material indicated on cross sections by Baker and others (1963).

Excessive ground-water pumpage from the lower part of the Trinity aquifer may allow significant amounts of more sulfate-rich water, from the Glen Rose or deeper more basinal waters, to be drawn into the production zone, resulting in lower water levels with an associated increase in pumping costs and production of poorer quality water (Rapp, 1988). The elongate fingering of higher TDS waters in the Dallas-Fort Worth area may indicate areas where over pumpage of the aquifer is occurring. Movement of poorer quality waters into the more permeable dip-elongate units, either from the basin or out of the adjacent less permeable units, may be the result of over stressing the aquifer. Areas of over production that may have resulted in a change in water quality occur throughout the northern part of the aquifer, for example, near Sherman in Grayson County and McKinney in Collin County. Additionally in the northwest outcrop of the aquifer, oil and gas production with its associated disposal of salt water has been indicated as a possible source of high constituent concentrations in the ground water in Parker, Wise, Eastland, and Comanche Counties (Klemt and others, 1975; Nordstrom, 1982).

Alluvium and Bolson Deposits

Water-bearing alluvium and bolson deposits of Tertiary to Recent age occur throughout the state (Figure 1). Although these sediments are completely separate geographically, they are collectively considered a single major aquifer due to their geologic and hydrologic similarities (Muller and Price, 1979). Alluvium deposits are composed of stream-borne, windborne, and playa lake sediments. Bolson deposits (a term applied in desert regions) are composed of deep alluvial accumulations washed into intermontane (valley) areas from the surrounding highlands (Bates and Jackson, 1980). The water-bearing sediments which form this aquifer are generally unconsolidated, alternating, and discontinuous beds of silt, clay, sand, gravel, and boulders with associated caliche, gypsum, conglomerate, volcanic ash, tuffs, and basalts (Muller and Price, 1979).

In some areas, alluvial and bolson deposits contain large volumes of good quality ground water (Muller and Price, 1979). Quality trends were mapped in three of the most productive areas of this aquifer, the alluvium and bolson deposits of West Texas (Figure 12), the alluvium of North-Central Texas (Figure 13), and the Brazos River Alluvium of Southeast Texas (Figure 14). Ground water also exists in other river alluviums of the state, however, data are too scarce to fully evaluate the water quality in these scattered deposits.

West Texas

Fifty-seven percent of ground water that is used for all purposes in this part of the state is supplied by alluvium and bolson deposits, with the majority of water being used for irrigation (Texas Department of Water Resources, 1984). A minor amount is used for livestock watering and in the more densely populated areas, ground water also supplies municipal, mining, manufacturing, and steam-electrical power generation purposes (Texas Department of Water Resources, 1984). Ground water is also used for petroleum and natural gas production, principally in Winkler County. Seven different alluvium and bolson deposits were mapped for water quality parameters (Figure 12). As delineated by Gates and others (1978) and Muller and Price (1979), the individual areas which make up the aquifer are the Mesilla and Hueco Bolsons in the El Paso area, Salt Bolson and its subareas, Eagle Flat Bolson, Red Light Draw Bolson, Green River Valley Bolson, Presidio and Redford Bolsons, and the Cenozoic Alluvium in the upper part of the Pecos River Valley (Figure 12). Bolson deposits may reach a total thickness of up to 9000 feet and fresh water occurs as deeply as 1200 feet in the Hueco Bolson (Texas Department of Water Resources, 1984). Cenozoic Alluvium deposits range up to 1500 feet or more in thickness (Muller and Price, 1979).

Precipitation and, to a minor extent, infiltration from the Rio Grande and Pecos River, are the principal sources of recharge to the alluvial and bolson deposits (Muller and Price, 1979). Ground-water movement in this area, as described by White and others (1980), begins with recharge along the foothills of the mountains and plateaus where the sediments are coarse grained and permeable, and possibly along the channels of ephemeral streams in the basins. Generally, recharge does not occur unless precipitation is sufficient to cause surface flow through the foothill areas and in the ephemeral streams, otherwise the water is either directly evaporated or lost from the shallow subsurface by evapotranspiration. Man-induced recharge to the Cenozoic Alluvium from saline water in the Pecos River has resulted in the highest concentrations of total dissolved solids, chloride, and sulfate occurring in areas adjacent to the river (Figure 12) where heavy irrigation pumpage has substantially lowered the ground-water potentiometric surface (Scalf and others, 1973).

Ground water moves from recharge areas to discharge in the topographically lower parts of the basins (White and others, 1980). Fresh water (TDS less than 1000 mg/L with low concentrations of sulfate and chloride) is generally located in recharge areas that flank the topographically higher basin edge (Figure 12), and may occur down gradient in distinct lenses intertongued with less permeable sediments which contain older, more saline waters. Total dissolved solids, chloride, and sulfate concentrations increase along the ground-water flow path by interaction with the rock matrix, dissolution of associated evaporite deposits, and/or evapotranspiration concentration. Basinward, slightly saline to saline ground water may discharge naturally through evaporation, which can result in accumulation of salts on the land surface; may leave the topographically closed basin through the rocks that underlie the basin; or discharge directly to surface drainage such as the Rio Grande (White and others, 1980).

Large amounts of man-induced ground-water discharge have occurred historically, where the aquifer was (and in some areas still is) utilized for irrigation in the Salt Bolson agricultural areas such as the Wild Horse and Michigan Flats areas north and west of Van Horn, Lobo Flats south of Van Horn, and in the Cenozoic Alluvium of the Pecos Valley (Texas Water Development Board, 1986). Currently, large amounts of ground water are withdrawn for municipal and industrial use in the El Paso area from the Hueco and lower Mesilla Bolsons. Overproduction of ground water may result in a rise in dissolved constituents due to mixing of fresh water with slightly saline to saline water withdrawn from the sediments which underlie, overlie, or adjoin the fresh-water bearing zones.

Two groups of wells that contain nitrate concentrations above the drinking water standard are associated with irrigation areas in the Cenozoic Alluvium in northwest Pecos County in the Coyanosa Irrigation Area and south of the Pecos in Reeves County (Figure 12). High nitrate values may be the result of man-induced contamination resulting from over fertilization. High salinity in the Cenozoic Alluvium may be the result of excessive irrigation water application with increasing ground-water salinity contributed by water which has leached accumulated salts from the soil zone, and percolated downward to the saturated zone. High nitrate contamination in the Hueco Bolson around the San Elizario area may be a result of sewage effluent infiltration, and nitrates in the Old Mesa Well Field area in El Paso near Fort Bliss, may be the result of contamination entering the aquifer through abandoned wells (White, 1987).

North-Central Texas

In twenty-three counties in North-Central Texas (Figure 13), isolated areas of alluvium (erosional remnants of the Seymour Formation) furnish water for irrigation and municipal supply, with a minor amount used for manufacturing and livestock watering (Texas Water Development Board, 1988). Additionally, in east central Tom Green County, the Leona Alluvium, an erosional outlier of the Ogallala Formation, yields water principally for irrigation (Muller and Price, 1979). The aquifer is generally composed of discontinuous beds of poorly sorted gravel, conglomerate, sand, silty clay, and caliche (Price, 1978 and 1979). Individual areas vary greatly in thickness, with a total thickness usually less than 100 feet (Texas Department of Water Resources, 1984). However, in isolated areas in the northern part of the aquifer, thickness may reach 360 feet from the filling of paleokarst features. Saturated thickness is generally less than 100 feet, and in the northern part is commonly less than 50 feet (Smith, 1970). Total saturated thickness of these deposits is directly related to the amount of erosional dissection from drainage development across these remnants, with increased dissection resulting in increased drainage of the water bearing units and decreased saturated thickness. Recharge is principally derived from precipitation on the outcrop with natural discharge occurring from seeps and springs along drainage areas on the edge of the aquifer, evapotranspiration by plants, evaporation from the water table, and leakage to the underlying Permian strata (R.W. Harden and Associates, 1978). Ground-water movement is generally from higher-elevation recharge areas to lower-elevation discharge areas or towards areas of man-induced discharge created by pumping large capacity wells.

Water quality varies greatly between and within the alluvial remnants (Figure 13). In a study by R.W. Harden and Associates (1978), lower TDS content correlated with recharge areas having sandy soils, and higher TDS values occurred away from recharge areas and may represent natural mineralization from rock-water interaction. However, pollution from oil field brine, which could increase the TDS content, has been documented (Price, 1978 and 1979; R. W. Harden and Associates, 1978). Sources or potential sources of brine pollution from oil field activities include unlined surface disposal pits, improperly plugged abandoned oil tests, faulty injection wells and oil wells, spills, and unplugged seismic and stratigraphic holes (R. W. Harden and Associates, 1978). High chloride concentrations could be the result of natural mineralization or inflow from Permian strata, however, pollution from oil field brines or septic tanks could increase the chloride content. Heavy pumping in some areas has caused a salinity increase which has rendered the water unusable for municipal or domestic use (Muller and Price, 1979). Sulfate distribution is similar to that of total dissolved solids and chloride.

Abnormally high nitrate concentrations occur in ground water over a wide geographic area (Figure 13). As discussed in the previous section on nitrate in ground water, this widespread distribution may be the result of leaching of soil and humus in agricultural areas once covered by nitrogen fixing vegetation such as grasses and/or mesquite groves (Kreitler, 1975). Some of the nitrate in the ground water may be the result of excessive nitrogen fertilizer application. Nitrate values above the normally high background nitrate concentration have been attributed to poorly functioning septic systems or infiltration of animal wastes from barnyards (Price, 1978 and 1979; R.W. Harden and Associates, 1978).

Southeast Texas

Along the Brazos River, between northern McLennan County and central Fort Bend County, stream-deposited alluvial material, ranging from less than one mile to about seven miles wide (Figure 14), supplies water mainly for irrigation and a minor amount for livestock watering and mining supply (Texas Department of Water Resources, 1984; Cronin and Wilson, 1967). Total thickness of the Brazos River Alluvium ranges from 15 to 200 feet with saturated thickness up to 85 feet or more (Muller and Price, 1979). Maximum thickness occur in the central and southeastern part of the aquifer. Recharge is derived primarily from precipitation on the outcrop, with other sources of water being inflow from underlying strata, infiltration from irrigation, recharge from the river in areas of high pumpage, and temporary bank storage from floods along the river (Cronin and others, 1963). Natural discharge from springs, seeps, and evapotranspiration, and artificial discharge due to pumpage, occur along the length of the river (Cronin and others, 1963).

Ground-water chemical quality varies widely, even within short distances (Figure 14). Areas where total dissolved solids exceed 1000 mg/L, and sulfate and chloride exceed drinking water standards, may be the direct result of the mixing of alluvial aquifer water with highly mineralized water naturally discharging from the underlying water-bearing units such as the Midway Group in southern Falls County (Cronin and Wilson, 1967), Yegua Formation and Jackson Group in central and southern Burleson County, and the Catahoula Formation in southern Brazos County, (all strata of Tertiary age). Wells which exceeded the drinking water standard for nitrate were few, and distributed throughout the aquifer, indicating a local rather than regional problem.

Gulf Coast

The Gulf Coast aquifer covers all or part of 53 counties (Figures 1 and 15), and is composed of Miocene to Holocene sediments of the Catahoula, Oakville, Lagarto, Goliad, Willis, Lissie, and Beaumont Formations, as well as overlying surficial deposits (Muller and Price, 1979). The principal water-bearing units are the Goliad, Willis, and Lissie Formations. Consisting of alternating beds of clay, silt, sand, and gravel, which are hydrologically connected, the aquifer is considered by Muller and Price (1979) to be a large, leaky artesian system. Ranging from a few feet in thickness in outcrop to tens of thousands of feet at the coastline (Baker, 1979), these sediments were deposited under fluvial, deltaic, and shallow marine environments and, in the Catahoula Formation, contain wind-transported volcanic ash. Water-bearing units thicken toward the Gulf of Mexico and are inclined in a gulfward direction, resulting in the younger units cropping out nearer the Gulf, with older sediment exposed at the surface farther inland (Muller and Price, 1979). Outcrops of the more permeable sediments (Goliad, Willis, and Lissie Formations), which are the aquifer's recharge areas, occur in bands that parallel the coast.

Ground water is used for public supply in densely populated areas and for irrigation and public supply elsewhere (Strause, 1987). Man-induced problems resulting from long term withdrawal of ground water from the Gulf Coast aquifer have been recognized by many authors. Overdraft upon the aquifer has resulted in land-surface subsidence in Houston and surrounding areas, increased chloride content in the ground water due to interaquifer exchange, saltwater encroachment along the coast (Muller and Price, 1979), and a lower potentiometric surface in parts of the aquifer, with a resulting increase in pumping lift, making it more expensive to produce ground water (Grubb, 1984).

Bulk rock mineral composition controls water quality and ground-water flow velocity in the aquifer. Sediments deposited under marine conditions contain brackish or highly mineralized waters. Aquifer flushing of brackish water by recharging fresh water occurs in outcrop areas and a limited distance down hydraulic gradient, depending upon the permeability of the sediments (Baker, 1986). The percentage of sand within the aquifer increases from west to east (Baker, 1979), with a significant increase in sand body thickness and resultant permeability occurring east of the San Marcos Arch (Figure 15). East of the arch, the maximum total aggregate sand thickness is about 1300 feet, while west of the arch, the maximum total sand thickness is about 700 feet (Muller and Price, 1979).

Better quality water, generally containing less than 500 mg/L TDS with few instances of chloride and sulfate concentrations above drinking water standards, occurs east of the San Marcos arch (Figure 15). In this area, water of less than 3000 mg/L TDS may be found to a maximum depth of 3200 feet from land surface (Muller and Price, 1979), however, the aquifer thickness containing water of this quality thins in a gulfward direction. More mineralized water occurs in sediments that have not been as flushed as those upgradient, especially along the Gulf. Isolated areas of more mineralized waters may indicate natural mixing of aquifer waters with more saline waters, either through dissolution of salt domes or mixing with deep basinal waters which have moved up along the flanks of the domes or along faults. Other more mineralized areas, such as central and western Harris County, may be due to over pumpage of the ground water that has resulted in encroachment of more saline waters into the producing zones of the aquifer (Muller and Price, 1979). No substantial areas are affected by high sulfate or chloride concentrations east of the Arch. Strause (1988) indicated that slightly more than 10 percent of all the analyses from wells throughout the Gulf Coast aquifer exceeded the drinking water standard for nitrate.

As discussed earlier in the section on radium, ground water in several areas of the Gulf Coast aquifer, east of the San Marcos Arch, contains high levels of radium and/or radon (Figure 7). The results of a study in this area by Cech and others (1987 and 1988) indicated that anomalous radium concentrations, up to 65 pCi/L, reached a peak at a depth range between 585 and 1140 feet below the surface and were associated with wells developed near salt domes and/or near streams. Radon concentrations tended to increase with depth and to increase in a gulfward direction. This study also indicated that the proximity of salt domes and associated fault systems was an important predictor for the presence of radon and radium in the ground water. Concentrations decreased as distance from domes increased. It was concluded that radium and radon in the ground water may have originated in the Catahoula Formation, a known source of uranium mineralization, and migrated upward into the shallower portion of the Gulf Coast aquifer. Avenues for migration may be located along the flanks of piercement-type salt domes, along faults, and through permeable sediments deposited by streams. Alternately, it was proposed that uranium could have migrated through the upper aquifer strata, and concentrated in the reducing halo surrounding the domes.

Ground-water quality decreases west of the San Marcos arch (Figure 15). The more mineralized ground water found in this part of the aquifer may indicate that the sediments which compose that aquifer have not been as flushed as their more permeable counterparts to the east, especially along the Gulf where greater than 10,000 mg/L or ppm TDS can be found. It should be noted, however, that Figure 15 was produced using water quality from wells completed at many different producing horizons, and that locally deviations from the regional trends may be found. Most waters average between 1000 and 1500 mg/L TDS, however, there are areas in Aransas, Calhoun, Cameron, Hidalgo, Kenedy, Kleberg, Nueces, San Patricio, and Willacy Counties where little to no appreciable amounts of ground water with less than 3000 mg/L TDS can be found (Muller and Price, 1979). Large areas of the aquifer have chloride and sulfate concentrations above drinking water standards. On barrier islands along the shoreline, ground water suitable for domestic and livestock use may be found in shallow sands (Muller and Price, 1979). Little of the water in the southwestern part of the aquifer is recommended for prolonged irrigation use due to either high salinity or alkalinity hazard, or both (Muller and Price, 1979). During times when the water quality and/or quantity of the Rio Grande does not meet the demand, supplemental ground water is pumped for irrigation as well as for municipal use in the Lower Rio Grande Valley (Muller and Price, 1979).

Edwards-Trinity (Plateau)

The Edwards-Trinity (Plateau) aquifer underlies the Edwards Plateau east of the Pecos River and the Stockton Plateau west of the Pecos River and extends from Gillespie County on the east to Culberson County in the Trans-Pecos area on the west, and from Kinney County on the south to Howard County on the north (Muller and Price, 1979; Figures 1 and 16). Principally, the aquifer is used for irrigation, however, municipal, industrial, livestock, and domestic supply is important (Texas Water Development Board, 1988). The production of oil and gas is a major industry, especially in the northwestern part of the region.

Aquifer strata were deposited under marine conditions and consist of the Comanche Series, which is further subdivided into the Trinity, Fredericksburg, and Washita Groups (Walker, 1979). Composed of saturated sediments of Lower Cretaceous age, the aquifer is made up of sands, sandstone, gravel, and conglomerates of the Trinity Group (Antlers Formation and lateral equivalents); and cherty, gypsiferous, clayey, cavernous limestones and dolomites of the Comanche Peak and Edwards Limestones of the Fredericksburg Group and the Georgetown Formation of the Washita Group (Muller and Price, 1979). The Santa Rosa Sandstone of Triassic age is considered to be part of the aquifer when it is in hydrologic continuity with the Edwards-Trinity strata.

Saturated thickness of the water-bearing units reaches a maximum of 800 feet (Walker, 1979). Recharge is primarily derived from precipitation, which infiltrates through the soil zone through dissolution openings and crevices in the limestone outcrop to reach the saturated zone. To a certain extent, ground-water flow direction is controlled by topography (Walker, 1979). Ground water generally flows in a southeasterly direction following the dip of the strata. Near the plateau edge, movement is towards major streams and rivers where ground water is discharged from springs (Walker, 1979). Locally, in areas of high artificial discharge, such as pumpage for irrigation and oil field supply, regional cones of depression in the water table have formed, resulting in ground water-flow being redirected towards the center of the pumped area (Rees and Buckner, 1980; Walker, 1979).

Ground water from the Edwards-Trinity (Plateau) aquifer has a wide range of TDS concentrations, with a general increase from southeast to northwest (Figure 16). Ground-water salinity increases toward regional discharge areas such as major rivers and streams which dissect the aquifer, for example, the Pecos River which marks the boundary between Pecos and Crockett Counties; the Llano River in central and northeastern Kimble County; the San Saba River in central Menard County; the South and Middle Concho Rivers and Spring Creek southwest of San Angelo in Tom Green County; and the North Concho River in southeastern Sterling County. In the northwest where the aquifer is overlain by younger sediments which contain saline water, the higher TDS, chloride, and sulfate concentrations may be due to leakage into the aquifer from these sediments (Scalf and others, 1973). In the trans-Pecos part of the aquifer, Rees and Buckner (1980) attribute the high concentrations of TDS, chloride, and sulfate to deep discharge to the Edwards-Trinity (Plateau) aquifer from the underlying evaporite deposits of the Castile and Rustler Formations in Culberson and northwest Reeves Counties and from the Rustler Formation in north central Pecos County. In some heavily irrigated areas, infiltration from water applied on fields may be entering the ground water to be cycled again onto the fields, causing a salinity increase due to the continual contribution of leached surface salts from the soil zone (Rees and Buckner, 1980). Elevated levels of nitrate in the ground water around one irrigation area in Pecos County were indicated by Rees and Buckner (1980).

Some areas of high chloride concentration are coincident with areas of heavy oil and gas production such as Sterling, Glasscock, Reagan, Upton, Crockett, and north-central Pecos Counties, and may be the result of oil field brine disposal activities (Rees and Buckner, 1980; and Walker, 1979). Contamination of the aquifer may be occurring from historic salt water disposal pits, brine disposal wells or playa lakes, or historic dumping of salt water into surface drainageways and on county roads (Walker, 1979).

Minor Aquifers

Minor aquifers provide water throughout the state (Figure 2) and contain the same dissolved minerals as the major aquifers, including calcium, magnesium, bicarbonate, sodium, chloride, sulfate, nitrate, iron, and radium, and dissolved gases like hydrogen sulfide, and methane (Texas Department of Water Resources, 1984). The Edwards-Trinity (High Plains), Ellenburger-San Saba, Marble Falls, Marathon, Bone Spring and Victorio Peak, Capitan, and Rustler aquifers are all composed of limestone and/or dolomite and contain water which is hard, and contain higher concentrations of calcium, magnesium, and bicarbonate (Texas Department of Water Resources, 1984). The Edwards-Trinity (High Plains), Bone Spring and Victorio Peak, Capitan, and Rustler aquifers have high concentrations of chloride and sulfate in some areas.

Sandstone aquifers, consisting of the Woodbine, Queen City, Sparta, Santa Rosa, Hickory, Nacatoch, and Blossom, contain higher concentrations of sodium, chloride, and sulfate ions (Texas Department of Water Resources, 1984). The Woodbine, Queen City, Sparta, and Hickory aquifers have areas of high iron concentrations. Hydrogen sulfide gas is abundant within the Queen City aquifer (Texas Department of Water Resources, 1984). Water from the Blaine, an aquifer composed of evaporitic deposits, is high in dissolved solids, chiefly calcium and sulfate.

Woodbine

From northern McLennan County northward to the Red River (Figures 2 and 17), the sand and sandstone beds of Cretaceous age which comprise the Woodbine aquifer furnish water for municipal, industrial, and small irrigation supplies (Muller and Price, 1979). The aquifer crops out in a narrow belt which trends south from southeastern Cooke County and is exposed in patches in a west-east direction paralleling the Red River in Grayson, Fannin, Lamar, and Red River Counties (Muller and Price, 1979). As described in a study by Nordstrom (1982), rainfall on the outcrop is the primary source of aquifer recharge, however, surface-water seepage from lakes and streams is considered to be an additional recharge source. Ground water flows to the east, following the dip of the aquifer into the subsurface. Discharge occurs naturally through springs and seeps, evaporation, and transpiration by plants. Most artificial discharge occurs through the pumping of wells, with a minor amount of discharge occurring from flowing wells along the Red River portion of the outcrop (Nordstrom, 1982).

The aquifer reaches a maximum thickness of about 600 feet and contains fresh to slightly saline water to a maximum depth of 2000 feet below land surface (Muller and Price, 1979). In the southern segment of the aquifer, the Woodbine is composed of friable, iron bearing fine-grained sand and sandstone with interbedded shale, sandy shale, and clay (Nordstrom, 1982). The northern segment is generally divided into lower, middle, and upper parts, with the upper being composed of fine-grained, well sorted, reddish-brown sandstone with concretions and shale present; the middle part being composed of reddish sandstone with interbedded gray to brown clay and shale; and the lower part being composed of interbedded, red-brown to white sandstone with ironstone and sandy, gray to brown clay (Nordstrom, 1982). In the northern segment, only the lower part of the aquifer is considered by Nordstrom (1982) to be suitable for water supply development.

Fresh, good quality water is produced from wells completed on or near the outcrop of the Woodbine aquifer (Nordstrom, 1982; Figure 17). High iron concentrations, which occur in the upper Woodbine sands (Nordstrom, 1982), make the water undesirable, as discussed earlier in the section on iron. Water quality deteriorates rapidly downdip from the outcrop, with total dissolved solids, sodium, chloride, and bicarbonate concentrations increasing (Nordstrom, 1982). High fluoride concentrations have been reported in some areas (Texas Water Development Board, 1988). A finger of higher TDS waters in Collin County, west of McKinney, corresponds to an area that is experiencing extensive ground-water pumpage with a resultant lowering of the ground-water potentiometric surface (Texas Water Development Board, 1988). High nitrate levels are not found naturally in aquifer waters, however, a few shallow dug wells produce water with nitrate levels above 45 mg/L (Nordstrom, 1982).

Queen City

Extending from the Frio River in Frio County northeastward to the Louisiana border (Figure 18), the Queen City aquifer of Eocene age consists principally of sand, loosely cemented sandstone, and interbedded clays (Muller and Price, 1979). North of Houston County, the aquifer is generally exposed at the surface with intense faulting in Cherokee and Anderson Counties. The arched outcrop in this segment of the aquifer curves around the Sabine Uplift (described in the "Carrizo-Wilcox" section) and, beginning in Cherokee and Anderson Counties, the sediments dip to the south (Payne, 1972). South of this area, the width of the outcrop narrows and is highly faulted from Milam to Gonzales Counties and then becomes wider again in Frio County. In the southern section, aquifer sediments dip to the south and southeast, towards the Gulf (Payne, 1972).

Variations in aquifer thickness and hydraulic conductivity are a reflection of the environments under which the sediments were deposited. Payne (1972) studied the Queen City aquifer and found that it is about 800 feet thick near the outcrop in Frio and Atascosa Counties and then thins eastward to 600 feet or less in the outcrop in Wilson and Gonzales Counties. The aquifer continues to thin in a northeastward direction to a minimum thickness of 50-100 feet and eventually the water-bearing sands pinch out in the vicinity of Lufkin, Angelina County. The thickest and highest percentage of sand units occurs in the southwestern part of the aquifer in a band from Wilson to Frio Counties. He determined that these sands were deposited in channels and as nearshore and alongshore bars associated with a delta complex centered in La Salle, McMullen, and Webb Counties. Eastward, the sands were deposited by minor fluvial systems. He concluded that the general elongation subparallel to the outcrop of the sands in Burleson and Walker Counties suggests that they were deposited in nearshore and alongshore bars and beach environments.

Recharge to the Queen City occurs by infiltration of rainfall on the outcrop, infiltration of water from streams, and by upward movement of water from the underlying Carrizo-Wilcox aquifer (Payne, 1972). In the southwestern part of the aquifer, discharge from the Carrizo Sand is considered to be a major source of recharge to the Queen City aquifer (Payne, 1972). Regional flow is down the dip of the aquifer to the south and southeast. Water discharges naturally through seeps and springs in the outcrop and through leakage to the overlying strata. Man-induced discharge from wells is used to supply water for rural, domestic, and livestock purposes on or near the outcrop, for municipal pumpage in central and northeast Texas, and for irrigation purposes in the southern part of the aquifer, especially in Wilson County (Texas Water Development Board, 1988).

Concentrations of total dissolved solids are generally low (less than 1000 mg/L) in outcrop areas (Figure 18), and probably reflect sediment flushing by recharging waters. Recharge through the large outcrop area north of Houston County is reflected by the large extent of less than 500 mg/L TDS waters. Intense faulting in the south-central part of the aquifer outcrop and orientation of the sand bodies perpendicular to flow direction may prevent deep penetration of recharge waters, resulting in a rapid deterioration of ground-water quality towards the basin. Throughout much of the aquifer in northeast Texas, the ground water has high acidity (low pH) and locally contains excessive concentrations of iron (Muller and Price, 1979). Hydrogen sulfide gas, present in some areas, gives the water a "rotten egg" odor.

Sparta

The Sparta aquifer extends from the Frio River in Frio County northeastward to the Louisiana border in Sabine County (Figure 19). Water from the aquifer is used for domestic and livestock purposes on or near the outcrop throughout its extent (Texas Water Development Board, 1988). The central and eastern parts of the aquifer supply water for public and industrial use, with minor amounts of water being utilized for irrigation in East Texas (Texas Water Development Board, 1988). The Sparta is recharged by infiltration of water from rainfall on the outcrop, by leakage from other aquifers, and by infiltration of water from streams, with natural discharge occurring primarily by leakage to the overlying and underlying confining beds (Payne, 1968).

Composed mainly of sands and interbedded clays of Eocene age which range in thickness from 100 feet in the southwest to 300 feet in the northeast, the sediments that make up the aquifer dip to the south and southeast from the outcrop area towards the Gulf (Payne, 1968). Regional ground-water flow parallels the dip of the aquifer. Payne (1968) divided the Sparta aquifer into two geographical areas which represent different depositional environments which affected water quality. He concluded that northeastward from Burleson County, the pattern of sand distribution is elongate into the basin, suggestive of a fluvial-deltaic plain environment. The more hydraulically conductive sediments trend parallel to the direction of ground-water flow, allowing a deeper penetration of less than 1000 mg/L TDS waters into the basin (Figure 19).

South and west of this area, the long axes of the sand bodies are parallel to the outcrop and trend normal to the direction of ground-water flow (Payne, 1968). These strata are predominantly near-shore bar and beach deposits rather than fluvial deposits (Payne, 1968). The limited extent of these sands into the subsurface, the disruption of their continuity by faulting in the outcrop in Bastrop through Wilson Counties, and their orientation perpendicular to the direction of ground-water flow are not conducive to extensive downdip migration of fresh, recharging waters. Water in this area may also have a high sulfate concentrations, which can represent up to 50 percent or more of the total anion content (Payne, 1968). Many areas throughout the aquifer contain iron in excess of the secondary drinking water standard (Muller and Price, 1979).

Santa Rosa

The lower part of the Triassic age Dockum Group, which consists of the Santa Rosa Formation and its lateral equivalents, makes up the Santa Rosa aquifer (Knowles and others, 1984). Majority of the pumpage from this aquifer is used for municipal, irrigation, and oil field water-flooding purposes (Texas Water Development Board, 1988). Principally composed of interbedded shale, sand, sandstone, and conglomerate strata, the aquifer underlies the High Plains (Ogallala) aquifer and the Cenozoic Alluvium in the Pecos River basin, and subcrops beneath the western part of the Edwards-Trinity Plateau aquifer (Muller and Price, 1979) (Figures 1 and 20).

Dutton and Simpkins (1986) studied the Dockum Group and presented the following pertinent conclusions. Dockum Group sediments were accumulated in a closed basin by fluvial, deltaic, and lacustrine processes. Sediments of the Santa Rosa aquifer were deposited from the outer edge of the basin towards its center in braided- and meander-stream, alluvial-fan, and deltaic environments. Total sand composition percentage decreases (resulting in decreased aquifer permeability) towards the basin center (generally outlined by areas of greater than 10,000 mg/L or ppm TDS concentration on Figure 20). Subsequently, the basin tilted to the east from New Mexico towards the eastern edge of the aquifer in Texas. The Dockum Group ranges from less than 100 to more than 2000 feet in thickness. Where the Santa Rosa aquifer is confined, it may contain saturated thickness of up to 700 feet (Muller and Price, 1979).

Dutton and Simpkins (1986) also postulated that the aquifer's original depositional environment, recharge areas and resulting flow patterns, and aquifer matrix composition control its ground water chemical composition. During Pleistocene time, the aquifer received recharge from rainfall on the outcrop to the west in New Mexico, with ground water flowing to the east into the basin. Since that time, the Pecos River has truncated the outcrop, and has become a discharge area for the Dockum Group (Dutton and Simpkins, 1986). As a result, they inferred that only limited recharge enters the aquifer, with the majority resulting from infiltration of precipitation on the outcrop and shallow subcrop (Figure 20). In Texas, the aquifer is exposed at the land surface east of the erosional caprock escarpment. Additional outcrop areas are exposed by the downcutting of the Canadian River in Oldham and Potter Counties and by erosion associated with the drainage area of the Colorado River in Borden and Mitchell Counties. Outcrop and shallow subcrop recharge areas generally contain ground water with a total dissolved solids content of 1000 mg/L or less. Where the two aquifers are in hydrologic communication, some deep percolation of ground water from the overlying High Plains (Ogallala) may provide a minor amount of recharge to the Santa Rosa (Dutton and Simpkins, 1986).

A basinward increase in total dissolved solids concentration (Figure 20) may be due to the lack of recharge water entering the basin and/or decreasing strata permeability (which would allow a longer time for ground water to dissolve the surrounding rock matrix). Dutton and Simpkins (1986) also attribute increased TDS to the inflow and mixing of ground water containing dissolved anhydrite and halite from the underlying Permian strata and the diffusion and mixing of paleo-seawater from overlying Cretaceous strata and from the lower permeability areas of the Dockum Group. The potential for interaquifer ground-water movement is illustrated by a man-induced occurrence in 1980 south of Kermit in Winkler County which was documented by Baumgardner and others (1982). The Wink Sinkhole formed as a result of ground water dissolving the underlying salt beds and subsequent collapse of the overlying sediments into the solution cavity. A plugged and abandoned well which was located within the circumference of the sinkhole may have provided a conduit for ground-water flow (Baumgardner and others, 1982).

Hickory Sandstone

The Hickory Sandstone aquifer crops out and dips into the subsurface in a radial pattern around the Llano Uplift region of Central Texas (Figures 2 and 21). Furnishing most of the ground water used in the area, the aquifer provides, in descending order of produced quantity, water supplies for irrigation, municipal, manufacturing, and livestock purposes (Texas Water Development Board, 1988). The aquifer is principally composed of sand and sandstone of the Hickory Sandstone Member of the Riley Formation of Cambrian age (Muller and Price, 1979) and is the oldest aquifer evaluated in this report.

Extensively faulted in the outcrop and subsurface (Figure 21), the aquifer strata dip steeply away from the Llano Uplift. The Hickory was deposited upon an unevenly eroded metamorphic and igneous rock surface with a topographic relief in excess of 300 feet, which resulted in a wide variability in the accumulated thickness (Walker, 1979; Black, 1988). These sediments were deposited along an east-west trending shoreline with the Cambrian sea located to the south of the Uplift (Black, 1988). Thickest accumulations occur southwest of the Uplift in Kimble County (500 feet) and thin to the east and northeast (Black, 1988). Subsequent erosion and faulting of the sediments have also contributed to aquifer thickness variability.

Although recharge from precipitation on the circular outcrop with ground-water movement downgradient in a radial direction into the aquifer does occur, the ground-water flow direction into and within the aquifer is modified by intense faulting as indicated in a study by Black (1988). He postulated that faults may either enhance recharge or discharge through overlying confining strata; may impede flow, causing ground water to stagnate down dip of a fault; or redirect flow around a fault. Water is naturally discharged from the aquifer by evapotranspiration, movement into or out of the underlying Precambrian or overlying limestone strata, and by spring flow and seepage into drainage areas (Black, 1988). He concluded that the aquifer could be divided into two parts, the outcrop and very shallow confined portions which are characterized by active recharge and ground-water flow; and the deeper, confined portion which is nearly stagnant, isolated from the outcrop, and receives recharge through only a small fraction of the area bordering the outcrop.

Ground water containing lower concentrations of total dissolved solids (less than 500 mg/L) surrounds the Llano Uplift and is indicative of recharge and active ground-water flow systems on and near the outcrop (Figure 21). Tongues of higher TDS water extend towards the outcrop in a northeast-southwest direction, along the general trend of the surface faults, and may indicate restricted subsurface flow areas. The downdip increase in TDS may reflect nearly stagnant flow conditions, and corresponds to mapped areas where the aquifer thins north and northeast of the Uplift (Black, 1988).

Natural contamination of the aquifer may result from inflow from other water-bearing strata and dissolution of the aquifer matrix. Radium, in excess of the drinking water standard (Table 3), occurs in public supplies along the northern flank of the Uplift (Figure 21). As discussed in the section on radium, the source of this ion is probably the underlying granite and the aquifer matrix itself (if the sediments were derived from a granitic source). Iron concentrations above the secondary drinking water standard (Table 3) occur naturally in wells completed in the upper part of the Hickory Sandstone aquifer (Walker, 1979; Black, 1988).

Ellenburger-San Saba

Composed of marine limestone and dolomite deposits of the San Saba Member of the Wilberns Formation of Cambrian age and the Ellenburger Group of Cambrian and Ordovician age, the Ellenburger-San Saba aquifer (Figure 2) yields small to moderate supplies of water for domestic, municipal, industrial, and minor irrigation needs in areas surrounding the Llano Uplift (Muller and Price, 1979). The San Saba Member and the Ellenburger Group are considered to be one aquifer due to their hydrologic interconnection and the difficulty in distinguishing the two stratigraphic units in the subsurface (Walker, 1979). As described earlier in the Hickory Sandstone aquifer section, the Ellenburger-San Saba is also exposed at the surface in a circular shape which surrounds the Llano Uplift and dips into the subsurface away from the Uplift (Figure 22). The aquifer is highly faulted in the surface and subsurface and was eroded prior to being covered by Cretaceous sediments, causing a large variation in aquifer thickness, ranging from 450 to 800 feet in Kimble and Mason Counties, 0 to 1000 feet in Gillespie County, and 280 to 600 feet in McCulloch County (Walker, 1979).

Precipitation on the outcrop, inflow from streams crossing the outcrop, and inflow from the overlying Hensel Sand of Cretaceous age infiltrate through fractures and solution channels to recharge the aquifer (Mount, 1962 and 1963; Muller and Price, 1979). Ground water then flows downgradient into the confined portion of the aquifer, and/or discharges naturally from seeps and springs (Muller and Price, 1979). Discharge from the aquifer supports the base flow of streams which cross the outcrop which include the Llano, San Saba, Pedernales, and Colorado Rivers.

As discussed in the Hickory Sandstone aquifer section, the Ellenburger-San Saba aquifer water quality probably reflects two distinct flow systems with a fault derived overprint (Figure 22). Ground water containing less than 1000 mg/L total dissolved solids reflects active recharge and flow within the aquifer and occurs in and near the outcrop. Downgradient, TDS increases with increased depth, probably reflecting restricted or stagnant flow areas. Interfingering of lower and higher TDS areas trends northeast-southwest, reflecting the regional faulting, and may indicate areas were faults have either enhanced recharge into the aquifer or restricted flow by isolating blocks of the aquifer.

Blaine Gypsum

Composed of water-bearing zones within the Blaine Formation, the Blaine Gypsum aquifer, is normally considered to extend in a narrow outcrop band from Wheeler to King Counties in the Rolling Plains (Muller and Price, 1979) (Figure 2). For the purpose of this evaluation, the aquifer quality map (Figure 23) was extended southward to Coke County, however, this portion of the aquifer contributes only a minor amount of water on a local basis. Irrigation (restricted to salt-tolerant crops, or to areas where soils have adequate drainage to prevent salt accumulation in the soil profile) comprises 97 percent of the total usage of water from the aquifer (Texas Water Development Board, 1988).

Deposited in a restricted marine environment, the Blaine Gypsum aquifer is located on the eastern fringe of thick evaporitic deposits of anhydrite and massive halite which were accumulated in Middle to Late Permian time (Richter and Kreitler, 1986). The aquifer is composed of red silty shale, gypsum, anhydrite, salt, and dolomite, and usable water occurs chiefly in solution channels and caverns dissolved from the beds of anhydrite and gypsum (Winslow and Kister, 1956; Smith, 1970; and Maderak, 1972 and 1973). Recharge from infiltration of precipitation on the Caprock Escarpment and Permian strata to the west, and on the Blaine outcrop, moves eastward along the solution channels and caverns, dissolving the evaporitic deposits, and discharging into topographically low areas through salt seeps and springs (Figure 23; Richter and Kreitler, 1986).

Total dissolved solids concentration increases as aquifer depth from the surface increases to the west, and in natural discharge areas along surface drainage. Less mineralized water, with a total dissolved solids content of less than 1000 mg/L (Figure 23), occurs in topographically higher (recharge) areas in the outcrop, and may be enhanced by recharge from the overlying alluvium (Maderak, 1972). Water from wells and springs tapping the lower TDS portions of the Blaine Gypsum is calcium- and magnesium-sulfate ion dominated, and in Childress County the water has been reported to contain up to four parts per million of boron (Winslow and Kister, 1956). Boron concentrations in this range may cause severe crop toxicity problems (Table 4).

Natural pollution of surface water by ground water issuing from salt springs and seeps is a long recognized problem in this part of the state. A study by Richter and Kreitler (1986) indicated that most salt-emission areas occur within the Blaine Formation outcrop (Figure 23). They attributed the occurrence of highly mineralized ground water within the Blaine Gypsum to two sources, halite dissolution by local ground-water flow through the Blaine and brine discharge from deep-basinal saline aquifers which underlie the High Plains. To date, efforts to control or reduce natural pollution of surface water, including plugging springs or applying backhead pressure in discharge areas, have only succeeded in shifting the problem from one place to another or delaying the problem for a relatively short period of time (Richter and Kreitler, 1986).

Rustler

Composed of Permian age dolomite, limestone, gypsum, minor amounts of salt (with increasing amounts of evaporites basinward, to the east), and a basal zone of sand, conglomerate, and shale, the Rustler aquifer provides water to the Trans-Pecos area (Muller and Price, 1979) (Figure 2). The aquifer yields water for irrigation, livestock, and oil reservoir water-flooding operations (Muller and Price, 1979), and has been used for brine disposal injection (Baumgardner and others, 1982).

Rustler sediments were deposited in a restricted marine environment during the final incursion of the Permian sea into the Delaware Basin (Adams, 1944). Highly transmissive zones within the dolomite, limestone, and gypsum strata may have been caused by a combination of processes including removal of the underlying and interbedded salt and other evaporites, dissolution of other parts of the rock matrix, and faulting and collapse of the unsupported sediments into underlying solution cavities (Adams, 1944; Hiss, 1975; and Baumgardner and others, 1982). Water is probably produced from higher permeability zones caused by these solution channels, caverns, and collapse breccia.

Recharge from the infiltration of precipitation on the outcrop (Figure 24) moves eastward into the basin, and may discharge into the overlying Edwards-Trinity (Plateau) aquifer (Rees and Buckner, 1980). Less mineralized water, with a total dissolved solids content of less than 1000 mg/L, occurs only in one area within the outcrop in southern Culberson County (Figure 24). An isolated area of less than 3000 mg/L TDS water in eastern Loving County corresponds to a portion of the aquifer that is relatively close to the surface (Adams, 1944), and may be the result of recharge which has infiltrated through the overlying permeable cover.

Total dissolved solids concentration increases downgradient, eastward into the basin (Figure 24), with a shift from sulfate to chloride as the predominant anion (Winslow and Kister, 1956). Highly mineralized ground water may be caused by the dissolution of evaporites within the Rustler due to local ground-water flow and/or mixing with brine which has discharged upward through collapse breccia from the deep-basinal saline aquifers underlying the Rustler (Hiss, 1975). An area of greater than 10,000 mg/L or ppm total dissolved solids around Pecos in Reeves County, which corresponds to a large dissolution collapse area mapped by Hiss (1975), may be an example of flow into the more transmissive aquifer sediments of high TDS waters derived from the dissolving bedded salts below the aquifer.

Nacatoch Sand

Arching in a northeastward direction around the western flank of the East Texas Basin, from Navarro to Bowie County, the Nacatoch Sand aquifer crops out in a narrow strip, four to seven miles wide (Ashworth, 1988; Figure 25). The Nacatoch Sand aquifer is composed of the Nacatoch Formation south of Greenville in Hunt County and the undifferentiated Navarro Group north of Greenville (Ashworth, 1988), and provides water for municipal, irrigation, and livestock watering purposes, with only a minor amount used for oil field production and manufacturing supply (Texas Water Development Board, 1988).

Cretaceous age strata which make up the aquifer consist of light gray, unconsolidated to cemented, massive, glauconitic, calcareous sand, and clay and ranges in thickness from 350 to 500 feet (Muller and Price, 1979). Deposited under near-marine and marine conditions, the strata have been geographically divided by McGowen and Lopez (1983) into different (but related) depositional environment areas which have influenced the aquifer water quality. Sand strata, the more hydraulically conductive units within the aquifer, were deposited in a deltaic environment and were oriented perpendicular to the paleoshoreline, which generally coincides with the northern outcrop (McGowen and Lopez, 1983). Deltaic sand accumulations are located in southern Red River County; eastern Hunt, southwestern Delta, and western Hopkins Counties; and southern Hunt County (mapped by McGowen and Lopez, 1983). The deltaic deposits were reworked by wave action and longshore currents, which resulted in sand body elongation parallel to the paleoshoreline. Therefore, between the deltas, the sand bodies are oriented parallel to the outcrop, suggesting to McGowen and Lopez (1983) the existence of a barrier island and broad tidal inlet environment, with the limited shelf sand sediments that occur in Navarro County being the southernmost extent of deltaic influence.

Orientation of sand units and faults, with respect to outcrop, ground-water flow direction, and present day topography and drainage, control ground-water quality (Figure 25). Recharge from precipitation on the outcrop infiltrates to the water table and then moves down hydraulic gradient, through the most conductive sediments, into the basin in a south and southeastward direction (Ashworth, 1988). Deltaic facies, usually containing greater than 40 feet of net sand (as mapped by McGowen and Lopez, 1983), are coincident with areas which contain water with less than 1000 mg/L TDS. The sand orientation parallel to the direction of ground-water flow has probably allowed deeper penetration and flushing of recharge waters into aquifer. South of Kaufman and between delta areas, the sands are oriented perpendicular to the direction of ground-water flow, and the depth of recharge water penetrating from the outcrop appears to be reduced.

Ground-water flow into the basin is interrupted by numerous and extensive faults of the Mexia-Talco Fault Zone (Figure 25). Ashworth (1988) indicated that these faults usually cause downdip flow to halt or be diverted parallel to the fault, due to the displacement of higher transmissive sediments adjacent to sediment of lower hydraulic conductivity. In many places, water quality changes abruptly from 1000 to 3000 mg/L TDS on the down gradient side of a fault (Ashworth, 1988; Figure 25). In outcrop, topography has influenced water quality, with lower TDS values occurring in topographically higher recharge areas, including areas where recharge is derived from the highly permeable alluvial deposits which overly the Nacatoch Sand aquifer (Ashworth, 1988). Higher TDS values occur in inferred discharge areas which correspond to the incised drainage feeders of the Sabine, Trinity, and Sulphur Rivers, and possibly in areas that may receive deeper discharge along faults such as the downgradient area which underlies the Sulphur River.

Blossom Sand

Extending from Fannin County eastward through Lamar, Red River, and Bowie Counties, the Blossom Sand aquifer (Figures 2 and 26) provides water for municipal, domestic, and livestock watering purposes (Muller and Price, 1979). Of the total water pumped, 88 percent is used for municipal supply, with Clarksville in Red River County being the largest consumer (McLaurin, 1988; Texas Water Development Board, 1988). The Blossom Sand Formation consists of 0 to 400 feet of Cretaceous age strata (Muller and Price, 1979). Composed of alternating layers of brown to light gray, unconsolidated, ferruginous, glauconitic sand, shale, clay, marl, and chalk, the sediments were deposited in a fluvial deltaic environment along the northern edge of the East Texas Basin (McLaurin, 1988). Sand units are the water producing strata of the aquifer, and the amount of sand within the aquifer decreases westward, with very little being present west of central Lamar County (McLaurin, 1988). The western edge of the aquifer is generally considered to be the city of Paris (McLaurin, 1988), however, a small amount of water is produced from the outcrop in Fannin County, and water quality was included for both areas (Figure 26).

A study of the aquifer by McLaurin (1988) indicated that recharge to the aquifer occurs by infiltration of precipitation on the outcrop and from infiltration through alluvial deposits which are in hydraulic communication with the Blossom, particularly in northeast Red River and Bowie Counties. Water with a total dissolved solids content of less than 1000 mg/L (indicative of more active recharge areas) generally occurs in the outcrop, except for an area of deeper penetration in the vicinity of Clarksville (Figure 26). The width of the aquifer that contains fresh to slightly-saline ground water decreases from east to west, corresponding to a decrease in net sand content (McLaurin, 1988) (which results in a decrease in hydraulic conductivity). High iron content occurs in localized areas (McLaurin, 1988), and may be controlled by the oxidization of iron bearing strata (ferruginous and glauconitic sands) by recharging waters, as presented in the previous discussion on iron. Ground water moves downgradient into the aquifer in a south to southeasterly direction, into the basin, and discharges through seeps and springs on the outcrop and through pumpage of wells (McLaurin, 1988). TDS content increases with increasing distance along the flow path (Figure 26), and may in part be influenced by lithologic changes in the strata which make up the aquifer.

Edwards-Trinity (High Plains)

Sands and sandstones of the Trinity Group and limestones of the Fredericksburg Group, both of Cretaceous age, make up the Edwards-Trinity (High Plains) aquifer in the Southern High Plains (Muller and Price, 1979) (Figure 2). With a total thickness of up to 300 feet, the aquifer underlies, and is generally in hydrologic communication with the overlying High Plains (Ogallala) aquifer (Muller and Price, 1979). Water quality is usually poorer than the overlying High Plains (Ogallala) aquifer, and is generally slightly to moderately saline. Poorest quality is found below salt-water playa lake areas (Texas Water Development Board, 1988). The major amount of water produced from this aquifer is used for irrigation, with minor amounts being utilized for secondary oil recovery, livestock, and municipal supply (Muller and Price, 1979).

Marble Falls Limestone

Exposed along the northern and eastern flanks of the Llano Uplift (Figure 2), the Marble Falls Limestone aquifer provides minor amounts of water for livestock, municipal, irrigation, manufacturing, and mining supply (Texas Water Development Board, 1988). The aquifer reaches a maximum thickness of 600 feet, with ground water occurring in cavities and fractures in the Pennsylvanian aged limestone (Muller and Price, 1979). The majority of aquifer recharge is probably derived from inflow along cavities and fractures from the underlying strata (Brune, 1975), and infiltration of precipitation on the outcrop. Discharge occurs from large springs issuing from the limestone (Brune, 1975). The quality of water produced from the aquifer is generally suitable for most purposes in and near the outcrop area with the downdip limit of slightly saline water being unknown (Muller and Price, 1979).

Igneous Rocks

In West Texas near Alpine and Marfa (Figure 2), the fissures and fracture of lava flows, tuffs, and related igneous rocks of Tertiary age, produce small to large amounts of good quality water for municipal, domestic, irrigation, livestock watering, and other uses (Muller and Price, 1979). In Presidio and Brewster Counties, towns such as Alpine, Fort Davis, and Marfa derive all or part of their municipal water supply from this aquifer (Texas Water Development Board, 1988). Thickness varies considerably, and wells can exceed 1000 feet in depth (Rees, 1987). Water quality ranges from fresh to moderately saline (Texas Department of Water Resources, 1984).

Marathon Limestone

Occurring in a small area in northwestern Brewster County (Figure 2), the Marathon Limestone of Lower Ordovician age is an up-folded limestone aquifer at or near the land surface (Muller and Price, 1979). Ground water occurs chiefly under water-table conditions in crevices, joints, and cavities. Total thickness ranges from 350 to 900 feet, but most wells are less than 250 feet deep (Muller and Price, 1979). Water quality usually ranges from 500 to 1000 mg/L total dissolved solids and is generally very hard (Muller and Price, 1979). Only a relatively small amount of water is pumped from the aquifer, primarily for municipal and domestic use in the town of Marathon (Texas Water Development Board, 1988).

Bone Spring and Victorio Peak Limestones

The Bone Spring and Victorio Peak Limestones aquifer occurs in the northeast corner of Hudspeth County (Figure 2). Composed of Permian age strata, the aquifer underlies a narrow north-trending topographic basin which is located between the Guadalupe Mountains on the east and the Diablo Plateau on the west. Ground water is contained in the joints, fractures, and solution cavities and varies in quality from 1000 to 8000 mg/L total dissolved solids (Muller and Price, 1979). Used principally for irrigation in the Dell City area, treatment is desirable prior to use for municipal and domestic purposes (Texas Water Development Board, 1988). Large amounts of man-induced ground-water discharge in the area have occurred historically. Increasing ground-water salinity in the Dell City area may be the result of excessive irrigation water application, with salinity contributed by water that has leached accumulated salts from the soil zone and percolated downward to the saturated zone (Texas Department of Water Resources, 1984).

Capitan Limestone

Originally deposited as a reef, consisting of limestone, dolomite, and talus, the Capitan Limestone (Permian age) is from 1500 to 2000 feet thick (Rees, 1987). The reef deposits parallel the margins of the Delaware Basin in an arcuate six to eleven mile wide strip extending from the Guadalupe Mountains southwest of Carlsbad, New Mexico, to the Glass Mountains southwest of Fort Stockton on the Pecos-Brewster County line, then northward through Ward and Winkler Counties (Hiss, 1975). Portions of the reef deposit which are considered to be the minor aquifer (Figure 2) occur where the limestone underlies the Salt Bolson deposits in the Diablo Farms area along the Culberson and Hudspeth County line, and where the limestone crops out in the Glass Mountains and Apache Mountains in southeastern Culberson County (Muller and Price, 1979).

Better quality water is found in the rocks with the highest dissolution permeability, where the original brines have been displaced by fresh water recharging from from the Glass and Guadalupe Mountains and other outcrop areas (Hiss, 1975). In the Diablo Farms area, the chemical quality of the ground water ranges from 850 to 1500 mg/L total dissolved solids concentration with the principal constituents being calcium, sulfate, and bicarbonate. In some instances, iron occurs in excessive amounts for domestic and municipal use (Muller and Price, 1979). In outcrop areas, the quality may be fresh to slightly saline (Rees, 1987). Water is principally used for irrigation and oilfield production supply, and minor amounts are utilized for municipal and livestock watering (Texas Water Development Board, 1988).

Other Undifferentiated

Throughout the state, these aquifers, although undifferentiated on the Figure 2, may represent the only source of ground water locally available. Limited deposits of Quaternary, Tertiary, Cretaceous, Permian, and Pennsylvanian age provide small to moderate quantities of fresh to slightly saline ground water for irrigation, municipal, domestic, and livestock watering purposes (Texas Water Development Board, 1988). Irrigation pumpage from the Quaternary and Tertiary deposits of the Nueces River Basin accounted for 40 percent of the total pumpage and 58 percent of the irrigation pumpage from this group of aquifers (Texas Water Development Board, 1988). Water-bearing sediments in north central Texas which consist of the Wichita Group, San Angelo Sandstone and Whitehorse Group (all Permian age) and the Cisco Group (Pennsylvania age) make up another important part of this category (Muller and Price, 1979).

DRASTIC - A SYSTEMATIC APPROACH TO GROUND-WATER POLLUTION POTENTIAL MAPPING

As part of its statewide ground-water assessment and protection program, the Texas Water Commission (TWC) has sought tools for the evaluation of ground-water pollution potential. Vulnerability mapping of the state's aquifers was begun by the TWC in 1987. DRASTIC, a methodology for delineating sensitivity to ground-water pollution, was developed in the mid-1980's to serve as a tool in ground-water assessment. This project was undertaken as an attempt to classify Texas aquifers according to their pollution potential and to test the feasibility and utility of the DRASTIC system on a statewide basis.

Objectives of this project were to develop two maps, one depicting general vulnerability to ground-water pollution and the other specifically aimed at pollution from certain agricultural practices, using the DRASTIC methodology.

DRASTIC Methodology

DRASTIC was developed as a tool for comparing land units on the basis of their vulnerability to ground-water pollution. Artificial classification of natural systems, including aquifers, has been used for years. A system for ranking ground-water pollution potential which took into consideration a relatively large number of parameters had not been developed, however. Through a consensus process, a group sponsored by the National Water Well Association and the Robert S. Kerr Environmental Research Laboratory developed the methodology used in this report (Aller and others, 1987).

Principles

DRASTIC is a systematic process for assessing the ground-water pollution potential of hydrogeologic settings. The DRASTIC system is a methodology which involves delineation of hydrogeologic settings and analysis of data to develop a single index number which represents the sensitivity of that setting to ground-water pollution potential. The method is simple, understandable, and has wide applicability as a management and learning tool. The system depends to some degree on subjective but skilled judgement by the user, as does any artificial system.

Hydrogeologic settings are delineated based on seven parameters, which are used to develop an index number for each setting. The parameters, or factors, have been organized to create the acronym DRASTIC. DRASTIC stands for:

D – Depth to water
R – Annual recharge
A – Aquifer media
S – Soil media
T – Topography
I – Vadose zone impact
C – Hydraulic conductivity

After development of the index numbers, maps can be constructed to present a graphic display of the pollution potential. For a more detailed description of the DRASTIC methodology, see Aller and others (1987) or Hart (1989).

The methodology was developed around a set of basic assumptions concerning a generic contaminant. The material, introduced at the land surface as a solid or liquid, travels to the aquifer with recharge waters derived from precipitation. Mobility of the contaminant is assumed to be equal to that of the ground water. Attenuation processes are assumed to go on in the soil, vadose zone, and aquifer.

The parameters used in the DRASTIC system are a combination of geologic, hydrologic, geomorphologic, and meteorologic factors which describe physical characteristics of the hydrogeologic setting. They include depth to water, annual recharge, aquifer media, soil media and thickness, topographic relief, vadose zone media, and hydraulic conductivity of the aquifer. Data sources include geologic maps, hydrogeologic and technical reports, well logging records, generalized data from standard references, and professional judgement.

Each parameter is divided into ranges with corresponding ratings. Rating values depend on the impact of the factor on contamination potential. The general and agricultural DRASTIC evaluations use the same ranges and rating values, only the weighting of the parameters changes. Weighting serves two purposes in the DRASTIC system. It represents an attempt to define the relative importance of each factor in its ability to affect pollution transport to and within the aquifer and it creates the differences between the general and agricultural indices.

Two pollution potential numbers, one for generalized pollution sources and one for pollution due to agricultural activities, are generated for each hydrogeologic setting. The formula for the index number is:

$$I = (Dr \times Dw)+(Rr \times Rw)+(Ar \times Aw)+(Sr \times Sw)+(Tr \times Tw)+(Ir \times Iw)+(Cr \times Cw)$$

I - DRASTIC index number
D,R,A,S,T,I,C - parameters
r - rating
w - weight

The maps are labeled with designators for the hydrogeologic settings and pollution potential numbers and the indices are then divided into ranges for color coding of the final maps.

Several terms used in this portion of the document should be clearly defined in the context of this project. **Ground-water pollution potential** means the potential for a contaminant, at levels which cause significant degradation, to travel to and within an aquifer. **Hydrogeologic settings** are mappable surface areas which share a common set of values for the parameters which make up the pollution potential number and hence a common vulnerability. The settings are determined by geologic, geomorphologic and hydrogeologic characteristics. The **DRASTIC index number** is the figure which represents the pollution potential of a hydrogeologic setting. It is derived by multiplying each factor by its weight and then summing these terms. **DRASTIC factors, or parameters**, are the physical components of the aquifer and related processes which are used to describe the pollution potential of a particular hydrogeologic setting.

General and Agricultural DRASTIC Maps

Two maps were developed. Plate 1 is a general pollution potential map which is intended to represent ground-water pollution potential from concentrated or localized point-of-application contaminants. Examples of this are residential, commercial, industrial, mining, transportation, and urban sources of contamination such as accidental spills, industrial wastes, septic tanks, underground storage tanks, pits, or landfills. Plate 2, the agricultural map, depicts pollution potential from widespread, surface-applied materials such as fertilizers, pesticides, aerial sprays, and other agricultural products. Diffuse sources from other activities such as silviculture and some waste disposal methods are also applicable to this map. The weighting for Plate 2 emphasizes those processes which affect pesticides in the soils by adjusting the weighting of the factors. It is perhaps the method of application and not the source of pollution which is important in determining which DRASTIC map is most applicable.

Statewide DRASTIC Maps

Initial maps were constructed using the Land Resources of Texas Map (Texas Bureau of Economic Geology, 1977) as a base. Land resource areas correlated in most cases with surface geologic features as shown on the Geologic Atlas of Texas sheets, also developed by the Bureau of Economic Geology. Each delineated area on the map was established by evaluating surface geologic and soil conditions, with areas of similar lithologic and soil types grouped to form a hydrogeologic setting. Soil maps for each county were used in conjunction with the other parameters to choose final boundaries for each hydrogeologic setting. Final maps are published at a scale of 1:2,000,000.

The hydrogeologic settings used were based on settings described in EPA Report 600/2-87/035 (Aller and others, 1987). Major ground-water regions of the United States are outlined in the report. Four of these regions are found in Texas: the High Plains, nonglaciated central, alluvial basins, and Atlantic and Gulf Coastal plain regions. Within these regions, standardized hydrogeologic settings are described, such as mountain slopes, alluvial mountain valleys, river alluvium, and unconsolidated and semi-consolidated aquifers. Each standard setting is assigned a set of representative ratings and an index number. These settings were used in creating the Texas map, although individual indices were calculated for each setting based on data collected for this project.

Indices for the general pollution potential map ranged from a low value of 58 to a high of 164. The agriculture map showed a range from 81 to 190, indicating greater sensitivity to pesticide-type pollution than general point-source pollution for most areas of the state. Agricultural values averaged 30 points higher than general values. The color code for the maps uses the same colors as the designated national color code described in the EPA report, but the ranges are defined using different break points. This was done to provide more contrast in the map and delineate at a finer level the various sensitivities of the hydrogeologic settings. Color codes and ranges are the same for both maps, allowing for direct comparison between the two.

Pollution Potential Mapping as a Tool

DRASTIC was designed to be of use to those concerned with planning and managing land and ground-water resources, to serve as a tool for setting priorities with regard to protection and monitoring of ground water, and to act as a learning tool. The indices and maps can be integrated with other information to provide a screening mechanism for decision-making. Regulatory agencies can apply DRASTIC to such programs as Resource Conservation and Recovery Act (RCRA), Superfund, Wellhead Protection, and state ground-water protection programs. Local and regional planning groups can use DRASTIC in determining land use and zoning priorities. State agencies can develop monitoring and remediation plans with pollution potential maps and complementary information. Systems which classify aquifers according to a set of physical parameters can also be useful for educators who wish to teach a logical method of analysis to students. DRASTIC parameters describe a set of basic relationships between the land surface, weather, soils, and the subsurface which create ground-water flow in aquifers. Students who develop an understanding of aquifers as a collection of related parameters may be better able to appreciate the complexities and difficulties in evaluation of natural systems.

An objective was to identify areas of the state sensitive to man-made contamination. Table 5 is a ranking of the major and minor aquifers according to their ground-water pollution potential as determined by DRASTIC. This table was created by comparing average sensitivity numbers for the outcrop of each aquifer. It is worth noting that many areas of the state which are sensitive to ground-water pollution are underlain by neither major nor minor aquifers. Although not classified as aquifers, these areas contain limited but vulnerable supplies of ground water, in most cases located close to the land surface.

Table 5.–Relative Pollution Potential Ranking of Major and Minor Aquifers in Texas

Major Aquifers (Ranked from higher to lower potential)

Rank	Aquifer
1.	Edwards (Balcones Fault Zone—Austin Region)
2.	Edwards (Balcones Fault Zone—San Antonio Region)
3.	Alluvial deposits
4.	Carrizo-Wilcox
5.	Edwards-Trinity (Plateau)
6.	Trinity Group
7.	Gulf Coast
8.	High Plains (Ogallala-North)
9.	High Plains (Ogallala-South)
10.	Bolson deposits

Minor Aquifers (Ranked from higher to lower potential)

Rank	Aquifer
1.	Ellenburger-San Saba
2.	Marble Falls Limestone
3.	Hickory Sandstone
4.	Nacatoch Sand
5.	Blossom Sand
6.	Queen City
7.	Rustler
8.	Blaine Gypsum
9.	Bone Spring and Victorio Peak Limestones
10.	Capitan Limestone
11.	Sparta
12.	Marathon Limestone
13.	Woodbine
14.	Santa Rosa
15.	Igneous Rocks
16.	Edwards-Trinity (High Plains)

DRASTIC has a number of limitations which should be considered. DRASTIC does not consider the impact of human activity on ground water, nor does it take into account natural or man-induced water quality problems. The methodology does not always accurately predict pollution potential for several reasons. Some physical parameters which are neglected by the current methods and have a strong influence on ground-water pollution include fracturing and faulting; the significant effects of precipitation duration and intensity; soil reactivity; differences in specific contaminant mobility; and anisotropy and heterogeneity in soil, vadose zone, and aquifer hydraulic conductivity.

The maps presented in this report represent pollution potential from surface sources only. However, other sources of contamination are affected by subsets of the DRASTIC factors. Surface pollutants are most affected by factors such as topography, soil media, recharge, and vadose zone media. Shallow subsurface pollutants are not affected by topographic relief and may not be affected by soil media. Recharge in combination with topography determines the runoff potential of a contaminant. Shallow and deep subsurface pollutants are therefore less affected by these two factors. Deep subsurface pollutants are unaffected by topography, depth to water, soil media, and vadose zone media. Hydraulic conductivity of the aquifer is important as a factor only after the contaminant has reached the aquifer. A modified DRASTIC system could be designed to evaluate the pollution potential of these subsurface contaminants, grouped by point of application.

AN ASSESSMENT OF KNOWN AND POTENTIAL SOURCES OF MAN-INDUCED GROUND-WATER CONTAMINATION WITHIN TEXAS

The many and varied practices of man produce numerous waste materials and by-products. These are often deposited or stored on the land surface or in shallow subsurface zones. Percolation from these locations may eventually be carried downward modifying the natural quality of ground water.

Many sources of pollution degrade the aquifers of the state. These have been categorized into subchapters under the following major headings: 1) Land Disposal of Waste Materials; 2) Water Wells; 3) Sewage and Waste Water Disposal Systems and Municipal Collection Lines; 4) Leaks and Spills; 5) Oil, Gas, and Mining Activities; 6) Agricultural Practices; 7) Ground-Water Withdrawals; and 8) Other Possible Ground-Water Pollution Sources.

A brief assessment of known and potential sources of ground-water contamination related to the above are described in sections which follow. Where possible, actual or suspected incidents of pollution are noted for each of the major categories and their subcategories. Numerous illustrations are also presented to show the statewide distribution of suspected or documented contamination and to explain hydrogeological relationships.

Land Disposal of Waste Materials

As is the case with most other states, Texas has a wide variety of wastes which are generated by private residents, municipalities, and industries. Most of these are disposed of on or near the land surface. These disposal sites can be a source of ground-water contamination, primarily because of the generation of leachate caused by water percolating through bodies of refuse and waste materials and infiltration of liquid waste through the unsaturated zone to ground water (Figure 27 and 28).

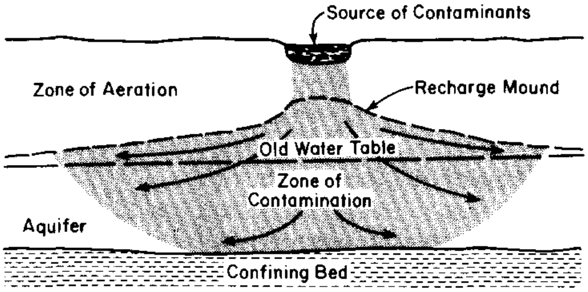


Figure 27.—Percolation of Contaminants From a Disposal Pit to a Water-Table Aquifer (U.S. Environmental Agency, 1977; After Deutsch, M., 1963)

Leachate is a fluid which is highly mineralized by a variety of organic chemicals; numerous metals such as iron, copper, and lead; as well as chloride, nitrate, and sodium. Hazardous constituents are often present in the leachate where manufacturing wastes are included. Examples of these are: cyanide, cadmium, chromium, chlorinated hydrocarbons, and polychlorinated biphyenyl (PCB). In some cases, the leachate may contain low-level radioactive wastes. In summary, the type of industry using a disposal site determines the constituents found in its leachates (Miller, 1980).

Subcategories which were considered during this assessment are Industrial Facilities, Abandoned Hazardous Waste Facilities, Sanitary Landfills, Industrial Waste Disposal Wells, and Graveyards.

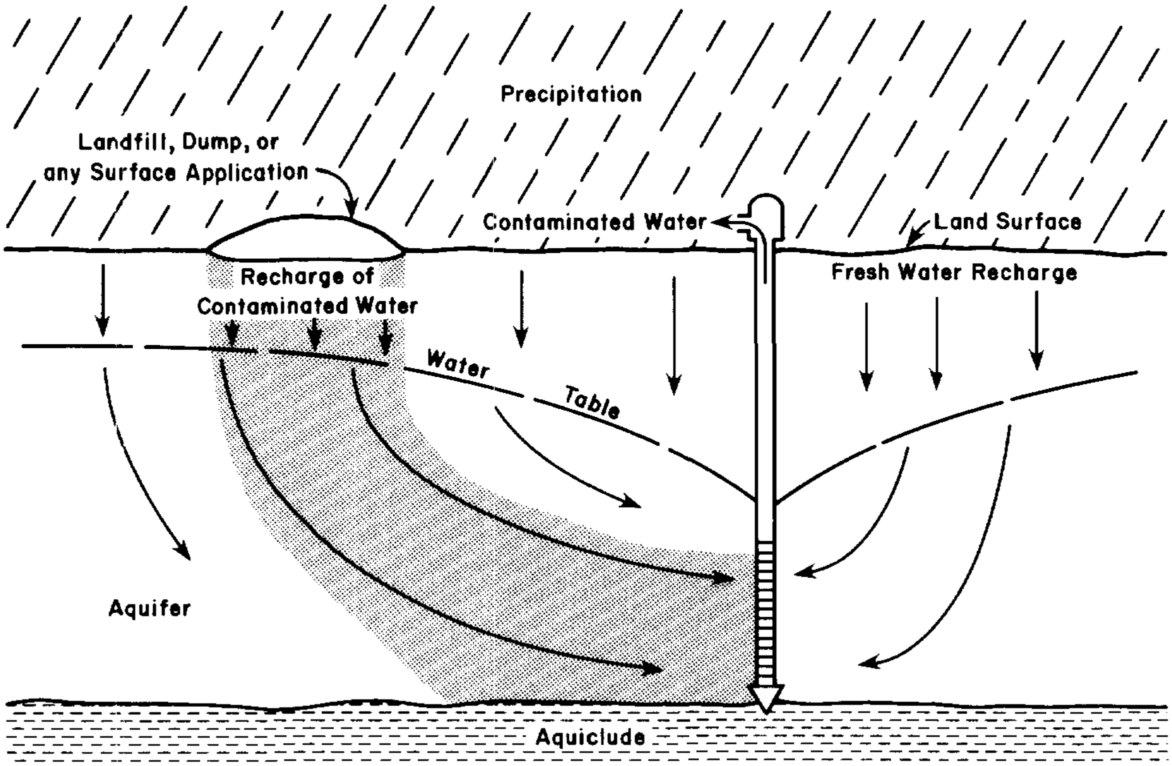


Figure 28.—Contamination of an Aquifer by Leaching of Surface Solids (U.S. Environmental Protection Agency, 1977; After Deutsch, M., 1963)

Industrial Facilities

Prior to enactment of the Texas Solid Waste Disposal Act (the Act) in 1969, there were no effective state regulations governing the disposal of industrial wastes. In many cases, wastes were dumped indiscriminately, without ample record keeping or consideration for environmental safeguards including the protection of ground water. With the passage of the Act, the foundation for the systematic control of industrial solid and liquid wastes was commenced.

The term **industrial solid waste** includes those solid wastes resulting from or incidental to any process of industry, manufacturing, mining, or agricultural operations. This definition includes waste materials associated with mining, concentrating, and refining of metallic ores and their ultimate fabrication; the refining of oil and natural gas; the manufacturing of chemical, stone, glass, paper, wood, machinery, and metal products; and wastes associated with the demolition of old buildings, highways, and bridges. Industrial solid wastes also include those incidental to the food processing industries such as canning, freezing, and dehydrating of fruits and vegetables; slaughtering and processing of meat animals; and the processing and packaging of dairy products. Agricultural solid wastes are those resulting from animal and crop production including animal manures, dead animals, pesticide and crop residues (Texas Department of Water Resources, 1981). In addition to solid wastes, these activities also generate liquid wastes.

Texans generate tons of waste each year. These wastes include common household trash, complex industrial wastes, municipal and industrial sewage sludge, agricultural wastes, and those produced by hospitals and laboratories or infectious wastes.

Not all of these wastes are hazardous. Certain characteristics of wastes can make them harmful. Hazardous wastes may be solids, liquids, sludges, or gases.

Texas has adopted the same definition of hazardous as set forth by the U.S. Environmental Protection Agency (40 CFR, Part 261). Specifically, wastes are designated as "hazardous" due to their exhibiting one or more of the following characteristics:

1) Ignitability—These wastes have the potential to create fires or explode under certain conditions.

2) Toxicity—Toxic wastes are harmful or deadly when absorbed by the skin or when swallowed.

3) Reactivity—These wastes normally react violently when they come in contact with water or air.

4) Corrosivity—Corrosive wastes include those which are acidic and those which eat away or corrode metal (Texas Water Commission, 1988c).

In addition to those substances having the above characteristics, approximately 400 other chemicals have been listed by the EPA as hazardous wastes. These are referred to as the "listed" hazardous wastes. These substances are divided into the three groups which follow and they are considered hazardous regardless of the amount of hazardous material a waste contains:

1) Generic Wastes—Wastes in this group are derived from common industrial and manufacturing processes and they include solvents and other substances used in degreasing operation from any industry.

2) Commercial Chemical Products—Certain chemicals products are on this list and they include products such as selected pesticides and creosote.

3) Source Specific Wastes—Included in this list are wastes from specific industries,such as wood preserving and petroleum refining. Other examples are wastes from treatment and industrial processes, including their waste waters and sludges (Texas Water Commission, 1988c).

Except for the above wastes, all others are considered as nonhazardous wastes.

Using the above characteristics, the TWC classifies industrial waste materials according to their degree of hazard and they are classified as Class I, Class II, and Class III wastes. **Class I** waste is any industrial solid waste or mixture of industrial solid waste which because of its concentration, or physical or chemical characteristics is toxic; corrosive; flammable; a strong irritant; a generator of sudden pressure by decomposition,heat or other means; and may pose a substantial present or potential danger to human health or the environment when improperly processed, stored, transported, disposed of, or otherwise managed, and includes hazardous industrial waste.

Class II wastes are those which present a relatively low level of hazard with respect to acute toxicity characteristics, and are generally degradable. Environmental problems related to Class II waste usually become significant when the wastes are accumulated in large quantities. These may include paper, wood, grease, plant trash, fabric waste, and other similar materials.

Class III wastes are inert and essentially insoluble materials including, but not limited to materials such as rock, brick, glass, dirt and certain plastics, and rubber, etc., that are not readily decomposable (Texas Department of Water Resources, 1981).

In Texas as of 1980, at least 15 million metric tons of Class I and Class II industrial solid waste were generated each year by more than 1,800 registered industrial facilities. Of these, 1258 generated Class I industrial waste. Table 6 shows the total volume (in metric tons) of Class I and Class II waste generated in Texas from 1977 to 1979. Quantities of Class III wastes were not reported.

Table 6.—Annual Volumes of Various Classes of Industrial Wastes Generated in Texas, in Metric Tons

	1977	1978	1979
Class I	11,544,464	13,608,886	11,885,053
Class II	6,728,453	3,931,309	3,863,763

Total volumes of Class I and II waste generated in Texas during 1979 by off-site and on-site designation:

	Class I	Class II
Off-site	1,322,051	2,812,422
On-site	10,563,002	1,051,341

Source: Texas Department of Water Resources, 1981

These data clearly indicate that Texas industry generated significant quantities of solid and hazardous waste at that time. A more recent estimate, provided by the U.S. Congressional Budget Office, suggested that Texas is the largest generator of hazardous waste in the United States with about 35 million metric tons being generated during 1983 (U.S. Congressional Budget Office, 1984).

Table 7 lists probable contaminants of industrial activities. Examples of business activities which commonly produce hazardous wastes are: construction, equipment repair, electroplating, furniture refinishing, hospitals, jewelry manufacturing, laboratories, laundry and dry cleaning, lawn and garden suppliers, motor and rail terminals, pesticide applica-

Table 7. —Probable Contaminants of Various Industrial Activities

Activity	Probable Contaminants
Metal Industries	
Stripping and Finishing	Acids or caustics, degreasing solvents, lead, chromium, zinc, cadmium, nickel, cyanide.
Metal Plating and High Tech Industries	Cyanide, acids or caustics, heavy metals, spent solvents.
Wood Industries	
Treating (Wolmanized)	Arsenic, phenols, fluoride.
Treating (Pentachlorophenol (PCP)-Creosote)	PCP, phenols, substituted phenols, P-Nitroaniline (PNA's), chromium, cadmium,
Pulp and Lumber	sulfide, styrene, phenols.
Inorganic Chemical Production	
Sulfuric Acid	Acidity, heavy metals, vanadium.
Sodium Hydroxide	Caustic.
Hydrochloric Acid	Chlorinated organics (by-product reaction).
Nitric Acid	Acidity.
Organic Chemical Production	
Ethylene Dichloride	Chlorinated ethanes,ethenes, methanes.
Benzene	Benzene, substituted benzenes.
Ethyl Benzene	Benzene, xylene.
Vinyl Chloride	Ethylene dichloride.
Styrene	Ethylbenzene, benzene.
Toluene	Toluene.
Xylenes	Petroleum by-products toluene.
Acetonitrile	Acetonitrile, acrylonitrile, cyanide.
Carbon Tetrachloride	Chlorinated ethanes, ethenes, benzenes.
Analine	Analine, nitrobenzene, diphenylamine, benzene.
Chlorobenzenes	Benzene and chlorinated benzenes.
Toluene Diamine	Toluene diamine, toluidine.
Dinitrotoluene	2, 4-Dinitrotoluene.
Other Organics	
Plastics	Phthalates, volatile organics, catalysts.
Ag Chemicals	Chlorinated pesticides, organophosphate pesticides, other pesticides, such as herbicides, fungicides,and others.
Oil Refining	
Wastes	Chromium, lead, cadmium, vanadium, PNA's, volatile organics.

From: Texas Water Commission, 1987, source unknown

tors, photographic, printing, service stations, vehicle maintenance shops, vocational shops, wood preserving, and many more (Texas Water Commission, 1986).

Both hazardous and nonhazardous waste leachates may seep from improperly designed storage or disposal facilities to the soil profile and render land unsuitable for farming or other uses. In time, they may percolate to and pollute ground water.

Numerous options have been or are presently employed for the handling of hazardous and nonhazardous solid wastes. Brief discussions of some of the techniques and their possible effects on ground water follow.

Regulated Hazardous and Nonhazardous Solid Waste Facilities

The relative simplicity and low operating costs have made surface-water impoundments the preferred technology for industrial waste water handling, treatment, and disposal of liquid wastes in most instances where they can be utilized. They are designed to hold an accumulation of liquid wastes and wastes containing free liquids (Texas Department of Water Resources, 1981).

Surface Waste-Water Impoundments

Surface waste-water impoundments such as lagoons, treatment basins, pits, or ponds are used for storage, treatment, or disposal of liquid or solid hazardous or nonhazardous wastes. These impoundments may serve many basic purposes, including: 1) storage or impoundment of settled solids, 2) settling and removal of suspended solids, 3) aeration, 4) equalization, 5) neutralization, 6) biological treatment, and 7) treatment through evaporation (Texas Department of Water Resources, 1981).

As the preferred technology for industrial waste water handling, treatment and disposal, these impoundments have been used extensively in the past and continue to be used to contain accumulations of liquid wastes and wastes containing free liquid.

Normally, industrial waste-water impoundments of the past were not subject to any special regulations unless it was shown that they might degrade surface- and/or ground-water quality. These impoundments at that time, were usually unlined, even though this is not a desirable feature. Certain precautions are now taken to reduce or eliminate leakage to ground water. Among these are the use of impermeable barriers (liners) composed of clay or synthetic material; or the replacement of the use of impoundments with alternatives such as clarifiers, filtration or centrifugation equipment, and aerobic or anaerobic digestion (Miller, 1980).

Even with newer precautions taken to eliminate possible ground-water pollution, past practices and possible mismanagement of these impoundments pose a serious threat to the environment. (Miller, 1980 and Texas Department of Water Resources, 1981). This is primarily due to the fact that they were or are confined to a relatively small area, the enormous volume of fluids involved, and the possibility of their leaking mobile hazardous and nonhazardous wastes to ground water (Figure 27).

Potential ground-water contaminants from leaking impoundments cover the broad range of organic and inorganic chemicals normally contained in industrial waste waters. Those documented as having polluted shallow aquifers elsewhere in the nation include phenols, acids, heavy metals, and cyanide (Miller, 1980).

Nationwide, major users of impoundments are primarily the paper and allied products industry, the petroleum and mining industry, and the chemical industry. Waste-water impoundments are also used for storage and disposal of municipal waste water and sludge, oil and gas extraction wastes (now very limited in Texas), concentrated animal feedlot and farm animal wastes, cooling waters, and utility wastes.

Industries, nationwide, process about five trillion gallons per year (gal/yr) of waste water before discharging it to the environment. About 1700 billion gal/yr are pumped to oxidation impoundments for future treatment or during the treatment process. Based on determined standard leakage coefficients and the total volumes of waste discharged, it is estimated that more than 100 billion gal/yr of industrial effluents enter the ground-water aquifers of the United States (Miller, 1980). Similar data are not available for Texas.

According to a 1983 EPA nationwide impoundment survey, there were 181,000 waste-water impoundments located at 80,000 sites. A breakdown of this total by type and percentage was: oil and gas brine pits (36), municipal (21), industrial (15), mining (14), agricultural (11), and unspecified (3). The size of these waste-management units varied from commonly less than 5 acres (industrial, municipal, oil and gas, and agricultural) to 1000 acres (20 industrial). The largest industrial lagoon covered 5500 acres. Normally, mining impoundments ranged from 5 to about 2000 acres. The depth of all types of impoundments ranged from 2 to 30 feet (U.S. Environmental Protection Agency, 1983). The practice of disposal of brines into evaporation pits within the state, was halted by the Railroad Commission of Texas (RCT) by a statewide no-pit order which became effective on January 1, 1969. Under special circumstances, some oil and gas related pits are still authorized. This action has significantly reduced the percentage of oil and gas brine pits present within Texas.

The previously cited assessment found that only about seven percent of the impoundments were located over geohydrological areas favorable for the protection of ground water. Of all of the structures evaluated, 30 percent were situated in areas underlain by highly transmissive aquifers containing potable water. Additionally, over 98 percent were located within one mile of useable quality ground water or drinking water sources.

Protection of underlying useable ground-water sources can be afforded by the siting of surface waste-water impoundments over impermeable clay soil layers or by employing clay or plastic liners. Between 1978 and 1980, EPA found that nationwide, liners were being used in these impoundments as follows: by industry (28 percent), municipalities (23), mining (17), agriculture (16), and by oil and gas industry (10). Liners usually employed were constructed of clay, rubber, and plastic (U.S. Environmental Protection Agency, 1983).

Surface waste-water impoundments are considered a threat to ground water due to the possibility of overflow, sudden release due to dike failures, and when they are unlined, from slow seepage. Nationwide assembled EPA data on these waste-water management units indicated that seepage was responsible for 80 percent of 277 documented cases of ground-water pollution. Additionally, dike failure and overflow were responsible for 10 percent. Liner failures and other causes were responsible for eight percent of contamination cases (U.S. Environmental Protection Agency, 1983).

As of January 1988, a total of 54 counties within the state had documented cases of ground-water contamination resulting from disposal of wastes at regulated industrial waste facilities. Many of these are due to the use of surface waste-water impoundments (Texas Water Commission, Hazardous and Solid Waste Enforcement Section, 1988). Incidences of confirmed cased of ground-water pollution due specifically to impoundments, were documented in at least six separate counties (Texas Water Commission, Field Offices, 1987). Additionally, numerous documented cases of ground-water contamination have resulted form the now discontinued practice of disposal of oil and gas produced brines into evaporation pits. These are discussed in the subchapter titled, "Oil and Gas Activities" which will follow.

In 1980, a total of 348 surface waste-water impoundments were located at registered on-site industrial solid waste facilities within Texas. Of these, 252 were used for storage of Class I wastes, 71 were receiving Class II wastes, and 25 were being used for Class III wastes (Texas Department of Water Resources, 1981). The statewide distribution of these is unknown.

By 1985, there were about 1000 active industrial waste management facilities operating in Texas. About one-half involved the use of landfills and/or surface waste-water impoundments. Ground-water contamination has been documented at a number of these sites. To date, these are very localized problems and they have not seriously impacted ground water (U.S. Environmental Protection Agency, 1985a).

The state has made significant strides in the reduction of ground-water pollution which results from the use of these impoundments. Those which are used for the disposal of hazardous wastes are well regulated. Holding ponds and lagoons used in connection with concentrated livestock feeding operations are also well controlled. The Railroad Commission of Texas' statewide no-pit order of 1969 has drastically reduced the number of impoundments used in oil and gas related activities. Other instances of control of these waste-water management units will follow in later sections.

Reduction of potential ground-water pollution by impoundments can be accomplished by siting these structures in less sensitive areas (Plates 1 and 2) and constructing them with liners, leachate collection systems, and/or monitoring wells.

Landfills

The most common method for disposal of industrial wastes in Texas is the landfill. Facility owners are finding it increasingly difficult and costly to site this type of disposal management unit because of public opposition. This opposition may be related to the disastrous results of improper management of hazardous waste which have occurred in other areas of the country in the past, such as the Love Canal incident in the northeast United States.

Landfills are land disposal sites in which liquid or solid wastes are located. In the past, they have been located with little or no regard for their possible effects on ground- or surface-water resources. Historically, they have been the most common method of disposing of wastes. Their wastes are classified as hazardous and nonhazardous (U.S. Environmental Protection Agency, 1987a).

Usually, municipal landfills receive solid waste products from residences, small industries, and from other commercial activities. These wastes are generally, but not always nonhazardous. Those municipal landfills which are designed to minimize adverse environmental impacts are known as sanitary landfills. Landfills used for disposal of wastes from large industry are industrial landfills. Wastes deposited in these facilities are often hazardous (Office of Technology Assessment, 1984).

Potential contaminants of landfills are organics, inorganics, microorganisms, and radionuclides (U.S. Environmental Protection Agency, 1987a). A wide variety of industrial wastes are disposed of on land. Examples of probable contaminants resulting from various industrial wastes have been previously introduced (Table 7).

The exact number of industrial solid waste land disposal sites, nationwide, is unknown. However, EPA has estimated that there are about 75,700 active landfill sites used for this purpose. Approximately 200 of these are hazardous waste facilities. A large portion of industrial solid wastes, including some of which are hazardous, are also known to be disposed of in some municipal landfills (Office of Technology Assessment, 1984).

Nationwide estimates of the amounts of nonhazardous and hazardous industrial solid wastes disposed of in landfills are questionable. Estimates for nonhazardous solid wastes range from 40 - 140 million wet tons per year. Of this total, it is estimated that a minimum of 40 million wet tons may be hazardous. During 1981, at least 0.81 billion gallons of hazardous wastes were disposed of in 199 landfill facilities nationwide (Office of Technology Assessment, 1984).

It is further estimated that about 30 million tons of solid waste, mostly fly and bottom ash derived from the burning of fossil fuels at various utilities, was also disposed of in these facilities.

In 1980, Texas had approximately 900 industrial solid waste management facilities, 875 were registered on-site operations and 23 were permitted commercial (off-site) facilities. Of these, 376 were landfills located at registered on-site industrial solid waste facilities. About 213 of these received Class I (hazardous) wastes, 112 received Class II wastes, and 51 handled Class III wastes (Texas Department of Water Resources, 1981).

Figure 29, illustrates the statewide distribution of waste-disposal sites regulated under the Federal Resource Conservation and Recovery Act (RCRA) of 1976; the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980; and Underground Injection Control (UIC) regulations.

As of September 1985, 168 hazardous-waste sites, situated at 19 separate Department of Defense (DOD) facilities located within Texas, had been identified as having potential ground-water contamination and these were included in DOD's Installation Restoration Program (IRP). Of the 168 sites in the IRP program, 52 sites contained known ground-waste contaminants, but did not present a hazard to the environment. Thirty-one sites, located at seven facilities, were considered to present a hazard significant enough to warrant a response action in accordance with CERCLA. Remedial action at three sites had been completed under the program. Remaining sites were scheduled for confirmation studies to determine if remedial action was required (Strause, 1987).

Additionally, about 180 active Texas industrial landfill hazardous waste sites (Figure 29) require ground-water monitoring under RCRA. At many of these sites, ground-water pollution has been found at shallow depths, but contamination has been minimal. Many of these waste-disposal sites are located on the outcrop of the Beaumont Formation in the Houston area, and this clay, which is relatively impermeable, has probably helped to prevent contaminants from invading deeper artesian aquifers which are used for public supply purposes (Strause, 1987).

The location of industrial landfills appears to coincide with the general population centers; consequently, these landfills are concentrated around population centers and industrial facilities (Figure 37).

In the past, it was thought that land disposal of industrial solid wastes containing harmful hazardous substances was reasonably safe. This was based on assumptions that substances would remain where they were buried and/or that they would degrade into harmless products. It has since been found that these assumptions were erroneous and that substances either degrade very slowly, do not degrade at all, or they degrade into other substances which are also hazardous. Additionally, it has been found that leachates generated by these wastes do not remain where they were originally stored and that they are moved to other locations by stormwater runoff, wind, and through seepage to underlying ground waters.

The greatest threat to both surface and ground water is the generation and the movement of leachates from these landfills. According to a nationwide survey, in 1983 only 1609 of almost 13,000 landfills surveyed were equipped with adequate systems for monitoring ground water, leachate collection, or gas emission (Office of Technology Assessment, 1984).

Ground-water contamination can be minimized by employing the proper design, construction, and operation and maintenance of a facility. Unfortunately, many of the older landfills were not sited using geological or hydrological considerations, many were unlined or minimally lined, others had no leachate collection system, ground water was unmonitored, they were not properly maintained nor covered, and some have been allowed to deteriorate. As a direct result, many of these are now a threat to the environment.

From the previous brief treatment of this subject, it can be seen that considerable local ground-water pollution has or may have resulted from landfill activities within the state. Problems with these facilities should continue for some time into the future.

It is no longer technically or economically practical to handle hazardous industrial solid wastes as they have often been handled in the past and they must be placed in specially designed landfills. These landfills should be sited in the proper geologic and hydrologic environment, they should be double lined with a leachate collection system, they should contain separate compartments for the separation of incompatible wastes, liquid wastes should not be accepted or they should be converted to solids, collected leachates should be treated or disposed of in deep subsurface waste disposal wells, and ground water should be monitored regularly to check for leachate escape. When a landfill is completed,it should be properly covered and vegetation planted to hold cover soil in place. Monitoring and leachate collection and its disposal should be continued until danger no longer exists. Then, these sites should be closed forever. No houses or other buildings should ever be erected on these sites.

Both federal and state regulations exist for the operation of these facilities; however, past management practices appear to have been inadequate for the proper protection of ground water. The EPA is now in the process of developing new regulations of these facilities which emphasize ground-water protection.

Landfills are regulated by both the Texas Water Commission and the Texas Department of Health. As of September 1, 1985, Texas legislation consolidated the management responsibility of all hazardous waste (both industrial and nonindustrial) with the TWC. The regulation of sanitary landfills is the responsibility of the TDH.

Small Quantity Generators

Originally, hazardous waste laws affected only those companies and businesses which produced relatively large quantities of hazardous or acutely toxic wastes. As a result of recent federal and state laws, formerly non-regulated generators of even small quantities of hazardous wastes are now regulated. Laws applying to these businesses became effective September 1, 1986. Activities of many of these formerly unregulated businesses may have locally affected ground water.

In general, any waste which if improperly stored, processed, transported, or disposed of, and may cause illness, death, or serious harm to the environment, is now subject to regulation.

The same definition of hazardous waste which applies to large generators, still applies to these affected businesses. Examples of businesses and or activities which commonly produce hazardous waste have been previously presented in the introductory discussion of hazardous waste. Some of the hazardous wastes now regulated are: solvents, strong acids or alkalis, bleaches, degreasing agents, metallic wastes, dyes, rust removers, etching materials, waste ink and sludges, photographic wastes, paint removers, pesticides, poisons, oxidizing agents, batteries, and many more (Texas Water Commission, 1986).

A business is considered as a small quantity generator if in a calendar month, it generates a total of less than 1000 kilograms (2200 pounds or approximately 265 gallons) of hazardous waste. There are two categories of business which are used to establish precise waste management requirements placed on small quantity generators. These are based on the total monthly quantity of waste generated and are:

1) Those who in a calendar month, produce an amount greater than 100, but less than 1000 kilograms. They are referred to as Small Quantity Generators (SQGs); and

2) Those generators who in a calendar month, produce a total of no more than 100 kilograms of hazardous wastes. They are referred to as Conditionally Exempt Small Quantity Generators (CESQGs).

When a generator generates greater than 1000 kilograms of waste per calendar month, he must comply with the regulations that apply to a large hazardous waste generator (Texas Water Commission, 1986).

All small quantity generators (SQGs and CESQGs) who in a single calendar month generate or who at any time accumulate on site, quantities of acute hazardous waste greater than set forth below in 1) and 2) are required to handle those acute hazardous wastes as "fully regulated wastes." These are:

1) A total of one kilogram of acute hazardous wastes as listed by EPA regulations; or

2) A total of 100 kilograms of any residue or contaminated soil, waste, or other debris resulting from the cleanup of a spill into or on any land or water, of any acute hazardous waste listed by EPA.

The term "fully regulated" simply means that any relaxation of waste management that might otherwise be afforded to CESQGs or SQGs does not extend to these amounts of acute hazardous wastes.

Activities which may impact ground water and are believed to possibly require greater monitoring in the future are: structural pesticide application, dry cleaning, automobile service stations, and automobile junk yards.

The small quantity hazardous waste generator program in Texas is the responsibility of the TWC. Authority to regulate hazardous waste in Texas is set forth in the Texas Solid Waste Disposal Act, Texas Civil Statutes, Article 4477-7. Amendments to the Act passed by the 69th Texas Legislature, became effective September 1, 1985, consolidated the management responsibility of all hazardous waste with the TWC. Rules of the TWC related to SQGs may be found in Title 31 TAC Chapter 335. Nonhazardous waste disposal of the small quantity generator is the responsibility of the TDH.

Abandoned Hazardous Waste Facilities

One of the largest threats to ground water is abandoned hazardous waste management facilities. Some of these require immediate clean-up actions. Nationwide, as of August, 1987, there was a total of 808 abandoned waste sites located in 48 states and five territories which were listed on EPA's National Priority List (NPL) (Texas Water Commission, 1988a). These were targeted for federally funded mitigation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly referred to as "Superfund". A total of 47 of these were federal facilities. Approximately 75 percent of these sites had documented ground-water pollution problems. An additional 149 sites were in the "proposed" category awaiting a decision on listing. There were 22 Texas sites on the NPL. Six of these CERCLA or Superfund sites have been documented to have shallow ground-water pollution. None are believed to have caused widespread contamination of deeper aquifer drinking-water supplies (Strause, 1987). Figure 29 depicts the statewide locations of these abandoned hazardous waste sites (CERCLA) as of 1987.

Numerous potentially toxic pollutants are known to be present at the nationwide sites. At last count, over 400 of these had been identified. The most commonly found contaminants include arsenic, benzene, cadmium, chloroform, chromium, lead, polychlorinated biphenyhls (PCBs), phenol, tetrachloroethylene (TCE), and toluene. In addition to the above listed pollutants, one or more of the most harmful pesticides were also found. At least two-thirds of the 400 identified toxic substances found at the abandoned sites were known to have contaminated ground water (U.S. Environmental Protection Agency, 1984e; and Culver, 1985).

In 1986, the Superfund Amendments and Reauthorization Act (SARA) amended CERCLA giving the Superfund program new responsibilities and authorities, and increased the size of the trust fund to $8.5 billion.

In addition to federal laws, Texas has authority to regulate and clean up hazardous waste under the Texas Water Code and the Texas Solid Waste Disposal Act (TSWDA). The TSWDA was originally passed in 1969 when the 61st Texas Legislature initiated the regulation of industrial solid waste management. Since then, Texas lawmakers have continued to amend the TSWDA to safeguard the health, welfare, and physical property of the public, and to protect the environment. In 1985, the TSWDA was amended to establish a state Superfund program to address those sites not eligible for funding under the federal Superfund program (Texas Water Commission, 1988a).

The federal and state programs work together to identify and respond directly to hazardous waste sites in Texas that may constitute an imminent and substantial endangerment to public health or the environment. It takes time to clean up complex environmental problems that may have developed over many years, and Superfund is helping to solve the hazardous waste problems found in some neighborhoods and communities in Texas.

In Texas, the Superfund program is addressing:

1) Contaminated ground water which supplies area drinking water;

2) Properties where chemicals were carelessly disposed of in pits or on the surface of the ground; and

3) Sites where industrial waste were abondoned in place.

The oversight for cleanup work at the Superfund sites on the NPL in Texas may be done by the EPA or by the TWC.

Frequently, new information from a citizen's complaint or a TWC probe will alert agency officials to a potential problem at a site. Once a potential site is identified, the first step federal and state officials take is to research existing information about the site. Investigators check through records, old photos,and news articles about the site. They try to determine what was buried or dumped there, when, and by whom. In addition, they review old inspection and legal records for the site or property (Texas Water Commission, 1988a).

Next, the TWC or EPA staff may make an initial inspection of the problem area. Staff members note obvious signs of trouble such as spills, stockpiled wastes, old barrels, and dead or discolored vegetation.

This initial evaluation of the site may also include an analysis of land slope, water movement, and the distance to homes, businesses, or water wells. Samples of waste, water, soil, and air may be taken during this inspection. Following the initial inspection, each site receives a numerical rating that indicates how hazardous the site may be (Texas Water Commission, 1988a).

The Hazardous Ranking System developed by the EPA is used to determine the numerical rating. The score a site receives depends on a number of factors, such as:

1) Whether contamination could be or is being released to the ground water, surface water, or air;

2) The distance to the nearest human population; and

3) The potential effect on the area environment.

Sites that receive relatively high scores are nominated for inclusion on the Superfund NPL. The NPL lists potentially hazardous sites from across the nation which may be eligible for long-term remedial actions under the Superfund program.

If a site does not score high enough to be added to the NPL, it may be added to the Texas Registry of hazardous waste sites. The Registry is similar to the NPL, in that it identifies the waste sites which may constitute a threat to the public's health and the environment. If a site is added to the Texas Registry, it may be eligible for remedial actions under the state Superfund program. Presently, there are 28 state sites on the Registry. The TSWDA requires that the property owner or the party legally responsible for the problem at a Registry site assume the financial burden of the cleanup. If this is not forthcoming, state funds may be available for remediation (Texas Water Commission, 1988a).

If a site is placed on the NPL, the federal Superfund program allows the TWC to conduct a more comprehensive site evaluation called a remedial investigation and feasibility study (RI/FS). Remedial investigations are conducted to collect and analyze the information needed to determine the extent and nature of the contamination. The feasibility study follows to identify and evaluate possible technical solutions for the site. When the feasibility study is completed, public input is solicited through public meetings and a comment period.

Once public comments have been received, the TWC and the EPA select a cleanup option that is:

1) Protective of public health,

2) Environmentally sound,

3) Cost-effective,

4) Technically feasible, and

5) Generally acceptable to the majority of the residents.

Then the final engineering plan, or remedial design (RD) of the remedy is drafted. The remedial action (RA), or construction activities at the site are conducted under the supervision of the TWC (Texas Water Commission, 1988a).

In addition to federal requirements, remedies in Texas must also meet the requirements of the TSWDA.

The TWC and the EPA encourage private parties who are responsible for hazardous sites to voluntarily clean up any problems they may have created. If the private party cleans up a site, the EPA or the TWC will oversee the cleanup activities to ensure that all threats to human health and the environment are addressed, and that the cleanup procedures comply with all relevant federal and state environmental regulations. In the cases where those responsible are unknown, or financially unable to cooperate, the TWC and/or the EPA provides for the cleanup work (Texas Water Commission, 1988a).

If the responsible parties are unwilling to cooperate, EPA can issue an administrative order or may take them to court to force them to clean up the site. If the responsible parties ignore an EPA cleanup order, then they may be liable for punitive damages up to triple the costs of the TWC or EPA cleanup actions.

Under the National Oil and Hazardous Substances Pollution Contingency Plan (NCP), primary responsibility for cleanup actions taken at Superfund sites resides with EPA. However, for some site cleanups EPA may delegate lead responsibility to the TWC by entering into a cooperative agreement with the state agency (Texas Water Commission, 1988a).

At state-lead sites, the TWC is responsible for planning and implementing the cleanup action to be undertaken at the site. Private contractors are hired to perform remedial work at state-lead sites. These contractors are financed by the Superfund program and are supervised by the TWC.

At federal-lead sites, the EPA has the responsibility for planning and implementing the response actions at a site. The U.S. Army Corps of Engineers manage the design of the remedy and construction activities at the site for the EPA. The Army Corps of Engineers may also provide technical assistance to EPA during the remedial investigation and feasibility study. The TWC maintains a role by reviewing and commenting on all plans and reports (Texas Water Commission, 1988a).

Although the exact combination of state and federal resources used at each site varies, in general when EPA and the TWC perform cleanup actions, Texas contributes 10 percent of the cost of remedial response actions undertaken at sites financed from the Superfund. If a site was owned and operated by the state or by a political subdivision within Texas, the state is then responsible for 50 percent of the cleanup cost. Following the first year after closure, Texas finances 100 percent of the post-closure operation and maintenance costs at all Superfund remedial action sites in Texas for a period of 30 years.

The Superfund finances 100 percent of the immediate removal actions conducted in Texas. Additionally, any post-closure operation and maintenance costs are also financed by the Superfund.

At sites where EPA and the responsible party have negotiated an agreement for the responsible party to undertake the cleanup action, the responsible party finances 100 percent of the cleanup action. At the expense and discretion of those responsible, the operation and maintenance of a site cleaned up by the responsible party may be delegated to the TWC (Texas Water Commission, 1988a).

Sanitary Landfills

The use of sanitary landfills is the preferred method of disposal of municipal solid wastes, provided that precautions are exercised in locating these facilities to insure the proper protection of surface and ground waters.

A **sanitary landfill** is a land disposal site which employs an engineered method of disposing of solid wastes on land. The designed method minimizes environmental hazards by spreading the wastes in thin layers and reducing them to the smallest practical volume. Cover material is then applied and compacted at the end of each operating day. True sanitary landfills are rare (Miller, 1980).

Landfills in the past were almost always located on land that was considered to have little or no value for other uses. Thus, abandoned sand and gravel pits, old strip mines, marshlands, or limestone sinkholes were often used. In most of these, the water table is at or very near the surface and, therefore, they are extremely susceptible to ground-water contamination. Even though many were originally engineered, control measures for minimizing pollution of ground water were not instituted (Miller, 1980) (Figure 28).

Wastes normally placed in a sanitary landfill are municipal solid waste products which are generally, but not always, nonhazardous. Thus, these landfills are referred to as municipal solid waste landfills.

Municipal solid waste landfill (MSWLF) sites generate leachate which is normally composed of highly mineralized liquids containing chemical constituents such as chloride, copper, iron, lead, nitrogen, sodium, and various organics as well as microorganisms. Previous illegally dumped industrial hazardous wastes may also have added the constituents of cadmium, chlorinated hydrocarbons, chromium, cyanide, and polychlorinated biphenyls (PCBs) (Novotny and Chesters, 1981). Table 8 lists typical constituents present in municipal solid waste which are generated under normal U.S. conditions.

The EPA estimated that during 1984, a nationwide total of 9284 MSWLFs handled about 133 million tons of waste (U.S. Environmental Protection Agency, 1987a). It was further projected that by the year 1990, that from 295 to 341 million metric tons of refuse will be produced annually in the United States (U.S. Environmental Protection Agency, 1988b). Leachate generated by this huge volume of material increases the potential for adversely affecting human health and the environment and it also can be a significant source of both surface- and ground-water pollution if it is not properly managed.

During 1977, landfills nationwide, combined with individual domestic septic systems were releasing an estimated 1700 billion gallons of contaminated liquid into the ground each year (U.S. Environmental Protection Agency, 1988b).

A 1976 nationwide survey, conducted by the EPA, found that 80 percent of all wastes were landfilled illegally with the rest being placed in authorized

Table 8.—Leachate Characteristics From Municipal Solid Waste [a]

Components	Median Value (mg/liter) b/	Ranges of All Values (mg/liter) b/
Alkalinity ($CaCO_3$)	3050	0-20,850
Biochemical oxygen demand (5 days)	5700	81-33,360
Calcium (Ca)	438	60-7200
Chemical oxygen demand (COD)	8100	40-89,520
Copper (Cu)	0.5	0-9.9
Chloride (Cl)	700	4.7-2500
Hardness ($CaCO_3$)	2750	0-22,800
Iron, total (Fe)	94	0-2820
Lead (Pb)	0.75	<0.1-2.0
Magnesium (Mg)	230	17-15,600
Manganese (Mn)	0.22	0.06-125
Nitrogen (NH_4)	218	0-1106
Potassium (K)	371	28-3770
Sodium (Na)	767	0-7700
Sulfate (SO_4)	47	1-1558
Total dissolved solids (TDS)	8955	584-44,900
Total suspended solids (TSS)	220	10-26,500
Total phosphate (PO_4)	10.1	0-130
Zinc (Zn)	3.5	0-370
pH	5.8	3.7-8.5

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[a]/Based on 20 samples
[b]/Where applicable

Source: Novotny and Chesters, 1981

disposal sites (U.S. Environmental Protection Agency, 1988b).

In July 1988, the U.S. Environmental Protection Agency concluded and published its findings related to nationwide studies on ground- and surface-water contamination resulting from MSWLFs. A brief summation of their ground-water related findings at 146 sites, selected from around the nation, follows.

At the 146 selected sites, ground-water pollution was the most commonly reported problem associated with the landfills. Contamination varied from simply elevated levels of various chemical constituents in ground waters below these sites to pollution of major aquifers and/or productive municipal well fields. Thirty-five landfill facilities were documented to have affected private and community water supply systems. Contamination resulted in the development of alternative water supplies in 17 of these cases. Numerous instances of surface-water contamination were also documented (U.S. Environmental Protection Agency, 1988b).

It was also found that various levels of corrective action had been initiated in response to the resulting ground-water contamination. Most common actions taken ranged from improvements in the design or operating requirements to actual site closure. In most cases, some actions were taken to prevent further pollution. Seldom were any measures taken to remove contaminant chemicals from ground water. Evaluation of the effectiveness of correction action was impossible due to the lack of information (U.S. Environmental Protection Agency, 1988b).

Problems which contributed to ground- and surface-water contamination appeared to have a common set of characteristics and these were:

1) The lack of or inadequate means of controlling leachate generation and its migration (e.g. final cover, run-on/run-off control systems, liners, or leachate collection systems); and

2) Poor choice of location (e.g. located in wetlands, on permeable soils, or in areas of shallow ground-water levels) which further aggravated the lack of environmental controls by permitting migration of the pollutants to both surface and ground water.

Current nationwide data, released by the EPA, indicate that only 25 to 30 percent of MSWLFs are equipped with ground-water monitoring systems. Additionally, information submitted to the U.S. EPA by the states during 1984, confirms that ground-water pollution has been detected at 586 active MSWLFs and that only about 25 percent of these facilities are now monitoring ground water (U.S. Environmental Protection Agency, 1988b).

Older sanitary landfills were often located without consideration for the potential for ground-water pollution, were usually unlined, and often left uncovered. Many of these have contaminated ground water on a local basis. New York State has estimated that 82 percent of its waste facilities leak or are suspected of leaking. Only about 28 percent of their sanitary landfills have liners (Ground Water Monitor, 1986).

Texas also has documented cases of MSWLFs having contaminated ground water. In their 1988 investigation of MSWLFs, the EPA confirmed ground-water contamination at landfills which follow. The counties in which these are located are shown in parenthesis when they are known. Those documented to be leaking are: Victoria (Victoria), Gainesville (Cooke), San Antonio-Pearsall Road (Bexar), Dallas-Fort Worth (Tarrant), Sunset Farms (unknown), and Atascocita (Atascosa). Other confirmed cases of pollution are known to be present in Harris County (U.S. Environmental Protection Agency, 1987a). An additional case of a landfill leak was located by personnel of the TWC during monitoring activities at a hazardous wastes site in Nueces County (Cole, Texas Water Commission, personal communication, 1988).

Figure 30 gives the approximate statewide distribution of known municipal landfill sites in Texas (Strause, 1987). A total of 950 active and several hundred closed and abandoned municipal solid waste sites were known to exist in Texas in 1984. In 1985, the TDH evaluated 163 landfills against the RCRA open dump inventory criteria and four of these were classified as open dumps. Of the 71 landfills which had ground-water monitoring facilities, three had contaminants in excess of background concentration (U.S. Environmental Protection Agency, 1985).

Landfills are believed to be a significant threat to ground water in the very near future. Ground-water contamination resulting from landfills is probably much more widespread than preliminary data indicates. The only reason it has not been found is that most of these facilities are unmonitored.

Landfills are regulated by the TDH under the oversight of the U.S. Environmental Protection Agency. New federal regulations are now being developed to correct problems related to these facilities.

Existing Regulations for Industrial, Hazardous and Nonhazardous Solid Waste Facilities, and Sanitary Landfills

Federal and state laws impose specific regulatory obligations on generators of industrial hazardous and nonhazardous wastes as well as municipal solid wastes. A very brief discussion of these follow.

The Resource Conservation and Recovery Act (RCRA) (40 CFR, various parts) provides the TDH with authority to regulate nonhazardous waste facilities such as municipal landfills and open dumps. Additionally, the Texas Solid Waste Disposal Act (Article 4477-7, V.T.C.S.) designates the TDH as the solid waste agency with respect to the management of municipal solid waste. Disposal of nonhazardous industrial solid waste (except radioactive material) is regulated by the TWC. Where both municipal and industrial wastes are involved, except for Class I industrial waste, the TDH is delegated jurisdiction. The TDH also regulates the use, handling, and transportation of radioactive materials, including the storage, processing, and disposal of low-level radioactive wastes including mining mill wastes.

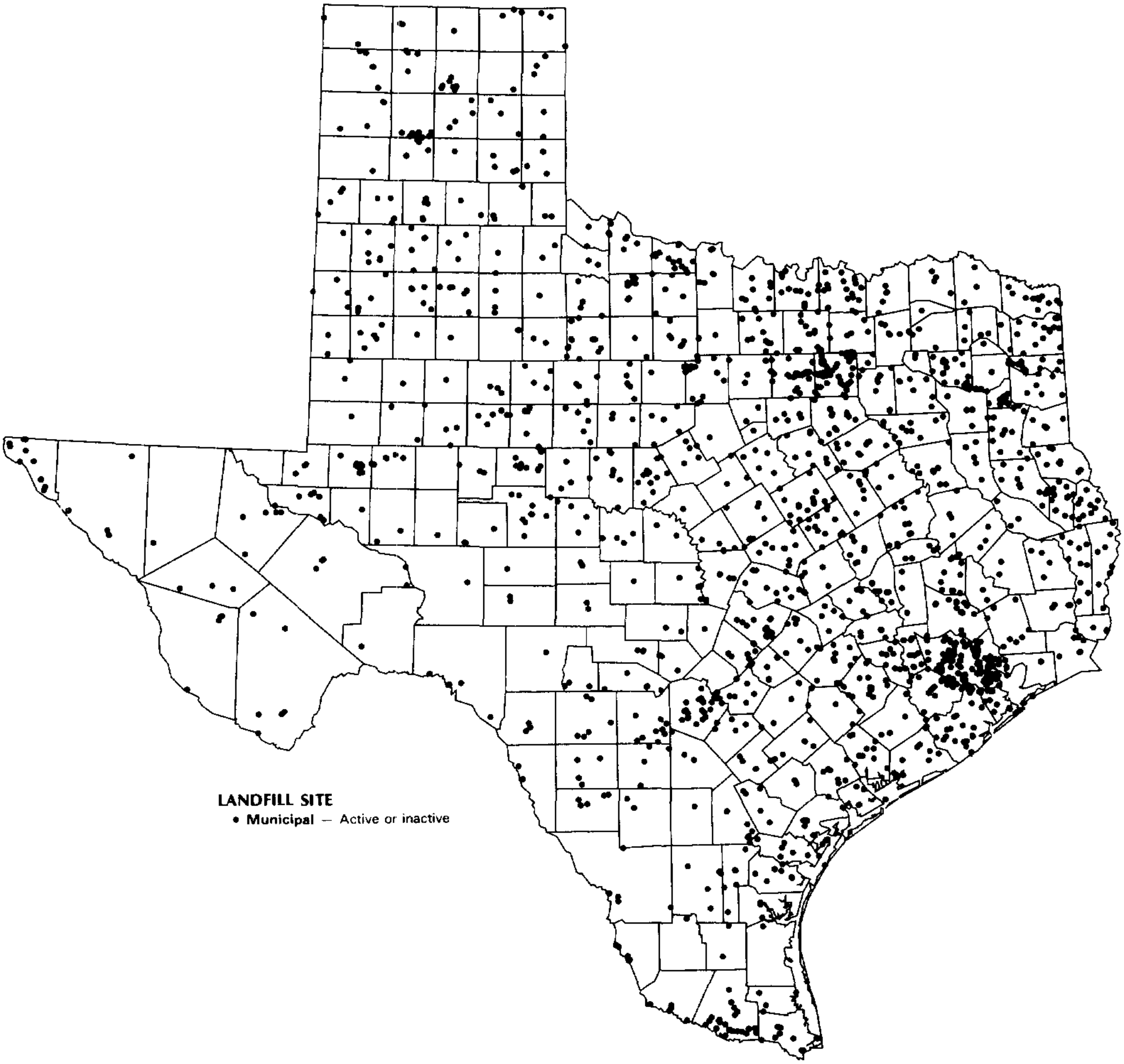


Figure 30.—Locations of Municipal Landfill Sites as of 1986 (Strause, 1987; From Texas Department of Health Files)

The authority to regulate hazardous waste in Texas is also set forth in the Texas Solid Waste Disposal Act (V.T.C.S., Article 4477-7). Amendments to the law, passed September 1, 1985, consolidated the management responsibility of all hazardous wastes (both industrial and nonindustrial) with the TWC.

The Comprehensive Environmental Response, Compensation and Liability Act (Superfund, 40 CFR, Parts 300-302) under the National Contingency Plan, authorizes the EPA and the TWC (Chapter 26, Texas Water Code) to respond to releases of hazardous materials which include remedial activities at sites on the National Priorities List (NPL) and emergency response activities at listed or unlisted sites.

The TWC regulates all activities related to water use and water-quality permits. Chapter 26 of the Texas Water Code contains provisions under which the TWC regulates most waste-water discharges and surface impoundments of nonhazardous and hazardous wastes.

Past improper disposal methods have created concern that hazardous wastes will come back to haunt those who have not properly closed their disposal facilities. Stiffer existing TWC requirements for closure, post-closure, financial requirements, and perpetual care have minimized such threats to the environment in the future and insure that these sites will be properly maintained without placing an undue burden on the tax payers of the state.

In cooperation with the states in 1988, the EPA completed a background document which addressed case studies on ground-water and surface-water contamination resulting from municipal solid waste landfills. This survey will enable the EPA and the states to evaluate their existing facilities. As a result of the study, EPA has proposed new rules governing municipal waste landfills. Under the proposed rules, virtually every municipal waste dump in the nation would be required to monitor for ground-water contamination.

Industrial Waste Disposal Wells

Texas ranks first among the states in the use of injection wells for industrial waste disposal. This results from three factors: (a) the industrial development of the state, especially in the chemical and petrochemical sector; (b) expertise in well technology from experience gained in oil and gas exploration, production, and development; and (c) the availability of suitable disposal reservoirs in many areas of Texas. Currently about five (5) billion gallons of industrial waste water are injected into subsurface reservoirs each year; this is approximately 60 percent of the waste disposed of each year in Texas by weight.

The advantages of underground disposal of waste water are: (a) the fate of the waste is, in general, known and understood; (b) the waste is contained and can be isolated from man's food, water, air, and activity; and, (c) the waste can be recovered if the need arises. To date, there has never been a case of usable-quality ground water being contaminated by an industrial waste disposal well in Texas. Usable quality ground water means water with less then 3000 mg/L total dissolved solids.

Potential contaminants derived from leaking wells of this type would vary depending on the industry generating the wastes. Fluids injected into these wells range from practically pure rain water, through sewage effluent, to highly toxic chemical wastes and radioactive substances (Miller, 1980). Normally, the contaminants would contain metals, nonmetals, organics, organic and inorganic acids, microorganisms, or radionuclides (U.S. Environmental Protection Agency, 1987a). Depending on the injectants, they may degrade ground water. A partial list of normally injected wastes is shown in Table 9 which follows. The typical waste stream in an industrial waste disposal well is: (a) relatively low volume; (b) not readily amenable to alternate disposal methods such as incineration or treatment and surface discharge; (c) within a neutral pH range; (d) very high in total dissolved solids concentration; (e) containing other process-related pollutants; and, (f) essentially without suspended solids. Waste water is usually filtered prior to injection. It is estimated that over 60 billion gallons of industrial wastes had been disposed of by disposal wells in the state prior to that time (Knape, 1984).

The rock units used as disposal zones in Texas range in geologic age from Ordovician to Tertiary. More wells use strata of the Miocene Series (Tertiary System) for waste injection than any other age rock because most chemical industries that generate waste water are located in areas of thick Miocene sediments. Therefore, most disposal wells inject into saline water-bearing zones of the Gulf Coast aquifer. These wells inject into horizons which contain waters of greater than 10,000 ppm total dissolved solids and these zones are located well below the potable water-bearing units. The majority of industrial waste disposal operations inject into sand strata; however,

Table 9.–Possible Injected Wastes of Industrial Waste Disposal Wells

- acetaladehyde
- acetate ammonia
- acroline
- activated sludge
- alcohols
- aldehydes
- aluminum hydroxide
- ammonia liquor
- ammonium chloride
- ammonium sulphate
- acids
  - acetic
  - adipic
  - chromic
  - formic
  - hydrochloric
  - sulfuric
- benzene
- bicarbonates
- boiler water
- BOD waste
- butadiene waste
- butanol
- brines
- bromides
- calcium chloride
- calcium carbonate particles
- calcium sulphate
- chloromycetin
- chlorinated hydrocarbons
- chlorinated organics
- chromates
- chromium
- clay particles
- COD waste
- coke quench water
- colloidal compounds
- contaminated storm drainage
- cooling tower water
- cresols
- cyanides
- caustic
- detergents
- diatomaceous earth
- drilling muds
- ethynol
- ferric chloride
- ferrous chloride
- ferrous sulphate
- hexamethylediamine chlorates
- heavy metal salts
- hydrocarbons
- ketones
- lime sludge
- laundromat waste
- magnesium sulphate
- mineral acids
- methyl cellulose
- mercaptans
- magnesium chloride
- methyldichlorophosphine
- nitriles
- naphthalene
- natural plasticizer wastes
- nitroles
- oils
- oil refinery waste
- organic phosphorus
- organic solvents
- organic nitrogen
- photo processing waste
- phosphorus trichloride
- pharmaceutical process waste
- phenol
- polyethylene waste
- pulping liquor
- paint removers
- propylene oxide
- silica
- stream drain
- steriods
- sodium hydroxide
- sodium sulphate
- sodium chloride
- uranium mill and radioactive laboratory wastes

Source: Miller, 1980

limestone and dolomite are also used. No waste disposal well permit has been issued for injection into fractured shale, igneous rock, or metamorphic rock (Knape, 1984).

A nationwide inventory of industrial waste disposal wells was completed by the U.S. Environmental Protection Agency in 1986. At that time, there were 555 known Class I injection wells in existence, of which 255 were classed as hazardous (U.S. Environmental Protection Agency, 1987a). In 1987 within Texas, a total of 118 wells were known to exist (Strause, 1987). The approximate breakdown of the types of these wells is as follows: 79 hazardous, 20 nonhazardous, and 19 uranium related (Kohler, Texas Water Commission, personal communication, 1988).

Pursuant to the Texas Injection Well Act, the TWC has full authority to regulate industrial waste disposal wells. Additionally, this category includes injection wells used for the disposal of production waste waters and aquifer restoration waters generated by the uranium solution-mining industry (Knape, 1984). The statewide distribution of Class I injection wells are shown on Figure 29.

Graveyards

In the past, very little thought has been given to graveyards as a possible source of ground-water contamination. Therefore, the appraisal of statewide burial grounds or cemeteries included in this report is very preliminary.

In cases where wooden coffins or nonleakproof caskets are used, it is possible for fluids produced by decomposing bodies to leak to underlying ground-waters. Areas of high rainfall and aquifers having shallow water tables are most susceptible to this type of contamination (Bouwer, 1978).

Potential pollutants from graves are embalming fluids; metals; nonmetals (primarily chlorides, sulfates, and bicarbonates); and microorganisms (U.S. Environmental Protection Agency, 1987a and Bouwer, 1978). In Berlin, Germany, during the late 1800's, it was found that people living near cemeteries had a higher incidence of typhoid fever. In Paris, France, water from wells close to cemeteries was noted, during hot summer months, to have a "sweetish taste and infected odor" (Bouwer, 1978).

Based on information assembled by van Haaren (1951) and Schraps (1972), Bouwer (1978) presented data related to possible ground-water pollution resulting from graveyards as follows.

It is estimated that about 6.7 pounds (lbs) of protein, 3.4 lbs of fat, and 0.3 lb of carbohydrate are contained in the average sized human corpse. Based on a leaching rate of about 16 inches per year in Holland, van Haaren (1951) estimated that bio-oxidation of this amount of body material would require about 10 years at about eight feet of burial depth in sandy soil. Assuming the above leaching rate, the total volume passing through a typical gravesite would be about 106 gallons per year. Additionally, Bouwer (1978) presented Tables 10 and 11 which list the average chemical parameters of shallow ground water found below graves as well as the expected ground-water quality in relation to distance from graves, respectively.

From the tables, it is apparent that in addition to other factors, a safe distance for the location of drinking water wells is important. They further suggests that pollution resulting from cemeteries, in some cases, may be very localized.

In areas underlain by cavernous or fractured reservoirs such as the Edwards (Balcones Fault Zone) aquifer or a sandstone water-bearing unit, caution in locating graveyards or drinking water wells in the vicinity of them should be exercised. Additionally, very coarse or sandy soils should also be avoided. Water well drillers, as well as prospective well owners, should be advised of the potential for ground-water pollution. A geologist or hydrologist is recommended regarding the locating of a cemetery and/or the placement of a drinking water well in the vicinity of one.

Table 10.–Average Chemical Parameters of Ground Water Below Grave Sites

Parameters	Amounts
Color (platinum-scale units)	75
Electrical conductivity	2.3 mmhos
COD (using $KMnO_4$)	95 mg/L
Chloride	500 mg/L
Sulfate	300 mg/L
Bicarbonate	450 mg/L

Source: Bouwer, 1978

Insofar as known, there are no state regulations regarding water well distance spacing from graveyards. Minimum distance between drinking water wells and cemeteries are required by law in England, France, and Holland. Required distances are 300, 328, and 164 feet, respectively. Extreme care should be exercised in locating any drinking water well down gradient from a cemetery.

In Europe, several incidents of ground-water pollution from cemeteries has been found. Schraps (1972) found contamination in the immediate vicinity of graves (Table 11); however, pollution diminished greatly in less than 20 feet from the graves. Depending upon soil and aquifer conditions, as well as the amount of rainfall, ground-water contamination could move a much greater distance than indicated in the table.

Within Texas, data are not available to document any ground-water pollution resulting from cemeteries. Monitoring of ground water down gradient

Table 11.–Ground-Water Quality in Relation to Distance From a Row of Graves

Distance from graves(ft)	1.6	4.9	8.2	11.5	14.8	18.0
Bacteria count (per ml):	6000	8000	8000	3600	1200	180
NH_4 (mg/L):	6	0.75	–	–	–	–
NO_3 (mg/L):	4.8	0.1	–	–	–	–
COD (mg/L, using $KMnO_4$):	26.7	16.4	15.4	15.4	11.4	11.4

Source: Modified From Schraps, 1972

should be conducted at selected locations around the state to check the impact of graveyards on ground water. Figure 31 shows the approximate distribution of known cemeteries within Texas. The location of these was determined using county maps prepared by the Texas Department of Highways and Public Transportation. Using the above data, it is estimated that about 7000 cemeteries were in existence as of 1986. However, the actual number of these cemeteries could be much higher.

In summary, contamination resulting from graveyards appears to be very localized. Several factors determine the potential for pollution of underlying ground waters. These are the soil types present, depth to ground water, types of caskets used, and the amount of annual rainfall (U.S. Environmental Protection Agency, 1987a).

Cemeteries are regulated by the Texas Funeral Service Commission, the State Purchasing and General Services Commission (the State Cemetery), Texas Banking Department (perpetual care of), and the State Property Tax Board (taxing thereof).

Current regulations included in Title 26 of the Texas Administrative Code, relating to cemeteries deal with the acquisition of property, cemetery locations, depth of body burial, cemetery operation, perpetual care thereof, their taxation, and graveyard abandonment. Statutes set forth required distances of cemeteries from incorporated cities. Distances range from one to five miles for cities of 200,000 inhabitants or less depending on their population. Burial requirements state that "no dead body shall be buried in such a manner that the top of the outside container within which said dead human body is placed in less than two feet below the surface of the ground, except that, if such container is made of steel, bronze, concrete, or the impermeable material, the top of such container shall be not less than one and one-half feet below the surface." There are no provisions included in these statutes which deal with the protection of ground water.

Neither the TDH nor the Texas Water Well Drillers Board (TWWDB) have any regulations related to distance requirements for the placement of drinking water wells near graveyards.

Water Wells

This topic includes abandoned wells, well construction, and testholes. Water wells are considered one of the greatest sources of pollution of ground water within Texas. Of greatest concern are improperly abandoned high-capacity municipal, industrial, and irrigation wells. Additionally, abandoned rig-supply wells, domestic or livestock wells, and unplugged testholes drilled in connection with fresh water well-field exploration and construction foundation testing also need to be addressed. These wells are part of a larger group which are discussed in a subchapter of this report titled, "Class V Injection Wells."

Many wells are old and improperly constructed. In many cases, there is inadequate or a total absence of casing within the holes, the surface casing has not been cemented, and most have been left uncapped. The wells are of various depths and in many, hydraulic communication is present between more than one water-bearing unit, allowing interaquifer exchange and water degradation (Figure 44). These conditions also allow an undetermined amount of contaminants to enter ground water during storm related events via vertical leakage from the surface (Figure 32). Additionally, they are also a safety hazard to humans and livestock.

In order to reduce the potential for future ground-water contamination, greater care should be exercised in locating the wells where surface waters containing potential contaminants could not enter the well bore easily (Figure 33). Proper completion techniques should be practiced to cement the surface casing and/or cement off intervals of poor water quality to prevent interaquifer transfer between water-bearing intervals of varying quality. Possibly stronger enforcement of existing water-well drilling standards should be required.

Since wells exist in every county of the state, they impact all the aquifers of the state in all river basins. There are 105 counties in which limited data indicate that a problem could possibly exist related to unplugged rig supply wells which have been inventoried to date. Figure 34 shows the approximate distribution of possible abandoned rig supply wells. This inventorying is a statewide ongoing program.

An exact count of all types of abandoned water wells is not presently available; however, it is conservatively estimated that possibly as many as 25 percent or about 150,000 of the state's 600,000 estimated total water wells may be involved (Knowles, Texas Water Development Board, personal communication, 1987). Dr. Knowles further estimates that an additional 20,000 new wells are being drilled, annually. As of August 5, 1988, the personnel of the TWC had located about 5100 of these wells.

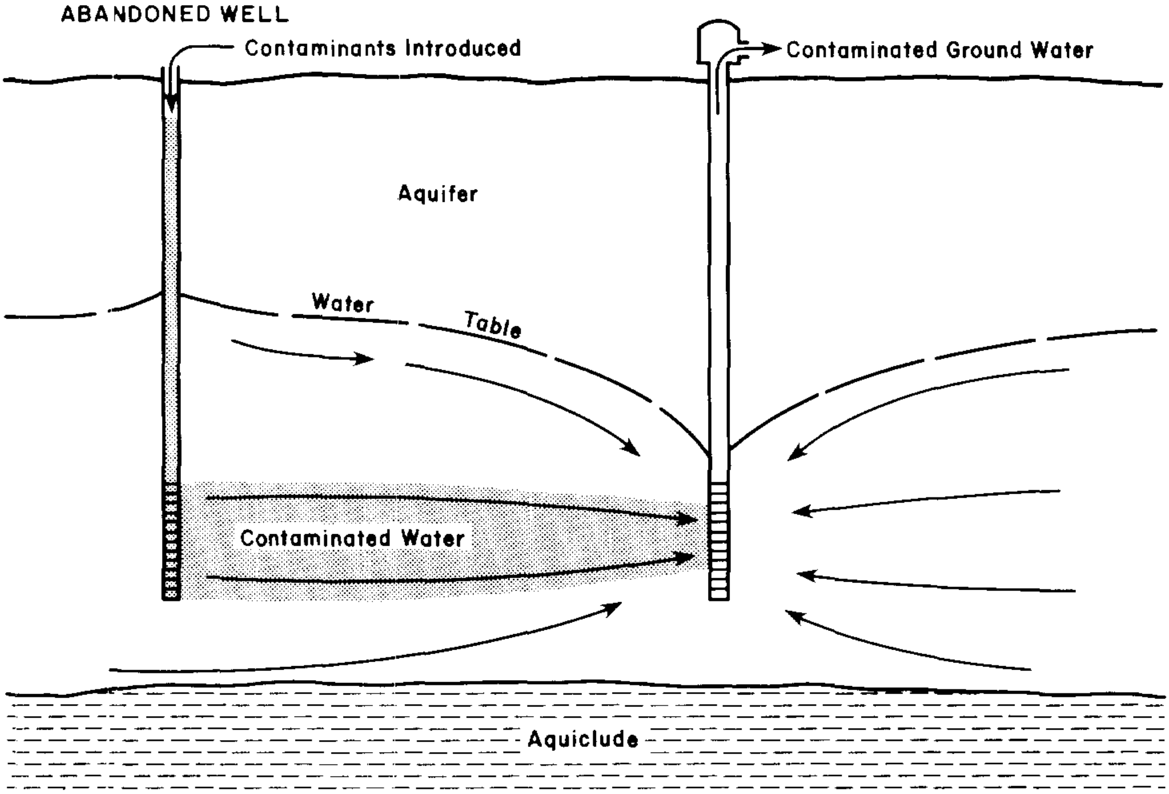


Figure 32.—Movement of Contaminants From an Abandoned Well to a Nearby Pumping Well. (U.S. Environmental Protection Agency, 1977; After Deutsch, M., 1963)

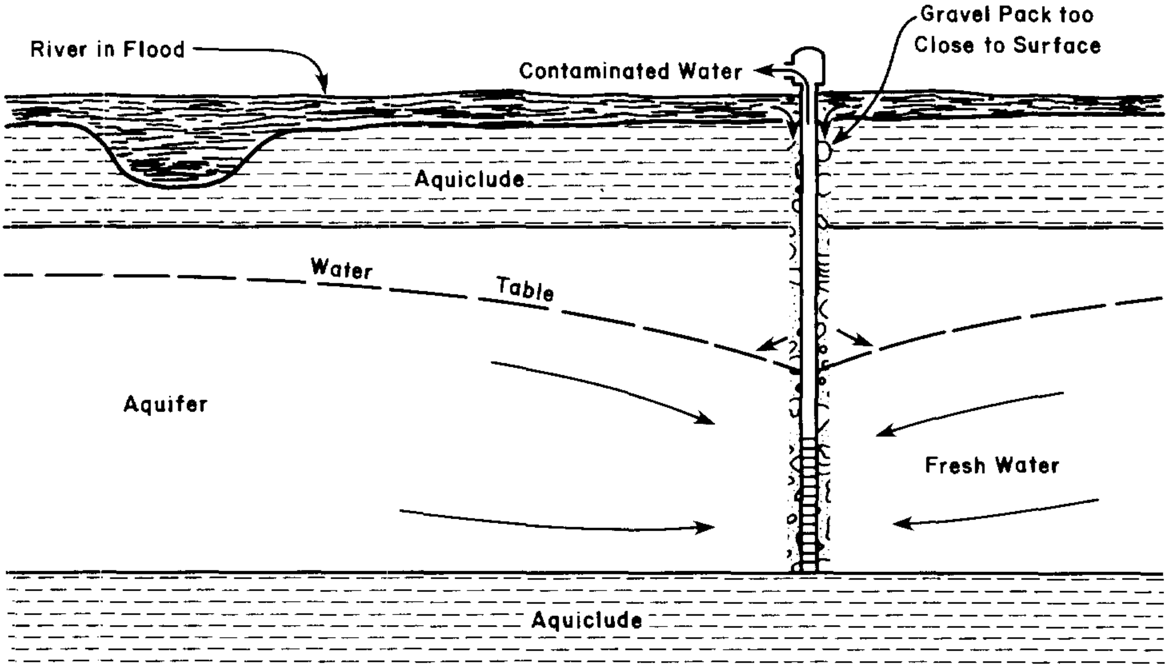


Figure 33.—Flood Waters Entering a Well Through an Improperly Sealed Gravel Pack. (U.S. Environmental Protection Agency, 1977; After Deutsch, M., 1963)

A tentative estimate of the possible pollution effects of abandoned wells is conservatively estimated using the following data:

Assumed average drainage area of a well	0.01 acre
Average mean annual rainfall for state (Larkin, Texas Water Commission, personal communication, 1987)	2.38 ft/yr
Total no. of abandoned wells	150,000
Assumed percent of abandoned wells contributing to pollution	80
Estimated amount of total volume as contaminants entering ground water	0.01 percent or 0.0001
Estimated percent of rainfall as runoff (Kingston and Crawford, 1987; and Larkin, 1983)	12

Employing the above data and assumptions, it is estimated that the average radius of influence of an individual well would be about 12 feet; that about 912 gallons (gals) of total fluid would be entering the impacted ground water beneath each well, annually; that about 0.09 gal/yr/well of potential contaminants could be entering affected ground water beneath each well. Cumulatively, wells which are thought to be contributing, could furnish a total of about 109.5 million gals of fluid of which about 11,000 gals of potential pollutants, annually, could be released to all of the aquifers of the state in all river basins. Additional estimates of loading of the aquifers related to interaquifer exchange between different water-bearing zones within the individual wells are not possible.

Abandoned water wells may rank first in priority for mitigation by the state. Ranking in relation to reduction of loadings vs. cost benefits could be relatively high since all that might be involved in many cases is location of wells through well inventory, and directing the owners to properly plug the wells or protect ground waters.

In Texas, regulatory authority over abandoned water wells is under the jurisdiction of the TWC and TWWDB. Under new Texas Administrative Code (T.A.C.) Chapter 287 Rules relating to the Water Well Drillers Act, the property owner, if so directed, is responsible for properly plugging or capping the abandoned well. If the well has no cement behind casing, then the casing must be removed and a cement plug extended from land surface to a depth of not less than ten (10) feet. Within thirty (30) days of plugging the well, a report must be filed with the Commission on forms supplied by the Texas Water Commission Drillers Board Assistance Program. This authority is now being exercised in the plugging of abandoned water wells statewide.

In order to reduce present statewide data gaps related to abandoned water wells, the TWC has an ongoing well inventory and assessment program for wells of this type. Additionally, through these efforts, the Commission has also located, inventoried, and evaluated rig-supply wells. All of these wells are also regarded by the TWC as new Class V injection wells. More specific discussions of Class V wells will follow under the heading of "Class V Injection Wells." As new detailed ground-water resources studies are completed by the TWDB, data related to abandoned domestic, livestock, irrigation, municipal, and industrial wells will also be incorporated into this program.

Sewage and Waste-Water Disposal Systems and Municipal Sewage Collection Lines

Private On-Site Sewage Disposal Systems

Most rural Texans rely on an on-site disposal system to manage their domestic waste water (Figure 35). During 1980, over 120,000 people in the state were reported to live in dwellings in which there were no bathroom facilities or toilets (Texas Rural Water Quality Network Project, 1986a). These people relied upon pit privies to meet their needs. Prior to the widespread use of drainfields, a significant number of rural people relied (and many still do rely) on less-sophisticated alternatives which include sewage disposal wells. These are composed of bored or dug holes in which the depth exceeds the diameter. Common disposal methods include boreholes, injection wells, cesspools, seepage pits, and seepage wells. Most of these wells dispose of septic-tank effluent while the remainder dispose of raw sewage (Knape and others, 1984).

In rural areas, septic tank systems and cesspools replaced the pit privy for domestic waste disposal as the rural electrification program of the 1940's made supplying water to indoor plumbing systems inexpensive and readily available. Septic tank treatment of domestic waste frequently employed the cesspool as an addition or replacement for a conventional soil adsorption system. Use of septic tanks and cesspools increased tremendously during the 1950's

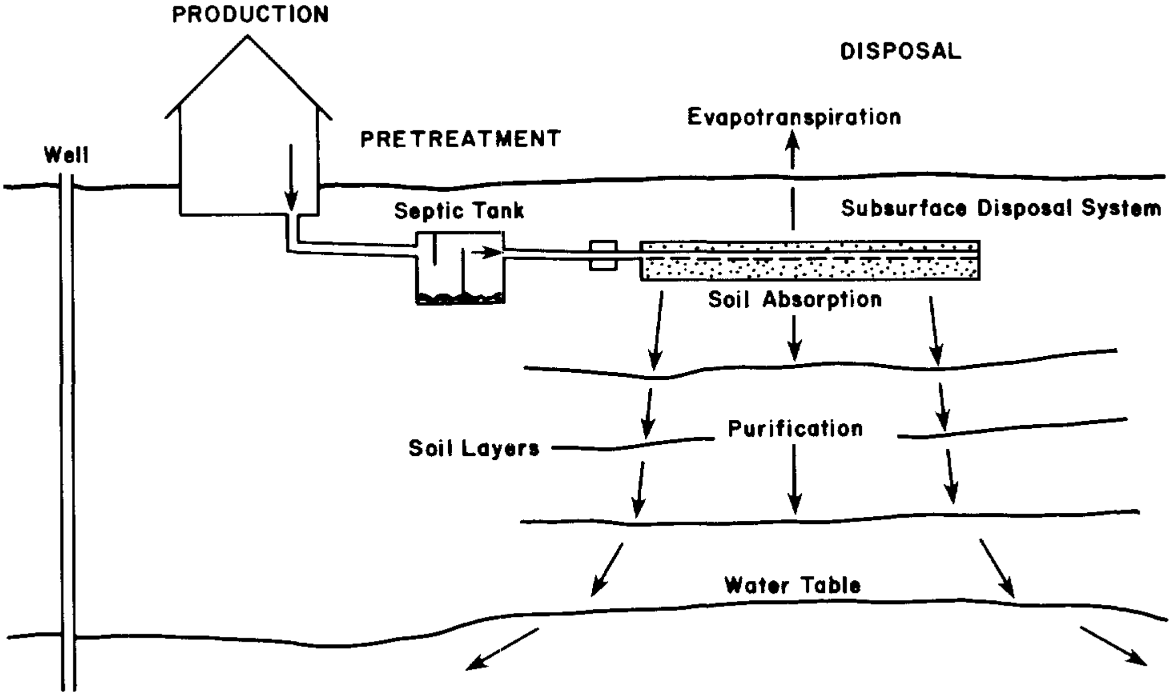


Figure 35.—A Typical Domestic Septic Tank System (U.S. Environmental Protection Agency, 1977; After Bouma, J., et al., 1972)

and steadily over the following two decades with rapid development of suburban areas around cities. Use of sewerage disposal wells also developed in areas where suburban development were not served by municipal sewerage systems and where soil conditions or lot size were unsuitable for soil adsorption systems.

The nature of pollution resulting from private on-site disposal systems can only be roughly appraised at this time, using very limited available data. In areas where the ground-water table is near surface such as in alluvial gravels, in the outcrop of the Trinity Group, the Carrizo-Wilcox, and the Gulf Coast aquifers, as well as where porous limestones are present, such as on the Edwards (Balcones Fault Zone) aquifer, septic tanks are of great concern (Figures 1 and 2). Both of the above conditions reduce the soil contact time available before the waste reaches ground water; therefore, increasing the chances of bacterial contamination of ground water. This type of contamination has been documented in widely scattered counties of the state.

Characteristics of typical septic tank effluent (Canter and Knox, 1985, p. 58) are as follows:

Characteristic	Range	Mean Value
pH	6.53 - 7.45	6.90
Total suspended solids (TSS)	68 - 624	176
Biochemical oxygen demand (BOD)	140 - 666	280
Chemical oxygen demand (COD)	240 - 2026	568
Soluble organic carbon (SOC)	24 - 190	73
Total phosphates (PO_4-P)	625 - 30.0	11.6
Ammonia nitrogen	77 - 111	97
Nitrate -N	0.00 - 0.10	0.026
Total soluble iron	0.00 - 20.0	2.63
Chlorides	37 - 101	53

All values except pH are milligrams per liter.

If the above concentration of constituents entered the water table five (5) feet below the land surface, the concentrations of constituents which would be entering ground water (Canter and Knox, 1985, p. 58) would be:

TSS	18 – 53 mg/L
BOD	28 – 84 mg/L
COD	57 – 142 mg/L
SOC	7 – 18 mg/L
Total phosphates	6 – 9 mg/L
Ammonia nitrogen	10 – 78 mg/L

Aside from the dangers of pathogens in sewage-contaminated ground water, chemical constituents of sewage can also cause ground-water problems ranging from the nuisance of mineralized taste of the water (nitrates cause a bitter taste) to more serious health problems such as methemoglobinemia in infants when nitrates are in excess of 45 mg/L. Additionally, research data conducted by the Suffolk County Department of Health Services, Suffolk County, Long Island, New York, has confirmed that the use of organic solvents for cleaning on-site subsurface waste-water disposal systems are also a major source of ground-water contamination (Suffolk County Department of Health Services and W.F. Cosulich Associates, 1980). Their study confirmed that the halogenated hydrocarbon group of organic solvents should be prohibited. Except for "Drainz", brand names of specific household products involved are not available, however, halogenated hydrocarbons parameters measured during the study were as follows:

Basic Group	**Parameters**
Halogenated Hydrocarbons	1,1,2 Trichloro1,2,2 Trifluoroethane Chloroform 1,1,1 Trichloroethane Carbon Tetrachloride 1,1,2 Trichloroethylene Chlorodibromomethane Tetrachloroethylene Bromoform Bromodichloromethane Methylene Chloride 1,2 Dichloroethylene 1,2 Dichloroethane Trichloroethylene 1,1,2 Trichloroethane

Some of the above chemicals are considered insoluble in water and have a specific gravity greater than water, thus making them a lesser immediate threat to ground-water pollution since they would collect in the bottom of the tank. However, these contaminants would be present in sludge pumped from these tanks.

Data are not presently available to effectively evaluate pollution resulting from the septic tank systems of Texas. However, documented ground-water contamination related to on-site sewage disposal systems have been confirmed in 47 separate counties. These are bacterial contamination and other problems related to septic tanks (22 cases), waste-water discharge (3), cesspools (5), lagoons (1), boreholes (4), and other (18) (Texas Water Commission Files, 1987; Scalf and others, 1973; and Ramirez, Consumer Protection Division, Office of the Attorney General, personal communication, 1987).

It is difficult, at present, to establish the location and the number of single-family residences and other establishments using septic tank systems and/or sewage disposal wells within Texas, for two reasons. First, there is generally no above-ground equipment associated with these facilities to aid in their location since both of these systems are normally buried beneath the surface and are not easily detected. Second, lack of regulation has precluded adequate record keeping of existing installations. However, it is estimated that these facilities are present in all counties of Texas and that they impact the ground waters of all aquifers to some degree. The TDH estimated that about 1,212,600 private on-site septic tank systems were in operation within the state in 1985 (Salgado, written and personal communication, 1987). This estimate, along with other pertinent data supplied to the TDH by Mr. David Pimentel formerly with the Texas Department of Agriculture (TDA), was derived using the following information:

Percent of population on septic tanks	20
Average area of drainfield	1400 ft^2
Estimated population of Texas (1985)	16,369,586
Estimated waste-water flow per person per day	50 gallons
Estimated persons per residence	2.7

Therefore:

$$\frac{(.20)(16{,}369{,}586)}{2.7} = 1{,}212{,}600 \text{ septic tanks in Texas}$$

(1,212,600 total septic tanks)(135 gal/da/residence)

= 164 X 10^6 gallons/day of total septic tank effluent produced

$$\frac{(1400)(1{,}212{,}600)}{43{,}560} = 38{,}972 \text{ acres of land in state used for drainfields}$$

(1,212,600 total tanks)(2.7 persons/residence)
(50 gal effluent/person/da) (365 da/yr)

=59.7 billion gallons total effluent generated/yr.

As is evident from the above data, these systems could have total annual effluent releases into the ground waters of the state of about 59.7 billion gallons. Mr. Bob Silvus (Texas Water Commission, personal communication, 1987) estimates that less than 0.1 percent of the total effluent which passes through a septic tank system is hazardous waste since any greater amount would kill the bacterial action necessary for degradation of wastes. If one arbitrarily assumes that one tenth of the above percentage were additives or influent of various household products which were hazardous, then 0.01 percent (0.0001) or about 6.0 million gallons of harmful wastes could be entering the state's aquifers, annually. These would cover an area somewhat larger than approximately 39,000 acres underlying the drainfields of the septic tanks.

At present, 78 counties have adopted local ordinances regulating on-site systems (Figure 36). Most counties that do not have septic tank control orders are essentially unregulated.

The standards entitled "Construction Standards for On-Site Sewerage Systems" replaced old existing standards on January 1, 1988. These new standards recognized new technology, require a registered professional engineer or registered sanitarians to design non-standard systems for approval, increase requirements for submittal of innovative designs, increase lot size requirements, and reflect other improvements over the old standards.

The 70th Legislature enacted H.B. 1875 which became effective September 1, 1987, relating to on-site sewage disposal, and affects the TWC, the TDH, and local organizations. H.B. 1875:

1) Recognizes, until September 1, 1989, the TWC as the authority that approves local governmental ordinances relating to on-site sewage disposal. After September 1, 1989, the TDH will assume that authority.

2) Allows the TDH to collect fees for on-site sewage disposal permits in an area not locally regulated and to assess a charge-back fee to the local governmental entity for administrative costs relating to the permitting function that are not covered by the permit fees collected.

3) Requires the TDH to provide educational training, testing, and licensing programs for both on-site sewage disposal system installers and agents of the local governmental agencies.

4) Requires that all persons comply with the legislation and applicable rules promulgated by the TWC, TDH, and the local governmental authority.

5) Provides that the TDH, its authorized agent, or a designated representative is not liable for damages resulting from the TDH's or authorized agent's approval of the installation and operation of an on-site sewage disposal system.

6) Requires the TWC and the TDH to each promulgate and implement rules relating to grey water usage, depending on the nature of the usage.

In summary, H.B. 1875 will provide statewide regulation of on-site disposal systems and will implement the training and registration of on-site system installers, the permitting of disposal systems, the inspection of these systems, and the monitoring by the TDH of local regulating entities for compliance with the bill. The intent of these requirements is to reduce the potential for ground- and surface-water pollution.

All new on-site sewage disposal systems handling over 5000 gallons per day must be permitted by the TWC (Morris, Texas Water Commission, personal communication, 1987).

Municipal Sewage Collection Lines

As the name implies, these lines are used to collect and transport raw sewage from private residences and other wastes to city sewage treatment facilities. These sewage pipelines are, therefore, most often located in densely populated areas (Figure 37). They are either constructed of clay (about 52 percent) or of polyvinyl chloride (PVC) (about 48 percent) (Rose, Texas Water Development Board, written communication, 1987).

Infiltration and inflow are quite often serious problems which lead to raw sewage discharges from the collection system (which can affect ground water), and overloaded treatment plants which leads to the surface (bypasses), usually from manholes or lift stations, occur when the collection system is overloaded. This usually occurs during wet weather when rainwater and high water-table ground water infiltrates into deteriorated lines and overwhelms the hydraulic capacity of the collection systems. Certain old, overloaded collection systems also bypass during dry weather. Raw sewage discharges to the surface can contaminate the local surface and/or ground water. During dry weather, at times when the water table is below the collection lines, these same deteriorated sewage lines can discharge raw sewage on a continuous basis to ground water (Figure 38) (Rashin, Texas Water Commission, written communication, 1987).

Potential contaminants from leaking lines are organics, metals, inorganic acids, and microorganisms (U.S. Environmental Protection Agency, 1987a, p. 103). Waste influent characteristics of typical municipal waste water, which contains some industrial waste and some infiltration, are as follows (U.S. Environmental Protection Agency, 1980, p. 2-22):

Waste Influent Characteristics

Temperature:		
Summer	23°	Degrees Centigrade
Winter	10°	Degrees Centigrade
Suspended solids	200	mg/L
Volatile solids	60	Percent of suspended
Settleable solids	15	mg/L
BOD5	250	mg/L
SBOD (Soluble)	75	mg/L
COD	500	mg/L
SCOD (Soluble)	400	mg/L
pH	7.6	
Cations	160	mg/L
Anions	160	mg/L
PO_4 (as P)	18	mg/L
TKN (as N)	45	mg/L
NH_3 (as N)	25	mg/L
NO_2 (as N)	0.0	mg/L
NO_3 (as N)	0.0	mg/L
Oil and grease	80	mg/L

The above waste-water characteristics are based on 100-120 gallons/day/capita waste (Rose, Texas Water Development Board, written communication, 1987). Additionally, it must be kept in mind that fluids which leak from municipal sewage lines will not necessarily be full strength due to screening dependent upon the size of opening in the pipe (Salgado, Texas Department of Health, personal communication, 1987).

In 1986, the estimated number of municipal sewage collection systems in Texas was 1554 (U.S. Environmental Protection Agency, 1987c, p. C-3).

Using 1980 census of population and housing data, it is estimated that 4,461,444 housing units in Texas are serviced by public sewers (Rose, Texas Water Development Board, written communication, 1987). Conservative estimates of the total miles of municipal sewage lines within the state are based on the following data:

Urban population (1980 TWDB data)	11,148,647
Average no. of feet of sewer per person (Rose, Texas Water Development Board, written communication, 1987)	20
No. of feet per mile	5280

Therefore:

11,148,647 X 20 = 222,972,940 Total feet of municipal sewer lines in Texas; or

$\frac{222,972,940}{5280} = 42,230$ Total miles of municipal sewer lines in Texas

A conservative estimate of the total amount of municipal waste water generated per day, within Texas, is about 1.8 billion gallons (Rose, Texas Water Development Board, written communication, 1987).

An accurate estimate of the volume of waste water that leaks out of sewage collection lines (exfiltration) throughout the state is not easily derived. Determining factors such as geology, pipe material, size, and age of the lines vary throughout the state. Engineers involved in the design of collection and treatment facilities are primarily concerned with ground water that leaks into sewers (infiltration) (Salgado, Texas Department of Health, written communication, 1987).

During periods of wet weather, in most areas the sewage lines will be 100 percent full due to load and infiltration. In dry weather, the lines will normally be less than 50 percent full. Exfiltration takes place during this time (Rose, Texas Water Development Board, personal communication, 1987).

Leakage from municipal sewage lines is usually more prevalent where exfiltration occurs due to arid (dry) conditions (Figure 38). Additionally, more leakage occurs in older parts of cities and from the lines of older cities which have a history of slower growth rate (this is due to greater density of clay lines). In East Texas, there is greater rainfall and water tables are closer to land surface. Under these conditions, infiltration is normally greater (Salgado, Texas De-

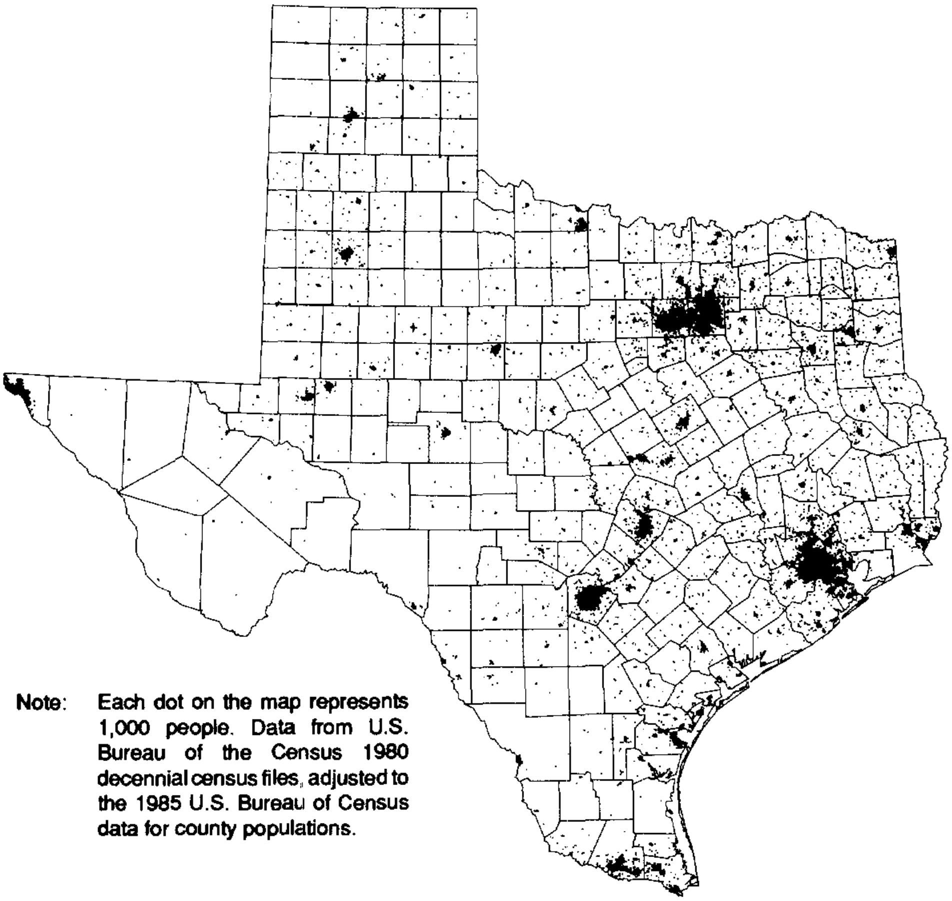


Figure 37.—Population Distribution as of 1985 (Figure courtesy of the U.S. Geological Survey, Open-File Report 87-0754, Strause, 1987)

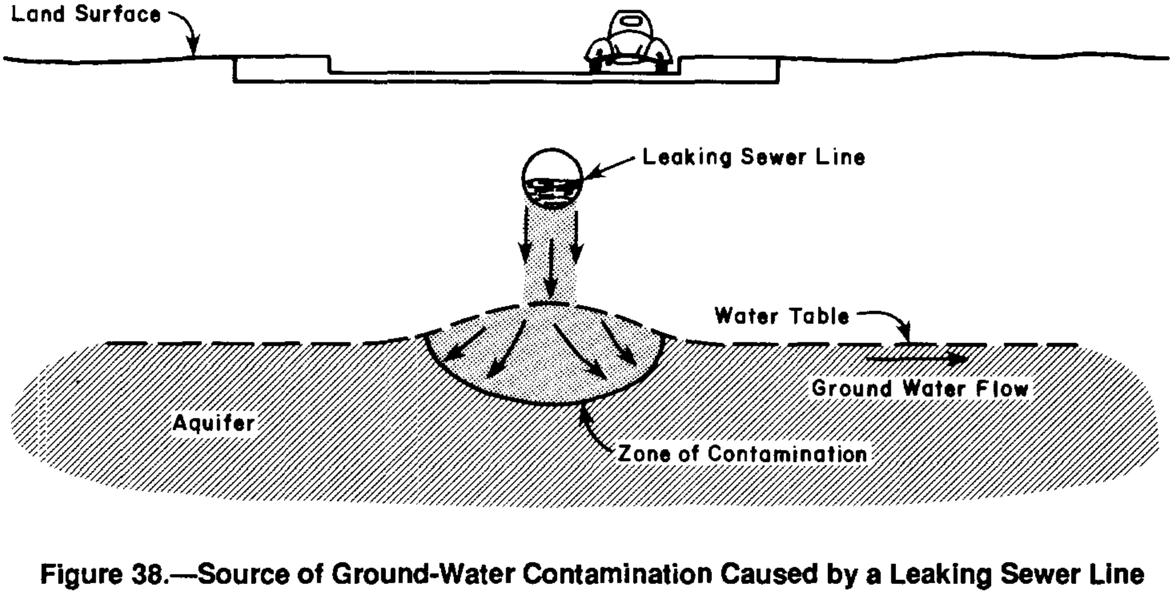


Figure 38.—Source of Ground-Water Contamination Caused by a Leaking Sewer Line (U.S. Environmental Protection Agency, 1977)

partment of Health, personal communication, 1987). Therefore, it is the more arid parts of the state (West Texas) which are of greatest concern.

Assuming a worst case scenario, the following amounts of exfiltration could be infiltrating the aquifers of Texas:

Total amount of waste water generated per day (gallons) (Rose, TWDB, written communication, 1987)	1.80314×10^9
Urban population (1980 TWDB data)	11,148,647
Average infiltration per day (Salgado, Texas Department of Health, personal communication, 1987)	80 gal/da/capita

Then:

$$\frac{1.80314 \times 10^9 \text{ gpd}}{11{,}148{,}647 \text{ people}} = 162 \text{ gpd/c total waste generated}$$

Then:

162 gpd/c	Waste generated + infiltration
- 80 gpd/c	Infiltration
82 gpd/c	Estimated dry weather flow

82 gpd/c x .1=8.2 gpd/c Estimated exfiltration

8.2 gpd/c x 11,148,647 people= 91.4×10^6 gal/day exfiltration from lines

$$\frac{91.4 \times 10^6 \text{ gpd}}{42{,}230 \text{ mi of line}} = 2165 \text{ gpd/mi of line during dry weather flow}$$

In the past, incorporated cities and towns individually were responsible for overseeing their municipal sewage collection lines. They were required to dispose of human wastes through methods approved by the TDH. Following the passage of House Bill 1326, effective September 1, 1987, all municipal engineering plans and specifications must now be approved by the TWC. This includes municipal sewage collection lines. These new installations must now conform to general statewide Commission Rules 31 TAC 317. Older lines are still subject to local oversight; however, Chapter 26 of the Texas Water Code gives the TWC the authority to abate the pollution of local ground waters. For older facilities, cities may either increase plant capacity or improve collection lines to comply with TWC directives to cease polluting. When a city comes under enforcement for violations of its waste-water permit, the collection system and its problems are considered along with other factors when corrective actions are developed.

Since June, 1981, the TWC "Design Criteria for Sewerage Systems" limits the allowable amount of exfiltration in new sewers not to exceed 200 gallons per inch diameter per mile per 24 hours with a test head of two feet. Sewage collection lines properly installed since 1981 may be considered to be virtually water tight. It can be expected that as cities expand in size, leaking sewers installed prior to 1981 will be rehabilitated or replaced with collection systems constructed of superior pipe materials. (Salgado, Texas Department of Health, written communication, 1987).

Disposal of Municipal and Industrial Waste-Water Treatment Plant Sludges

Sewage, also referred to as waste water, is derived from the wastes of communities or from those generated by industries. Domestic waste waters originate primarily, from the many sinks, bathtubs, toilets, dishwashers, washing machines, and drains of individual homes. Various industries connected to a sewage treatment plant's collection system, also contribute a variety of wastes. Sewage is over 99 percent water.

Solids removed from waste waters as it moves through a treatment facility are referred to as **sludges**. These debris accumulate on screens and in settling chambers as waste water is processed through the system (Texas Department of Water Resources, 1981). These sludges may be derived from either municipal treatment plants or they may be derived from industrial facilities. The treated waste waters which remain as an end product are known as **effluent**.

Previous topics entitled, "Municipal Sewage Collection Lines" and "Surface Waste-Water Impoundments" also discussed the impacts of sewage and waste waters on ground water. Additionally, the subchapter titled, "Stormwater Runoff" includes the mechanisms for controlling potential contaminant runoff from industrial and other sources. Discussions presented here are primarily concerned with the effects of the disposal of sludges on ground water.

Potential contaminants of these wastes commonly include nitrogen, phosphorous, heavy metals, hydrocarbons, microorganisms, and radionuclides (U.S. Environmental Protection Agency, 1987a).

Several of the more common pollutants such as microorganisms, phosphates, and BOD remain near the application area and are of less concern. As these waters pass through the soil, bacterial and viruses usually die off quite rapidly. Present evidence indicates that it is the mobile pollutants such as nitrates, which are of greatest concern (Novotny and Chesters, 1981). Table 6 lists various industries and their probable contaminants.

Municipal and industrial sludge may be disposed of at a landfill or a lagoon, incinerated, spread on land, or composted. The suitability of the disposal option will vary considerably from place to place. Lagoons have limited utility unless ample space and favorable conditions for evapotranspiration are present. Incinerators may face problems of air quality emissions standards as well as with the disposal of heavy metals remaining in the ash. Land spreading and composting suffer from uncertainty about government regulations restricting the use of sludge on lands that may produce food-chain crops. Composting options are also complex because reliable, long-term markets for the compost must be found (Texas Department of Water Resources, 1981).

Sludge management usually involves its conveyance to a landfill, either as a place for disposal or as a reserve facility for resource recovery. Disposal at landfills and land spreading are the most common disposal methods for sludge. Landfill owners and operators may not be willing to accept sludge because it requires special accommodations (to deal with the high water content, meet the needs of sludge trucks, etc.). Texas Department of Health regulations require that only sludges containing 10-100 percent solids may be accepted at municipal landfill facilities (Texas Department of Water Resources, 1981).

If sludge is not contaminated, it is valuable as a soil amendment. Contamination may be caused by pathogens, persistent organic compounds (pesticides and solvents) or trace inorganics (including heavy metals and trace elements).

Land systems, primarily surface impoundments, for both municipal and industrial waste-water disposal have been used on a small scale since the inception of water collection systems. However, in this activity, the major emphasis has been placed on disposal only. With the adoption of a federal "no pollution discharge" policy, interest increased in land disposal of liquid wastes. Typical liquids now disposed of are waste-water sewage effluents, sewage sludge, animal and feedlot wastes, and industrial wastes. For the most part, wastes generated by these varied activities are nonhazardous. However, industry contributes both hazardous and nonhazardous wastes. Even though the soil has a great capacity for the attenuation of contaminants, the resulting ground water found below these disposal areas undergoes changes, some of which are undesirable.

Many of the same problems associated with land disposal of waste water are similar to those discussed in more detail in the section titled, "Private On-Site Sewage Disposal Systems"; however, it must be noted that in the instances now being discussed, that much greater volumes of wastes are concentrated within a relatively confined area.

In 1970, more than 5000 of the existing 22,000 waste-water treatment plants in the nation had stabilization ponds. These ponds were seldom lined and almost never monitored by wells. At that time, more than two billion gallons per day of sewage treatment plant effluent discharged to the land did not meet secondary treatment standards (Miller, 1980).

It is estimated that slightly over 70 percent of disposal facilities for municipal, industrial, and agricultural operations are surface impoundments. These are usually man-made holding areas such as lagoons and ponds; however, they may include modified playa lakes in the High Plains area of West Texas.

Surface impoundments are used for both waste-water storage and sludge disposal. However, most municipal sludge is trucked to a landfill for disposition. Treatment of waste water in these facilities is accomplished in several ways: chemical coagulation and precipitation, pH adjustment, biological oxidation, separation of suspended solids, and temperature reduction. Some facilities discharge their "treated" liquid wastes into nearby surface water bodies. This may occur continuously or periodically. Liquid loss from nondischarging impoundments is accomplished through subsurface seepage or evaporation (U.S. Environmental Protection Agency, 1987a).

A 1986 EPA study reported that there were about 192,000 of these surface impoundments nationwide. Various types of facilities with their respective percentage shown in parentheses were: industrial (8), municipal (1.2), agricultural (9), mining (10), oil and gas related (65), and others (6.8). Additionally, approximately 400 known hazardous waste facilities nationwide have about 3200 surface-water impoundments which are used for treatment, storage, and disposal of waste water (U.S. Environmental Protection Agency, 1987a).

Livestock waste treatment lagoons and holding ponds are also used to collect and dispose of runoff from concentrated livestock feeding operations. These are located primarily, in the High Plains of West Texas. However, they are also found at scattered areas around the state. Clay liners are required for these facilities to reduce the possibility of percolation of waste to the ground-water system.

Surface impoundments are considered to be one of the greatest threats to ground water, based on the volumes of waste involved. Nationwide, about 37 percent of these are located over aquifers used as sources of drinking water. Additionally, about 70 percent of the known impoundments are located over hydrologically vulnerable areas (Plates 1 and 2) (U.S. Environmental Protection Agency, 1987a). Geographically, these surface waste-water impoundments are scattered throughout the United States. The same holds true within Texas. Of the states with the highest number of these nonhazardous facilities, Texas ranks eighth nationwide (U.S. Environmental Protection Agency, 1987a).

Many municipalities, industrial operations, concentrated feedlots, and rural farms dispose of their wastes using land treatment methods. Additionally, some radioactive uranium wastes are disposed of by this method.

Land treatment is a waste management method in which waste materials are incorporated into the soil or applied to the land surface. Waste materials are usually sludges or slurries derived from waste waters. This practice utilizes the physical, chemical, and biological abilities of the plant-soil system to serve as the ultimate receiver of the wastes. During these operations, wastes are generally applied in thin layers using common farming techniques such as tilling, contour plowing, and erosion control. In some cases, fertilizers (nitrogen and phosphorus) may also be added to enhance microbial degradation of organic waste constituents (Texas Department of Water Resources, 1981).

The EPA (1984e) reported that about 25 percent of all municipal sludge generated, nationwide, was disposed of by some form of land application. About eight percent of all publicly owned treatment facilities were applying sludges of various concentrations to the land. Other industrial operations were also disposing of hazardous and nonhazardous liquid wastes through this same method.

EPA (1987a) reported that, nationwide, at least 2464 publicly-owned treatment works presently are applying thickened or liquid sludge to the land. Additionally, of the over seven million dry tons of sludge produced by these treatment plants, over 20 percent is now being applied directly to the land. Data are lacking on industrial sludge.

In 1986, EPA further estimated that the nationwide total number of nonhazardous land application units was about 19,900. A breakdown follows: 11,937 municipal; 5605 industrial; 726 were oil and gas related; and 621 were other facilities (U.S. Environmental Protection Agency, 1987a).

About 0.4 million metric tons of hazardous wastes were disposed of by land application methods during 1981, by about 70 land spreading operations (Westat Incorporated, 1984). The number of systems spreading hazardous waste had increased to 200 by the year 1983. At that time, there were also over 1000 nonhazardous facilities spreading their wastes over cropland (National Research Council, 1983). During 1985, farmers were estimated to have land disposed of about 159 metric tons of manure nationwide (U.S. Department of Agriculture, 1986).

Larger concentrated animal feeding operations within Texas apply both livestock manure and waste water to the land. Application rates to soils must be matched to expected plant uptake of nutrients and crop yield goals to assure that ground-water contamination does not occur. With the proper application rates, crop yields equal to or exceeding the yields with commercial fertilizers, have been realized. Additionally, following application of manure nutrients, yields are often sustained several years longer than with commercial fertilizer. This is due to the slower release of nutrients and micronutrients (Sweeten, 1988).

In many areas of the state, agricultural soil has low nitrogen and micronutrient status and benefits from manure application. However, nitrogen and phosphorus accumulate in the root zone following manure applications, which greatly exceed nutrient requirements. These buildups can be subject to leaching to ground water with time. To assess this possibility, annual soil/water/plant testing to guide fertilization application rates should be made (Sweeten, 1988).

The most promising approaches to land spreading are generally grouped into three main categories: 1) infiltrating-percolation, 2) cropland irrigation, and 3) spray-runoff (Scalf and others, 1973).

Systems using the infiltration-percolation approach have been used for many years. Operations using this method are designed for high hydraulic rates which necessitates rapidly permeable soils and length of drying and wetting periods which greatly influence the treatment efficiency, especially nitrogen removal. The filtering and ion-exchange action of the soil determines the treatment efficiency of the systems. Since most of the waste water percolates to ground water, the effect on ground water quality can be significant. These systems are not in general use within the state except for the widely used septic tanks which may constitute a significant ground-water problem (Scalf and others, 1973).

Cropland irrigation is a well established practice which is used both for an additional water source as well as a waste-management approach. Scalf and others (1973) reported that since the beginning of this century, many municipalities in Texas have practiced cropland irrigation disposal of wastes. Some of these cities were recorded to have had these operations in existence for 70 to 80 years, prior to 1965. Known cities which use sewage effluent for land application practices for cropland, parks, golf courses, and cemeteries are Abilene, Amarillo, Lubbock, and San Antonio. Undoubtedly, there are many more.

Lubbock, Texas has used municipal effluent for cropland irrigation since the 1930s in the Buffalo Springs-Ransom Canyon Lake area of Lubbock County. A recently completed study by Russell and others (1988), documented definite changes in the ground-water chemistry underlying this area. A plume or ridge of high nitrate concentration has been confirmed south and east of the effluent storage lagoons, on the property. Nitrates as nitrogen ($N0_3$- N), found in ground water, ranged from 3.45 to 33.59 mg/L underlying the operation. In addition to high nitrates, chlorides ranged from 68 to 633 mg/L and total dissolved solids ranged from 532 to 1914 mg/L. The study also suggests that sources other than municipal effluent also may contribute to the contamination. Other suggested sources of pollution were septic systems and back flowing effluent to ground water through abandoned wells.

Figures 48A through 48C show the location of concentrated animal feeding operations within the state, many of which use cropland irrigation for waste disposal. Ground-water analyses collected underlying 80 of the cattle feedlots in the Texas High Plains area determined that about one-fourth of the feedlots contributed to increased nitrate levels which approached or exceeded EPA's drinking water standards of 10 mg/L in their immediate vicinity. New TWC regulations enacted in 1987, place rigid requirements on confined, concentrated livestock and poultry feeding operations by requiring that all lagoons and holding ponds be constructed so as to prevent potential ground-water pollution. Feedlots which have been abandoned without manure removal may offer greater potential for ground-water contamination than active feedlots (Sweeten, 1988).

A relatively recent approach to land disposal is spray-runoff. This method of disposal has been found to be very applicable to industrial wastes. Tight soils are most suitable for this technique, since more than one-half of the applied waste water returns to surface water as controlled runoff. Efficiencies of treatment depend on the biological, chemical, and physical processes which take place as liquid moves slowly along the soil surface (Scalf and others, 1973).

Since most of the applied waste water runs off the surface and additional waters are lost due to evaporation, this technique of land application probably has the least effect on ground water, since the quality of water which reaches the potentiometric surface is of good quality. An excellent example of an operation employing the spray-runoff technique is at the Campbell Soup Company of Paris, Texas. This operation applies about three million gallons of cannery waste water per day to about 300 acres without any detectable deterioration of ground-water quality (Scalf and others, 1973).

The limiting factor in almost all of the above land application soil systems appears to be nitrogen concentrations present within waste-water effluents.

Land treatment requires careful planning and management to avoid impacts on the environment since the rate that the plant-soil systems can assimilate waste materials varies considerably. When used properly land application can provide a safe treatment method, it can add nutrients to the soil, and return good quality water to ground-water systems underlying these operations (U.S. Environmental Protection Agency, 1984e).

Leaks and Spills

Leaking Underground Storage Tanks

Included under this topic are all underground storage tanks (USTs) and their associated piping systems, which are used to store not only petroleum products, but a wide range of other products such as acids, metals, industrial solvents, technical grade chemicals, and their wastes. Due to the regional distribution of these tanks, the estimated number of leaking USTs, and the fact that they can place a significant loading on the ground-water aquifer systems, these tanks are considered to be one of the most significant sources of ground-water contamination within the state.

Underground storage tanks sometimes lie within the saturated zone (Figure 39). This causes continually saturated conditions to exist in shallow deposits below the tanks. Therefore, when these leak, high concentrations of contaminants may occur. Common potential pollutants of ground water resulting from leakage are organics (hydrocarbons), metallic substances, inorganic acids, microorganisms, and radionuclides. To date, most confirmed leaking underground storage tanks within the state are leaking gasoline, diesel, number two fuel oil, naptha, acetic acid, mixed solvents, xylene, toluene, used motor oil, hydraulic oil, and methyl ethyl ketone.

As of July 12, 1988, there were 117 counties (46 percent) of the state which had confirmed leaking underground storage tanks. The total number of confirmed leaking USTs on this date was 954. The statewide distribution of these is shown on Figure 40. These leakers have impacted or have the potential to impact all of the major aquifers. Additionally, leaking tanks have been confirmed in counties of the state which do not have either a major or minor aquifer; however, they may impact localized alluvial or other small water-bearing units. Ultimately, these tanks will probably impact all aquifers of the state as well as every county. The extent of underground tanks within Texas is widespread. They are present in every county of the state and are concentrated in population centers (Figure 37).

A total of 123,000 tanks had been registered with the TWC by July 19, 1988. These tanks are located at about 45,800 separate facilities. Ultimately, there are estimated to be about 154,000 total tanks. The Commission is receiving notice of confirmed leaking tanks at an average rate of 62 per month. The U. S. Environmental Protection Agency (1988c) conservatively estimates that at least 25 percent of the total number of underground storage tanks will ultimately be confirmed as leakers. If this is true, then about 38,500 of the estimated total tanks have a reasonable probability of leaking. The National Fire Prevention Association (NFPA No. 329) requires that precision tank testing be capable of detecting a leak rate of at least 0.05 gallons per hour. The leak rate of 0.05 gallon per hour equals 1.2 gallons per day, which is a yearly total of 438 gallons. For the purposes of this analyses, it is assumed that each leaker will leak an average of at least 500 gallons per year before a leak is detected. If this is indeed realistic, then the potential minimum loading to all of the aquifers of the state would be on the order of 38,500 times 500 or about 19 million gallons of contaminants, annually.

Texas Water Commission personnel are presently actively mitigating these problems. Since August 1986, 143 cases have been resolved.

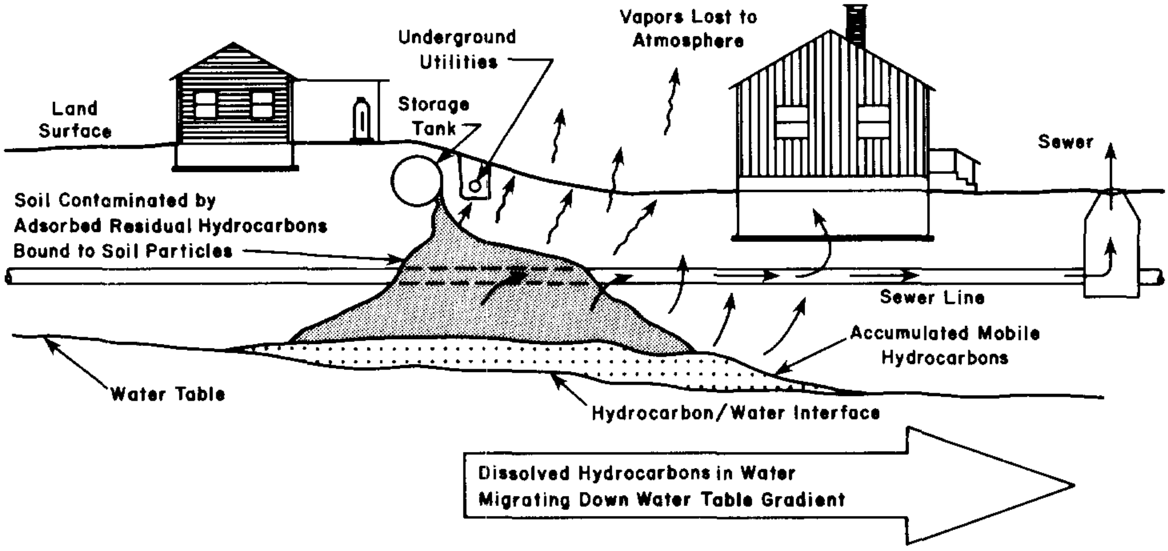


Figure 39.—Common Occurances, Avenues of Hydrocarbon Migration, and Reduction Following the Leak of an Underground Storage Tank (After Yaniga, P. M., 1986)

On April 17, 1987, the EPA published proposed federal Underground Storage Tank rules covering design, construction, installation, and compatibility standards for new tank systems as well as requirements applicable to all tank owners concerning leak detection, recordkeeping, reporting, closure, corrective action, and financial responsibility. These proposed federal rules were finalized in September, 1988.

The Commission's Storage Tank Program was authorized by Senate Bill 779 (70th Legislature) which added a new Subchapter I to Chapter 26 of the Texas Water Code. The TWC promulgated initial UST rules in September 1987 to be followed with comprehensive rules later. These rules are codified in Chapter 334 of 31 TAC of the Texas Water Code. The directives address UST registration and notification requirements and general construction and installation performance standards. A regulatory program pertaining to UST installations located within the Edwards (Balcones Fault Zone) aquifer recharge and transition zones is found in 31 TAC Chapter 313. These requirements specify new USTs to be of double-wall or equivalent construction with interstitial monitoring.

Existing TWC regulations are planned to be supplemented with comprehensive UST regulations which should become effective in the spring of 1989. These will address the areas of: 1) design, construction, and installation of new USTs; 2) operation, maintenance, and record keeping; 3) upgrading of existing USTs to provide for release detection, overfill protection, and corrosion protection; 4) reporting of releases and corrective action requirements; and 5) closure and abandonment of out-of-service USTs.

Leaking Surface-Storage Tanks

To date, there is little evidence that Texas has devoted much attention to above-ground storage facilities. These vessels are stationary devices designed to store accumulations of waste and nonwaste materials. They are primarily used for storage of various chemicals generated and/or used in industrial, agricultural, or commercial operations. Additionally, they include those tanks located at private facilities (U.S. Environmental Protection Agency, 1987a).

Available data do not indicate that there has been a nationwide or statewide assessment made of the total number of these tanks nor the potential threat they may pose to ground water. The mechanism is now in place within the state for reporting the frequency and amounts of leaks and spills resulting from these tanks (Emergency Spill Response Program). These vessels can leak and cause the pollution of ground water if they are not properly installed, maintained, and operated.

Releases from surface-storage tanks usually result from spills, overflows, operator errors, or leaks. The U.S. Environmental Protection Agency (1987a) reports that expected potential contaminants from these vessels are organics, metal/nonmetallic inorganic, inorganic acids, microorganisms, and radionuclides.

These tanks are normally constructed of welded or bolted carbon steel or stainless steel, fiberglass, plastic, reinforced plastic, or concrete. Carbon steel tanks, which are probably the most common type in use, are more likely to corrode than fiberglass, but may be coated to protect them from most chemicals. Therefore, their structural strength makes them the preferred type for most purposes. Fiberglass tanks are primarily used for the storage of acids. For safety reasons, many tanks used for the storage of flammable liquids are placed below ground surface.

Above-ground tanks within Texas are used primarily for bulk storage of crude oil and petroleum products. The largest of these can contain as much as one million gallons. Large numbers of these, which are referred to as "tank farms", are often concentrated at petroleum off-loading facilities and are also used for the storage of petroleum at refineries. Additionally, anywhere from three to six of these tanks may be located at each of the hydrocarbon producing leases which are scattered throughout the state. Numerous other tanks are located at other private facilities.

In the absence of a reporting system, a reliable statewide estimate of the number of these tanks is difficult to obtain. However, some information has been assembled which enables one to make a rough estimate.

In 1987, a spokesman for the American Petroleum Institute stated that there was an estimated 984 million barrels (40 billion gallons) of major petroleum products (gasoline and fuel oil) located in storage facilities throughout the nation. It was further estimated that another 10 billion gallons of other petroleum allied products were also stored in above-ground tanks. During 1983, Texas refineries alone had crude oil capacities of about 4.1 billion barrels (Kingston and Crawford, 1987).

Additionally, the state of New York estimated that about 30 percent of its total storage tanks were above-ground tanks (State of New York, Department of Environmental Conservation, 1985). Assuming that this figure was representative of the national average and based on the API data, it estimated that as many as one million of these tanks may exist nationwide. In early 1986, EPA estimated that from 42,000 to 47,000 of the above-surface tanks which were regulated by RCRA, contained hazardous materials. At that time, they postulated that about 24,000 tanks contained used oil (U.S. Environmental Protection Agency, 1986e).

Based on the number of underground storage tanks reported within the state to date, it has been projected that there should ultimately be a total of about 154,000 located and registered tanks statewide (Jameson, Texas Water Commission, personal communication, 1988). If this is an accurate estimate, and if it represents 70 percent of the total tanks, as in the case of New York State, then a conservative estimate of the total number of above-ground tanks present in Texas would be about 66,000. These tanks should be located in every county of the state; however, there should be greater concentrations of these in areas where hydrocarbon refineries are located. Plate 3 shows the locations of hydrocarbon producing areas where large numbers of these should also be present.

There are a variety of ways in which tanks could cause ground-water problems. These include leaks, primarily from those resting directly on the ground. Older tanks of this type may corrode with time, and leak their contents to ground water. Other spills which may also occur are from leaks from pipe joints, valves, and those which may occur during loading and unloading operations. Future limited leaks of residual materials may also occur when these tanks are improperly abandoned.

Surface-tank leaks can be reduced or prevented by employing some or all of the following practices. Tanks should be constructed of noncorrodible materials and be placed on impermeable surfaces or raised above ground, if possible. Systems should also be developed to prevent or capture spilled materials. This may include the construction of containment berms around the facilities and programs for immediate and thorough cleanup of spills to prevent ground-water contamination. Additionally, possible leaks may be monitored by periodic inventory of stocks.

Even though there have undoubtedly been numerous instances of ground-water contamination which have resulted from leaks or spills from these tanks, documented data are not now readily available. In other areas of the nation, pollution resulting from these tanks has been confirmed. Available data indicate that further evaluation of this possible ground-water problem is merited.

Above-ground storage tanks containing hazardous wastes are federally regulated under Subtitle C of the Resource Conservation and Recovery Act (RCRA). Recently revised federal standards for treatment of hazardous waste in tanks or storage in above-surface tanks are designed to protect ground water (51 CFR 25422). Senate Bill 2020, the Above-ground Storage Prevention Act of 1988, is also federal legislation which is designed to prevent environmental catastrophes. This bill requires the EPA to promulgate national requirements concerning these tanks. It applies specifically to those tanks which posed a risk of catastrophic failure, such as rupture or collapse. Such tanks have the capacity to contain at least one million gallons of petroleum and are at least 30 years old, or have been relocated, or reconstructed (Tank Talk, 1988).

At present, many surface-storage tanks are under the regulatory authority of the RCT. Numerous surface-storage tanks are used in connection with energy development activities. The Railroad Commission regulates above-ground storage tanks used for the storage of produced hydrocarbon products. Many of these are "tank batteries" which are located on the numerous oil and gas producing leases situated in 231 of the 254 counties of the state. Specific regulations are found in Chapters 91 and 141 of the Texas Natural Resources Code.

Federal and state programs, administered by the TWC, that are applicable to the regulation of surface-storage tanks used for the storage of hazardous products follow.

Tanks which are located on the Edwards (Balcones Fault Zone) aquifer are subject to specific rules and special requirements are imposed on the storage of hazardous substances and static hydrocarbons. State regulations specifically applicable are found in Chapter 26 of the Texas Water Code and in rules set out in Title 31 TAC Chapter 313.

The Commission has received authorization from EPA to administer its hazardous waste program in lieu of the federal program. When hazardous materials or wastes are stored in these tanks, they are regulated by the TWC. Commission rules related to tanks were adapted from 40 CFR 264, Subpart J. The TWC permits only above-ground tanks used for hazardous waste. Tanks are regulated by the Texas Solid Waste Disposal Act (Article 4477-7, V.T.C.S.) by specific Commission rules set out in Title 31 TAC Chapter 335. Chapter 26 of the Texas Water Code designates the Commission as the lead agency for emergency spill response to direct cleanup if accidental spills of hazardous waste occur associated with these tanks. Surface-storage tanks used to store nonhazardous materials remain unregulated.

Transportation Related Activities

The two major topics considered under this subsection are "Oil and Chemical Spills" and "Midnight Dumping." Activities pertinent to ground water are related to material transport operations by highway vehicles or railcars. These operations involve the movement of various nonhazadous and hazardous substances, including oil and hazardous wastes. Also included are pipelines which collect, transport, and distribute hazardous substances.

Data which follow may be useful in the assessment of the potential risk to the state's aquifers related to the subject topics. Texas presently has 250,000 miles of municipal and rural highways. In 1980, the total railroad mileage was 12,753. In 1985, there was a total of 202,623 miles of hydrocarbon pipelines in Texas. Of this, 72,615 miles were used for the movement of crude oil and 130,008 miles were used to transport natural gas (McBride, Bureau of Economic Geology, personal communication, 1988). A total of 853,981 barrels of oil were transported by pipelines and 14,243 barrels were transported by railway tank cars and trucks during 1982. Other commodities transported by rail during 1981, which could impact ground waters, were as follows (Kingston and Harris, 1983):

Commodity	Total Tonnage
Chemicals and allied products	33,315,465
Nonmetallic minerals	32,887,325
Petroleum and coal products	12,081,052
Metallic ores	1,943,377

Oil and Chemical Spills

The principal concern from materials transported by highway vehicles or railcars is the spill of fluids which may result in contamination of ground water. Also of concern are potential ground-water pollution spills which do not result in prompt cleanup or in cases where cleanup is inadequate. These events pose a risk to ground water in many areas of the state. Crude oil and gasoline spills, due to accidental breaks of transmission lines or vehicle tank ruptures, are also a serious problem.

Within the state, these sources have, in the past, been considered a more serious threat to surface water than to ground water. This is not necessarily true. However, transportation related spills receive more attention regarding potential impact to surface waters principally because the effects are so readily apparent when an incident occurs (Barker, Texas Water Commission, written communication, 1987).

Substances spilled on the land surface can be a serious threat if surface and subsurface materials are sufficiently permeable to permit downward movement. Many spill pollutants may migrate through the unsaturated zone to the water table. If these fluids are less dense than ground water, they will float on top of ground water (Figure 41). Typical contaminants of this type are petroleum and other hydrocarbon products. Other contaminants may be miscible with water. These may pollute the entire thickness of the aquifer in the immediate vicinity of the spill. If the contaminant is denser than water, it may sink to the base of the aquifer. In all cases, they form a plume which will move down gradient to a point of discharge.

Only five documented accidental spills of gasoline were gathered during this assessment which are suspected or known to have polluted ground water. These spills occurred in Burnet, Gray, Hays, Llano, and Travis Counties. The Burnet County spill is believed to have possibly impacted the Trinity Group, Marble Falls and/or the Hickory aquifers; the Gray County spill is thought to have impacted the High Plains (Ogallala) aquifer; Hays and Travis Counties spills are thought to have possibly impacted the Edwards (Balcones Fault Zone) aquifer; and the Llano County spill is not believed to have impacted a major or minor aquifer.

Midnight Dumping

Midnight dumping addresses illegal dumping by haulers of saltwater, septic tank wastes, nonhazardous municipal sludges and similar wastes, and hazardous materials (either products or wastes). Generally, pollution resulting from these hauling activities includes tank valve leaks, accidents, and illegal dumping. Commonly, illegal dumping is reported to be the decision of the hired driver and not the fleet owner. Operators have the responsibility to inform their employees of the consequences of illegal dumping. Penalties and remedies specified in Chap-

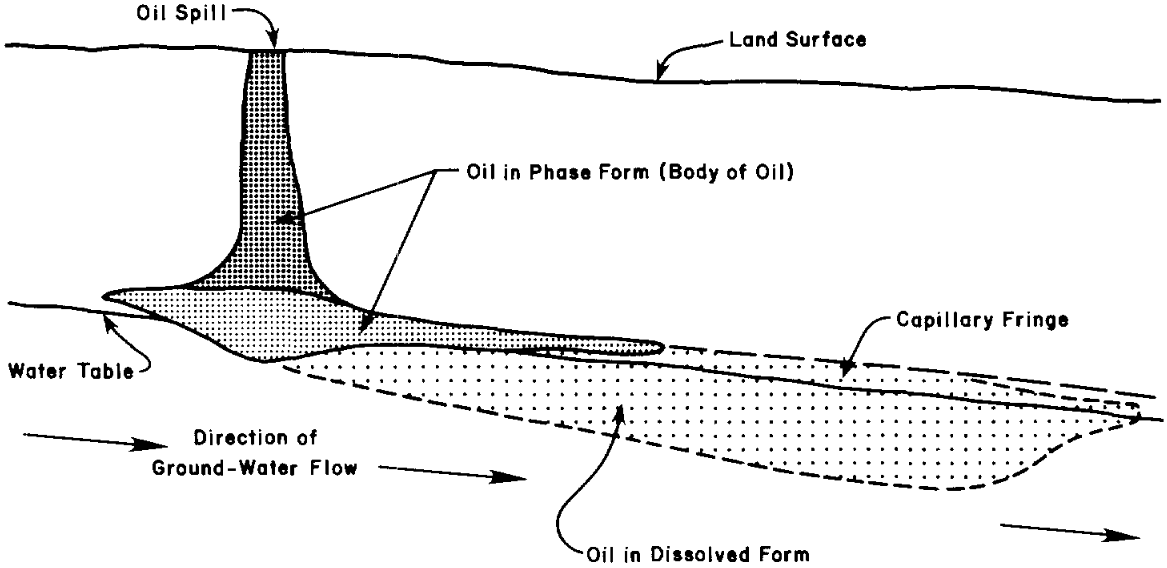


Figure 41.—Movement of Light-Density Fluid in the Ground-Water System. Contamination Caused by a Spill of Hydrocarbons (Miller, J.C., and Others, 1977; After Water and Petroleum Study Group, 1970)

ter 26 of the Texas Water Code and other statutes administered by the TWC, RCT, and TDH are the major deterrents to illegal dumping.

Prompt containment and removal of midnight dumping materials are necessary to prevent a risk of ground-water contamination in areas of permeable soils, resulting from downward percolation of various materials.

Available data do not confirm any cases of actual ground-water pollution attributable to the subcategory of Midnight Dumping; however, numerous reports of the practice of "saltwater dumping" have been found related to oil and gas activities. As more data becomes available, this subcategory may be confirmed as a problem. This is a known source of contamination of surface waters.

Statewide Distribution of Chemical Spills and Midnight Dumping

There are many instances where spills or midnight dumping are known to have polluted surface water; however, the number of suspected, but yet unconfirmed cases of ground-water contamination is unknown (Barker, Texas Water Commission, written communication, 1987.)

During the fiscal year 1987, the TWC investigated 1176 (about 74 percent) of the more serious of a total of 1592 known spill or midnight dumping incidents. Other participating state agencies and/or local entities supervised cleanup of the remaining spills. Figure 42 illustrates the magnitude and distribution of these statewide.

It is the stated policy of the state to "prevent the spill or discharge of hazardous substances into the waters in the state and to cause the removal of such spills and discharges without undue delay." The TWC has been designated as lead agency for the program under Subchapter G, Chapter 26 of the Texas Water Code. Further, Subsection 8(b) of the Solid Waste Disposal Act, Article 4477-78, Revised Civil Statutes, provides authority to obtain criminal penalties against any person who knowingly transports, or causes to be transported for storage, processing, or disposal, any hazardous waste to any location which does not have a permit. Therefore, the state has ample authority to address and abate accidental spills. Midnight dumping incidents are also expressly prohibited under state law, and the TWC has authority to act to cause the clean up of the dumped material.

In addition to the TWC, primary agencies and entities involved in spill response are: Railroad Commission of Texas, Texas Parks and Wildlife Department, Texas Department of Health, Texas Air Control Board, Texas Department of Highways and Public Transportation, Texas Department of Agriculture, Office of the Attorney General, General Land Office, Department of Public Safety (Division of Emergency Management), State Fire Marshall, Texas A&M University - Engineering Extension Service, local governments, federal agencies, and other local entities.

Statewide Rule 8 of the RCT regulates the transportation for hire of saltwater off a lease, unit, or other oil or gas producing property by any method other than by pipeline. Saltwater haulers must be permitted. Crude oil spills and pipeline breaks are caused by accidents such as punctures of pipelines by construction equipment, collisions involving tank trucks, or train derailments. Crude oil spills must be reported to the RCT under statewide Rule 20. Responses to crude oil spills that occur during transportation are handled in accordance with the "State of Texas Oil and Hazardous Substances Spill Contingency Plan." Data are not readily available to pinpoint specific oil spills and pipeline breaks.

Rules pertaining to the transportation of nonhazardous municipal sludges and similar wastes were promulgated by the TDH under the authority granted it by the Solid Waste Disposal Act, Article 4477-7, Vernon's Texas Civil Statutes. These rules require transporters to register with the TDH and to operate in accordance with minimum standards.

Oil, Gas, and Mining Activities

This subchapter assesses potential and/or actual ground-water contamination associated with the production of hydrocarbons as well as possible pollution problems related to the mining of ores and minerals; primarily those surface-mining operations connected with strip mining of lignite.

Oil and Gas Activities

In 1866, Lyne T. Barret drilled and completed the first commercial oil well in Texas at Melrose in Nacogdoches County (Kingston and Crawford, 1987). Most of Texas' subsequent hydrocarbon development occurred during the first part of this century. Initially, large volumes of hydrocarbons were produced, followed by a period of declining well yields. Presently, many of the older fields produce small amounts of oil and/or gas and enormous amounts of brine.

Brine, as used in the following discussion, refers to saline ground waters, usually high in total dissolved solids (normally 50,000 ppm average chloride), which are associated with oil and/or gas below ground. Large volumes of brine often flow or are pumped to the surface when hydrocarbons are produced. It is this produced brine which is one of the principal pollutants of the state's aquifers. The amount of saline water produced by an individual well varies greatly depending on its field location, the geologic unit from which it produces, and, normally, the age of the well. Many wells may yield a small amount of brine at first, and this may increase with time. Other wells yield large quantities of saline water initially. Wells usually produce more brine with age.

In the early years of the state's hydrocarbon production history, brine disposal was uncontrolled. It was usually discharged directly into gullies and/or to streams. Later, the accepted practice of disposal into evaporation pits came into use.

Initially, shallow unlined surface disposal pits were constructed and salt water was pumped directly into them for evaporation (Figure 27). Later, some of these pits were lined to reduce the possibility of brine seepage to ground water. Originally, it was thought that all of the salts would be lost to the atmosphere. However, it was later found that only fresh-water vapor was lost through evaporation and that the salts and minerals remained. When the pits were located in areas where the soil was permeable, brine seepage from these pits, with time, may have reached the water table and may have contaminated ground water immediately below these pits.

Often, overflow resulted when excessive amounts of brine were pumped into the pits or their capacity was exceeded during heavy rainfall. This resulted in uncontrolled discharges which had the potential to contaminate surface waters as well as possibly ground waters (Figure 43).

The practice of brine disposal into evaporation pits was halted by the RCT by a statewide no-pit order which became effective on January 1, 1969. With the advent of the no-pit order, brines were then disposed of in special injection wells constructed specifically for that purpose or reinjected into producing zones during water-flooding operations. (Under special circumstances, some pits are still authorized.) These wells are very expensive and occasionally several operators will join together in constructing a disposal well. If the well is located some distance from a producing lease, then the brine must be trucked. During this time, there are dangers of accidental spills and/or midnight dumping incidents. At times, in an effort to reduce costs, dry holes located on producing leases may be converted to brine disposal wells.

When injecting brines into deep saline water-bearing zones, care must be taken to insure that there is no hydraulic connection created between the injected zone and a fresh-water zone. If injection pressures are high,large volumes of brines are to be disposed of, and poor completion techniques have been employed, the poor quality water can be forced

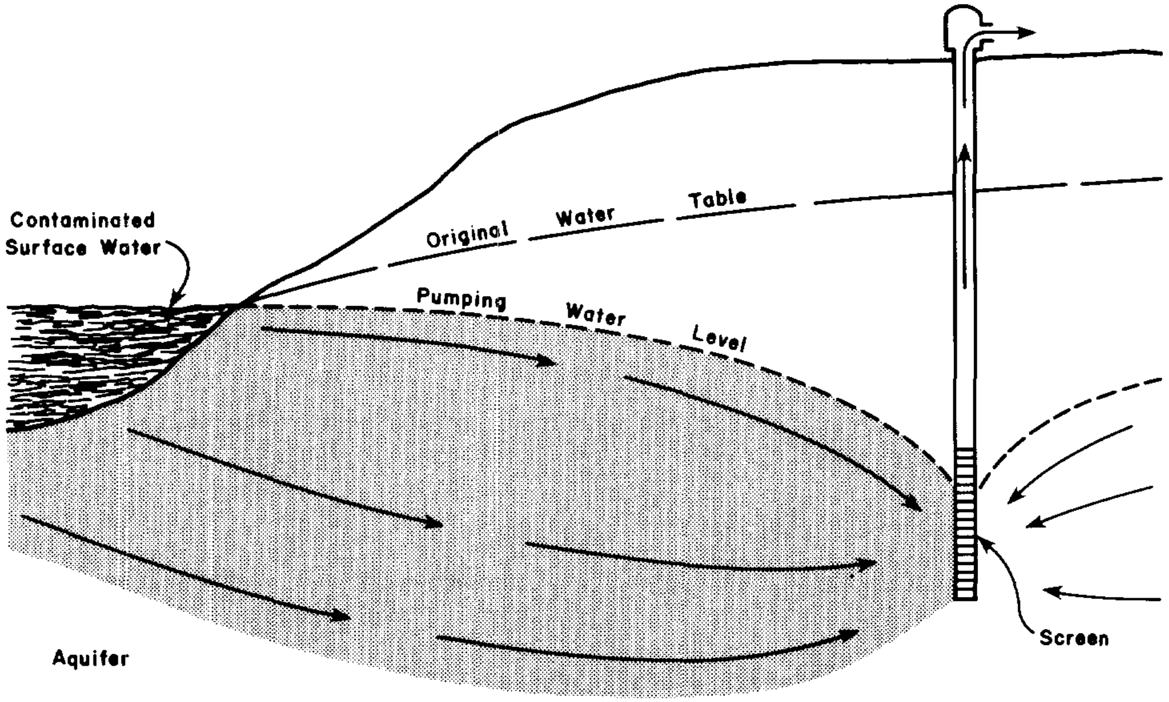


Figure 43.—Induced Infiltration of Contaminated Surface Water (U.S. Environmental Protection Agency, 1977; After Deutsch, 1963)

upward into fresh-water zones (Miller, 1980). Care must also be exercised to prevent extremely high injection pressures from unintentionally fracturing the injection zone, thus creating vertical avenues for brine movement to fresh-water zones.

Brines are highly corrosive and well casings often have to be coated with plastic or inert material to prevent rapid casing material deterioration. It is estimated that approximately 1,583,600 total holes have been drilled within the state during the past 80 years in the search for hydrocarbons (Railroad Commission of Texas, 1986; and Kingston and Crawford, 1987). About 258,200 of these holes were stratigraphic and core tests, service wells, and dry holes. The majority of these holes have not had the casing treated and many of these may leak in the future. If this happens, saline-water zones with higher pressures than fresh-water horizons may degrade fresh water-bearing zones due to interaquifer exchange (Figure 44). Additionally, improperly plugged abandoned wells and test holes are excellent avenues for the upward migration of brine. The RCT assesses a $100 fee for each drilling permit application. This practice was authorized by the 68th session of the Texas Legislature and has been in effect since September 1, 1983. The proceeds from the state-funded well plugging reserve are to be used to plug improperly abandoned wells as well as to enforce the laws, rules, and regulations relating to the abatement of pollution. A total of 919 improperly abandoned wells were plugged, at a cost of $3.8 million by the RCT using this fund during 1986 (Railroad Commission of Texas, 1986).

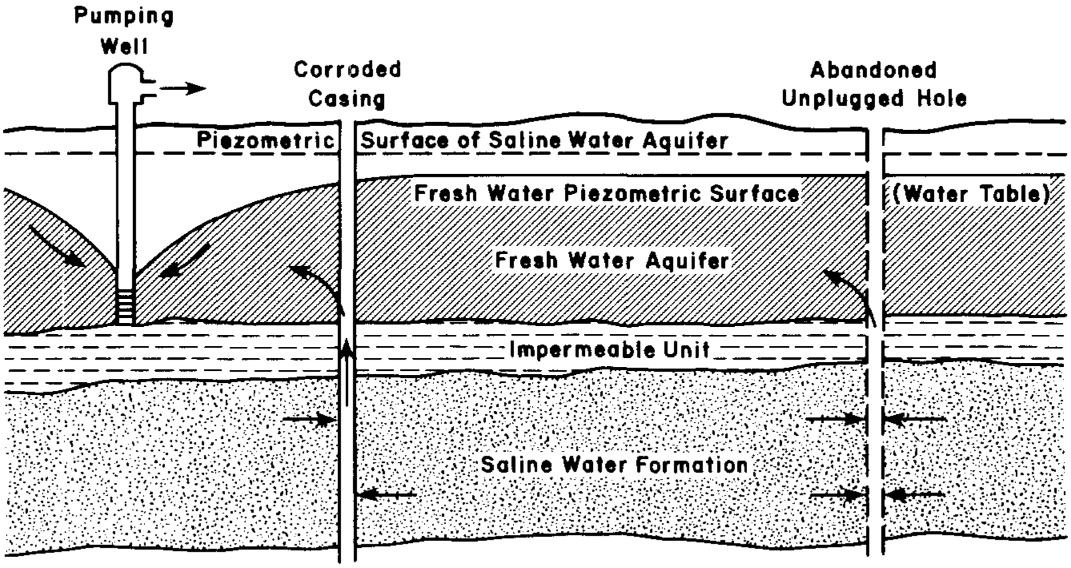
Table 12 which follows lists the typical composition of an oil field brine (Miller and others, 1977):

Table 12.—Range of Constituents Found in a Typical Oil Field Brine, in ppm

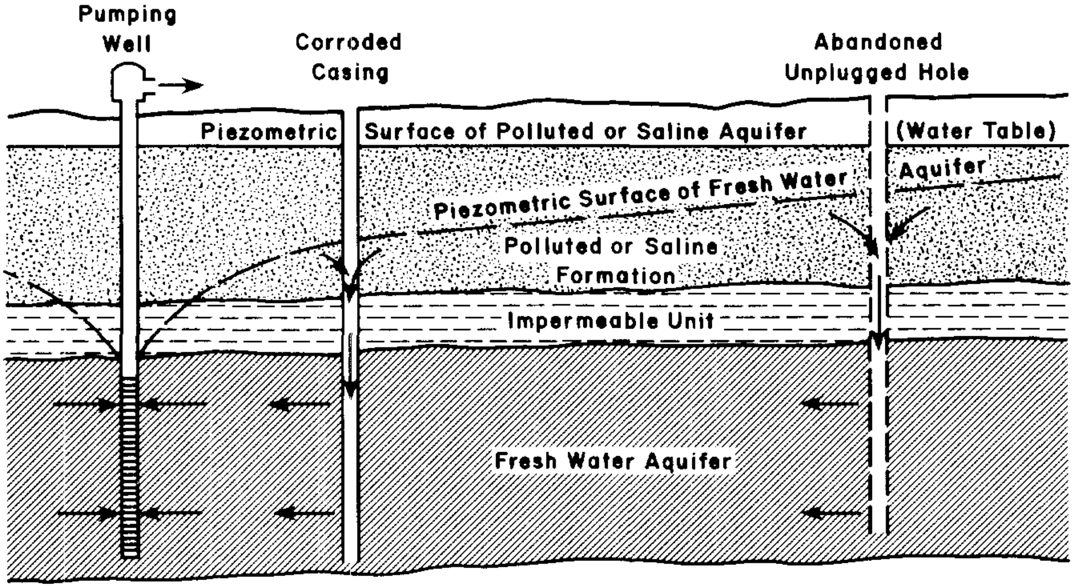
Element	Range, ppm		
Sodium	12,000	to	150,000
Potassium	30	to	4,000
Lithium	1	to	50
Rubidium	0.1	to	7
Cesium	0.01	to	3
Calcium	1,000	to	120,000
Magnesium	500	to	25,000
Strontium	5	to	5,000
Barium	0	to	1,000
Chloride	20,000	to	250,000
	(50,000 average)		
Bromine	50	to	5,000
Iodine	1	to	300

Source: Miller and others, 1977

In addition to elements listed above, there are other potential ground-water contaminants which are inherent in oil and gas exploration and development activities. These include oil and gas, drilling fluids, chemicals used in treating wells, other additives, and



Upward Flow Through Open, Unsealed, or Corroded Casing



Downward Leakage Through Open, Unsealed, or Corroded Casing

Figure 44

Upward Flow and Downward Leakage Through Open, Unsealed, or Corroded Casings corrosion inhibitors. Various additive chemicals such as barium sulfate are found in drilling fluids. Numerous acids are used in fracturing producing zones to improve permeability. These include hydrochloric, nitric, sulfuric, hydrofluoric, formic, and acetic (Miller, 1980). Corrosive inhibitors contain arsenic compounds. Certain oils contain mercury in concentrations exceeding the recommended standards set for drinking water. Gases often contain hydrogen sulfide which may give ground water the odor of rotten eggs. As previously stated, brines also contain an average chloride content of 50,000 ppm. Other brines contain toxic chemicals such as lead and barium. All of the above constituents have the potential to contaminate ground water when spilled on the surface or if they leak to ground water or move into fresh-water aquifers via interaquifer exchange.

There should be a general correlation between past disposal practices, the volume of brine produced, and areas of potential ground-water pollution. Miller (1980) stated that in 1963 that the total volume of brines produced in Texas was 6,127,671 barrels per day. A breakdown of this total volume, in barrels per day, and the various methods used for disposal are as follows: injected for waterflood - 2,736,755; disposed of in unlined pits - 1,262,719; discharged to rivers and streams - 615,566; and unaccounted for - 39,677. Current data are not readily available regarding the volume of produced brine; however, the practice of unlined pit disposal of brine was discontinued on January 1, 1969. Since that time, except under special circumstances, brine disposal has been permitted in disposal wells only.

The very nature of this category makes it difficult to estimate the true extent of ground-water contamination. Due to extensive exploration, production, and transportation activities associated with this industry throughout the state and their relationship to the outcrop areas of the state's major and minor aquifers, oil and gas practices do contribute to ground-water pollution. Fortunately, many of the oil producing areas of the state where pollution problems occur are situated in localities where there is an absence of both major and minor aquifers and this reduces the threat of pollution (Plate 3).

Ground-water quality has been impacted by past, now prohibited practices; by accidental spills, pipeline leaks; blow outs; and by situations that are noncompliant with rules of the RCT (Ginn, Railroad Commission of Texas, written communication, 1987).

Numerous documented instances where potential or actual pollution occurred can be considered an indicator of the extent of undocumented pollution (Ginn, Railroad Commission of Texas, written communication, 1987). Examples of potential or actual pollution are cited in the following referenced material: Nativ, 1988, p. 39; Nativ and Gutierrez, 1987, p. 20; U.S. Environmental Protection Agency, 1973a, p. 87-88; Price, 1978, p. 97; Price, 1979, p. 91; Richter and Kreitler, 1985, p. 21-23; and Richter, Dutton, and Kreitler, 1987, p. 23.

Some areas of high chloride concentration are coincident with areas of heavy oil and gas production such as in Sterling, Glasscock, Reagan, Upton, Crockett, and north-central Pecos Counties, and these may be the result of oil field brine disposal activities (Rees and Buckner, 1980 and Walker, 1979). Contamination of the aquifer may be occurring from historical salt-water disposal pits, brine disposal wells or playa lakes, or historic dumping of salt water into surface drainageways and on county roads (Walker, 1979) (Figure 16). Many other incidences of probable oil and gas related contamination are suggested when a comparison of individual aquifer water quality maps and the location of known hydrocarbon producing fields (Plate 3) are made.

Potentially, ground water could be affected by oil and gas activities in 231 of the total of 254 counties within the state. To further illustrate the possible extent of potential ground-water contamination which may have resulted from now prohibited past open-pit disposal practices, one needs only to compare the statewide distribution of oil and gas fields with the location of the state's aquifers (Plate 3) and their sensitivity to possible pollution (Plates 1 and 2). Using these data and the fact that there may have been several of these brine-disposal pits located on a single oil lease, and that numerous leases were located within a single oil field, it is clearly evident that there were many opportunities for potential pollution of the state's aquifers. If in fact pollution did result from these practices, there possibly is a saline-water plume located beneath many of the former pit locations which are now moving down gradient to discharge areas. Many incidents of pollution could result from these in the near future (Figure 45). It is not believed to be practical, nor economical, to attempt to locate and mitigate these areas.

All oil and gas activities are presently regulated by the RCT through a number of programs. Under their jurisdiction are about 56,000 active Class II injection/disposal wells, associated with oil and gas production; approximately 202,623 miles of oil and gas transmission lines; and an estimated 1,583,600 total holes which have been drilled in the past 80

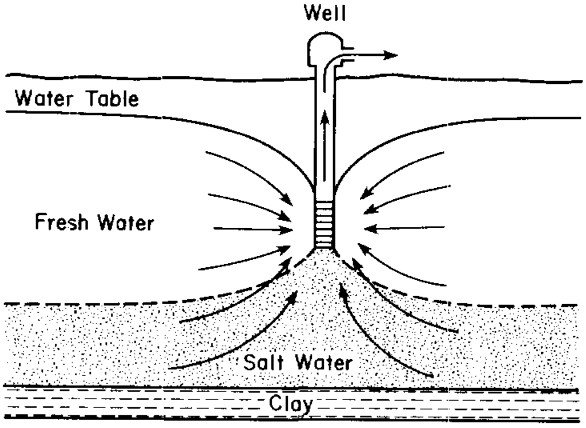


Figure 45.—Migration of Salt Water Upward into the Fresh Water Zone When a Well is Pumped (Scalf and Others, 1973)

years in the search for hydrocarbons within the state (Railroad Commission of Texas, 1986; and Kingston and Crawford, 1987).

Regulatory programs pursuant to Chapter 91 of the Texas Natural Resources Coded are now in effect to address the handling, storage, and the above-ground disposal of all oil and gas wastes, including produced water, drilling fluid, basic sediment, well treatment fluids, and gas plant wastes. Most of these wastes are generated at a well site, plant site, or other specific location so that control is appropriate through application and permit or authorization by rule. In cases where pollution has occurred or is likely to occur as a result of noncompliance, appropriate remedies can be enforced. Non-compliant activities such as salt water hauler dumping or other indiscriminate discharges that are not oil and gas lease oriented are more difficult to detect without complaints and information from the general public.

Existing point source regulatory programs are adequate to address pollution of surface and subsurface water from oil and gas activities. The RCT statewide Rule 8 requires that the disposal of oil and gas waste by any method other than injection, or the use of a pit to store or dispose of oil and gas waste or oil field fluids, must either be authorized by or permitted under the rule. Rule 8 also requires salt water haulers to be permitted. Statewide Rules 9, 46, and 74 require permits for injection wells that are related to oil and gas activities (Class II injection wells). Pipelines used to transport oil, gas, or geothermal resources require operating permits under statewide Rule 70. The casing, cementing, drilling, completion, and plugging of oil and gas wells are regulated under statewide Rules 13 and 14 (Ginn, Railroad Commission of Texas, written communication, 1988).

Most of the RCT's pollution prevention programs are oriented toward individual wells or leases or oil and gas waste handling, storage, and disposal. Although Rule 8 expressly prohibits oil and gas operators from causing or allowing the pollution of surface or subsurface water in the state, incidents of accidental flow line breaks, tank leaks or overflows, and other similar problems are not completely unavoidable, because of mechanical or electrical failures.

The TWC assists the RCT by recommending the depth of usable-quality ground water to be protected from pollution . In this capacity during 1985, the TWC processed over 30,000 plugging and surface casing recommendations. However, due to the downturn in industry activities during 1987, this number had been reduced to 18,500 (Jeter, Texas Water Commission, personal communication, 1988).

Mining Activities

Mining operations, which encompass the extraction and processing of rock materials, ores, and minerals, are relatively unnoticed because they are generally located in sparsely populated areas. Local conditions of geology, hydrology, and topography; environmental constraints; as well as the mineral being mined, determine the mining method employed (U.S. Environmental Protection Agency, 1987a). Underground and surface mining methods are used in Texas. Almost all of the early mining activities were underground operations; today, most mining operations use surface and solution mining practices. Quarrying, open pit mining, and solution mining are the preferred methods for the removal of many minerals in Texas. Limited underground mining has been and continues to be employed. All forms of mining can result in conditions and waste products which may degrade the quality of ground water. The most common sources of ground water contamination include mine drainage, surface storage of materials, dewatering activities, wellhead contamination, and runoff from smelting and processing wastes. Land subsidence can also result from mining and affect water quality.

Economic minerals found in Texas include lignite, crushed and building stone, cement, salt, gypsum, sand and gravel, aluminum, iron ore, zinc, talc, sulfur, mercury, and uranium. There are mining activities scattered throughout the state. These include mining, quarrying, milling, and smelting operations. Mercury has been mined in Brewster and Presidio Counties. Iron ores are being mined primarily from open pit mines in Cass, Cherokee, Morris, and Nacogdoches Counties, and ore processing mills for metal ores are located in Brazoria, Calhoun, El Paso, Galveston, Harris, Moore, and Potter Counties (Scalf, Keeley, and LaFevers, 1973).

Coal mining operations and mapped coal or lignite deposits are shown on Figure 46. Mining operations are found in Atascosa, Bastrop, Brazos, Coleman, Erath, Fayette, Freestone, Gregg, Grimes, Harrison, Henderson, Hopkins, Lee, Limestone, Marion, Milam, Panola, Robertson, Rusk, Titus, Walker, and Webb Counties.

Class III sulfur and uranium solution mining wells are located in Culberson and Wharton Counties (Figure 47). Sulfur has also been mined in Andrews, Brazoria, Ector, Fort Bend, Franklin, Hockley, Jefferson, Liberty, Matagorda, Pecos, Van Zandt, and Wood Counties (Scalf, Keeley, and LaFevers, 1973). Counties with known uranium deposits which can be solution mined are Bee, Duval, Jim Hogg, Karnes, Kleberg, Lee, Live Oak, and Webb. Sodium sulfate solution mining is carried out in Lynn County.

Wastes from the mining of minerals include mine wastes, processing wastes, slag, and fly ash. Wastes which cannot be reclaimed are generally stockpiled on the land surface and create the potential for leaching of contaminants to ground water. Contaminants associated with various minerals are:

Coal—acids, toxic inorganics (heavy metals and nutrients). Texas lignite is similar to other U.S. lignites and is locally high in selenium and arsenic; usually low in uranium.

Metallic Ores—Sulfuric acid, lead, copper, cadmium, arsenic, sulfate, manganese, molybdenum, radium, selenium, thorium, uranium, vanadium, and cyanide from certain leaching operations.

Phosphate—radium, uranium, and fluoride (U.S. Environmental Protection Agency, 1987a).

Both surface and subsurface disposal techniques are used by the mining industry. Liquid and slurry wastes are disposed of in ponds, sumps, lagoons, or injection wells; or discharged into surface waters. Ponds, sumps, or lagoons are usually surface depressions excavated from native soil. These serve as collection points for mine drainage and process waste water. Liquids are transported via pipelines or ditches. Suspended solids settle out in the ponds and liquids may be discharged to surface water drainages. Solids fill these depressions and may later be abandoned or dredged out. If these areas are unlined, contaminants may move through the soil profile or downward to the ground water system. Liquid wastes too toxic for disposal by other methods (from uranium operations) are disposed of through deep injection wells (Knape, 1984). Discussion of these wells is presented in the section, "Industrial Waste Disposal Wells."

During 1973, mining and mineral processing waste generation in the United States was four times the rate of municipal waste generation. In 1972, excluding discharges from coal and petroleum, in excess of 861.5 billion gallons of waste water were discharged from mining and ore processing operations. At that time, Texas reported 26.6 billion gallons per year of waste-water discharges (Miller, 1980). These figures are very conservative, however, since most of the state's present mining activities are lignite related and since these discharges were not included. Data are not readily available to include up-to-date estimates of lignite mining related wastewater discharges within the state.

Land application of mining solid wastes usually occurs around underground mines, open pit operations, quarries, and ore extraction plants. Examples of these are spoil piles which are composed of overburden from open pit mining operations and waste rock from underground mining activities. Solid wastes, derived from on-site processing operations are known as tailings. Wastes can become permanent features of the landscape. Leachate is produced when water dissolves the various constituents present in the waste and moves it to the soil profile or to the water table (Figure 28) (Miller, 1980).

Regulation of mining activities with respect to ground-water protection is the joint responsibility of the RCT, the TWC, and the TDH. While certain activities and processes are under the jurisdiction of state agencies, many aspects of mining are presently unregulated in Texas.

Surface Mining

Surface mining, by its very nature, is a destructive process. As of January 1, 1974, Texas had 214,303 acres of disturbed land related to mining activities (Grim and Hill, 1974); most of this was from sand and gravel operations. Texas has sizeable reserves of coal. As of January 1, 1968, it was estimated that about 1.3 billion short tons of lignite were strippable by surface mining methods (Grim and Hill, 1974). Surface mining is the preferred method for coal and lignite production within the state. The most significant threats to ground-water quality from

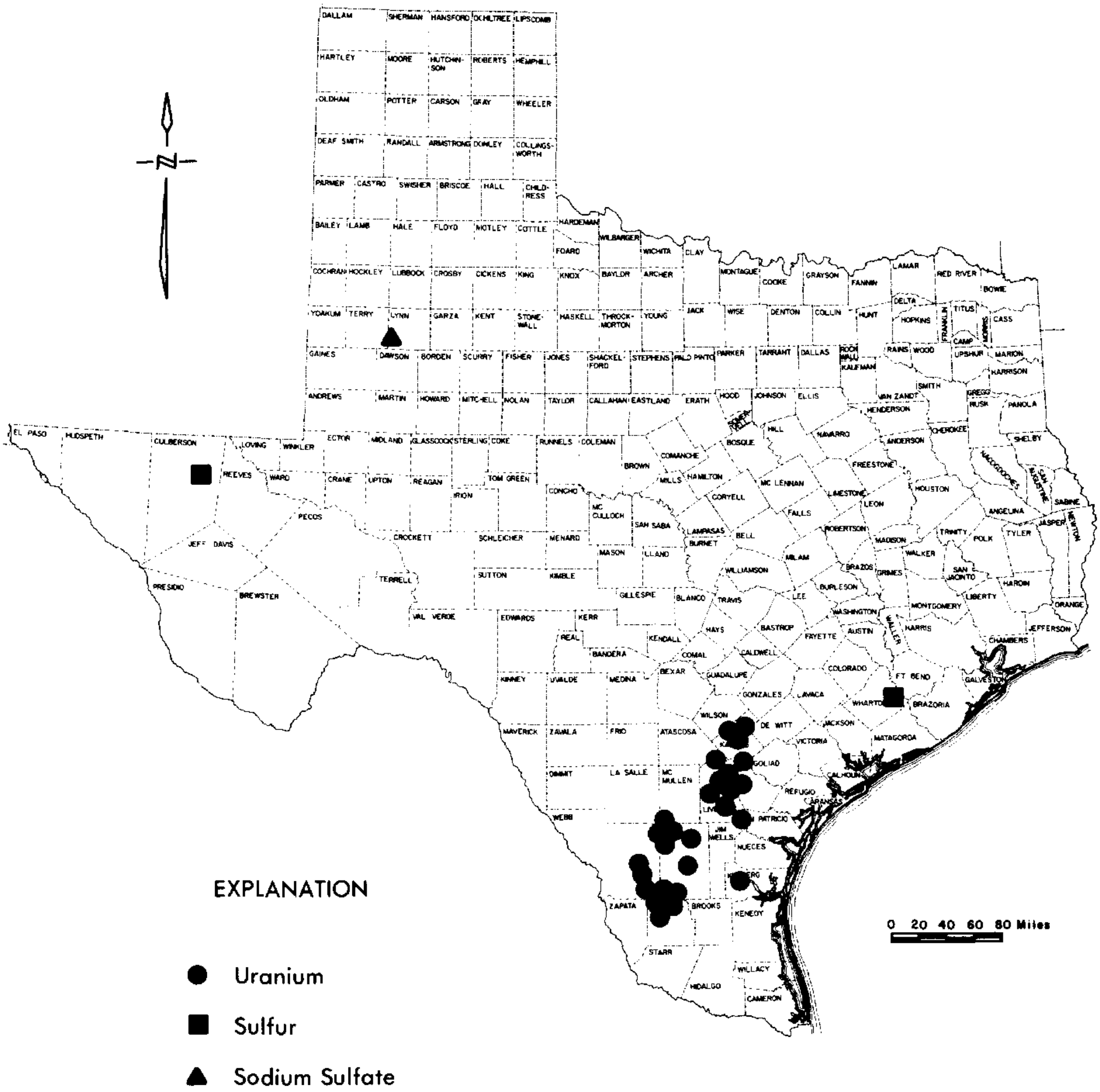


Figure 47
Location of Class III Wells (In-Situ Mining Operations), as of January 1988

surface mining in Texas are from acid mine drainage and dewatering. Strip mining can be done responsibly without permanent damage to the land and water. Additionally, technology now exists for effective reclamation of mined lands; a requirement for mining operations in Texas.

It is expected that Texas lignite will be the preferred fuel of many public utilities in the future. This is due to low transportation costs and ease of compliance with the federal and state environmental regulations. Extraction of lignite by open pit mining occurs primarily within the Carrizo-Wilcox, a major aquifer in Texas. The potential for lignite mining to affect ground-water quality and quantity is great. Therefore, past and future impacts to ground water must be considered.

Surface and ground waters which leach minerals from mine wastes are referred to as **acid mine drainage**. Rainwater and ground water can pass through sulfide minerals in tailings, spoils piles or the mine itself and may release large quantities of sulfuric acid (Miller, Hackenberry, and De Luca, 1977). Dewatering of the aquifer results in oxidation of sulfide minerals present within the rocks. When oxidized in the presence of water, sulfuric acid (H_2SO_4) is formed from sulfides. Additionally, high iron and sulfate concentrations are associated with this acidic solution (Miller, Hackenberry, and De Luca, 1977). Acid-bearing waters are the most common cause of ground-water pollution near mines.

In any mining operation, the presence of ground water makes mineral extraction difficult. Removal of ground water as a part of mine development or dewatering can lead to degradation of ground water due to mixing of waters from different aquifers. Ground water may move into the mined area following dewatering operations if hydrologic conditions are such that the hydrostatic head in the lower zone is higher than that in the mine. This can cause an upward movement of water from below.

In an effort to reduce the effects of acid mine waters on ground water, land reclamation practices are now in effect nationwide. The primary purpose is reduction or prevention of acid mine drainage to streams. The most practical method for control of acid drainage is through removal of as much surface water as possible, either through drainage systems or grading techniques. Oxidation of waste materials is minimized and the formation of acid water is limited (Miller, Hackenberry, and De Luca, 1977).

Although lignite mining within the state has been carried out since about 1890, little evidence of ground-water pollution has been documented. Minimal changes in water chemistry have been noted, however. In Freestone County, water samples were analyzed from the partially saturated zone in both mine spoil and unmined sediments at the Big Brown Mine. Low permeability spoil materials composed of relatively fine-grained sediments ranged from four to seven years old (Dutton, 1982). The water chemistry of the areas is noted in Table 13.

Similar samples of ground water from 25 year old mine spoils were also collected at the Sandow Mine in Milam County (Pollock, 1982). The sediments of the original overburden material consisted of a fine-grained mud facies. Pollock found neutral pH water which contained total dissolved solids (TDS) ranging from 3300 to 3700 ppm. Table 14 summarizes the results of the analysis.

At a very old abandoned mine site located in Bastrop County, sample data suggested that mining has caused only minimal degradation of local ground water. In general, lignite mining to date has not generated significant amounts of highly contaminated ground water. Data collected by Underground Resources Management, Inc. (1982) from seven monitoring wells in an abandoned underground mine are tabulated in Table 15.

With one exception, the pH range was near neutral and values for TDS ranged between 260 and 3714 ppm. In one monitoring well, pH was 5.1 and TDS were 4255. In summary, abandoned and existing lignite mining operations have caused only minor or local ground-water degradation. Nonetheless, monitoring of these facilities needs to be continued. Impacts beyond minimal ground-water contamination include disruption of recharge areas and depletion of ground-water resources due to depressurization and dewatering. Future impacts may be more serious, depending on mining practices and mine/aquifer relationships. Problems could result from the increasing number and depth of mines. Collective effects of closely spaced mines could be far more serious than a single shallow mine. To enable a better understanding of reclaimed and abandoned mines, future ground-water monitoring efforts need to be expanded (Fogg and Charbeneau, 1985).

Protection of ground water from surface mining activities is administered by the TWC through Chapter 26 of the Texas Water Code and the Texas Solid Waste Disposal Act; and the RCT through Chapter 131 of the Natural Resources Code, which includes the regulations concerning coal, uranium, and iron ore mining. The Texas Surface Mining and Reclamation Act requires ground-water monitoring of mining

Table 13.–Chemistry of Mine Spoil Water in the Partially Saturated Zone at Big Brown Mine, Freestone County (Dutton, 1982)

	Reclaimed Mud Facies	Unmined Mud Facies
pH	6.9 - 7.65	6.65 - 7.5
TDS	~2270 - 5840 ppm	~2070 - 5930 ppm
Dominant ions	Ca, Mg, SO_4, Cl	Ca, Na, Mg, HCO_3
	to HCO_3, Cl	to Ca, Na, Mg, Cl

Source: Fogg and Charbeneau, 1985

Table 14.–Ground-Water Chemistry of Resaturated Mine Spoil at the Sandow Mine in Milam County (Pollock, 1982)

pH	6.7 - 6.9
TDS (ppm)	3300 - 3700
Dominant Cations (ppm)	
Calcium	380 - 600
Magnesium	150
Sodium	265 - 550
Dominant Anions (ppm)	
Bicarbonate	700 -900
Sulfate	750 - 1100
Chloride	500 - 900
Type Water	Ca-Na-SO_4-HCO^3-Cl

Source: Fogg and Charbeneau, 1985

Table 15.–Chemistry of Water in Abandoned Mine Cavities at the Powell Bend Mine in Bastrop County (Underground Resource Management, 1982).

	Typical Range (ppm)	Worst Case (ppm)
pH	6.2 - 7.5	5.1
TDS	260 - 3714	4255
Fe	<.1 - 7.0	400
SO_4	90 - 1900	2900

Source: Fogg and Charbeneau, 1985

sites to measure water quality, quantity, and the recovery of water levels. Jurisdiction over uranium surface mining is with the Railroad Commission. Jurisdiction for solution mining of uranium is with the TWC.

Solution Mining

Brine, sodium sulfate, sulfur, and uranium are mined using solution-mining techniques. The solution-mining method is advantageous in that it disturbs less of the land surface and the subsurface environment. A minimum amount of land and aquifer restoration is required when mining operations cease. In 1985, there were approximately 70 brine, 3 sodium sulfate, and 3 sulfur producing operations in Texas. Salt brine is mined by injecting fresh water into a salt-bearing unit and producing brine. Sodium sulfate is produced by injecting brine into the mineral-bearing zone and extracting the mineral. During the production of sulfur, superheated water is injected into the sulfur-bearing unit; sulfur is heated above its melting point and transported to the surface as a liquid (Peters and Charbeneau, 1985).

In Texas, uranium is sometimes found in aquifers which contain usable quality ground water. Solution mining of other minerals does not require aquifer restoration. Uranium-bearing formations of South Texas lie within the Gulf Coast aquifer. Ground-water quality in the aquifer varies with depth and proximity to source of recharge. The ground water is mostly sodium bicarbonate and sodium chloride type, with TDS concentrations generally ranging from 1250 to 3000 mg/L (Figure 15). Local areas, however, have TDS levels outside this range. Heavy metal concentrations generally are within accepted public health limits in all uranium mining areas. Levels of radioactive parameters such as radium-226, gross alpha, and gross beta, however, are commonly above recommended public health standards in samples taken from water in contact with the ore bodies (Thompson and others, 1978).

At sites in Karnes, Bee, Live Oak, Webb, and Duval Counties, uranium has been produced through in-situ solution mining of shallow ore deposits. In this process, a leaching solution (lixiviant) is injected into an array of wells completed in the ore body. Lixiviant dissolves uranium minerals from the voids in sand and gravel deposits. Uranium compounds in solution are pumped to the surface through production wells. At the surface, compounds are removed from solution by ion exchange and chemical precipitation and the product (U_3O_8) is put in containers for shipment. South Texas uranium solution mines operate numerous aquifer monitor wells to detect excursions of contaminated fluids from the mining zone. Excursions normally can be controlled and recaptured by adjusting fluid production from the mining zone to exceed fluid injection rates (Kohler, 1984).

The TWC regulatory program for uranium solution mines requires aquifer restoration to pre-mining conditions at the termination of mining. The ground-water sweep method of aquifer restoration has been the most favored method, but may require disposal of large amounts of waste water. Systems for waste-water disposal include waste disposal wells, solar evaporation ponds, and land irrigation with treated water (Kohler, 1984). When operations are conducted using sound mining methods, ground water can be adequately protected. There are additional threats to aquifers, however, if the mined materials are not properly stockpiled on the land surface.

Solution mining of uranium has a potential for local aquifer contamination around mine sites. The local effects on ground water are elevated uranium and TDS concentrations. Water quality in the Gulf Coast aquifer near the mine sites investigated ranges from fresh to moderately saline, and in many places exceeds current U.S. Environmental Protection Agency drinking water standards for TDS, chloride, and radium-226. At many sites, no other drinking water is readily available and, consequently, this water must suffice for a variety of agricultural, domestic, and municipal uses (Kohler, 1984).

Chapter 91 of the Texas Natural Resources Code, and the Injection Well Act, Chapter 27 of the Texas Water Code, describe regulation of solution mining activities in Texas. The Injection Well Act established the Underground Injection Control program which gave the TWC authority to regulate underground injections, including wells for solution mining of uranium, potash, sodium sulfate, and sulfur (Greene, 1983). This program includes all injection wells not under the jurisdiction of the Texas Railroad Commission. The TDH ground-water protection program includes regulatory responsibilities related to the Uranium Mill Tailings Radiation Control Act of 1978. Chapter 26 of the Texas Water Code, the Texas Water Quality Act, provides for regulation of some injection well activities which may be found in mining applications, and is administered by the TWC under the UIC program (Knape, 1984).

Agricultural Practices

Included in this subchapter are several agricultural related topics. These are: 1) Feedlots and Animal Wastes, 2) Agricultural Chemicals, 3) Infiltration of Irrigation Waters, 4) Agricultural Drainage Wells, and 5) Tillage. Discussions of potential and/or documented ground-water pollution, along with other pertinent data follow.

Feedlots and Animal Wastes

Feeding operations for animals are located on individual farms and on commercial feedlots. Commercial feedlots are areas in which cattle are held and fed until they are ready to be marketed.

Prior to about 1960, almost all beef animals were raised in individual pastures where animal wastes were easily assimilated into the soil without significant surface- or ground-water pollution. About 1960, cattle producers began to establish many large and concentrated feeding operations in order to meet an increased demand for more and better quality of beef. These were located primarily in the High Plains region of Texas. As a direct result, the TWC had permitted, as of June 1987, a total of 210 of these commercial beef cattle feedlots within the state. These lots have individual feeding capacities ranging from 200 to 60,000 head. A beef animal's average stay in these lots is from 120 to 150 days. A total of 125 of these feedlots were located on the High Plains (Ogallala) aquifer in 28 different counties (Figures 48A). Using data furnished by the High Plains Underground Water Conservation District No. 1 and adjusting the data with information provided by the TWC, it is conservatively estimated that about 4.6 million head of cattle were fed in this area during 1986 (The Cross Section, 1987, p. 1 and 3).

Potential pollutants derived from animal wastes include nitrogen, phosphates, salts, and infectious agents. In addition to large feedlots, others of primary concern are animal concentrations such as dairies, hog operations, poultry operations, and sheep feedlots. Normally, animals on pasture or range do not produce enough waste concentrations to be of concern.

Over a half-ton of manure, on a dry weight basis, is produced by each animal during its stay in one of the large feedlots. This, combined with the large concentration of animals, overburdens the natural capacity of the receiving soil to assimilate these enormous concentrations of waste. Runoff comes in contact with this manure and carries high concentrations of chlorides, nitrogen, bacteria, viruses, and phosphates to receiving ponds which are usually playa lakes or constructed holding ponds. Ground water can be polluted by contaminated rainfall runoff held in these areas or from the feedlot itself. Fortunately, these runoff-holding facilities are naturally lined or engineered to be lined with clay bottoms which are practically impermeable and restrict most of the vertical flow. Vertical flow is possibly permitted, however, when an above average rainfall fills the holding facilities above their normal capacities resulting in more permeable sediments being exposed to waste water in the impoundments. Most feedpen surfaces are either covered with concrete or a surficial material which is poorly permeable due to compaction and cementation. This further restricts vertical flow.

Site-specific instances of documented pollution resulting from feedlots and animal wastes are restricted mainly to high nitrates in the soil profile below some feedlots. Analysis of ground-water samples collected from beneath 80 feedlots in the area of the northwest Texas Panhandle indicate that very little contamination had reached the water table during the period in which the feedlots had been in existence (Texas Tech University, 1971a). However, in about one fourth of these, slightly elevated nitrate levels were noted below the feedlots. Data on specific locations and the individual counties involved were not available. Feedlots may have or may eventually impact the High Plains (Ogallala) aquifer. One instance of documented pollution of ground water was located in Coryell County which impacted the Trinity Group aquifer.

It is fortunate that the main concentration of cattle feedlots is located on the northern one-half of the High Plains (Ogallala) aquifer and not the more sensitive southern High Plains area (Plates 1 and 2). In the northern High Plains, less permeable (but still potentially sensitive) soils combine with relatively deep water tables, low rainfalls, and high evaporation rates to restrict movement of waste waters. Areas considered as sensitive, within the area of the High Plains (Ogallala) aquifer, are those areas where fine sandy loams (permeable soils) are on the surface and the water table underlying the area is fairly shallow. This condition exists on essentially the south two-thirds of the southern High Plains.

Some large feedlots in other parts of the state are located on geologic units conducive to ground-water pollution. These are situated on highly permeable sand aquifers and/or in areas of highly porous limestones with limited soil cover. In these areas, recharge feedlot contaminants could reach the water table before they can be assimilated by the soil. Texas Water Commission permitting rules §§321.31-321.41, Subchapter B, regulate the placement of livestock and poultry facilities including the containment of contaminated rainfall runoff and seepage control of waste from these facilities for ground-water protection.

Both depth to the water table and soil permeability, which control the time required for pollutants to reach the water table, should be considered in designing feedlots. If sufficient time is allowed, most contaminants will be removed from feedlot waste waters by a combination of dilution, sorption, and biodegradation. Given time and the proper soil medium, biological denitrification can reduce the nitrates before they reach the water table (Scalf and others, 1973).

Most of the large animal confined feeding operations (beef, dairy, hogs, sheep, chicken, and/or turkey) are permitted by the TWC. In addition to the beef cattle feedlots, the TWC has also permitted the following commercial feedlots: 41 swine, 9 sheep, 35 dairies, 9 confined poultry industries, 6 poultry, and 7 turkey. These are widely scattered around the state in 64 separate counties. They are located on all major and at least three minor aquifers (Figures 2, 48B, and 48C). Many more dairies are known to exist, but most of these have only recently become subject to permitting, and the process of permitting, in most cases, is still in the early stages. Dairies are required by the Texas Health Department to regularly flush and wash certain facilities, creating additional water which, along with contaminated surface runoff, is usually impounded in constructed ponds. This collected runoff is disposed of by irrigation (Morris, Texas Water Commission, personal communication, 1987). It is not known if any ground-water contamination has or will result from these facilities.

Aqricultural Chemicals

Fertilizers

Fertilizers are those chemicals used in agricultural and other operations to improve the growth of crops or other plants. These nutrients are potential sources of ground-water pollution.

Phosphorus, nitrogen, and potassium are of primary concern as possible pollutants resulting from the application of fertilizers. The transport method for the movement of these nutrients, to either streams or ground water, is a complex process which is dependent on chemical, biological, and hydrological processes.

Phosphorus is found in soils in both organic and inorganic forms. Inorganic forms normally occur in soils where organic matter accumulates. Erosion is the primary mover of phosphorus due to its strong adsorption by soil particles. When phosphorus is applied to sandy soils or those containing peat, there is little reaction with them and surface-water transport or subsurface infiltration is possible.

Nitrogen is found in many different forms in soil. It is derived from natural sources such as geologic weathering, microbial reactions, precipitation, and chemical fixation. Chemical fertilizers and organic materials are other sources. Each form of nitrogen has different characteristics which determine its mode of transport. The nitrate form of nitrogen is water soluble and it is readily leached to ground water or transported in runoff water. Ammonium nitrogen is adsorbed to soil particles and is, therefore, transported with sediment. Urea is highly water soluble and can be transported in water, however, it is converted to ammonium within four to seven days. Sediment provides the major transport mechanism for organic nitrogen (Texas State Soil and Water Conservation Board, 1978).

Nitrate is a common ground-water pollutant because it is derived from so many sources. However, it is those sources resulting from man's activities with which we are concerned when considering their effect on ground water. As previously stated, these sources include runoff from concentrated animal feedlots, pastures and barnyards; effluent from septic systems, privies, and/or sewage lagoons; sanitary landfills; excessive nitrogen fertilization; and changes in the soil organic regime which result from land-clearing or agricultural practices.

All of the above sources undoubtedly contribute to the occurrence of abnormally high nitrate concentrations which are present in ground water over a large area of north central Texas (Figure 49). Some groups contend that almost all of this nitrate is derived from the application of fertilizers; however, this may not be the only source. It is difficult and expensive, but not impossible to refine data to allow determination of the relative effects of these nitrate sources. Existing data do not now permit such determinations.

Limited data which are available related to high nitrates present in ground water of the state follow.

(2) The amount of rainfall and irrigation must exceed evapotranspiration to provide excess water for downward percolation; and

(3) The soil and substrata must be sufficiently porous to allow water and NO_3 to percolate to the ground water.

Item (1) is dependent upon the management of fertilizers during farming activities, and items (2) and (3) are factors which must be considered in each application area. These are influenced, to a large degree, by climate, weather, and geological conditions (Hendry, 1988).

Other pertinent comments related to localized high nitrate concentrations follow.

Many of the wells containing excessive nitrate are possibly contaminated due to the effects of sewage from nearby septic tanks or animal wastes from barnyards. This would account not only for high concentrations of nitrate, but also for part of the increase in chloride since the two are associated (Hem, 1985).

Abnormally high nitrate concentrations often occur in ground waters over wide geographic areas, and these are difficult to explain. It has been suggested that the leaching of soil and humus in old mesquite groves, which have been converted to farm land, is the cause of high nitrate in certain areas of California (Huberty, Pillsbury, and Skoloff, 1945, p. 14-15). Another explanation for high nitrate is that it may be due to the leaching of nitrate from grasslands after they were put into cultivation. Nitrogen, bound in organic form, is believed to be highest in soils under grass vegetation. Organic nitrogen in such soils decreases rapidly due to mineralization when these lands are placed in cultivation. One or both of these explanations may be the cause of the high nitrate content of waters in the affected area, since much of the area was formerly in grassland or covered by mesquite groves.

Some of the high nitrate in the ground waters undoubtedly may be due to the extensive use of nitrogen fertilizers in the areas of cultivation which are underlain by alluvium. However, research to date has not been conclusive enough to fully evaluate the effects of fertilizers on ground water.

During this assessment, no actual conclusive cases of contamination of ground water resulting from fertilizer use were documented, except that which was documented and discussed in the section "Agricultural Drainage Wells."

Figure ~~26~~ 49 illustrates the areas of the problem. A total of 57 counties, predominantly in West Texas within the Alluvial and Bolson Deposits and the High Plains (Ogallala) aquifer, have greater than 41 percent of their chemical analyses exceeding the recommended standard of 10 mg/L nitrate-nitrogen.

The problem of documenting cases resulting from the use of fertilizers is properly interpreting the data. This data could possibly be used to construct residual NO_3 maps from which specific areas with concentrations that exceed background could be delineated for more sophisticated studies that would separate areas of man-induced nitrogen (N) from those which contain naturally occurring N. Recent work by various authors suggests that it is possible to differentiate the various sources of N in ground waters by running more complete water-quality and soil analyses to determine the nitrogen cycle or family and/or isotope ratios. Jones (1973) conducted a study of N isotope ratios for determining the various species related to a N problem in Runnels County. Kreitler, in 1975, also documented techniques using N isotope ratios of ammonium and nitrate ions from soil and water samples. Wolterink and others (1979) published a document containing techniques to be used in identifying sources of subsurface nitrate pollution using stable N isotopes. Also, recent work by Novotny and Chesters (1981) suggests that it is possible to differentiate possible sources of N in ground water by running more complete water-quality parameters. In summary, additional studies and/or research will be required to separate naturally high soil nitrates from high nitrates leached into ground waters as the result of agricultural fertilizers and/or resulting from contamination from feedlots, septic tanks, or natural causes.

To further resolve this problem in the future, additional consideration should be given to possibly constructing regional aquifer residual nitrate maps which remove normal regional nitrate values; thus, leaving anomalous areas requiring additional study. These areas could then be further evaluated as to whether the high nitrates present were the result of natural conditions or due to the application of fertilizers associated with agricultural activities. These maps could be constructed using available water sample data, presently on file with the TWDB; techniques developed by the oil industry; and geological and chemical interpretation.

Commercial fertilizers in Texas are regulated by the Texas Feed and Fertilizer Control Service, a subunit of the Office of the State Chemist. The State Chemist is appointed by the Director of the Texas

Agricultural Experiment Station at Texas A & M University. State law (Agriculture Code, Chapter 63) requires the Feed and Fertilizer Control Service to set standards for commercial fertilizers, require permits for manufacturers and distributors, register fertilizers, prescribe label requirements, and inspect registrants. The law does not specify any ground-water protection authority as part of the fertilizer regulatory program.

The TSSWCB and/or the TAEX have voluntary and educational programs dealing with fertilizers.

At present, data are not sufficient to indicate fertilizer use is a threat to ground water. This issue is now being reviewed and a statewide ground water protection strategy addressing fertilizers and pesticides will be prepared in the not too distant future.

Pesticides

Pesticides discussed here include: herbicides, insecticides, fungicides, defoliants, rodenticides, and nematicides. At present, there are over 50,000 pesticide products licensed for use (Deason, 1986). These chemicals are used to control weeds, insects, and other undesirable organisms. The majority of these pesticides are used in agricultural operations. However, large quantities are also used by governmental agencies, industrial/commercial organizations, and for garden and home use. Isolated cases of ground-water pollution related to pesticides were identified during this assessment.

The U.S. Environmental Protection Agency (1987a, p. 106) estimates that there are presently 1200 - 1400 active ingredients used as pesticides. It further estimates that 1.1 billion pounds of pesticides are used in the United States annually, 77 percent of which are applied in agricultural production. Industrial, commercial, and governmental use account for 16 percent of the total; and home and garden use for seven percent. With about 30 million acres of cropland, Texas ranks near the top among states in the volume of pesticides applied in agriculture, accounting for an estimated 10 percent of the national total (Texas Department of Agriculture, written communication, 1988).

Of the total volume used, herbicides (chemicals which kill weeds or regulate plant growth) account for 60 percent; insecticides (used to kill insects, mites, or roundworms) account for 27 percent; and fungicides (for molds, mildews, blights, rusts, and mushrooms), disinfectants (for bacteria and viruses), rodenticides (for rodent control), and molluscicides (for snails and slugs) account for 13 percent (Texas Department of Agriculture, written communication, 1988).

Until a few years ago, it was erroneously believed that ground water was protected by the overlying soil and geologic units. However, with the discovery of agricultural chemicals in a number of water wells across the country in the 1970's, this belief began to change. In 1982, a pesticide contaminant of serious concern, ethylene dibromide (EDB), was found in two wells in California and in three wells in Georgia. This prompted increased nationwide ground-water monitoring and by the end of 1983, EDP pollution had been confirmed in 16 counties in California, Florida, Georgia, and Hawaii. As a result of these findings, EPA issued an immediate suspension of all EDB soil uses (U.S. Environmental Protection Agency, 1987d).

Prior to these discoveries, no serious effort was made to monitor pesticides in ground water, either at a federal or state level. Many states, including Texas, still do not have an aggressive pesticide monitoring program. (Texas is now in the process of expanding its program.) With the discovery of aldicarb (DBCP) and EDB in isolated areas of the country, monitoring was increased to investigate the seriousness of the problem nationwide. By 1986, a total of 19 different pesticides had been documented in ground water in 24 states. One instance of pesticide contamination in Hidalgo County (aldicarb) was found, however, on retesting of the affected ground waters, it was not substantiated. Table 16 which follows, lists those pesticides and related chemicals which have been determined by the EPA to have the greatest potential for leaching to ground water.

The required general differences in the chemical properties of pesticides, their environmental fate in soils, and the variations which control their tendency to leach to ground water have been previously discussed in a subchapter entitled "Contamination."

EPA states (1987d) that ground water may become contaminated at various points in the pesticide use cycle. These points of pollution may occur during manufacture, distribution, storage, use on agricultural lands or in industrial settings, or during disposal. Isolated cases of pollution by pesticides related to several of these points in the use cycle have been confirmed within the state. Discussions of these follow.

Although monitoring to date has been very limited, several documented cases of ground-water contamination in Texas by pesticides were located (Figure 50). In 1984, arsenic was found in concentrations exceeding federal standards for safe drinking water in 34 water wells out of 101 wells tested in Howard and Martin Counties. The contamination is related to improper disposal of gin trash containing

Table 16.—Pesticides and Related Chemicals Included in U.S. Environmental Protection Agency's National Survey of Pesticides in Well Water

Pesticides

Acifluorfen (H)
Alachlor (H)
Aldicarb (I)
Ametryn (H)
Atrazine (H)
Bromacil (H)
Butylate (H)
Carbaryl (I)
Carbofuran (I)
Carbofuran-3-OH
Carboxin (F)
Chloramben (H)
alpha-Chlordane (I)
gamma-Chlordane (I)
Chlorothalonil (F)
Cyanazine (H)
Cycloate (H)
2,4-D (H)
Dalapon (H)
Dibromochloropropane (N)
DCPA (H)
Diazinon (I)
Dicamba (H)
3,5-Dichlorobenzoic acid (H,I)
1,2-Dichloropropane (N)
Dieldrin (I)
Dinoseb (H)
Diphenamid (H)
Disulfoton (I)
Diuron (H)
Endrin (I)
Ethylene dibromide (I,N)
Fluometuron (H)
Heptachlor (I)
Hexachlorobenzene (S)
Methomyl (I,N)
Methoxychlor (I)
Metolachlor (H)
Metribuzin (H)
Oxamyl (I)
Pentachlorophenol (H)
Picloram (H)
Propachlor (H)
Propazine (H)
Propham (H)
Propoxur (I)
Simazine (H)
2,4,5-T (H)
2,4,5-TP (H)
Tebuthiuron (H)
Terbacil (H)
Trifluralin (H)

Pesticide Metabolites

Aldicarb sulfone
Aldicarb sulfoxide
Atrazine, dealkylated
Carboxin sulfoxide
DCPA acid metabolites
5-Hydroxy dicamba
Disulfoton sulfone
ETU
Fenamiphos sulfone
Fenamiphos sulfoxide
Heptachlor epoxide
Hexazinone
Methyl paraoxon
Metribuzin DA
Metribuzin DADK
Metribuzin DK
Pronamide metabolite, RH 24850

F – Fungicide
H – Herbicide
I – Insecticide
N – Nematicide
S – Seed Protectant

Source: U.S. Environmental Protection Agency, 1988a

arsenic and poor well construction. Other cases involve ground-water contamination at commercial pesticide-applicator sites, as well as scattered findings of contamination from monitoring of wells in several counties.

The TDA is conducting an ongoing study of potential contamination of rural water wells by agricultural chemicals. Recent analyses of water samples collected in Comanche, Haskell, and Knox Counties to monitor for pesticides have confirmed the presence of herbicides in ground water. Of the 75 wells sampled, 25 each in Haskell, Knox, and Comanche Counties, TDA laboratories found that five contained pesticide residues (two in Haskell, two in Knox, and one in Comanche). Pesticides confirmed in ground waters included prometon; atrazine; dicamba; 2,4,5-T; 2,4-DB, and metolachlor. Each was found in either one or, in the case of prometon, in two of the wells (Piltz, Texas Department of Agriculture, personal communication, 1987). Contaminants in Haskell and Knox Counties impact the Alluvium and Bolson Deposits aquifer (Seymour Formation) and in Comanche County, they impact the Trinity Group aquifer. It is believed that these instances of pollution are on-site problems and cover very small areas and are presently being addressed by the TDA.

Additionally, pesticides have been reported in counties which follow with the aquifer which is impacted being shown in parenthesis: Brown (Trinity Group), Deaf Smith (High Plains), Hidalgo (Gulf Coast), and Llano (Hickory ?) (Field Offices, Texas Water Commission, personal communication, 1987; Knape, 1984). In almost all cases, the area affected by pesticide contamination is very limited in area.

Ground-water contamination due to chemicals commonly used in agricultural activities has also been confirmed in several other counties. Various pesticides have been detected in ground water associated with cleanup of aerial spraying equipment in the following counties: Cameron, Harris, Jim Wells, and Refugio Counties. These have impacted the Gulf Coast aquifer. The same activities have impacted the High Plains aquifer in Parmer and Sherman Counties. Additionally, pollution resulting from these practices has been documented in Loving County where it affects the Alluvium and/or Bolson deposits (Ferguson, Texas Water Commission, personal communication, 1987). These problems are presently being addressed by the TWC.

In an effort to correct obvious deficiencies in statewide sampling for pesticides, several state agencies and/or other entities are now in the process of sampling or are planning on instigating programs to gather data to more fully access the pesticide problem. Discussions of programs which are now in progress or are being planned follow.

The TWDB, which maintains a statewide groundwater quality monitoring program, has reevaluated and expanded its sampling program to include additional constituents, some of which may be applicable to herbicides. A total of 592 samples are to be collected in 74 counties in the near future. Since pesticide sampling is extremely expensive, it is not realistic to try to routinely sample all wells within their monitoring system for pesticides.

Texas Department of Agriculture is now resampling known pesticide contaminated wells in Howard and Martin Counties. They have also just completed the resampling of confirmed contaminated wells in Knox, Haskell, and Comanche Counties. Additionally, TDA is presently sampling shallow ground water in alluvial deposits in El Paso County.

EPA's National Pesticide Survey was commenced in April 1988 and is scheduled to be completed in 1989. This is a nationwide program designed to investigate the presence of pesticides in drinking water wells as well as to target needed ground-water monitoring requirements. This survey will include approximately 600 community water systems as well as an undetermined number of domestic wells nationwide which were randomly selected. Within Texas, 50 community water systems and one domestic well are scheduled to be sampled. These samples will be tested for over 100 pesticides selected to determine their leaching potential.

In an effort to assess possible effects of agricultural pesticide use on ground water, the High Plains Underground Water Conservation District No. 1 conducted a program which monitored for the presence of pesticides within the High Plains (Ogallala) aquifer (Figure 1). This water testing effort was initiated in late spring of 1988 and completed by November 1988 (McReynolds, 1988).

During the investigation, water samples were collected from 90 irrigation wells in 15 separate counties within the District's service area. To reduce costs, composite samples were compiled from groups of two or three wells which were closely located. These composite samples were then analyzed for 19 pesticides which had been used in the largest quantities and over the longest period of time. From these, a total of 589 separate analyses were conducted on 31 composite samples (The Cross Section, 1988; and McReynolds, 1988).

Preliminary test results from the composite samples revealed trace amounts of six chemicals in 14 of the 589 total analyses which were conducted. All of the trace amounts detected fell below EPA's proposed health advisory limits for each identified chemical (The Cross Section, 1988). Pesticides confirmed in trace amounts in ground water were: diuron; bromacil; atrazine; 2,4-D; dicamba; and glyphosate. Specific counties with chemicals identified were: Castro - bromacil, atrazine, and 2,4-D; Crosby - diacamba; Deaf Smith - bromacil and atrazine; Floyd - bromacil and atrazine; Hale - 2,4-D; Lamb - atrazine and glyphosate; Lubbock - diuron; Potter - diuron and bromacil; and Randall - atrazine (McReynolds, 1988).

Since samples were compiled from groups of two or three wells, individual irrigation wells will be resampled and analyzed for the chemical found in the first test. A third sample effort will involve collection of several water samples from each suspect well at timed intervals to check for an increase or decrease in the amount of chemicals found in an effort to determine if it is in fact coming from the aquifer or is a case of local contamination (McReynolds, 1988).

Preliminary data indicate that it is highly unlikely that solutions containing these chemicals could percolate through the thick soil profile to the water table (Plates 1 and 2). Direct access by way of wells is now considered to be the most likely route of potential pollution at this time. The exact causes of degradation are now being thoroughly investigated (The Cross Section, 1988).

Other known planned pesticide water sampling programs are to be initiated at a later date by the Lower Colorado River Authority and the TSSWCB. The total number of samples involved are unknown.

A great deal of data on ground-water contamination by pesticides has been collected by some chemical manufacturers. These data have generally not been made available to the state agencies responsible for pesticide registration and ground-water protection. A requirement that pesticide registrants report known instances of ground-water contamination could greatly facilitate the identification of problem areas (Piltz, Texas Department of Agriculture, written communication, 1987).

Most of the application of pesticides in Texas is performed by commercial firms and the remainder by individuals. Existing regulatory programs related to pesticides follow.

Pursuant to the Texas Water Code, the TWC is charged with the major responsibility for ground-water protection programs. By letter dated April 15, 1988, Governor Clements formally designated the TWC as Texas' lead agency with respect to the administration of ground-water protection programs under EPA's proposed pesticide strategy with the exception of licensing of applicators, which is the responsibility of the TDA.

The TDA has primary responsibility for regulating pesticide use in Texas under federal and state law and EPA oversight. Texas Department of Health and TWC have concurrent responsibility for regulating storage and disposal of pesticide wastes. In addition to TDA, the Structural Pest Control Board has responsibility to license applicators of pesticides in and around homes and other structures. The TDH has responsibility to license applicators of certain pesticides for health related pest control, such as mosquito control. The Texas Feed and Fertilizer Control Service has responsibility to regulate the distribution of fertilizers, including mixes of pesticides with fertilizers. Additional responsibilities related to nonregulatory activities related to the management of agricultural chemicals rest with the TSSWCB. The Texas Agricultural Extension Service has statewide research and educational responsibilities. Other nonregulatory activities are performed by public service agencies.

Silvicultural Activities

The term **silviculture** encompasses all forestry practices. Within the state, forestry activities are confined essentially to East Texas. Known pollution problems related to silviculture activities are relatively limited. There are five potential types of pollution, sediment, nutrients, organics, temperature, and introduced chemicals. Almost all of these are surface water concerns, however, introduced chemicals have been documented as a problem related to ground-water quality within the state. Specifically, ground-water contamination problems have resulted from wood preservation facilities. Pollution resulting from this activity falls under the regulatory responsibility of the TWC. The TSSWCB has agricultural responsibilities applicable to silvicultural best management practices within the state. Additionally, other existing federal and state organizations which could influence the implementation of silvicultural control measures related to pollution of ground water are the U.S. Forest Service (USFS) and the Texas Forest Service (TFS).

In addition to the TWC, other existing federal and state organizations which could influence the implementation of silvicultural control measures related to pollution of ground water, the U.S. Forest Service (USFS) and the Texas Forest Service (TFS) are the primary agencies.

The USFS is the federal agency which has been mandated to provide for protection and utilization of the nation's forest resources. Its responsibilities include the management of timber, forage, recreation, wildlife, and water resources of national forests. In Texas, there are four national forests representing a combined acreage of about 660,000 acres (Texas Water Institute, 1978, p. 143). By law, the various resources of forest lands must be managed so as to provide a "sustained yield" of each national forest. Management practices are also to be selected to minimize adverse environmental impacts.

National research conducted by the USFS has, along with other areas, been directed toward the relationship between forest practices and water quality and quantity. The State Forestry branch also provides a variety of different types of assistance to state and private forest owners.

The TFS was established to assure Texas an adequate supply of timber, to provide fire protection, to control insect and disease pests, to provide management assistance, and to educate and inform the public on forestry programs and the ecological and economic conditions of Texas forests. The agency has jurisdiction covering 53 counties in East Texas. This agency cooperates with other government agencies and private organizations in natural resource planning and environmental impact statements related to forestry. Pest control services are provided through aerial surveillance. The TFS reports infestations to landowners and will take the necessary control measures on request (Texas Water Institute, 1978, p. 149 and 150). In so far as is known, they have made no attempt to monitor ground-water quality underlying state forests.

In 1978, the Texas Water Resources Institute, under an interagency contract with the Texas Department of Water Resources (TDWR), assessed problems and developed solutions to silvicultural activities. This document is titled "Silvicultural Activities in Relation to Water Quality in Texas: An Assessment of Potential Problems and Solutions."

Wood Preservation

According to TWC records, there are only 33 wood preserving facilities in Texas. These are located in the eastern part of the state. Several of these facilities are not being operated at this time.

Wastes associated with wood preserving operations include contaminated waste water from the treating process; sludges from waste-water treatment; soil contamination caused by spills, loading and unloading of lumber into treating cylinders; and "weeping" of chemicals from freshly treated wood products. These wastes generally contain organic constituents from use of creosote and pentachlorophenol (penta), and/or inorganic constituents from use of chromated copper arsenate (CCA). Because CCA processes tend to use more water than they generate, they are becoming increasingly popular in the industry, and some plants which have used creosote or penta in the past are changing over to CCA.

Another aspect in the wood treating industry is the incidence of private individuals and small, unlicensed wood treating operations which commonly treat fence posts and lumber in earthen pits (known in the wood treating trade as "dippers"). It is not known how many of these small operators exist, but it is certain that such operations pose a significant threat to ground-water quality in localized areas (Moore, Texas Water Commission, written communication, 1988).

Reported ground-water contamination related to wood preservation activities have been found in seven counties of East Texas. These counties with the impacted aquifer shown in parenthesis, were: Angelina (none), Bowie (Carrizo-Wilcox and Nacatoch Sand), Grayson (Woodbine), Gregg (Carrizo-Wilcox and Queen City), Harris (Gulf Coast), Jasper (Gulf Coast), and Polk (Gulf Coast) (Figure 50).

Control of ground-water contamination resulting from wood preservation activities falls under the regulatory responsibilities of the TWC. Existing TWC regulations used to control contaminants resulting from wood preservation are, as in case of wastes derived by the application of pesticides, also derived from authority documented in Chapter 26 of the Texas Water Code and from authority defined in the Texas Solid Waste Disposal Act (Moore, Texas Water Commission, written communication, 1988).

Chapter 26 of the Texas Water Code is used to control discharges of wood preservation wastes into or adjacent to water in the state (including ground water), and it specifies actions to be taken in response to spills of oil and hazardous materials.

The Texas Solid Waste Disposal Act is also used to control solid wastes resulting from wood treating operations. Wastes from the operations are classed as industrial solid waste, and are thus regulated in accordance with rules which have been adopted by the Commission for industrial wastes; new rules regarding management of hazardous waste are being developed to comply with the continuously evolving federal regulations (Resource Conservation and Recovery Act).

Infiltration of Irrigation Water

Whenever surface and/or ground waters are applied to agricultural lands to assist in the production of crops, portions of this applied water returns to the water table via deep percolation. Many irrigated areas of the state have geological and soil characteristics which favor water losses. Often these waters are of poor quality.

As plants use water, salts accumulate in the soil and/or build up in surface and/or ground waters (van Schilfgaade, 1986). The most common problem is normally a salinity increase or buildup of the salts, sulfates, chloride, sodium, or calcium. More recently, actual or potential surface - and ground-water contamination resulting from fertilizers and pesticides has been of concern. In the arid portion of Texas, natural precipitation is usually insufficient to leach accumulated salts from the soil; however, when excess irrigation waters are applied, these salts may move to the subsoil and/or to ground water (Scalf and others, 1973).

Irrigated agriculture provides the economic base for much of Texas. During 1984, an estimated 6.7 million acres of Texas crop land was irrigated (Figure 51). Ground water was used for irrigating about 80 percent of this land. The total water used in 1984 on irrigated crops was 9.3 million acre-feet. About 2.06 million acre-feet of surface water was used on irrigated crops, an estimated 6.79 million acre-feet of ground water, and about 0.45 acre-feet of combined waters were utilized (Texas Water Development Board, 1986). Figure 51 illustrates the distribution of these waters. The exact percentage of applied irrigation water (pumpage) which infiltrates or returns to the water table is unknown, but it is estimated to be on the order of about 20 percent (Brune, 1969).

Within the High Plains area of West Texas, only a small amount of these flows returns to the river systems and most of the infiltrating solubles rejoin ground water. However, due to the high quality of most of the ground waters, the surface geologic units present, and the large storage capacity of the High Plains aquifer, the possible effects of most of the irrigation water seepage have been masked to date. In the southern High Plains, where favorable geologic soil conditions such as shallow depth to water table and thin saturated thicknesses of the aquifer exist (Plate 2), eventually, irrigation seepage water may become a problem.

Only one incident of possible ground-water contamination due to these activities was reported during this assessment and that was located in Deaf Smith County (Figure 50).

Excess precipitation in the gulf coastal region of the state highly dilutes irrigation return seepage and is not a large part of the hydrological system. In these instances, problems should be minimal and very localized (Scalf and others, 1973).

The highly mineralized ground and surface waters in the upper reaches of the Pecos River of west Texas may be the result of irrigation return seepage originating in New Mexico and Texas (Scalf and others, 1973). This could be the partial cause of ground-water degradation, however, most of it is believed to be due to more highly saline surface waters (resulting from natural salt dissolution) moving into the Cenozoic Alluvium. This occurs near the Pecos River where excessive irrigation pumpage has created a reversal in the gradient of the potentiometric surface of the aquifer away from the river.

The TWC, at present, has no existing regulatory program specifically addressing this subject. However, it is recommended that to prevent direct infiltration of pesticide and fertilizer laden irrigation return seepage waters into abandoned or improperly completed wells, the wells should be modified, properly capped, and/or plugged.

Agricultural Drainage Wells

Agricultural drainage wells are presently in use in Hidalgo County in the Lower Rio Grande Valley of Texas. These wells are considered to be Class V injection wells. They were initially introduced during the 1950's to help alleviate the problem of perched water tables in certain agricultural areas. Drainage well systems act to collect surface and very shallow subsurface water and drain them, by gravity flow, into a well for disposal into a permeable subsurface geological unit. The potential for contamination of ground water resulting from the use of agricultural drainage wells is high. Possible pollutants are pesticides, fertilizers, pathogens, metals transported by sediments, and salts.

Based on a 1982 inventory and assessment of this type of Class V well, it was estimated that about 300 agricultural drainage well systems were in operation within a 250 square mile study area in southwestern Hidalgo county. Within this area, the uppermost or shallow subsurface zone consists of medium to coarse grained gravel. It has been used extensively as a disposal zone for drainage well fluids. Fluids, which had been collected for later injection, contained high concentrations of dissolved solids, nitrate, and two herbicides, bromacil and simazine (Knape, 1984). Possible contaminates have been documented in fluids which were to be injected in a water-bearing zone located immediately above two usable quality water intervals.

These practices potentially impact the Gulf Coast aquifer (Figure 1). The possible affected area covers an estimated 250 square miles or about 160,000 acres near Mission, Texas in southern Hidalgo County. An average of 1.37 acre-foot/acre or about 16.4 inches of irrigation surface water is applied, annually, to the citrus groves (Texas Water Development Board, 1986). Additionally, the area has an average annual rainfall of about 23 inches. Table 17 gives an estimate of the amount of pesticides and fertilizers applied annually to an average citrus grove in Hidalgo County.

Gross estimates of loading on the impacted area are as follows:

Kh = permeability in the horizontal direction
= 500 gals/da/ft^2 (Molofsky, 1985)

Kv = permeability in the vertical direction
= assume 10 percent of Kh
= 50 gals/da/ft^2

Average depth to water level = 21.1 feet (Molofsky, 1985)

Average diameter of pipe in wells = 4 inches (Molofsky, 1985) = 0.333 feet

Porosity = ϕ = 30 percent (Freeze and Cherry, 1979)

Then velocity (V) of the water as it exits from the end of the pipe is:

$V = \frac{Kv\,dh/dl}{\phi}$ (where dh/dl is the change in hydraulic head, assumed to be half of the average depth to water)

and Volume = V + A (where A is the cross sectional area)

Volume =

$$\frac{\frac{50\ \text{gal/da}}{\text{ft}^2} \times 10.55\ \frac{\text{ft}}{\text{ft}}}{.30} \times \frac{\pi\,(0.333\ \text{feet})^2}{4}$$

= 153.45 gals/da/well when used

QTotal = 153.45 gals/da/well X 300 wells x 365 da/yr X 0.5 yr (estimated time in use)

= 8,401,388 gals/yr over 160,000 acres or 250 mi^2

Therefore:

Q/mi^2 = 33,606 $\text{gals/mi}^2\text{/yr}$ of contaminated water could be injected to the ground-water aquifer.

There are a number of governmental institutions in the Lower Rio Grande Valley which have influence on development and use of water and land resources. There are eight drainage districts which can levy and collect taxes to construct, operate, and maintain district drainage facilities. Thirty-three irrigation districts have the authority to levy and collect taxes; construct, operate, and maintain works of improvement; acquire land, easements, and rights-of-way; and contract with the federal government. Soil and Water Conservation Districts assist farmers and others with erosion control, flood prevention, and water management operations. The Lower Rio Grande Development Council was formed in 1967 and is primarily involved with industrial and economic development of the region and strengthening cooperation among local governmental subdivisions. The Council has also supported environmental assessments for the region.

The Agricultural Stabilization Conservation Service of the U.S. Department of Agriculture provides cost-share assistance for development of drainage well systems under the Agriculture Conservation Program. Funds are channeled through the U.S. Soil Conservation Service which provides technical assistance for design and construction of drainage well systems. The Service has established design specifications for drainage wells in the National Handbook of Conservation Practices (U.S. Department of Agriculture, Soil Conservation Service, 1978). These design standards specify that the practice of drainage well use is applicable only in locations where a determination has been made that it will not cause pollution of underground waters.

There are also an undetermined number of agricultural drainage wells ranging from 35 to 40 feet in depth, located in south-central Runnels County. These are located on the outcrop of Permian age sediments which are not classified as either a major or minor aquifer (Figures 1 and 2). However, ground

Table 17.—Typical Pesticide and Fertilizer Applications on a 20-Acre Citrus Grove Over a One-Year Period

Substance	Date of Application	Amount Applied
Nitrogen Fertilizer	Dec. 1981	100 lb/acre
Karmex	Mar. 1982	4 lb/acre
Simazine	Mar. 1982	2 lb/acre
Acaraben	Apr. 1982	1/2 gallon/acre
Methidathion	Apr. 1981	1/2 gallon/acre
Karmex	Aug. 1982	2 lb/acre
Simazine	Aug. 1982	2 lb/acre
Kelthane	Sept. 1982	1 1/2 gallons/acre

Source: Boyd Davis, Drainage Tile Contractor, Edinburg, Texas water may be present. Arsenic contamination was documented in waters to be injected which were collected and analyzed from these drainage well systems. The source of this potential pollution is thought to possibly have been associated with defoliation of cotton which is grown in the immediate area. Other agricultural drainage wells are also known to exist in Oldham County, however, specific details of these are not now available. Any problems related to these wells would possibly impact the High Plains (Ogallala) aquifer.

Drainage wells are considered as Class V Injection Wells and, therefore, are under the regulatory responsibility of the TWC. These wells are covered by regulations dealing with Class V Injection wells. The TSSWCB has no regulatory programs relative to drainage wells. However, there are soil and water conservation programs which provide assistance to agricultural producers relative to drainage of agricultural land. Existing programs will be utilized in the abatement of ground-water contamination to the extent feasible. New programs and approaches will be developed as needed (Texas State Soil and Water Conservation Board, written communication, 1988).

Tillage

Tillage is the operation of cultivating the land. This operation is commonly performed to prepare a suitable seedbed for grain germination, to bury excess residues, to control weeds, and to incorporate agricultural chemicals (Logan and others, 1987). Since tillage practices can increase the infiltration rate, constituents derived from fertilizers, pesticides, organic matter, and sediments are of concern as potential contaminants.

In some areas of the state located near cotton gins, many farmers secure gin trash and spread it upon their fields. Later tillage of this material into the soil increases its organic content. This gin trash is usually arsenic bearing due to the use of the cotton defoliant orthoarsenic acid during harvesting operations. Additionally, there have also been reported cases of this trash being used as insulation around water wells, as a prevention against winter freezing.

The practice of tilling arsenic-bearing trash into the soil and/or the piling of it around wells is believed to have increased background natural arsenic content of ground water through the downward percolation of contaminated fluids through the soil profile or through poor to nonexistent well annulus seals (Nichols and others, 1977; and Nativ, 1988).

Arsenic pollution was reported in Deaf Smith, Howard, Martin, and Willacy Counties. Data indicate that this pollution is not an aquifer wide problem and that improper waste disposal practices, not normal field use of a pesticide, resulted in ground-water contamination in the immediate area.

Activities related to tillage practices are the responsibility of the TSSWCB and the TAEX. The TDA is responsible for ensuring compliance with federal and state laws and regulations relating to pesticide distribution and use through its pesticide enforcement program.

Class V Injection Wells

This subchapter includes miscellaneous injection wells used for the subsurface emplacement of certain fluids. These well types *exclude* Class I, II, III, and IV wells, and residential cesspools or septic system disposal wells. (Residential cesspools and septic system disposal wells are regulated by guidelines of the TDH and may be regulated by specific counties where septic tank orders exist.) Brief descriptions of these classes are: Class I, hazardous and nonhazardous waste disposal wells for injection below underground sources of drinking water; Class II, fluid injection and disposal wells related to oil and gas activities; Class III, solution mining wells; Class IV, hazardous waste disposal wells injected into or above underground sources of drinking water.

Class V includes all other injection wells. More specifically, Class V includes wells of the following EPA groups: 1) drainage, 2) geothermal reinjection, 3) domestic waste-water disposal, 4) mineral and fossil fuel recovery related, 5) industrial/commercial/utility disposal, 6) recharge, and 7) miscellaneous. Currently, nationwide there are at least 30 different types of Class V wells which fall in the seven major groups. Within Texas, representative types of each of the major groups are known to exist.

Class V Well Types

Agricultural drainage wells are used to receive irrigation tailwaters, other field drainage, and dairy and concentrated animal feedlot runoff.

Storm water drainage wells receive surface storm water runoff from paved areas such as parking lots, streets, residential subdivisions, building roofs, and highways.

Industrial drainage wells are wells located in industrial areas primarily to collect storm water runoff, but are susceptible to spills, leaks, or other chemical discharges.

Heat pump/air conditioning wells are shallow wells used for underground injection of water which has been produced from a source well for heating or cooling in a heat pump (Knape, 1984).

Sewage disposal wells included all bored or dug holes in which the depth exceeds the diameter, and which are used for disposal of water-borne human wastes or effluent resulting from partial treatment of these wastes (Knape, 1984).

Mine backfill wells are normally defined as wells drilled into mined-out portions of below ground mines for the purpose of filling them by injection of a slurry of sand, mill tailings, or other solids (Knape, 1984).

Automobile service station disposal wells are those wells which receive waste from repair bay drains. These are suspected of being used for disposal of dangerous or toxic wastes.

Artificial recharge wells are used to recharge depleted aquifers. Fluids injected may be derived from various sources such as treated waste water, irrigation tailwaters, water from lakes and streams or from other aquifers.

Abandoned water wells include improperly abandoned high-capacity municipal, industrial, and irrigation wells, abandoned oil rig-supply wells, and domestic or livestock wells.

Potential Contaminants of Class V Wells

Contamination potential for each of the above specific types has been assessed (Engineering Enterprises, Inc., 1987). Based on various parameter characteristics of each type of well, a rating scheme of high, moderate, or low was developed. Table 18 which follows, lists the well type, contamination potential, and potential contaminants.

Table 18.—Class V Wells of Concern

Well Type	Contamination Potential	Potential Contaminants
Agricultural Drainage	High	Pesticides, fertilizers, pathogens, metals via soil sediments, salts.
Storm Water Drainage	Moderate	Heavy metals (Cu, Pb, Zn), organics, coliform bacteria, contaminants from streets, pesticides.
Industrial Drainage	High-Moderate	Usually organic solvents, acids, pesticides, and various other industrial waste constituents. Usually higher concentrations than storm drainage wells.
Heat Pump/Air Conditioning Return Flow	Low	Potable waters (90° - 110°F) may contain scale or corrosion inhibitors.
Sewage Disposal (septic systems)	High-Low	Suspended solids, nitrates, chlorides, sulfates, sodium, calcium, and fecal coliform.
Mine Backfill	Moderate	Acidic waters.
Automobile Service Station	High	Heavy metals, solvents, cleaners, used oil and fluids, detergents, and organic compounds.
Artificial Recharge	High-Low	Variable, sediments, pesticides, fertilizers, water is generally of good quality.
Abandoned Water	Moderate	Potentially any fluid, saline waters, hazardous chemicals, fertilizers, sewage, sediments.
Others	Unknown	Variable.

Source: U.S. Environmental Protection Agency

Inventory of Class V Wells

An exact count of the various types of Class V wells is not known at present. The total number is thought to exceed 150,000 wells since it has been estimated there are at least that many abandoned water wells within Texas. (For a more complete discussion of these, please refer to the subchapter titled, "Water Wells.") Figures 52 and 34 show the approximate distribution of known Class V wells other than abandoned water wells. Unless otherwise noted, all well inventories cited in this section will be as of August 5, 1988.

A total of 108 agricultural drainage wells have been located within the state. Since these are considered as problem wells, a more complete discussion of these can be found in the section titled, "Agricultural Drainage Wells."

Data on confirmed storm water drainage wells is very sketchy. Statewide, there are thought to be only about 50 of these wells. These are primarily located in Edwards and Travis Counties and in the Panhandle area of Texas (Musick, personal communication, 1988). Personnel of the TWC have inventoried 42 of these wells.

Figure 52 also reflects the area of known heat pump/air conditioning return flow wells. The total number of such wells statewide, is probably on the order of several thousand. These are known to be located in at least 52 separate counties. An ongoing inventory of these wells is now in progress by the staff of the TWC. A total of 1752 wells have been located.

The approximate locations of confirmed sewage disposal wells are also shown on Figure 52. The staff of the TWC inventoried those sewage disposal wells serving 20 or more persons. As of December 1984, there were four well systems located on the High Plains: one in Gray, two in Potter, and one in Oldham Counties. Additionally, there were 10 well systems in Edwards County, 12 well systems in Nueces County, and one system in Hidalgo County (Knape, 1984). A recent count of these wells indicates that 509 have been located in scattered counties of the state (Figure 52).

In the Terlingua mercury mining district in Brewster County, a mine backfill project was instigated during 1982 to eliminate the dangers of open mine shafts. Railroad Commission of Texas personnel identified at least 88 mine shafts in the immediate area which were considered as public hazards. This group of shallow shafts and workings, which are to be filled with solids, are classed as mine backfill wells. As of August 5, 1988, a total of 108 of these backfill wells had been located by TWC personnel (Figure ~~40~~ 52). Due to the scarcity of ground water in the area, it is believed that this disposal had no impact on groundwater resources (Knape, 1984).

A total of 46 artificial recharge injection wells have been inventoried. Located primarily in the western part of the state, known wells are found in Carson, Castro, Dawson, El Paso, Edwards, Floyd, Hale, Hockley, Hudspeth, Lamb, Lubbock, Martin, Midland, Swisher, and Yoakum Counties (Figure 52). Some of the total number of wells may be located in other counties of the state. All wells are not presently in operation (Knape, 1984).

Data are not available on the number of industrial drainage and automobile service station disposal wells. Additional data definitely needs to be gathered on these wells.

Texas Water Commission's regulatory program for Class V injection wells is included under 31 TAC Chapter 331 (UIC). Existing Class V wells are authorized by rule. In order to maintain authorization by rule, existing Class V operators were required to register their wells by January 6, 1983. Proposed new Class V injection wells must be registered with the Commission prior to construction of the wells to assure authorization by rule. The Commission has the discretion to regulate Class V wells through the existing registration program as provided by rule, or to develop more appropriate regulatory approaches for specific categories of Class V wells. Such approaches might involve regulation by site specific permit, by special rules, or by a local agency.

Most Class V injection wells must be drilled by a licensed water well driller. The owner, operator, and driller of such an injection well is required to submit to the Executive Director of the Commission information with regard to each proposed injection well.

Stormwater Runoff

Stormwater runoff is that part of the total precipitation which flows over the urban or rural land surface. Under normal conditions during and following a rainfall, stormwater flows within a watershed area to lower elevations where it is either recharged to the ground-water system or it drains to creeks, rivers, bays, or lakes. Urban runoff is usually channeled by drainage ditch networks into stormwater sewer systems, recharge and/or sediment basins, into stormwater drainage (dry) wells, into other systems, or into the natural surface-water stream drainage system. Rural runoff is usually channeled by the natural drainage networks.

A broad range of pollutants are associated with stormwater runoff activities. Stormwater, as runoff or as infiltration, is the vehicle by which contaminants move across the land surface, through the soils to ground water, or to surface waters. Potential contaminants include suspended solids, pesticides, bacteria, petroleum residues, nutrients, and toxic substances which include hydrocarbons and heavy metals (U.S. Environmental Protection Agency, 1987a). Ground-water contamination from the above pollutants may enter the aquifers through leaks in storm sewers, storm sewer overflows, flows directly from city streets into the ground, or seep from recharge and/or sediment basins or stormwater drainage wells.

Information gathered during this assessment related to this category is not sufficient to support a reliable evaluation. Limited documented cases of actual or potential ground-water pollution were found. In Deaf Smith County, possible ground-water pollution has resulted from the use of stormwater runoff ditches. This locally impacts the High Plains (Ogallala) aquifer. There also have been times when sewage contamination has been found at Barton Springs in Travis County following large rains over the watershed (Baskin, Texas Water Commission, personal communication, 1987).

The Edwards (Balcones Fault Zone) aquifer is considered to be the most susceptible aquifer to this type of ground-water pollution. This aquifer is very cavernous and it also contains numerous faults. Cities located on the recharge zone of this aquifer have or should develop best management plans to mitigate any problems related to activities of this category. Counties which may experience ground-water pollution are: Bell, Bexar, Comal, Hays, Kinney, Medina, Travis, Uvalde, and Williamson (Figure 1).

The TWC has jurisdictional responsibility for the protection of ground water relating to urban stormwater runoff. The TSSWCB has voluntary responsibilities related to rural agricultural and silvicultural stormwater runoff. Additionally, new federal regulation will further address problems related to this subject.

Other Possible Ground-Water Pollution Sources

Open Dumps

Very little information is available on this source of potential ground-water contamination. Even though these disposal areas have been illegal since 1976, many of these are believed to still exist in rural areas of the state. These facilities, for the most part, have not been identified and investigated due to the lack of sufficient funds. They are believed to pose a risk to health and the environment.

An **open dump** is an unauthorized and unsupervised solid waste disposal site where wastes are deposited without regard to the consequences of dumping. These are normally located in gulleys, ravines, or land areas considered unsuitable for other purposes and can pose a constant and uncontrolled threat to ground water. Items discarded are old applicances, automobiles, tin cans, rubber tires, trees and yard trash, construction wastes, and many other items. Often, unconfined quantities of hazardous or nonhazardous wastes are "midnight dumped" at these sites.

Minimum estimates of nationwide open dumps range from about 1900 to 2400. This is probably a conservative figure since many of these are believed to still be unidentified. Open dumps have been reported in every state and most territories of the United States (U.S. Environmental Protection Agency, 1987a). Open dumps are subject to the criteria EPA has developed for classification of solid waste disposal facilities and practices under RCRA.

Solid waste disposal facilities in the state are regulated by the Texas Department of Health under regulations more completely discussed in the previously presented section titled, "Sanitary Landfills."

Material Stockpiles

These are storage piles of substances produced or used in a production process. They are normally materials stored or used in large bulk. Texas examples are coal, uranium ore, sand and gravel, iron ore, gypsum, sulfur, manure, and other materials frequently stored in stockpiles.

Soluble substances contained in these stockpiles can be carried to ground water and are dependent upon the material stockpiled (U.S. Environmental Protection Agency, 1987a). Potential contaminants from coal stockpiles are; aluminum, iron, calcium, magnesium, sodium, potassium, sulfur, phosphate, and trace levels of arsenic, cadmium, mercury, lead, zinc, selenium, uranium, copper, and cobalt; and from other stockpiles include metals and nonmetals.

Very little is known about the actual amounts of stockpiled materials within Texas. Nationwide, it is estimated that there may be as much as 700 million tons per year of material which is stockpiled. This is based on a percentage of total annual materials production of 3.4 billion tons (U.S. Environmental Protection Agency, 1987a). Geographically, these stockpiles may be widely scattered in related areas of activities.

Leachate migration from stockpiles may be prevented or reduced by locating them on impermeable surfaces, keeping them covered, or installing a leachate collection system. Some of these stockpiles are controlled by presently regulated mining activities. Some manure stockpiles are regulated under feedlot rules. Material stored in connection with unregulated mining activites are possibly still uncontrolled.

Containers

Included under this category are storage barrels and drums of various waste and non-waste products that can be moved around with relative ease. Often they are illegally buried or "midnight dumped" into rural open dumps. These containers, when they ultimately leak, can be a threat to ground water.

Potential contaminants from containers are organic chemicals, metals, nonmetals, inorganic acids, microorganisms, and radionuclides (U.S. Environmental Protection Agency, 1987a).

Available information on containers is very limited. Information which is known results from studies on those containers regulated under RCRA. In 1981, about 3577 facilities regulated under RCRA used containers to store at least 0.16 billion gallons of hazardous wastes (U.S. Environmental Protection Agency, 1987a). Many more of these facilities should be located and controlled when small quantity generators comply with state regulations.

The graphical distribution of these containers is unknown, however, they should be located around population centers, where small quantity generators and industrial facilities are known to be located (Figure 37).

Documented cases of ground-water contamination resulting from storage containers are limited; however, some of the cases related to the activities of agricultural aerial sprayers may have resulted from leakage from containers. These are more fully discussed in the section titled, "Agricultural Chemicals."

The TDA and the TWC have concurrent responsibility for regulating storage and disposal of pesticides. The TWC controls containers used for storage of all hazardous wastes, both industrial and non-industrial. Chapter 76 of the Texas Agricultural Code authorizes TDA to regulate pesticide use, storage, and disposal. Authority for TWC to regulate hazardous waste storage containers is set out in the Texas Solid Waste Disposal Act.

Automobile Junk Yards

One area of possible ground-water pollution which needs to receive more attention is auto junk yards which are generally concentrated around population centers (Figure 37). The exact amount of their liquid wastes is unknown; however, wastes which are involved result from battery acids, radiator antifreeze and coolants, transmission fluids, motor oils, gasoline, and diesel fuels. Most of these are believed to be indiscriminately dumped on the surface of these yards. Many of these fluids are hazardous and extremely dangerous if they seep to ground water.

Residential Disposal

Many residential activities have the potential to contaminate ground water. There are many hazardous and toxic substances commonly found in household wastes. In some cases, when these are improperly used or discarded, they may seep to ground waters. Actual cases of contamination resulting from these activities are not readily available, but they are thought to exist.

Possible ground-water contamination can be avoided if individuals are aware of the pollution potential. Many individuals make a special effort to dispose of their residential wastes in specific facilities designed to receive these wastes (e.g., municipal landfills or special locations set up to receive these items); however, others also dispose of their wastes indiscriminately, without supervision, into septic tanks, gutters, sewers, storm drains, and in some areas, backyard burning pits (Office of Technology Assessment, 1984). In some cases, substances may be accidentally spilled, but at times they are intentionally dumped on the ground.

Potential contaminants, found in a wide variety of house wastes, may be derived from paint products, pesticides, cleaners, automobile products, asphalt and roofing tars, batteries, and possibly many others (Office of Technology Assessment Assignment, 1984).

Nationwide, homeowners are thought to use up to five million metric tons of cleaners, annually. It is further estimated that homeowners may account for up to 10 percent of U.S. pesticide use (about 80 million pounds in 1980). Significant amounts of toilet bowl and other household cleaners are also used (Office of Technology Assessment, 1984).

Individuals should follow a few simple precautions to avoid contaminating ground waters. These are: think before you throw it out; follow instructions for use and disposal of hazardous household products; consider buying nontoxic alternatives; when programs are available, turn unused quantities over to hazardous-waste collection facilities; be aware of what are hazardous and toxic substances; and never pour any of these out on the ground or dispose of them in any septic tank, storm drain, stream, river, or lake.

Ground-Water Withdrawals

Over pumpage of ground water has occurred in numerous localities within the state (Figure 53). Overdevelopment of several fresh-water aquifers has, or eventually will have, resulted in uneconomical pumping costs, created ground-water shortages due to local dewatering of aquifers, and has, or ultimately will have, caused ground-water degradation problems such as the migration of saline water toward centers of pumpage within fresh-water aquifers and, in some areas, possibly land-surface subsidence. This degradation results from excessive withdrawals from municipal, irrigation, and industrial wells.

Potential contaminants, in addition to saline-water intrusion, are brackish water upswelling from below due to interaquifer exchange (Figures 44 and 45); increases in organics, inorganics, and radionuclides; and potential natural pollutants derived from intensified leaching (U. S. Environmental Protection Agency, 1987a).

Water-Level Declines

Water-level fluctuations indicate a change in the amount of ground-water stored within an aquifer. These changes may be local or regional in nature. Basically, water level changes are caused by adjustments resulting from recharge and discharge to and from an aquifer (Muller and Price, 1979).

When recharge is reduced, as in the case of a drought, some of the water discharged from the aquifer must be withdrawn from storage which results in a decline of water levels. If water levels are lowered excessively, springs and shallow wells may go dry. However, when sufficient precipitation resumes, the volume of water drained from storage during the drought may be completely or partially replaced and the water levels will rise accordingly. When a water well is pumped, the water level in its vicinity is drawn down to form a shape of an inverted cone with its apex located at the well.

The development and growth of this cone depends on the aquifer's coefficients of transmissivity and storage. As pumping continues, the cone expands until it intercepts a source of replenishment capable of supplying sufficient water to satisfy the pumping demand. This source of replenishment can be either intercepted natural discharge or induced recharge. If the quantity of water received from these sources is adequate to compensate for the water pumped, the growth of the cone will cease and new balances between recharge and discharge are achieved. In areas where recharge or intercepted natural discharge is less than the amount of water pumped by wells, water is removed from storage within the aquifer and water levels will continue to decline.

Where intensive ground-water development has taken place, each well superimposes its cone of depression on the cone of neighboring wells. This results in the development of a regional cone of depression. When the cone of a well overlaps the cone of another, interference occurs and the lowering of water levels is compounded as the wells compete for water by expanding their cones of depression. The amount or extent of interference between cones of depression depends on the rate of pumping from each well, the spacing between wells, and the hydraulic characteristics of the aquifer in which the wells are completed (Muller and Price, 1979).

Long-term water-level measurements, obtained from a water-level monitoring network maintained by TWDB, indicate that water levels have declined significantly during the decade from 1975-1985, in several areas around the state (Figure 53). Cumulative declines, within these areas, have been considerably higher since the turn of the century. Records are not readily available to allow a statewide appraisal of the true extent of potential contamination resulting from ground-water withdrawal activities. Major areas of concern are discussed below.

Within the Dallas-Fort Worth metropolitan area, the Trinity Group aquifer has been severely overdeveloped. In 1977, water levels in the area ranged from 400 to about 1200 feet below land surface. This condition has probably worsened since that time. In the Waco and adjacent area within this aquifer, similar artesian water-level declines exist (greater than 100 feet from 1975-1985) (Figure 53). In the absence of alternate surface-water sources for these areas, water-levels will continue to decline since ground-water withdrawals exceed the annual effective recharge. Water-quality problems, such as encroachment at the fresh-saline water interface and pumping costs, will increase as water levels continue to be excessively lowered in the aquifer (Muller and Price, 1979). Figure 11 illustrates the general ground-water quality of this aquifer. Higher TDS ground waters in the Dallas-Fort Worth areas may reflect over pumping of the aquifer. Other possible areas of water quality change may also have occurred in Collin and Grayson Counties.

In the High Plain region of Texas, there are two separate areas which are presently experiencing appreciable water-level declines. The principle aquifer of this region is the High Plains (Ogallala) aquifer (Figure 1). Water-level declines of greater than 40 feet have occurred within this water-table aquifer in an area extending from Dallam through Hartley, Moore, Hutchinson, Hansford, and Ochiltree Counties. Another sizeable affected area extends primarily through Parmer, Castro, Lamb, Hale, Swisher, and Floyd Counties. The principal cause of these declines is excessive irrigation pumpage (Figure 53).

Numerous areas are present in the southern two-thirds of the southern High Plains (underlain by the High Plains aquifer) which may have also been influenced by pumpage (Figure 8). This is indicated by not only high total dissolved solids content, but also by high chloride and sulfate values.

Since managed ground-water mining is occurring in the Mesilla and Hueco Bolson aquifers in El Paso County, it is possible that some of the water withdrawn between now and the year 2030 will be slightly saline because of saline-water encroachment from the induced recharge source (Rio Grande) and the movement of slight to moderately saline ground waters from adjoining bolson deposits (Muller and Price, 1979) (Figure 53). Figure 12 indicates that waters within the Hueco Bolsons along the Rio Grande are of poorer quality.

Several other scattered smaller areas of decline are present within the Edwards-Trinity (Plateau) and Carrizo-Wilcox aquifers (Figure 53). In the water-table areas, declines are in excess of 40 feet. These are located in Leon, Rains, Van Zandt, and Schleicher Counties. Artesian declines of greater than 100 feet occur, locally, in Anderson, Gregg, Rusk, Nacogdoches, Smith, and Henderson Counties (Figure 53). With the exception of the Schleicher County area, these declines are not underlain by hydrocarbon producing fields.

Quality data are not such that specific instances of actual ground-water degradation can be attributed to each area of water-level decline discussed above. However, the general water quality may be determined by comparison of the water quality of the various aquifers involved with the areas in which water-level decline has occurred (Figures 8, 9A through 9D, 12, and 16).

Even though Figure 53 does not reflect water-level declines during the decade 1975-1985, it is believed that past irrigation pumpage from the Cenozoic Alluvium aquifer, in the western part of the state, created a reversal of the potentiometric surface near the Pecos River in the counties of Crane, Pecos, Loving, Reeves, and Ward. As a result, saline ground waters, ranging from 4000 to 12,000 part per million total dissolved solids, now fill the aquifer near the river (Figure 12). Saline surface waters found within the Pecos River are believed to be derived from Permian salt dissolution activities occurring in New Mexico.

Significant artesian water level declines of greater than 100 feet have occurred in Brazoria, Fort Bend, Harris, Montgomery, and Wharton Counties (Figures 15 and 53). Water level declines in excess of 40 feet have occurred in these same counties in areas under unconfined or water table conditions. These are the result of, primarily, ground-water pumpage which has also resulted in land-surface subsidence in some instances. A brief explanation of land-surface subsidence and those areas experiencing subsidence is included in the discussion which follows on critical areas.

Critical Areas

When an area of the state is experiencing or is expected to have ground-water problems resulting from ground-water overdrafts from an aquifer it is classed as a critical area. Out of the 17 original areas located throughout the state which were initially designated as potential "critical areas", 10 were considered serious enough to warrant detailed studies. They are presently being investigated for possible creation of underground water conservation districts. Most of these areas are affected by water-level declines or land-surface subsidence (Figure 54).

It now appears that one of the most economical and effective method for control of water-level declines is through local underground water conservation districts.

SELECTED REFERENCES

Aieta, E. M., Singley, J. E., Trussell, A. R., Thorbjarnarson, K. W., and McGuire, M. J., 1987, Radionuclides in drinking water: An overview: American Water Works Association Journal, v. 79, no. 4, p. 144 - 152.

Adams, J. E., 1944, Upper Permian Ochoa Series of Delaware Basin, west Texas and southeastern New Mexico: American Association of Petroleum Geologist Bulletin v. 28, no. 11, p. 1596-1625.

Alexander, W. H., and Patman, J. H., 1969, Ground-water resources of Kimble County, Texas: Texas Water Development Board Report 95, 106p.

Alexander, W. H., White, D. E., 1966, Ground-water resources of Atascosa and Frio Counties, Texas: Texas Water Development Board Report 32, 219p.

Aller, L., Bennett, T., Lehr, J. H., Petty, R. J., and Hackett, G., 1987, DRASTIC: A standardized system for evaluating ground water pollution potential using hydrogeologic settings: U. S. Environmental Protection Agency, EPA/600/2-87/035, 622p.

Alvarez, H. J., and Buckner, A. W., 1980, Ground-water development in the El Paso region, Texas, with emphasis on the resources of the lower El Paso valley: Texas Department of Water Resources Report 246, 348p.

Anders, R. B., 1960, Ground-water geology of Karnes County, Texas: Texas Board of Water Engineers Bulletin 6007, 110p.

______1967, Ground-water resources of Sabine and San Augustine Counties, Texas: Texas Water Development Board Report 37, 123p.

Anders, R. B., Baker, E. T., 1961, Ground-water geology of Live Oak County, Texas: Texas Board of Water Engineers Bulletin 6105, 128p.

Anders, R. B., McAdoo, G. D., Alexander, W. H., 1968, Ground-water resources of Liberty County, Texas: Texas Water Development Board Report 72, 154p.

Anderson, K. E., ed., 1981, Water well handbook, fourth edition: Missouri Water Well & Pump Contractors Assn., Inc., Belle, Mo., 218p.

Ashworth, J. B., 1983, Ground-water availability of the lower Cretaceous formations in the hill country of south-central Texas: Texas Department of Water Resources Report 273, 172p.

______1988, Ground-water resources of the Nacatoch aquifer: Texas Water Development Board Report 305, 150p.

Ayers, W. B., and Lewis, A. H., 1985, The Wilcox Group and Carrizo Sand (Paleogene) in east-central Texas: depositional systems and deep-basin lignite: University of Texas at Austin, Bureau of Economic Geology, 30 plates, 19p.

Baker, B. B., Dillard, J. W., Souders, V. L., and Peckham, R. C., 1963, Reconnaissance investigation of the ground-water resources of the Sabine River Basin, Texas: Texas Water Commission Bulletin 6307, 57p.

Baker, E. T., Jr., 1960, Geology and ground-water resources of Grayson County, Texas: Texas Board of Water Engineers Bulletin 6013, 155p.

______1964, Geology and ground-water resources of Hardin County, Texas: Texas Water Commission Bulletin 6406, 199p.

______1965, Ground-water resources of Jackson County, Texas: Texas Water Development Board Report 1, 229p.

______1971, Relation of ponded floodwater from Hurricane Beulah to ground water in Kleberg, Kenedy, and Willacy Counties, Texas: Texas Water Development Board Report 138, 33p.

______1979, Stratigraphic and hydrogeologic framework of part of the coastal plain of Texas: Texas Department of Water Resources Report 236, 43p.

______1986, Hydrology of the Jasper Aquifer in the southeast Texas coastal plain: Texas Water Development Board Report 295, 64p.

Baker, E. T., Jr., Follett, C. R., McAdoo, G. D., and Bonnet, C. W., 1974, Ground- water resources of Grimes County, Texas: Texas Water Development Board Report 186, 109p.

Baker, E. T., Jr., Long, A. T., Jr., Reeves, R. D., and Wood, L. A., 1963, Reconnaissance investigations of the ground-water resources of the Red River, Sulphur River, and Cypress Creek Basin, Texas: Texas Water Commission Bulletin 6303, 127p.

Baker, E. T., Jr., Slade, R. M., Jr., Dorsey, M. E., and Ruiz, L. M., 1986, Geohydrology of the Edwards aquifer in the Austin area, Texas: Texas Water Development Board Report 293, 217p.

Baker, E. T., Jr., and Wall, J. R., 1976, Summary of appraisals of the Nation's ground-water resource —Texas-Gulf Region: U.S. Geological Survey Professional Paper 813-F, 29p.

Baker. R. C., and Dale, O. C., 1961, Ground-water resources of the Lower Rio Grande Valley area, Texas: Texas Board of Water Engineers Bulletin 6014, 88p.

Baker, R. C., Dale, O. C., and Baum, G. H., 1967, Ground-water conditions in Menard County, Texas: Texas Water Commission Bulletin 6519, 92p.

Barnes, V. E., 1981, Llano sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Barnes, V. E., and Schofield, D. A., 1964, Potential low-grade iron ore and hydraulic-fracturing sand in Cambrian sandstones, Northwestern Llano region, Texas: University of Texas, Austin, Bureau of Economic Geology Report of Investigation No. 53, 58p.

Bates R. L., and Jackson, J. A., eds., 1980, Glossary of geology, second edition: Falls Church, Va., American Geological Institute, 749p.

Baumgardner, R. W., Hoadley, A. D., and Goldstein, A. G., 1982, Formation of the Wink Sink, a salt dissolution and collapse feature, Winkler County, Texas: University of Texas at Austin, Bureau of Economic Geology Report of Investigation No. 114, 38p.

Bayha, D. C., 1964, Occurrence and quality of ground water in Stephens County, Texas: Texas Water Commission Bulletin 6412, 96p.

Bayha, D. C., 1967, Occurrence and quality of ground water in Montague County, Texas: Texas Water Development Board Report 58, 107p.

Bedinger, M. S. and Sniegocki, R. T., 1976, Summary appraisals of the Nation's ground-water resources — Arkansas-White-Red Region: U.S. Geological Survey Professional Paper 813-H, 31p.

Bennett, R. R., and Sayre, A. N., 1962, Geology and ground-water resources of Kinney County, Texas: Texas Water Commission Bulletin 6216, 163p.

Black, C. W., 1988, Hydrogeology of the Hickory Sandstone aquifer, Upper Cambrian, Riley Formation, Mason and McCulloch Counties, Texas: Masters Thesis, The University of Texas at Austin, 195p.

Bouma, J., and others, 1972, Soil absorption of septic tank effluent: University of Wisconsin, Soil Survey Division, Information Circular Number 20.

Bouwer, Herman, 1978, Groundwater Hydrology: McGraw-Hill Book Company, N.Y., 480p.

Broadhurst, W. L., and Twichell, T., 1942, Water supply in the Sandflat area and adjacent territory in Rusk, Nacogdoches and Shelby Counties, Texas, United States Geological Survey.

Broom, M. E., 1966, "Iron water" from wells: Causes and prevention: Ground Water, v. 3, no. 1.

______1968, Ground-water resources of Wood County, Texas: Texas Water Development Board Report 79, 89p.

______1969, Ground-water resources of Gregg and Upshur Counties, Texas: Texas Water Development Board Report 101, 83p.

______1971, Ground-water resources of Cass and Marion Counties, Texas: Texas Water Development Board Report 131, 73p.

Broom, M. E., Alexander, W. H., Jr., and Myers, B. N., 1965, Ground-water resources of Camp, Franklin, Morris, and Titus Counties, Texas: Texas Water Commission Bulletin 6517, 155p.

Broom, M. E., and Myers, B. N., 1966, Ground-water resources of Harrison County, Texas: Texas Water Development Board Report 27, 74p.

Brown, J. B., Cepeda, N. J., and Daugherty, F. W., 1979, Emory Peak-Presidio sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Brown, L. F., Jr., Goodson, J. L., and Harwood, P., 1972, Abilene sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Brown, L. F., Jr., Morton, R. A., McGowen, J. H., Kreitler, C. W., and Fisher, W. L., 1974, Natural hazards of the Texas coastal zone: University of Texas at Austin, Bureau of Economic Geology, 27p.

Brown, T. E., Waechter, N. B., and Barnes, V. E., 1983, San Antonio sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Brown, T. E., Waechter, N. B., and Owens, F., 1976, Crystal City—Eagle Pass sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Browning, L. A., 1977, Source of nitrate in water of the Edwards aquifer, south central Texas: University of Texas at Austin, Master's thesis, 90p.

Brune, Gunnar, 1969, How much underground water storage capacity does Texas have?: Texas Water Development Board unnumbered publication, 25p.

________1975, Major and historical springs of Texas: Texas Water Development Board Report 189, 95p.

Brune, G., and Duffin, G. L., 1983, Occurrence, availability, and quality of ground water in Travis County, Texas: Texas Department of Water Resources Report 276, 231p.

Burnitt, S. C., 1963, Reconnaissance of soil damage and ground-water quality, Fisher County, Texas: Texas Water Commission Memorandum Report 63-02, 59p.

Canter, L. W., and Knox, R. C., 1985, Septic tank system effect on ground water quality: Chelsea, Michigan, Lewis Publishers, Inc., 336p.

Carter, W. T., 1928, Soil survey (reconnaissance) of the Trans-Pecos area, Texas: United States Department of Agriculture, Soil Conservation Service.

Cech, Irina, Kreitler, Charles, Prichard, Howard, Holguin, Alfonso, and Lemma, Mengistu, 1988, Radon distribution in domestic water of Texas: Ground Water, v. 26, no. 5, p. 561-569.

Cech, I. M., Prichard, H. M., Mayerson, Adele, and Lemma, Mengistu, 1987, Pattern of distribution of radium 226 in drinking water of Texas: Water Resources Research, v. 23, no. 10, p. 1987-1995.

Charbeneau, R. J., and Rohlich, G. A., 1981, Resource impact evaluation of in-situ uranium ground-water restoration: Center for Research in Water Resources CRWR-184, The University of Texas at Austin, Bureau of Engineering Research.

Clement, T. J., and Sharp, J. M., Jr., 1987, Hydrochemical facies of the Edwards aquifer, Williamson and Bell Counties, Texas, *in* Yelderman, J. C., Jr., Slade, R. M., Jr., Sharp, J. M., Jr., and Woodruff, C. M., Jr., Hydrogeology of the Edwards aquifer in the northern Balcones and Washita Prairie segments: Field trip guide, South Central G.S.A., Baylor University, Waco, Texas, p. 61-70.

Core Laboratories, Inc., 1972, A survey of the subsurface saline water of Texas: Texas Water Development Board Report 157, v. 1., 113p.

Cothern, C. R., 1987, Estimating the health risks of radon in drinking water: American Water Works Association Journal, v. 79, no. 4, p. 153 - 158.

Couch, H. E. and Muller, D. A., 1972, Water well and ground-water chemical analysis data, Glasscock County, Texas: Texas Water Development Board Report 143, 69p.

Cronin, J. G., Follett, C. R., Shafer, G. H., and Rettman, P. L., 1963, Reconnaissance investigation of the ground-water resources of the Brazos River Basin, Texas: Texas Water Commission Bulletin 6310, 163p.

Cronin, J. G., and Wilson, C. A., 1967, Ground water in the flood-plain alluvium of the Brazos River, Whitney Dam to vicinity of Richmond, Texas: Texas Water Development Board Report 41, 223p.

Cross, B. L., 1986a, Status report (new class V injection wells): Unpublished report in files of the Texas Water Commission, Austin, Submitted to EPA as Part of the Underground Injection Control (UIC) Grant Agreement (FY 86), 9p.

Cross, B. L., 1986b, Preliminary delineations of critical ground-water areas: Texas Water Commission, unnumbered publication, 1p.

______1987a, Status report (new class V injection wells): Unpublished report in files of the Texas Water Commission, Austin, Submitted to EPA as Part of the Underground Injection Control (UIC) Grant Agreement (FY 87), 7p.

______ 1987b, A regulatory approach for class V injection wells, in Proceedings of International Symposium on Class V Injection Well Technology, Washington, D.C.: Oklahoma City, OK, Underground Injection Practices Council, p. 695-701.

Crouch, R. L., 1964, Investigation of ground-water contamination in the Juliana and West Jud Oil Fields, Haskell and Stonewall Counties, Texas: Texas Water Commission LP-0364.

Culver, A. A., 1985, Residues from the past: The incidence of 12 hazardous pesticides in superfund sites across America: San Francisco, CA: Pesticide Education and Action Project, June, 1985, p. 1-23.

Dale, O. C., 1952, Ground-water resources of Starr County, Texas: Texas Board of Water Engineers Bulletin 5209, 50p.

Dale, O. C., and George, W. O., 1954, Ground-water resources of Cameron County, Texas: Texas Board of Water Engineers Bulletin 5403, 66p.

Dale, O. C., Moulder, E. A., and Arnow, T., 1957, Ground-water resources of Goliad County, Texas: Texas Board of Water Engineers Bulletin 5711, 97p.

Davis, M. E., and Gordon, J. D., 1970, Records of water levels and chemical analyses from selected wells in parts of the Trans-Pecos region, Texas, 1965-68: Texas Water Development Board Report 114, 49p.

Davis, S. N., and DeWiest, R. J., 1966, Hydrogeology: John Wiley & Sons, Inc., N.Y., 463p.

Deason, J. P., 1986, U.S. Department of the Interior investigations of irrigation-induced contamination problems, *in* Summers, J. B., and Anderson, S. S., eds., Toxic substances in agricultural water supply and drainage, Proceedings from the 1986 Regional Meetings, Sponsored by U.S. Committee on Irrigation and Drainage, Denver, CO, p. 201-210.

DeCook, K. J., 1960, Geology and ground-water resources of Hays County, Texas: Texas Board of Water Engineers Bulletin 6004, 170p.

______1961, A reconnaissance of the ground-water resources of the Marathon Area, Brewster County, Texas: Texas Board of Water Engineers Bulletin 6111, 54p.

Deutsch, M., 1963, Groundwater contamination and legal controls in Michigan: U.S. Geological Survey Water Supply Paper 1691, 79p.

Dietrich, J. W., Owen, D. E., and Shelby, C. A., 1983, Van Horn - El Paso sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Dillard, J. W., 1960, Memorandum report of preliminary ground-water investigation of Shelby County, Texas: Texas Board of Water Engineers Miscellaneous Publication M248, 9p.

Dillard, J. W., 1963, Availability and quality of ground water in Smith County, Texas: Texas Water Commission Bulletin 6302, 35p.

Doll, W. L., Meyer, G., and Archer, R. J., 1963, Water resources of West Virginia: West Virginia Department of Natural Resources, Division of Water Resources, 134 p.

Dorsey, M. E., and Slagle, D. L., 1987, Hydrologic and geologic data for the Edwards aquifer recharge zone near Georgetown, Williamson County, Texas, 1986-87: U.S. Geological Survey Open-File Report 87-691, 66p.

Dragun, James, 1988a, The fate of hazardous materials in soil (What every geologist and hydrologist should know) - Part 1: Hazardous Materials Control, v. 1, no. 2, p. 31-78.

______1988b, The fate of hazardous materials in soil (What every geologist and hydrologist should know) - Part 2: Hazardous Materials Control, v. 1, no. 3, p. 41-65.

Duffin, G. L., 1974, Subsurface saline water resources in the San Antonio area, Texas: Texas Water Development Board San Antonio District Office Open-File Report, 39p.

______1984, Ground-water conditions in the Triassic Aquifer in Deaf Smith and Swisher Counties: Texas Department of Water Resources LP-196, 121p.

Dutton, A. R., 1982, Hydrogeochemistry of the unsaturated zone at Big Brown lignite mine, East Texas: Ph.D. Dissertation, The University of Texas at Austin, 239p.

Dutton, A. R., and Simpkins, W. W., 1986, Hydrogeochemistry and water resources of the Triassic Lower Dockum Group in the Texas Panhandle and Eastern New Mexico: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 161, 51p.

Eaton, F. M., 1950, Significance of carbonates in irrigation waters: Soil Science, v. 59, p. 123 - 133.

Eifler, G. K., Jr., 1967, Lubbock sheet: University of Texas at Austin at Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

_______1968, Plainview sheet: University of Texas at Austin at Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

_______1969, Amarillo sheet: University of Texas at Austin at Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

_______1974, Big Spring sheet: University of Texas at Austin at Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

_______1975, San Angelo sheet: University of Texas at Austin at Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

_______1976, Pecos sheet: University of Texas at Austin at Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Eifler, G. K., Jr., and Fay, R. O., 1970, Perryton sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Eifler, G. K., Jr., Fay, R. O., and Trauger, F. D., 1984, Dalhart sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Eifler, G. K., Jr., and Reeves, C. C., Jr., 1974, Brownfield sheet: University of Texas, Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

_______1976, Hobbs sheet: University of Texas at Austin at Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Eifler, G. K., Jr., and Reeves, C. C., Jr., 1977, Clovis sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Eifler, G. K., Jr., Trauger, F. D., and Hawley, J. W., 1983, Tucumari sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Elder, G. R., Duffin, G. L., and Rodriguez, E., 1980, Records of wells, water levels, pumpage, and chemical analyses of water from the Carrizo aquifer in the Winter Garden area, Texas, 1970 through 1977: Texas Department of Water Resources Report 254, 127p.

Engineering Enterprises, Inc., 1987, Report to Congress, class V wells—Current inventory effects on groundwater technical recommendations: Engineering Enterprises, Inc., Prepared for U.S. Environmental Protection Agency, Washington, D.C., EPA Contract No. 68-03-3416, Assignment No. 0-5, 685 p., 5 appendices.

Feliciano, D. V., 1985, Groundwater: What is it, and how it is being protected: Congressional Research Service, Environment and Natural Resources Policy Division, Washington, D.C., Report 58-191 ENR, 50p.

Ferguson, J. F., and Gavis, J., 1972, A review of the arsenic cycle in natural waters: Department of Geography and Environmental Engineering, The Johns Hopkins University, Baltimore, MD, Water Research Pergamon Press, 1972, Printed in Great Britain, p. 1259-1274.

Ferris, J. G., Knowles, D. B., Brown, R. H., and Stallman, R. W., 1962, Theory of aquifer tests: U. S. Geological Survey Water-Supply Paper 1536-E, 174p.

Fetter, C. W., 1980, Applied hydrogeology: Charles E. Merrill Publishing Company, Columbus, Ohio, 488p.

Fink, B. E., 1963, Ground-water geology of Triassic deposits, northern part of the Southern High Plains of Texas: High Plains Underground Water Conservation District No. 1 Report No. 163, 79p.

_______1965, Investigation of ground- and surface-water contamination near Harrold, Wilbarger County, Texas: Texas Water Commission LD-0365, 22p.

Fogg, G. E., and Charbeneau, R. J., 1985, Impacts of lignite mining on groundwater in Texas, *in* Smerdon, E. T., and Jordan, W. R., eds., Issues in groundwater management, Water Resources Symposium no. 12, Center for Research in Water Resources, Bureau of Engineering Research, College of Engineering, The University of Texas at Austin, p. 361-377.

Fogg, G. E., Kaiser, W. R., and Ambrose, M. L., in press, The Wilcox Group and Carrizo Sand (Paleocene-Eocene) in the Sabine Uplift area, Texas: Ground-water hydraulics and hydrochemistry: The University of Texas at Austin, Bureau of Economic Geology.

Follett, C. R., 1942, Wood County, Texas, records of wells and springs, drillers' logs, water analyses, and map showing locations of wells and springs: Texas State Board of Water Engineers Miscellaneous Publication 303, 43p.

______1943, Rusk County, Texas, (Northwestern part) records of wells, drillers' logs, water analyses and map showing locations of wells: Texas State Board of Water Engineers Miscellaneous Publication 238, 58p.

______1944, Ground water resources in the vicinity of Vernon, Texas: Texas State Board of Water Engineers Miscellaneous Publication 286, 46p.

______1956a, Records of water level measurements in Bexar County, Texas: Texas Board of Water Engineers Bulletin 5606, 61p.

______1956b, Records of water-level measurements in Comal and Guadalupe Counties, Texas: Texas Board of Water Engineers Bulletin 5610, 34p.

______1956c, Records of water-level measurements in Kinney, Uvalde and Val Verde Counties, Texas, 1929 to March 1956: Texas Board of Water Engineers Bulletin 5611, 72p.

______1956d, Records of water-level measurements in Childress, Cottle, Hardeman, and King Counties, Texas, 1940 to January 1956: Texas Board of Water Engineers Bulletin 5613, 28p.

______1956e, Records of water-level measurements in Foard and Wilbarger Counties, Texas, 1936 to January 1956: Texas Board of Water Engineers Bulletin 5614, 32p.

Follett, C. R., 1956f, Records of water-level measurements in Dimmit, Maverick, and Zavala Counties, Texas, 1920, 1928 to September 1956: Texas Board of Water Engineers Bulletin 5617, 76p.

______1966, Ground-water resources of Caldwell County, Texas: Texas Water Development Board Report 12, 140p.

______1970, Ground-water resources of Bastrop County, Texas: Texas Water Development Board Report 109, 145p.

______1973, Ground-water resources of Blanco County, Texas: Texas Water Development Board Report 174, 96p.

______1974, Ground-water resources of Brazos and Burleson Counties, Texas: Texas Water Development Board Report 185, 197p.

Follett, C. R., Gabrysch, R. K., 1965, Ground-water resources of De Witt County, Texas: Texas Water Commission Bulletin 6518, 113p.

Freeze, R. A., and Cherry, J. A., 1979, Groundwater: Englewood Cliffs, N. J., Prentice-Hall Inc., 604p.

Gabrysch, R. K., 1984, Ground-water withdrawals and land-surface subsidence in the Houston-Galveston region, Texas, 1906-80: Texas Department of Water Resources Report 287, 64p.

Gabrysch, R. K., and McAdoo, G. D., 1972, Development of ground-water resources in the Orange County area, Texas and Louisiana, 1963-71: Texas Water Development Board Report 156, 47p.

Gabrysch, R. K., Naftel, W. L., McAdoo, G. D., and Bonnet, C. W., 1974, Ground-water data for Harris County, Texas, volume II, records of wells, 1892-1972: Texas Water Development Board Report 178, 181p.

Garza, Sergio, 1966, Ground-water resources of the San Antonio area, Texas, a progress report on studies, 1960-64: Texas Water Development Board Report 34, 31p.

Gates, J. S., and Stanley, W. D., 1976, Hydrologic interpretation of geophysical data from the southeastern Hueco Bolson, El Paso and Hudspeth Counties, Texas: U.S. Geological Survey Open-File Report 76-650, 37p.

Gates, J. S., White, D. E., Stanley, W. D., and Hans, D. A., 1978, Availability of fresh and slightly saline ground water in the basins of westernmost Texas: U.S. Geological Survey Open-File Report 78-663, 115p.

George, W. O., and Johnson, C. E., 1941, Memorandum on ground-water resources in the vicinity of Crowell, Texas: Texas State Board of Water Engineers Miscellaneous Publication 63, 33p.

Gordon, C. H., 1913, Geology and underground waters of the Wichita region, North-central Texas: United States Geological Survey Water-Supply Paper 317.

Greene, C. J., 1983, Underground injection control technical assistance manual - subsurface disposal and solution mining: Texas Department of Water Resources Report 274, 61p.

Grim, E. C., and Hill, R. D., 1974, Environmental protection in surface mining of coal: National Environmental Research Center, Office of Research and Development, U.S. Environmental Protection Agency, Mining Pollution Control Branch (Cincinnati, Ohio), Industrial Waste Treatment Research Laboratory, Edison, N.J., Program Element No. 1BB040, 277p.

Ground Water Monitor, 1986, New York study says 82 percent of waste is dumped in landfills that leak: Ground Water Monitor, June 10, 1986, 92p.

Grubb, H. F., 1984, Planning report for the Gulf Coast regional aquifer-system analysis in the Gulf of Mexico coastal plain, United States: U.S. Geological Survey Water-Resources Investigations Report 84-4219, 30p.

Gutentag, E. D., Heines F. J. , Krothe, N. C., Luckey, R. R., and Weeks, J. B., 1984, Geohydrology of the High Plains Aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400-B, 63p.

Hammond, W. W., 1969, Ground-water resources of Matagorda County, Texas: Texas Water Development Board Report 91, 180p.

Harris, H. B., 1965, Ground-water resources of La Salle and McMullen Counties, Texas: Texas Water Commission Bulletin 6520, 96p.

Hart, M. A., 1989, DRASTIC: a systematic approach to ground water pollution potential mapping in Texas, *in* Proceedings of the 22nd Water for Texas Conference: College Station, Texas, Texas Water Resources Institute.

Hem, J. D., 1985, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 263p.

Hendry, Jim, 1988, The nitrate problem: Water Well Journal, v. 42, No. 8, p. 4 - 5.

Henningsen, E. R., 1962, Water diagenesis in lower Cretaceous Trinity aquifers of central Texas: Baylor Geological Studies Bulletin No. 3, 38p.

Henry, C. D., and Gluck, J. K., 1981, A preliminary assessment of the geologic setting, hydrology, and geochemistry of the Hueco Tanks geothermal area, Texas and New Mexico: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 81-1, 48p.

Hentz, T. G., and Brown, L. F., Jr., 1987, Wichita Falls-Lawton sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

High Plains Underground Conservation District No. 1, 1988, Observation well water level data and water quality data from selected wells: High Plains Underground Conservation District No. 1, Lubbock, TX, individual reports on all counties within the District.

Hiss, W. L., 1975, Stratigraphy and ground-water hydrology of the Capitan aquifer, southeastern New Mexico and western Texas: U.S. Geological Survey, Review copy in the files of the Texas Water Commission, 396p.

Hobday, D. K, Woodruff, C. M., Jr., and McBride, M. W., 1981, Paleotopographical and structural controls on non-marine sedimentation of the lower Cretaceous Antlers Formation and correlatives, north Texas and southeastern Oklahoma: Society of Economic Paleontologists and Mineralogists Special Publication No. 31, p. 71-87.

Howard, J. W., 1968, Water-level data from observation wells in the Northwestern Gulf Coastal Plain of Texas: Texas Water Development Board Report 70, 212p.

Huberty, M. R., Philsbury, A. F., and Sokoloff, V. P., 1945, Hydrologic studies in Coachella Valley, California: California University, College of Agriculture, Division of Irrigation, preliminary rept., p. 14-15.

Huggins, L. P., 1936, Foard County, Texas, records of wells, drillers' logs, and water analyses, and maps showing location of wells: State Board of Water Engineers Miscellaneous Publication 84, 61p.

Iglehart, H. H., 1967, Occurrence and quality of ground water in Crockett County, Texas: Texas Water Development Board Report 47, 165p.

Johnson, G. V., 1988, Soil testing as a guide to prudent use of nitrogen fertilizers in Oklahoma agriculture, *in* Fairchild, D. M., ed., Ground water quality and agricultural practices: Chelsea, Michigan, Lewis Publishers, Inc., p. 127-135.

Jones, D. C., 1973, An investigation of the nitrate problem in Runnels County, Texas: U.S. EPA; Office of Research and Monitoring; Washington, D.C.; Environmental Protection Technology Series EPA-R2-73-267, 215 p.

Kaiser, W. R., and Ambrose, M. L., 1986, Hydrochemical mapping in the Wilcox-Carrizo aquifer, Sabine Uplift area, *in* Kaiser, W. R., and others, Geology and ground-water hydrology of deep basin lignite in the Wilcox Group of East Texas: University of Texas at Austin, Bureau of Economic Geology, Special Publication, p. 85-99.

Kaiser, W. R., Fogg, G. E., and Ambrose, M. L., in progress, The Wilcox Group and Carrizo Sand (Paleocene-Eocene) in the East Central area, Texas: Ground-water hydraulics and hydrochemistry: The University of Texas at Austin, Bureau of Economic Geology.

Kier, R. S., Brown, L. F., Jr., and Harwood, P., 1976, Brownwood sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Kier, R. S., Garner, L. E., and Brown, L. F., Jr., 1977, Land resources of Texas: The University of Texas at Austin, Bureau of Economic Geology Special Report Map, scale 1:500,000.

Kingston, Mike and Crawford, M. G., eds., 1987, 1988-1989 Texas almanac and state industrial guide: Dallas, TX, The Dallas Morning News, 640p.

Kingston, M. T., and Harris, Ruth, eds., 1983, 1984-1985 The Texas almanac and state industrial guide: Dallas, TX, The Dallas Morning News, 704 p.

Klemt, W. B., 1981, Evaluating the ground-water resources of the High Plains of Texas, Neutron-probe measurement of deep soil moisture as an indication of aquifer recharge rates: Texas Department of Water Resources LP-142, 31p.

Klemt, W. B., Duffin, G. L., and Elder, G. R., 1976, Ground-water resources of the Carrizo Aquifer in the Winter Garden area of Texas: Texas Water Development Board Report 210, v. 1, 73p., and v. 2, 467p.

Klemt, W. B., Perkins, R. D., and Alvarez, H. J., 1975, Ground-water resources of part of central Texas with emphasis on the Antlers and Travis Peak Formations: Texas Water Development Board Report 195, v. 1, 63p.

______1978, Ground water resources of part of central Texas with emphasis on the Antlers and Travis Peak Formations: Texas Water Development Board Report 195, v. 2, 535p.

Knape, B. K., ed., 1984, Underground injection operations in Texas—A classification and assessment of underground injection activities: Texas Department of Water Resources Report 291, 197p.

Knowles, D. B., 1952, Ground-water resources of Ector County, Texas: Texas Board of Water Engineers Bulletin 5210, 117p.

Knowles, D. B., and Kennedy, R. A., 1958, Ground-water resources of the Hueco Bolson northeast of El Paso, Texas: U.S. Geological Survey Water-Supply Paper 1426, 186p.

Knowles, Tommy, Nordstrom, Phillip, and Klemt, W. B., 1984, Evaluating the ground- water resources of the High Plains of Texas: Texas Department of Water Resources Report 288, V. 1, 177p.

Kohler, D. P., 1984, Uranium solution mining wells, *in* Knape, B. K., ed., Underground injection operations in Texas, Texas Department of Water Resources Report 291, p. 4-1 through 4-21.

Kreitler, C. W., 1975, Determining the source of nitrate in ground water by nitrogen isotope studies: University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 83, 57p.

Kreitler, C. W., Senger, R. K., and Collins, E. W., 1987, Geology and hydrology of the northern segment of the Edwards aquifer with an emphasis on the recharge zone in the Georgetown, Texas, area: The University of Texas at Austin, Bureau of Economic Geology Contract No. IAC(86-87)-1046 Report, 115 p.

Larkin, T. J., and Bomar, G. W., 1983, Climatic atlas of Texas: Texas Department of Water Resources LP-192, 151p.

Lee, J. N., 1986, Shallow ground-water conditions, Tom Green County, Texas: U. S. Geological Survey Water-Resources Investigations Report 86-4177.

Logan, T. L., Davidson, J. M., Baker, J. L., and Overcash, M. R., 1987, Effects of conservation tillage on groundwater quality—Nitrates and pesticides: Chelsea, Michigan, Lewis Publishers, Inc., 281p.

Lonsdale, J. T., and Day, J. R., 1937, Geology and ground-water resources of Webb County, Texas: United States Department of the Interior, Geological Survey Water-Supply Paper 778.

Loskot, C. L., Sandeen, W. M., and Follett, C. R., 1982, Ground-water resources of Colorado, Lavaca, and Wharton Counties, Texas: Texas Department of Water Resources Report 270, 245p.

Lyle, W. M., 1937, Rusk County, Texas, records of wells, drillers' logs, and water analyses, and map showing location of wells: Texas State Board of Water Engineers Miscellaneous Publication 237, 87p.

______1938, Panola County, Texas, records of wells, drillers' logs, and water analyses, and map L. F. showing location of wells: Texas State Board of Water Engineers Miscellaneous Publication 202, 46p.

Maclay, R. W., Land, L. F., and Woodward, D. G., 1985, Influence of barrier faults on ground water flow in the Edwards aquifer, San Antonio region, Texas, *in* Proceedings of the Association of Ground Water Scientists and Engineers, Southern Regional Ground Water Conference, Sept. 18-19, 1985, National Water Well Association, Worthington, Ohio, 13p.

Maclay, R. W., Rettman, P. L., and Small, T. A., 1980, Hydrochemical data for the Edwards aquifer in the San Antonio area, Texas: Texas Department of Water Resources LP-131, 38p.

Maclay, R. W., and Small, T. A., 1983, Hydrostratigraphic subdivisions and fault barriers of the Edwards aquifer, south-central Texas, U.S.A.: Journal of Hydrology, Elsevier Scientific Publishing Co., Amsterdam, v. 61, p. 127-146.

______1986, Carbonate geology and hydrology of the Edwards aquifer in the San Antonio area, Texas: Texas Water Development Board Report 296, 90 p., also published in 1984 as U. S. Geological Survey Open-File Report 83-537, 72 p.

Maclay, R. W., Small, T. A., and Rettman, P. L., 1980, Water-level, recharge, discharge, specific capacity, well yield, and aquifer test data for the Edwards Aquifer in the San Antonio area, Texas: Texas Department of Water Resources LP-133.

Maderak, M. L., 1972, Ground-water resources of Hardeman County, Texas: Texas Water Development Board Report 161, 45p.

______1973, Ground-water resources of Wheeler and eastern Gray Counties, Texas: Texas Water Development Board Report 170, 66p.

Maier, F. J., 1950, Fluoridation of public water supplies: American Water Works Association Journal, v. 42, pt. 1, p. 1120 - 1132.

Mason, C. C., 1961, Ground-water geology of the Hickory Sandstone Member of the Riley Formation, McCulloch County, Texas: Texas Board of Water Engineers Bulletin 6017, 89p.

______1963, Ground-water resources of Refugio County, Texas: Texas Water Commission, Bulletin 6312, 127p.

Maxcy, K. F., 1950, Report on the relation of nitrate concentrations in well waters to the occurrence of methemoglobinemia: National Research Council Bull. Sanitary Eng. and Envir., app. D., 265p.

McFarland, Mike, 1988, Treating water containing nitrates: Water Well Journal, v. 42, no. 8, p. 4-5.

McGowen, M. K., and Lopez, C. M., 1983, Depositional systems in the Nacatoch Formation (Upper Cretaceous), northeast Texas and southwest Arkansas: University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 137, 59p.

McKalips, D. and Barnes, V. E., 1981, Sonora sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

McLaurin, Celeste, 1988, Occurrence, availability and chemical quality of ground water in the Blossom Sand aquifer: Texas Water Development Board Report 307, 38p.

McMillion, L. G., 1958, Ground-water geology in the vicinity of Dove and Croton Creeks, Stonewall, Kent, Dickens and King Counties, Texas, with special reference to salt-water seepage: Texas Board of Water Engineers Bulletin 5801, 57p.

McReynolds, Don, 1988, District pesticide sampling procedures: The Cross Section, Published Monthly by High Plains Underground Water Conservation District No. 1, Lubbock, TX, November 1988, v. 34, no. 11, p. 1-4.

Meinzer, O. E., 1923, Outline of ground-water hydrology, with definitions: U. S. Geological Survey Water-Supply Paper 494, 71p.

Meinzer, O. E., and Wenzel, L. K., 1942, Movement of ground water and its relation to head, permeability and storage, *in* Physics of the earth, Part 9, Hydrology: New York, McGraw-Hill, p. 444-478.

Miller, D. W., 1980, Waste disposal effects on ground water—A comprehensive survey of the occurrence and control of ground-water contamination resulting from waste disposal practices: (From: "The Report to Congress, Waste Disposal Practices and Their Effects on Ground Water" issued in 1977 by the Office of Water Supply and the Office of Solid Waste Management Programs, U. S. Environmental Protection Agency), Berkley, Premier Press, 512p.

Miller, J. C., Hackenberry, P. S., and DeLuca, F. A., 1977, Groundwater pollution problems in the southeastern United States: Geraghty & Miller, Inc., Post Washington, New York, Contract no. 68-03-2193, for Robert S. Kerr Environmental Research and Development Laboratory, U. S. Environmental Protection Agency, Ada, Oklahoma, Ecological Research Series EPA-600/3-77-012, 361p.

Molofsky, S. J., 1985, Ground-water evaluation from test hole drilling near Mission, Texas: Texas Department of Water Resources Report 292, 60 p.

Monitoring Work Group, 1986, Ground-Water Monitoring Workshop, and Temple, Barker and Sloane, Inc. under contract no. 68-01-7002, U.S. Government Printing Office: 1986-620-458/40660, 54p.

Morris, D. E., 1964, Occurrence and quality of ground water in Young County, Texas: Texas Water Commission, Bulletin 6415, 106p.

______1967, Occurrence and quality of ground water in Archer County, Texas: Texas Water Development Board Report 52, 85p.

Mosteller, M. A., 1970, Subsurface stratigraphy of the Comanchean Series in east central Texas: Baylor Geological Studies Bulletin No. 19, Baylor University Press, Waco, TX, 34p.

Mount, J. R., 1962, Ground-water conditions in the vicinity of Burnet, Texas: Texas Water Commission Memorandum Report No. 62-01, 63p.

______1963, Investigations of ground-water resources near Fredericksburg, Texas: Texas Water Commission Memorandum Report No. 63-03, 115p.

Mount, J. R., Rayner, F. A., Shamburger, V. M., Peckham, R. C., and Osborne, F. L., 1967, Reconnaissance investigation of the ground-water resources of the Colorado River Basin, Texas: Texas Water Development Board Report 51, 119p.

Mulder, R. D., 1954, Verontreiniging van grondwater: Meded No. 2 Raad Bijstand van Samenwerkende Waterleidinglaboratoria, Keuringsinstituut voor Waterleidingartikelen, The Hague, p. 19-22.

Muller, D. A., and Couch, H. E., 1972, Water well and ground-water chemical analysis data, Reagan County, Texas: Texas Water Development Board Report 145, 59p.

Muller, D. A., and Price, R. D., 1979, Ground-water availability in Texas—Estimates and projection through 2030: Texas Department of Water Resources Report 238, 77p.

Muse, W. R., 1966, Water-level data from observation wells in Culberson, Jeff Davis, Presidio and Brewster Counties, Texas: Texas Water Development Board Report 16, 62p.

Myers, B. N., and Dale, O. C., 1966, Ground-water resources of Bee County, Texas: Texas Water Development Board Report 17, 105p.

______1967, Ground-water resources of Brooks County, Texas: Texas Water Development Board Report 61, 102p.

Naftel, W. L., Vaught, K., Fleming, B., 1976, Records of wells, drillers' logs, water-level measurements, and chemical analyses of ground water in Harris and Galveston Counties, Texas, 1970-1974: Texas Water Development Board Report 203.

National Fire Prevention Association, 1987, Recommended practice for handling underground leakage of flammable and combustible liquids: Committee on Flammable Liquids, Technical Committee on Tank Leakage and Repair Safeguards, NFPA 329, 26p.

National Research Council, 1983, Management of hazardous industrial wastes—Research and development needs: National Research Council, National Advisory Board, National Academy Press, Washington, D.C., p. 42.

Nativ, Ronit, 1988, Hydrology and hydro-chemistry of the Ogallala aquifer, Southern High Plains: University of Texas at Austin, Bureau of Economic Geology, report in preparation.

Nativ, Ronit, and Gutierrez, G. N., 1987, Hydrogeology and hydrochemistry of Cretaceous aquifers, Texas Panhandle and Eastern New Mexico: University of Texas at Austin, Bureau of Economic Geology, OF-WTWI-1987-2, 57p.

Nativ, Ronit, and Smith, D. A., 1987, Hydrogeology and geochemistry of the Ogallala aquifer, Southern High Plains: Journal of Hydrogeology, 91, (1987), p. 217-253.

Nichols, C. E., Butz, T. R., Cagle, G. W., and Kane, V. E., 1977, Wide-spaced uranium geochemical survey in the Plainview, Lubbock, and Big Spring Quadrangles, Texas: National Uranium Resource Evaluation Program, Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennessee, Report Number K/UR-10, 71p.

Nordstrom, P. L., 1982, Occurrences, availability, and chemical quality of ground water in the Cretaceous aquifers of north-central Texas: Texas Department of Water Resources Report 269, v. 1, 109p.

______1987, Ground-water resources of the Antlers and Travis Peak Formations in the outcrop area of North-Central Texas: Texas Water Development Board Report 298, 297p.

Novotny, V., and Chesters, G., 1981, Handbook of nonpoint sources of pollution—Sources and management: Van Nostrand Reinhold Environmental Engineering Series, New York, Van Nostrand Reinhold Company, 311p.

Office of Technology Assessment, 1984, Protecting the nation's groundwater from contamination, Volume II: Office of Technology Assessment, Congress of the United States, Congressional Board of the 98th Congress, Washington, D.C., OTA-0-276, 503p.

Ogilbee, W., and Osborne, Jr., F. L., 1962, Ground-water resources of Haskell and Knox Counties, Texas: Texas Water Commission Bulletin 6209, 185p.

Ogilbee, William, Weselman, J. B., and Irelan, Burdge, 1962, Geology and ground-water resources of Reeves County, Texas: Texas Water Commission Bulletin 6214, volume I and II, 56p. and 245p., respectively.

Outlaw, D. E., and others, 1952, Winter Garden District, Dimmit and Zavala Counties and eastern Maverick County, Texas, records of wells, drillers logs, water analyses, and map showing locations of wells: Texas Board of Water Engineers, Bulletin 5203, 59p.

Payne, J. N., 1968, Hydrologic significance of lithofacies of the Sparta Sand Formation in Arkansas, Louisiana, Mississippi, and Texas–Geohydrology of the Claiborne Group: U.S. Geological Survey Professional Paper 569-A, 17p.

______1972, Hydrologic significance of lithofacies of the Cane River Formation or equivalents of Arkansas, Louisiana, Mississippi, and Texas—Geohydrology of the Claiborne Group: U.S. Geological Survey Professional Paper 569-C, 17p.

Peckham, R. C., 1965, Availability and quality of ground water in Leon County, Texas: Texas Water Commission Bulletin 6513, 43p.

Peters, J. L., and Charboneau, R. J., 1985, Ground-water impacts of solution mining, *in* Smerdon, E. T., and Jordan, W. R., eds., Issues in ground-water management, Water Resources No. 12, Center for Research in Water Resources, Bureau of Engineering Research, College of Engineering, The University of Texas at Austin, p. 379-382.

Pieper, M. K., Haenggi, W. T., and Wright, A. C., 1965, Tyler sheet: University of Texas, Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Pieper, M. K., Shelby, C. A., and Wright, A. C., 1966, Texarkana sheet: University of Texas, Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Pollock, C. R., 1982, Ground-water hydrogeology and geochemistry of a reclaimed lignite surface mine: Master's Thesis, Texas A&M University, College Station, 152p.

Pool, J. R., 1972(a), Water well and ground-water chemical analysis data, Irion County, Texas: Texas Water Development Board Report 146, 39p.

______1972(b), Water well and ground-water chemical analysis data, Sterling County, Texas: Texas Water Development Board Report 148, 40p.

Popkin, B. P., 1971, Ground-water resources of Montgomery County, Texas: Texas Water Development Board Report 136, 149p.

______1973a, Ground-water resources of Donley County, Texas: Texas Water Development Board Report 170, 66p.

______1973b, Ground-water resources of Hall and eastern Briscoe Counties, Texas: Texas Water Development Board Report 167, 84p.

Preston, R. D., 1969, Occurrence and quality of ground water in Shackelford County, Texas: Texas Water Development Board Report 100, 75p.

______1970, Occurrence and quality of ground water in Throckmorton County, Texas: Texas Water Development Board Report 113, 51p.

Preston, R. D. 1977, Ground-water conditions in the vicinity of Jacksboro, Jack County, Texas: Texas Department of Water Resources LP-4.

______1978, Occurrence and quality of ground water in Baylor County, Texas: Texas Department of Water Resources Report 218, 117p.

______1983, Occurrence and quality of ground water in the vicinity of Brownsville, Texas: Texas Department of Water Resources, Report 279, 99p.

Price, R. D., 1978, Occurrence, quality, and availability of ground water in Jones County, Texas: Texas Department of Water Resources Report 215, 235p.

______1979, Occurrence, quality, and quantity of ground water in Wilbarger County, Texas: Texas Department of Water Resources Report 240, 231p.

Price, R. D., Walker, L. E., and Sieh, T. W., 1983, Occurrence, quality, and availability of ground water in Callahan County, Texas: Texas Department of Water Resources Report 278, 157p.

Proctor, C. V., Jr., Brown, T. E., and Young K., 1974, Austin sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Proctor, C. V., Jr., McGowen, J. H., and Brown, T. E., 1979, Seguin sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Proctor, C. V., Jr., McGowen, J. H., and Haenggi, W. T., 1970, Waco sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

R. W. Harden and Associates, 1978, The Seymour aquifer, ground-water quality and availability in Haskell and Knox Counties, Texas: Texas Department of Water Resources, Report 226, v. 1, 63p., v.2, 261p.

Railroad Commission of Texas, 1966, Annual report-1986—Oil and Gas Division: Railroad Commission of Texas, 835p.

Rapp, K. B., 1988, Groundwater recharge in the Trinity aquifer, Central Texas: Baylor Geological Studies Bulletin No. 46, Baylor Printing Services, Waco, Texas, 34p.

Ratzlaff, K. W., 1982, Land-surface subsidence in the Texas coastal region: Texas Department of Water Resources Report 272, 26p.

Rayner, F. A., 1959a, Records of water-level measurements in Bell, McLennan and Somervell Counties, Texas, 1930 through 1957: Texas Board of Water Engineers Bulletin 5902, 20p.

______1959b, Records of water-level measurements in Crane and Midland Counties, Texas, 1937 through 1957: Texas Board of Water Engineers Bulletin 5906, 19p.

______1959c, Records of water-level measurements in Mitchell, Nolan, Sterling, and Tom Green Counties, Texas, 1938 through 1957: Texas Board of Water Engineers Bulletin 5907, 30p.

Rees, R. W., 1987, Records of wells, water levels, pumpage and chemical analyses from selected wells in parts of the Trans-Pecos Region, Texas, 1968 - 1980: Texas Water Development Board Report 301, 325p.

Rees, Rhys, and Buckner, A. W., 1980, Occurrence and quality of ground water in the Edwards-Trinity (Plateau) aquifer in the Trans-Pecos Region of Texas: Texas Department of Water Resources Report 255, 41p.

Reeves, C. C., Jr. and Miller, W. D., 1978, Nitrate, chloride and dissolved solids, Ogallala aquifer, West Texas: Ground Water, v. 16, no. 3, p. 167.

Reeves, R. D., 1969, Ground-water resources of Kerr County, Texas: Texas Water Development Board Report 102, 71p.

Reeves, R. D., and Lee, F. C., 1962, Ground-water geology of Bandera County, Texas: Texas Water Commission Bulletin 6210, 78p.

Reeves, R. D., and Small, T. A., 1973, Ground-water resources of Val Verde County, Texas: Texas Water Development Board Report 172, 145p.

Renfro, H. B., Feray D. E., and King P. B., 1973, Geological highway map of Texas: American Association of Petroleum Geologist, United States geological highway map series, Map No. 7.

ReVelle, Charles, and ReVelle, Penelope, 1974, Sourcebook on the environment, the scientific perspective: Houghton Mifflin Company, Boston, Mass., 332p.

Rettman, P. L., 1987, Ground-water resources of Limestone County, Texas: Texas Water Development Board Report 299, 99p.

Richter, B. C., Dutton, A. R., and Kreitler, C. W., 1987, Sources of salt-water pollution in western Tom Green County: University of Texas at Austin, Bureau of Economic Geology, IAC(86-87)-1003, 100p.

Richter, B. C., and Kreitler, C. W., 1985, Sources of shallow saline ground water in Concho, Runnels, and Tom Green Counties: University of Texas at Austin, Bureau of Economic Geology, IAC(84-85)-2122, 62p.

______1986, Geochemistry of salt-spring and shallow subsurface brines in the Rolling Plains of Texas and Southwest Oklahoma: University of Texas at Austin, Bureau of Economic Geology Report of Investigation No. 155, 47p.

Rogers, L. T., 1967, Availability and quality of ground water in Fayette County, Texas: Texas Water Development Board Report 56, 125p.

Russell, J. N., Peters, Joe, and Weeger, M. A., 1988, Ground water contamination investigation report (Complaint by the town of Ransom, Canyon, and Buffalo Springs in Lubbock County, Texas, regarding city of Lubbock's effluent disposal operations/Gray farm irrigation project): Duplicated report in the files of Texas Water Commission, 44p.

Samuell, J. H., 1937, Eastland County, Texas, records of wells, drillers' logs, water level measurements, analyses of water from wells, streams, and lakes, and map showing locations: State Board of Water Engineers Miscellaneous Report 76, 59p.

Sandeen, W. M., 1968, Ground-water resources of San Jacinto County, Texas: Texas Water Development Board Report 80, 100p.

______1972, Ground-water resources of Washington County, Texas: Texas Water Development Board Report 162, 105p.

______1984, Ground-water resources of Rusk County, Texas: U. S. Geological Survey Open-File Report 83-757, 118p.

Sandeen, W. M., and Wesselman, J. B., 1973, Ground-water resources of Brazoria County, Texas:

Texas Water Development Board Report 163, 199p.

Sayre, A. N., and Livingston, Penn, 1945, Ground-water resources of the El Paso area, Texas: U.S. Geological Survey Water-Supply Paper 919, 190p.

Scalf, M. R., Keeley, J. W., and LaFevers, C. J., 1973, Ground water pollution in the south central states: U.S. EPA, National Environmental Research Center, Office of Research and Monitoring, Corvallis, OR, Environmental Protection Technology Series EPA-R2-73-268, 182p.

Sceva, J. E., 1968, Liquid waste disposal in the lava terrain of central Oregon: Technical Projects Branch, Northwest Region, Federal Water Pollution Control Administration Report FR-4.

Schraps, W. G., 1972, Die Bedeutung der Filtereigenschaften des Bodens für die Anlage von Friedhofen. Mittilungen Deutsche Bodenkundl, Gesellschaft 16, p. 225-229.

Senger, R. K., and Kreitler, C. K, 1984, Hydrogeology of the Edwards aquifer, Austin area, central Texas: University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 141, 35p.

Seni, S. J., 1980, Sand-body geometry and depositional systems, Ogallala Formation, Texas: University of Texas at Austin, Bureau of Economic Geology Report of Investigation No. 105, 36p.

Shafer, G. H., 1956, Ground-water resources of the Crane Sandhills, Crane County, Texas: Texas Board of Water Engineers Bulletin 5604, 105p.

______1957, The use of ground water for irrigation in Childress County, Texas: Texas Board of Water Engineers Bulletin 5706, 21p.

______1965, Ground-water resources of Gonzales County, Texas: Texas Water Development Board Report 4, 93p.

______1970, Ground-water resources of Aransas County, Texas: Texas Water Development Board Report 124, 81p.

Shafer, G. H., 1974, Ground-water resources of Duval County, Texas: Texas Water Development Board Report 181, 117p.

Shafer, G. H., and Baker, E. T., 1973, Ground-water resources of Kleberg, Kenedy, and southern Jim Wells Counties, Texas: Texas Water Development Board Report 173, 162p.

Shelby, C. A., Pieper, M. K., and Wright, A. C., 1968, Palestine sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Slade, R. M., Jr., Dorsey, M. E., and Stewart, S. L, 1986, Hydrology and water quality of the Edwards aquifer associated with Barton Springs in the Austin area, Texas: U.S. Geological Survey Water-Resources Investigations Report 86-4036, 117p.

Smith, J. T., 1970, Ground-water resources of Collingsworth County, Texas: Texas Water Development Board Report 119, 115p.

Soil Conservation Service, U. S. Department of Agriculture, 1903-1986, Soil surveys of Texas counties: Washington, D.C., 184 volumes, county publication.

State Board of Water Engineers, 1936, Foard County, Texas, record of wells, drillers' logs, and water analyses, and maps showing location of wells: Texas State Board of Water Engineers Miscellaneous Publication 84, 61p.

______1939, Records of wells and springs, drillers' logs, water analyses, and map showing locations of wells and springs, San Saba County, Texas: Works Projects Administration Project 10444, Texas Water Development Board Miscellaneous Publication 243, 50p.

St. Clair, A. E., Evans, T. J., and Garner, L. E., 1976, Energy Resources of Texas 1976: University of Texas at Austin, Bureau of Economic Geology, ERM Maps, scale 1:1,000,000.

Stearman, J., 1960a, A reconnaissance investigation of alleged contamination of irrigation wells near Lockett, Wilbarger County, Texas: Texas Board of Water Engineers Miscellaneous Publication 163, 12p.

______1960b, Water levels in observation wells in Cameron, Hidalgo, and Starr Counties, Texas, 1950-1959: Texas Board of Water Engineers Bulletin 6008, 9p.

Strause, J. L., 1987, Texas ground-water quality: U. S. Geological Survey Open-File Report 87-0754, 12p.

Suffolk County Department of Health Services and Cosulich, W. F., Associates, 1980, Cesspool cleanser study final report: Suffolk County Department of Health Services, Hauppange, N.Y., Unnumbered Report, 35p.

Swartz, B. W., 1957, Records of water levels in Bastrop and Caldwell Counties, Texas, 1937 through December, 1956: Texas Board of Water Engineers Bulletin 5702, 24p.

Sweeten, J. M., 1988, Groundwater quality protection for livestock feeding operations: Third Annual Groundwater Protection Seminar, Texas Water Commission, Austin, Texas, October 27-28, 1988, Unpublished paper in files of Texas Water Commission, 11p.

Tank Talk, 1988, Special section: Aboveground tanks: Published Monthly by Steel Tank Institute, Northbrook, Il., July 1988, v.3, no. 7, 8p.

Tarver, G. E., 1966, Ground-water resources of Houston County, Texas: Texas Water Development Board Report 18, 89p.

______1968a, Ground-water resources of Tyler County, Texas: Texas Water Development Board Report 74, 106p.

______1968b, Ground-water resources of Polk County, Texas: Texas Water Development Board Report 82, 122p.

Taylor, H. D., 1976, Water-level and water-quality data from observation wells in Northeast Texas: Texas Water Development Board Report 198, 294p.

______1978, Occurrence, quantity, and quality of ground water in Taylor County, Texas: Texas Department of Water Resources Report 224, 135p.

______1979, Water-level data from observation wells in the Southern High Plains of Texas, 1971-77: Texas Department of Water Resources, Report 228, 484p.

Tewalt, S. J., 1986, Chemical characterization of Texas lignite: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 86-1, 54p.

Texas Agricultural Statistics Service, 1985, Texas field crop statistics: Texas Department of Agriculture and U.S. Department of Agriculture, 100p.

Texas Department of Agriculture, 1988, Investigation of arsenic contamination of groundwater occurring near Knott, Texas: Texas Department of Agriculture unnumbered report, 53p.

Texas Department of Health, 1988, Drinking water standards governing drinking water quality and reporting requirements for public water supply systems—25 TAC 337.1 - 337.18: Adopted by the Texas Department of Health on April 26, 1988.

Texas Department of Water Resources, 1981, Solid waste management plan for Texas 1980 - 1986: Texas Department of Water Resources LP-137, 101p.

______1984, Water for Texas—A comprehensive plan for the future, Texas Department of Water Resources GP-4-1, v. 1, 72p., v. 2, Technical Appendix.

Texas Rural Water Quality Network Project, 1986, Challenge of the colonias—Small community wastewater management in the Lower Rio Grande Valley: Texas Department of Agriculture, 13p.

Texas State Board of Water Engineers, 1936, Foard County, Texas, records of wells, drillers' logs, water analyses, and maps showing location of wells: Miscellaneous Publication 84, 61p.

______1942, Childress County, Texas, record of wells, drillers' logs, water analyses, and map showing locations of wells: Miscellaneous Report 50, 39p.

Texas State Soil and Water Conservation Board, 1978, Statewide control strategy for agricultural nonpoint source pollution in Texas: Texas State Soil and Water Conservation Board Unnumbered Report, 207p.

Texas Tech University, 1971, Infiltration rates and groundwater quality beneath cattle feedlots, Texas High Plains: Texas Tech University at Lubbock, Department of Geosciences, for the Water Quality Office, Environmental Protection Agency Project #16060EGS, Contract #14-12-804, Water Pollution Control Research Series 16060 EGS 01/71, 55p.

Texas Water Commission, 1986, Small quantity generator program: Texas Water Commission, Office of Public Information Circular C 86-02, 8p.

______1988a, Superfund in Texas: Texas Water Commission, Office of Public Information Circular C 88-03, 14p.

______1988b, What is hazardous waste?: Texas Water Commission, Office of Public Information Circular C 88-05, 4p.

______1988c, What is wastewater treatment?: Texas Water Commission, Office of Public Information Circular C 88-06, 6p.

Texas Water Development Board, 1986, Surveys of irrigation in Texas 1958, 1964, 1969, 1974, 1979, and 1984: Texas Water Development Board Report 294, 243p.

______1988, Ground-water conditions in Texas, 1980-1985: Texas Water Development Board Report 309, 53p.

The Cross Section, 1987, Texas beef production remains State's largest ag industry: Published Monthly by High Plains Underground Water Conservation District No. 1, Lubbock, TX, June 1987, v. 33, no. 6, p. 1 and 3.

______1988, Pesticide trace amounts found in a few samples: Published Monthly by High Plains Underground Water Conservation District No. 1, Lubbock, TX, November 1988, v. 34, no. 11, 4 p.

Thompson, D. R., 1967, Occurrence and quality of ground water in Brown County, Texas: Texas Water Development Board Report 46, 150p.

Thompson, G. L., 1966, Ground-water resources of Lee County, Texas: Texas Water Development Board Report 20, 135p.

______1967, Ground-water resources of Ellis County, Texas: Texas Water Development Board Report 62, 128p.

______1969, Ground-water resources of Johnson County, Texas: Texas Water Development Board Report 94, 95p.

______1972, Ground-water resources of Navarro County, Texas: Texas Water Development Board Report 160, 63p.

Thompson, W. E. and others, 1978, Ground-water elements of in situ leach mining of uranium, final report: Geraghty and Miller, Inc., for U.S. Nuclear Regulatory Commission.

Todd, D. K., 1959, Ground-water hydrology: New York, John Wiley and Sons, Inc., 336p.

Trace Metal Data Institute, 1979, Restoration of in situ uranium leaching sites incorporating reverse osmosis technology: Trace Metal Data Institute Report 605.

Turner, S. F., Robinson, T. W., White, W. N., 1960, Geology and ground-water resources of the Winter Garden District Texas, 1948: U.S. Geological Survey Water-Supply Paper 1481.

Underground Resource Management, Inc., 1982, Investigation of ground-water conditions as affected by past and proposed lignite mining, Powell Bend area, Bastrop County, Texas: Report prepared for the Railroad Commission of Texas and Engineering Science, Inc.

U. S. Bureau of Reclamation, 1973, Water Resources of El Paso County, Texas: Texas Water Development Board.

U.S. Congressional Budget Office, 1984, Hazardous waste management: U.S. Congressional Budget Office, Washington, D.C., p. 22.

U.S. Department of Agriculture, Soil Conservation Service, 1978, National handbook of conservation practices: U.S. Department of Agriculture, Soil Conservation Service.

U.S. Environmental Protection Agency (EPA), 1977, The report to Congress—Waste disposal practices and their effect on ground water: U.S. EPA, Office of Water Supply, Office of Solid Waste Management Programs, Washington, D.C.; Report January 1977, 512p.

______1980, Design manual—Onsite wastewater treatment and disposal systems: U.S. EPA, Office of Water Program Operations, Washington, D.C.; Office of Research and Development, Municipal Environmental Research Laboratory, Cincinnati, OH; Technology Transfer EPA/625/180-D12, p. 2-22.

______1983, Surface impoundment assessment, national report: U.S. EPA, Office of Drinking Water, Washington, D.C., p. 73-125.

U.S. Environmental Protection Agency (EPA), 1984a, Ground-water protection strategy: U.S. EPA, Office of Water, Office of Ground-Water Protection, Washington, D.C., 70p.

______1984b, Protecting ground water: The hidden resource: U.S. EPA, EPA Journal, Office of Public Affairs (A-107), Washington, D.C., v. 10, no.6, p. 17-19.

______1984c, Report to congress: Nonpoint source pollution in the U.S.: U.S. EPA, Office of Program Operations, Water Planning Division, January 1984, 122p.

______1984d, Environmental regulations and technology — Use and disposal of municipal wastewater sludge: U.S. EPA, Washington, D.C., p. 10.

______1984e, Text of EPA draft "son of superfund" report: Inside EPA Weekly Report, February 3, 1984, Special Supplement, p. 3.

______1985a, Overview of state ground-water program summaries, Volume 1: U.S. EPA, Office of Water, Office of Ground-Water Protection (WH-550G), Washington, D.C., 57p.

______1985b, A ground-water monitoring strategy for the U.S. Environmental Protection Agency: U.S. EPA, Office of Ground-Water Protection, With Assistance from: Office of Ground-Water Protection, Ground-Water Monitoring Work Group, Ground-Water Monitoring Workshop, and Temple, Barker and Sloane, Inc. under contract no. 68-01-7002, U.S. Government Printing Office: 1986-620-458/40660, 54p.

______1985c, Final report on the federal/state/ local nonpoint source task force and recommended national nonpoint source policy: U.S. EPA, Office of Water, January 1985, 49p.

______1986a, State program briefs—Pesticides in ground water: U.S. EPA, Office of Water, Office of Ground-Water Protection, Washington, D.C., p. 58-59.

______1986b, Pesticides in ground water: Background document: U.S. EPA, Office of Water, Office of Ground-Water Protection (WH-550G), Washington, D.C., 72 p.

U. S. Environmental Protection Agency (EPA), 1986c, Septic systems and ground-water protection—An executive's guide: U.S. EPA, Office of Water, Office of Ground-Water Protection, Washington, D.C., 13 p.

______1986d, Septic systems and ground-water protection—A program manager's guide and reference book: U.S. EPA, Office of Water, Office of Ground-Water Protection, Washington, D.C., 134p.

______1986e, Underground storage tanks/ environmentalists' briefing, February 13, 1986: U.S. EPA, Office of Underground Storage Tanks, Washington, D.C., p. 2.

______1987a, EPA activities related to sources of ground-water contamination: U.S. EPA, Office of Ground Water Protection (WH-550G), February 1987, 125 p.

______1987b, Handbook—Groundwater: U.S. EPA; Center for Environmental Research Information, Cincinnati, OH 45268; Robert S. Kerr Environmental Research Laboratory, Ada, OK 74820; Technology Transfer EPA/625/6-87/016, 212 p.

______1987c, 1986 needs survey report to congress-Assessment of needed publicly owned wastewater treatment facilities in the United States: U.S. EPA, Office of Municipal Pollution Control (WH-546), Washington, D.C., EPA 430/ 9-87-001, p. C-3.

______1987d, Agricultural chemicals in ground water—Proposed pesticide strategy: U.S. EPA, Office of Pesticides and Toxic Substances, Washington, D.C., December 1987, 150 p.

______1987e, Nonpoint source guidance: U.S. EPA; Office of Water, Office of Water Regulations and Standards, Washington, D.C., duplicated rept., July 1987, 28p.; Appendix A, B., and C.

______1988a, Protecting ground water—Pesticides and agricultural practices: U.S. EPA, Office of Ground-Water Protection, Washington, D.C., February 1988, 71p.

______1988b, Case studies on ground-water and surface water contamination from municipal solid waste landfills, criteria for municipal solid waste landfills (40 CFR part 258), subtitle D of

Resource Conservation and Recovery Act (RCRA): U.S. EPA, Office of Solid Waste, Washington, D.C., July, 1988, 91p.

U.S. Environmental Protection Agency (EPA), 1988c, Musts for USTs—A summary of the new regulations for underground storage tank systems. U.S. EPA, Office of Underground Storage Tanks, Washington, D.C., September 1988, 40 p.

U.S. Geological Survey, 1937, Geologic map of Texas: U. S. Geological Survey Map.

van Haaren, F. W. J., 1951, Kerkhoven als bronnen van waterverontreiniging (Cemeteries as sources of groundwater contamination), Water 35(16), p. 167-172.

van Schilfgaade, Jan, 1986, Agriculture, irrigation and water quality, *in* Summers, J. B., and Anderson, S. S., eds., Toxic substances in agricultural water supply and drainage: Proceedings from the 1986 Regional Meetings, Sponsored by U.S. Committee on Irrigation and Drainage, Denver, CO, p. 173-180.

Waechter, N. B., Lozo, F. E., Jr., and Barnes, V. E., 1972, Dallas sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

______1977, Del Rio sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Walker, L. E., 1967, Occurrence and quality of ground water in Coleman County, Texas: Texas Water Development Board Report 57, 103p.

______1979, Occurrence, availability, and chemical quality of ground-water in the Edwards Plateau region of Texas: Texas Department of Water Resources Report 235, 337p.

Water and Petroleum Study Group, 1970, Evaluation and treatment of oil and spill accidents on land with a view to the protection of water resources, Bonn, West Germany, Federal Ministry of the Interior, Second Edition, December.

Welder, F. A., and Reeves, R. D., 1962, Geology and ground-water resources of Uvalde County, Texas: Texas Water Commission Bulletin 6212, 262p.

Wesselman, J. B., 1967, Ground-water resources of Jasper and Newton Counties, Texas: Texas Water Development Board Report 59, 186p.

Wesselman, J. B., 1971, Ground-water resources of Chambers and Jefferson Counties, Texas: Texas Water Development Board Report 133, 183p.

______1972, Ground-water resources of Fort Bend County, Texas: Texas Water Development Board Report 155, 176p.

West, S. W., and Broadhurst, W. L., 1975, Summary appraisals of the Nation's ground-water resource–Rio Grande Region: U.S. Geological Survey Professional Paper 813-D, 39p.

Westat Inc., 1984, National survey of hazardous waste generators and treatment, storage and disposal facilities regulated under RCRA in 1981: Westat Inc., Rockville, MD, April 1984, Prepared for U.S. EPA, Office of Solid Waste, Washington, D.C., Figures 17 and 34, p. 104 and 205, respectively.

White, D. E., 1968, Ground-water resources of Upton County, Texas: Texas Water Development Board Report 78, 133p.

______1971, Water resources of Ward County, Texas: Texas Water Development Board Report 125, 227p.

______1973a, Ground-water resources of Sabine and San Augustine Counties, Texas: Texas Water Development Board Report 37, 123p.

______1973b, Water resources of Rains and Van Zandt Counties, Texas: Texas Water Development Board Report 169, 81p.

______1987, Summary of hydrologic information in the El Paso, Texas area, with emphasis on ground-water studies, 1903-80: Texas Water Development Board Report 300, 75p.

White, D. E., Gates, J. S., Smith, J. T., and Fry, B. J., 1980, Ground-water data for the Salt Basin, Eagle Flat, Red Light Draw, Green River Valley, and Prisido Bolson in westernmost Texas: Texas Department of Water Resources Report 259, 97p.

White, W. N., 1940, Northern part of Jim Hogg County, Texas - record of wells, driller's logs, water analyses, and map showing location of wells: Texas State Board of Water Engineer Miscellaneous Publication 147, 16p.

Wilcox, L. V., 1955, Classification and use of irrigation waters: U.S. Department of Agriculture Circular 969, 19p.

William F. Guyton & Associates, 1970, Ground-water conditions in Angelina and Nacogdoches Counties, Texas: Texas Water Development Board Report 110, 167p.

_______1972, Ground-water conditions in Anderson, Cherokee, Freestone, and Henderson Counties, Texas: Texas Water Development Board Report 150, 335p.

Willis, G. W., and Knowles, D. B., 1953, Ground-water resources of the Odell Sand Hills Wilbarger County, Texas: Texas Board of Water Engineers Bulletin 5301, 57p.

Wilson, C. A., 1973, Ground-water resources of Coke County, Texas: Texas Water Development Board Report 166, 87p.

Winslow, A. G., 1950, Geology and ground-water resources of Walker County, Texas: Texas Board of Water Engineers Bulletin 5003, 49p.

Winslow, A. G., and Kister, I. R., 1956, Saline-water resources of Texas: U.S. Geological Survey Water-Supply Paper 1365, 105p.

Wolterink, T. J., Williamson, H. J., Jones, D. C., Grimshaw, T. W., and Holland, W. F., 1979, Identifying sources of subsurface nitrate pollution with stable nitrogen isotopes; U.S. EPA; Robert S. Kerr Environmental Research Laboratory, Office of Research and Development, Ada, OK; Research Reporting Series EPA-600/4-79-050, 151 p.

Woodruff, C. M., and McBride, M. W., 1979, Regional assessment of geothermal potential along the Balcones and Luling-Mexia-Talco Fault Zones, Central Texas: University of Texas at Austin, Bureau of Economic Geology Final Report, prepared for U. S. Department of Energy, Division of Geothermal Energy, Contract No. DE-AS05-78ET28375, 151p.

Yaniga, P. M., 1986, Aquifer restoration: Comprehensive address to organic chemical contamination, in Proceedings of the NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water — Prevention, Detection and Restoration: Houston, Texas, National Water Well Association, Water Well Journal Publishing Co., p. 487-538.