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THE IMPACT OF SURFACE LIGNITE MINING ON SURFACE- AND GROUND-WATER QUALITY IN TEXAS

Contract J0295016
Texas A&M University

BUREAU OF MINES ★ UNITED STATES DEPARTMENT OF THE INTERIOR

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THE IMPACT OF SURFACE LIGNITE MINING
ON SURFACE-AND GROUND-WATER QUALITY IN TEXAS

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The impact of surface mining of Texas lignites on surface- and ground-water systems has been investigated. Surface-water and/or hydrogeologic analyses were conducted at two active and three proposed mines in the Texas lignite belt. Field studies supplemented by laboratory studies measured the infiltration characteristics of surface mined land, determined the quality of surface water runoff, and analyzed the hydrogeologic impacts of surface mining on ground-water quality and quantity in resaturated mine spoil. Adverse impacts of surface mining were found to be minimal in deltaic and coastal lagoon lignite deposits, which have shale-rich overburden; disturbances to the hydrologic balance were negligible. Mining of fluvial lignites associated with thick aquifer sands may result in degraded ground-water quality and quantity, but long-term impacts are projected to be minimal. Runoff from mined land is similar to that from unmined native soils; both have high suspended loads.

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FOREWORD

This report was prepared by the Texas A&M Research Foundation, Texas A&M University, College Station, Texas under USBM Contract No. J0295016. The contract was initiated under Public Law 95-465 (92 Stat. 1286). It was administered under the technical direction of Denver Mining Research Center with Mr. Gary McIntosh as Technical Project Officer. Mr. William R. Case was the contact administrator for the Bureau of Mines. This report is a summary of work recently completed as part of this contract during the period September 1978 to August 1979. This report was submitted by the authors in July 1982.

This project report presents the results of many interrelated research contracts or grants and is submitted as part of the contract requirements for the U.S. Bureau of Mines (Contract No. J0295016) and the Texas Energy Advisory Council (Contract No. IAC (78-79)1289; Project No. L-2-3), which is now the Texas Energy and Natural Resources Advisory Council. The Center for Energy and Mineral Resources and the Engineering Geosciences Research Program at Texas A&M University, The Aluminum Company of America, The Paul Weir Company, San Miguel Electric Cooperative, Southwestern Electric Power Company, Sunoco Energy Development Company and the Texas Municipal Power Agency also provided significant support for this research. This report presents the results of research that was completed during the period 1977-1982.

The authors are indebted to the many graduate students whose work is incorporated in this document: Leslie M. Levitan, William J. Schneider, Mary A. Bishop, Linda G. Bowman, Robert J. Charles, Jorge E. Rangel, John W. Snedden, Joseph Q. Watson, Gail L. Pepper, James L. Kennedy, Clifford R. Pollock and Kenneth W. Launius.

No patentable inventions were conceived during the course of this contract.

EXECUTIVE SUMMARY

This report presents the results of research performed under Contract No. J0295016, entitled "The Impact of Surface Lignite Mining on Surface- and Ground-Water Qualtiy in Texas."

A comprehensive investigation was carried out for the Bureau of Mines with matching support from the Texas Energy Advisory Council, the Center for Energy and Mineral Resources at Texas A&M University, and the Texas lignite industry to determine the impact of surface mining of Texas lignites on surface- and ground-water systems. Sub-objectives included measuring the infiltration characteristics of undisturbed and reclaimed mine soils, determining runoff quality from reclaimed mined land, and analyzing the hydrogeologic impacts of surface mining on the quantity and quality of ground water in resaturated mine spoil.

To accomplish these contract objectives, surface-water and hydrogeologic analyses were conducted at field sites at two active mines and three proposed mines throughout the Texas lignite districts. Laboratory studies supplemented the field work.

Adverse impacts of surface mining have been found to be minimal in most Texas lignite districts. Many lignite deposits are associated with clay-shale overburden that is not an aquifer. Disturbances to the hydrologic balance in shale-rich surface-mine land have been found to be negligible. Where thick aquifer sands are present in the overburden, such as in East Texas fluvial lignite mines, ground-water quality and quantity will be significantly degraded during active mining. However, the long-term impacts will be minimal. Delta plain lignite deposits will not experience such adverse conditions. Runoff water quality of reclaimed mined land is similar to that of unmined native soils. The suspended solids standard established by the Office of Surface Mining appears to be unrealistically low for typical Texas surface lignite mines. Infiltration rates on reclaimed mine spoil are less than those for many native soils, but the water retention in increased and the spoil has more available water.

Hydrogeologic and hydrochemical models of reclaimed Gulf Coast lignite mines have been developed. Graphs have been prepared that predict the hydraulic conductivity of mine spoil as a function of lithology, burial depth and percent sand in the overburden. The hydraulic conductivity of sand-rich spoil is almost constant with increasing burial depth; it is similar to that of the unmined sandy overburden. The hydraulic conductivity of shale-rich spoil in upper 10 m to 16 m of spoil is significantly greater than that of the unmined shale overburden, due primarily to swelling of the mine spoil during the mining process. The hydraulic conductivity of shale-rich spoil below 30 m of burial is similar to that of the unmined shale overburden, because shale-rich spoil is highly compressible.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Surface mining of Eocene Age, Gulf Coast lignite deposits will involve extensive acreages in Texas. Typical mines may disturb as much as 20,000 acres of land to depths up to 61 m. Mine spoil contains a variety of salts, acid-forming materials and potentially toxic elements that could, if improperly managed, eventually degrade surface- and ground-water quality. Also, changes in the infiltration characteristics of reclaimed mined land or in the flow characteristics of aquifers could adversely affect the hydrologic balance in the vicinity of the mine.

A comprehensive investigation has been carried out for the Bureau of Mines with numerous co-sponsors to determine the impact of surface mining of Texas lignites on surface- and ground-water systems. Sub-objectives included measuring the infiltration characteristics of undisturbed and reclaimed mine soils, determining the quality of runoff from reclaimed mined land, and analyzing the hydrogeologic impacts of surface mining on the quantity and quality of ground water in resaturated mine spoil. This study concentrates on the conditions in Texas; however, it also applies to Gulf Coast Eocene lignite deposits in Louisiana, Arkansas, Mississippi and Alabama.

Complete studies which include both hydrogeologic and surface-water quality analyses were done at field study sites in Atascoas, Grimes and Harrison Counties. A surface-water quality study was carried out at the Angelina County site. Hydrogeologic and infiltration rate studies were done at the Milam County site. Table 1 compares and contrasts the major climatic, soils, vegetation, hydrogeologic and geologic characteristics of the field sites. Figure 1 shows the location of the field test sites within the Texas lignite districts.

The investigation was originally divided into four tasks, namely infiltration characteristics, water quality, hydrogeology and regional geology. For clarification and convenience, the results of the research are reported under three major headings, which are geology and hydrogeology of Texas lignite deposits, hydrogeology of reclaimed Gulf Coast lignite surface

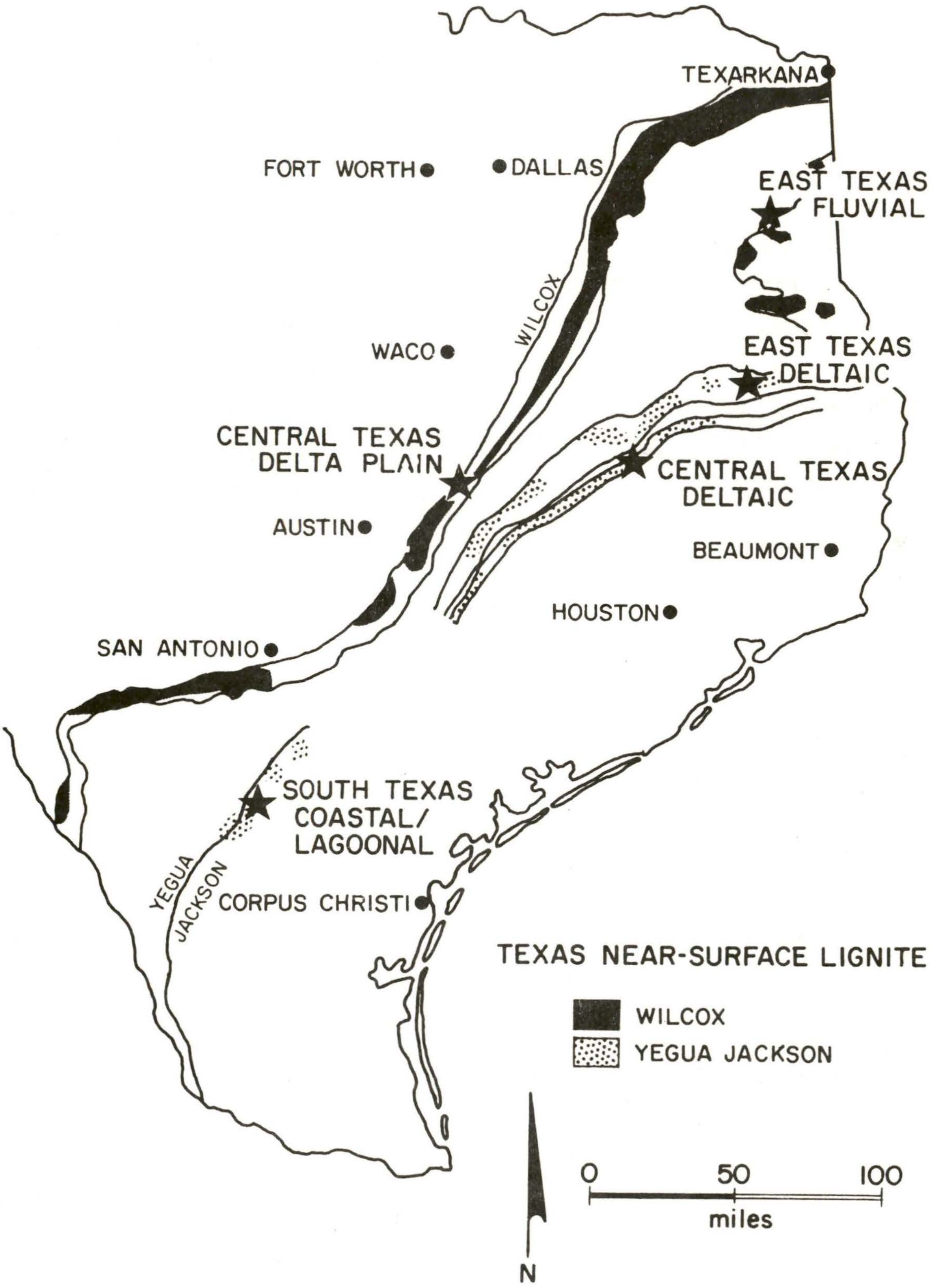

Figure 1. Distribution of near-surface lignite deposits in Texas (after Kaiser, 1974). Field test sites are designated by stars.

mines, and geochemistry and hydrochemistry of Texas lignite deposits.

Table 1. Description of Field Study Sites

County	Formation	Type of Overburden	Depositional Environment	Climate	Water Table	Vegetation
Angelina	Yegua/ Jackson Gp.	Clay	Deltaic	Humid	Shallow	Piney Woods
Atascosa	Jackson Gp.	Clay	Lagoonal	Semi-arid	Deep	Grasses
Grimes	Jackson Gp.	Clay	Deltaic	Moist sub-humid	Shallow	Post Oak
Harrison	Wilcox Gp.	Sand/Clay	Fluvial	Humid	Shallow	Piney Woods
Milam	Wilcox Gp.	Sand/Clay	Deltaic	Dry sub-humid	Shallow	Post Oak

BACKGROUND

Surface Mine Hydrogeology

Surface mining of lignite removes stratified overburden materials and replaces them in an unstratified condition behind the mining operation. The resulting mine spoil consists of a heterogeneous mixture of redistributed pre-mining overburden sediments. Pennington (1978) and Mathewson (1979) state that existing shallow aquifers are destroyed and the local water table is temporarily disrupted.

Mine spoil in Texas lignite mines expands in volume following mining to become more porous and permeable (Schneider, 1977). Herring (1977) notes that cast overburden in Kentucky subbituminous mines becomes an aquifer as it begins to refill by lateral discharge from previously mined areas and by vertical recharge through infiltration of surface waters. Increased permeability of spoil is also reported by Brown and others (1980) at the Nucla bituminous surface mine in southwestern Colorado.

The hydraulic conductivity of mine spoil in lignite surface mines should have significantly different directional properties than those of the pre-mine overburden (Bowman, 1978). Pre-mine overburden in Texas surface lignite mines consists of layers of high and low horizontal hydraulic conductivity with a very low vertical hydraulic conductivity. Bowman (1978) predicts that the mine spoil should become more nearly isotropic as the horizontal hydraulic conductivity decreases and the vertical hydraulic conductivity increases with respect to the pre-mine overburden. Van Voast (1974) makes a similar prediction for mine spoil at a Montana surface coal mine. He concludes that spoil produced by surface mining will have a greater vertical hydraulic conductivity than the material it replaces, but approximately the same horizontal hydraulic conductivity.

Van Voast and Hedges (1975) feel that the importance of the hydraulic conductivity of mine spoil lies not so much in the actual values as in their relationship to those of the unmined system. They identify the hydraulic conductivity and the storage coefficient of the mine spoil as the key characteristics which govern the volumes of water that can be transmitted through mined areas.

Rehm and others (1980) report that reclaimed spoil consists of parallel bands of high and low hydraulic conductivity which correspond to the spoil valleys and ridges respectively. The orientation of the spoil ridges with respect to the direction of the regional ground-water flow controls the flow rate through the spoil. Flow rates will be minimal when the spoil ridges are perpendicular to the regional flow direction. They will be at a maximum when they parallel the flow direction.

Surface Mine Hydrochemistry

Mine spoil is essentially a new entity in the hydrologic system in which it occurs. The effect, however, of this new material on the complex coal-bearing hydrologic system is poorly understood. Hounslow and others (1978) conclude that water composition changes that result from surface mining will always include some increase in dissolved solids. Moran and others (1978) suggest that the chemical quality of mine-spoil ground water in northern Great Plains lignite mines might be similar to lower-quality water in the pre-mine overburden. Van Voast and others (1977) reach a similar conclusion for younger spoil at a Montana subbituminous mine. They also note that water chemistry in mine-spoil ground water can vary sharply over even small lateral or vertical distances. As a general rule, ground water in cast overburden will have higher dissolved solids with much of the increase due to the sulfate ion (Herring, 1977).

The composition of mineral matter and organic matter in contact with soil water determines the water chemistry of the resulting ground water. Modification of the chemical character of water can occur by chemical precipitation, physical adsorption, ion exchange and sulfate reduction (Hem, 1959). Hydrochemical processes operate almost exclusively above the water table, with only ion exchange and sulfate reduction occurring actively below the water table (Groenewold et al., 1980). Moran and others (1978) note that soil texture regulates the rate of water flow through a soil. Thus, coarse-grained permeable materials that permit rapid water movement will experience a strong flushing of chemical constituents into the ground water. Finer-grained materials that are less permeable will permit slow water movement, which results in a weak flushing of chemical constituents into the ground water. In post-mining settings, Groenewold and others (1980) have found that groundwater quality is dependent on processes operating in the spoil.

Brown and others (1980) report that ground water at the Nucla bituminous surface mine in Colorado is of the $Ca\text{-}Mg\text{-}SO_4$ type, with lesser concentrations of Na and HCO_3 ions. Ground water derived from shales and coals is generally found to be $Ca\text{-}Mg\text{-}SO_4$ type water with high dissolved soilds (Hounslow et al., 1978). Ground water in spoil in Kentucky subbituminous surface mines is of the $Ca\text{-}Mg\text{-}SO_4\text{-}HCO_3$ type (Herring, 1977). French (1979) finds that mine-spoil water at the Big Brown lignite surface mine in Central Texas is high in Fe^{2+}, SO_4^{2-}, Cl^- and dissolved solids. He attributes the high SO_4^{2-} concentrations to pyrite oxidation, gypsum precipitation with subsequent dissolution, sulfate sorption by mine soil, and leaching of soil sulfate compounds. Moran and others (1978) propose a similar origin for high sulfate water in northern Great Plains surface lignite mines. Groenewold and others (1980) note that high $Na\text{-}SO_4$ water can develop in mine spoil which is derived from pyritic and sodium montmorillonitic flood basin sediments.

RESEARCH METHODOLOGY

Five research sites were selected for this study; three are in proposed lignite mines having test pits and two are at active surface mines (Table 2). Bulk sampling pits (test pits) were excavated by dragline through approximately 13 m of overburden to obtain 3-5 short tons of lignite. The lignite samples were used for burn tests in power plant boiler design. Typical pit dimensions were 26 m x 30 m x 13 m deep. Reclaimed test pits provide a small study area that has disturbed (mined) and undisturbed land. Active surface mines have also been studied. These mines provide actual mined-land field conditions where time effects of surface mining on ground water can be investigated. Test sites have been selected at these mines based on time since mining and reclamation, topography and reclamation practices.

Table 2. Data Acquisition at Field Study Sites

County	Lignite Formation	Comments
Angelina	Yegua Fm./ Jackson Gp.	Water quality -- test pit
Atascosa	Jackson Group	Complete study -- active mine
Grimes	Jackson Group	Complete study -- test pit
Harrison	Wilcox Group	Complete study -- test pit
Milam	Wilcox Group	Hydrogeology and ground-water quality -- active mine

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Complete studies include both hydrogeologic and water quality analyses. Required geologic data to make a hydrogeologic evaluation of the Angelina lignite deposit was not available for this study. Surface-water qualtiy analyses were not conducted at the Milam County lignite mine.

The research was divided into four components: infiltration characteristics, water quality, hydrogeologic analyses and mine hydrogeology.

Infiltration Characteristics

Infiltration characteristics of natural and reclaimed mine soils have been measured in the field using a rainfall simulator on three major soil series existing before mining, on leveled spoil piles when available, and on revegetated portions of the existing test pits. The rainfall simulator was selected for this study due to the difficulty in obtaining sufficient field data in the limited project period.

Bench marks were established and 12 plots of equal size were cordoned in a random block design. The actual plot size was limited to the test pit area, but a minimum plot size of 3 m by 6 m was employed. Twelve plots provide at least three replications for four liming treatments. A minimum of three soil profiles were sampled in each plot. Soil physical and chemical properties have been determined, and the variance in the data has been analyzed to evaluate the spatial variability between plots and treatments. Hydrological parameters were evaluated using simulated rainfall to evaluate infiltration and runoff characteristics of the native and mine soils. Additionally, three sites in each predominant soil series in the respective mine areas were evaluated in the same manner as the spoil test plots. These results have served as the background controls from which statistical comparisons have been made using analyses of variance and correlations to assess the significance of the data.

Water Quality

Total analyses for As, B, Be, Fe, Co, Cr, Zn, Ni, Cd, Cu, Mn, Pb, Hg, V, Se, other ions, pH, and total dissolved salts have been determined on mine spoil materials at the available test pit sites. Those elements which occur in significant quantities may be soluabilized in the spoil material or soils and contaminate runoff or ground water. Existing soil values (background levels) were used to evaluate the impact of surface mining. Leachate and surface water were then analyzed for those elements indicated as potential contaminants, primarily Fe and Mn, from the background profile distributions Leachate water was collected from column experiments on mine soils, overburden cores and mine spoil samples.

All water samples generated in the rainfall runoff study have been analyzed for pH, total salts, Fe and Mn. Plots on revegetated test pits in Angelina, Grimes and Harrison Counties were equipped with a buried 5 gallon pail at the lowest point in each plot to catch runoff from natural rainfall. Samples were gathered monthly, depending on rainfall events; they were analyzed for pH, electric conductivity, Fe and Mn. Data has been gathered from both artificial and natural rainfall to determine the quality of runoff.

Attempts to obtain samples of ground water from the reclaimed test pits were not successful. The drilling equipment available to the study was not able to drill in the saturated clay materials. Whenever the drill hole penetrated below the saturated zone, the hole would immediately squeeze closed which prevented the placement of a sampling well. However, water samples were collected and analyzed from monitoring wells in resaturated mine spoil at an active delta plain lignite mine.

Hydrogeologic Analyses

The hydraulic conductivity of aquifers and aquitards and the local hydrogeologic characteristics of the overburden have been determined for the pre-mine conditions using undisturbed samples and *in situ* measurements. Measurements were then made in test pits and the active mines to determine the post-mining hydrogeologic characteristics. Hydraulic conductivity values of the upper 2 m of the test pit (mined soils) and unmined soils has been determined from laboratory testing of undisturbed samples. Undisturbed mine spoil, partially disturbed mine spoil and simulated spoil samples were tested in the laboratory using a falling-head permeameter attached to a soil consolidometer. Effective stress analyses were used to reproduce the stress conditions that would be experienced by resaturated mine spoil at various burial depths.

At the Milam County mine, *in situ* hydraulic conductivity measurements have been made at 6 m below the ground surface in mined lands that were mined approximately 1, 3, 5, 7, 10 and 20 years ago. A geophysical survey of 275 acres of reclaimed land ranging from active to 7 years old were made to map the ground-water table. This survey was intended to determine the rate of formation and the characteristics of the reclaimed mine ground-water system. Pumping tests and piezometer analyses have been made in 25 year old mined land to determine the hydrologic characteristics of resaturated mine spoil. Four shallow, completely penetrating, 10 cm diameter monitoring wells were used for this study. Sand-rich overburden at the Harrison County test pit has been excavated and reclaimed to determine the changes in hydrologic properties of aquifer sands that have been disturbed by surface mining.

Mine Hydrogeology

The stratigraphic position and environment of deposition of the lignite deposits at the field test sites have been determined by analysis of continuous cores, geophysical logs and highwall exposures. The mine-site geologic characteristics have been investigated to determine whether the test pit sites are representative of the hydrogeologic conditions in the proposed mines. These studies provide background data on the stratigraphic relationship between the test pit site and the entire mine site. They allow for extrapolation of site-specific results to regional conditions in similar geologic environments.

The stratigraphy of the east Texas fluvial lignite deposit and overburden formations was determined by analyzing 11 continuous cores and 400 geophysical logs. Continuous cores range in length from 23 m to 49 m and have been taken from locations throughout the site. Each core was described in detail, noting lithology, grain size, color, texture, sorting, sedimentary structures, and other characteristic features. Forty-five thin sections were made from selected sand samples and point-counted for composition and texture. The geophysical logs, most of which were obtained from 61 m deep rotary drill holes, included gamma-gamma density, natural gamma and single-point electrical resistivity readings.

The stratigraphy of the Central Texas deltaic lignite deposit and associated sediments was determined from an analysis of 9 continuous cores and more than 600 geophysical logs. Each core, which was 61 m long, was described in the same detail as the east Texas fluvial lignite cores. The geophysical logs were analog gamma-gamma density, natural gamma and single-point electrical resistivity logs. A few digital gamma-gamma density, natural gamma and borehole caliper logs were collected late in the project, as well as three digital electrode resistivity logs. Digital logging equipment was not available during the overburden coring program. Geophysical logs were calibrated against the overburden cores.

The stratigraphy and environment of deposition of the Central Texas delta plain lignite deposit was investigated by studying highwall exposures in an active pit at the mine. Exposed strata were measured and described, noting stratigraphic relationships among the sediments. Lithologic units were described in detail, noting lithology, grain size, color, texture, sorting, sedimentary structures and other characteristic features.

The stratigraphy of the South Texas coastal plain lignite deposit and associated overburden was determined from analysis of 3 continuous cores and more than 600 geophysical logs. The cores ranged from 20 m to 61 m in length and were described in detail, noting the characteristic composition, texture and sedimentary structures. Forty-three thin sections were point-counted for composition and texture to determine quantitative sedimentologic data. The core descriptions were used to calibrate the log characteristics of the geophysical logs.

GEOLOGY AND HYDROGEOLOGY OF TEXAS LIGNITE DEPOSITS

Regional Geology

Lignites in the Gulf Coast are associated with Tertiary continental sedimentation along the edge of the Gulf Coast basin. Lignite-bearing sediments crop out in bands that generally parallel the shoreline of the modern Gulf of Mexico. Lignite-bearing units occur in the Coastal Plain of Texas, Tennesse, Alabama, Louisiana, Mississippi and Arkansas. They are generally associated with non-marine sandstones and shales at the outcrop, which grade downdip into interbedded sandstones and shales of the shoreline and shallow marine environments, and then further downdip into deep water marine shales.

The major non-marine sandstone and shale units form a series of stacked wedges that thin and disappear Gulfward as they grade into marine sediments. Listed in their ascending order in Texas, these non-marine sedimentary wedges are the Wilcox Group, the Yegua Formation of the Claiborne Group, the Jackson Group, and the Frio Formation. Younger wedges of Miocene and Pleistocene age are found offshore and in southern Louisiana. Lignites in the Gulf Coastal Plain are located within updip non-marine sediments of the Wilcox Group, Yegua Formation and Jackson Group. Near-surface lignite deposits in commercial quantities occur mainly in the Calvert Bluff Formation of the Wilcox Group, the Yegua Formation of the Claiborne, and the Manning Formation of the Jackson Group.

Gulf Coast lignite is found as a component facies in ancient fluvial, delta plain and coastal plain depositional systems (Figure 2). The lignite was deposited as peat in poorly drained swamps and marshes situated away from sites of clastic sedimentation. Primary environments of deposition are stagnant, anaerobic bodies of water on slowly subsiding, low lying fluvial and coastal areas. In Texas, these environments were controlled by the location of Tertiary streams that supplied clastic sediments to the Gulf Coast basin. Coastal plain lignites are found in south Texas, farthest distant from the fluvial sources; delta plain and fluvial lignites occur in central Texas and east Texas. Figures 3 and 4 are schematic diagrams of

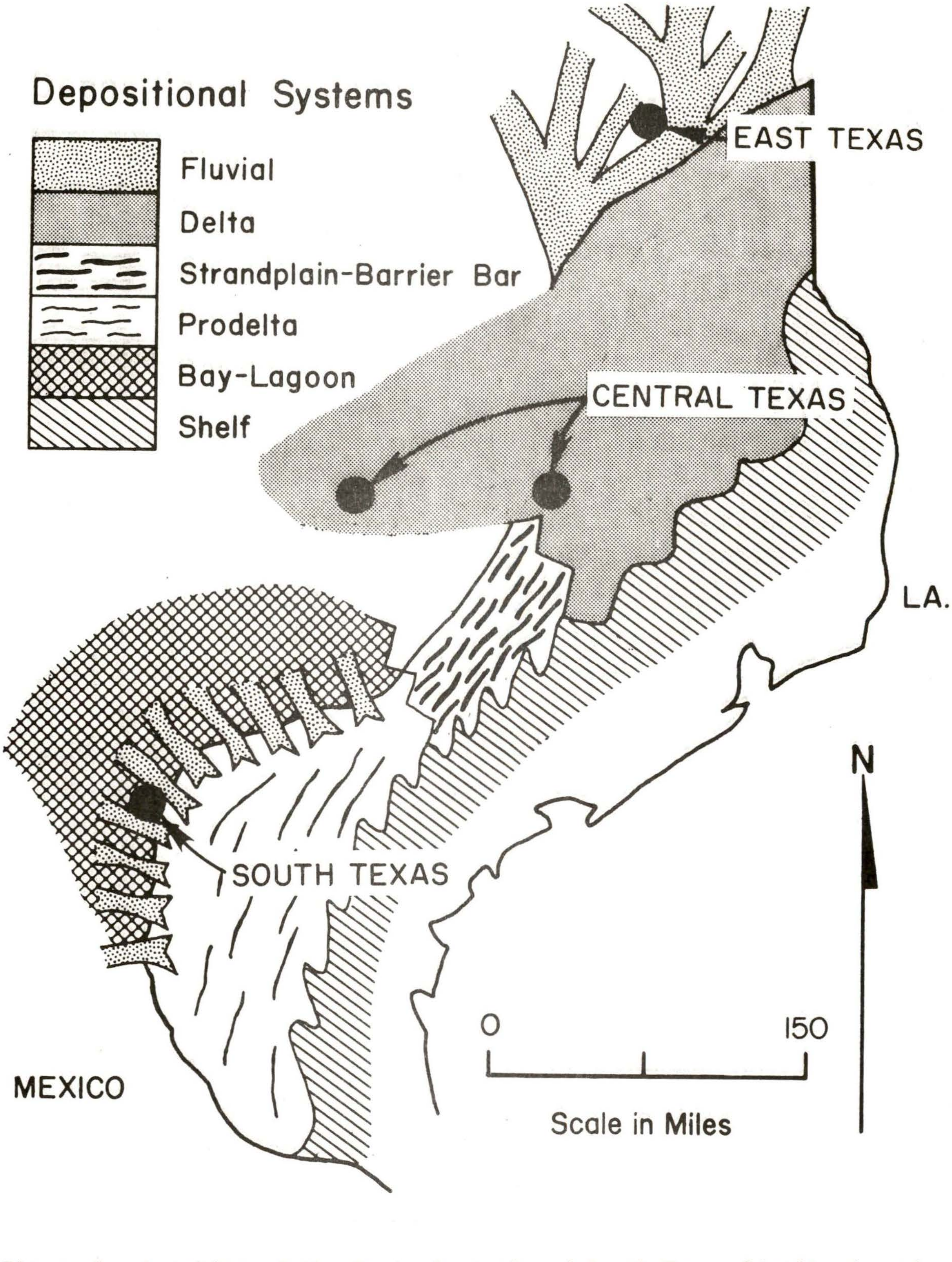


Figure 2. Location of the East, Central and South Texas lignite deposits and their associated depositional systems (modified from Mathewson, 1982b).

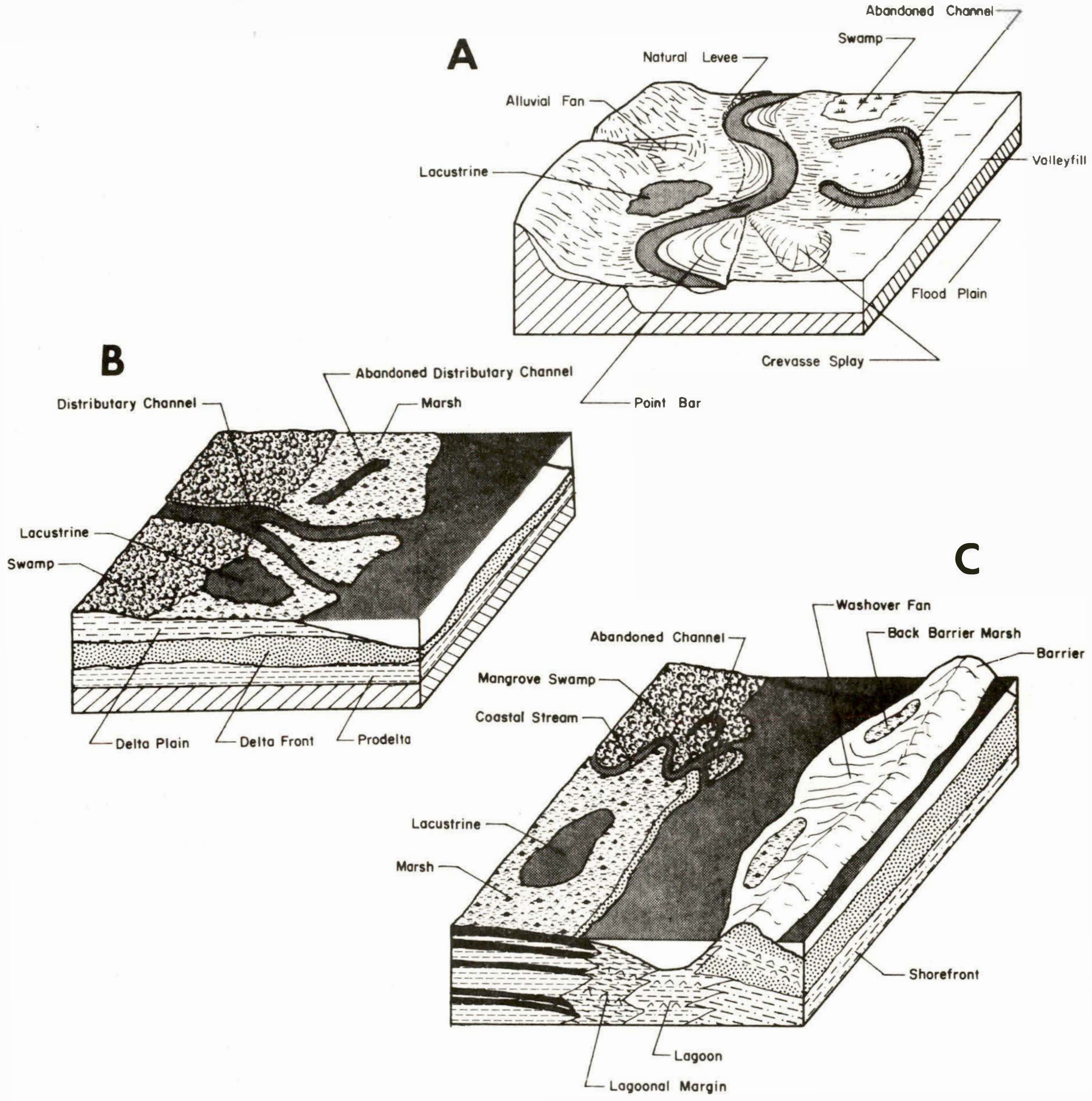


Figure 3. Schematic block diagrams showing the common depositional environments associated with lowland, meandering streams (A); delta systems (B); and coastal systems (C) (Mathewson, 1982a).

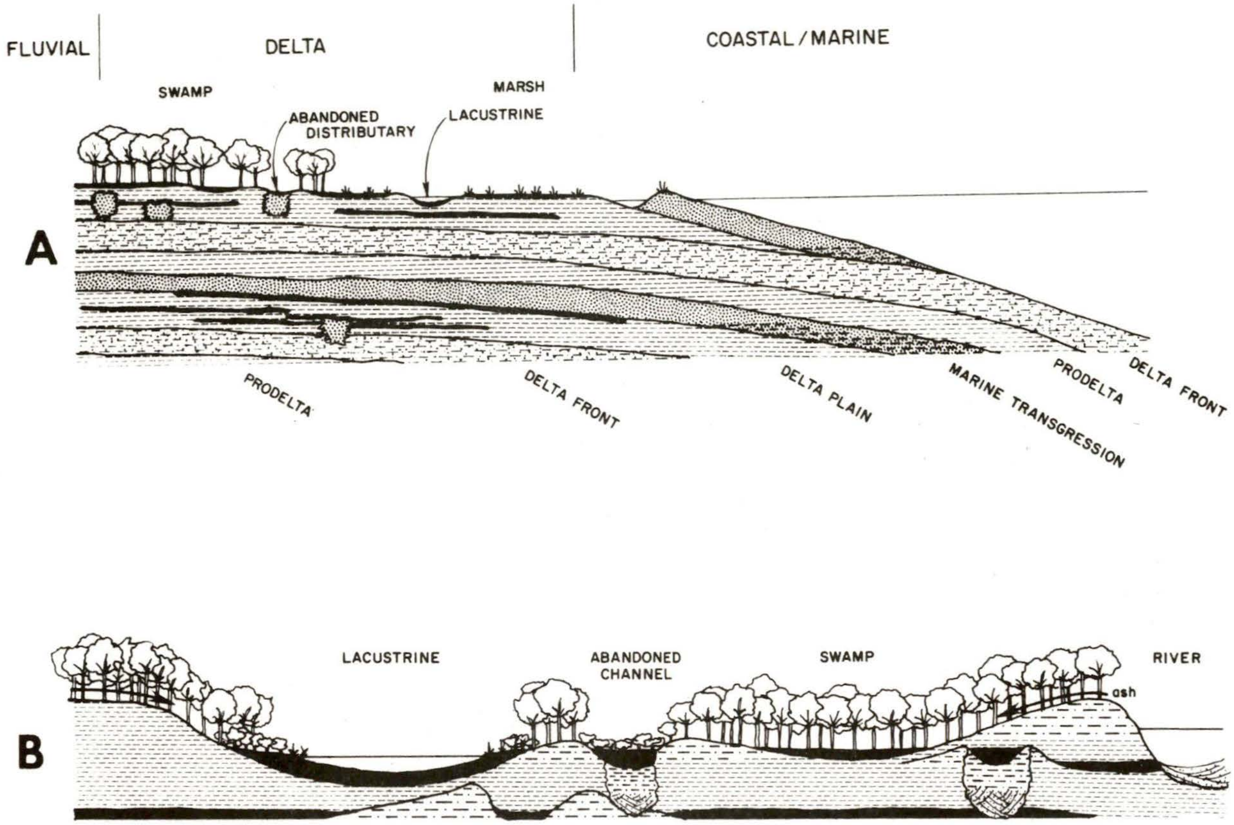


Figure 4. Schematic cross section of various environments of coal formation in delta/coastal-marine systems (A) and a fluvial system (B) (Mathewson, 1982a).

the common depositional environments of Gulf Coast lignites.

Geology of Field Test Sites

East Texas Fluvial Site

The East Texas field site is a test pit on an ancient terrace of the Sabine River in Harrison County 15 mi. south of Hallsville, Texas. Watson (1970) studied the geology of the Wilcox lignite deposit. The stratigraphy of the prospect is complex and variable; it consists of lignites and poorly consolidated sandstones, siltstones and shales. In ascending geologic order, the stratigraphic intervals present are the Wilcox Group; the Carrizo, Reklaw and Queen City Formations; and Quaternary alluvium. These intervals were deposited by fluvial processes during two major regressions, and by marine shelf processes during the Reklaw transgression. Lithologic units within and between formations grade into each other both laterally and vertically (Figure 5).

The Wilcox Group is composed of finely interlaminated sand and clay, which makes up the bulk of the Wilcox section; finely laminated clay; and lignite, with the main seam within the finely laminated clay facies. The Wilcox was deposited in a low lying interchannel floodplain, predominantly as overbank deposits but including periodic fresh-water swamp deposits.

The Carrizo Formation unconformably overlies the Wilcox Group. It consists of overbank deposits of interbedded sandstone and shale and thick, clean channel sandstones that grade into each other both laterally and vertically. The Carrizo was deposited in a fluvial environment where channels prograded over Wilcox sediments.

The Reklaw Formation conformably overlies the Carrizo Formation. It was deposited in a shallow water, transgressive marine environment. Lower Reklaw sediments consist of glauconitic sands and clayey sands; Upper Reklaw sediments consist of bioturbated shale and non-bioturbated black shales. Black lagoonal muds were deposited at the top of the sequence as the basin of

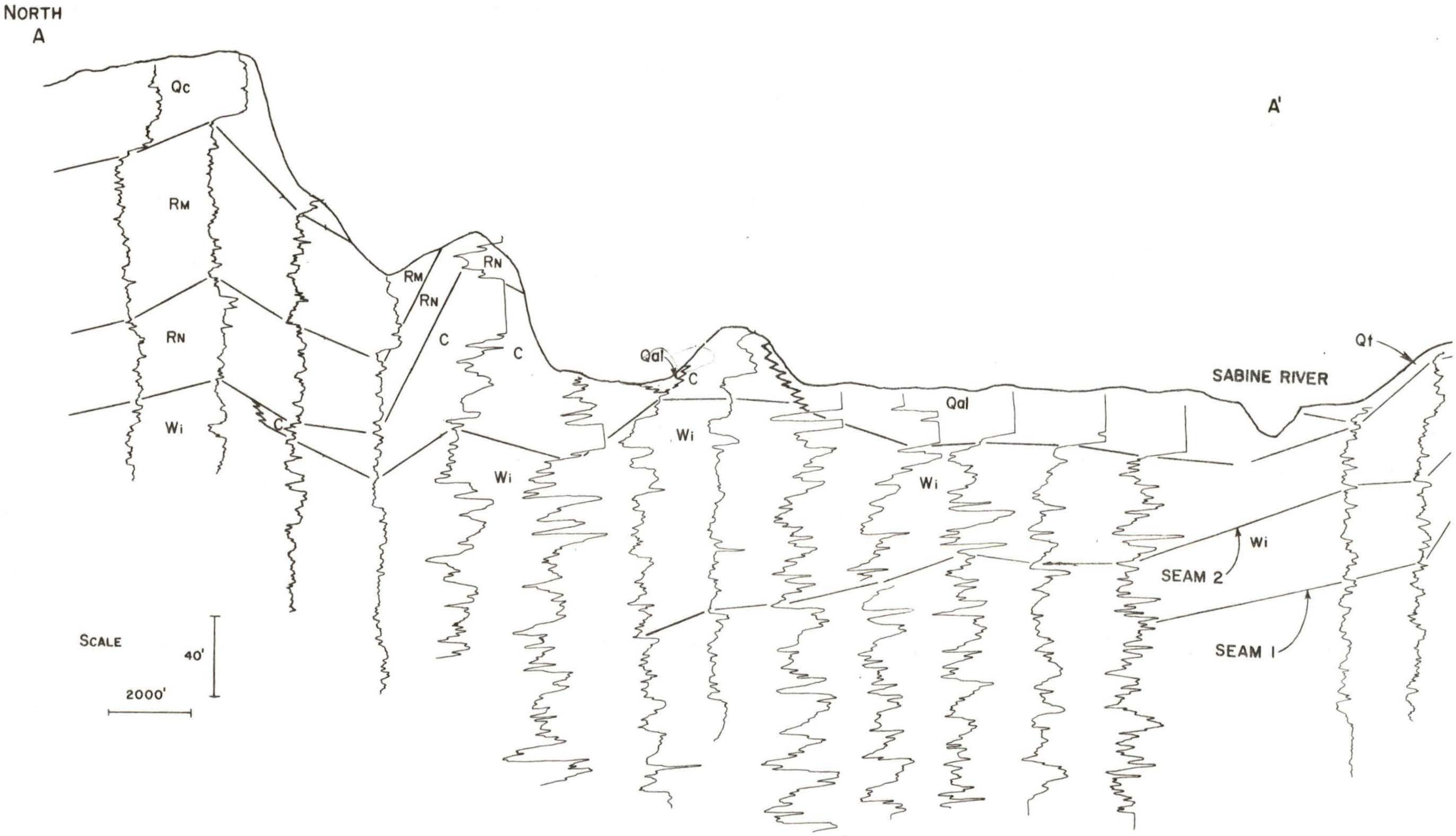


Figure 5. North-south cross-section through study site, showing stratigraphic relationships of the East Texas fluvial lignite deposit (Watson, 1979). Symbols represent following stratigraphic intervals: Q_{al}--Quaternary; Q_c--Queen City Formation; R_m--Reklaw Formation, Marquez Shale Member; R_n--Reklaw Formation, Newby Sand Member; C--Carrizo Sand; W_i--Wilcox

deposition became isolated from the open sea.

Both the Queen City Formation and Quaternary sediments represent point bar deposition in a meandering river that prograded over previously deposited sediments. The Queen City Formation unconformably overlies the Reklaw Formation. Quaternary sands are confined to the floodplains of local streams and to the terrace and floodplain of the Sabine River.

Central Texas Deltaic Site

The Central Texas deltaic site is located in Grimes County near Carlos, Texas. The test pit was excavated and reclaimed in May 1976. Bishop (1978) studied the geology of the lignite deposit, which consists of four main seams numbered 1 through 4 in ascending order. The stratigraphy of the site consists of poorly cemented silty to clayey sandstones, siltstones and shales deposited in a series of stacked delta systems (Figure 6).

Lignite seams 1 and 4 are overlain by delta plain sequences, while seams 2 and 3 are overlain by thick delta front sand sequences. Bishop (1978) originally interpreted overburden sequences 2 and 3 as transgressive marine units, but Mathewson (1982b) reinterpreted them as delta front sand sequences on the basis of additional cores and electric logs. Each overburden sequence is designated by the number of the underlying lignite seam. The sediments below seam 1 represent another delta plain sequence. Delta sequence 1 contains delta plain swamp deposits alternating with lignite seams, channel sands and overbank levee deposits. Delta sequence 4 contains thick delta front deposits overlain by prodelta deposits, channel sands and floodplain deposits. Delta sequence 1 (Figure 7) was deposited on a delta plain and represents interdistributary bay deposits of a constructional delta; delta sequence 4 represents deposition in the distal margins of a construction delta.

Delta front sequences 2 and 3 (Figure 8) represent intervals of rapid delta development (Mathewson 1982b). Delta plain swamp deposits overlie the delta front sands in sequence 2. Sequence 3 is similar but contains a greater thickness of sand; it is topped by delta plain sediments.

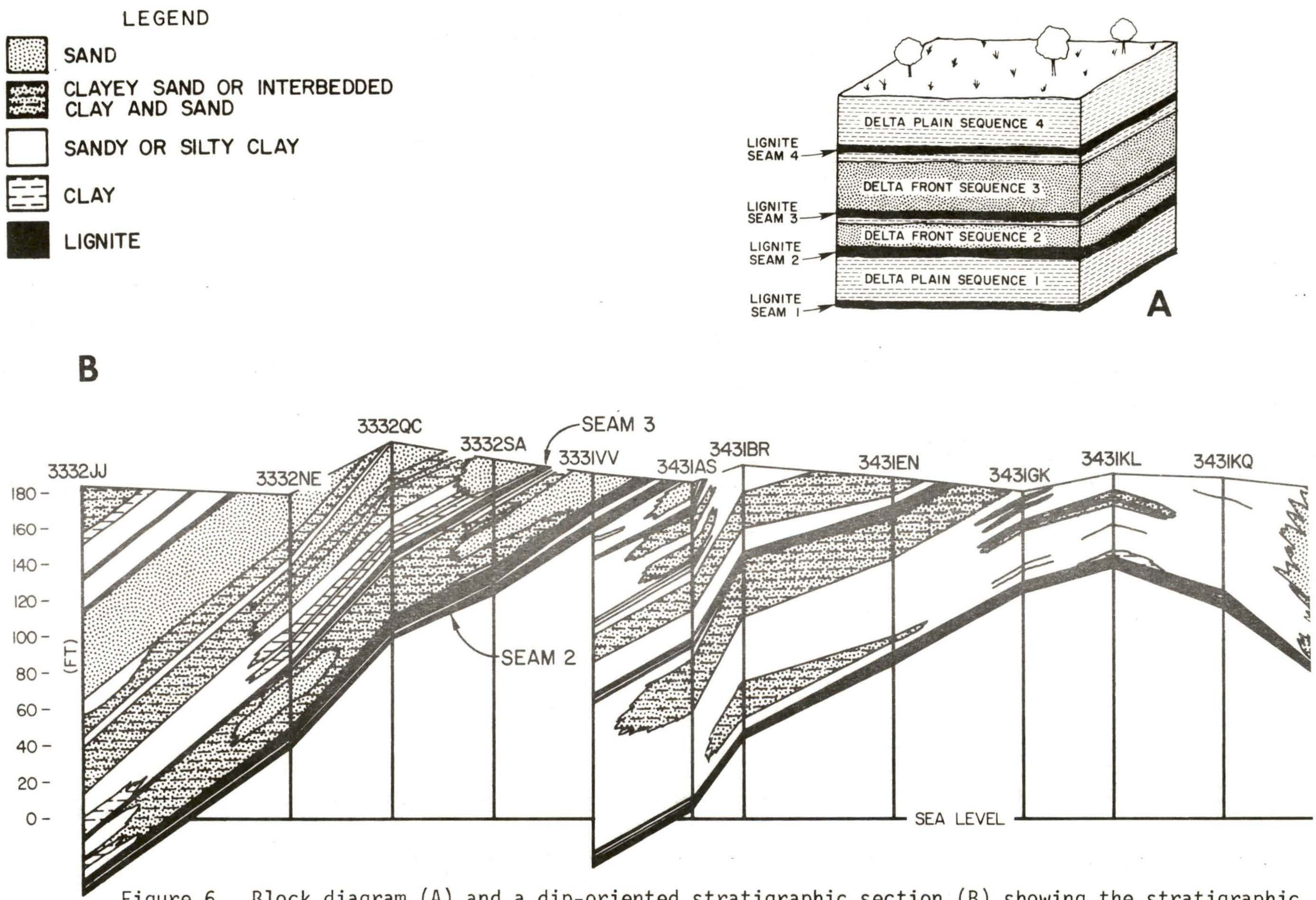


Figure 6. Block diagram (A) and a dip-oriented stratigraphic section (B) showing the stratigraphic relationships of the Central Texas deltaic lignite deposit. After Bishop (1977). Block diagram revised by Mathewson (1982b).

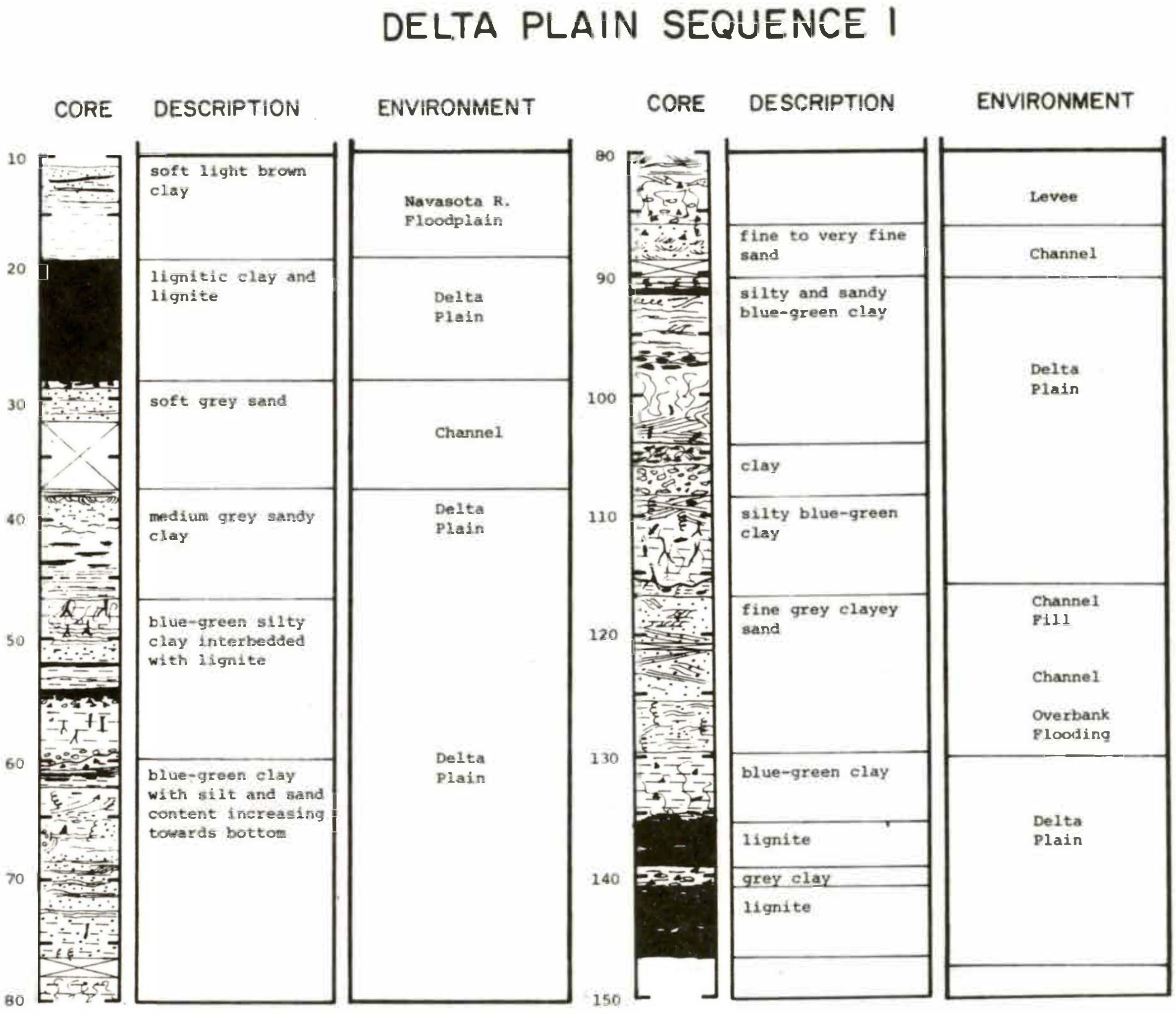


Figure 7. Stratigraphic description of a core from delta plain sequence 1. After Bishop (1977).

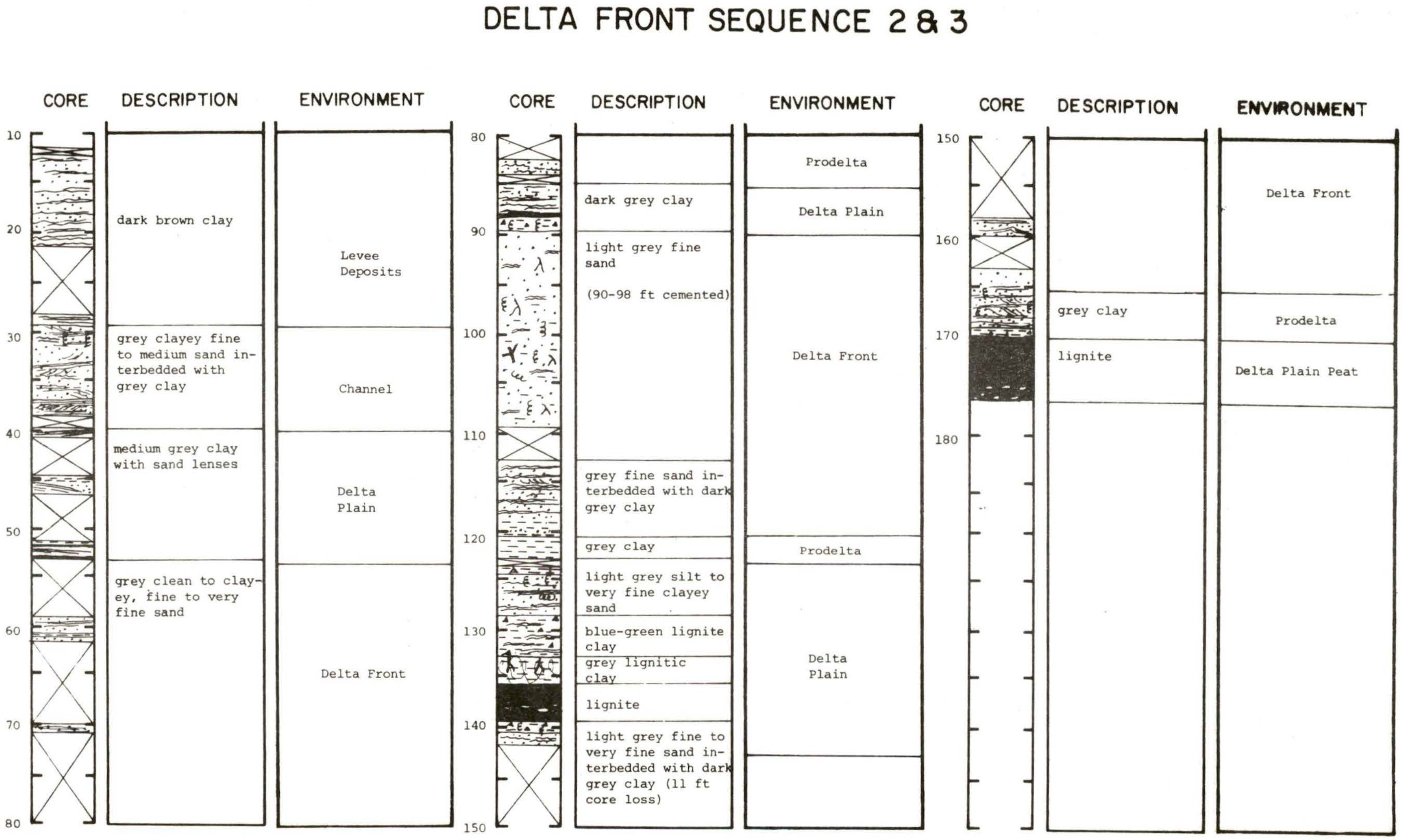


Figure 8. Stratigraphic description of a core from delta front sequences 2 and 3. After Bishop (1977) reinterpreted by Mathewson (1982b).

Central Texas Delta Plain Site

An active surface lignite mine in Milam County near Rockdale, Texas serves as the field test site. Schneider (1977) studied the geology of this Wilcox lignite deposit. The mine is contained entirely within the outcrop of the Eocene Calvert Bluff Formation of the Wilcox Group. The stratigraphy of the deposit is relatively simple; it consists of unconsolidated mudstones, sands, interbedded silty sands and mudstones, and lignites (Figure 9).

Calvert Bluff deposits represent the delta plain facies of the Rockdale Delta System. Kaiser (1978) describes the Calvert Bluff as a lower fluvial, upper delta plain system analogous to the Holocene Des Allemandes-Barataria and Atchafalaya basins of the Mississippi River System. It is characterized regionally as a complex network of elongate channel sands separated by much larger interchannel basins. Interchannel deposits consist of interdistributary mudstones and lignites, with thin crevasse splay and overbank levee sands and silts. Peat accumulation occurred in the upper part of the basin distant from the effects of the Gulf Coast and active streams.

Morphology of the lignite seams at the site is varied. The main seam is typically 3 m thick and can be traced for at least 10 mi. along strike and 2 mi. along dip (limits determined by exploration boundaries). The main seam is absent in several places due to faulting or erosion. Variation in thickness and continuity reflect changes in the stability of the environment of deposition. Lignites above the main seam are thinner and less continuous.

Drilling records indicate a clay below the main lignite. The clay is interbedded with thick carbonaceous clay seams. Immediately above the lignite is a gray or black clay that varies in thickness and organic matter. It contains a few silt/sand lenses. The clays are overlain by a sequence of wavy discontinuous silt/clay laminae that grade upward into another clay, followed by a lignite. Upper lignites are thinner and less continuous than the main seam due to the influence of meandering streams which crossed the area after the main seam was deposited; accompanying sediments are coarser-

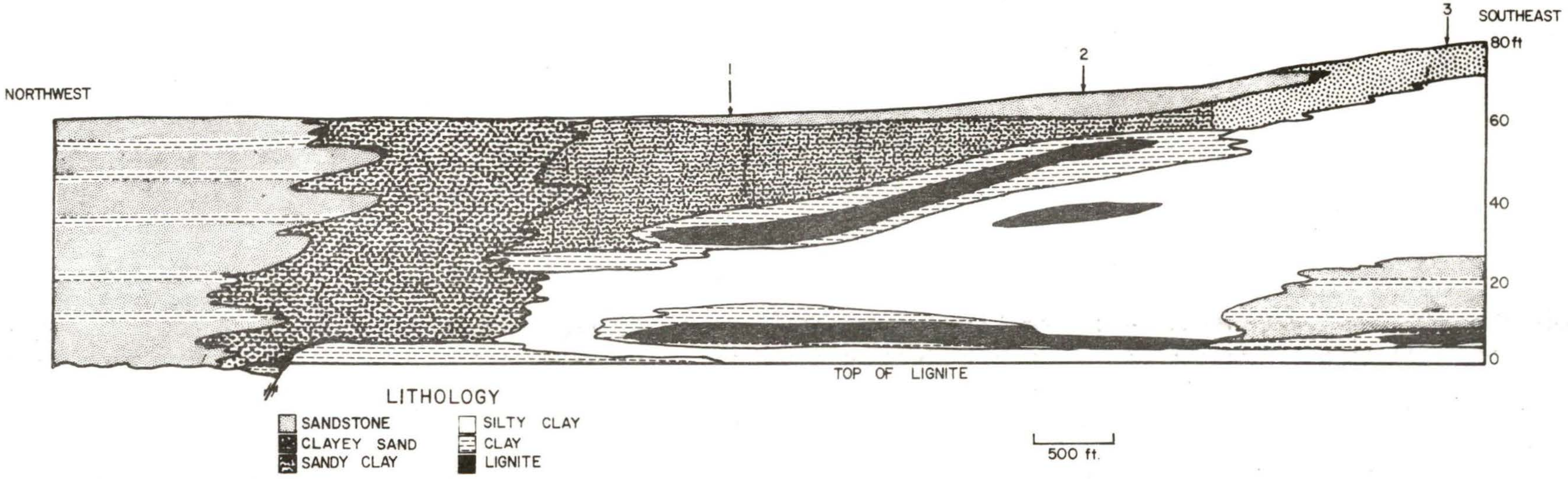


Figure 9. Generalized strike-oriented stratigraphic section showing the stratigraphic relationships of the Central Texas delta plain lignite deposit (Schneider, 1977).

grained. The entire depositional cycle consists of a fresh-water marsh followed by a lake that filled in with muds and silt/clay laminae to become another freshwater marsh. Lignite deposits are the result of organic accumulation in the marshes.

South Texas Coastal Plain Site

The fourth test site involved a coastal plain lignite deposit in Atascosa County approximately 50 mi. southeast of San Antonio, Texas. The stratigraphy of the site was studied in detail by Snedden (1979), who concluded that the lignite accumulated in a coastal swamp, fronted by a coastal lagoon and adjacent barrier island. Snedden (1979) places the lignite in the Manning Formation of the Jackson Group. The lignite and surrounding sediments are part of the South Texas lagoonal-coastal plain system, an updip equivalent of a well-developed strandplain-barrier bar system known from subsurface exploration.

Cores from the study site contain four lithofacies, numbered in descending order from the top (Figure 10). The lignite interval is in lithofacies 2. Lithofacies 1 consists of a rippled sandstone deposited by a meandering stream near base level in a coastal swamp. Lithofacies 2 consists of poorly sorted, highly bioturbated siltstones and shales deposited in the lagoonal margin on grassflats of a coastal lagoon. Deposition occurred landward of the deeper part of the lagoon and seaward of the coastal swamp. Lithofacies 3 consists of a massive claystone with numerous fossiliferous and marly beds that was deposited in the deeper parts of the lagoon, seaward of the coastal grassflats. Lithofacies 4, which occurs at the base of each core, is a medium-to fine-grained, poorly sorted carbonaceous sandstone that was deposited in the back-barrier flats of a coastal barrier island. It includes washover fan and ponded back-barrier marsh sediments, and represents the transition zone between the subaqueous lagoon and eolian dune fields on the landward side of the barrier islands.

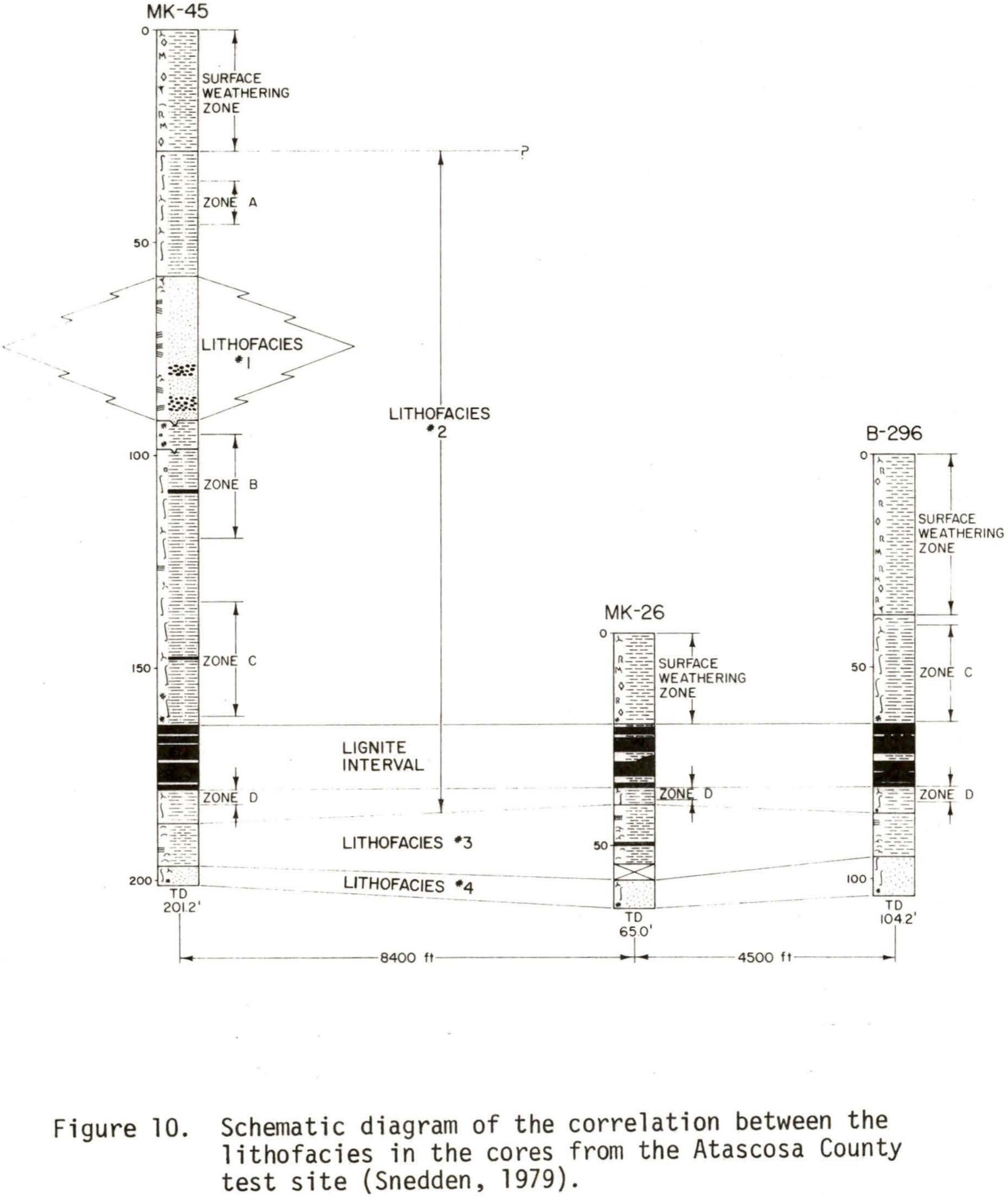


Figure 10. Schematic diagram of the correlation between the lithofacies in the cores from the Atascosa County test site (Snedden, 1979).

Hydrogeology of Field Test Sites

East Texas Fluvial Site

The major hydrogeologic unit in Harrison County is the Cypress Aquifer (Broom and Myers, 1966). The Cypress Aquifer consists of lenticular beds of sandstone, siltstone and shale of the Wilcox Group, Carrizo Formation, Reklaw Formation and Queen City Formation. All of these units are hydraulically connected. Rainwater infiltrates readily through the sandy soil on the outcrop of the aquifer to recharge the aquifer.

Charles (1979) studied the hydrogeologic conditions at the test site, shown in Figure 11. The ground-water table is shallow, generally within 6 m of the surface; it is a subdued expression of the rolling surface topography. The hydraulic conductivity of various sands of the Cypress Aquifer were determined using field well tests and laboratory permeameter tests. The Carrizo Sandstone and Quaternary terrace sands had a hydraulic conductivity of 1.1×10^{-3} cm/sec to 2.5×10^{-3} cm/sec and 4.1×10^{-4} cm/sec respectively.

Ground-water seepage problems and ground-water drawdown impacts on the ground-water system will occur during surface mining operations. The test pit was excavated through an aquifer sand and experienced significant seepage problems while it was open. The test pit resulted in a regional drawdown of the water table level that required more than 2 years to recover. During reclamation of the test pit, the aquifer unit was reconstructed but at a decreased hydraulic conductivity; pre-test pit hydraulic conductivity was 2.0×10^{-2} cm/sec, which reduced to 10^{-4} to 10^{-5} cm/sec after reclamation. These field results are similar to those obtained in laboratory studies.

The reclaimed test pit rapidly resaturated. Water samples were collected from a well cased in galvanized iron pipe that was placed after reclamation. Water analyses indicate that mining and reclamation decrease local water quality slightly. Differences in water quality between shallow or intermediate depth wells and deep wells completed in the Cypress Aquifer were noted by

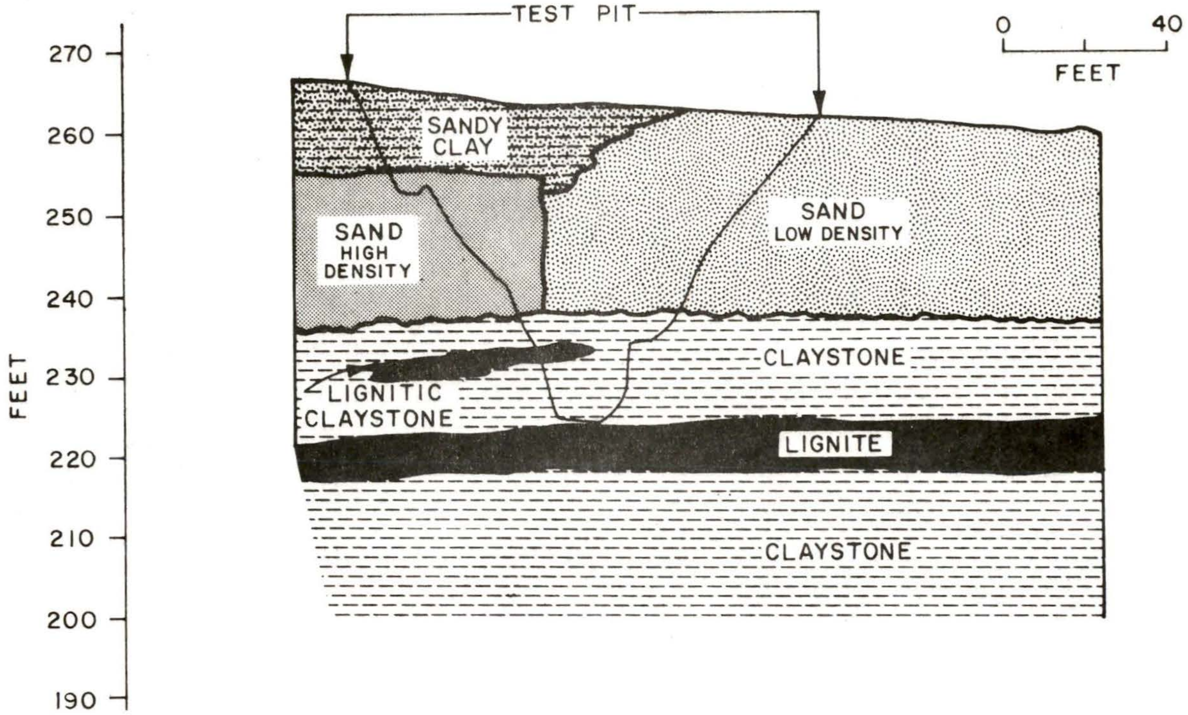


Figure 11. North-south cross-section of the East Texas fluvial lignite test pit site (after Charles, 1979).

Charles (1979). He cites the differences as evidence that the hydraulic connection between the Wilcox sands (deep wells) and sands of the overlying formation (shallow and intermediate depth wells) is poor or absent.

Central Texas Deltaic Site

The Jackson Group in Grimes County is a source of fresh to slightly saline ground water. Its aquifer properties were described in detail by Baker and others (1974). The Jackson Group in Grimes County consists of gray, laminated to massive, fine-to medium-grained sand; brown, lignitic clay; indurated, massive, fine-to medium-grained sandstone; and brown, tuffaceous siltstone. The maximum thickness of the Jackson Group in Grimes County is approximately 488 m. It will yield small to moderate amounts of fresh to moderately saline water to wells on the outcrop of the unit and to wells 1 mi. downdip (southeast) of the outcrop. Quaternary alluvium and terrace deposits do not form significant aquifers at the test site.

Levitan (1976) did a detailed study of the hydrogeology of the test site. The overburden of the lignite consists of sandy clays and clayey sands with the sands having a maximum hydraulic conductivity of 1.0×10^{-3} cm/sec. Three types of sand were identified at the test site. Within the Manning Formation, distributary channel sands in the delta plain sequences have a hydraulic conductivity ranging from 10^{-4} to 10^{-6} cm/sec, and delta front sands have a hydraulic conductivity ranging from 10^{-3} to 10^{-5} cm/sec. Delta plain clays in the Manning Formation had a hydraulic conductivity ranging from 10^{-6} to 10^{-8} cm/sec. Quaternary alluvium has an average hydraulic conductivity of 10^{-2} cm/sec. The sands experience indistinct facies changes from clayey sand to sandy clay and back to clayey sand.

The ground-water table at the test site is a subdued expression of the topography, being near the surface in the floodplains of local creeks and reaching a depth of 9 m on hilltops (Levitan, 1976). Localized artesian conditions exist in areas that overlie the delta front sands below seam 4. These sands are used as local aquifers, although the ground-water quality is poor.

The test pit is located in lignite seam 4. Considerable ground-water seepage through the lignite seam was observed during pit excavation. An exploration hole located about 45 m from the test pit showed the presence of an artesian system; water in the drill hole flowed freely. After the test pit was reclaimed, the ground-water table reformed within a single year. Recharge occurred through the lignite seam by artesian pressure in the underlying delta front sands.

Central Texas Delta Plain Site

The major water-producing unit in Milam County is the Simsboro Formation of the Wilcox Group (Basciano, 1978). The main lignite deposits occur in the lower part of the Calvert Bluff Formation, which lies directly above the Simsboro Formation. The ground-water table lies at a depth of 3 m to 14 m, generally 6 m to 8 m, and is a subdued expression of the gently-rolling topography.

At the test site, three aquifers have been identified: Calvert Bluff channel sands, the upper Simsboro sand and the lower Simsboro sand (Railroad Commission of Texas, 1976). The upper and lower Simsboro sands are 31 m and 61 m thick respectively; they are separated by 24 m of clay. Major channel sands are not present at the test site; however, three minor channel deposits have been noted in highwall exposures at the operating mine (Schneider, 1977). These deposits are approximately 15 m thick and up to 61 m wide. Smaller distributary channel deposits up to 15 m wide and 3 m thick are noticeable in pits as areas of seepage.

Sand and silt units are located both above and below the main lignite seam at the test site. Parts of the main lignite seam are underlain by sandy silt, but most of the seam is underlain by dense clays and silty clays. Pollock (1982) reports that the oldest part of the mine has more than 15 m of clays and carbonaceous seams between the mine floor and the upper Simsboro sand.

Numerous sands, which can produce limited quantities of high-quality water, are present in the overburden; however, they are discontinuous and quite variable in thickness. Although they can produce fresh water, they lack sufficient recharge to provide a dependable long-term water supply. Consequently, these sands are of little significance as aquifers.

South Texas Coastal Plain Site

In Atascosa County, the principal aquifer is the Carrizo Sandstone of the Claiborne Group. Water from the Carrizo provides almost all of the ground-water needs of the county. The Yegua Formation and the Jackson Group do not form significant aquifers in Atascosa County. The Yegua Formation is 220 m to 344 m thick and consists of clay that contains gypsum, sand and thin lignite seams. It yields only small quantities of slightly to moderately saline water to wells in the outcrop zone. The Jackson Group is approximately 335 m thick and yields small quantities of slightly to moderately saline water to wells. It consists of an upper unit of tuffaceous sandstone, bentonitic clay and thin lignite seams; and a lower unit of shale, thin sandstones and thin lignite seams.

The ground-water table is over 300 m below the ground surface. Isolated lenses of saturated sandstones that do not represent a ground-water resource have been reported at the mine site. The test pit contains no ground water, due primarily to the deep regional ground-water system and the semi-arid climate. Surface recharge by infiltration following rainfalls will not occur because evaporation greatly exceeds precipitation.

HYDROGEOLOGY OF RECLAIMED SURFACE MINES

Hydrologic Properties

Surface mining of lignite creates a new material, the cast overburden or mine spoil, with physical and hydrologic properties that are significantly different from those that existed prior to mining. Mine spoil in Texas lignite mines is a heterogeneous mixture of unconsolidated overburden sediments.

Texas lignite mines are generally located in sand-poor overburden areas of fluvial-deltaic depositional systems. Sand-rich overburden areas occur as isolated channel sands in fluvial-deltaic systems; in lagoonal/strandplain depositional systems; and as sand-rich fluvial systems not related to the lignite-forming environment. The effect of various sand-shale overburden mixtures on the hydraulic conductivity of spoil as a function of burial depth has been evaluated in the laboratory and confirmed in the field. Results have shown that the hydraulic conductivity of sand-rich spoil is almost constant at 10^{-4} cm/sec with increasing burial depth, which indicates that sand-rich spoil has a similar or slightly reduced hydraulic conductivity with respect to the unmined overburden. The hydraulic conductivity of shale-rich spoil ranges from 10^{-4} cm/sec above 10 to 16 m of burial to less than 10^{-7} cm/sec below 30 m of burial. This represents a significant increase in hydraulic conductivity in the upper portion of the spoil, but a minimal change in the lower portion with respect to the unmined shale overburden.

Schneider (1977) determined from field and laboratory studies that the surface of a reclaimed lignite surface mine settles very rapidly (Figure 12A). More than 50 percent of the ultimate settlement occurs within 100 days after reclamation and more than 80 percent within 5 years (Figure 12B). Hydraulic conductivity and porosity decrease as the spoil redensifies. Rangel (1979) investigated in the laboratory the effect of mine stratigraphy on the settlement of a reclaimed mine. Five mined stratigraphic models were tested, which contained sand-clay mixtures ranging from 95 percent sand, 5 percent clay to zero percent sand, 100 percent clay. Rangel (1979) found that the compressibility of reclaimed spoil and the amount of surface subsidence in-

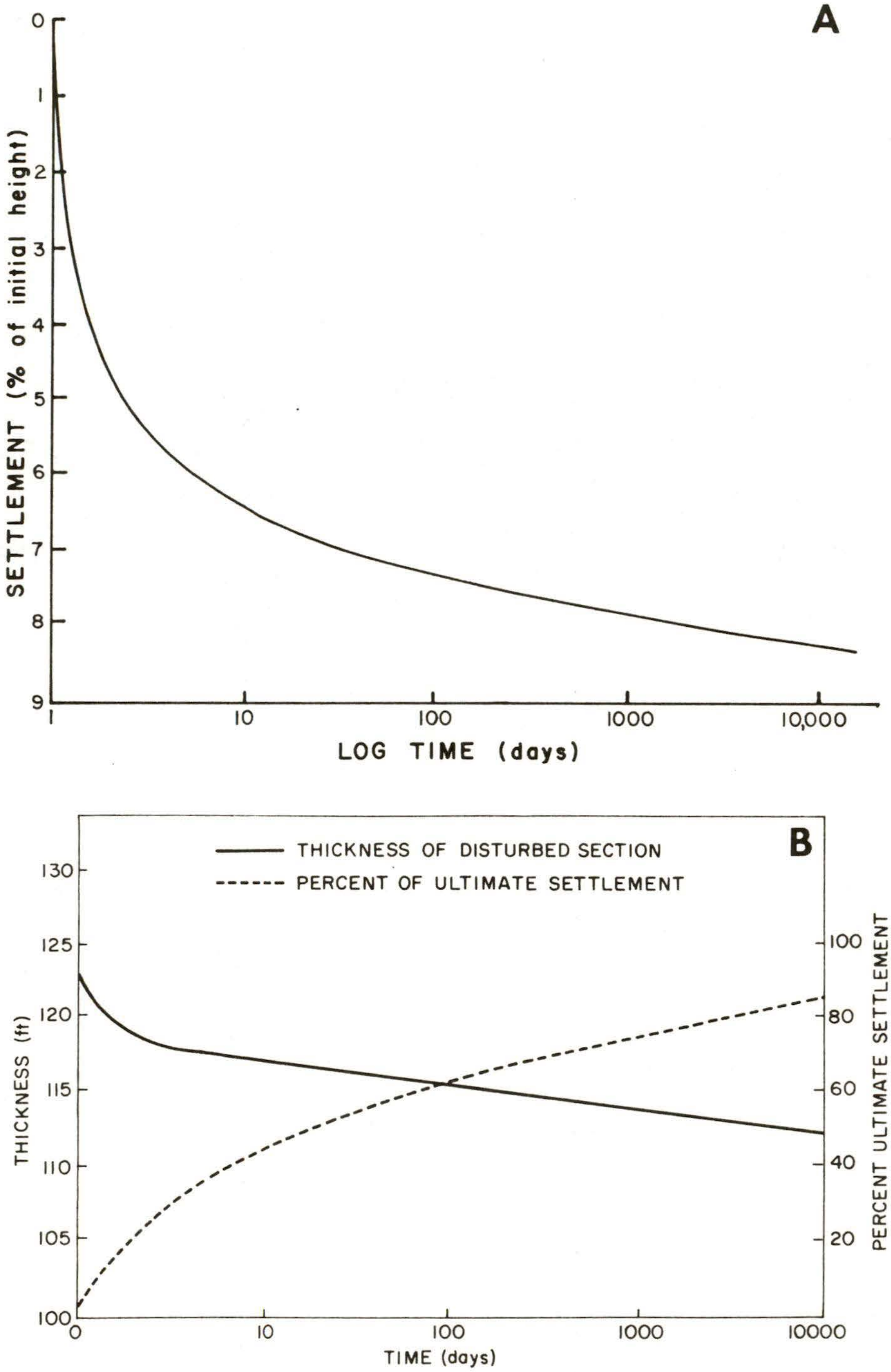


Figure 12. Time-settlement charts for reclaimed Texas surface lignite mines, plotting settlement rate (A) and thickness (B) of mine spoil as a function of time since mining (Schneider, 1977). Percent ultimate settlement vs. time is also shown in (B). The original pre-mine overburden was 100 ft thick, and a 24% swell factor was used for initial expansion.

crease as the percentage of sand decreases (or as the percentage of clay increases). Figure 13 shows percent settlement vs. time curves for the five stratigraphic models.

The geology of the overburden will control the amount of shale and sand in the mine spoil; therefore, it will control the compressibility and hydraulic conductivity of the mine spoil as well (Kennedy and Pepper, 1980). Overburden consisting of fluvial backswamp and deltaic clays will lead to spoil with a high shale content and a relatively compressible reclaimed material. This shale-rich spoil will experience a large decrease in permeability with depth of burial (Kennedy, 1981). Overburden consisting of fluvial channel and marine strandplain sands will have a hydraulic conductivity that is independent of burial depth. Laboratory values of hydraulic conductivity as a function of burial depth are shown in Figure 14 for selected overburden materials that are characteristic of the Gulf Coast.

The hydraulic conductivity of reclaimed mine spoil can be predicted from diagrams that plot hydraulic conductivity as a function of burial depth and percent sand in the overburden (Figure 15). An assessment of the impact of surface mining on ground-water hydrology can be predicted from this data when it is used in conjunction with percent sand maps and overburden isopach maps that have been constructed from exploration data.

Infiltration Characteristics of Mine Soils

Infiltration characteristics of mine soils were determined at proposed and existing lignite mines using field test plots established on pre-mine native soils, on leveled spoil piles at active mines, and on revegetated portions of existing test pit and mines. At each site except that in Milam County, plots established on each of three native soil series were compared with plots established on reclaimed test pits. The test pit plots received various liming treatments, including several where part of the lime requirement was supplied by gypsum and one where no lime was used. These field plots were limed, fertilized and seeded with bermuda grass. The native soil plots received no treatment other than periodic harvesting. At the Milam

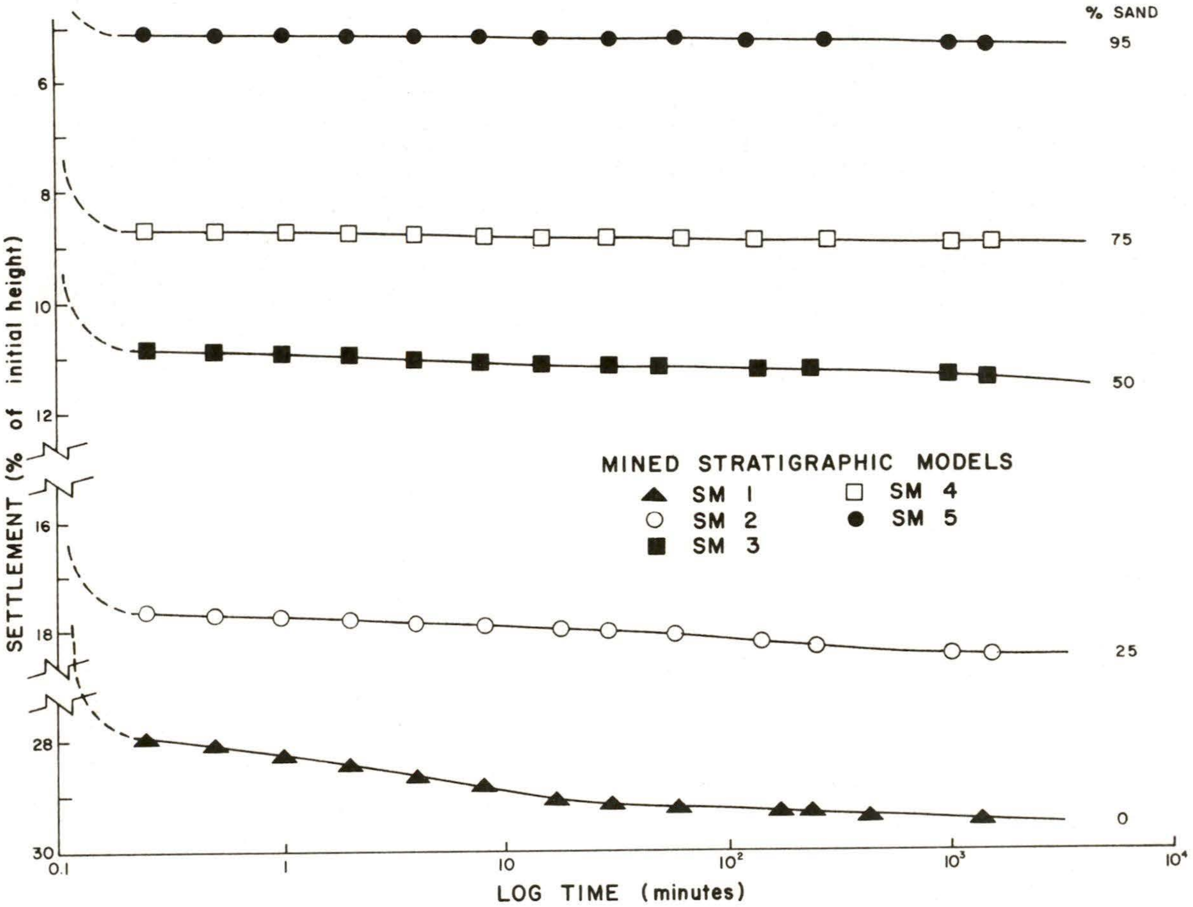


Figure 13. Percent settlement vs. time curves for stratigraphic models having various sand-clay mixtures (Rangel, 1979). Models were constructed using clay aggregates and loose sand.

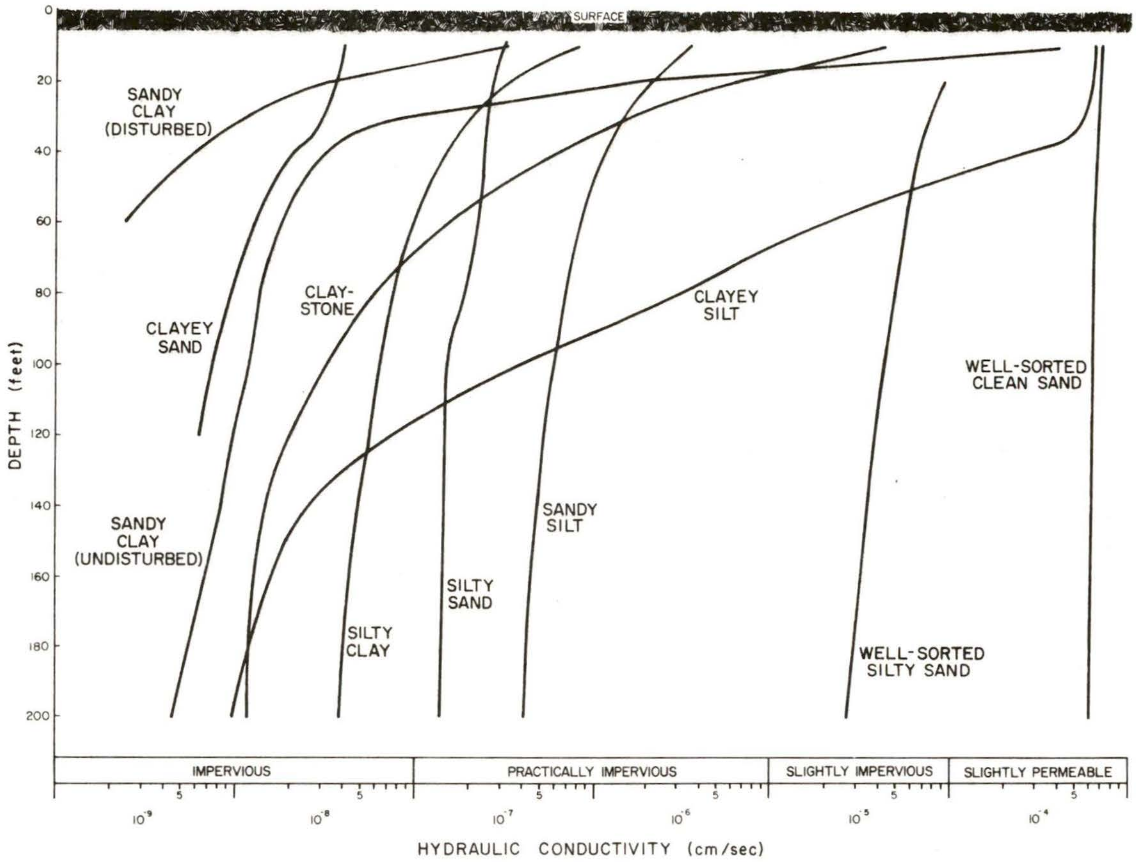


Figure 14. Hydraulic conductivity vs. depth of burial for selected overburden materials characteristic of the Gulf Coast (Kennedy, 1981).

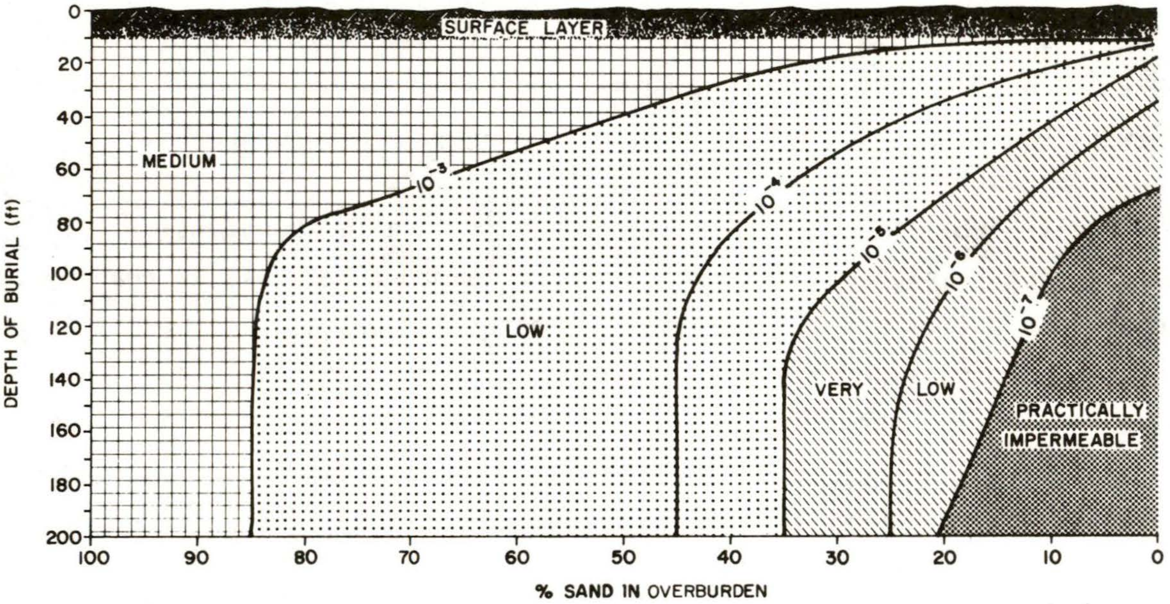


Figure 15. Hydraulic conductivity vs. depth of burial and percent sand in the overburden (Kennedy, 1981).

site, three native soils were compared with plots established on fresh and 7 year old piles.

A rainfall simulator was used to generate runoff from a 10 year, 1 hour intensity storm (8.9 cm/hr for 1 hour). Each plot was subjected to two simulated rainfall events. The first was made on dry ground to investigate the dry soil conditions. The second was made on the same plot 24 hours later to investigate the wet soil conditions. Runoff was collected from each 1 hour simulation at 5 minute intervals to allow accurate calculation of the infiltration rates.

Results from simulated rainfall events in Angelina County (Table 3) indicate that rainwater infiltrates into reclaimed mine soils as readily as it does into native soils. Infiltration rates at the Harrison County site (Table 4) were considerably lower in the reclaimed mine spoil than in the native soils. Infiltration into vegetated areas of young spoil in Milam County (Table 5) was greater than that into barren areas of the young spoil; however, infiltration rates were lower than those into native soils.

Most native soils in East Texas are sandy surface soils underlain by a clay subsoil. While the initial infiltration rate may be high, the sandy soil layer soon becomes saturated; the remaining water runs off. The depth of infiltration in reclaimed mine soils is greater than that in native soils, because the commonly existing clay subsoil is destroyed by the mining process. The water-holding capacity of reclaimed mine soils is greater than that of the native soils, as demonstrated in Figure 16.

Hydrogeology of Resaturated Mine Spoil

The hydrogeology of resaturated mine spoil has been investigated at the Central Texas delta plain field site. This is an active surface lignite mine that has been in continuous operation since 1954. Pepper (1980) studied the hydrogeology of young (1 to 8 year old) spoil at the mine; Pollock (1982) investigated the hydrogeology of "old" (25 year old) spoil. The overburden at the mine is shale-rich and contains three channel sands. There is a thick

Table 3. Infiltration Rates from Reclaimed Test Pit and Native Soil Plots in Angelina County, Texas

	Rain 1*	Rain 2*
Test Pit		
Treatment A	0.32 ± 0.16	0.11 ± 0.05
B	0.34 ± 0.14	0.20 ± 0.08
C	0.50 ± 0.21	0.45 ± 0.18
D	0.26 ± 0.12	0.34 ± 0.07
Native Soil (Untreated)		
Crafish	0.42 ± 0.14	0.40 ± 0.05
Lufkin	0.28 ± 0.03	0.27 ± 0.01
Rosenwall	0.65 ± 0.02	0.22 ± 0.14

* -- all measurements expressed in cm/hr; and results expressed as the mean value ± 1 standard deviation

Table 4. Infiltration Rates from Reclaimed Test Pit and Native Soil Plots in Harrison County, Texas

	Rain 1*	Rain 2*
Test Pit		
Treatment A	0.22 ± 0.03	0.28 ± 0.21
B	0.09 ± 0.08	0.25 ± 0.16
C	0.29 ± 0.01	0.22 ± 0.05
D	0.23 + 0.08	0.22 + 0.18
Native Soil (Untreated)		
Bowie	0.50 ± 0.06	0.38 ± 0.04
Cuthbert	0.36 ± 0.06	0.25 ± 0.02
Kirvin	0.38 ± 0.12	0.36 ± 0.04

* -- all measurements expressed in cm/hr; and results expressed as the mean value ± 1 standard deviation

Table 5. Infiltration Rates from Reclaimed Mine Spoil and Native Soil Plots in Milam County, Texas

	Rain 1*	Rain 2*
Active Mine		
7 year old spoil (clover)	0.86 ± 1.34	3.81 ± 2.37
7 year old spoil (grass)	2.45 ± 1.18	1.00 ± 0.32
7 year old spoil (barren)	0.43 ± 0.50	0.37 ± 0.28
New spoil, barren, ungraded	0.71 ± 0.63	0.09 ± 0.04
New spoil, barred regraded	0.15 ± 0.01	1.33 ± 1.81
Native Soil (Untreated)		
Demona	1.6 ± 2.4	0.07 ± 0.03
Roder	6.3 ± 0.6	2.03 ± 0.95
Axtell	1.2 ± 1.7	0.13 ± 0.13

* -- all measurements expressed in cm/hr; and results expressed as the mean value ± 1 standard deviation

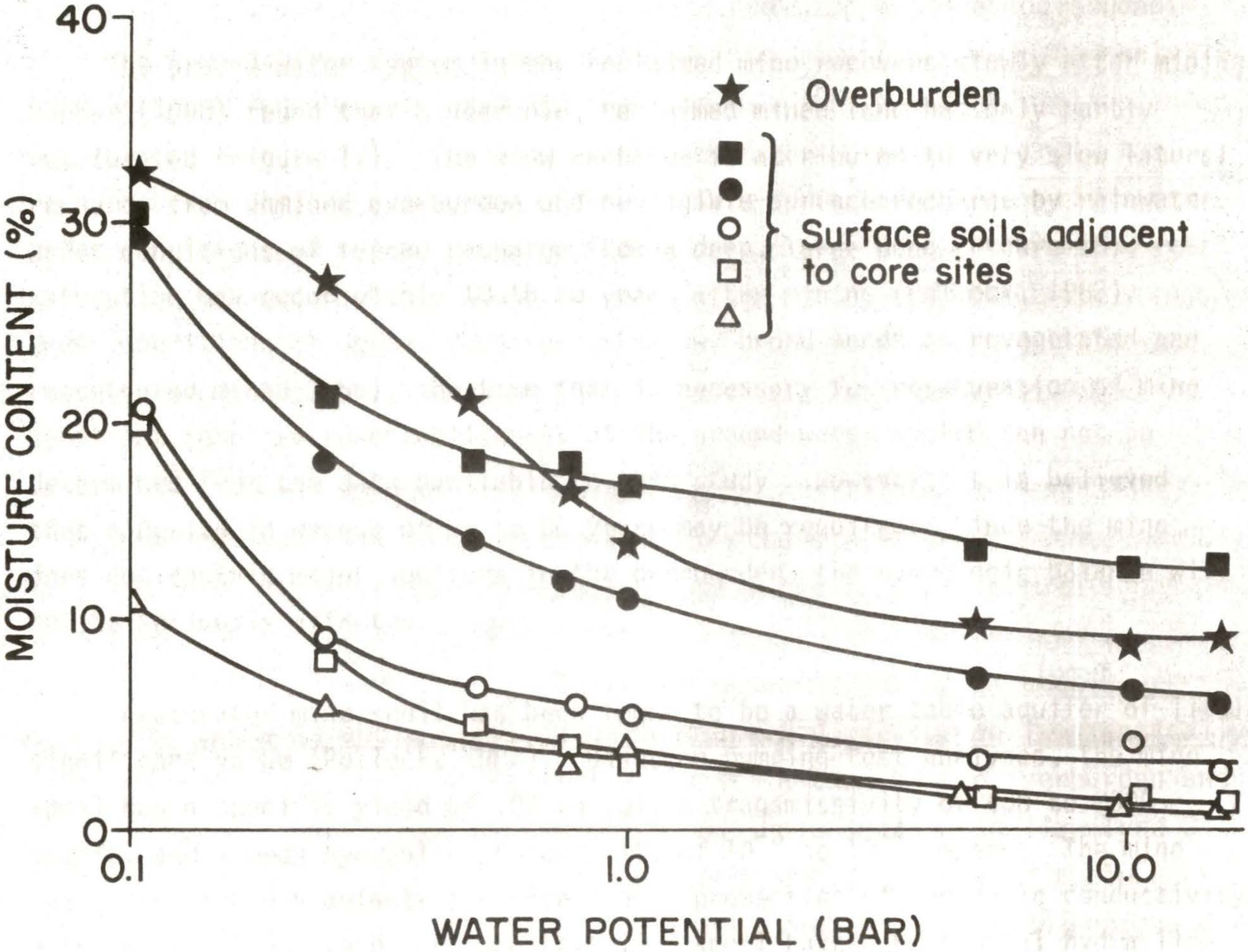


Figure 16. Moisture content of mine spoil and native topsoils as a function of water potential (Launius, 1980).

underburden of lower Calvert Bluff shales and carbonaceous claystones between the mine floor and the upper Simsboro channel sandstones. The pre-mine ground-water table was shallow, generally 6 m to 8 m deep, and was a subdued expression of the gentle rolling topography.

The ground-water system in the reclaimed mine recovers slowly after mining. Pepper (1980) found that 8 year old, reclaimed mined land has only partly resaturated (Figure 17). The slow recharge is attributed to very slow lateral recharge from unmined overburden and negligible surface recharge by rainwater. Under conditions of forced recharge from a deep, large pond (Figure 18), resaturation may occur within 10 to 20 years after mining (Pollock, 1982). Under conditions of normal recharge (shallow, broad ponds on revegetated and recontoured mined land), the time that is necessary for resaturation of mine spoil and complete re-establishment of the ground-water system can not be determined from the data available to this study. However, it is believed that a period in excess of 35 to 50 years may be required. Since the mine does not contain major aquifers in the overburden, the hydrologic balance will not be seriously affected.

Resaturated mine spoil has been found to be a water table aquifer of little significant value (Pollock, 1982). Based on pumping test analyses, the mine spoil has a specific yield of .02 to .04, a transmissivity of 400 to 2000 gpd/ft, and a mean hydraulic conductivity of 10^{-3} to 10^{-4} cm/sec. The mine spoil has strongly anisotropic directional properties of hydraulic conductivity. Both the pre-mine overburden and post-mine spoil have a horizontal hydraulic conductivity of 10^{-3} to 10^{-4} cm/sec and a vertical hydraulic conductivity of 10^{-6} to 10^{-8} cm/sec. The transmissivity of the mine spoil is similar to that of minor Calvert Bluff channel sands. It is three orders of magnitude higher than that of the predominantly shale-rich overburden, so surface mining has enhanced the water-carrying capacity of the overburden sediments. The resaturated mine spoil is at least as good a ground-water resource as was the pre-mine overburden.

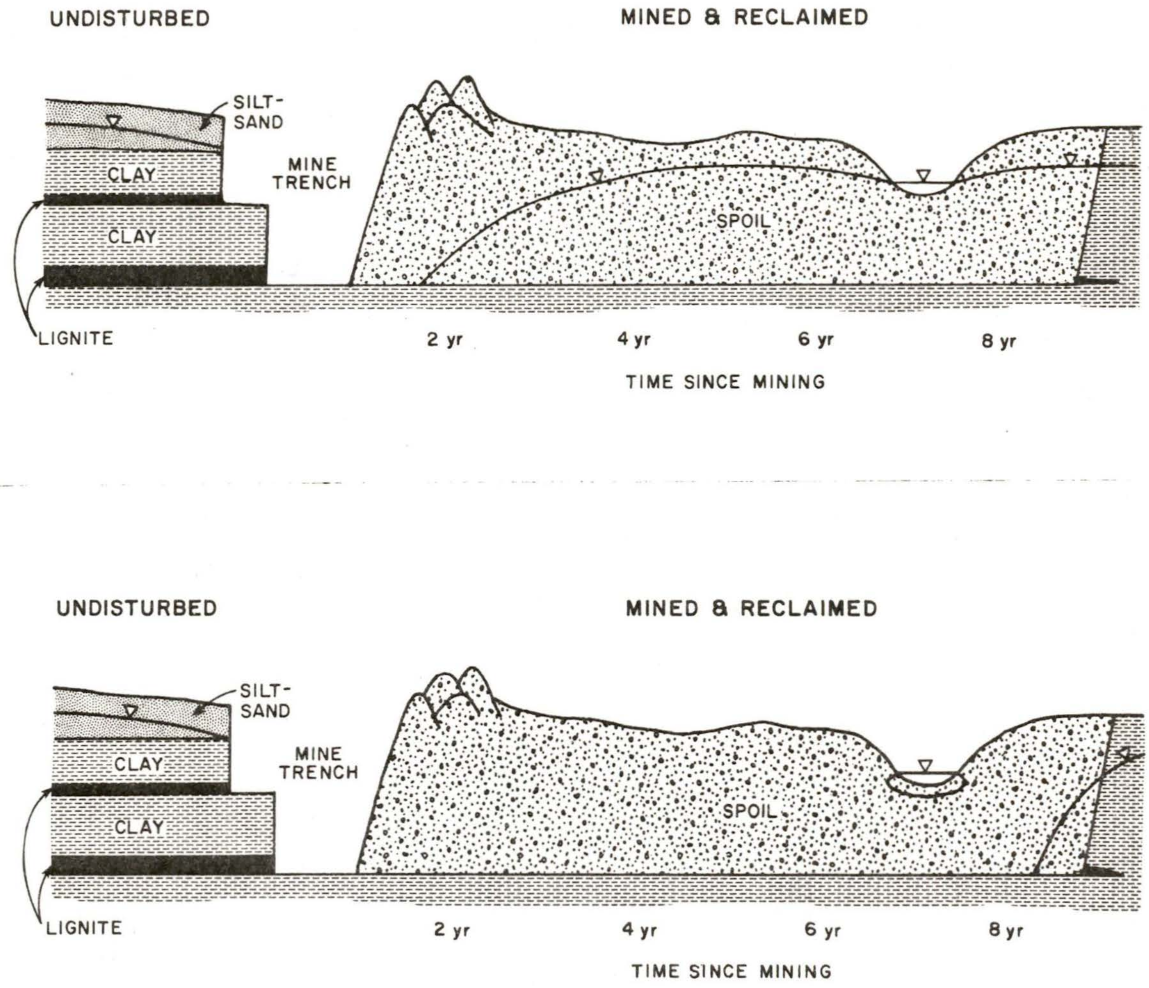


Figure 17. Schematic cross-section illustrating expected (A) and actual ground-water conditions (B) in young soil in a reclaimed surface mine (Pepper, 1980).

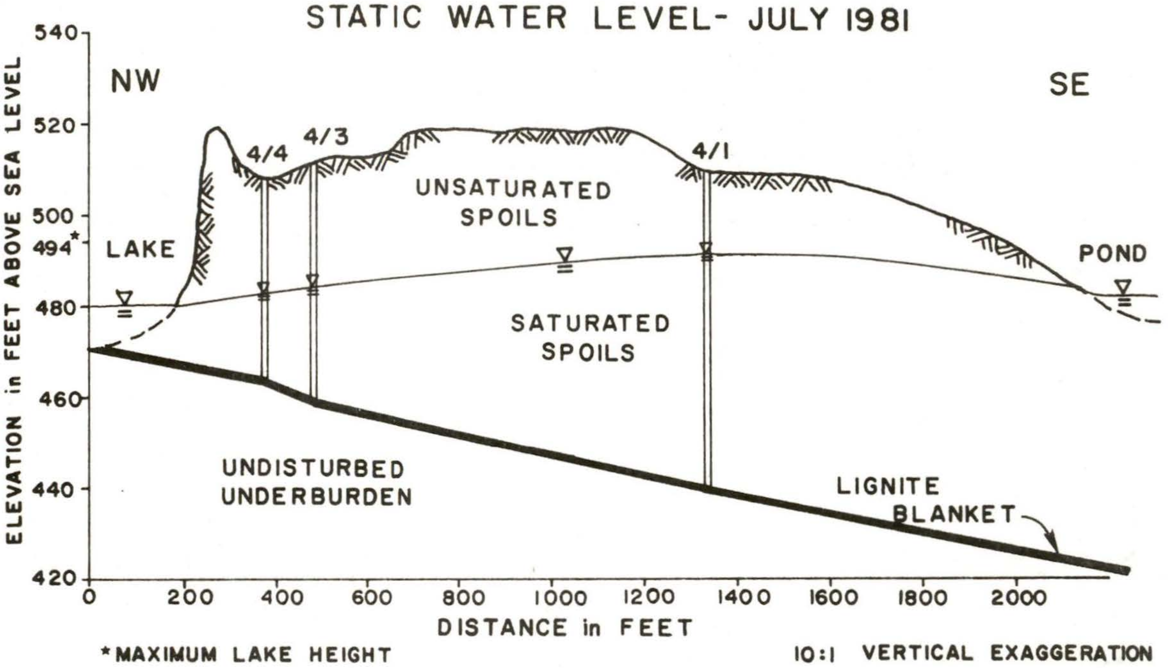


Figure 18. Schematic cross-section illustrating the ground-water system in oil spoil in a reclaimed surface mine (Pollock, 1982).

Hydrogeologic Models of Reclaimed Mines

Four hydrogeologic types of reclaimed surface mines have been defined, based on climate, stratigraphy and pre-mine hydrogeology (Figure 19). Predictions of the hydrogeology of a reclaimed mine are based on the stratigraphy of the overburden and underburden, and on the pre-mine hydrogeologic conditions. The depositional environment controls the amount of sand and shale in the spoil, which in turn controls the compressibility and hydraulic conductivity of the mine spoil. The depositional environment also controls the texture and infiltration capacity of the surface mine spoil; clay-rich overburden will produce low hydraulic conductivity soils and sand-rich overburden will produce soil with a relatively higher hydraulic conductivity. The location of the regional ground-water table and confined aquifers will influence the amount of water that is available for recharge from unmined aquifers below the lignite.

Type 1 and Type 2 mines of Mathewson and others (1979) and Kennedy (1981) have partly saturated, shale-rich spoil. Type 1 conditions occur in mines in arid climates where the ground-water table is below the lignite seam and surface recharge is minimal. Type 2 conditions occur in humid climates where the ground-water table is above the lignite seam and the overburden is practically impermeable: lateral recharge is limited by the nature of the overburden and surface recharge is inhibited by the weathered shale surface spoil. Type 3 and Type 4 mines have fully saturated spoil with the ground-water table near its original level. They consist of nearly impermeable shale-rich spoil and permeable sand-rich spoil respectively. Type 3 conditions occur where a confined aquifer below the lignite seam recharges the spoil from below: the very low hydraulic conductivity that existed before mining redevelops in the mine spoil, and the shallow water table reforms. Type 4 conditions occur where an aquifer unit overlies the lignite seam and lateral and surface recharge reestablishes the ground-water system.

Hydrogeologic types for the lignite belt of Texas, which have been determined from an analysis of the regional geology and the climate, are given in Figure 20. Complex stratigraphic conditions in some areas produce more than

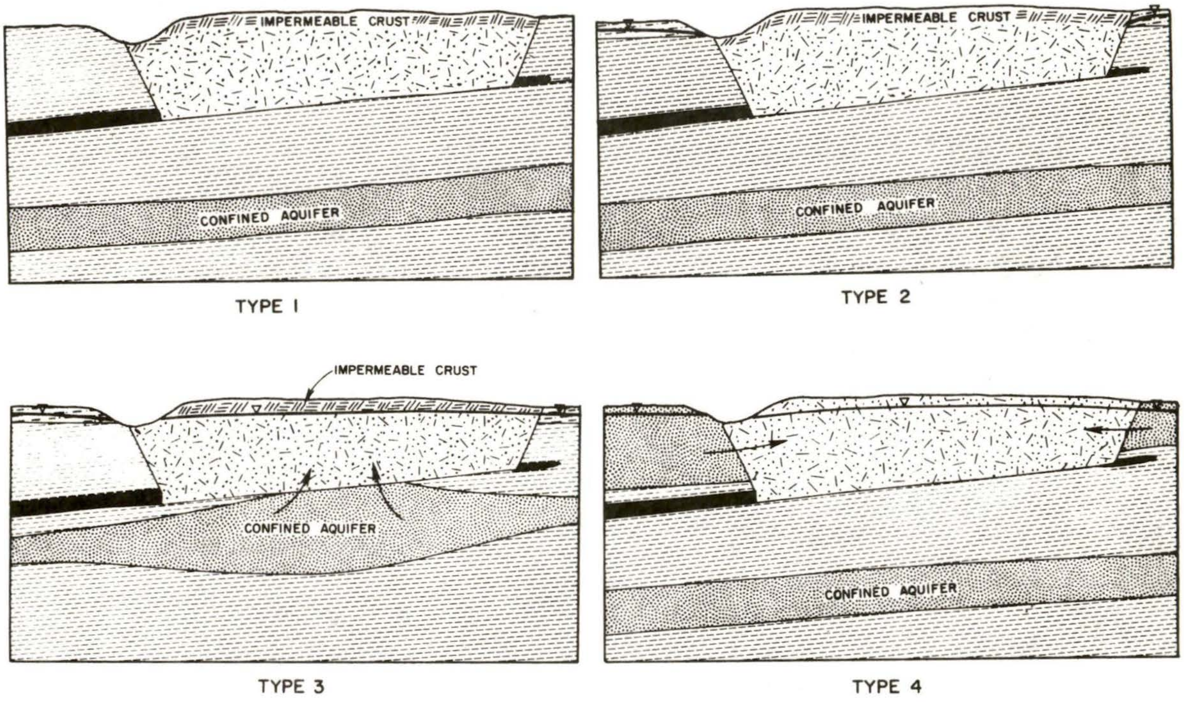


Figure 19. Classification of hydrogeologic types in reclaimed surface lignite mines in Texas (Kennedy, 1981). Type 1 and Type 2 mines have partly saturated, shale-rich spoil with a deep and a shallow premine ground-water table respectively. Type 3 mines have saturated shale-rich spoil and a shallow ground-water table. Type 4 mines have saturated sand-rich spoil and a shallow ground-water table.

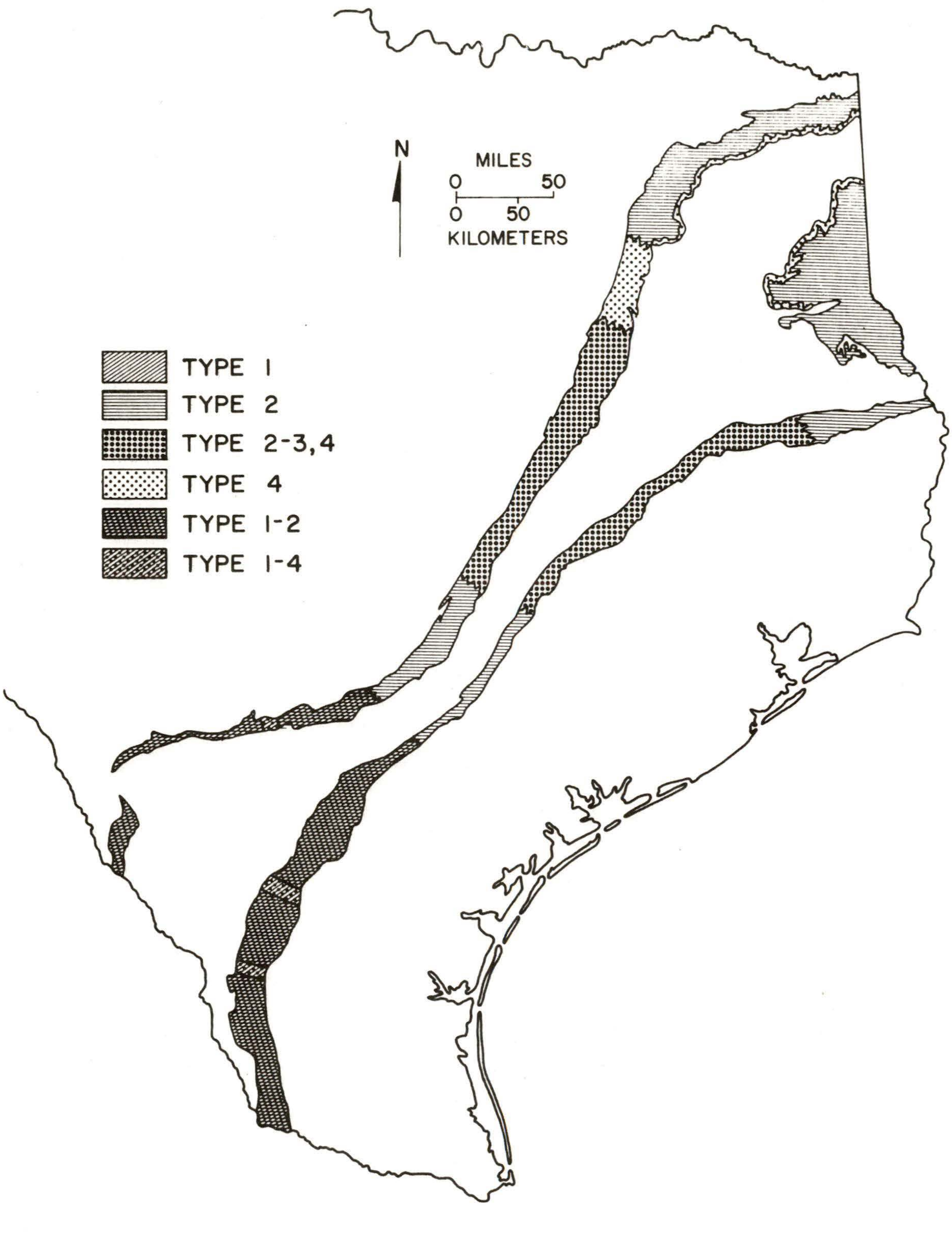


Figure 20. Potential occurrence of hydrogeologic types in lignite districts of the Texas Gulf Coast (Kennedy, 1981).

one hydrogeologic type in an area. It is not possible to differentiate the exact type of conditions at this map scale without site-specific data.

Computer Models of Reclaimed Mines

Numerical analyses have been used by Kennedy (1981) to predict ground-water flow conditions in Type 3, Type 4 and resaturated Type 2 reclaimed surface lignite mines. Two-dimensional, finite-element mathematical models of steady-state ground-water flow through reclaimed mines have been run on a computer. The program is SEEP-2DFE and was written by Dr. C. S. Desai of Virginia Polytechnic Institute and State University. The models assume a saturated, isothermal ground-water flow with constant fluid properties that moves through an anisotropic, inhomogeneous material which has constant hydraulic conductivity properties. The models include three-layer anisotropic systems with an impermeable lower boundary, three-layer anisotropic systems with a permeable lower boundary, and randomly mixed spoil with a permeable lower boundary. Hydraulic head in the aquifers dictated the lateral boundary conditions. Boundary conditions involved constant head, constant flux and no-flux situations.

The typical distribution of spoil hydraulic conductivity in a reclaimed Gulf Coast surface lignite mine is layers of decreasing hydraulic conductivity with increasing depth. A layer of higher conductivity sand-rich spoil or expanded shale-rich spoil is present near the surface. Consolidation under the weight of overlying materials creates spoil layers of lower hydraulic conductivity beneath the upper layer. Type 3, Type 4 and resaturated Type 2 hydrogeologic conditions can be analyzed most suitably by using three-layer anisotropic systems with permeable or impermeable lower boundaries.

Computer analyses indicate that most of the ground water will be discharged to surface waters within the mine site, because the ground-water system will behave as a water table system. Figures 21, 22 and 23 show the results of analyses of various three-layer models with anisotropic conditions and permeable or impermeable lower boundaries. Ground-water may flow through sand-rich spoil into confined aquifers beneath a mined-out lignite

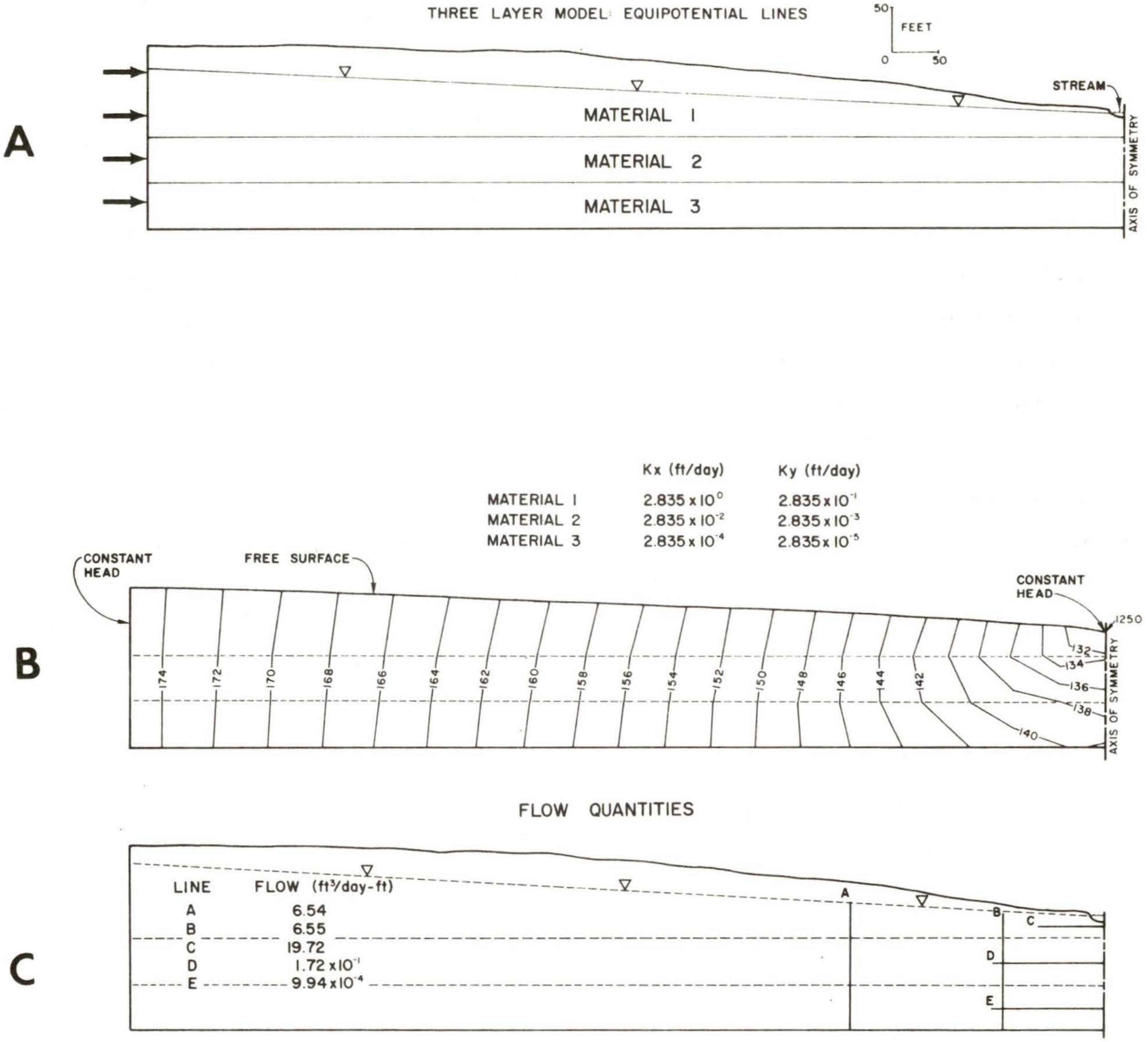


Figure 21. Three-layer system model with permeable lower boundary, showing equipotential lines (A), hydrologic conditions (B), and flow quantities in various flow sections (C) (after Kennedy, 1981).

	Kx (ft/day)	Ky (ft/day)
MATERIAL 1	2.835×10^{-4}	2.835×10^{-5}
MATERIAL 2	2.835×10^{-4}	2.835×10^{-5}
MATERIAL 3	2.835×10^{-1}	2.835×10^{-2}

LINE	FLOW (ft^3/day-ft)
A	2.28×10^{-3}
B	2.76×10^{-3}
C	1.26×10^{-2}
D	2.25×10^{-3}
E	2.96×10^{-3}

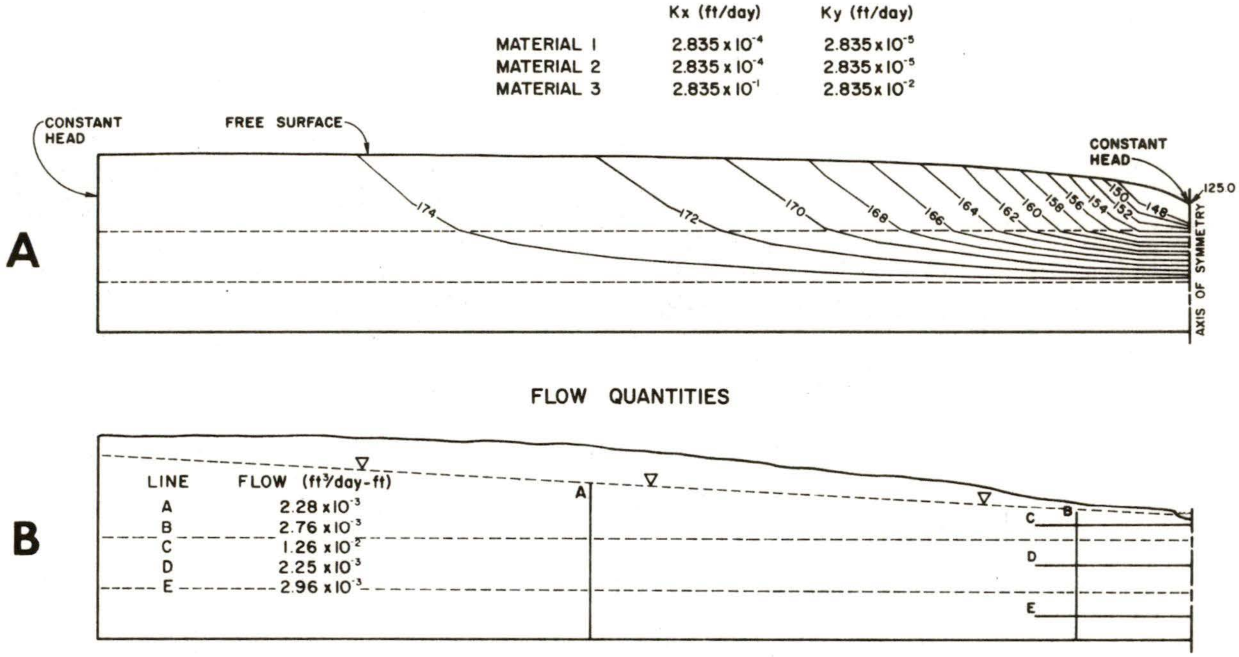
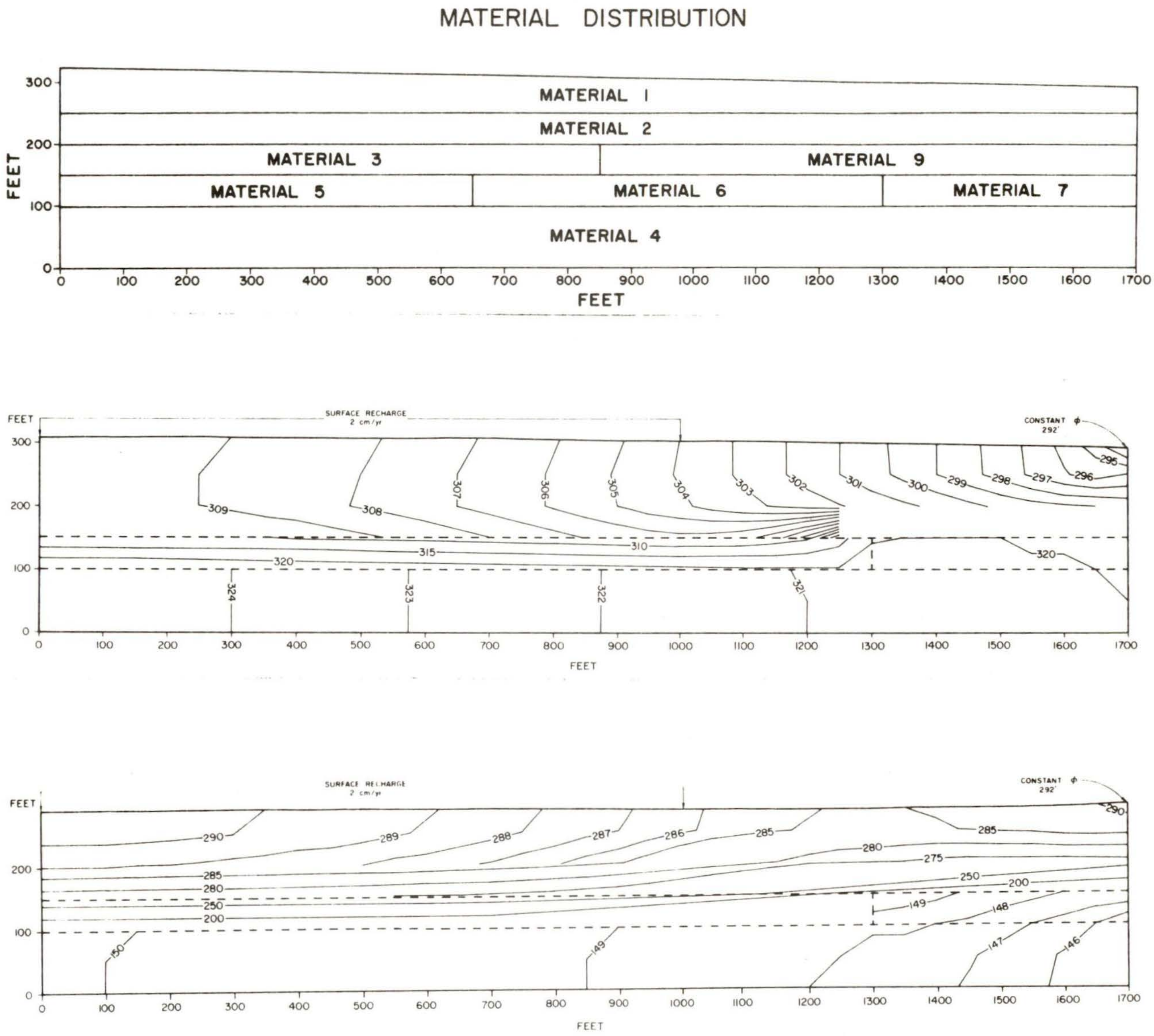


Figure 22. Three-layer model with impermeable lower boundary, showing hydrologic conditions (A) and flow quantities in various flow sections (B) (after Kennedy, 1981).



Material	Kx cm/sec	Ky cm/sec
1	10^{-4}	10^{-5}
2	10^{-5}	10^{-6}
3	10^{-6}	10^{-7}
9	10^{-6}	10^{-7}

Figure 23. Three-layer system model with permeable lower boundary, showing material distribution (A), and hydrologic conditions with piezometric surface above aquiclude (A) and within aquiclude (B) (Kennedy, 1981).

seam only if the piezometric surface of the confined aquifer is below the base of the reclaimed mine and no hydrologic seal exists between the mine spoil and the aquifer.

Overburden Analyses

Mine spoil at various test pits has been analyzed for total arsenic, boron, beryllium, iron, cobalt, chromium, zinc, nickel, cadmium, copper, manganese, lead, mercury, vanadium and selenium; for total dissolved salts; and for equilibrium pH. Analyses indicate that iron and manganese are the primary metals in spoil runoff. In addition, overburden cores were taken from the surface to the main lignite seam near each test pit. A total of 322 separate lithologic layers in 22 cores were analyzed for texture, water retention, nutrients, metals, sulfur compounds and equilibrium pH. The distribution of each metal for all the cores forms a somewhat skewed normal curve. In most cases, the layers in any one core span almost the same range of concentrations as those found in all the cores. The maximum frequency for a single core will generally occur at about the same concentration as that for all the cores.

For arsenic, copper and chromium, the maximum frequency occurs well below the normal concentration for native soils; for lead and zinc, it occurs slightly above the normal concentration. Other metal data generally fall within the normal range for native soils, with the exception of selenium found in a few layers of some deposits. Typical distribution curves are shown in Figure 24 for total zinc and total lead. Since most of the metal concentrations are well within the normal range, they should present no toxicity problems to plants or animals, as long as the spoil is properly limed to prevent acidification which could enhance metal solubilities.

Mine Soil Geochemistry

Mobility and redistribution of soluble metals in oxidized mine spoil has been evaluated at the Grimes County test site by Launius (1980). Field test plots were established on revegetated portions of the reclaimed test pit to investigate the distribution of Na, Mn and Zn in limed and unlimed mine spoil profiles. Column leaching tests in the laboratory determined the relative mobilities of Na, Mn and Zn. Twelve 100 cm long, 2.5 cm diameter columns

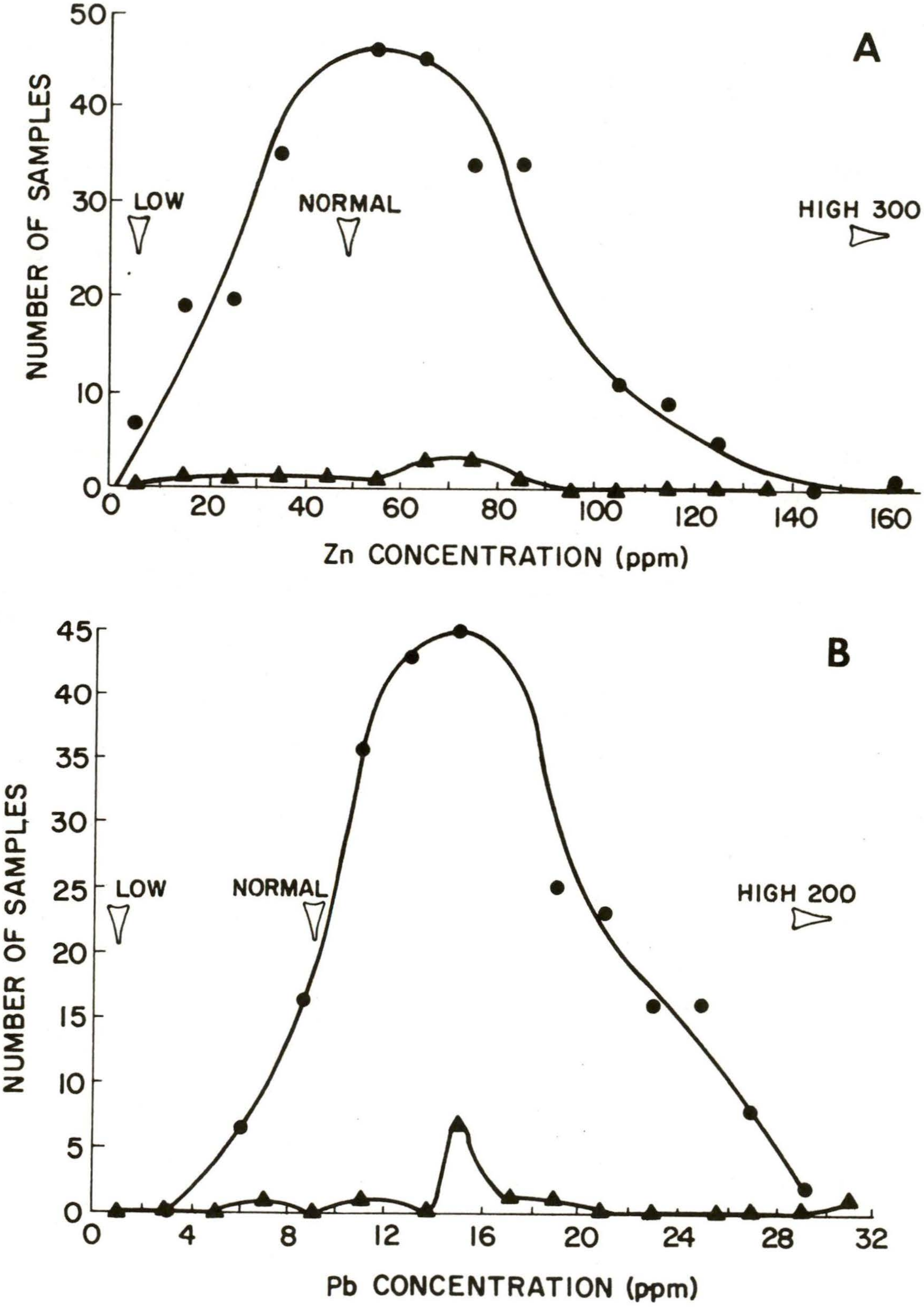


Figure 24. Frequency distribution of total zinc (A) and total lead (B) in the lithologic layers of 22 lignite overburden cores collected across Texas (Deuel and Brown, 1980).

were packed with untreated, oxidized mine spoil; another 12 columns were packed with oxidized spoil that had been treated with lime to raise the pH to 6.8. Duplicate columns from each treatment were leached with 1, 5 and 10 pore volumes of both deionized water and 0.001 N HCl (to simulate acidification in spoil pore water). Following leaching, the columns were extruded and sectioned. The sections were analyzed for water soluble and acid (0.1N HCl) extractable Na, Mn and Zn; for pH and electrical conductivity; and for easily extractable sulfate sulfur (SO_4-S).

The field study showed that liming treatments retard the downward movement of Mn and Zn and enhances Na movement. Redistribution of all three metals occurred in unlimed mine spoil and below the zone of lime ($CaCO_3$) incorporation in the limed mine spoil. Liming decreased the solubility of Mn and Zn and limited their mobility to the upper 10-15 cm of the spoil profile. The pH of the upper 15 cm of the mine spoil increased from 4.0 to 5.0 on field plots amended with varying rations of lime and gypsum; full lime treatment increased the mine spoil pH to 6.0. Gypsum-amended spoil exhibited higher electrical conductivity than lime-amended spoil.

The laboratory study clearly demonstrated enhanced mobility of Na, Mn and Zn in untreated (pH 4.0) mine spoil. Treating the spoil with lime decreased the mobility of Mn and Zn, but it had little effect on Na mobility. Increased leaching with 5 and 10 pore volumes of deionized water and 0.001 N HCl effectively displaced the majority of soluable metals from 100 cm columns of spoil. Liming reduced the solubility of Zn ten-fold and reduced the amount of Mn available for leaching. Use of 0.001 N HCl as a leaching solution did not significantly increase the mobility of any of the metals in unlimed overburden. Figure 25 demonstrates the mobility of Mn in treated and untreated mine spoil.

Of the three metals, only Mn appears to be a potential threat to groundwater quality. It is projected that 150 ppm Na, 17 ppm Mn and 5 ppm Zn could be leached from the mine spoil. This is based on cumulative losses of 600-700 g/m^2 Na, 80 g/m^2 Mn and 1.3 g/m^2 Zn per unit area from a typical 100 cm spoil profile and the displacement of 10 pore volumes to the ground-water table. The majority of Mn may be precipitated or adsorbed as it moves downward. Laun-

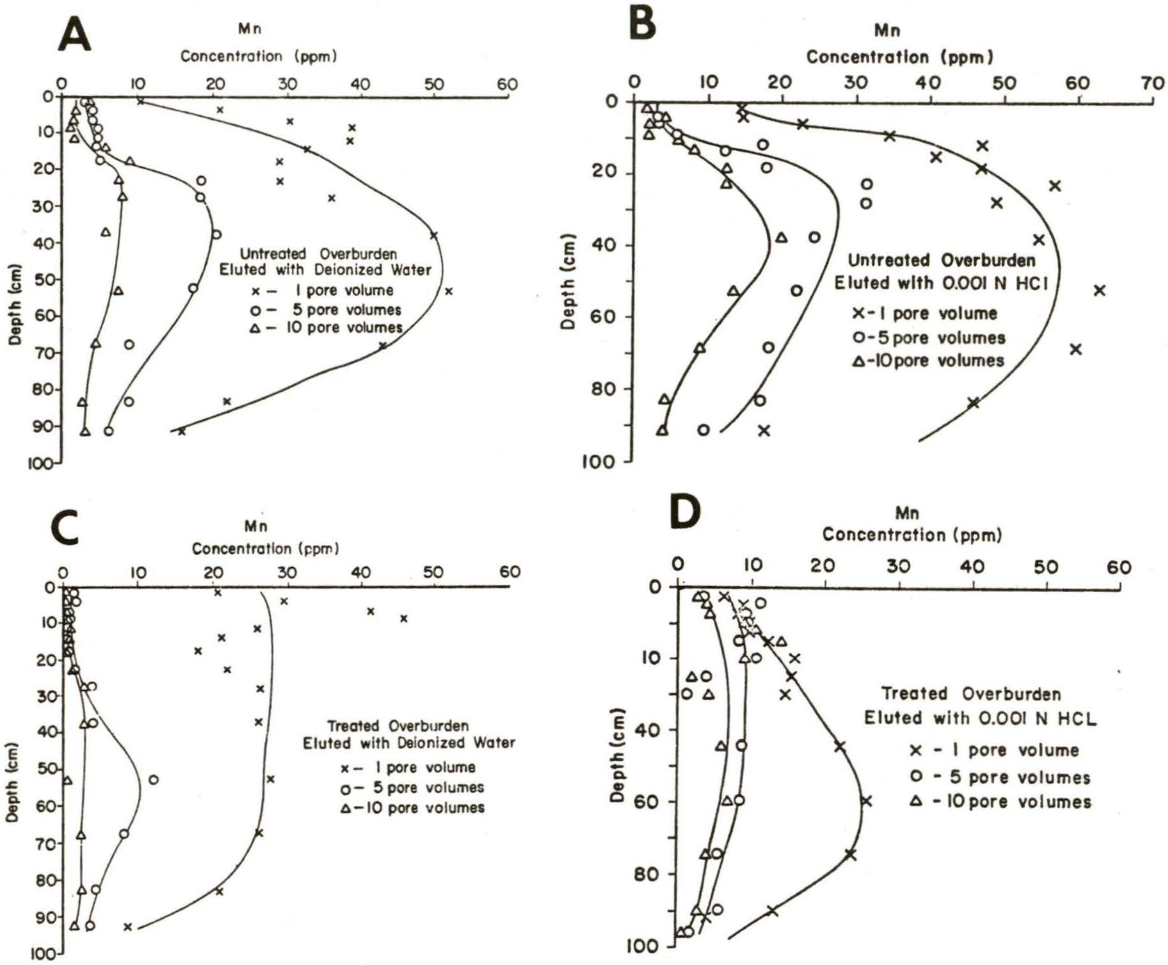


Figure 25. Water soluble Mn as a function of depth in untreated mine spoil leached with deionized water (A) and 0.001 N HCl (B); and in treated mine spoil leached with deionized water (C) and 0.001 N HCl (D) (Launius, 1980).

ius (1980) calculated that it is probable that Mn in excess of the OSM standard (0.05 ppm) will move into the ground water.

Brown and others (1982) have investigated the leaching of salts from mine spoil at the Angelina, Grimes and Harrison County test sites. The electrical conductivity of the mine soil to a depth of 0.5 m was somewhat lower for limed than unlimed mine spoil at Grimes and Harrison Counties; no significant differences in salt content of limed and unlimed mine spoil were noted at Angelina County. Salts have leached to a depth of 0.1 m in 2 year old spoil at Angelina County, and to a depth of 0.2 m in 2 year old spoil at Grimes and Harrison Counties.

Runoff Quality

Runoff quality has been determined at proposed and existing lignite mines where water samples from natural rainfalls were collected approximately monthly from buckets sunk into the ground at the lowest end of the same field plots that were used in the infiltration study. In addition, composite samples of the runoff from each 1 hr rainfall simulation were collected. The natural and simulated rainfall runoff samples were analyzed in the laboratory for pH, electrical conductivity, suspended solids, iron and manganese.

The pH of natural runoff is cyclical on a seasonal basis, varying from low pH values during the dry seasons to high pH values during the wet seasons (Figure 26A). The electrical conductivity, although slightly cyclic, shows a decrease with time (Figure 26B). Iron (Figure 27A) and manganese (Figure 27B) concentrations are highest in natural runoff from unlimed test pits. During dry seasons, these concentrations may be significantly greater than corresponding values in native soil runoff.

Simulated rainfall runoff has essentially the same pH value for reclaimed spoil runoff as for native soil runoff. At the Harrison County site, all the measured parameters for reclaimed spoil runoff were similar to those for native soil runoff. At the Grimes County site, untreated spoil runoff was significantly degraded in water quality as compared to native soil runoff.

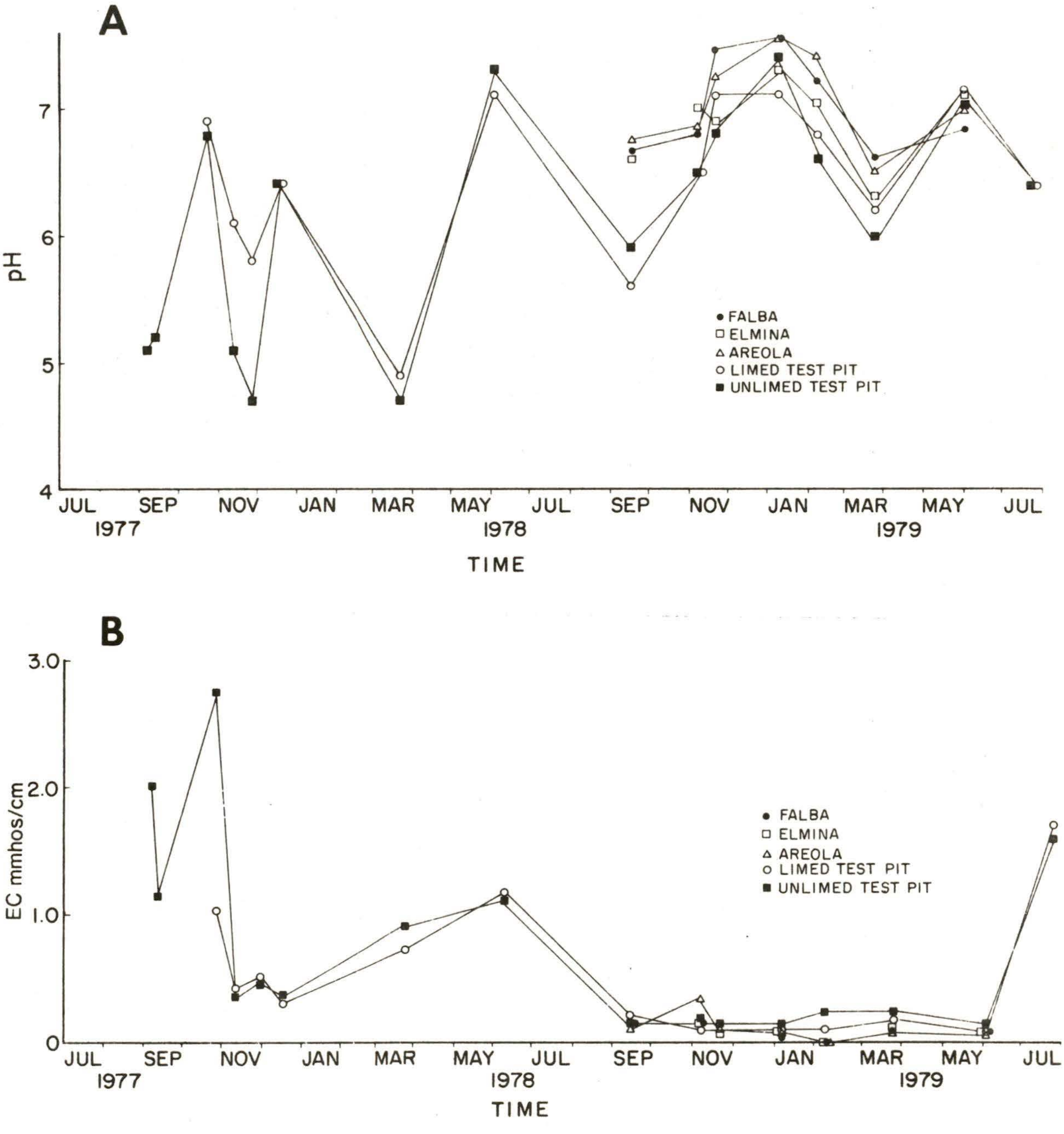


Figure 26. Changes in pH (A) and electrical conductivity (B) of the natural runoff water with time for the test pit and native soil sites in Grimes County, Texas (Deuel and Brown, 1980).

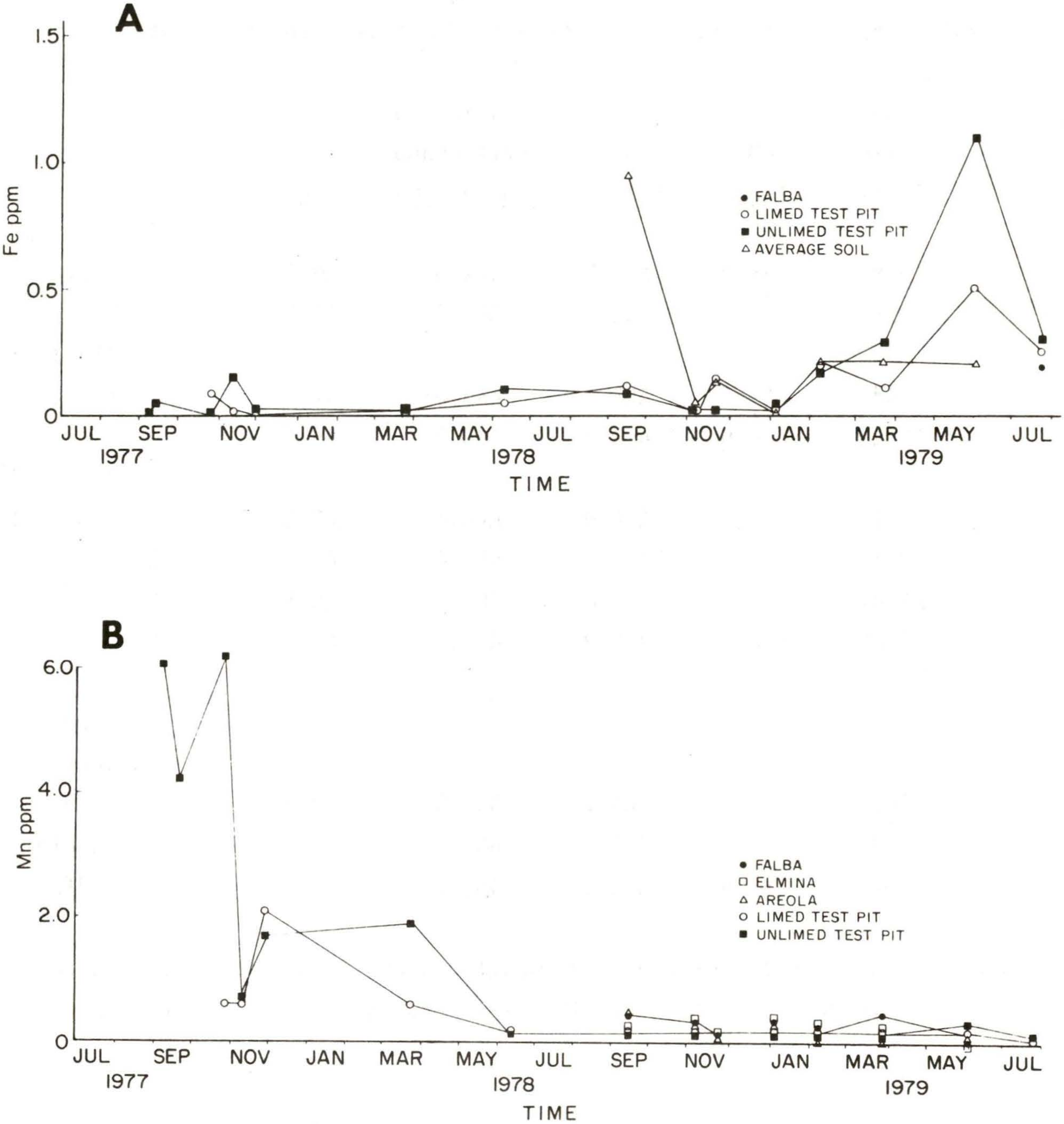


Figure 27. Changes in Fe (A) and Mn (B) of the natural runoff water with time for the test pit and native soil sites in Grimes County, Texas (Deuel and Brown, 1980).

Iron, manganese and electrical conductivity in treated spoil runoff are generally higher than in native soil runoff, but they are within the accepted allowable water quality standards of OSM. At the Angelina County site, iron and manganese concentrations in spoil runoff are higher than in native soil runoff; however, the suspended solids are much lower than in native soil runoff. The results are shown in Table 6 for the Grimes County site, Table 7 for the Angelina County site, and Table 8 for the Harrison County site.

The suspended solids from all the field test plots, including those on native soils, and the iron concentrations in spoil runoff at the Grimes County and Angelina County sites were above the maximum allowable values in Office of Surface Mining regulations. The pH of runoff from all the field test plots was essentially neutral. Sediment transport induced by the intense simulated rains may explain why the iron values are much higher than those found in the natural rainfall experiments.

Ground-Water Quality

Ground-water quality has been investigated in resaturated mine spoil in a Type 2 reclaimed mine. Pollock (1982) investigated the ground-water quality in 25 year old mine spoil at a Central Texas delta plain lignite surface mine. Mine-spoil ground water is similar in quality to that in the pre-mine overburden. Ground water in both is typically a highly mineralized, neutral pH water with high concentrations of sulfate, bicarbonate, chloride, calcium and sodium. Spoil ground-water contains slightly more total dissolved solids than ground-water that has evolved in shale-rich overburden and is two or three times higher than ground-water that has evolved in sand-rich overburden (Table 9).

Sulfate reduction and cation exchange in the saturated zone alter the composition of mine-spoil ground-water as it moves downdip through the reclaimed mine. It is predicted that the spoil water that emerges from the downdip mine boundary will be similar in quality and composition to the ground-water in nearby unmined sand aquifers at the same depth. Consequently, surface mining should not significantly affect the quality of ground-water

Table 6. Chemical Characteristics and Sediment Load of Runoff Water From Reclaimed Test Pit and Native Soil Plots in Grimes County, Texas

	pH	Electrical Conductivity (mmhos/cm)	Fe (mg/l)	Mn (mg/l)	Suspended Solids (mg/l)
Native Soil					
Rain 1	6.9B*	0.23B	2.66A	0.48A	860A
Rain 2	7.1A	0.39A	2.60A	0.39A	720A
Test Pit					
Rain 1	7.1A	0.64A	8.24A	1.17A	2560A
Rain 2	7.2A	0.61A	6.69A	0.58A	1200A
Test Pit					
Treatment A	7.2A	0.64A	5.4 A	0.6 A	1160A
B	7.2A	0.62A	6.8 A	0.7 A	1190A
C	7.2A	0.63A	8.6 A	1.2 A	1620A
D	7.1A	0.61A	9.2 A	1.0 A	3550A
Native Soil (Untreated)					
Areola	6.8B	0.10C	1.48B	0.47A	490B
Elmina	7.2A	0.40B	1.42B	0.17B	510B
Falba	6.8B	1.10C	2.23B	0.54A	1100A

* Data in column of each group followed by the same letter do not differ significantly at the 5 percent level of statistical variance.

Table 7. Chemical Characteristics and Sediment Load of Runoff Water From Reclaimed Test Pit and Native Soil Plots in Angelina County, Texas

	pH	Electrical Conductivity (mmhos/cm)	Fe (mg/l)	Mn (mg/l)	Suspended Solids (mg/l)
Native Soil					
Rain 1	6.7A*	0.25A	2.98A	0.70A	5580A
Rain 2	6.5A	0.18B	1.91B	0.30B	2780A
Test Pit					
Rain 1	6.7A	0.35A	5.09A	1.20A	1140A
Rain 2	6.8A	0.31B	3.26B	0.49B	600B
Test Pit					
Treatment A	6.8A	0.33B	4.4 A	0.78B	800A
B	6.8A	0.36A	4.7 A	0.72B	1110A
C	6.7A	0.32BC	3.2 A	0.71A	750A
D	6.7A	0.31C	4.5 A	1.16A	810A
Native Soil (Untreated)					
Crayfish	6.9A	0.23B	2.26B	0.23B	5380AB
Lufkin	6.5B	0.13C	1.39C	0.15B	7130A
Rosenwall	6.2C	0.17C	1.69C	0.85A	2950B

* Data in column of each group followed by the same letter do not differ significantly at the 5 percent level of statistical variance.

Table 8. Chemical Characteristics and Sediment Load of Runoff Water From Reclaimed Test Pit and Native Soil Plots in Harrison County, Texas

	pH	Electrical Conductivity (mmhos/cm)	Fe (mg/l)	Mn (mg/l)	Suspended Solids (mg/l)
Native Soil					
Rain 1	6.9B*	0.14A	2.50A	0.21A	1310B
Rain 2	7.1A	0.12B	2.15B	0.07B	520A
Test Pit					
Rain 1	6.9B	0.20A	2.43A	0.22A	690A
Rain 2	7.2A	0.13B	1.98B	0.16B	680A
Test Pit					
Treatment A	7.1A	0.18A	2.2 A	0.17B	860A
B	7.1A	0.19A	2.2 A	0.23A	750A
C	7.0A	0.14A	2.3 A	0.18AB	550A
D	7.1A	0.14A	2.1 A	0.19AB	580A
Native Soil (Untreated)					
Bowie	7.1A	0.10B	2.26A	0.10A	420A
Cuthbert	6.8B	0.10B	2.46A	0.17A	1990B
Kirvin	7.0A	0.12B	2.38A	0.11A	380A

* Data in column of each group followed by the same letter do not differ significantly at the 5 percent level of statistical variance.

Table 9. Ground-Water Chemistry of Delta Plain Lignite Surface Mines

	Resaturated Mine Spoil	Delta Plain Channel Sand	North Dakota Shale-Rich Overburden
pH	6.7 - 6.9	6.6 - 7.6	7.8 - 8.0
TDS (ppm)	3300 - 3700	1250 - 1600	3340 - 3640
Dominant Cations (ppm)			
Calcium	380 - 600	200 - 260	135 - 400
Magnesium	150	45 - 60	100 - 225
Sodium	265 - 550	115 - 200	600 - 700
Dominant Anions (ppm)			
Bicarbonate	700 - 900	160 - 170	750 - 1100
Sulfate	750 - 1100	430 - 460	1500 - 2650
Chloride	500 - 900	160 - 500	15 - 50
Type Water	Ca-Na-SO_4-HCO_3-Cl	Ca-Na-SO_4-Cl-HCO_3	Na-Ca-SO_4-HCO_3 Na-SO_4-HCO_3

beyond the mine boundaries. There is little danger of significant acid mine drainage from the Texas lignite mines. This is due to the relatively low pyritic sulfur content and/or abundance of carbonates in the mine spoil which neutralize free acid as it is produced by pyrite oxidation.

A hydrochemical model developed for Gulf Coast lignite mines (Pollock, 1982) suggests that infiltrating water after normal rainfall events will be trapped in the root zone by evapotranspiration, where it will dissolve readily soluble minerals in the root zone. Salts will accumulate in the root zone after repeated cycles of infiltration and evapotranspiration. The capacity of the soil to hold water will be exceeded after periods of heavy or sustained rainfall, such as the fall-winter rainy season. Infiltrating water will move through the root zone flushing accumulated salts into the ground-water system. Spoil water will, therefore, have a character that has been imposed on it by hydrochemical processes active in the unsaturated zone. Processes of oxidation, solution, precipitation and ion exchange will produce a highly mineralized water of the $Ca-Na-SO_4-HCO_3-Cl$ type. Where mine spoil ground water moves slowly, it may become distinctly zoned. High $Ca-SO_4$ water at the water table should grade into increasingly higher $Na-HCO_3$ water as the depth in the water column increases. Figure 28 shows a schematic diagram of this hydrochemical model.

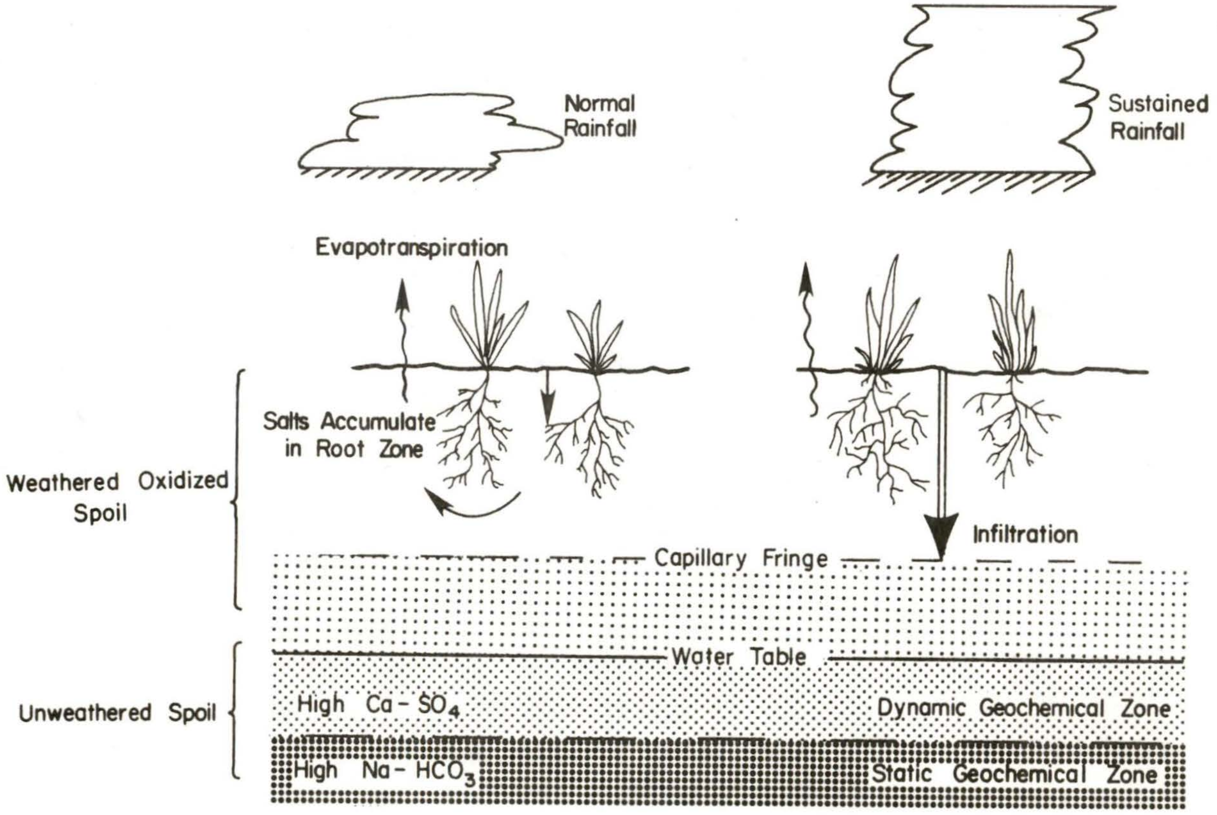


Figure 28. Schematic diagram of the hydrochemical model for a Gulf Coast reclaimed lignite mine (Pollock, 1982).

CONCLUSIONS

The impact of surface mining on Texas ground-water resources has been found to be minimal for most of the lignite districts in the state. The geologic conditions that existed during deposition of the organic matter also deposited clays. Consequently, many lignite deposits are associated with clay-shale overburden that is not an aquifer. In most cases where sand units are associated with the overburden, such as in the East Texas fluvial lignite mines, shallow ground-water resources will be affected.

Disturbances to the hydrologic balance in surface-mined land are slight to negligible in Type 1, Type 2 and Type 3 mines; ground-water resources will not be affected. Under conditions of forced recharge, resaturation in Type 2 mines may be completed within 20 years but may take more than 35 to 50 years under normal recharge conditions. Resaturation in Type 3 and Type 4 mines should be completed within 5 to 10 years. In Type 4 mines where major sand aquifers are present in the overburden, selective mining practices that replace sand over clay-shale may be needed to minimize the impact on ground-water resources. The assertion of Pennington (1978) and Mathewson (1979) that surface mining destroys existing shallow aquifers in Gulf Coast lignite mines is untrue in Type 4 mines where selective mining practices reconstruct shallow aquifers.

Ground water in resaturated mine spoil is similar in quality and composition to that in shale-rich overburden, and is similar in composition but more mineralized than that in sand-rich overburden. Spoil water evolution parallels the natural evolution of ground water in unmined lignite-bearing formations. There is little danger of significant acid mine drainage from Texas surface mines, because abundant carbonates in the spoil neutralize free acid as it is produced by pyrite oxidation.

Runoff quality from recently-revegetated spoil plots is within acceptable limits for pH, electrical conductivity, Fe and Mn, but the runoff contains very high suspended solids (sediment load). Runoff from reclaimed mine spoil initially contains elevated concentrations of solids, Fe and in some cases Mn;

however, these concentrations decrease within a year to approximately the background levels of runoff from native soil plots. Sediment loads in runoff from mine spoil plots exceed the OSM standard but generally do not differ significantly from the sediment loads in native soil runoff in many Texas lignite districts.

Conditions in reclaimed mined lands in Texas favor successful revegetation. Overburden materials suitable for reclamation are present above the lignite deposits. Selective placement may be necessary in some instances to assure that suitable materials are on the surface of regraded spoil and that undesirable materials are buried below the root zone. The infiltration rates on reclaimed mine spoil are equal to or slightly less than those for native major soil series. Although the infiltration rate in mine spoil may be slightly lower, the removal of the restrictive clay subsoil that is common to native soils will allow deeper water penetration in the mine spoil. Combined with increased water retention, this results in more plant-available water in the mine spoil. This increased water availability offers a greater potential for plant growth in the mine spoil. Properly managed field plots on mined soils throughout the Texas lignite districts have yielded harvests that are comparable to those from native soil plots.

The results of this research are summarized in Table 10, which compares the hydrologic impacts of surface mining of Texas lignites in the various hydrogeologic types of mines.

Table 10. Impacts of Surface Mining of Texas Lignites

Hydrogeol. Condition	Hydrologic Balance	Ground-Water Resources	Resaturation Period	Ground-Water Quality	Runoff Quality
Type 1	Slight	None	Not Applicable	None	Moderate
Type 2	Slight to Moderate	Slight	Slow (20+ yrs)	Slight to Moderate	Slight to Moderate
Type 3	Slight	Slight	Medium (5+ yrs)	Moderate; Slight at 5+ yrs	Moderate
Type 4	Slight	Moderate	Rapid	Moderate	Slight

REFERENCES

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: Texas Department of Water Resources, Austin, TX, 109 p.

Basciano, J.M., 1978, Application of Environmental Geology to Ground-Water Hydrology of the Wilcox Lignite Belt. In Kaiser, W.R. (editor), Proceedings 1976 Gulf Coast Lignite Conference: Geology, Utilization, Environmental Aspects, Report of Investigation 90: Bureau of Economic Geology, University of Texas, Austin, TX, pp. 221-230.

Bishop, M.A., 1977, Engineering Geology Study of Highwall Stability for a Proposed Lignite Mine in Grimes County, Texas: Unpublished Master of Science Thesis, Department of Geology, Texas A&M University, College Station, TX, 142 p.

Bowman, L.G., 1978, Analysis of the Risk of Deep Groundwater Pollution Due to Surface Mining for Lignite in Grimes County, Texas: Unpublished Master of Science Thesis, Department of Geology, Texas A&M University, College Station, TX, 99 p.

Broom, M.E. and Myers, B.N., 1966, Groundwater Resources of Harrison County, Texas, Texas Water Development Board Report 27: Texas Department of of Water Resources, Austin, TX, 74 p.

Brown, K.W. and Deuel, L.E., 1980, Revegetation of Drastically Disturbed Lands. In Mathewson, C.C. (editor), Lignite: Texas A&M University Lignite Symposium: Texas A&M University, College Station, TX, p. 19.0-19.9.

Brown, K.W.; Thomas, J.C.; and Launius, K.W., 1982, Distribution of Bermuda grass Roots in Native Soils and Reclaimed Lignite Spoil: Reclamation and Revegetation Research (in review).

Brown, P.; Smith, R.; and Wendt, G., 1980, Interrelationship of Ground-Water with Overburden and Reclaimed Spoil at an Active Surface Mine in Southwestern Colorado. In Graves, D.H. and DeVore, R.W. (editors), Preceedings 1980 Symposium of Surface Mining Hydrology, Sedimentology and Reclamation, Bulletin 123: University of Kentucky, Lexington, KY, pp. 225-234.

Charles, R.J., 1979, Hydrogeology of a Proposed Surface Lignite Mine, Southwestern Harrison County, Texas: Unpublished Master of Science Thesis, Department of Geology, Texas A&M University, College Station, TX, 126 p.

Deuel, L.E. and Brown, K.W., 1980, Impact of Surface Mining on Water Quality. In Mathewson, C.C. (editor), Lignite: Texas A&M University Lignite Symposium: Texas A&M University, College Station, TX, p. 16.1-16.6.

French, L.N., 1979, Hydrogeologic Aspects of Lignite Strip Mines Near Fairfield, Texas: Unpublished Master of Arts Thesis, Department of Geology, University of Texas, Austin, TX, 105 p.

Groenewold, G.H.; Rehm, B.W.; Cherry, J.A.; Koob, R.L.; Moran, S.R.; Palmer, C.D.; and Peterson, W.M., 1980, Potential Hydrochemical Impacts of Surface Mining in the Northern Great Plains. In Graves, D.H. and DeVore, R.W. (editors), Proceedings 1980 Symposium on Surface Mining Hydrology, Sedimentology and Reclamation, Bulletin 123: University of Kentucky, Lexington, KY, pp. 465-473.

Hem, J.D., 1959, Study and Interpretation of the Chemical Characteristics of Natural Water, United States Geological Survey Water-Supply Paper 1473: United States Government Printing Office, Washington, D.C., 269 p.

Herring, W.C., 1977, Groundwater Re-establishment in Cast Overburden. In Seventh Symposium on Coal Mine Drainage Research: National Coal Association, Louisville, KY, pp. 72-87.

Hounslow, A.; Fitzpatrick, J.; Cerrilo, L.; and Freeland, M., 1978, Overburden Mineralogy as Related to Ground-Water Chemical Changes in Coal Strip Mining, United States Environmental Protection Agency Publication EPA 600/7-78-156: Robert S. Kerr Environmental Research Laboratory, Ada, OK, 299 p.

Kaiser, W.R., 1974, Texas Lignite: Near-Surface and Deep-Basin Resources, Report of Investigation 79: Bureau of Economic Geology, University of Texas, Austin, TX, 70 p.

Kaiser, W.R., 1978, Electric Power Generation from Texas Lignite, Geological Circular 78-3: Bureau of Economic Geology, University of Texas, Austin, TX, 18 p.

Kennedy, J.L., III, 1981, Hydrogeology of Reclaimed Gulf Coast Lignite Mines: Unpublished PhD Dissertation, Department of Geology, Texas A&M University, College Station, TX, 285 p.

Kennedy, J.L. and Pepper, G.L., 1980, Hydraulic Properties and Hydrogeologic Mapping of Reclaimed Gulf Coast Lignite Mines. In Mathewson C.C. (editor), Lignite: Texas A&M University Lignite Symposium: Texas A&M University, College Station, TX, pp. 17.1-17.14

Launius, K.W., 1980, A Field Evaluation of the Movement of Selected Metals in Revegetated Strip Mine Overburden and Laboratory Assessment of Transport Mechanisms: Unpublished Master of Science Thesis, Department of Soil Science, Texas A&M University, College Station, TX, 119 p.

Levitan, L.W., 1976, Effects of Hydrogeology on Lignite Recovery in the Manning Formation, Grimes County, Texas: Unpublished Master of Science Thesis, Department of Geology, Texas A&M University, College Station, TX, 75 p.

Mathewson, C.C., 1979, Groundwater and Hydrology and Their Impact of Mining. In Proceedings, Gulf Coast Lignite Conference, Houston, TX, 59-67.

Mathewson, C.C., 1982a, Exploration and Development, Gulf Coast Lignite. In Symposium Sobre Prospecion de Carbon: Escuela Tecnica Superior de Ingenineros de Minas, Oviedo, Spain.

Mathewson, C.C., 1982b, Case Histories of Three Lignite Deposits in Texas. In Symposium Sobre Prospecion de Carbon: Escuela Tecnica Superior de Ingenineros de Minas, Oviedo, Spain.

Mathewson, C.C.; Kennedy, J.L.; and Pepper, G.L., 1979, Hydrogeology of Reclaimed Gulf Coast Lignite Mines. In Carpenter, S.B. and DeVore, R.W. (editors), Proceedings 1979 Symposium on Surface Mining Hydrology, Sedimentology, and Reclamation, Bulletin 119: University of Kentucky, Lexington, KY, pp. 321-330

Moran, S.R.; Groenewold, G.H.; and Cherry, J.A., 1978, Geologic, Hydrologic and Geochemical Concepts and Techniques in Overburden Characterization for Mined-Land Reclamation, Report of Investigation 63: North Dakota Geological Survey, Fargo, ND, 152 p.

Pennington, D., 1978, Hydrogeological Factors Which Influence the Reclamation of Lignite Mines. In Kaiser, W.R. (editor), Proceedings 1976 Gulf Coast Lignite Conference: Geology, Utilization, Environmental Aspects, Report of Investigation 90: Bureau of Economic Geology, University of Texas, Austin, TX, pp. 218-227.

Pepper, G.L., 1980, Hydrogeology of a Reclaimed Central Texas Lignite Mine:

Unpublished Master of Science Thesis, Department of Geology, Texas A&M University, College Station, TX, 77 p.

Pollock, C.R., 1982, Ground-Water Hydrogeology and Geochemistry of a Reclaimed Lignite Surface Mine: Unpublished Master of Science Thesis, Department of Geology, Texas A&M University, College Station, TX, 152 p.

Railroad Commission of Texas, 1976, Application for Surface Mining Operation Permit Form MS-3, Agency Review, Aluminum Company of America (Rockdale): Public Document, Railroad Commission of Texas, Surface Mining Division, Austin, TX.

Rangel, J.E., 1979, The Effect of Stratigraphy and Soil Plasticity on the Settlement Characteristics of Reclaimed Surface Mined Land: Unpublished Master of Science Thesis, Department of Geology, Texas A&M University, College Station, TX, 109 p.

Rehm, B.W.; Groenewold, G.H.; and Morin, K., 1980, Hydraulic Properties of Coal and Related Materials, Northern Great Plains: Ground Water, Vol. 18, No. 6, pp. 551-561.

Schneider, W.J., 1977, Analysis of the Densification of Reclaimed Surface Mined Land: Unpublished Master of Science Thesis, Department of Geology, Texas A&M University, College Station, TX, 125 p.

Snedden, J.W., 1979, Stratigraphy and Environment of Deposition of the San Miguel Lignite Deposit, Northern McMullen and Southeastern Atascosa Counties, Texas: Unpublished Master of Science Thesis, Department of Geology, Texas A&M University, College Station, TX, 161 p.

Van Voast, W.A., 1974, Hydrologic Effects of Strip Coal Mining in Southeastern Montana--Emphasis: One Year Mining Near Decker, Bulletin 93: Montana Bureau of Mines and Geology, Butte, MT, 24 p.

Van Voast, W.A. and Hedges, R.B., 1975, Hydrogeologic Aspects of Existing and Proposed Strip Coal Mines Near Decker, Southeastern Montana, Bulletin 97: Montana Bureau of Mines and Geology, Butte, MT, 31 p.

Van Voast, W.A.; Hedges, R.B.; and McDermott, J.J., 1977, Hydrogeologic Conditions and Projections Related to Mining Near Colstrip, Southeastern Montana, Bulletin 102: Montana Bureau of Mines and Geology, Butte, MT, 43 p.

Watson, J.Q., 1979, The Stratigraphy and Environment of Deposition of the Wilcox Lignite Deposit South of Hallsville, Harrison County, Texas:

Unpublished Master of Science Thesis, Department of Geology, Texas A&M University, College Station, TX, 224 p.