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Effect of sinkholes on soil moisture and ground water recharge at an abandoned underground coal mine near Wilton, North Dakota

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EFFECT OF SINKHOLES ON SOIL MOISTURE AND GROUND WATER RECHARGE AT AN ABANDONED UNDERGROUND COAL MINE NEAR WILTON, NORTH DAKOTA

by

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This thesis, submitted by Michael M. Sonderman in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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This thesis meets the standards for appearance, conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

Dean of the Graduate School

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Date ______________________

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ABSTRACT

Subsidence at abandoned underground mines in south-central and southwest North Dakota has produced numerous sinkholes. Previous studies in the Northern Great Plains have suggested depression-focused recharge may be a significant ground water recharge mechanism in this region. Thus, sinkholes may increase soil moisture and ground water recharge. Current reclamation practices include filling sinkholes with non-topsoil fill material. However, the benefits of increases in soil moisture and ground water supplies may outweigh the benefits of expensive reclamation. The purpose of this study was to determine whether soil moisture and, hence, the potential for ground water recharge, was greater in sinkholes than non-collapsed settings at an abandoned underground coal mine near Wilton, North Dakota.

Site stratigraphy consists of till overlying interbedded sands, silts, clays, and coal. The water table lies within or slightly above the coal seam mined at the site, at a depth of 40 to 110 feet, with the exception of two wells set in structural highs in the coal seam. The topography is gently rolling hills with integrated drainage. Annual precipitation is 17 inches, 80% of which falls from April 1 through September, which is also the period of greatest evapotranspiration.

Relative changes in soil moisture were measured in six sinkholes and five non-collapsed settings with a neutron probe. Tensiometers were installed to establish the direction of hydraulic gradients in the shallow unsaturated zone. Climatic data were obtained from the National Weather Service station in Wilton.

Soil moisture conditions were monitored from the middle of February 1990 through early December 1990. These data show that soil moisture was greater in sinkholes than non-collapsed settings during

this entire monitoring period, producing conditions more conducive to ground water recharge in sinkholes. Deep infiltration occurred only in sinkholes. Correlation of climate and soil moisture data suggest deep infiltration, possibly leading to storage or recharge, will occur only in sinkholes under normal climatic conditions. These data also indicate the greatest potential for deep infiltration and ground water recharge are in the spring and fall. Reasons for greater soil moisture in sinkholes include snow and run-off capture. Sediments in sinkholes also have greater porosity and permeability due to collapse.

Although deep infiltration was measured in some sinkholes and not in non-collapsed settings, estimates of recharge indicate that the recharge measured was several orders of magnitude lower than the flux of water from the local water table to a lower aquifer. Reclamation would eliminate these sinkholes as recharge mechanisms but their loss as a recharge mechanism may not be that important. Because of the benefits of increases in soil moisture (creating more productive pasture) and ground water recharge potential, sinkholes at abandoned underground mines in this region could be left unreclaimed if they do not endanger surface structures and are not at risk of contamination. If they pose a threat to the general public or are at risk of contamination, they should be reclaimed.

INTRODUCTION

General

Starting in the 1870's and continuing into the 1930's, underground mining of coal was common in North Dakota with at least 73 mines in existence prior to 1900 (Oihus, 1983, p. 5). Although underground mining of coal has given way to strip mining in North Dakota, its legacy remains in the numerous abandoned underground mines in the south-central and southwestern regions of the state.

Subsidence at abandoned underground coal mines in North Dakota has resulted in the formation of numerous sinkholes. Aside from creating hazards to surface structures such as roads and buildings, sinkholes may influence soil moisture and the potential for ground water recharge. Current reclamation practices include filling sinkholes with mine spoils or other available materials. The purpose of this study was to determine what effect sinkholes might have on soil moisture and ground water recharge at an abandoned underground coal mine. Current reclamation practices may need to be modified if the net effect of sinkholes on soil moisture and ground water recharge is found to be beneficial to local land and ground water users.

The Abandoned Mined Lands Division (AML) of the North Dakota Public Service Commission (PSC) has been given the responsibility of identifying these abandoned mined lands and designing and overseeing reclamation projects to ensure public safety and minimize state liability. In the past, reclamation has included filling of tunnels with sand and gravel and the filling of sinkholes, mine slopes, and pit mines with mine spoils or other earth materials.

In 1988 the Energy and Environmental Research Center (EERC), at

Figure 1. Location of the study area near Wilton, Burleigh County, North Dakota.

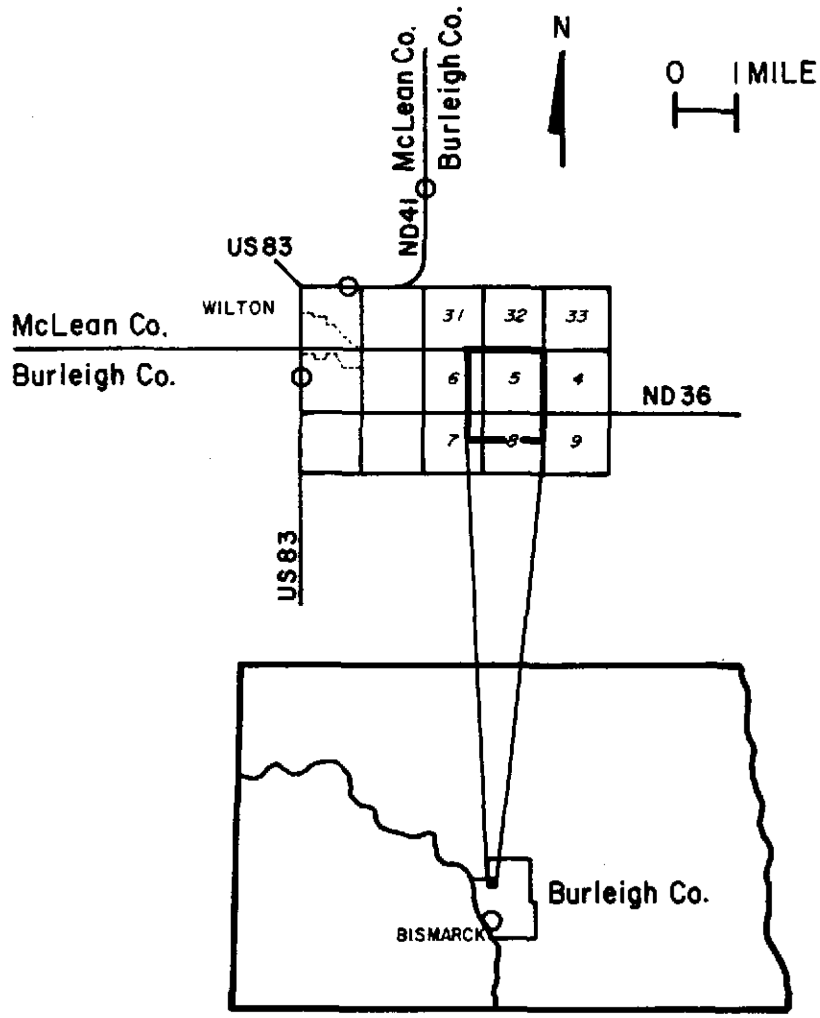

McLean Co.
Burleigh Co.
N
0 1 MILE
US83
ND41
WILTON
McLean Co.
Burleigh Co.
31
32
33
6
5
4
7
8
9
ND36
US83
Burleigh Co.
BISMARCK

Figure 2. Site location in relationship to physiographic districts and subdistricts in Burleigh County (modified from Kume and Hansen, 1965). See Figure 1 for location of Burleigh County.

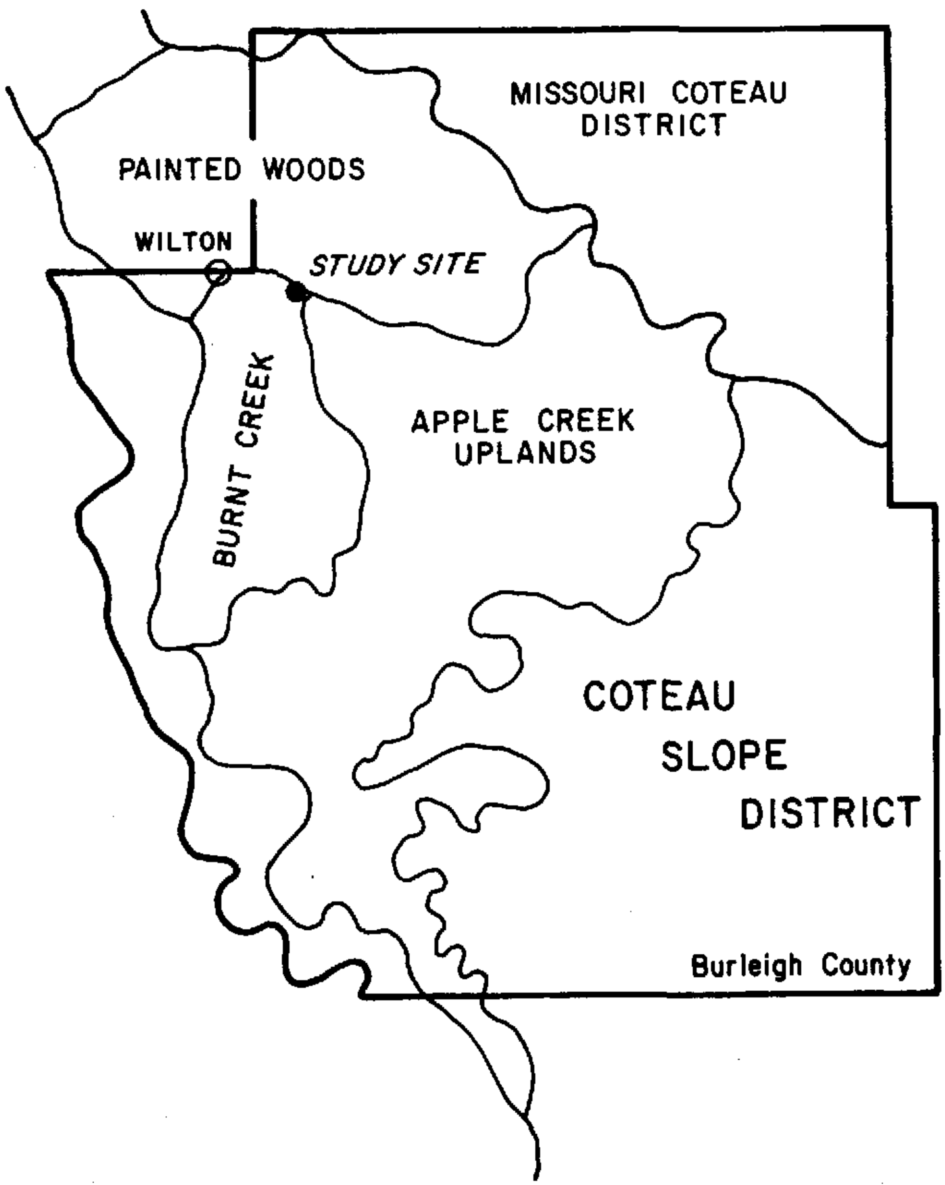

MISSOURI COTEAU
DISTRICT
PAINTED WOODS
WILTON
STUDY SITE
BURNT CREEK
APPLE CREEK
UPLANDS
COTEAU
SLOPE
DISTRICT
Burleigh County

Figure 3. Topographic map with locations of wells (numbered 1 to 13), gauging posts (denoted as GP-1 and 2), geologic cross-section (labeled A-A'), two hydrostratigraphic cross-sections (B-B'), and some reclaimed areas at the site. The mine pits in Sections 7 and 8 and the sinkholes in area I were reclaimed in 1989. The mine pit in the southeast corner of Section 5 and the sinkholes in area II were reclaimed at an earlier date. Soil moisture monitoring equipment was installed in area III (See Figure 15). The area enclosed by the heavy dashed line represents the border of Figures 6 and 45 (modified from USGS 7.5 minute, Grass Lake topographic quadrangle, 1979).

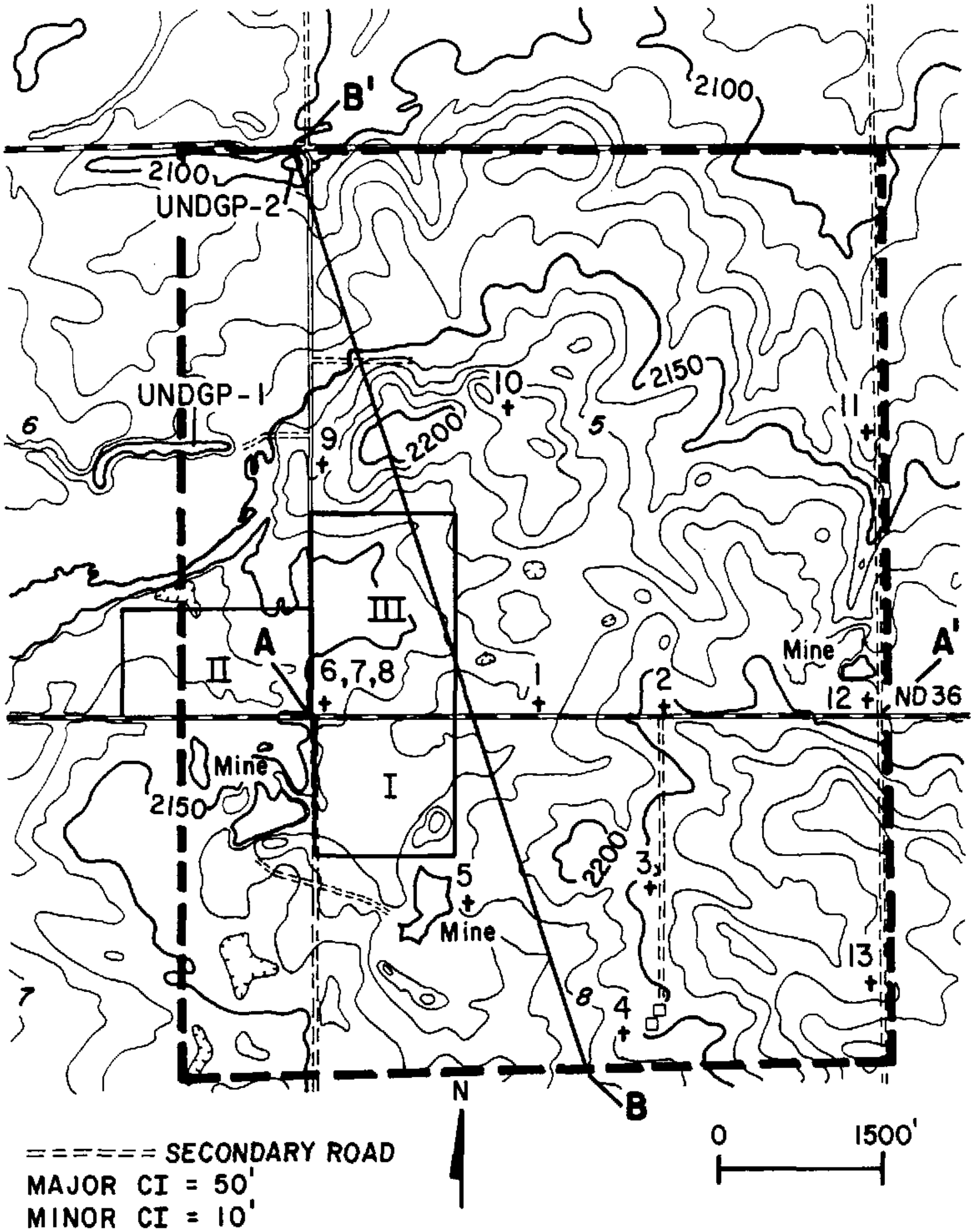
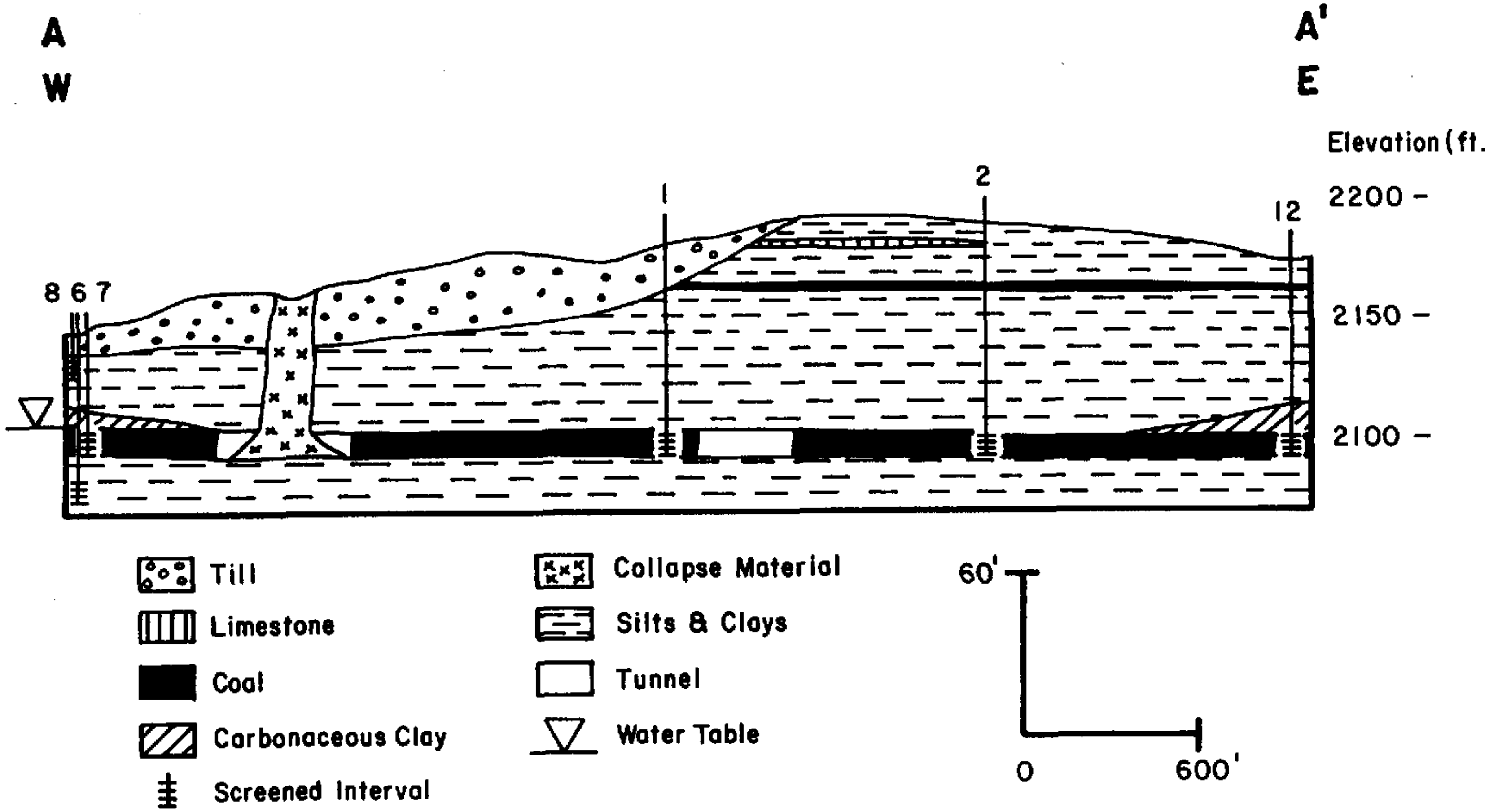

2100
B'
2100
UNDGP-2
2150
UNDGP-1
10
11
9
2200
6
5
III
II
I
A
6,7,8
1
2
Mine
A'
12
ND36
2150
Mine
5
Mine
2200
3
13
8
4
7
B
N
0
1500'
SECONDARY ROAD
MAJOR CI = 50'
MINOR CI = 10'

Figure 4. Generalized stratigraphic column for northwest Burleigh County (Bluemle, 1988).

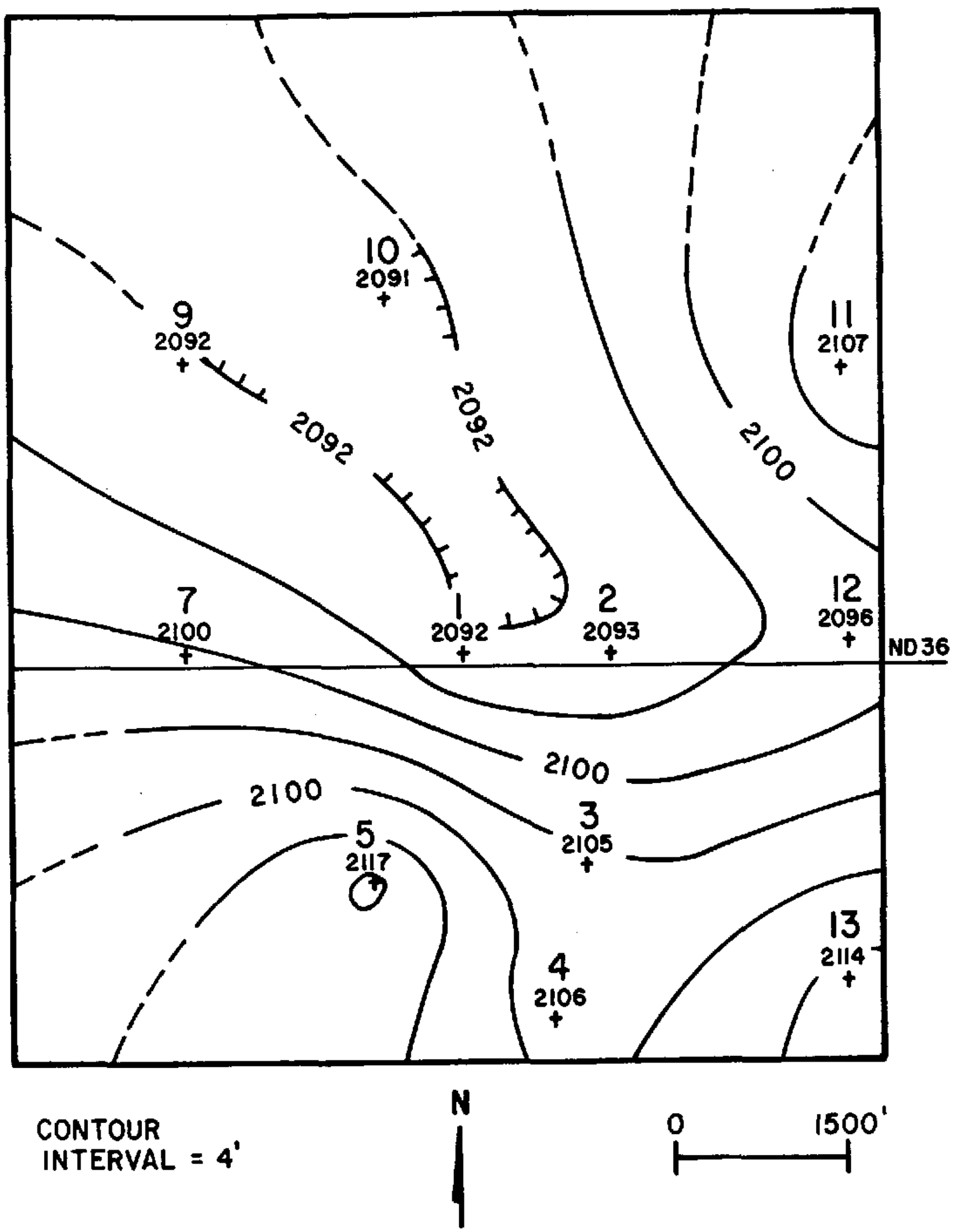
Quaternary	Pleistocene	COLEHARBOR GP.
Tertiary	Paleocene	SENTINEL BUTTE FM.?
		BULLION CREEK FM.
		CANNONBALL FM.
		LUDLOW FM.
Upper Cretaceous		HELL CREEK FM.
		FOX HILLS FM.
		PIERRE FM.

Figure 5. Geologic cross-section parallel to North Dakota State Highway 36. Six wells installed along the cross-section have been included on the figure. See Figure 3 for the locations of the cross-section and wells. Stratigraphically, the till belongs in the Coleharbor Group. The remainder of sediments in the cross-section are part of the Bullion Creek Formation.



A
W
A'
E
Elevation (ft.)
2200 -
2150 -
2100 -
1
2
12
8 6 7
Till
Limestone
Coal
Carbonaceous Clay
Screened Interval
Collapse Material
Silts & Clays
Tunnel
Water Table
60'
0
600'

Figure 6. Contour map of the base of the coal seam. Elevations of the base are posted below corresponding well numbers. Well locations are represented by plus signs. The heavy-dashed line on Figure 3 represents the border of this map. Well locations can also be found on Figure 3.



10
2091
9
2092
11
2107
2092
2092
2100
7
2100
1
2092
2
2093
12
2096
ND36
2100
2100
3
2105
5
2117
13
2114
4
2106
CONTOUR
INTERVAL = 4'
N
0
1500'

Vertical fractures in the till can be seen in sinkhole walls and on the walls and roofs of caves that have formed in the sides of sinkholes. These fractures are often mineralized, containing calcite or iron oxide. Vertical fractures can also be found in selected cores collected from bedrock sediments. Fracture surfaces are indicated by iron oxide coatings.

Regional Hydrogeology

Ground water supplies in Burleigh County occur in bedrock, glacio-fluvial, and alluvial deposits. Approximately 70% of the domestic and stock wells are set in bedrock aquifers, although aquifers with the greatest potential yield are in buried channel deposits, alluvial deposits, and glacio-fluvial (outwash) deposits (Randich and Hatchett, 1966).

Water-bearing units in Cretaceous and Tertiary bedrock materials in Burleigh County include fractured rock, sands, and sandstones. Lignites may also serve as local aquifers in Tertiary deposits. Quaternary buried channel deposits are composed of glacio-fluvial and alluvial sediments, mainly sand and gravel. The major alluvial deposits are associated with the Missouri River and also consist of sand and gravel. Well yields from the different aquifer types are extremely variable (Table 1).

Regionally, ground water recharge to deeper aquifers occurs from streams, potholes, buried channel deposits, and glacio-fluvial deposits during periods of high precipitation and run-off. Locally, under similar climatic conditions, recharge may occur in surficial sand and gravel deposits (Randich and Hatchett, 1966), in small surface depressions and ephemeral streams (Lissey, 1968), and sloughs (Meyboom, 1966).

TABLE 1

Average well yields and total dissolved solids for various aquifers in Burleigh County. Data and terms in quotes from Randich and Hatchett (1965).

	Well Yields (gpm)	Total Dissolved Solids (ppm)
Quaternary Aquifers:		
"Buried Channel Deposits"	> 1000	600 - 1500
"Alluvial Deposits"	> 1000	1000 - 1300
"Glacio-fluvial Deposits"	< 20	1000
"Glacial Drift"	< 20	800 - 1500
Tertiary Bullion Creek Fm.	< 20	500 - 1900
Cretaceous Aquifers	< 50	450 - 2500

Ground water flows from streams and potholes into shallow aquifers during wet periods. In turn, water from these shallow aquifers will recharge deeper aquifers. The direction of ground water flow may be altered by dry periods. Ground water flow in the buried channel deposits is toward the Missouri River (Randich and Hatchett, 1966).

Rehm and others (1980) summarized the hydraulic properties of sediments at 13 coal mine sites in the Northern Great Plains, reporting a range of hydraulic conductivities of 1×10^{-3} ft/s to 3×10^{-9} ft/s, with a mean of 1×10^{-5} ft/s for 70 measurements in Paleocene aquifers, which includes the Bullion Creek Formation. These values were found to be the same for coal, sand, and sandstone aquifers, although values for the sand and sandstone aquifers were more strongly skewed toward lower conductivities. Sixty-three measurements in Paleocene silts and clays ranged from 3 x 10^{-5} ft/s to 3 x 10^{-11} ft/s, with a mean hydraulic conductivity of 1 x 10^{-7} ft/s.

Twenty-seven hydraulic conductivity measurements made in Quaternary sands and gravels ranged from 3 x 10^{-2} ft/s to 3 x 10^{-6} ft/s, with a mean hydraulic conductivity of 2 x 10^{-4} ft/s (Rehm and others, 1980). Values for thirty-five measurements for pebble loam, or till, ranged from 3 x 10^{-6} ft/s to 3 x 10^{-11} ft/s, with a mean of 2 x 10^{-8} ft/s (Rehm and others, 1980). Hydraulic conductivities of 3 x 10^{-5} ft/s to 3 x 10^{-6} ft/s have been reported for fractured tills in central North Dakota (Sloan, 1972), while hydraulic conductivities of 1 x 10^{-10} ft/s have been reported for unfractured tills (Grisak and Cherry, 1975). Rehm and others (1980) attribute the wide range of values for all these materials to fractures.

Two types of porosity exist in the till at the Wilton site, intergranular and fracture. Intergranular porosities ranging from 0.18 to 0.40 have been reported for unfractured borehole samples of till in the Interior Plains region of Canada (Grisak and Cherry, 1975), which are lithologically similar to the tills in North Dakota (Grisak and others, 1976). Grisak and others (1976) calculated fracture porosities for till of approximately 0.0002, using two different methods. This number seems negligible, and probably does not reflect highly fractured till.

Water Composition

Water in Cretaceous aquifers in Burleigh County varies between sodium chloride bicarbonate, sodium bicarbonate, and sodium sulfate types (Randich and Hatchett, 1966; Naplin, 1979). Water in Tertiary rocks varies from sodium bicarbonate to sodium bicarbonate sulfate in the Cannonball Formation to either sodium or calcium-magnesium bicarbonate water in the Bullion Creek Formation (Naplin, 1979). Total dissolved solids for Cretaceous and Tertiary rocks are listed in Table 1 (from Randich and Hatchett, 1966, and Naplin, 1979). Values reported for the Sentinel Butte Formation by Naplin (1979) have been included in values for the Bullion Creek Formation, since the sediments identified as Sentinel Butte by Naplin (1979) have been included as part of the Bullion Creek Formation in this study.

Aquifers

There are two aquifers at the site, an unconfined one, which lies slightly above or within the Wilton coal seam, and a confined one in a clayey, silty sand below the coal seam. The two aquifers are separated by a thick gray clay. The depth to the water table ranges from about 40 to more than 115 feet. The ground water flow conditions at the site are discussed in detail later.

Factors Affecting Infiltration

Several factors may determine whether moisture infiltrates beyond the root zone and/or effective depth of evapotranspiration in any given setting. These factors include the amount and timing of precipitation, antecedent soil moisture conditions, evapotranspiration, depth to the water table, topography, and the composition and texture of materials in the unsaturated zone.

Moisture from a single precipitation event is unlikely to infiltrate directly to the water table as ground water recharge, because of the depth to the water table. Infiltration can occur as moisture drains downward in conjunction with spring melt and successive precipitation events. Moisture that infiltrates into the subsurface is not considered to be ground water recharge until it reaches the water table.

Most precipitation in northwest Burleigh County occurs during the summer when evapotranspiration rates are the highest. As a result much of the annual precipitation is lost before it infiltrates to any appreciable depth. Because most precipitation occurs as thunderstorms of short duration, infiltration during summer is most likely to occur after a series of successive storms that produce excess soil moisture.

When the rate of precipitation exceeds the infiltration capacity of a soil, surface run-off will occur. Surface run-off intercepted by sinkholes will be partially protected from the evaporative effects of wind and direct sunlight providing a greater possibility for deeper infiltration, in comparison to non-collapsed settings.

An increase in soil moisture will result in a higher unsaturated hydraulic conductivity (Freeze and Cherry, 1979, p. 42) until the moisture content exceeds the field capacity of the soil. The rate of infiltration reaches a constant value as the soil pores become saturated (Freeze and Cherry, 1979, p. 211). Birkeland (1984, p. 18) defines field capacity as the point at which the force that holds a film of water in pore spaces in a soil is equal to the downward force of gravity. Fetter (1980, p. 472) defines it as the maximum amount of water a soil can hold in its pores against gravity. Thus, if rain storms occur in close succession, soil moisture can remain at higher levels, reducing the effect of evapotranspiration. The wetter soil conditions allow successive precipitation to infiltrate faster because of higher hydraulic conductivities. This provides a greater chance for moisture to infiltrate beyond the depth that evapotranspiration is effective in depleting soil moisture. The end result is that wetter soil conditions will generally increase the potential for moisture to infiltrate into storage, and eventually, into the saturated zone.

Soil texture also plays a role in determining whether infiltration occurs or not, or how much infiltration occurs. At moderate to high moisture content, flow of water in coarser, unconsolidated deposits, such as sand, is greater than flow in fine-textured, unconsolidated deposits, such as silts and clays. But at low moisture contents, a fine-textured soil might have a greater unsaturated hydraulic conductivity than a coarse soil because the finer soil will hold more water in its pore spaces due to a greater particle surface area, facilitating water movement through the pores (Fetter, 1980, p. 91). Pores in a coarse-grained soil will drain more than a fine soil resulting in a lower unsaturated hydraulic conductivity at low moisture contents, because the pores must be rewetted by subsequent moisture to re-establish saturation. Regardless of the texture, increases in soil moisture in fine or coarse soils results in higher hydraulic conductivities, until the soil becomes saturated.

The presence of mineralized layers in soils is important in at least two ways. A mineralized zone may define a depth to which water typically infiltrates, but not normally beyond. Soluble minerals such as calcite and gypsum may be precipitated in these zones. Mineralized layers can develop to the extent that water is restricted or prevented from infiltrating any deeper. A common mineral found in the glacial sediments at the Wilton site is calcite. A soil zone in which calcite has accumulated, where calcite is less than 50 % of the horizon, is referred to as a Bk horizon (Birkeland, 1984, p. 8).

There should be no significant differences in the amount of flushing of soluble minerals in sinkholes and non-collapsed settings that do not receive run-off. During winter, however, sinkholes tend to collect and hold snow (Figure 7), creating moist soil conditions. Infiltrating moisture from this snow might be sufficient to flush soluble minerals to greater depths in sinkholes. Translocation of clay minerals may also be enhanced in sinkholes. This would create greater permeability in the flushed zone but would reduce permeability at greater depth where the clay accumulates.

Another factor influencing infiltration is the presence of joints, fractures, or any other form of secondary porosity that can increase the permeability of sediments. Inter-block channels and porosity are formed

Figure 7. Photograph of sinkholes holding snow. Note lack of snow on non-collapsed areas.

pg. 26

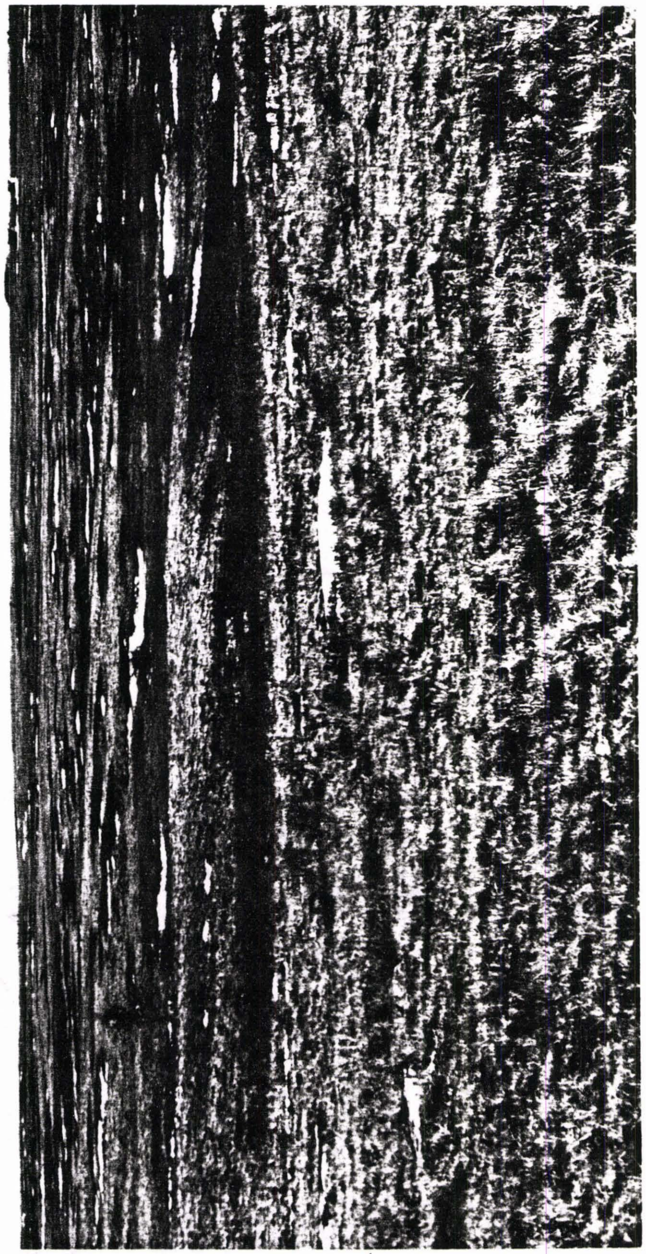


Figure 8. Photograph of cave developed in the side of a sinkhole. Note both the inter-block channels/porosity between blocks on the cave floor and the arched roof. Calcite-coated fracture surfaces can be seen in the cave roof in foreground. Also note the presence of calcite, the ubiquitous white material, in the cave.

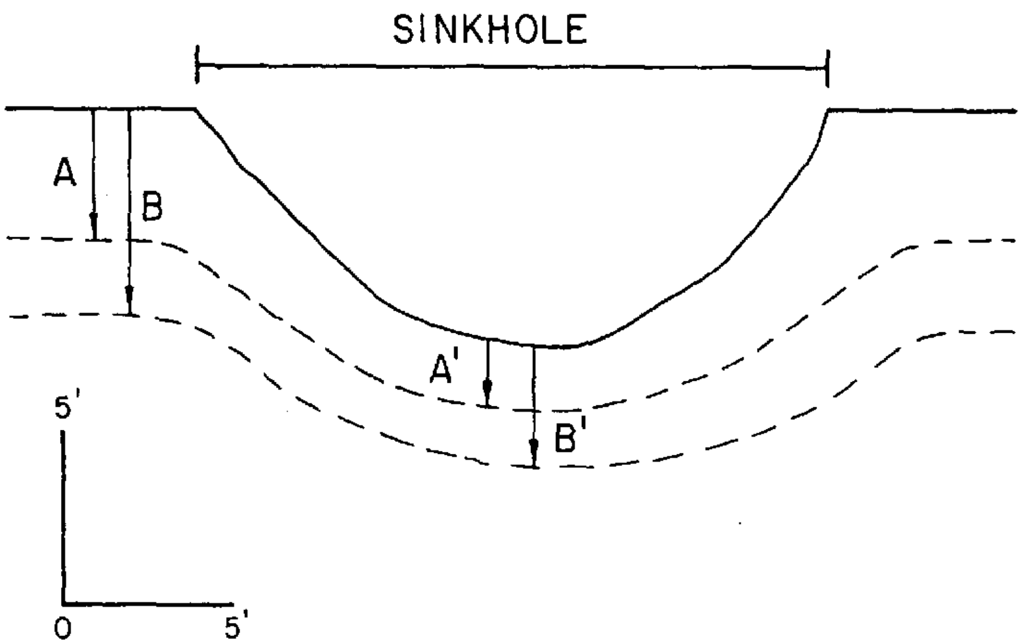
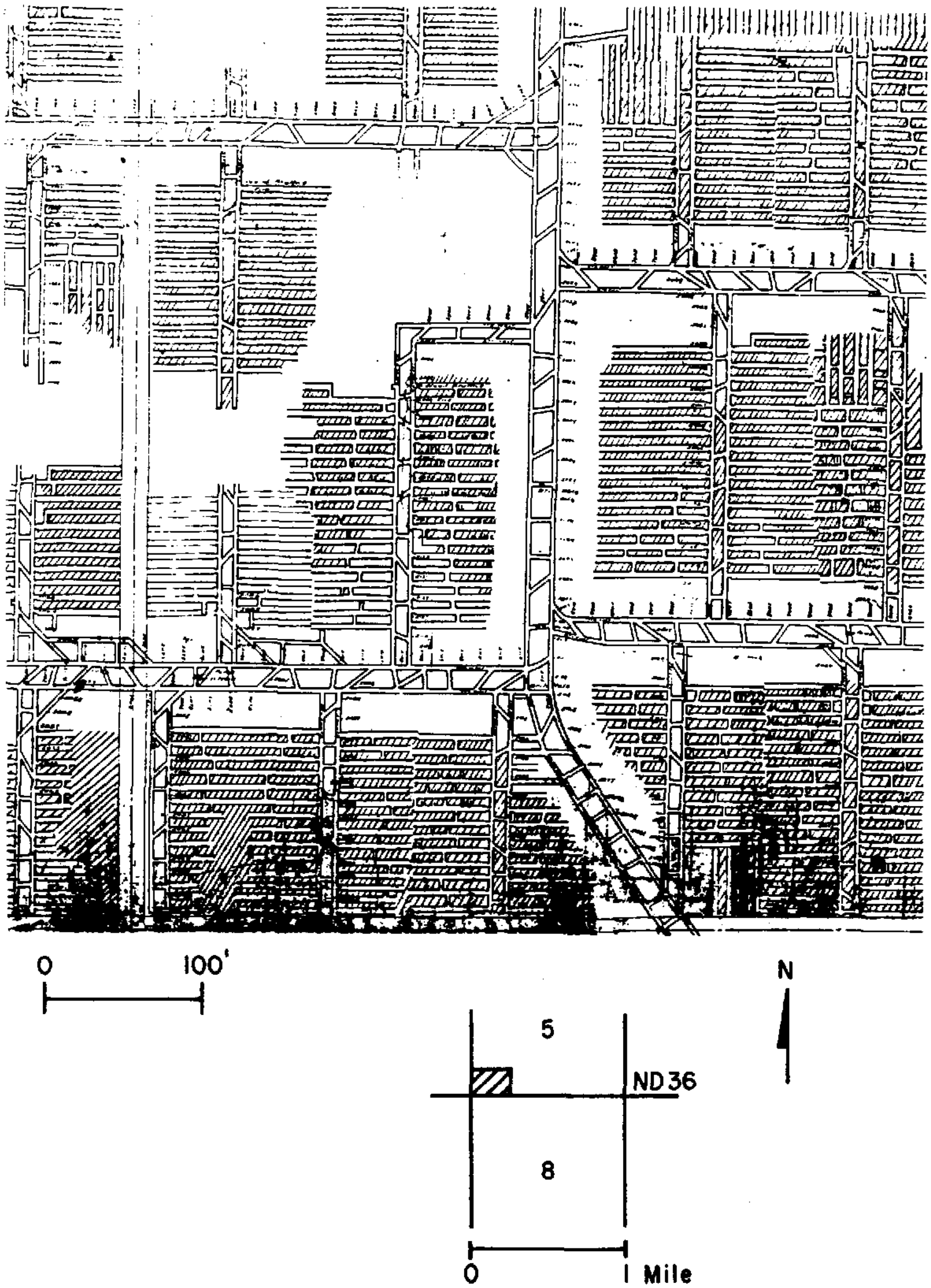


Figure 9. The relationship between soil moisture and collapsed versus non-collapsed settings. A and A′ represent the depth to a given level of soil moisture, as do B and B′(e.g., A and A′ mark the occurrence of 20% volumetric moisture content and B and B′ mark 30%).

Figure 10. A portion of the Wilton mine map illustrating geometry of mine tunnels and rooms beneath the study site in the southwest corner of Section 5 (see Figure 3 for the location of Section 5). Slanted-line pattern indicates coal pillars (modified from mine map by Thomas, 1929).


0
100'
N
5
ND36
8
0
1 Mile

typically 10 to 14 feet wide and 8 to 9 feet high, and from several yards to more than 1 mile in length (Figure 10).

Pillar extraction leads to almost immediate collapse of the mined areas. In mines where the pillars are left intact, collapse may occur over many years. New sinkholes are still forming at the Wilton site,although underground mining ended no later than the mid 1940s, and much earlier than that in older portions of the mine. This continued collapse at Wilton suggests that coal pillars are still effective in controlling subsidence patterns.

As a result of the mine geometry at Wilton, the sinkholes are generally circular or oval and aligned in linear patterns. Individual sinkholes are usually less than 25 feet wide and 15 feet deep. Length varies because sinkholes may coalesce over time, or collapse may follow a tunnel, resulting in a trench. The orientation of these trenches mirrors the orientation of underlying mine tunnels and rooms. The pattern of sinkholes and trenches is readily observable in the field and on aerial photographs of the site (Figure 11).

Several large caves, all of which have a similar morphology, have developed in the sides of sinkholes. The cave walls are vertical, which give way to an arched roof that extends horizontally away from the sinkhole (Figure 8). Cave widths approximate the average width of underlying tunnels in the mine, with cave length varying. The greatest observed height of a cave roof was approximately 7 feet. These caves have been observed only in glacial sediments at the site. Whether or not the process of collapse just described occurs in deeper bedrock sediments is unknown. Similar void morphology is likely to have been produced in the unconsolidated bedrock sediments at the site, although this was not observed.

In the caves formed in till, sediments have spalled off the cave roofs and walls in blocks ranging from a few inches to three or more feet in length (Figure 8) producing inter-block channels and porosity.

Figure 11. Reproduction of aerial photograph of the SW1/4 Sec.5 T. 142 N., R. 79 W., illustrating distribution and impact of sinkholes on landscape. The road at the bottom of the photo is ND 36. The scale is 1:4800.

Pg 36

This permeability and porosity are most likely reduced, but not eliminated, by the weight of overburden materials as collapse continues upward and the material exposed on the floor of a void is buried. The presence of these inter-block channels undoubtedly increases the vertical hydraulic conductivity of the collapsed zones, thereby enhancing the hydraulic connection between the water table and ground surface. The collapse zone can extend more than 100 feet in depth at Wilton, or the entire thickness of the unsaturated zone.

Concentric patterns of vertical fractures can be observed on the ground surface in areas surrounding sinkholes. These fracture zones are wider than the underlying room or tunnel, and are produced as the sides of a sinkhole expand outward at ground level through erosion. Whether concentric fractures occur in the bedrock surrounding collapse zones is unknown.

Mine Reclamation

Reclamation projects were conducted during the summer of 1989 by the NDPSC. These projects included the filling of mine tunnels within the ND 36 highway right-of-way, a mine pit and numerous sinkholes in the northwest quarter of Section 8, and a mine pit in the northeast quarter of Section 7 (Figure 3). The mine pit in Section 8 contained several large gullies, 4 to 7 feet in depth, indicating that run-off into the pit was substantial. Several reclamation projects have been carried at this mine site since the early 1980s.

Land Use

Abandoned mined land near Wilton is used in several ways. Some areas covered with mine spoils have been converted into wildlife management areas. Unreclaimed areas with sinkholes are used for grazing. Most land containing reclaimed sinkholes is used for grazing, although some is used as cropland.

METHODS

In order to quantify differences in soil moisture or ground water recharge potential between non-collapsed settings and sinkholes, changes in soil moisture, direction of soil moisture movement, timing and amount of precipitation, the total area of sinkholes, and the configuration of the water table were determined.

Relative changes in soil moisture were measured with a neutron probe. Soil tension and the direction of hydraulic gradients in the unsaturated zone were monitored with tensiometers.

Precipitation data were provided by the National Oceanic and Atmospheric Administration, which maintains a nearby observation station in the city of Wilton. The amount of snow capture in sinkholes was quantified by measuring snow volume in several sinkholes and converting those values to equivalent moisture.

The total area of sinkholes was measured using a digitizer and topographic maps of the site. The topographic maps were previously generated from an aerial survey conducted in May, 1981, for the NDPSC.

The configuration of the water table was determined through exploratory drilling and the monitoring of ground water wells installed at the site. Also, water samples were collected from wells and surface ponds to establish background water quality.

Monitoring Design

Monitoring wells were completed in the coal seam mined at the site to determine relative head values, and thus, the general direction of ground water flow. A total of thirteen wells were installed to provide this and other information, including stratigraphy and water quality across the site.

The southwest quarter of Section 5 was chosen for the installation of soil moisture monitoring equipment. The NDPSC had no immediate plans to reclaim the numerous sinkholes in this section.

Soil moisture monitoring equipment, including 11 access tubes for neutron probe applications and 4 tensiometer nests, were selectively located to determine differences in soil moisture and direction of soil moisture movement in collapsed and non-collapsed settings. There are variations between the non-collapsed and collapsed settings in terms of topography, the size, depth, and overall geometry of sinkholes, and the capacity to collect run-off.

Four distinct settings were identified on a topographic basis and instrumented with soil moisture monitoring equipment: 1) sinkholes with low run-off accumulation potential; 2) sinkholes with high run-off accumulation potential; 3) non-collapsed areas with low run-off accumulation potential; 4) non-collapsed areas with high run-off accumulation potential. A location with a high run-off accumulation potential receives run-off from a large surface area. Conversely, settings with low run-off accumulation potential receive little if any surface run-off. High run-off accumulation potential locations include sinkholes or non-collapsed areas situated at the base of slopes, or at the end of a small ditch or drainage feature leading to those sinkholes or non-collapsed areas. Low run-off accumulation potential areas include sinkholes or non-collapsed settings on local topographic highs or that are surrounded by many other sinkholes or surface drainage features that intercept run-off.

Well Construction

The initial three wells, MW-1, 2, and 3, were used to determine the general direction of ground water flow in the Wilton coal seam (See

Figure 3 for well locations and Table 2 for well depths). The remaining

Table 2

List of well depths, MSL elevation of well base, riser height, and top-of-casing elevation.

Well Number	Well Depth	Elev. of Well Base	Riser Height	Elev. of Top of Riser
MW-1	85.4	2091.0	3.4	2179.8
MW-2	109.7	2091.9	3.3	2204.9
MW-3	98.1	2103.6	1.5	2203.3
MW-4	81.9	2104.6	2.8	2189.4
MW-5	66.5	2116.0	2.6	2185.1
MW-6[1]	71.1	2081.2	2.4	2154.7
MW-7[1]	51.9	2100.4	2.2	2154.5
MW-8[1]	25.2	2127.1	2.1	2154.3
MW-9	67.3	2091.8	2.2	2161.4
MW-10	105.0	2090.2	2.5	2197.7
MW-11	27.2	2105.9	2.3	2135.4
MW-12	84.7	2095.7	2.0	2182.4
MW-13	116.5	2113.6	2.5	2232.6

All measurements are in feet
(1) MW-6, 7, and 8 are nested

10 wells were installed later to provide detailed information on ground water flow direction, hydraulic gradients, and background water quality (See Appendix VI for well completion summaries). One well nest (MW-6, 7, and 8) was installed to determine the vertical hydraulic gradient. Stratigraphic logs were compiled during the installation of each well (See Appendix VII for lithologic logs).

Borings were completed with an air-rotary drill rig, with some water used occasionally during drilling. The wells were constructed of schedule 40, flush-joint threaded PVC plastic pipe, with 0.010 inch, continuous-slot PVC screens. Five-foot screens were used for MW-6 and 8, with ten-foot screens used for the remaining wells.

With the exception of MW-6 and 8, the bottoms of the monitoring wells were set at the base of the Wilton coal seam. The base of MW-6 was set 19 feet below the coal seam and the base of MW-8 was set 17 feet above the coal seam.

A filter pack of 12/30-grade commercial silica sand was slurried down a tremie pipe to a height of about 1 foot above the top of the screen. The tremie pipe was placed near the base of the well and raised as the annular space around the screen filled with sand. Approximately one foot of bentonite pellets were placed on top of the filter pack to form a seal.

The wells were then grouted to ground level using neat cement, consisting of portland cement with six percent bentonite. A portable grout pump was used to mix and pump the grout through a tremie pipe set at the top of the bentonite pellet seal. The grout was pumped until it reached ground surface, thereby filling the annular space around the well casing from the bottom up. Figure 12 is a schematic diagram of a completed well. The monitoring wells were developed by hand-bailing at least three casing volumes, or to dryness in wells with minimal recharge.

Neutron Probe

Relative changes in soil moisture were determined using a neutron probe manufactured by Campbell-Pacific Nuclear, Inc. The probe contains an americium-241/beryllium-9 radioactive source that produces fast neutrons. Thermalized neutrons are measured using a boron tri-fluoride detector, which is adjacent to the source.

The americium-241 emits alpha particles which strike the beryllium-9. The beryllium-9 then emits fast neutrons which collide predominantly with hydrogen nuclei, such as those in soil water. Upon collision, these neutrons slow down, or are thermalized. A cloud of thermalized neutrons forms within the radius of influence of the source. The number of collisions recorded by the detector is scaled to represent the relative amount of hydrogen in the material being monitored. The

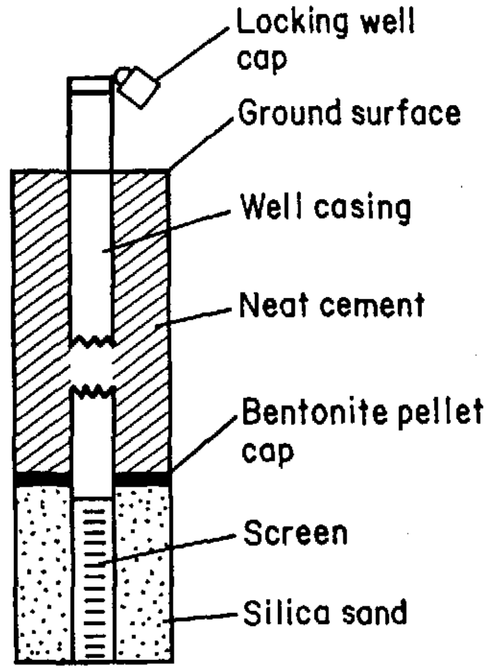


Figure 12. Schematic of well design.

amount of hydrogen measured is assumed to represent free moisture in the soil. Goodspeed (1981) and Bell (1976) are sources of detailed explanations of neutron probe theory.

Measurements were made by placing the probe shield on top of an access tube installed in the ground, which consists of a 9 or 10-foot long piece of 2-inch (inside diameter) aluminum conduit pipe. Access tubes prevented the radioactive source from becoming wedged in the ground and protected it from sediment and water. The source was lowered into the access tube to the desired depth by means of a coaxial cable, which was graduated to ensure that readings were taken at consistent intervals. Two 30-second measurements were taken at various depths during monitoring (Appendix I).

Use of Calibration Curves

The number of counts recorded by the neutron probe were converted to volumetric soil moisture content using a calibration curve, which is a plot of counts-per-minute versus volumetric moisture content. Either the field measured counts-per-minute or the ratio of the field measured counts-per-minute and counts-per-minute in a standard, usually water, is used. A neutron probe user can develop site-specific calibration curves, or can use curves derived for standard soils by the probe manufacturer. Site-specific curves are more accurate (Freeze and Banner, 1970). There are no units of measurement for volumetric moisture content because this value is a ratio of the volume of water present in a given volume of sediment, causing the units to cancel out. The volumetric moisture content multiplied by 100 is the percent moisture in the sediment being measured.

Graecen and others (1981, p. 54-60) discuss how an inaccurate calibration curve might be developed due to improper statistical methods. Improper methods cited include the grouping of data for materials with different absorption cross-sections or different bulk densities into one calibration curve.

Calibration Curve Development

Calibration curves were derived for different materials at the Wilton site to provide the greatest accuracy. Sediment samples were collected at the depths to be measured with the neutron probe. As soon as a hole was augered, an access tube was installed and neutron probe readings taken.

Sediment samples were collected at all appropriate depths using a 2-inch diameter soil auger designed for clay-rich sediments. Each sample collected represented 4 inches of material, extending 2 inches above and below the interval of interest. The samples were taken from the center of the auger head, which has two steel re-inforcing bands 4 inches apart with an inside diameter of 2 inches. Samples were then sealed in airtight containers for transport back to the laboratory.

Sediment samples were weighed and then dried in a convection oven for a period of 24 hours at 105°C, as suggested by Gardner (1965, p. 92). Drying at temperatures higher than this causes loss of constitutional hydrogen from the lattices of clay minerals and from organic material (Holmes, 1955). Each sample was again weighed to determine the dry weight. The dry weight was subtracted from the wet weight to determine the amount of free water present in the sample. These data were used to determine dry bulk density and volumetric moisture content (Graecen and others, 1981, p. 77). Neutron probe counts and soil moisture data collected for the calibration curves were fitted to a regression curve to convert probe readings to volumetric moisture content (See Appendix I for neutron probe data, calibration equations, and probe readings converted to volumetric moisture content).

Till is generally defined as unsorted, non-stratified sediment deposited by glacial processes (Bird, 1980, p. 44-45; Ritter, 1986, p.

380). Bluemle (1975) identified the till at the site as ground moraine that includes material dropped as the retreating glacier melted. Clayton and others (1980, p. 40) identified the surface sediments at Wilton as thin drift, unbedded, draped overlying a pre-existing bedrock landscape. The till appears to have a relatively homogeneous bulk density and mineralogical and textural composition. This homogeneity should provide uniform absorption cross-sections and levels of constitutional hydrogen. Therefore, the calibration curve developed for access tubes in this till (Figure 13) includes data from different depth intervals. The correlation coefficient (r) for this curve is 0.92.

However, a separate calibration curve was developed for two access tubes, AT-5 and AT-8 (Figure 14), because the sediments at these two sinkholes sites are darker and less sandy than the till. This textural change, resulting from a difference in the amount of clay present in the two types of sediments, alters the amount of constitutional hydrogen present, effectively producing separate absorption cross-sections. The correlation coefficient (r) for this curve is 0.91.

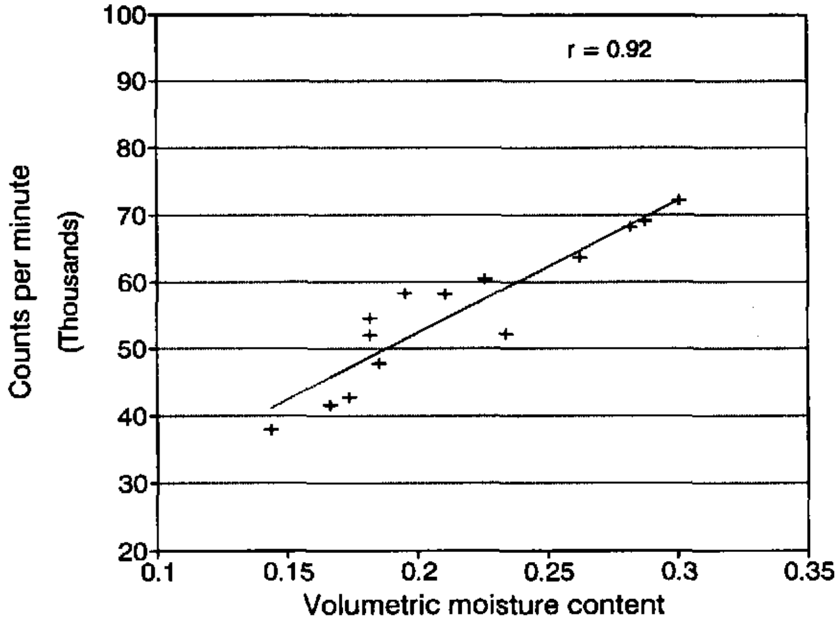
Although the two calibration curves are similar in slope, a curve including data from both graphs would shift the regression line of the till curve to the right and of the non-till curve to the left for any given number of probe counts-per-minute. This indicates there is some difference in the neutron absorption cross-sections for the two materials, requiring the use of separate curves.

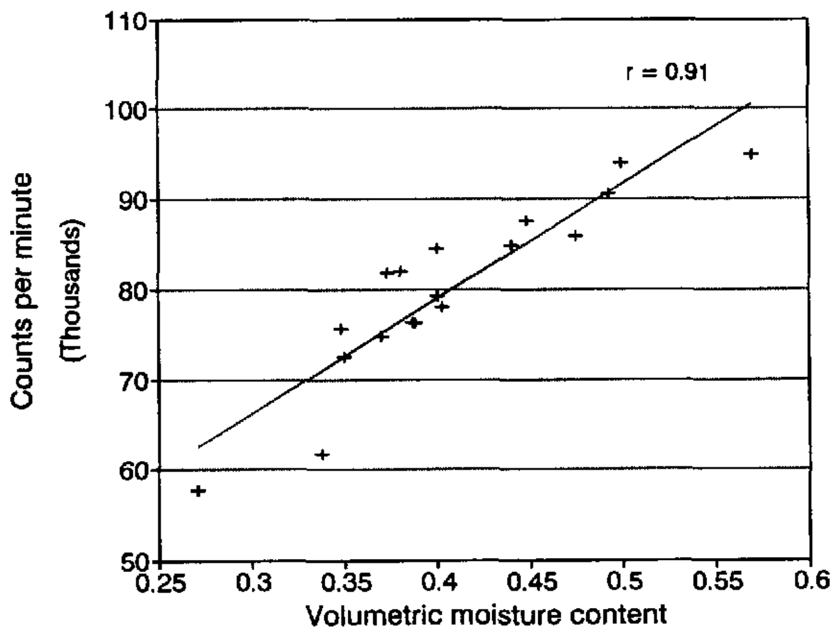
<u>Access Tubes</u>

Several factors may affect data collected with a neutron probe. The presence of neutron-absorbing elements, such as chlorine, iron, and boron, can affect neutron probe readings. Other factors include the presence of cavities against the access tube, the type of material used for access tubes (Prebble and others, 1981, p. 82-85), differences in bulk density (Graecen and Schrale, 1976; Graecen and others, 1981, p.

Figure 13. Neutron probe calibration curve for till at the study site. Correlation coefficient is posted in upper right hand corner of graph.

Figure 14. Neutron probe calibration curve for non-till sediments. Correlation coefficient is posted in upper right hand corner of graph.


r = 0.92
Counts per minute (Thousands)
Volumetric moisture content
100
90
80
70
60
50
40
30
20
0.1
0.15
0.2
0.25
0.3
0.35


r = 0.91
Counts per minute (Thousands)
Volumetric moisture content
110
100
90
80
70
60
50
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6

53-54), the presence of constitutional hydrogen, high content of organic matter (Holmes, 1955), condensation on the inside of an access tube, and instrument drift (Williams and Sinclair, 1981, p. 37).

Neutron probe results can be adversely affected by improper access tube installation and by the material used for access tubes. Proper installation of access tubes requires a tight fit between the access tubes and the surrounding sediments. The presence of a cavity within the radius of measurement of the probe will reduce the actual volume of sediment being measured, leading to an inaccurate estimate of the amount of soil moisture present. An overestimate of soil moisture occurs if a cavity within the sphere of measurement held an amount of water exceeding the volumetric moisture content of the surrounding soil, while an underestimate of soil moisture would occur if the volumetric moisture content of the cavity was less than the volumetric moisture content of the surrounding soil.

Aluminum was chosen over PVC and stainless steel for access tube material because it is transparent to fast neutrons. Chlorine and iron, contained in PVC and steel, respectively, are neutron absorbers. A calibration curve for PVC or steel tubes could be determined, but may be less accurate due to possible heterogeneities in composition or thickness within a tube.

The till at the site is relatively homogeneous in terms of bulk density and the distribution of any minerals containing a relatively large amount of constitutional hydrogen. Therefore, no corrections for these factors were applied to the calibration curves.

Access tubes were swabbed with a dry rag before readings were taken to remove condensation from their inner walls. Also, the upper 1 foot of sediment at access tube sites was not monitored because of the organic content and presence of numerous roots. There is also a safety factor of placing the radioactive source too close to the ground surface.

No correction factors were applied to the curves to account for instrument drift because there have been no comparative studies performed with the neutron probe used for this study. Conditions to check would include behavior under a range of temperatures, humidity, and time since the battery was last charged.

Eleven access tubes were installed, with 5 in non-collapsed settings, for background comparison, and 6 in sinkholes (Figure 15 and Table 3), using 2-inch (inside-diameter) aluminum conduit pipe.

Table 3

List of access tubes and topographic classification.

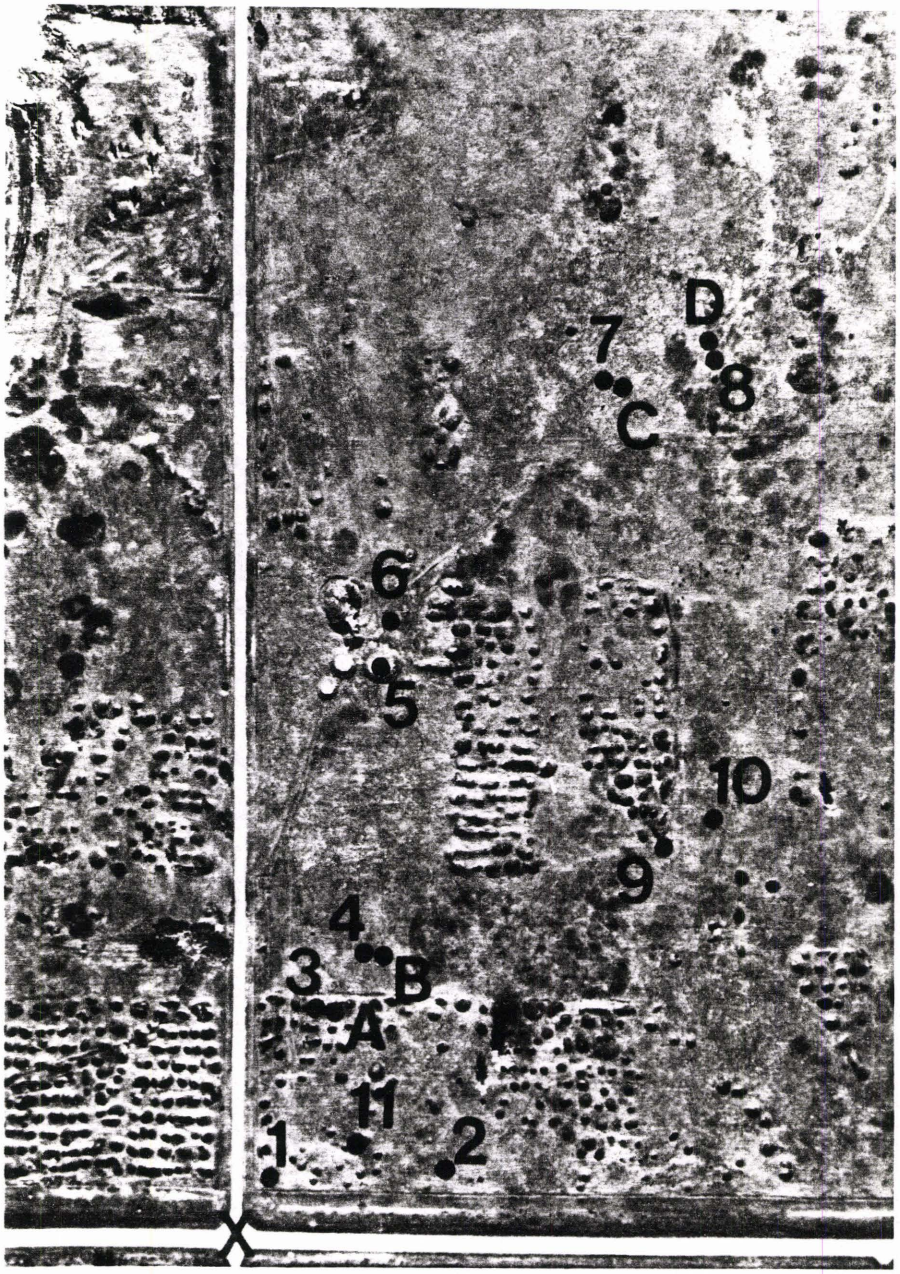
Access Tube Number	Setting	Interval Monitored (ft)
AT-1	C,Lr	2-9
AT-2	Nc,Lr	2-9
AT-3	C,Lr	2-8
AT-4	Nc,Lr	2-9
AT-5	C,Hr	2-9
AT-6	Nc,Hr	2-9
AT-7	Nc,Lr	2-9
AT-8	C,Hr	2-9
AT-9	C,Hr	2-9
AT-10	Nc,Hr	2-9
AT-11	C,Lr	2-9

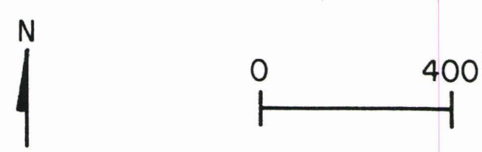
C = collapsed (sinkhole)
Nc = non-collapsed
Lr = low run-off potential
Hr = high run-off potential

These were installed using a power auger or hand auger. At least 2 to 3 inches of conduit were left above ground on which to rest the neutron probe shield. The access tubes were tapped into slightly undersized holes with a hammer, to insure a tight fit. PVC expanding wingnut caps were used to plug the tops of the access tubes to keep out precipitation. Because the tubes were well above the water table, they were left open at the bottom.soil moisture movement.

Figure 15. Location of access tubes (numbered) and tensiometer nests (A,B,C,D) on a reproduced aerial photograph of the SW1/4 Sec. 5, T. 142 N., R. 79 W, marked by X. The road at the bottom of photograph is ND 36. A corresponds to TNAT-3, B to TNAT-4, C to TNAT-7, and D to TNAT-8. Scale is 1:4800.

Pg 51





Tensiometers

Although the neutron probe allows the determination of relative values of soil moisture, it does not directly indicate the direction of soil moisture movement. The best method to determine this direction is with tensiometers, which measure soil tension, or pressure head. The hydraulic head is equal to the sum of the pressure head and the elevation head. Hydraulic head values are used to determine the direction of moisture flow in the soil.

The basic components of a tensiometer consist of a pressure measuring device and a sealed plastic tube with a porous ceramic cup at the base. Available measuring devices include Bourdon gauges, mercury manometers, and pressure transducers (Morrison, 1983). The type of tensiometer used for this study consists of a Bourdon gauge and reservoir at the top of the tube (Figure 16). The reservoir allows for easy replacement of water lost through the ceramic cup to the surrounding soil. The tube body and ceramic cup are 7/8 inch in outside diameter.

The ceramic cup provides the hydraulic connection between the soil and the water in the tube. Under dry conditions the soil pulls moisture from the tube through the ceramic cup, creating a vacuum in the tube. Gauge readings will stabilize when the pressure in the tube is equal to the pressure in the soil surrounding the cup. The ceramic cups used have an air entry rating of 0.98 atmosphere. Soil tensions are normally below this value.

The elevation head will be different for the gauge and the ceramic cup because they are at different depths. To account for this, 0.01 atmosphere should be subtracted for every 4 inches of depth when using a Bourdon gauge tensiometer at depths greater than 25 inches (Richards, 1965, p. 158).

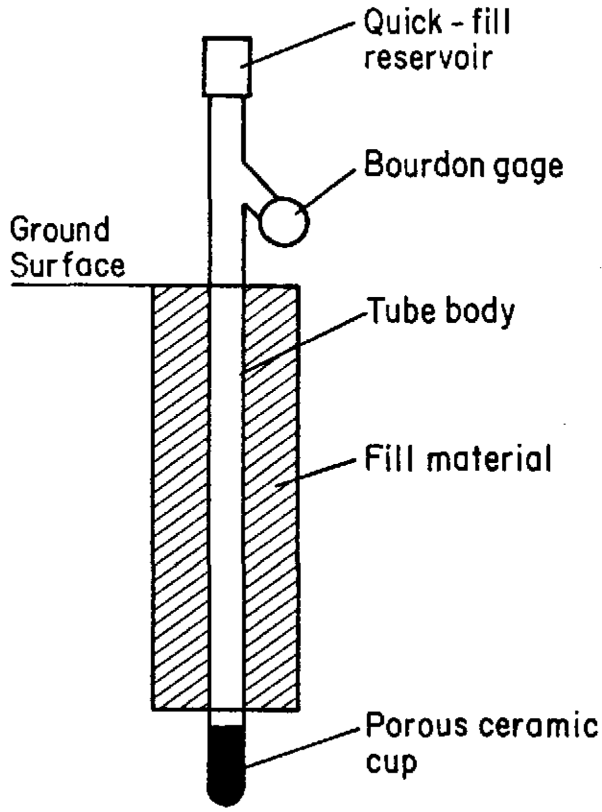


Figure 16. Schematic of tensiometer design. Cuttings from the borehole were used as fill material.

The tensiometers were assembled and filled in the field according to the instructions provided by the manufacturer. De-ionized, distilled water containing an algal growth inhibitor was used to fill the tensiometers. Air was evacuated from the tensiometers using a hand pump supplied by the manufacturer. This procedure is necessary to remove air bubbles from the water, ceramic cup, tube body, and Bourdon gauge.

In order for the ceramic tip to operate, it must be in intimate contact with the surrounding soil. Different methods of installation, developed to handle a variety of soil types, have been reported in the literature (Richards, 1965; Ingersoll, 1981; SoilMoisture, Inc., 1990).

A 1.5 to 2-inch diameter hole was bored using a power or hand auger to install the tensiometers to within 4 to 5 inches of the desired depth. A 0.5-inch inside diameter black iron pipe was then driven the remaining 4 to 5 inches into the bottom of the hole. The hole created by a 0.5-inch inside-diameter pipe is slightly less than 7/8 inch, providing the tight fit desired for the ceramic cup. Excavated material was used to back fill the annular space surrounding the tensiometer. This material was tamped with a metal rod to prevent water from flowing down along the sides of the tensiometers.

Four tensiometer nests were installed, with each nest placed near an access tube. Two nests of three tensiometers were installed in non-collapsed settings, while two nests of four tensiometers were installed in sinkholes (Figure 15). The nests were placed near access tubes in the four different topographic settings in order to determine the direction of moisture movement in each setting (Table 4). The tensiometers were set at 2-foot intervals. None were installed beyond 8 feet because they do not work well at greater depths. The amount of vacuum lost because of the weight of the water column in tensiometers at greater depths limits the range of soil tensions the gauge can measure. Using the water table as a datum, a topographic map was used to determine the elevation head for each tensiometer, the pressure head being taken from the tensiometer gauge, and converted to feet of water.

Table 4

Tensiometer nests and their topographic classification (See Figure 15 for locations).

Nest Number	Type of Setting	Intervals Monitored (ft)	Access Tube Adjacent To
TNAT-3	sinkhole	2,4,6,8	AT-3
TNAT-4	non-collapsed	2,4,6	AT-4
TNAT-7	non-collapsed	2,4,6	AT-7
TNAT-8	sinkhole	2,4,6,8	AT-8

Equivalent Moisture

Snow depths were measured in more than 20 sinkholes in March, 1989, to determine the amount of equivalent moisture, and to estimate the contribution of snow capture to soil moisture. The equivalent moisture is determined by comparing the depth of snow in a cylinder to the resulting depth of water, upon melting of the snow, in the same cylinder. This value may be reported as a ratio of the volume of snow versus the volume of water produced by melting. A cylinder was inserted into snow, removed, and the snow was then melted. Equivalent moisture ratios reported in this study are depth of snow to depth of equivalent water.

Depth of snow in the sinkholes was measured by forcing a graduated pole through the snow to the base of a sinkhole. Several snow depths were measured in each sinkhole to insure the pole had not encountered a boulder or some other irregularity on the floor of the sinkhole. An average value for snow depth for each sinkhole was recorded.

The amount of snow in sinkholes ranged from nearly none to full, which in the deepest sinkholes observed could be as much as 15 feet. The sinkholes selected for snow depth measurement were typically nearly full of snow. Sinkholes full of snow were chosen for measurement to illustrate the greatest potential contribution of snow capture. Also, the snow in many partially filled sinkholes rested along one side of the sinkhole rather than at the base of the sinkhole, making equivalent moisture determinations difficult because of the asymmetrical geometry of the snow deposits.

Water Sample Collection

Water samples were collected to determine background water quality at the site. A teflon hand-bailer was used to collect the samples from developed monitor wells. At least three casing volumes were removed, when possible, before a water sample was collected.

The temperature, pH, and electrical conductivity of each sample were measured in the field with digital meters. Water samples for major anion and cation analyses and trace metal analyses were collected for most of the wells and two nearby surface ponds.

All samples were filtered using a pre-filter and a 0.45 micron membrane filter. The filtering device was rinsed with distilled, deionized water and flushed with water from the well to be sampled. Sample bottles were also rinsed with filtered sample when enough water was available. Samples collected for trace metals analysis were preserved with 1% nitric acid. Water analyses were performed by EERC analytical research laboratory staff (See Appendix V for analytical equipment used and water composition data).

RESULTS

Precipitation

The drought years of 1988 and 1989 (Figure 17) produced extremely dry soil conditions. Although precipitation in 1990 was about average, soil conditions remained very dry. The distribution of precipitation during 1990 (Figure 18) was normal, with approximately 80% of the precipitation occurring during April through October. Most of the soil moisture data were collected during this period. The bulk of summer precipitation coincides with the period of highest evapotranspiration.

Soil Moisture Profiles

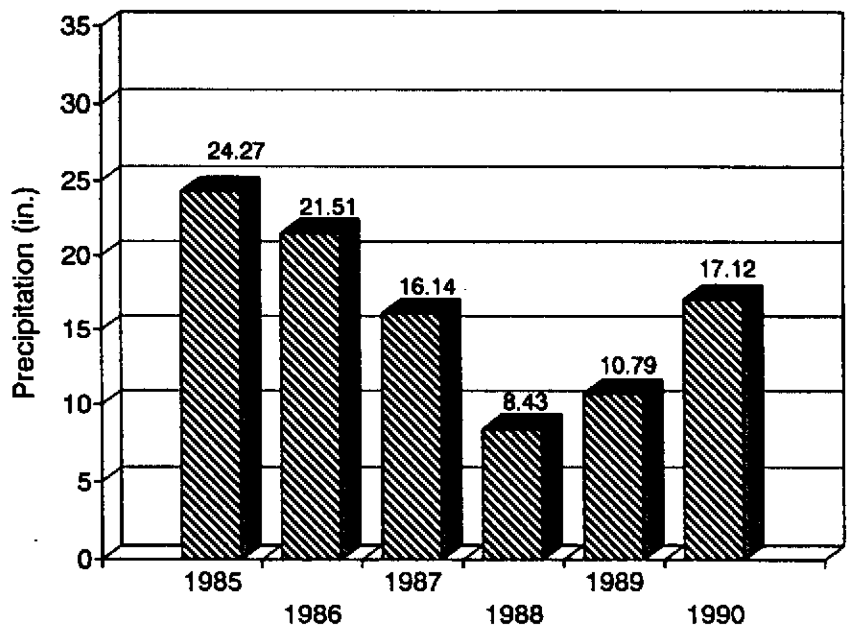
Changes in soil moisture during the monitoring period can be shown using a series of volumetric moisture content versus depth profiles. The monitoring dates presented in profiles discussed in the upcoming sections were selected to display the greatest variation in volumetric moisture content and do not represent the total number of monitoring dates (See Appendix I for complete listing of neutron probe data).

Non-collapsed settings

Soil moisture data collected on 2/17/90, 3/23/90, and 4/24/90, show little change in soil moisture content deeper than 24 inches at most of the access tube locations. In fact, profiles for the five access tubes in non-collapsed settings, AT-2, AT-4, AT-6, AT-7, and AT-10 (Figures 19-23), show almost no change in volumetric moisture content at all until 6/6/90. Soil moisture profiles for AT-2, AT-4, and AT-7 (Figures 19, 20 and 22, respectively) show no change in volumetric

Figure 17. Precipitation for years 1985 through 1990 (National Weather Service data for Wilton station).

Figure 18. Temporal distribution and amount of precipitation for 1990 (data from National Weather Service station in Wilton).


35
30
25
20
15
10
5
0
Precipitation (in.)
24.27
21.51
16.14
8.43
10.79
17.12
1985
1986
1987
1988
1989
1990

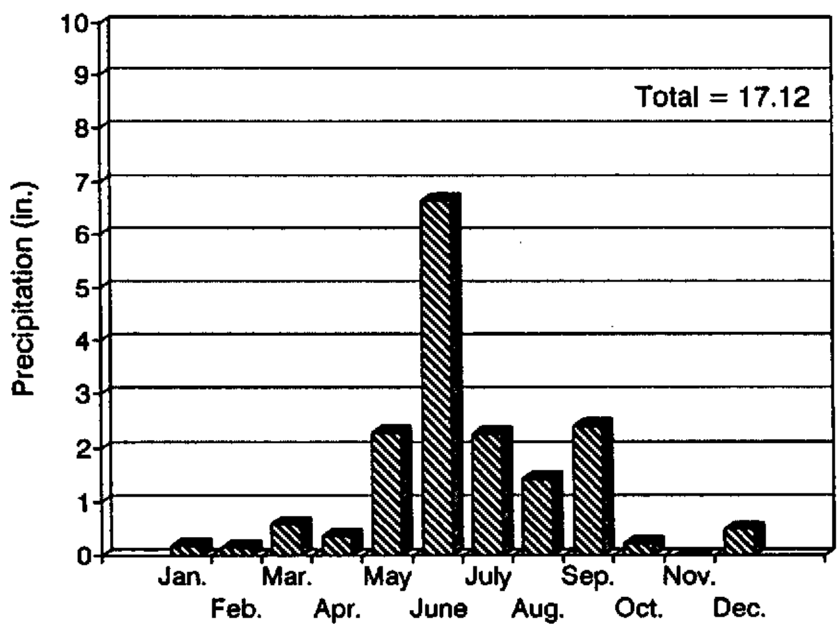
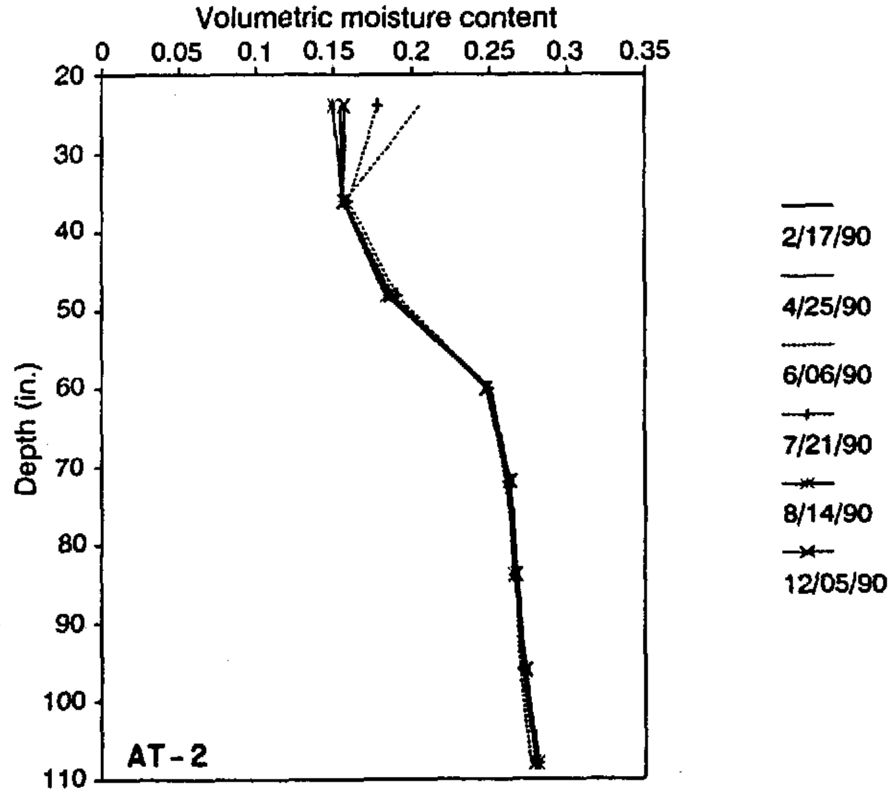
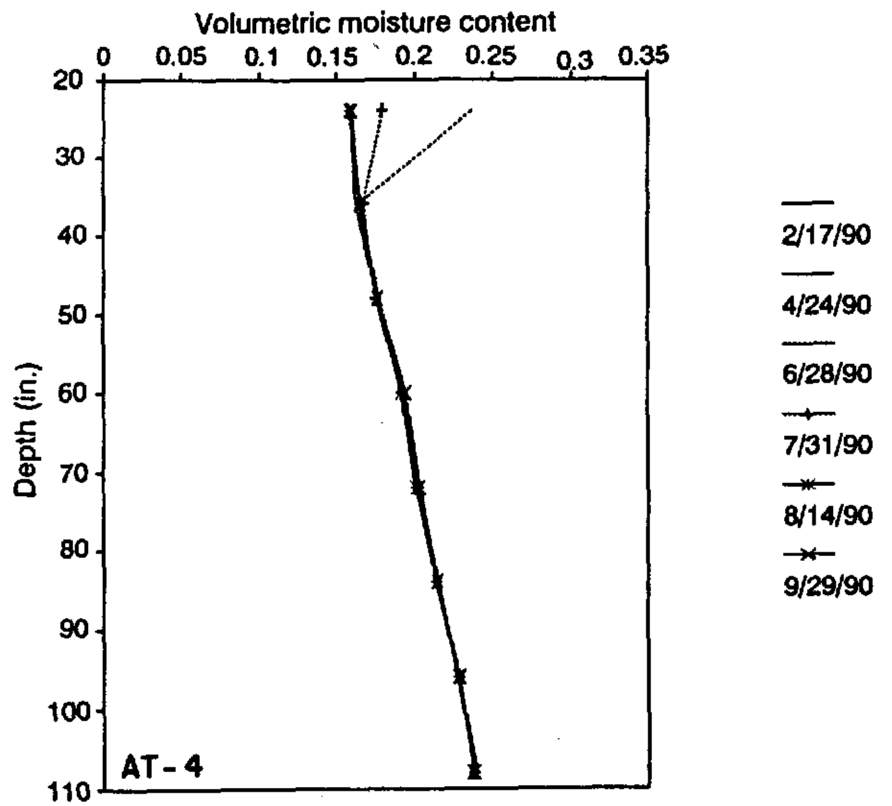

10
9
8
7
6
5
4
3
2
1
0
Precipitation (in.)
Total = 17.12
Jan.
Feb.
Mar.
Apr.
May
June
July
Aug.
Sep.
Oct.
Nov.
Dec.

Figure 19. Volumetric moisture content profile for AT-2, set in till; non-collapsed, low run-off accumulation potential.

Figure 20. Volumetric moisture content profile for AT-4, set in till; non-collapsed, low run-off accumulation potential.



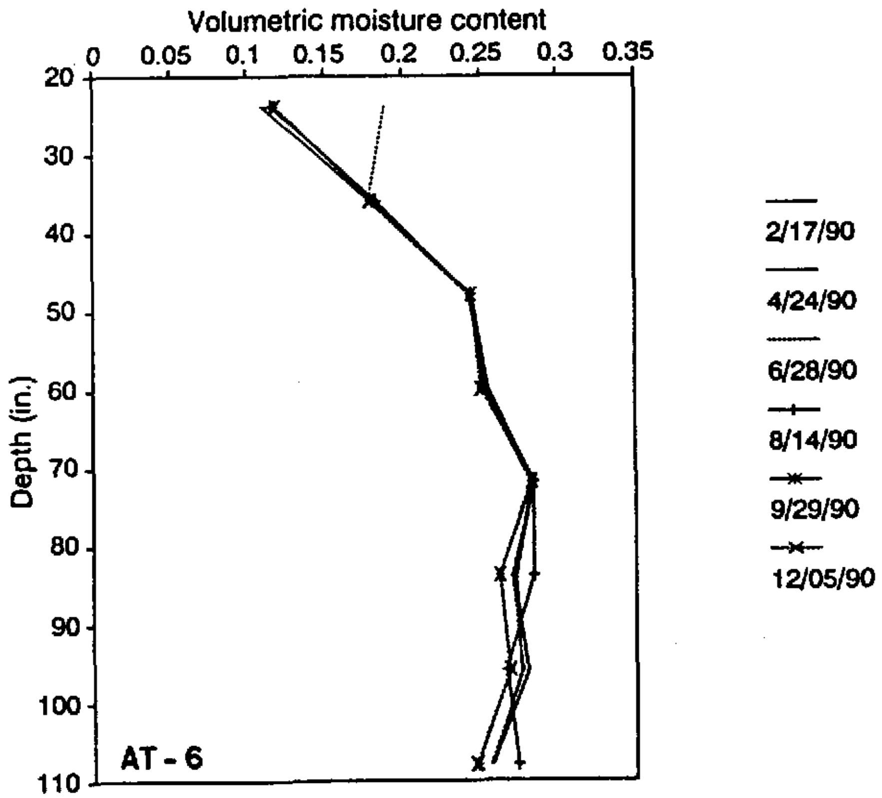
Volumetric moisture content
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Depth (in.)
20
30
40
50
60
70
80
90
100
110
AT-2
2/17/90
4/25/90
6/06/90
7/21/90
8/14/90
12/05/90



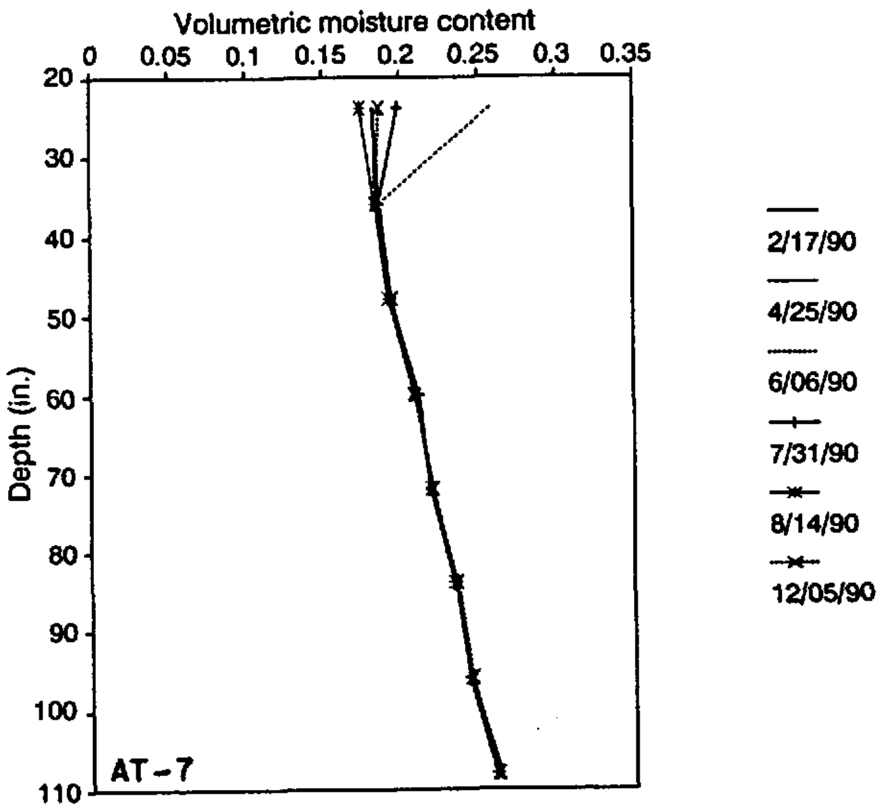
Volumetric moisture content
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Depth (in.)
20
30
40
50
60
70
80
90
100
110
AT-4
2/17/90
4/24/90
6/28/90
7/31/90
8/14/90
9/29/90

Figure 21. Volumetric moisture content profile for AT-6, set in till; non-collapsed, high run-off accumulation potential.

Figure 22. Volumetric moisture content profile for AT-7, set in till; non-collapsed, high run-off accumulation potential.

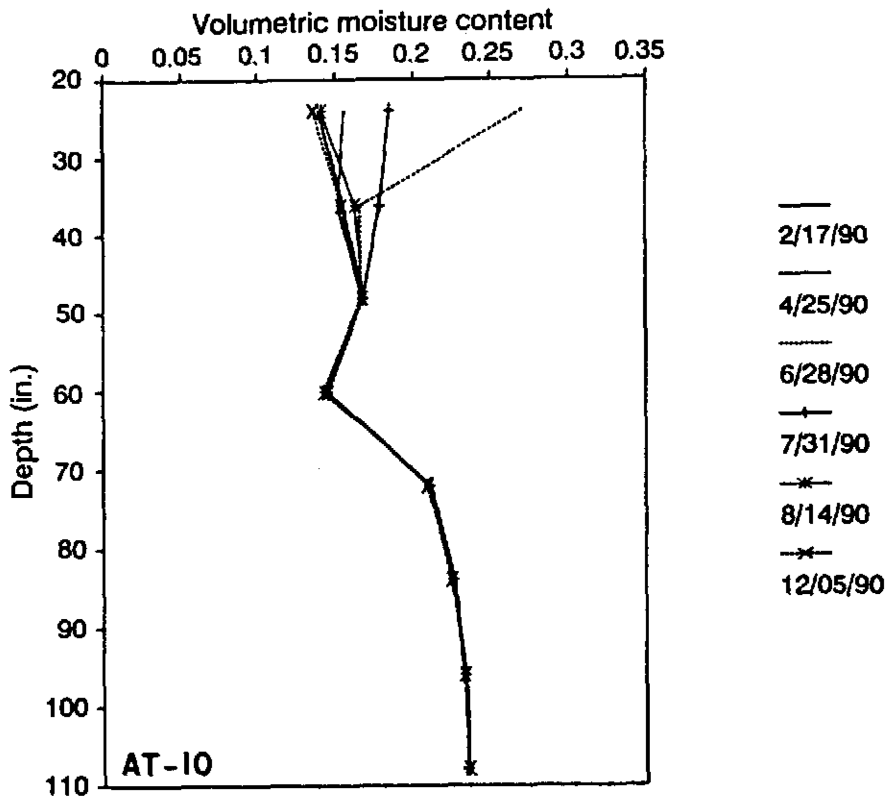


Volumetric moisture content
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
20
30
40
50
60
70
80
90
100
110
Depth (in.)
AT - 6
2/17/90
4/24/90
6/28/90
8/14/90
9/29/90
12/05/90



Volumetric moisture content
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
20
30
40
50
60
70
80
90
100
110
Depth (in.)
AT - 7
2/17/90
4/25/90
6/06/90
7/31/90
8/14/90
12/05/90

Figure 23. Volumetric moisture content profile for AT-10, set in till; non-collapsed, high run-off accumulation potential.



Volumetric moisture content
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
20
30
40
50
60
70
80
90
100
110
Depth (in.)
AT-10
2/17/90
4/25/90
6/28/90
7/31/90
8/14/90
12/05/90

moisture content deeper than 36 inches during the entire monitoring period.

The profile for AT-6 shows little variation in moisture content between 35 and 70 inches, but shows changes in moisture content between 70 and 108 inches (Figure 21). Although AT-6 was classified as a high run-off accumulation potential site, it was not affected by run-off. The increase in moisture content at the lower intervals may be due to soil moisture migrating upward or laterally from infiltration in nearby sinkholes.

Changes in volumetric moisture content at AT-10 were recorded to a depth of approximately 48 inches (Figure 23), or about 12 inches deeper than the other access tubes set in non-collapsed material. No changes in moisture content greater than 1% were recorded below 48 inches during the monitoring period.

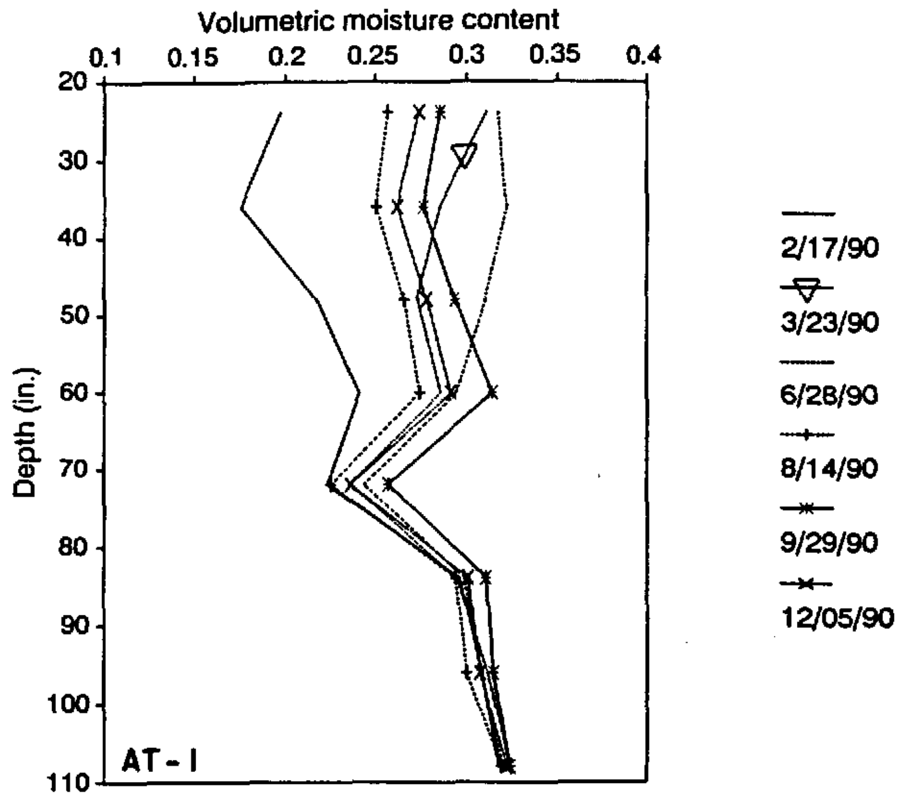
Collapsed settings

The volumetric moisture content profiles for access tubes set in sinkholes, AT-1, AT-3, AT-5, AT-8, AT-9, and AT-11, show greater variations in depth and the amount of change in soil moisture (Figures 24-29). Changes in volumetric moisture content were recorded during the February-June monitoring period in all but one of the access tubes set in sinkholes (AT-11 was installed at a later date). The first increase in volumetric moisture content in the sinkholes was recorded on the 3/23/90 sampling date, which coincided with the spring thaw.

With the exception of AT-9, changes in volumetric moisture content were observed over the entire depth of each access tube set in a sinkhole. Variations of 8% to 18% were measured at the 24-inch depth, with variations of about 2% being measured at the 108-inch depth (96-

Figure 24. Volumetric moisture content profile for AT-1, set in till; sinkhole, low run-off accumulation potential.

Figure 25. Volumetric moisture content profile for AT-3, set in till; sinkhole, low run-off accumulation potential.


Volumetric moisture content
0.1 0.15 0.2 0.25 0.3 0.35 0.4
Depth (in.)
20 30 40 50 60 70 80 90 100 110
AT - I
2/17/90
3/23/90
6/28/90
8/14/90
9/29/90
12/05/90

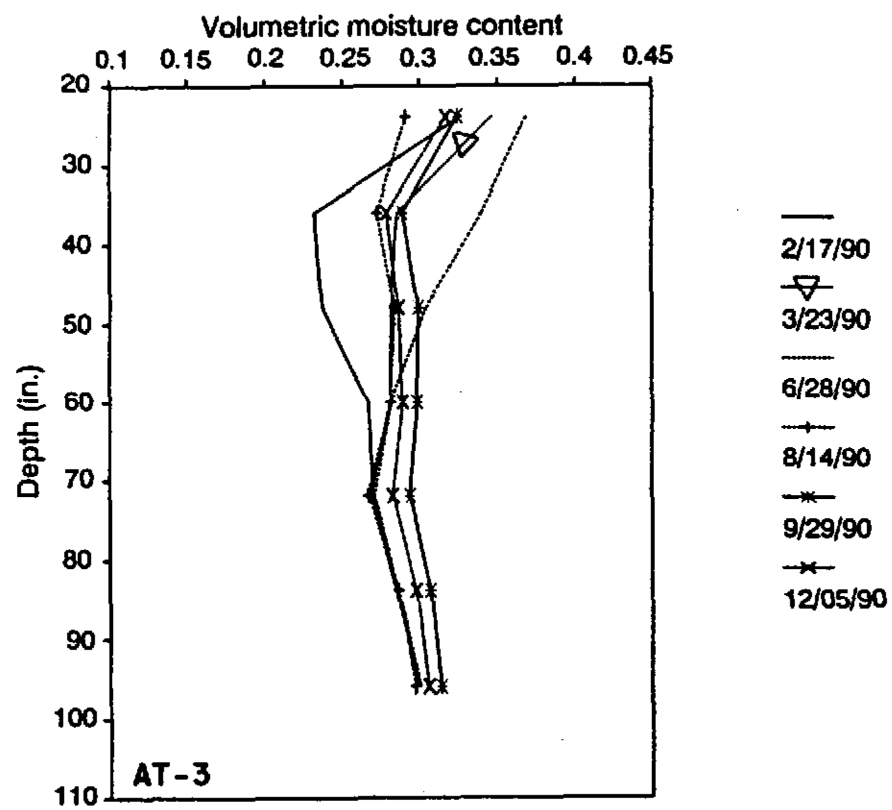
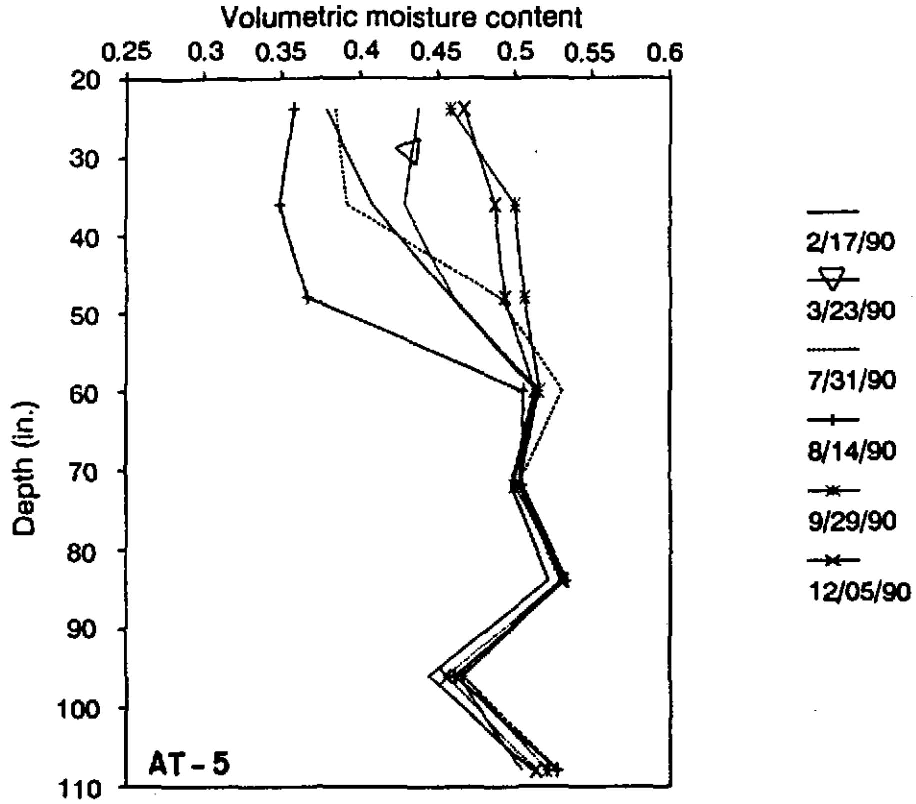
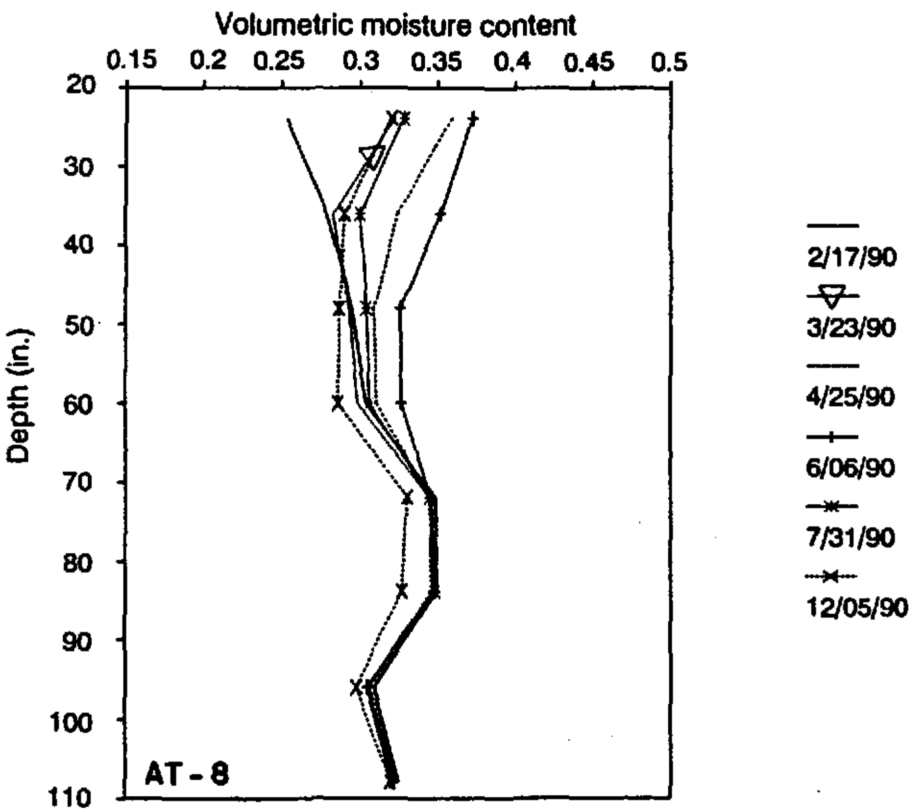

Volumetric moisture content
0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45
Depth (in.)
20 30 40 50 60 70 80 90 100 110
AT - 3
2/17/90
3/23/90
6/28/90
8/14/90
9/29/90
12/05/90

Figure 26. Volumetric moisture content profile for AT-5, set in non-till sediments; sinkhole, high run-off accumulation.

Figure 27. Volumetric moisture content profile for AT-8, set in non-till sediments; sinkhole, high run-off accumulation.



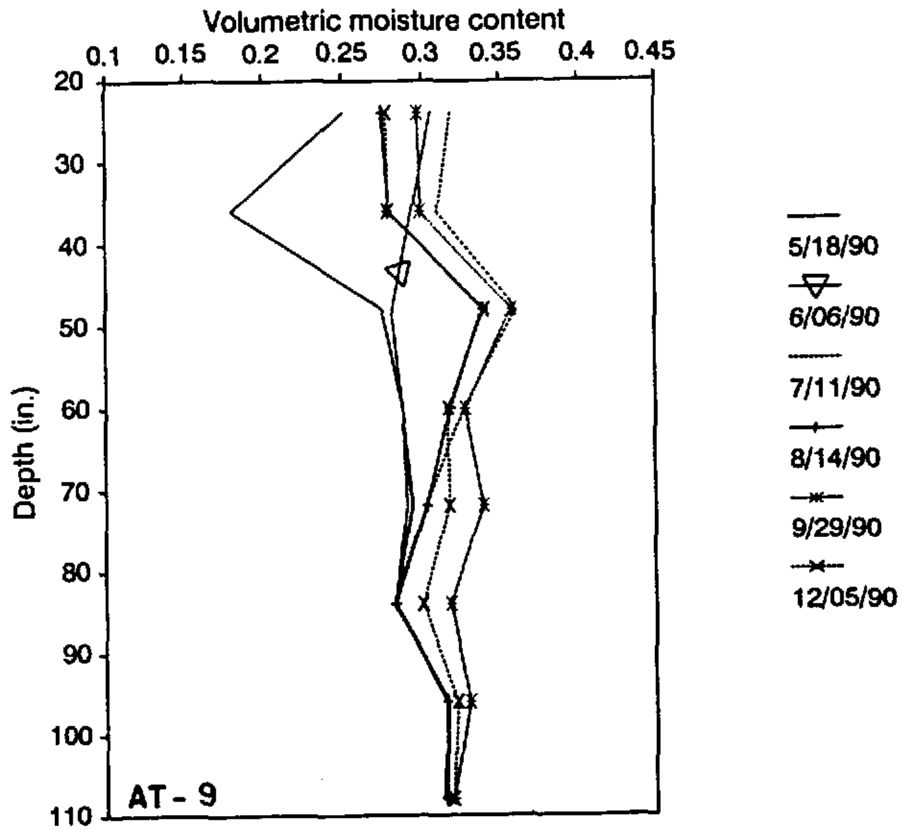
Volumetric moisture content
0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6
Depth (in.)
20 30 40 50 60 70 80 90 100 110
AT - 5
2/17/90
3/23/90
7/31/90
8/14/90
9/29/90
12/05/90



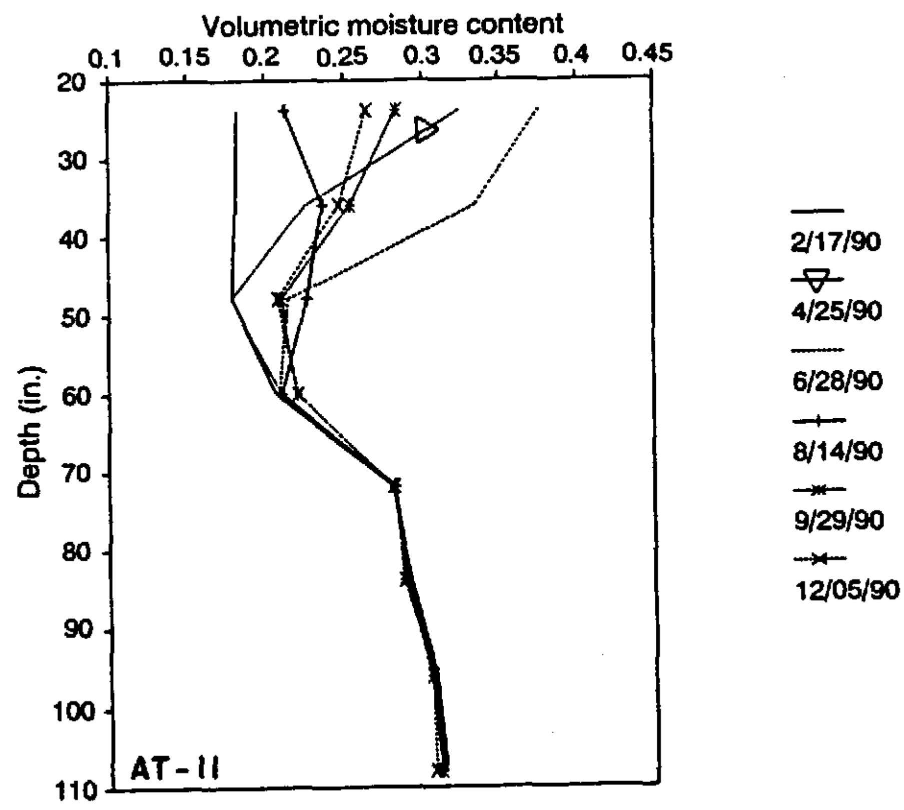
Volumetric moisture content
0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5
Depth (in.)
20 30 40 50 60 70 80 90 100 110
AT - 8
2/17/90
3/23/90
4/25/90
6/06/90
7/31/90
12/05/90

Figure 28. Volumetric moisture content profile for AT-9, set in till; sinkhole, high run-off accumulation potential.

Figure 29. Volumetric moisture content profile for AT-11, set in till; sinkhole, low run-off accumulation potential.



Volumetric moisture content
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
20
30
40
50
60
70
80
90
100
110
Depth (in.)
AT - 9
5/18/90
6/06/90
7/11/90
8/14/90
9/29/90
12/05/90



Volumetric moisture content
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
20
30
40
50
60
70
80
90
100
110
Depth (in.)
AT - 11
2/17/90
4/25/90
6/28/90
8/14/90
9/29/90
12/05/90

inch depth for AT-3). Regardless of the estimated run-off accumulation potential, the greatest variation occurred at depths of 24 to 48 inches in all the access tubes set in sinkholes. This interval is very susceptible to evapotranspiration.

AT-5 and AT-8 are the only two access tubes in non-till material. Average values of volumetric moisture content were much higher at AT-5 (Figure 26) in comparison to the other access tubes, with values at AT-8 (Figure 27) being most similar to those measured at access tubes in sinkholes in till. The profile for AT-5 (Figure 26) shows that volumetric moisture contents were near or above the normal range of field capacity for soils most of the summer. A long, narrowl drainage ditch empties into the sinkhole containing AT-5.

The lowest or nearly lowest volumetric moisture content in the upper part of the soil column at most of the access tubes was measured on 2/17/90, with the exception of AT-5 and AT-11. A few access tubes had slightly lower levels on either 8/14/90 or 9/29/90, but these differences were within 1% to 2% of the volumetric moisture content on 2/17/90.

Many of the soil moisture profiles exhibit sharp deflections toward higher or lower moisture contents, as opposed to a gradual or linear change (Figure 23). The causes of these deflections can be attributed to such heterogeneities as changes in stratigraphy in the non-till settings (AT-5), the presence of stones within the sphere of neutron bombardment, or a layer rich in a neutron-absorbing element, such as iron. In cases where the deflection is toward drier conditions in till, stones or a large stone may be within the sphere of neutron bombardment. This interpretation is based upon the presence of gravel to boulder-sized material in the till. The sharp deflection measured at the 96-inch depth at AT-5 (Figure 26) is the result of a stratigraphic heterogeneity. Neutron probe readings from a second access tube installed for calibration purposes showed a similar deflection at the

96-inch depth. Both tubes were set in the same sinkhole, within a few inches of each other in terms of elevation, but approximately 20 feet apart. Regardless of such heterogeneities, relative changes in soil moisture with increasing depth are still apparent.

Effects of Precipitation and Evapotranspiration on Soil Moisture

Increases in soil moisture content at all the access tube locations correlate with the timing and amount of *precipitation, and in* the case of sinkholes, the spring thaw.

Fluctuations in moisture content above 36 to 48 inches at all access tubes correlate with precipitation events and subsequent evapotranspiration. Increases in volumetric moisture content between April 24 and June 6 ranged from 4% to 10% at 24-inch depth with no change occurring below 36 inches in the non-collapsed sites. The first significant increase in soil moisture levels in the non-collapsed settings were recorded on 6/6/90, which was preceded by nearly 4 inches of rain in the last three weeks of May (Table 5).

The highest volumetric moisture content measured at 24 inches in all monitored sinkholes occurred on 6/28/90, after more than 6 inches of rain during June alone (Table 5). AT-5 and AT-11 were not monitored because water had accumulated in the access tubes.

By 7/31/90, soil moisture had decreased at most depths at nearly all of the access tube sites, although soil moisture levels were still higher than levels prior to June, from the precipitation that occurred in June and July. However, evapotranspiration was greatest during June, July, and August, resulting in most infiltration being returned to the atmosphere. Average daily high and low temperatures increased from June through July (Table 5).

Table 5

Climatic data for summer of 1990 (National Weather Service data for Wilton station).

	May	June	July	Aug.	Sep.
Average daily high (°F)	**	75.6	79.1	83.3	75.4
Average daily low (°F)	**	52.1	55.2	55.8	48.2
Precipitation: (in.)					
Week 1	0.09	1.84	1.01	0.00	1.88
Week 2	0.00	0.47	0.52	0.05	0.00
Week 3	1.31	2.44	0.45	0.45	0.39
Week 4	0.89	1.91	0.28	0.94	0.14
Total	2.29	6.66	2.26	1.44	2.41

** data not available

By 8/14/90, soil moisture had declined to the lowest levels of the summer. September's average daily high was nearly identical to June's, but the average daily low was 4°F cooler than in June. Soil moisture increased significantly by 9/29/90 in sinkholes, but relatively no change was measured in access tubes in non-collapsed areas. In fact, the highest levels of soil moisture below 48 inches for most of the monitored sinkholes were measured on 9/29/90. By 12/05/90, levels of soil moisture had declined again.

Unsaturated Hydraulic Head

Soil moisture and hydraulic head profiles for July through September 1990 show the relationship between moisture content and hydraulic head, and the direction of moisture movement within the soil. Soil moisture flows from higher to lower hydraulic head. But increases in moisture content at shallow depths does not always lead to downward moisture movement to greater depth because of evapotranspiration. Hydraulic gradients may be downward at shallow depths immediately after a rain, but evapotranspiration removes this moisture before it can infiltrate very deep.

Changes in the slope of the hydraulic gradient are represented by pivot points. These changes in hydraulic gradient mark the confluence of downward and upward moisture movement. However, more tensiometers are needed to determine the precise depth of changes in hydraulic gradient (See Appendix II for complete listing of hydraulic head data).

Non-collapsed Settings

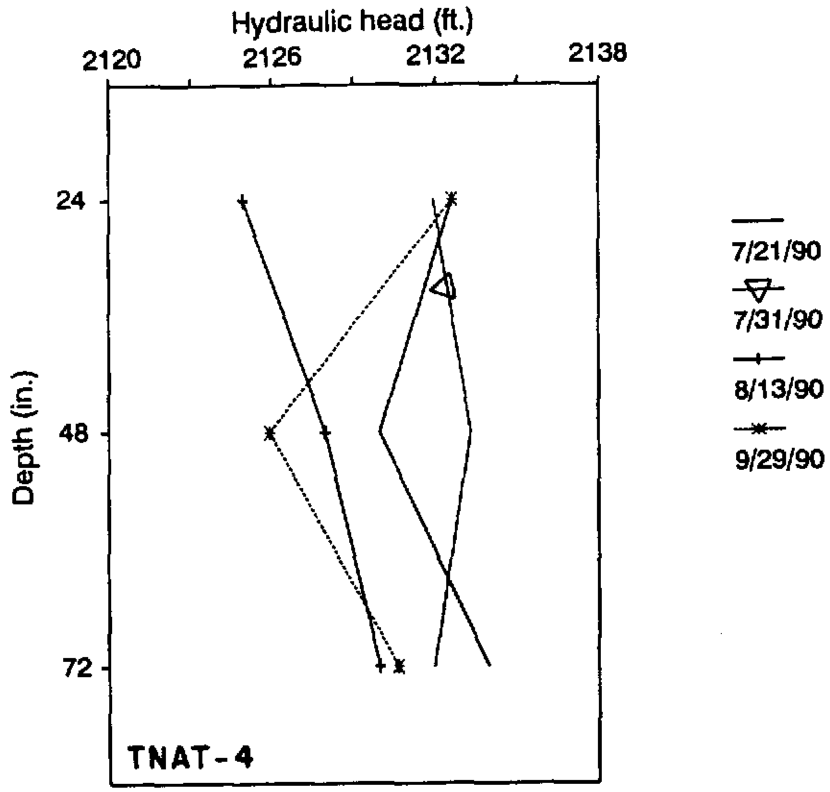
The hydraulic head data, along with the volumetric moisture profiles, show that infiltration was limited to shallow depths in the non-collapsed settings monitored. The hydraulic head profile for TNAT-4 (Figure 30) shows that the hydraulic gradient above 48 inches was variable, with a downward gradient on 7/21/90 and 9/29/90, and an upward gradient on 7/21/90 and 8/13/90. Upward gradients were measured below 48 inches on three of the four monitoring dates. The volumetric moisture profile for AT-4 (Figure 31) shows no change in moisture content, even with the one downward gradient.

The hydraulic gradient above 48 inches was downward on three monitoring dates for TNAT-7 (Figure 32), with slight upward gradient on 8/13/90. Hydraulic gradients were upward for the 48 to 72-inch depths on all four monitoring dates for TNAT-7. No changes in volumetric moisture content were measured below 48 inches in AT-7 (Figure 33).

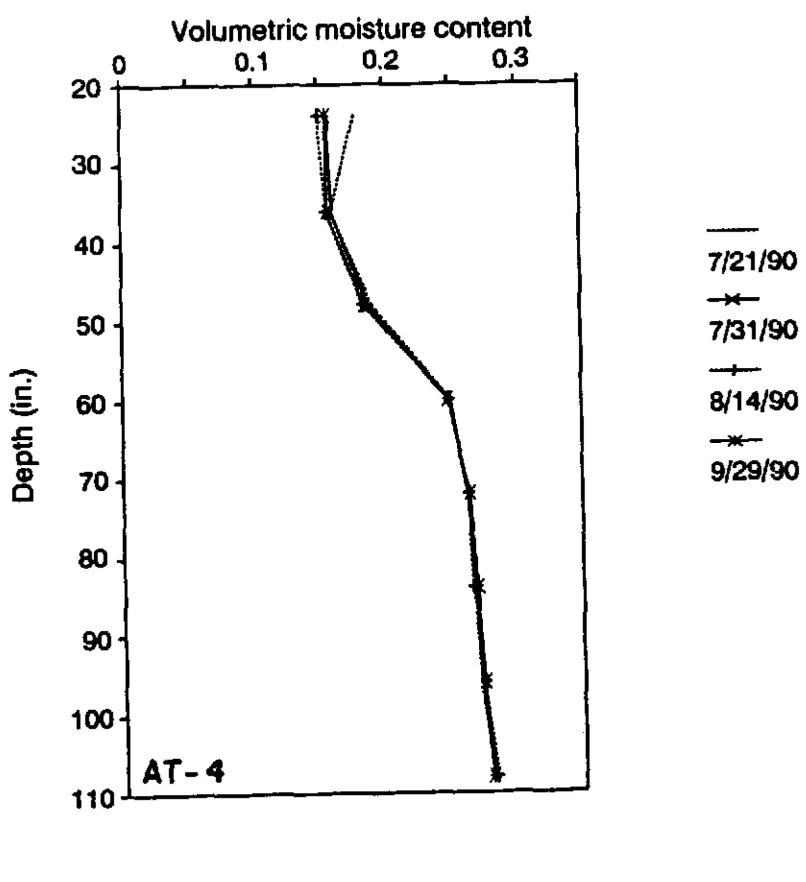
The hydraulic head profiles for TNAT-7 (Figure 32) show no change in the direction of hydraulic gradients, even though the relative magnitude of head decreased during July. The changes in head indicate at least a small change in volumetric moisture content should have occurred but this was not observed, probably because tensiometer

Figure 30. Unsaturated hydraulic head profile from tensiometer data for TNAT-4, set in till; non-collapsed, low run-off accumulation potential.

Figure 31. Volumetric moisture content profile for AT-4 with monitoring dates that correspond to monitoring dates for tensiometer nest TNAT-4.



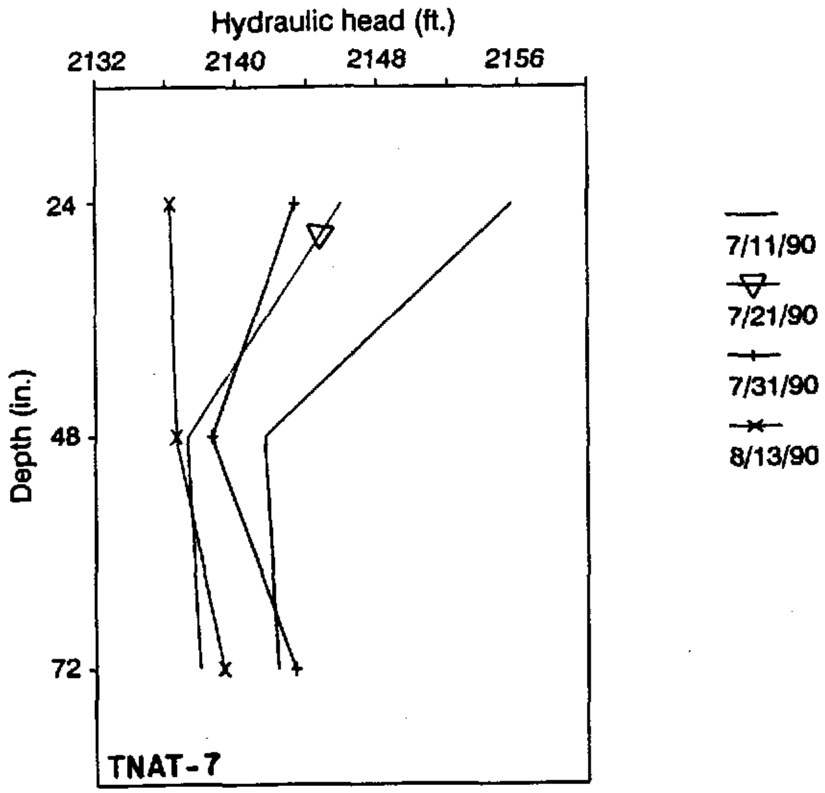
Hydraulic head (ft.)
2120
2126
2132
2138
Depth (in.)
24
48
72
TNAT-4
7/21/90
7/31/90
8/13/90
9/29/90



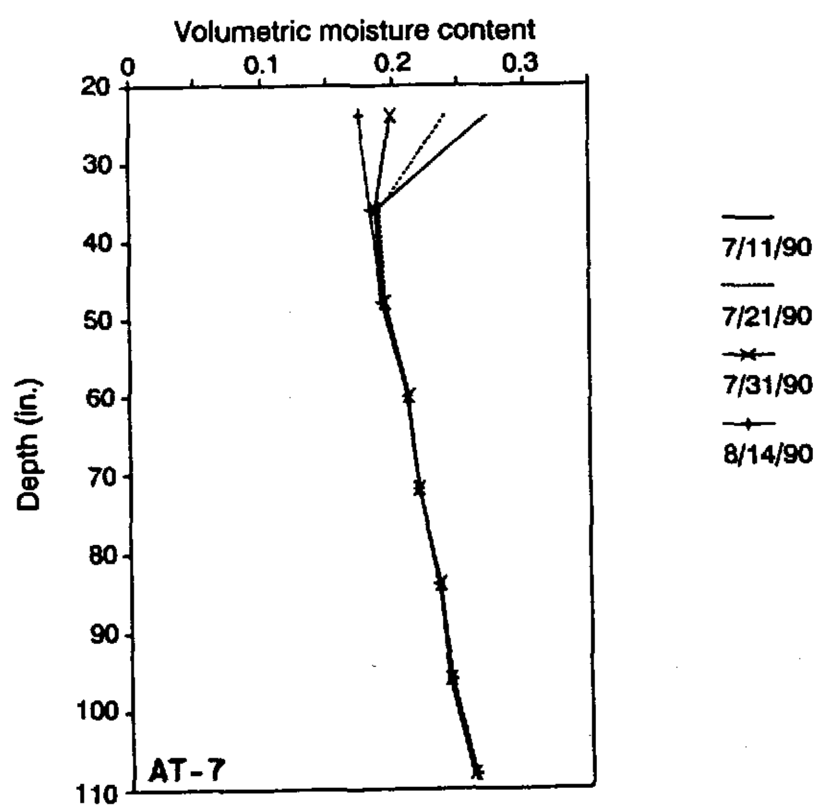
Volumetric moisture content
0
0.1
0.2
0.3
Depth (in.)
20
30
40
50
60
70
80
90
100
110
AT-4
7/21/90
7/31/90
8/14/90
9/29/90

Figure 32. Unsaturated hydraulic head profile from tensiometer data for TNAT-7, set in till; non-collapsed, high run-off accumulation potential.

Figure 33. Volumetric moisture content profile for AT-7 with monitoring dates that correspond to monitoring dates for tensiometer nest TNAT-7.



Hydraulic head (ft.)
2132
2140
2148
2156
Depth (in.)
24
48
72
TNAT-7
7/11/90
7/21/90
7/31/90
8/13/90



Volumetric moisture content
0
0.1
0.2
0.3
Depth (in.)
20
30
40
50
60
70
80
90
100
110
AT-7
7/11/90
7/21/90
7/31/90
8/14/90

monitoring was not frequent enough, and soil moisture movement had equilibrated so that pre-existing gradients were re-established between monitoring dates.

Collapsed Settings

The hydraulic head profile for TNAT-3 (Figure 34) shows that a downward gradient was present over the entire depth monitored for all dates except 8/13/90. An upward gradient accompanied by a decline in soil moisture was measured on 8/13/90 above 48 inches, with a downward gradient below 48 inches. Downward gradients were present even though the amount of soil moisture was fluctuating (Figure 35). The strongest downward gradient and highest moisture content below 48 inches at TNAT-3 were recorded on 9/29/90, which resulted from a combination of the late August/early September precipitation and lower evapotranspiration rate.

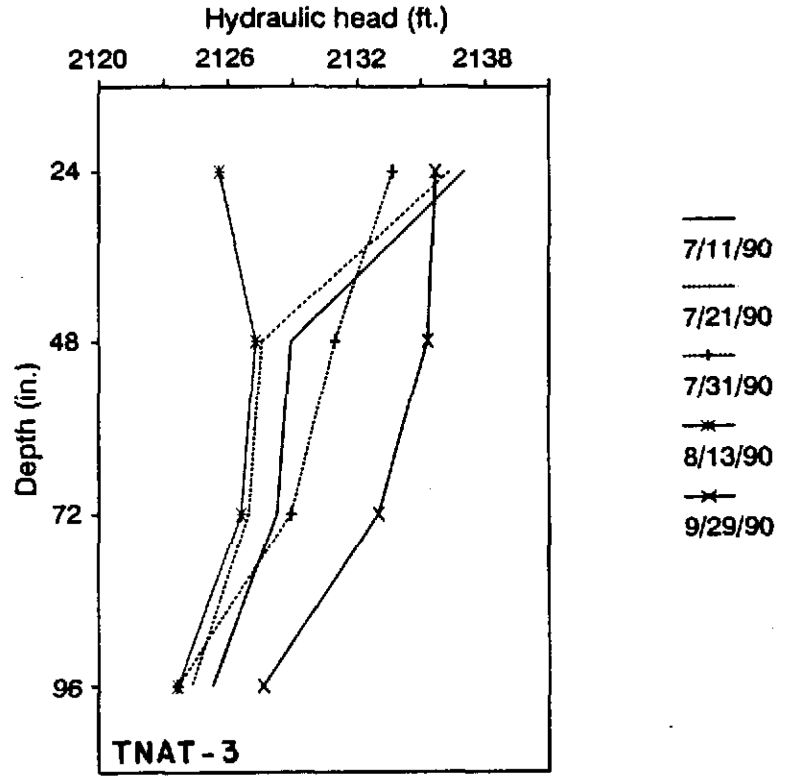
At TNAT-8 the highest hydraulic head (Figure 36) and volumetric soil moisture content (Figure 37) were measured in early July. During the remainder of the monitoring period, simultaneous declines in hydraulic head levels and volumetric moisture content were measured at TNAT-8 and AT-8, respectively. The hydraulic gradient was usually upward above 72 inches at TNAT-8, and downward below 72 inches, during the monitoring period.

Area of Sinkholes and Equivalent Moisture Data

The total surface area of sinkholes in the southwest quarter of Section 5 was measured to emphasize the potential impact of infiltration in sinkholes on soil moisture conditions, mainly through snow capture. If only a few sinkholes existed in the area, the potential for contributions by sinkholes to infiltration would be very low. The measured surface area in the southwest quarter of Section 5, is more than 6.3 acres, or about 4% of the quarter section, as determined from a

Figure 34. Unsaturated hydraulic head profile from tensiometer data for TNAT-3, set in till; sinkhole, low run-off accumulation potential.

Figure 35. Volumetric moisture content profile for AT-3 with monitoring dates that correspond to monitoring dates for tensiometer nest TNAT-3.


Hydraulic head (ft.)
2120
2126
2132
2138
Depth (in.)
24
48
72
96
TNAT-3
7/11/90
7/21/90
7/31/90
8/13/90
9/29/90

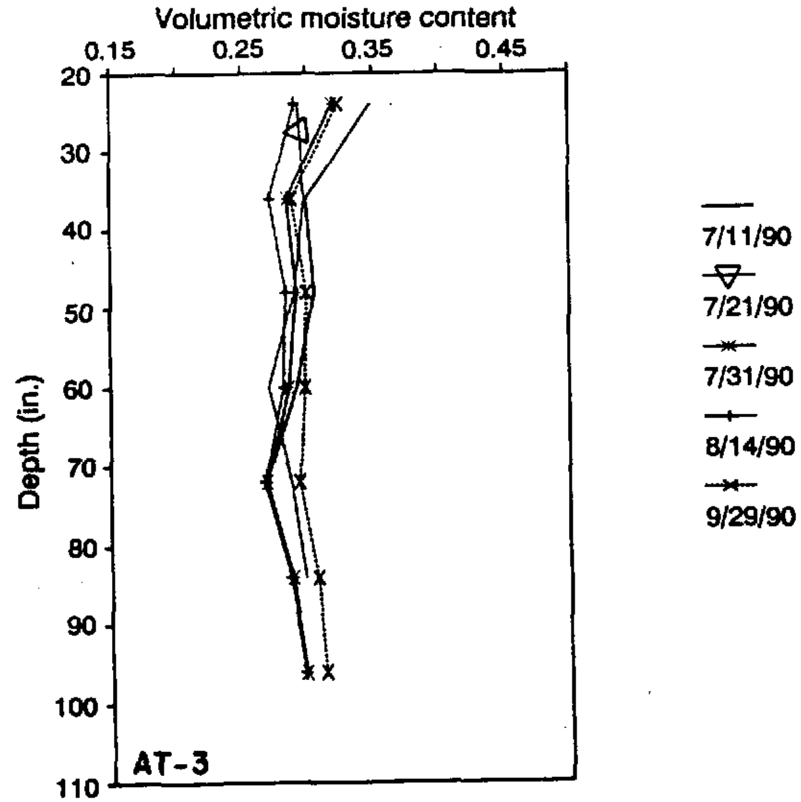
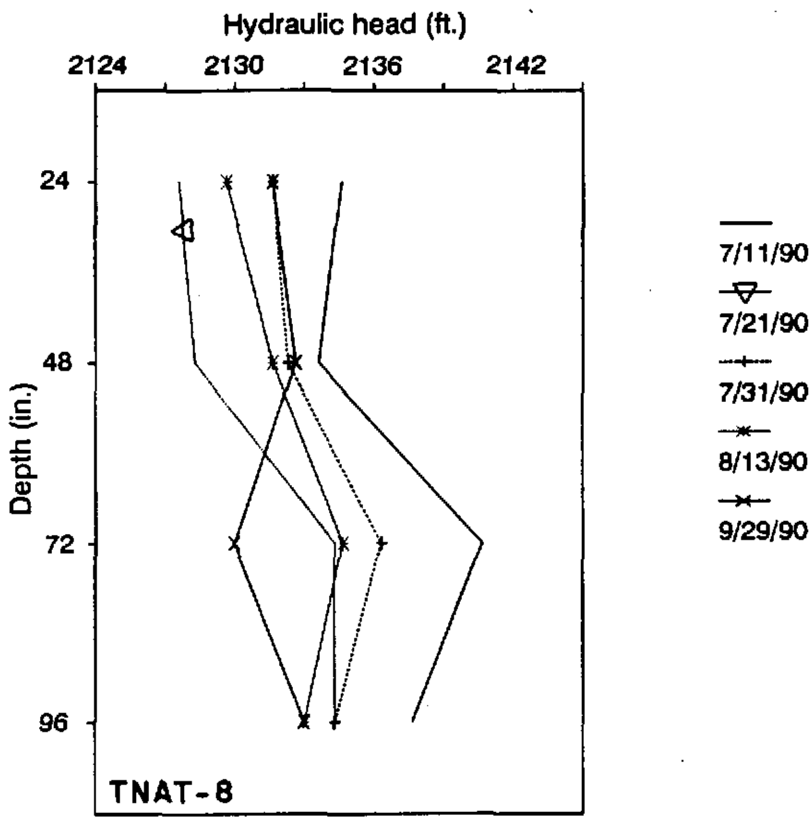
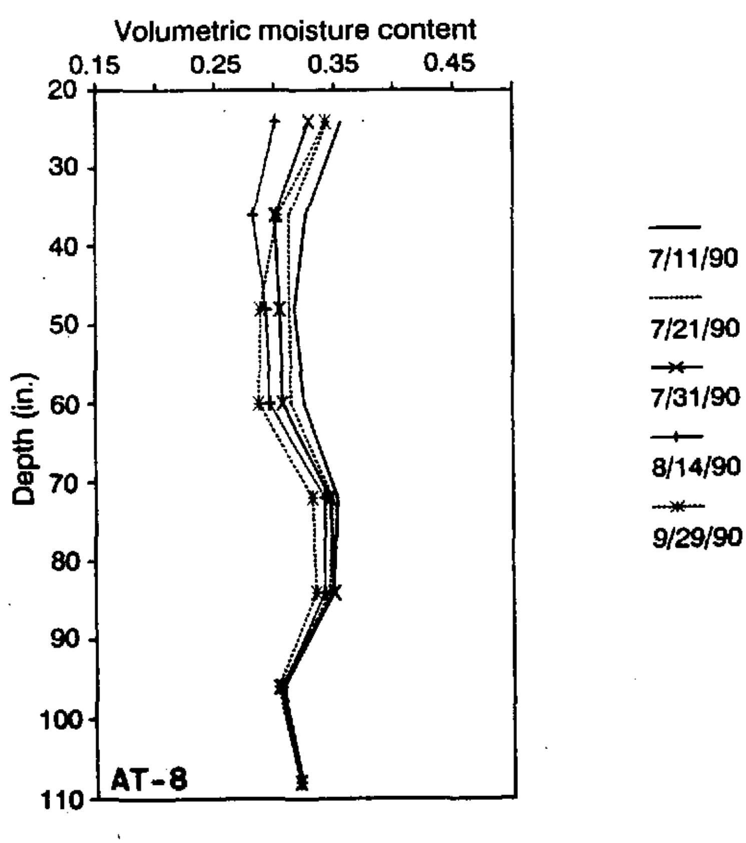

Volumetric moisture content
0.15
0.25
0.35
0.45
Depth (in.)
20
30
40
50
60
70
80
90
100
110
AT-3
7/11/90
7/21/90
7/31/90
8/14/90
9/29/90

Figure 36. Unsaturated hydraulic head profile from tensiometer data for TNAT-8, set in non-till sediments; sinkhole, high run-off accumulation potential.

Figure 37. Volumetric moisture content profile for AT-8 with monitoring dates that correspond to monitoring dates for tensiometer nest TNAT-8.



Hydraulic head (ft.)
2124
2130
2136
2142
Depth (in.)
24
48
72
96
TNAT-8
7/11/90
7/21/90
7/31/90
8/13/90
9/29/90



Volumetric moisture content
0.15
0.25
0.35
0.45
Depth (in.)
20
30
40
50
60
70
80
90
100
110
AT-8
7/11/90
7/21/90
7/31/90
8/14/90
9/29/90

topographic map produced from air photos taken in 1981. More sinkholes have formed since 1981, so 6.3 acres is a conservative value. A ratio 2.4:1.0 of depth of snow to depth of equivalent water was obtained from measurements in seven sinkholes in March 1989. Values for the depth of equivalent water in the sinkholes ranged from 0.85 to 3.39 feet (Table 6). The ratio is high because of warm temperatures, creating slushy conditions. Under normal conditions, the average snow/equivalent water ratio is 10 inches:1 inch (Oliver and Hidore, 1984, p. 84). Whichever ratio is used, the area of sinkholes available for snow capture is significant.

Table 6

Equivalent moisture data for March 1989 in SW1/4 Sec.5, T. 142 N., R. 79 W.

Sinkhole Number	Length (ft)	Width (ft)	Depth of Snow(ft)	Equivalent Water (ft)
1	28.0	19.8	3.00	1.27
2	31.0	30.5	5.75	2.44
3	25.0	24.0	5.00	2.12
4	21.0	17.0	2.75	1.17
5	19.0	19.0	3.00	1.27
6	15.5	13.0	2.00	0.85
7	20.0	18.0	2.75	1.17
8	24.0	22.0	3.67	1.56
9	19.0	17.5	2.25	0.95
10	24.0	18.0	3.50	1.48
11	20.0	17.0	2.50	1.06
12	9.0	8.0	7.50	3.18
13	28.0	28.0	8.00	3.39
14	72.0	24.5	7.00	2.97
15	7.0	7.0	4.00	1.70
16	21.0	17.0	7.00	2.97
17	26.0	22.0	6.00	2.54
18	11.0	10.0	7.00	2.97
19	29.0	23.0	4.00	1.70
20	19.0	18.0	3.00	1.27
21	35.0	11.0	4.00	1.70

Water Levels

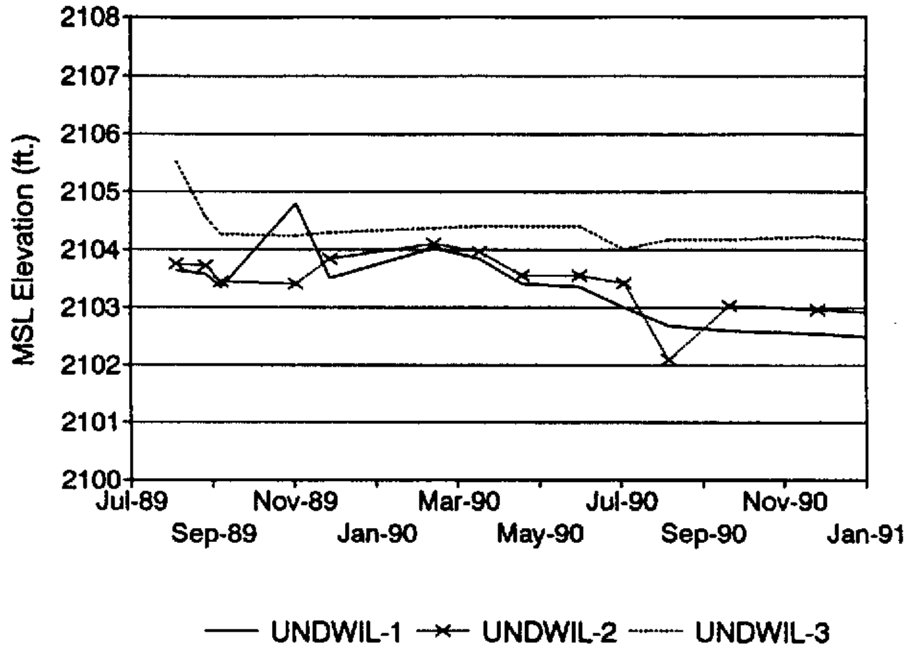
Ground water levels and the water levels of two ponds were monitored to determine the vertical and horizontal components of ground water flow at the Wilton site (Appendix III). Water levels steadily declined over the entire monitoring period in the wells set in the Wilton coal seam and the one well set below the Wilton coal seam (Figures 38 and 39). The water levels in the surface ponds experienced marked seasonal fluctuations but no strong trend of increasing or decreasing levels are apparent (Figure 40). A north-northwest hydraulic gradient of 11 ft/mi. is present at the site, measured from MW-4 to GP-2 (See Figure 41 for hydrograph of wells along this line). MW-1, 2, and 3, which are close to ND Highway 36, experienced a sharp fluctuation in water levels during the summer of 1989 (Figure 38). The timing of these fluctuations coincided with reclamation of mine tunnels within the highway right-of-way. Aside from these fluctuations, water levels declined at a fairly steady rate during the monitoring period.

MW-6, 7, and 8 are nested, with MW-6 the deepest. The top of the screen of MW-6 is 14 feet below the base of the screen of MW-7, the base of MW-7 is at the base of the Wilton coal seam, and the base of MW-8 is about 17 feet above the coal seam (Table 2). A downward hydraulic gradient of approximately 0.21 ft/ft exists between MW-7 and MW-6 (Figure 39). Dl, the change in length term of the gradient Dh/Dl, was measured from the water level in MW-7 to the top of the screen in MW-6. MW-8 held water only in June 1991.

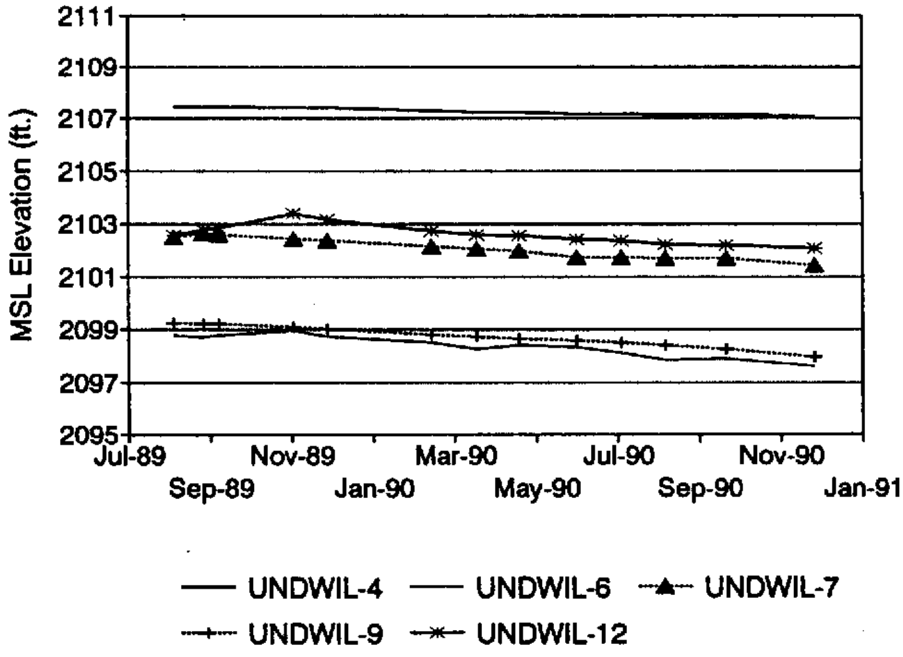
Slug or bail tests were not conducted in wells set in the coal seam because recovery was almost immediate after bailing. Using the Hvorslev method (Hvorslev, 1951), a hydraulic conductivity of 2×10^{-6} ft/s was calculated from a bail test performed in MW-6, the only well screened below the Wilton coal seam (See Appendix IV for bail test data).

Figure 38. Hydrograph of Wells MW-1,2,3. See Figure 3 for well locations.

Figure 39. Hydrograph of Wells MW-4,6,7,9,12. See Figure 3 for well locations.



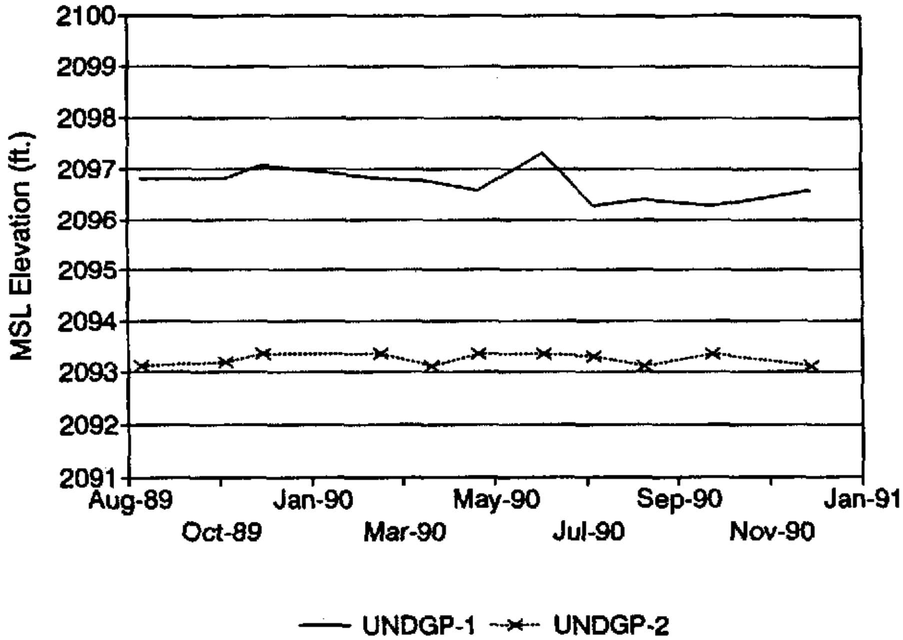
2108
2107
2106
2105
2104
2103
2102
2101
2100
MSL Elevation (ft.)
Jul-89
Sep-89
Nov-89
Jan-90
Mar-90
May-90
Jul-90
Sep-90
Nov-90
Jan-91
UNDWIL-1
UNDWIL-2
UNDWIL-3



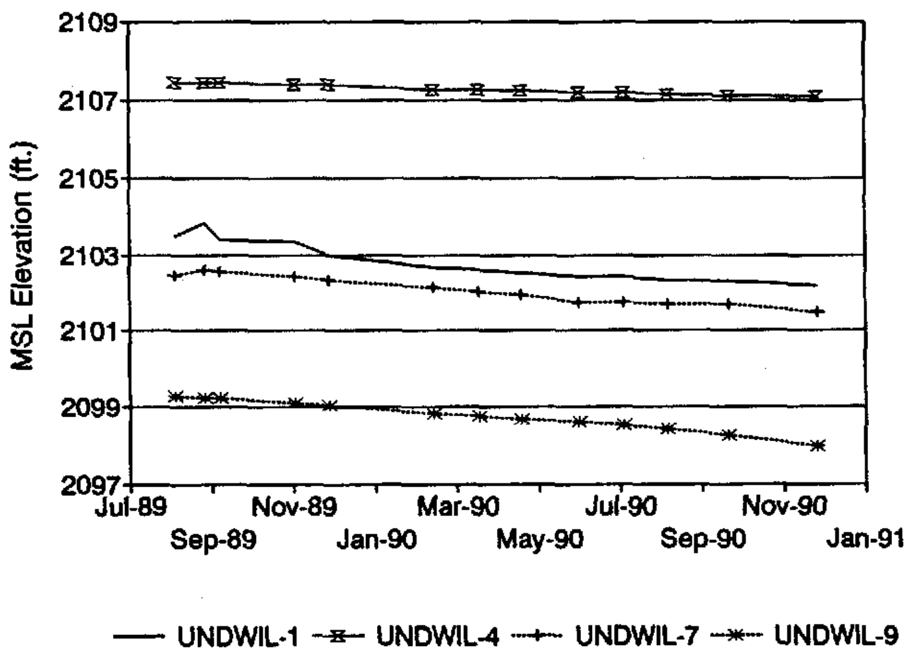
2111
2109
2107
2105
2103
2101
2099
2097
2095
MSL Elevation (ft.)
Jul-89
Sep-89
Nov-89
Jan-90
Mar-90
May-90
Jul-90
Sep-90
Nov-90
Jan-91
UNDWIL-4
UNDWIL-6
UNDWIL-7
UNDWIL-9
UNDWIL-12

Figure 40. Hydrograph of gauging posts set in two ponds. See Figure 3 for location of posts.

Figure 41. Hydrograph of wells MW-1,4,7,9 (or 4,1,7,9, in order from upgradient to downgradient). See Figure 3 for location of wells.



MSL Elevation (ft.)
2100
2099
2098
2097
2096
2095
2094
2093
2092
2091
Aug-89
Oct-89
Jan-90
Mar-90
May-90
Jul-90
Sep-90
Nov-90
Jan-91
UNDGP-1
UNDGP-2



MSL Elevation (ft.)
2109
2107
2105
2103
2101
2099
2097
Jul-89
Sep-89
Nov-89
Jan-90
Mar-90
May-90
Jul-90
Sep-90
Nov-90
Jan-91
UNDWIL-1
UNDWIL-4
UNDWIL-7
UNDWIL-9

Gauging posts were installed in two ponds at the site. GP-1 is at the base of strip mine spoils in the east-central portion of Section 6 (Figure 3). The pond has no feeder or discharge streams. GP-2 is in a pond in the northeast corner of Section 6. This pond is a small, spring-fed marsh. Water drains from this marsh toward the northeast by means of a drainage culvert.

The water level at GP-1 remained fairly constant, experiencing mainly seasonal fluctuations, such as one sharp increase during June of 1990 (Figure 40), a month of high precipitation. The water level at GP-2 also remained relatively constant (Figure 40) because of the presence of the drainage culvert.

Water Composition

Water samples were collected to provide background water quality. Samples were collected from the two ponds and selected wells and analyzed for major anions and cations and for trace elements (Appendix V). The most abundant cations in the wells and ponds sampled are Ca^{2+} and Mg^{2+}, with SO_4^{2-} and HCO_3^- as the most abundant anions (Table 7). Field and laboratory values for pH range from 6.7 to 8.0.

Between a pH of 7 and 10, dissolved carbonate species will be predominantly HCO_3^- (Drever, 1988, p. 51-52). Some carbonate species will be present as H_2CO_3 when the pH approaches 6.4, or as CO_3^{2-} when the pH approaches 10.2. The concentrations of HCO_3^- and H_2CO_3 are approximately equal at a pH of 6.4, with concentrations of HCO_3^- and CO_3^{2-} being approximately equal at a pH of 10.2. Under most conditions total alkalinity is equal to the carbonate alkalinity (Drever, 1988, p. 52). Thus, considering the pH of water samples collected from Wilton, the carbonate alkalinity is assumed to be equivalent to the concentration of HCO_3^-.

Table 7

Wells sampled for water quality.

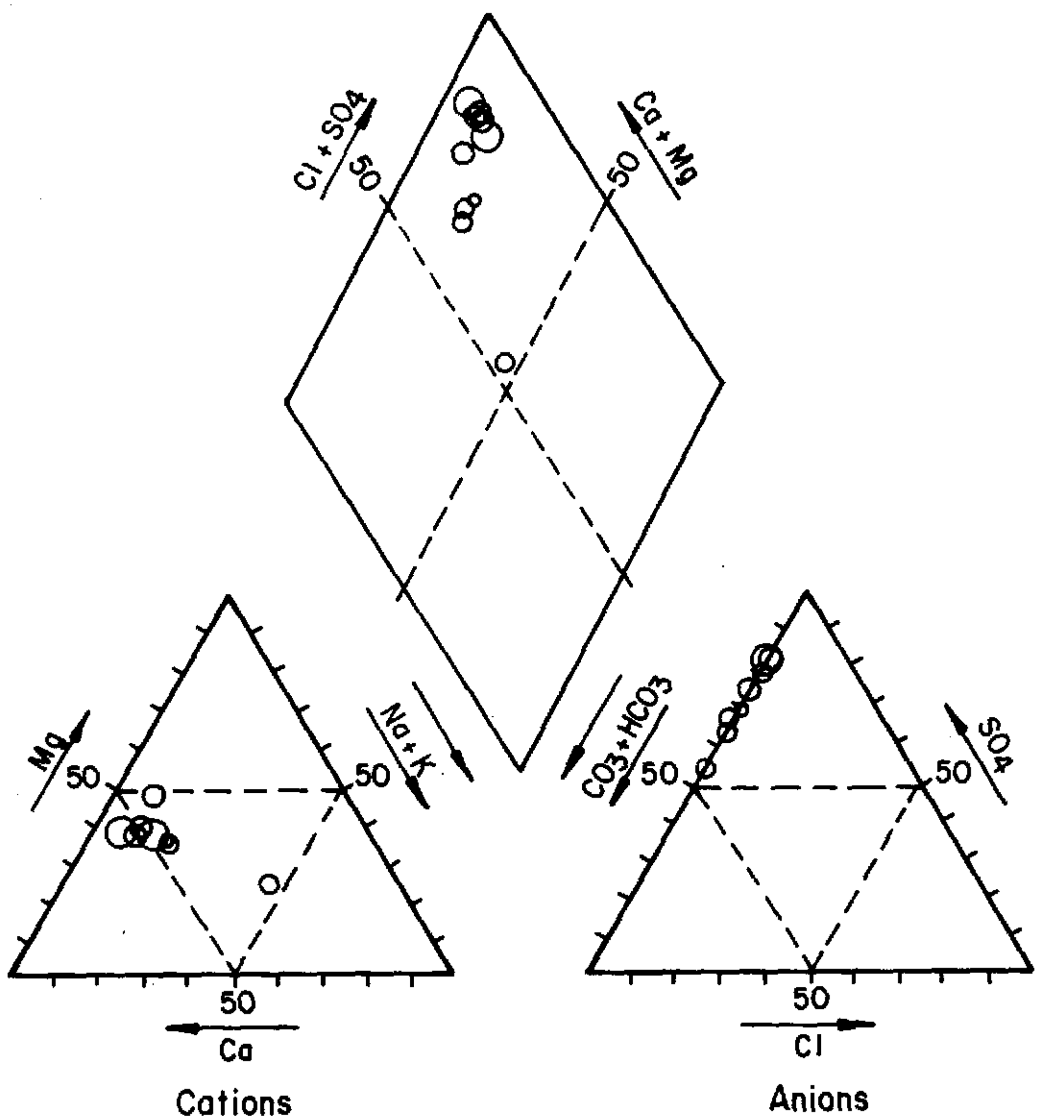
Well Number	Screen Length (ft)	Enclosing Material	Sampled for Water Quality
MW-1	10	coal	m,t
MW-2	10	coal	m,t
MW-3	10	coal	m,t
MW-4	10	coal	m,t
MW-5	10	coal	---
MW-6[1]	5	sandy cl.	m,t
MW-7[1]	10	coal	m,t
MW-8[1]	5	silty cl.	---
MW-9	10	coal	m,t
MW-10	10	coal	---
MW-11	10	coal	---
MW-12	10	coal	m,t
MW-13	10	coal	---

1 = MW-6, 7, and 8 form a well nest
m = major anions and cations
t = trace metals

A trilinear plot of the major anions and cations of the water samples (Figure 42) shows that the composition of water in the Wilton coal seam is of a calcium magnesium bicarbonate sulfate type. Most water samples plot on top or very near each other on the diagram (Figure 42). Ground water below the coal seam (MW-6) is a sodium bicarbonate sulfate type.

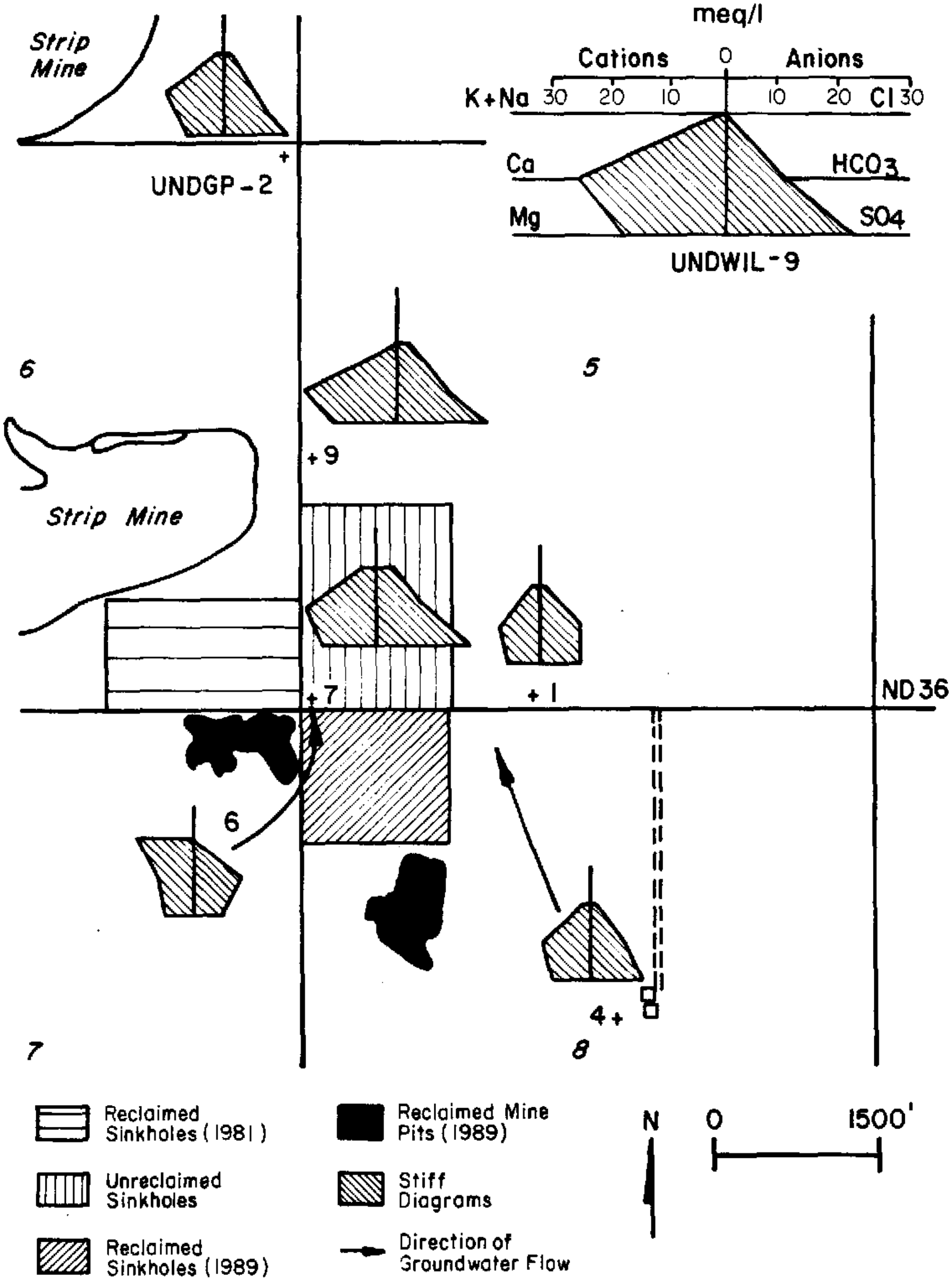
Ground water composition varies across the site, as illustrated with a series of Stiff diagrams for selected wells (Figure 43). Stiff diagrams are geometric shapes used to quickly illustrate differences in water composition (Stiff, 1951). Keep in mind that a northwest hydraulic gradient exists in the Wilton coal, and a downward hydraulic gradient exists between MW-6 and 7. Water samples from MW-1 and 4, located upgradient, have similar compositions, calcium magnesium sulfate bicarbonate. Moving northwest, samples from MW-7 and 9 are also of a calcium magnesium sulfate bicarbonate type, but with greater concentrations Ca^{2+}, Mg^{2+}, SO_4^{2-}, and HCO_3^-, and greater TDS than either MW-

Figure 42. Trilinear diagram showing classification of water samples by composition. The size of the circles indicates relative abundance of total dissolved solids, with the larger circles having greater TDS (Appendix V). The single circle indicating higher values of Na^+ represents MW-6, which is screened below the Wilton coal seam.



Cl + SO4
50
Ca + Mg
50
Mg
50
Na + K
50
CO3 + HCO3
50
SO4
50
50
Ca
Cations
50
Cl
Anions

Figure 43. Stiff diagrams overlaid upon map showing selected well locations and suspected recharge areas, including reclaimed mine pits and sinkholes. MW-6 and 7 are nested, with the top of the screen of MW-6 14 feet below the base of MW-7.



Strip Mine
UNDGP-2
meq/l
Cations
0
Anions
K+Na
30
20
10
10
20
Cl
30
Ca
HCO3
Mg
SO4
UNDWIL-9
6
5
+9
Strip Mine
+7
+1
ND36
6
4+
7
8
Reclaimed Sinkholes (1981)
Unreclaimed Sinkholes
Reclaimed Sinkholes (1989)
Reclaimed Mine Pits (1989)
Stiff Diagrams
Direction of Groundwater Flow
N
0
1500'

1 and 4. Water collected from MW-6 has a distinct composition, sodium sulfate bicarbonate. Water from the pond in which GP-2 is set is compositionally intermediate to water samples from MW-1 and 4, and MW-7 and 9. These changes in composition occur in the direction of the slope of the water table (see horizontal vector of ground water flow in Figure 43). The other wells sampled but not shown in Figure 43 have compositions similar to MW-1 and 4.

MW-7 and 9, which are downgradient of the reclaimed mine pits and sinkholes in Sections 7 and 8, have the highest concentrations of Ca^{2+}, Mg^{2+}, SO_4^{2-}, and TDS of all the wells and ponds sampled.

Bk Horizon

A pronounced Bk soil horizon is present at all access tubes and tensiometer nests set in non-collapsed areas. This horizon starts at 18 to 30 inches below ground surface and varies from approximately 12 to 24 inches in thickness. This Bk horizon was not found in any of the sinkholes monitored.

DISCUSSION

Soil Moisture and Ground Water Recharge

Infiltration deeper than 48 inches was measured only in sinkholes. The range of moisture in the upper half of the soil profile was greater in sinkholes than in non-collapsed areas, as was average moisture content, during the entire monitoring period. Conditions for deep infiltration and recharge were better in sinkholes than non-collapsed areas because of greater soil moisture. The differences in soil moisture between the collapsed and non-collapsed areas can be attributed to differences in snow accumulation, run-off interception, and to some degree, differences in the effects of evapotranspiration.

Winter and early spring precipitation in 1990 was less than 2 inches. Increases in soil moisture during late winter/early spring occurred at the 12 to 36-inch depths in all the monitored sinkholes, with increases of 1% or less within the same intervals in non-collapsed settings. This difference in moisture conditions is attributed to snow capture and run-off interception. Even sinkholes in topographically higher areas registered increases in soil moisture in the upper 12 to 24 inches during the spring thaw. These increases cannot be attributed to run-off, suggesting snow capture and infiltration, possibly under frozen conditions, or redistribution of soil moisture, as explanations.

Snow capture is effective in supplying moisture to sinkholes. This moisture may have infiltrated through partially frozen soil or may have remained ponded until the soil thawed. Moisture may also have migrated upward toward the frost zone during the winter, only to return to lower depths as the spring thaw progressed, meaning soil moisture was just redistributed. The presence of snow in sinkholes suggests that snow capture is an important mechanism for concentrating precipitation. Monitoring throughout the winter would be necessary to determine the magnitude of these processes.

The greatest impact of frozen soils on soil moisture at the site is during spring melting. Drier soil conditions, which occur in non-collapsed areas, result in more open pore space during the spring thaw (Horak, 1988), which should result in infiltration of moisture in non-collapsed settings. But the potential for infiltration during the spring melt might be greater in sinkholes than in non-collapsed areas because the sinkholes often contain snow when very little snow is found in non-collapsed areas. Also, the melting of snow begins before the ground has thawed, resulting in the concentration of run-off in low spots and sinkholes. The water remains ponded until it evaporates or infiltrates. The lack of change in moisture content at depths below 36 inches at most sites in the late winter/early spring indicates spring melting did not produce any deep infiltration in either sinkholes or non-collapsed areas. This does not preclude the possibility that deep infiltration may occur in association with spring melting under wetter conditions.

Changes in soil moisture observed during the summer and fall correlate with precipitation events, run-off, and evapotranspiration. The fluctuation of soil moisture in the upper part of the soil profile is much greater than in the deeper half of the profile. Precipitation that occurred was normally only enough to replenish soil moisture at shallow depths, most of which was lost to evapotranspiration before it could infiltrate beyond the effective root zone. This interpretation is supported by the hydraulic head data, which show upward hydraulic gradients in the upper soil profile under most conditions.

The amount of water that infiltrated beyond the root zone during the summer was kept to a minimum because this is also the period of greatest evapotranspiration. The maximum depth of infiltration measured for sinkholes ranged from 48 to at least 108 inches, the greatest depth monitored, with infiltration deeper than 36 inches being measured at only one non-collapsed setting. Even with 6.6 inches of rain in June and 2.2 inches in July, soil moisture declined during the last two weeks of July. Further declines in soil moisture in August were the result of lower precipitation and higher average daily temperatures than in July.

The largest increases in soil moisture beyond 48 inches in the sinkholes occurred in September, with the exception of AT-8. Although the nearly 1 inch of rain in the last week of August (Table 5) and the 2 inches in September encountered the driest levels of soil moisture for the summer, soil moisture increased at depth in monitored sinkholes because evapotranspiration rates were lower, due to declining temperatures and dormant vegetation. The largest increase in soil moisture at AT-8, with a high run-off accumulation potential, occurred on 7/11/90, or after the 6.6 inches of rain in June.

Volumetric moisture content in non-collapsed settings ranged from 0.14 to 0.30 and from 0.16 to 0.37 in sinkholes. AT-5, in a sinkhole, is an exception, with a high value of 0.53. Most of these values are within the range of values reported for porosities for unfractured till in this region (Grisak and Cherry, 1975). The presence of a swelling clay, montmorillonite, results in the production of desiccation cracks and joints in the till upon wetting and drying, which contribute to higher porosities and, hence, to higher moisture content than might be expected in non-collapsed settings. These same factors and inter-block channels produced in collapsed material contribute to higher moisture content in the sinkholes.

Precipitation in 1990 was average, but antecedent moisture conditions were poor because of two years of severe drought. Soil moisture profiles indicate that under such circumstances, deep infiltration might only occur in sinkholes. Moisture profiles for non-collapsed areas show that infiltration was restricted to the upper 36 inches of the soil profile in June and July, after a total of nearly 9 inches of rain during these two months. Therefore, it is unlikely significant infiltration leading to storage, and possibly ground water recharge, occurred at all during the summer months in non-collapsed areas. Deep infiltration may possibly occur during a summer of unusually high precipitation, but even under these conditions, the soil moisture data suggest that deep infiltration is more likely in the sinkholes.

Under normal climatic conditions deep infiltration and recharge appears to be restricted to spring and fall. This seasonal restriction of recharge was found at two sites north and northwest of Wilton, at the Coal Creek Power Station near Center (Johnson, p. 57, 1990) and near Falkirk, North Dakota (Rehm and others, 1982), which is about 25 miles northwest of Wilton.

A rough estimate of the amount of water moving into storage at access tube sites where deep infiltration was measured can be made by converting the volumetric moisture to inches of water at each interval. A 100-inch column of soil with a 30% volumetric moisture content would contain 30 inches of water by volume. A 12-inch long core with a 30% volumetric moisture content would contain 3.6 inches of water. In this way, fluxes in volumetric moisture content can be expressed in terms of inches of water or the volume of water measured at each interval. Consider a sinkhole with a diameter of 10 feet, which is equivalent to approximately 78.5 square feet using the equation of area = πr^2. Also, assuming that the infiltrating water is following a cylindrical path of the same diameter as the sinkhole, and that this sinkhole experienced 2.0 inches (0.17 ft) of deep infiltration, approximately 13.3 cubic feet of water would have moved into storage. Moisture may also be infiltrating outward from the base of the sinkhole, decreasing the amount available to move deeper beneath the sinkhole.

The sides of most sinkholes normally slope in toward the bottom, so that water ponds over only a fraction of the total surface area of a sinkhole. Also, access tubes were installed at the lowest points in sinkholes, never along the side of a sinkhole. In order to estimate the area through which recharge is occurring, several access tubes would have to be installed in a transect across one or more sinkholes to determine changes in soil moisture laterally, because soil moisture may be migrating outward from, as well as downward through, a sinkhole. This area is necessary to calculate the total volume of water infiltrating at depth.

A measured increase or decrease in soil moisture at any given depth may not represent the total flux past that interval since the last monitoring date, merely the conditions at that time. For example, the volumetric moisture and hydraulic head profiles for AT-3 and TNAT-3, respectively, indicate increases in soil moisture accompanied by downward flow on 9/29/90 below the 48-inch depth. The moisture content converted to inches of water at each depth show increases ranging from 0.18 to 0.40 inches. Rehm and others (1982) state that at the Falkirk study site, evapotranspiration is insignificant at depths below approximately 4.9 to 6.5 feet. Adding the increases in water volume at the 7 and 8-foot intervals yields 0.55 inches of water in the sinkhole in which AT-3 was set. This sinkhole has a diameter of approximately 8 feet, giving an area of about 50 square feet. The area times the increase in soil moisture, 0.55 inches or 0.046 feet, gives a volume of about 2.3 cubic feet of water. This represents the amount of water that had moved into storage at AT-3 when readings were taken on 9/29/90. How much water passed the 7 and 8-foot intervals before and after 9/29/90 is not known. This is why the estimate of water moving into storage is a minimum amount. This amount is known to have reached a depth where evapotranspiration is considered ineffective.

Bk Horizon

Infiltrating water dissolves soluble salts and minerals and transports them downward. Evapotranspiration removes this water from the soil before it has a chance to infiltrate very deep in the non-collapsed settings. When water carrying dissolved salts and carbonates is removed through evapotranspiration, the dissolved minerals precipitate out in the soil. Repetition of this shallow flushing of soluble minerals and subsequent precipitation caused by evapotranspiration concentrates the soluble minerals. This process is responsible for the Bk horizon in the non-collapsed settings. The existence of a well-developed Bk horizon in the non-collapsed till, but not in till in sinkholes, indicates there are differences in the amount of flushing and, hence, infiltration, that occurs in the two settings. Any Bk horizon present before collapse would have been disrupted by sinkhole formation, but calcite from the Bk horizon should still be abundant in the collapsed material. Less calcite in sinkholes is the result of deeper transport of the calcite by deeper infiltration, indicating moisture is moving through the soil profile, beyond the effects of evapotranspiration. The great depth of the water table, 40 to more than 115 feet, eliminates the possibility of calcite precipitation from discharge processes.

Equivalent Moisture

The equivalent moisture data confirm the significant contribution of snow capture to soil moisture in sinkholes. Many sinkholes were at least partially, if not completely, filled with snow, though very little snow cover existed in non-collapsed areas. If the sinkholes were not present, the snow would be distributed elsewhere across the landscape. But by being concentrated in sinkholes, snow accumulates to depths of several feet or more. Ponded conditions result upon melting of the snow.

These ponded conditions might have occurred in natural topographic lows if the sinkholes were not present. But snow and melted snow distributed across the non-collapsed areas would be more susceptible to sublimation and evaporation because of a greater surface area exposed to the sun and wind. Ponding of water probably would not have reached depths of 1 to 3 feet were sinkholes not present.

The equivalent moisture data are unusual in that the snow:equivalent water ratio is quite high. This can be explained by the fact that samples for equivalent moisture were collected from the surface of snow deposits. The upper surface was exposed to high enough temperatures to cause melting of the snow, making it more icy or more dense. But saturation of the snow was not limited to the upper surface. For example, water flowed for several minutes from a hole created by pushing a graduated pole to the base of snow in one sinkhole. The snow was seven feet deep, and was saturated through its entire depth, so the measured ratio might be accurate for some of the sinkholes. Under normal conditions the amount of equivalent water will still be greater in the sinkholes than in non-collapsed settings because of snow capture and run-off from spring thaw.

Hydrogeology

Water Levels

Water levels at the study site showed relatively steady declines during the entire monitoring period. Randich and Hatchett (1965) reported that most wells in Burleigh County tend to recover to the same levels from one year to the next, but that steady declines occur in some areas due to irrigation. No irrigation has been observed at the study site.

If these declining water levels are the result of the dry conditions of 1988 and 1989, water table response to climate must be fairly rapid. When the depth to the water table is considered, 40 to more than 115 feet, the decline of water levels is difficult to explain only in terms of precipitation. The declines could be the result of several factors, including low precipitation, response to conditions prior to monitoring, impacts from reclamation projects, and increased use of ground water supplies.

Water level declines may be partly in response to events that occurred prior to the time monitoring began. The years 1985 and 1986 were wetter than normal, with 1987 being slightly below average. The water table may have been higher than normal due to these wetter years, with the decline in water levels representing a return to more normal conditions. Long-term monitoring of water levels might reveal a similar water table response if a series of wet years were encountered.

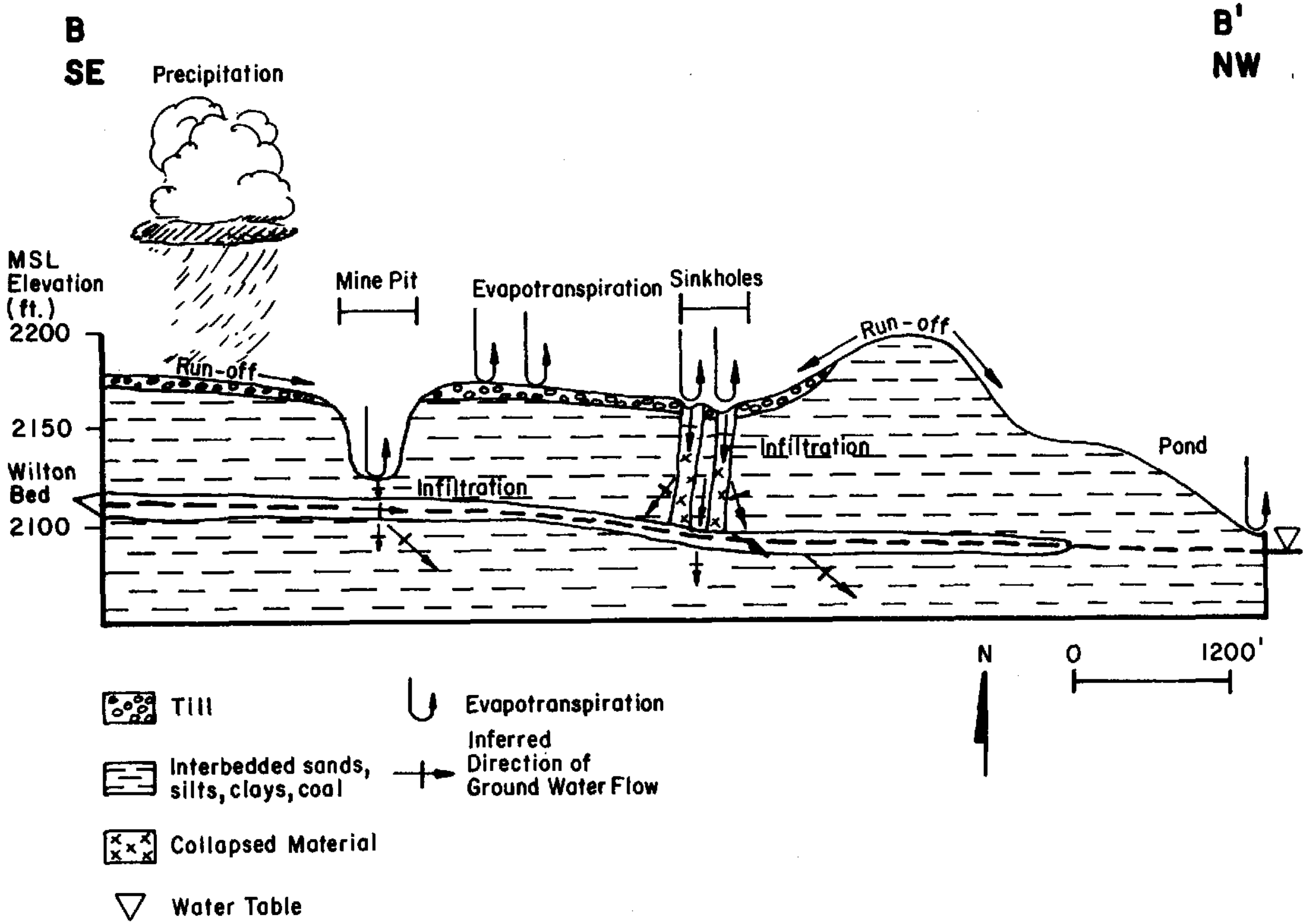
The decline in water levels may also be attributed to the reclamation of the mine pits in Sections 7 and 8 (Figure 3) during the summer of 1989, and the reclamation of sinkholes at the site. The base of each pit was within 20 to 25 feet the coal seam, providing a short path for run-off to reach the water table. Reclamation eliminated the chance for run-off to infiltrate directly to the water table, although water levels were already declining when these pits were reclaimed. These early declines may therefore have been a seasonal response that continued due to the reclamation of the pits.

Another possible, but less likely, factor could be increased utilization of water stored in the coal seam by local residents. Information concerning estimates of annual water usage was not collected for this study. Usage is limited to a few nearby domestic and livestock wells.

Model of Infiltration, Recharge, and Ground Water Flow

Figure 44 is a conceptual diagram illustrating the likely paths of infiltration and ground water flow at the Wilton site. Precipitation, in the form of rain and snow capture, is concentrated in sinkholes and

Figure 44. Hydrostratigraphic cross-section showing interaction of precipitation, evapotranspiration, infiltration, and direction of ground water flow. The mine pit has been superimposed upon cross-section. See Figure 3 for location of cross-section.



B
SE
B'
NW
Precipitation
MSL
Elevation
(ft.)
2200
2150
2100
Wilton
Bed
Run-off
Mine Pit
Evapotranspiration
Sinkholes
Run-off
Infiltration
Infiltration
Pond
N
0
1200'
Till
Interbedded sands, silts, clays, coal
Collapsed Material
Water Table
Evapotranspiration
Inferred Direction of Ground Water Flow

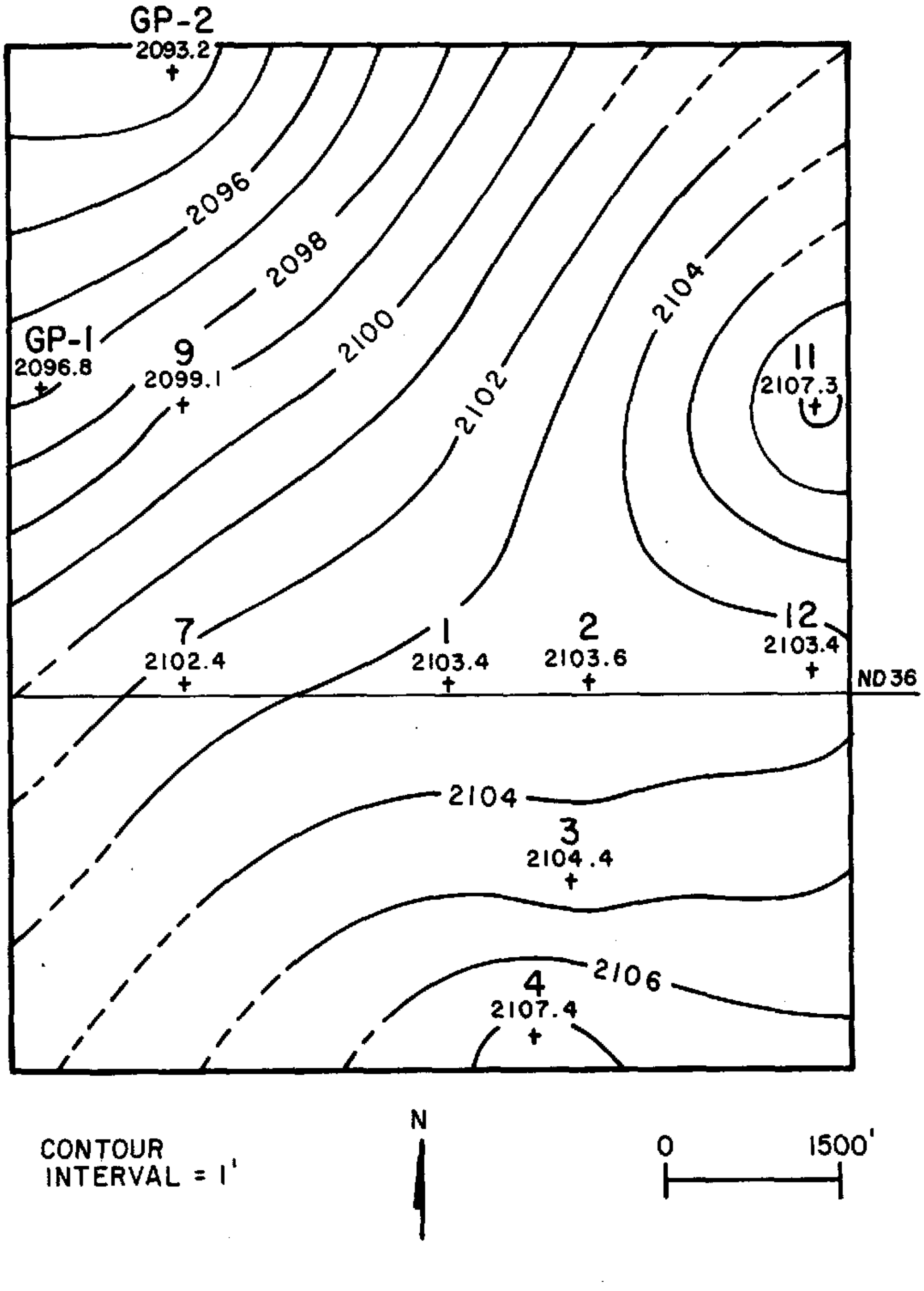
topographic lows. Prior to reclamation, precipitation was also concentrated in the mine pits in Sections 7 and 8 (Figures 3). As indicated by arrows in Figure 44, moisture probably moved into storage in the mine pits and sinkholes, which could possibly drain to the water table present in the Wilton coal seam. Ground water flow in the coal seam has both a horizontal and vertical component.

The configuration of the water table appears to be strongly influenced by the geometry of the base of the Wilton coal seam (Figure 45), rather than the configuration of mine tunnels. This indicates that ground water is not readily drained by the mine tunnels. Therefore, the mine tunnels appear to have little overall effect on ground water velocity across the mine.

Because the room and pillar mining method used at the site removes approximately only 60% of the coal, and not all areas of the coal seam were mined, a volume of coal remains that is probably at least equal to the combined volume of open tunnels, collapsed tunnels, and reclaimed tunnels. One way to estimate the hydraulic properties of the coal is to assume that the tunnels do not affect ground water flow in the coal seam. Values for the hydraulic properties of the unmined coal can be estimated from studies carried out at nearby sites, such as Falkirk (Rehm and others, 1980).

Most of the effective porosity and permeability in coal is from fractures (Rehm and others, 1980). If fractures in the coal are assumed to provide the porosity within the coal, the specific yield can be used as a measure of effective porosity (Rehm and others, 1980). Values for fracture porosity of coal are normally a fraction of 1% (Freeze and Cherry, 1979, p. 157). There are few data on measured fracture porosities or specific yield of coal in this region. A specific yield of 0.01 was determined from a pump test in an unconfined coal aquifer in North Dakota (Moran and others, 1978).

Figure 45. Contour map depicting configuration of water table on 11/4/89 (in feet). Well numbers are posted as single-digit numbers, with well positions marked by plus signs. MSL elevations of the water table are posted below the well and gauging post numbers. The heavy-dashed line on Figure 3 represents the border of this map.



GP-2
2093.2
2096
2098
2100
2102
2104
GP-1
2096.8
9
2099.1
11
2107.3
7
2102.4
1
2103.4
2
2103.6
12
2103.4
ND36
2104
3
2104.4
2106
4
2107.4
CONTOUR
INTERVAL = 1'
N
0
1500'

Assuming fractures account for the porosity of the coal seam, an estimate of ground water velocity can be made using an average value for hydraulic conductivity for lignite deposits in this region. The equation used is

$$v = Ki/n$$

where K is the hydraulic conductivity, i is the hydraulic gradient, and n is the porosity. Using 1×10^{-5} ft/s for hydraulic conductivity (Rehm and others, 1980), a porosity of 0.01 (Moran and others, 1978), and a gradient of 11 ft/mile (2×10^{-3} ft/ft) measured at the site, the average ground water velocity in the coal seam would be 2×10^{-6} ft/s, or approximately 63 ft/yr, assuming that all ground water flow in the coal seam remains horizontal, which may not be the case.

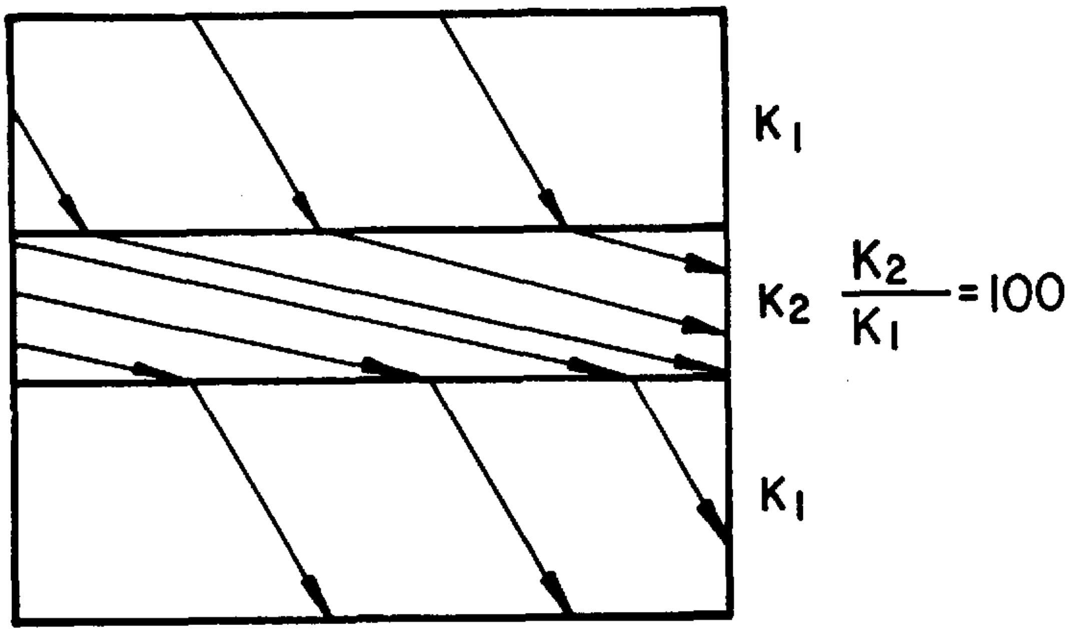
The actual length water will travel in the Wilton coal seam before moving downward is difficult to quantify with assumed values of hydraulic conductivity. The presence of the clay between the coal seam and the clayey, silty sand, and the difference in water composition between the two water-bearing units suggests that ground water flow may be predominantly horizontal. But, the difference in water quality between MW-6 and 7 can be explained by the process of cation exchange as ground water passes from the coal through the clay. Also, the water levels of MW-6 and MW-7 show simultaneous declines during the monitoring period, suggesting hydraulic connection between the two water-bearing units. Additional information that may support the interpretation of a stronger downward flow component, rather than horizontal, is the apparent lack of effect of mine tunnels on flow within the coal seam.

Flow lines can be drawn for sediments above the coal, within the coal, and the underclay, using estimates for the hydraulic conductivities of the coal and the underclay. Once again assuming a hydraulic conductivity of 1×10^{-5} ft/s for the coal and an average value of 1×10^{-7} ft/s for the hydraulic conductivity of the underclay (value for Paleocene aquitards from Rehm and others, 1980), flow lines can be drawn using the relationship of tangential refraction of flow in heterogeneous materials (Figure 46), as described by Freeze and Cherry (1979, p. 173). This diagram indicates refraction causes flow lines in the coal seam to be locally horizontal, but without knowing the actual values of hydraulic conductivity for the coal and the underclay, the length of the horizontal pathline cannot be determined. A pump test in the lower aquifer, with piezometers in the coal, underclay, and lower aquifer could further clarify the horizontal and vertical components of ground water flow in and through the Wilton coal seam. Another unknown is the local stratigraphic variability of the underclay and the lower silty sand. Additional exploratory drilling and monitoring wells are needed to examine these relationships in more detail.

Water Composition and Ground Water Recharge

The geochemical evolution of ground water at the site begins with water infiltrating into the soil. CO_2 and O_2 are concentrated in the soil as a result of the decay of organic material and respiration of plant roots (Freeze and Cherry, 1979, p. 240). Levels of CO_2 and O_2 are normally higher in the soil than the atmosphere because of biochemical activity and restricted gas circulation in the soil (Trainer and Heath, 1976). As water percolates through the soil, carbonic acid is formed: $CO_2 + H_2O \rightarrow H_2CO_3$. This acid production allows for the dissolution of carbonate minerals that are abundant in the till, namely calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). Continued biologic activity replenishes CO_2 consumed in the dissolution of carbonates, in effect creating an acid pump (Freeze and Cherry, 1979). The dissolution of carbonates frees HCO_3^- along with the Ca^{2+} and Mg^{2+}, producing a calcium magnesium bicarbonate water. This process explains the major constituents of the ground water in the coal seam with the exception of SO_4^{2-}, which is probably supplied by one or two sources at the site. Ca^{2+} and SO_4^{2-} can be supplied by the dissolution of gypsum ($CaSO_4 \bullet 2H_2O$), and SO_4^{2-}

Figure 46. Diagram illustrating refraction of flow lines (modified from Freeze and Cherry, 1979, p.173). K_1 and K_2 represent hydraulic conductivities, with K_2 being 100 times greater than K_1.


K1
K2 $\frac{K_2}{K_1} = 100$
K1

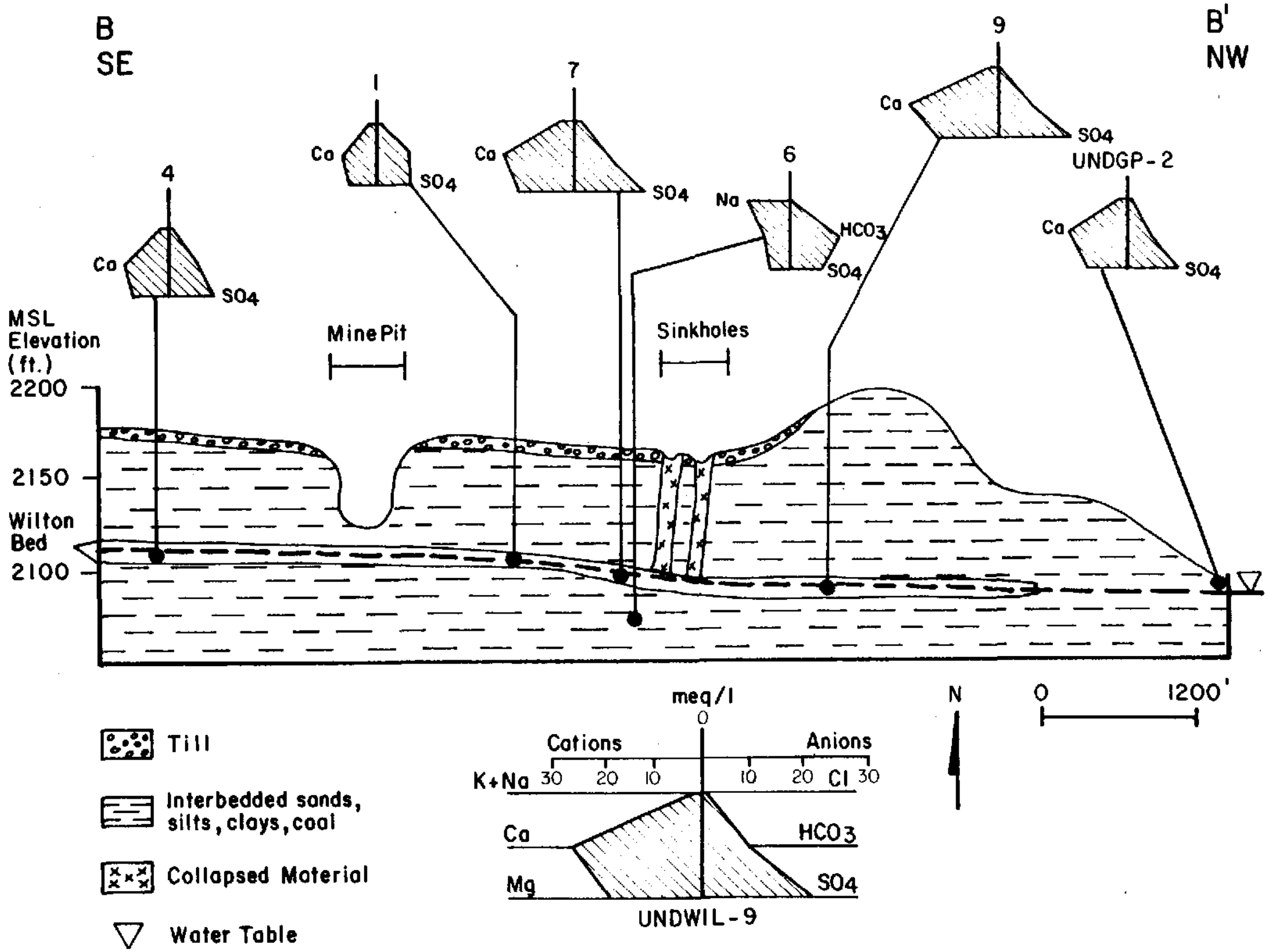
also by the oxidation of iron sulfides (FeS_2). Both gypsum and iron sulfides are common in Tertiary sediments (Bullion Creek Formation at the site) of North Dakota Groenewold and others, 1979, p. 7).

The downward gradient between the aquifer in the coal seam and the underlying confined aquifer, along with the topographically high position of the site, suggest recharge is the source of water for the coal seam. The composition of the water in the coal seam is similar to the calcium sulfate bicarbonate Type III water of Freeze and Cherry (1979, p. 284), which they associate with ground water in glacial deposits in the Northern Great Plains. This agrees with the interpretation that recharge is occurring at the study site.

Figure 47 is similar to Figure 43 in that it shows the distribution of different water compositions at the site. Figure 47 provides a more graphic illustration of the potential contribution of the now-reclaimed mine pits and sinkholes to water composition. The differences in composition between MW-6, which is screened below the coal seam, and the wells screened in the coal seam indicate geochemical evolution of ground water as it moves from the coal seam to the lower aquifer. One possible explanation for this difference is that Ca^{2+} and Mg^{2+} are substituting for Na^+ through cation-exchange as ground water from the coal seam moves downward. The predominant clay minerals in Tertiary rocks in North Dakota are illite and sodium-rich montmorillonite (Groenewold and others, 1983). Montmorillonite has a high cation-exchange-capacity, in which calcium and magnesium easily exchange for sodium. As ground water migrates downward through the clay underlying the coal, its composition changes from a calcium magnesium bicarbonate sulfate to a sodium bicarbonate sulfate composition.

Another possibility is the anaerobic reduction of SO_4^{2-}, causing HCO_3^- to become the dominant anion. The reduction of SO_4^{2-} could result in the precipitation of gypsum and iron sulfides. As ground water loses $Ca^{2+}$and SO_4^{2-}, and Ca^{2+} and Mg^{2+} exchange with Na^+ on clay particle

Figure 47. Hydrostratigraphic cross-section with geochemical data presented as Stiff diagrams, and with wells and mine pit projected on to line of section. See Figure 3 for location of cross-section and wells.



B
SE
B'
NW
4
1
7
6
9
UNDGP-2
Ca
SO4
Na
HCO3
MSL
Elevation
(ft.)
2200
2150
2100
Wilton
Bed
Mine Pit
Sinkholes
Till
Interbedded sands, silts, clays, coal
Collapsed Material
Water Table
meq/l
0
Cations
Anions
K+Na
30
20
10
Cl
Mg
UNDWIL-9
N
0
1200'

surfaces, water compositions should change from a calcium magnesium sulfate to a sodium bicarbonate composition, which is observed between MW-6 and 7.

The differences in water composition between MW-7 and 9 and the remaining wells in the coal can also be explained in terms of recharge. The values for TDS, Ca^{2+}, Mg^{2+}, and SO_4^{2-} are higher in MW-7 and 9 than in the other wells and ponds (Appendix V). Greater recharge upgradient of MW-7 and 9 might explain why these values are higher than values for surrounding wells in the coal seam. The mine pits and sinkholes reclaimed in 1989 are upgradient of MW-7 and 9, and the greatest concentration of sinkholes remaining at the site, and the sinkholes reclaimed in 1981, are upgradient of MW-9 (Figures 43 and 47). These two pits, due to the proximity of their bases to the coal seam, and the sinkholes probably contributed more to ground water recharge than non-collapsed settings.

If the differences in water composition between MW-1 and 4 and MW-7 and 9 are the result of greater recharge upgradient of MW-7 and 9, this relationship might also be observed elsewhere, such as the spring-fed pond in the northeast corner of Section 6 (GP-2). The composition of water samples collected from this pond is intermediate in terms of TDS, Ca^{2+}, Mg^{2+}, and SO_4^{2-} when compared to water samples from MW-7 and 9 and the other wells in the coal seam (Figure 43). This may be the result of mixing of surface water and ground water similar to that in MW-7 and 9, with ground water similar to that of the other wells in the coal seam, which might indicate that water discharges to this pond from different directions.

Estimating Recharge

A rough estimate of recharge that occurs in sinkholes can be calculated from the soil moisture data. This estimate is not very accurate but does show the relative magnitude of recharge in sinkholes for 1990. A flux of water through the Wilton coal seam over one year can be calculated using the following equation:

$$Q = KiA$$

where Q is the discharge, K is the hydraulic conductivity in the coal seam, i is the vertical gradient, and A is area. Using an estimate of 1 x 10^{-5} ft/s (315 ft/yr) for hydraulic conductivity for regional coal seams (Rehm and others, 1980), a downward gradient of .21 ft/ft, and an area of approximately 7 x 10^{6} ft^{2} (area of a quarter section), an annual flux of 4.6 x 10^{8} ft^{3}/yr can be calculated for the coal seam. The measured surface of area of sinkholes in the southwest quarter of Section 5 was about 6.3 acres, which represents approximately 3.9% of the surface area of a quarter section. Multiplying the value of 0.046 ft of deep infiltration measured in AT-3 for September by the total area of sinkholes (3.9% of 7 x 10^{6} ft^{2}) gives a volume of recharge of 1.3 x 10^{4} ft^{3}. A comparison of these estimated values shows that recharge through sinkholes is several orders of magnitude less than flux through the coal seam. The estimate of recharge used assumes that the same amount of recharge occurs in all sinkholes in the southwest quarter of Section 5, which the soil moisture data show was not the case for 1990. Also, the amount of recharge is based on soil moisture data collected in a year following two years of drought. But even with a wet year, the amount of recharge occurring in sinkholes will probably represent a very small number in comparison to the flux through the coal seam over one year.

If sinkholes do not supply much recharge to the coal seam, then recharge to the water table must be coming from other sources, such as topographic lows and formerly from unreclaimed mine pits. It may be that ground water use has been low enough that ground water levels have not declined dramatically since this area was settled. Continued use of local ground water supplies may outpace the capacity for recharge at the site, which would result in continued declines in water levels.

CONCLUSIONS

1. Data show that soil moisture was greater in sinkholes than non-collapsed areas throughout the monitoring period, which may have resulted in higher hydraulic conductivities in sinkholes, producing conditions more conducive to infiltration and ground water recharge in sinkholes. Also, the formation of inter-block cracks and channels in collapsed sediment results in greater permeability in sinkholes than in non-collapsed areas.

2. Measurement of hydraulic head in soils show that the hydraulic gradient was always upward at depths below 48 inches in non-collapsed settings monitored with tensiometers, with the exception of one monitoring date for TNAT-4 (Figure 30). No changes in moisture content were measured below 48 inches in non-collapsed areas, indicating there was no downward flow of moisture below this, even though temporary downward gradients may have existed immediately after a rain. The only downward movement of soil moisture below 48 inches occurred in sinkholes.

3. No deep infiltration or recharge occurred in sinkholes or non-collapsed areas as a result of the spring thaw in 1990 due to lack of winter precipitation and antecedent dry soil conditions. That is, field capacity was never exceeded during the spring thaw at any of the settings monitored. Moisture content did increase in the upper few feet of soil in the monitored sinkholes, though.

4. The only measured deep infiltration occurred in sinkholes. This deep infiltration represents water that may have moved into storage. Future infiltration events and drainage by gravity could possibly move this moisture deeper.

5. Only very rough estimates of the total amount of water that moved into storage in sinkholes during 1990 can be made because infiltration below the effective root zone was not measured in all monitored sinkholes. Also, the amount of infiltration measured was variable between monitored sinkholes. Estimates of deep infiltration or recharge made are for specific sinkholes on specific monitoring dates, can be extrapolated to include all the sinkholes, but his provides only an order-of-magnitude estimate, which is not necessarily very accurate. But it does provide a means for comparing the flux of ground water through the Wilton coal seam to recharge in the sinkholes in the southwest quarter of Section 5. This estimate shows that recharge in the sinkholes is several orders of magnitude less than the flux of ground water through the Wilton bed. More frequent monitoring of access tubes and more access tubes in sinkholes would be required to provide a statistical average of deep infiltration in sinkholes, and therefore a more accurate estimate of annual recharge in sinkholes, during any monitoring period.

6. Soil moisture and climatic data from this and other studies in this region indicate that the highest potential for ground water recharge occurs in spring and fall. High evapotranspiration rates minimize the potential for recharge during the summer season, even though most precipitation occurs during this time.

7. Deep infiltration or recharge is unlikely to occur in non-collapsed settings during summers with a normal amount and normal temporal distribution of precipitation. Most, if not all summer precipitation will be evapotranspired before it can infiltrate beyond the effective root zone in non-collapsed settings. If enough precipitation to lead to deep infiltration in non-collapsed settings did occur, recharge would be much greater in sinkholes than in non-collapsed settings.

8. Water levels will probably continue to stabilize as a result of

reclamation of several recharge sites, including pit mines and possibly sinkholes.

9. Simultaneous declines in water levels in both aquifers suggest hydraulic connection between the two. The apparent lack of effect of tunnels on the water table might suggest that the downward flow component is stronger than the horizontal flow component at the site.

10. Water quality data suggest that the mine pits in Sections 7 and 8, which were reclaimed during the summer of 1989, may have contributed significantly to ground water recharge.

11. While differences in water composition might be interpreted as indicating hydraulic isolation between the Wilton bed and the silty sand, these differences can be explained by cation exchange and sulfate reduction as ground water moves through the clay underlying the Wilton coal seam.

12. The greatest potential for recharge at ground surface was most likely in topographic lows prior to disruption of the landscape by mining. Recharge in the post-mining landscape occurs in topographic lows, mine pits, and sinkholes. The topographic position of the site and the downward hydraulic gradient between the Wilton coal seam and the lower clayey, silty sand suggests that recharge occurs at the site from the water table, which lies slightly above or within the Wilton coal seam, to underlying units.

Although deep infiltration was measured in some sinkholes and not in non-collapsed settings, estimates of recharge indicate that recharge was several orders of magnitude lower than the flux of water from the local water table to a lower aquifer. Reclamation would eliminate these sinkholes as recharge mechanisms but their loss as a recharge mechanism may not be that important. If the amount of estimated recharge is tripled, it would still be orders of magnitude less than the flux of water through the coal seam. But the ground water at the site must have a source. Either ground water levels have continuously declined since initiation of ground water or other mechanisms contribute the major portion of recharge to the coal seam aquifer.

Even so, because of the benefits of increases in soil moisture (creating more productive pasture) and ground water recharge potential, sinkholes at abandoned underground mines in this region could be left unreclaimed if they do not endanger surface structures and are not at risk of contamination, saving the expensive cost of reclamation. If they pose a threat to the general public or are at risk of contamination, they should be reclaimed.

RECOMMENDATIONS FOR FUTURE WORK

The deep infiltration measured during this study was the amount that had occurred only at the time of measurement, not before or after a specific monitoring date. The total increase in soil moisture beyond the zone of effective evapotranspiration could be measured more accurately by monitoring on a daily basis during the spring thaw through the fall, until the surface freezes.

Tensiometers should be installed at one-foot intervals or less. The two-foot intervals used for this study were not adequate to pinpoint deflections in the hydraulic head profiles. The tensiometers should also be monitored on a daily basis. Daily monitoring could be scheduled to measure diurnal effects on soil moisture movement. Remote data loggers could be used to record pressure head data, along with water level and precipitation data.

Access tubes could be monitored throughout the year to study soil moisture redistribution during the winter. It would be interesting to see if any infiltration occurs while the ground is partially or completely frozen, and whether or not there is a difference in infiltration rate between sinkholes and non-collapsed settings during this time.

For a relatively accurate estimate of recharge, a greater number of sinkholes should be monitored, due to the variations in infiltration between the six sinkholes monitored. Access tubes of at least 20 feet long would be very useful in determining if the assumption of 6.5 feet as the lowest depth of effective evapotranspiration is valid. Also, at least a few sinkholes should be monitored with one or more transects of access tubes across their widths, to determine the amount of, if any, lateral flow of soil moisture occurs from the sides of the sinkholes.

Lysimeters could be installed at the site to provide data in at least three different areas. One would be to determine the chemical evolution of water from precipitation to recharge. Another area of study would be to determine whether infiltration mounds around an isolated sinkhole, or whether infiltrating moisture stays mostly within the collapsed material as it moves downward. Lysimeters could also be used to track wetting fronts at greater depths.

The hydraulic properties of the coal seam were estimated from studies done at other sites. A pump test in the Wilton coal seam would provide site-specific data, but this data may be difficult to interpret. Flow rates during a pump test might be greater in the tunnels if the pumping well is situated near an indurated tunnel. Directional differences in hydraulic conductivities between different materials within the aquifer would be difficult to assess because the distribution of all open tunnels and collapsed tunnels, along with the presence of reclaimed tunnels and remaining coal is not known.

Of more use would be a pump test in the aquifer below the coal. This would determine the amount of hydraulic connection between the Wilton coal seam and the lower aquifer. It would also determine whether the horizontal or vertical flow component in the coal was dominant.

The differences in water composition between the nested wells, MW-6 and 7, may be the result of cation exchange and not hydraulic separation. Isotope analysis might show whether the ages, and therefore, sources of water are different for the coal and clayey, silty sand. This may also help determine the connection between the two aquifers.

APPENDIX I

NEUTRON PROBE DATA

CALIBRATION EQUATIONS

VOLUMETRIC MOISTURE CONTENTS

NEUTRON PROBE COUNTS-PER-MINUTE

TUBE NUMBER	DATE	DEPTH (in) 24	36	48	60	72	84	96	108
	02/17/90	51052	45889	55740	61269	57007	73962	76814	78987
	03/23/90	77408	71344	68600	71630	60017	73607	77605	80388
	04/25/90	73390	69320	71280	73628	60122	74668	76768	80119
	06/06/90	74473	74721	74076	71849	59360	74738	76335	80089
	06/28/90	78857	79879	77244	73723	61851	74547	76772	79450
AT-1	07/11/90	75029	72091	74563	75632	59512	73981	76089	79668
	07/31/90	69264	67143	70635	72494	59017	73992	76063	79543
	08/14/90	64733	63325	66839	68961	57527	73448	74960	79309
	09/29/90	71355	69312	73366	78216	64901	77310	78326	80453
	12/05/90	68670	66018	69778	73008	60152	75015	76607	80002
	06/15/91	78970	78928	78641	81240	66310	78606	79750	82887
	02/17/90	42199	43742	46191	50234	52422	55088	57857	60947
	03/23/90	42287	43649	46203	50325	52108	55010	58144	60053
	04/25/90	42217	42915	46048	50315	52502	54586	58399	60219
	05/17/90	43047	43561	46096	50332	52154	54384	58322	60322
	06/06/90	56512	43499	46525	49812	52012	55002	57990	60384
AT-2	06/28/90	60242	43547	46459	50306	52229	54902	58079	60377
	07/11/90	61390	44302	46447	50472	52016	54738	58745	60194
	07/31/90	46917	44265	45963	49761	52195	54722	58180	60292
	08/14/90	42120	43641	46106	49626	51850	54830	58050	60599
	09/29/90	42496	43691	46181	50370	52396	54863	58367	60170
	06/15/91	28869	49414	45851	49934	52083	54823	58188	60039
	02/17/90	80819	58982	60188	67101	67778	71197	74485	
	03/23/90	85496	71389	70496	70369	67466	71276	74635	
	04/25/90	80188	69870	70092	69277	67258	71584	74219	
	06/06/90	85495	76744	73662	68584	66916	71843	74822	
	06/28/90	90466	83860	75595	70492	68118	71462	74867	
AT-3	07/11/90	86025	74734	76182	72837	67387	71981	74256	
	07/31/90	79353	71394	72870	71575	67587	71963	74254	
	08/14/90	72695	68361	71091	70428	67103	71603	74087	
	09/29/90	80420	72264	74548	74395	73313	76394	77879	
	12/05/90	78669	69783	71636	72273	70789	74171	76103	
	06/15/91	89773	79070	78388	76042	72997	76096	76825	
	02/17/90	41167	41527	48576	63473	66284	67285	68548	70260
	03/23/90	41549	41457	48562	63377	66193	67192	68317	70150
	04/25/90	41990	41859	48799	62683	66003	67075	68751	70152
	05/17/90	42457	41967	48937	62974	65937	67201	67750	69773
	06/06/90	52727	41959	48952	62946	65578	67164	67781	69374
AT-4	06/28/90	52712	42578	49382	63213	66179	67207	69970	
	07/11/90	51632	42883	49976	62886	65942	67509	68106	69862
	07/21/90	46701	42472	49454	63110	65896	67084	67981	70244
	07/31/90	41958	42616	48742	62799	65995	67408	68447	69721
	08/14/90	40140	41533	47736	62975	66004	66783	68626	70579
	09/29/90	41535	41673	48179	62667	66322	67558	68521	69939
	12/05/90	41864	41762	48370	62581	66537	67397	68830	69931
	06/15/91	53700	55661	49923	61910	65570	67003	68191	69455
	02/17/90	75383	79840	87628	96031	93598	97299	85511	95651
	03/23/90	84318	83014	87859	96379	94427	98540	88208	94646
	04/25/90	81458	79929	88766	96714	93808	97306	85051	95227
AT-5	05/17/90	89009	82110	88139	96643	93660	97471	84454	94831
	07/31/90	76214	77382	92431	98681	94352	98381	88823	98181
	08/14/90	72218	70829	73468	94797	94738	99059	88041	98106
	09/29/90	87539	93955	94868	96452	93876	98865	88831	97080
	12/05/90	88849	91957	92921	95964	94383	98539	87191	95994
	02/17/90	30834	46743	61951	64406	71077	68049	70187	64728
	03/23/90	31468	45567	61724	63708	71612	67979	69609	64388
	04/25/90	31904	47523	61246	64445	71064	68476	69004	64849
	06/06/90	42808	46486	61454	64653	71446	67492	69956	64302
	06/28/90	49032	46631	61451	64031	71337	67738	69398	64428
AT-6	07/11/90	50719	47336	61270	64293	71201	67626	69665	63713
	07/21/90	42686	48001	61901	63557	70695	67750	69707	64335
	07/31/90	35746	47788	61779	64946	70941	67403	68905	63468
	08/14/90	32190	47740	61788	63679	71182	71187	66841	68668

TUBE NUMBER	DATE	DEPTH (in) 24	36	48	60	72	84	96	108
	09/29/90	32886	47154	61751	63517	70599	65931	67290	62690
AT-6	12/05/90	32753	46783	61751	63261	70927	65851	67454	62407
	06/15/91	40717	51027	61692	63784	70383	65562	66488	61370
	02/17/90	47610	48789	50070	53906	56462	59742	61866	66129
	03/23/90	47393	48083	50023	54210	56223	59695	61522	65841
	04/25/90	47862	48056	49831	54075	56317	59714	61788	65305
	05/18/90	48337	48347	50092	53407	55807	59516	61670	65306
	06/06/90	65028	48627	50081	53744	56339	60054	62063	65846
AT-7	06/28/90	68315	48451	50364	53936	56392	60001	61947	65837
	07/11/90	68375	48759	49864	54305	56164	59668	61290	65183
	07/21/90	60974	49316	50479	54174	56308	59523	62004	65507
	07/31/90	51291	48721	50358	54462	56004	59858	61596	65531
	08/14/90	45747	47888	49746	54078	56083	59488	61753	65895
	09/29/90	49435	47559	50215	54295	56076	59587	61643	65344
	12/05/90	48688	48165	50444	53638	56529	60033	62164	65611
	06/15/91	56302	48955	49241	53794	55666	59402	61704	65366
	02/17/90	64033	70011	73666	75815	86195	86499	76923	80692
	03/23/90	80060	71029	73298	74495	85264	86377	77030	80734
	04/25/90	88509	80500	77011	77423	85391	85544	76362	80224
	05/18/90	90096	80564	76744	77772	84844	85971	76446	79264
	06/06/90	91594	86932	80958	81084	85449	85887	75961	79924
AT-8	06/28/90	92570	81973	79575	81049	86834	86053	76353	79813
	07/11/90	87658	80827	78655	80487	86863	86156	76422	79862
	07/21/90	85057	77692	77695	78076	85992	85411	75979	79436
	07/31/90	81390	74929	75853	76433	85264	86281	75744	79525
	08/14/90	74948	70815	73266	74008	84399	84429	76042	79632
	09/29/90	84530	75477	72136	71892	81991	82743	75212	79520
	12/05/90	79576	72611	71880	71686	81911	81236	74270	79437
	06/15/91	90895	85635	80804	82722	89418	91529	79055	
	02/17/90	47816	47396	47013	53303	70314	73031	76465	77971
	04/25/90	80616	57702	46812	54050	70644	72781	76860	78140
	06/06/90	89127	80593	47756	53907	70439	72836	76399	77181
	06/28/90	92678	82933	55162	53800	70560	72801	76715	77963
AT-9	07/11/90	86458	84401	60623	54622	70745	72670	76519	77129
	07/31/90	71898	75026	60647	54165	70546	72598	76165	77983
	08/14/90	54761	60150	57828	54286	70688	72345	76048	77421
	09/29/90	71047	64110	54067	56364	70621	72001	75929	77381
	12/05/90	66696	62467	53547	56563	70522	72135	76078	76366
	06/15/91	85116	88476	76826	81684	84540	82158	82790	83010
	02/17/90	37792	41405	44211	38953	54176	57905	59196	59962
	03/23/90	40161	41192	44227	38548	54063	57669	59049	59796
	04/25/90	41570	40519	43902	38266	54532	57485	59574	60133
	06/06/90	66301	40954	43844	38899	54629	57090	59295	59779
AT-10	06/28/90	68116	43764	43739	38827	54165	57731	59166	59904
	07/11/90	65092	47877	44153	38559	54039	57478	59383	59672
	07/31/90	48168	46723	44167	39029	54253	57676	59465	59722
	08/14/90	38211	43129	44233	38553	53985	57406	59381	59907
	09/29/90	37246	41017	44387	38960	54645	57623	59679	59381
	12/05/90	37000	41116	44032	39045	53758	57501	59325	60084
	06/15/91	51765	61276	50865	38611	54171	57931	59590	59717
	05/18/90	63539	47300	68969	72039	73363	70700	78380	78187
	06/06/90	76341	73332	70497	71944	72489	70752	78781	77794
	07/11/90	79339	77284	89160	81200	75451	70368	78587	78336
AT-11	07/31/90	72677	73469	86965	79611	76075	71042	78569	78398
	08/14/90	34577	69957	84023	78995	75459	70795	78431	78362
	09/29/90	74251	74656	88317	81322	84040	79024	81891	79426
	12/05/90	69763	70058	84104	78792	78893	74851	80082	79302

Equation used to convert neutron probe counts to volumetric moisture content:

$$\text{Till:} \quad \theta = 4.32 \times 10^{-6}(n) - 0.02316$$
$$\text{Non-till:} \quad \theta = 6.54 \times 10^{-6}(n) - 0.11463$$

where n = number of neutron probe counts.

AVERAGE BULK DENSITY Till = 1.41 g/cm^3
Non-till = 1.43 g/cm^3

VOLUMETRIC MOISTURE CONTENT
(X 100 = % Moisture Content)

TUBE NUMBER	DATE	DEPTH (in) 24	36	48	60	72	84	96	108
	02/17/90	0.20	0.18	0.22	0.24	0.22	0.30	0.31	0.32
	03/23/90	0.31	0.29	0.27	0.29	0.24	0.29	0.31	0.32
	04/25/90	0.29	0.28	0.28	0.29	0.24	0.30	0.31	0.32
	06/06/90	0.30	0.30	0.30	0.29	0.23	0.30	0.31	0.32
AT-1	06/28/90	0.32	0.32	0.31	0.30	0.24	0.30	0.31	0.32
	07/11/90	0.30	0.29	0.30	0.30	0.23	0.30	0.31	0.32
	07/31/90	0.28	0.27	0.28	0.29	0.23	0.30	0.31	0.32
	08/14/90	0.26	0.25	0.27	0.27	0.23	0.29	0.30	0.32
	09/29/90	0.29	0.28	0.29	0.31	0.26	0.31	0.32	0.32
	12/05/90	0.27	0.26	0.28	0.29	0.24	0.30	0.31	0.32
	06/15/91	0.32	0.32	0.32	0.33	0.26	0.32	0.32	0.33
	02/17/90	0.16	0.17	0.18	0.19	0.20	0.21	0.23	0.24
	03/23/90	0.16	0.17	0.18	0.19	0.20	0.21	0.23	0.24
	04/25/90	0.16	0.16	0.18	0.19	0.20	0.21	0.23	0.24
	05/17/90	0.16	0.17	0.18	0.19	0.20	0.21	0.23	0.24
	06/06/90	0.22	0.16	0.18	0.19	0.20	0.21	0.23	0.24
AT-2	06/28/90	0.24	0.16	0.18	0.19	0.20	0.21	0.23	0.24
	07/11/90	0.24	0.17	0.18	0.19	0.20	0.21	0.23	0.24
	07/31/90	0.18	0.17	0.18	0.19	0.20	0.21	0.23	0.24
	08/14/90	0.16	0.17	0.18	0.19	0.20	0.21	0.23	0.24
	09/29/90	0.16	0.17	0.18	0.19	0.20	0.21	0.23	0.24
	06/15/91	0.10	0.19	0.17	0.19	0.20	0.21	0.23	0.24
	02/17/90	0.33	0.23	0.24	0.27	0.27	0.28	0.30	
	03/23/90	0.35	0.29	0.28	0.28	0.27	0.28	0.30	
	04/25/90	0.32	0.28	0.28	0.28	0.27	0.29	0.30	
	06/06/90	0.35	0.31	0.30	0.27	0.27	0.29	0.30	
	06/28/90	0.37	0.34	0.30	0.28	0.27	0.29	0.30	
AT-3	07/11/90	0.35	0.30	0.31	0.29	0.27	0.29	0.30	
	07/31/90	0.32	0.29	0.29	0.29	0.27	0.29	0.30	
	08/14/90	0.29	0.27	0.28	0.28	0.27	0.29	0.30	
	09/29/90	0.32	0.29	0.30	0.30	0.29	0.31	0.31	
	12/05/90	0.32	0.28	0.29	0.29	0.28	0.30	0.31	
	06/15/91	0.36	0.32	0.32	0.31	0.29	0.31	0.31	
	02/17/90	0.15	0.16	0.19	0.25	0.26	0.27	0.27	0.28
	03/23/90	0.16	0.16	0.19	0.25	0.26	0.27	0.27	0.28
	04/25/90	0.16	0.16	0.19	0.25	0.26	0.27	0.27	0.28
	05/17/90	0.16	0.16	0.19	0.25	0.26	0.27	0.27	0.28
	06/06/90	0.20	0.16	0.19	0.25	0.26	0.27	0.27	0.28
AT-4	06/28/90	0.20	0.16	0.19	0.25	0.26	0.27	0.28	
	07/11/90	0.20	0.16	0.19	0.25	0.26	0.27	0.27	0.28
	07/21/90	0.18	0.16	0.19	0.25	0.26	0.27	0.27	0.28
	07/31/90	0.16	0.16	0.19	0.25	0.26	0.27	0.27	0.28
	08/14/90	0.15	0.16	0.18	0.25	0.26	0.27	0.27	0.28
	09/29/90	0.16	0.16	0.18	0.25	0.26	0.27	0.27	0.28
	12/05/90	0.16	0.16	0.19	0.25	0.26	0.27	0.27	0.28
	06/15/91	0.21	0.22	0.19	0.24	0.26	0.27	0.27	0.28
	02/17/90	0.38	0.41	0.46	0.51	0.50	0.52	0.44	0.51
	03/23/90	0.44	0.43	0.46	0.52	0.50	0.53	0.46	0.50
	04/25/90	0.42	0.41	0.47	0.52	0.50	0.52	0.44	0.51
AT-5	05/17/90	0.47	0.42	0.46	0.52	0.50	0.52	0.44	0.51
	07/31/90	0.38	0.39	0.49	0.53	0.50	0.53	0.47	0.53

TUBE NUMBER	DATE	DEPTH (in) 24	36	48	60	72	84	96	108
	08/14/90	0.36	0.35	0.37	0.51	0.50	0.53	0.46	0.53
AT-5	09/29/90	0.46	0.50	0.51	0.52	0.50	0.53	0.47	0.52
	12/05/90	0.47	0.49	0.49	0.51	0.50	0.53	0.46	0.51
	02/17/90	0.11	0.18	0.24	0.26	0.28	0.27	0.28	0.26
	03/23/90	0.11	0.17	0.24	0.25	0.29	0.27	0.28	0.25
	04/25/90	0.11	0.18	0.24	0.26	0.28	0.27	0.27	0.26
	06/06/90	0.16	0.18	0.24	0.26	0.29	0.27	0.28	0.25
	06/28/90	0.19	0.18	0.24	0.25	0.29	0.27	0.28	0.26
AT-6	07/11/90	0.20	0.18	0.24	0.25	0.28	0.27	0.28	0.25
	07/21/90	0.16	0.18	0.24	0.25	0.28	0.27	0.28	0.25
	07/31/90	0.13	0.18	0.24	0.26	0.28	0.27	0.27	0.25
	08/14/90	0.12	0.18	0.24	0.25	0.28	0.28	0.27	0.27
	09/29/90	0.12	0.18	0.24	0.25	0.28	0.26	0.27	0.25
	12/05/90	0.12	0.18	0.24	0.25	0.28	0.26	0.27	0.25
	06/15/91	0.15	0.20	0.24	0.25	0.28	0.26	0.26	0.24
	02/17/90	0.18	0.19	0.19	0.21	0.22	0.23	0.24	0.26
	03/23/90	0.18	0.18	0.19	0.21	0.22	0.23	0.24	0.26
	04/25/90	0.18	0.18	0.19	0.21	0.22	0.23	0.24	0.26
	05/18/90	0.19	0.19	0.19	0.21	0.22	0.23	0.24	0.26
	06/06/90	0.26	0.19	0.19	0.21	0.22	0.24	0.24	0.26
AT-7	06/28/90	0.27	0.19	0.19	0.21	0.22	0.24	0.24	0.26
	07/11/90	0.27	0.19	0.19	0.21	0.22	0.23	0.24	0.26
	07/21/90	0.24	0.19	0.19	0.21	0.22	0.23	0.24	0.26
	07/31/90	0.20	0.19	0.19	0.21	0.22	0.24	0.24	0.26
	08/14/90	0.17	0.18	0.19	0.21	0.22	0.23	0.24	0.26
	09/29/90	0.19	0.18	0.19	0.21	0.22	0.23	0.24	0.26
	12/05/90	0.19	0.18	0.19	0.21	0.22	0.24	0.25	0.26
	06/15/91	0.22	0.19	0.19	0.21	0.22	0.23	0.24	0.26
	02/17/90	0.25	0.28	0.30	0.30	0.35	0.35	0.31	0.33
	03/23/90	0.32	0.28	0.29	0.30	0.35	0.35	0.31	0.33
	04/25/90	0.36	0.32	0.31	0.31	0.35	0.35	0.31	0.32
	05/18/90	0.37	0.32	0.31	0.31	0.34	0.35	0.31	0.32
	06/06/90	0.37	0.35	0.33	0.33	0.35	0.35	0.30	0.32
AT-8	06/28/90	0.38	0.33	0.32	0.33	0.35	0.35	0.31	0.32
	07/11/90	0.36	0.33	0.32	0.32	0.35	0.35	0.31	0.32
	07/21/90	0.34	0.31	0.31	0.31	0.35	0.35	0.31	0.32
	07/31/90	0.33	0.30	0.30	0.31	0.35	0.35	0.30	0.32
	08/14/90	0.30	0.28	0.29	0.30	0.34	0.34	0.31	0.32
	09/29/90	0.34	0.30	0.29	0.29	0.33	0.33	0.30	0.32
	12/05/90	0.32	0.29	0.29	0.29	0.33	0.33	0.30	0.32
	06/15/91	0.37	0.35	0.33	0.33	0.36	0.37	0.32	
	02/17/90	0.18	0.18	0.18	0.21	0.28	0.29	0.31	0.31
	04/25/90	0.33	0.23	0.18	0.21	0.28	0.29	0.31	0.31
	06/06/90	0.36	0.33	0.18	0.21	0.28	0.29	0.31	0.31
	06/28/90	0.38	0.34	0.22	0.21	0.28	0.29	0.31	0.31
AT-9	07/11/90	0.35	0.34	0.24	0.21	0.28	0.29	0.31	0.31
	07/31/90	0.29	0.30	0.24	0.21	0.28	0.29	0.31	0.31
	08/14/90	0.21	0.24	0.23	0.21	0.28	0.29	0.31	0.31
	09/29/90	0.28	0.25	0.21	0.22	0.28	0.29	0.30	0.31
	12/05/90	0.26	0.25	0.21	0.22	0.28	0.29	0.31	0.31
	06/15/91	0.34	0.36	0.31	0.33	0.34	0.33	0.33	0.34
	02/17/90	0.14	0.16	0.17	0.15	0.21	0.23	0.23	0.24
	03/23/90	0.15	0.15	0.17	0.14	0.21	0.23	0.23	0.24
	04/25/90	0.16	0.15	0.17	0.14	0.21	0.23	0.23	0.24
	06/06/90	0.26	0.15	0.17	0.14	0.21	0.22	0.23	0.24
AT-10	06/28/90	0.27	0.17	0.17	0.14	0.21	0.23	0.23	0.24
	07/11/90	0.26	0.18	0.17	0.14	0.21	0.23	0.23	0.23
	07/31/90	0.18	0.18	0.17	0.15	0.21	0.23	0.23	0.23
	08/14/90	0.14	0.16	0.17	0.14	0.21	0.22	0.23	0.24
	09/29/90	0.14	0.15	0.17	0.15	0.21	0.23	0.23	0.23
	12/05/90	0.14	0.15	0.17	0.15	0.21	0.23	0.23	0.24
	06/15/91	0.20	0.24	0.20	0.14	0.21	0.23	0.23	0.23

TUBE NUMBER	DATE	DEPTH (in) 24	36	48	60	72	84	96	108
	05/18/90	0.25	0.18	0.27	0.29	0.29	0.28	0.32	0.31
	06/06/90	0.31	0.29	0.28	0.29	0.29	0.28	0.32	0.31
	07/11/90	0.32	0.31	0.36	0.33	0.30	0.28	0.32	0.32
AT-11	07/31/90	0.29	0.29	0.35	0.32	0.31	0.28	0.32	0.32
	08/14/90	0.28	0.28	0.34	0.32	0.30	0.28	0.32	0.32
	09/29/90	0.30	0.30	0.36	0.33	0.34	0.32	0.33	0.32
	12/05/90	0.28	0.28	0.34	0.32	0.32	0.30	0.32	0.32

APPENDIX II

UNSATURATED HYDRAULIC HEAD DATA

UNCORRECTED TENSIOMETER GAUGE READINGS
(centibars)

DATE	Tens. Nest	DEPTH (ft) 2	4	6	8
07/11/90	TNAT-3	18	42	44	53
	TNAT-4	34	64	--	
	TNAT-8	49	52	31	40
	TNAT-7	13	55	53	
07/21/90	TNAT-3	20	46	48	56
	TNAT-4	52	60	48	
	TNAT-8	70	68	50	50
	TNAT-7	42	68	66	
7/31/90	TNAT-3	28	36	42	58
	TNAT-4	54	50	54	
	TNAT-8	58	56	44	50
	TNAT-7	50	64	50	
08/14/90	TNAT-3	52	47	49	58
	TNAT-4	75	66	60	
	TNAT-8	64	58	49	54
	TNAT-7	71	70	62	
09/19/90	TNAT-3	22	23	30	46
	TNAT-4	52	72	58	
	TNAT-8	60	55	63	54
	TNAT-7	--	--	50	

UNSATURATED HYDRAULIC HEAD DATA IN MSL ELEVATIONS

DATE	Tens. Nest	DEPTH (ft) 2	4	6	8
07/11/90	TNAT-3	2137	2129	2128	2125
	TNAT-4	2139	2129	2144	
	TNAT-8	2135	2134	2141	2138
	TNAT-7	2156	2142	2142	
07/21/90	TNAT-3	2136	2128	2127	2124
	TNAT-4	2133	2130	2134	
	TNAT-8	2128	2128	2134	2134
	TNAT-7	2146	2137	2138	
07/31/90	TNAT-3	2134	2131	2129	2124
	TNAT-4	2132	2133	2132	
	TNAT-8	2132	2132	2136	2134
	TNAT-7	2143	2139	2143	
08/13/90	TNAT-3	2126	2127	2127	2124
	TNAT-4	2125	2128	2130	
	TNAT-8	2130	2132	2135	2133
	TNAT-7	2136	2137	2139	
09/29/90	TNAT-3	2136	2135	2133	2128
	TNAT-4	2133	2126	2131	
	TNAT-8	2132	2133	2130	2133

APPENDIX III

WATER LEVEL DATA

WATER LEVEL MEASUREMENTS

Depths from top of casing for wells; from top of post for GP-1 & 2.

DATE	MW-1	MW-2	MW-3	MW-4	MW-5	MW-6	MW-7	MW-8
11/17/88	76.17	101.15	97.79					
12/16/88	76.24	101.18	98.75					
03/16/89	76.49	101.46	99.05					
06/03/89	75.03	101.50	99.07					
08/05/89	76.32	101.07	99.02	81.93	67.33	55.93	52.03	25.15
08/27/89	75.98	100.95	98.90	81.94	Dry	55.98	51.90	27.08
09/08/89	76.40	101.35	98.90	81.95	Dry	55.91	51.93	Dry
11/04/89	76.47	101.35	98.90	81.99	Dry	55.73	52.07	Dry
11/29/89	76.83	101.48	99.30	82.00	Dry	55.94	52.15	Dry
02/17/90	77.14	102.81	99.12	82.11	Dry	56.16	52.37	Dry
03/23/90	77.22	101.87	99.13	82.13	Dry	56.42	52.48	Dry
04/24/90	77.28	101.94	99.08	82.14	Dry	56.27	52.56	Dry
06/07/90	77.38	102.04	99.16	82.19	Dry	56.36	52.77	Dry
07/11/90	77.39	102.08	99.21	82.20	Dry	56.57	52.76	Dry
08/14/90	77.48	102.16	99.28	82.25	Dry	56.84	52.81	Dry
09/29/90	77.51	102.2	99.31	82.26	Dry	56.8	52.8	Dry
12/05/90	77.63	102.31	99.41	82.30	Dry	57.09	53.04	Trace
06/15/91	77.70	102.43	Dry	81.31	Dry	57.42	53.37	Dry

DATE	MW-9	MW-10	MW-11	MW-12	MW-13	GP-1	GP-2
11/17/88							
12/16/88							
03/16/89							
06/03/89							
08/05/89	62.12	98.27	27.07	79.88	115.07		
08/27/89	62.16	*	27.21	79.68	118.67		
09/08/89	62.16	*	27.26	79.62	Dry	2.75	3.00
11/04/89	62.30	*	28.16	79.06	Dry	2.75	2.92
11/29/89	62.36	*	28.64	79.28	Dry	2.50	2.75
02/17/90	62.56	*	Dry	79.70	Dry	2.75	2.75
03/23/90	62.64	*	Dry	79.87	Dry	2.81	3.00
04/24/90	62.72	*	Dry	79.90	Dry	3.00	2.75
06/07/90	62.80	*	Dry	80.04	Dry	2.25	-
07/11/90	62.86	*	Dry	80.06	Dry	-	2.81
08/14/90	62.97	*	Dry	80.21	Dry	3.16	3.00
09/19/90	63.14	*	Dry	80.26	Dry	3.3	2.75
12/05/90	63.42	*	Dry	80.38	Dry	3.30	2.75
06/15/91	63.70	*	Dry	80.52	Dry	3.16	2.75

* Destroyed

WATER LEVELS AS MSL ELEVATIONS

DATE	MW-1	MW-2	MW-3	MW-4	MW-5	MW-6	MW-7	MW-8
11/17/88	2103.65	2103.76	2105.52					
12/16/88	2103.58	2103.73	2104.55					
03/16/89	2103.34	2103.45	2104.25					
06/03/89	2104.80	2103.41	2104.24					
08/05/89	2103.50	2103.84	2104.28	2107.46	2117.78	2098.77	2102.47	2129.18
08/27/89	2103.84	2103.96	2104.40	2107.45	Dry	2098.72	2102.61	2127.25
09/08/89	2103.42	2103.55	2104.40	2107.44	Dry	2098.79	2102.58	Dry
11/04/89	2103.36	2103.55	2104.40	2107.40	Dry	2098.97	2102.43	Dry
11/29/89	2103.00	2103.43	2104.00	2107.39	Dry	2098.76	2102.35	Dry
02/17/90	2102.68	2103.10	2104.18	2107.28	Dry	2098.54	2102.13	Dry
03/23/90	2102.60	2103.04	2104.17	2107.26	Dry	2098.28	2102.02	Dry
04/24/90	2102.54	2102.97	2104.22	2107.25	Dry	2098.43	2101.94	Dry
06/07/90	2102.44	2102.87	2104.14	2107.20	Dry	2098.34	2101.73	Dry
07/11/90	2102.43	2102.83	2104.09	2107.19	Dry	2098.13	2101.74	Dry
08/14/90	2102.34	2102.75	2104.02	2107.14	Dry	2097.86	2101.69	Dry
09/29/90	2102.31	2102.71	2103.99	2107.13	Dry	2097.90	2101.70	Trace
12/05/90	2102.19	2102.60	2103.89	2107.09	Dry	2097.61	2101.46	Trace
06/15/91	2102.12	2102.48	Dry	2108.08	Dry	2097.28	2101.13	Dry

DATE	MW-9	MW-10	MW-11	MW-12	MW-13	GP-1	GP-2
11/17/88							
12/16/88							
03/16/89							
06/03/89							
08/05/89	2099.27	2099.44	2108.36	2102.56	2117.53		
08/27/89	2099.23	*	2108.22	2102.75	2113.93		
09/08/89	2099.23	*	2108.18	2102.82	Dry	2096.82	2093.12
11/04/89	2099.09	*	2107.28	2103.38	Dry	2096.82	2093.20
11/29/89	2099.03	*	2106.80	2103.15	Dry	2097.07	2093.37
02/17/90	2098.83	*	Dry	2102.73	Dry	2096.82	2093.37
03/23/90	2098.75	*	Dry	2102.56	Dry	2096.76	2093.12
04/24/90	2098.67	*	Dry	2102.53	Dry	2096.57	2093.37
06/07/90	2098.59	*	Dry	2102.39	Dry	2097.32	2093.37
07/11/90	2098.53	*	Dry	2102.37	Dry	2096.27	2093.31
08/14/90	2098.42	*	Dry	2102.22	Dry	2096.41	2093.12
09/29/90	2098.25	*	Dry	2102.17	Dry	2096.27	2093.37
12/05/90	2097.97	*	Dry	2102.05	Dry	2096.57	2093.12
06/15/91	2097.69	*	Dry	2101.91	Dry	2096.41	2093.37

* Destroyed

APPENDIX IV

HYDRAULIC CONDUCTIVITY DATA

Ho = starting hydraulic head value
h = hydraulic head value at specific time
H-h = unrecovered hydraulic head

Time (hrs.)	h (ft.)	H-h (ft.)	H-h/H-Ho	Time (hrs.)	h (ft.)	H-h (ft.)	H-h/H-Ho
0.008	70.98	13.90	0.969	0.425	61.13	4.05	0.282
0.017	70.33	13.24	0.924	0.433	61.05	3.96	0.277
0.025	69.91	12.82	0.895	0.442	60.96	3.88	0.270
0.033	69.64	12.56	0.876	0.450	60.86	3.77	0.263
0.042	69.23	12.15	0.847	0.458	60.78	3.70	0.258
0.050	69.06	11.98	0.835	0.467	60.69	3.60	0.251
0.058	68.87	11.79	0.822	0.475	60.60	3.52	0.245
0.075	68.51	11.43	0.797	0.483	60.53	3.45	0.240
0.083	68.19	11.10	0.775	0.492	60.45	3.37	0.235
0.092	67.99	10.90	0.761	0.500	60.38	3.30	0.230
0.100	67.68	10.60	0.739	0.508	60.31	3.23	0.225
0.108	67.40	10.32	0.720	0.517	60.24	3.16	0.220
0.117	67.11	10.03	0.699	0.525	60.17	3.09	0.215
0.125	66.88	9.79	0.683	0.533	60.11	3.02	0.211
0.133	66.62	9.54	0.665	0.542	60.03	2.95	0.205
0.142	66.38	9.29	0.648	0.550	59.97	2.88	0.201
0.150	66.11	9.03	0.630	0.558	59.90	2.81	0.196
0.158	65.95	8.87	0.618	0.567	59.85	2.77	0.193
0.167	65.69	8.60	0.600	0.575	59.79	2.70	0.189
0.175	65.42	8.34	0.581	0.583	59.73	2.64	0.185
0.183	65.25	8.17	0.570	0.592	59.69	2.60	0.182
0.192	65.05	7.96	0.556	0.600	59.64	2.56	0.178
0.200	64.84	7.76	0.541	0.608	59.57	2.48	0.173
0.208	64.63	7.54	0.526	0.617	59.52	2.44	0.170
0.217	64.47	7.38	0.515	0.625	59.47	2.38	0.166
0.225	64.26	7.18	0.501	0.633	59.43	2.34	0.164
0.233	64.15	7.07	0.493	0.642	59.37	2.28	0.159
0.242	63.92	6.84	0.477	0.650	59.31	2.23	0.155
0.250	63.75	6.67	0.465	0.658	59.27	2.19	0.152
0.258	63.59	6.51	0.454	0.667	59.24	2.16	0.150
0.267	63.44	6.35	0.443	0.675	59.19	2.10	0.147
0.275	63.29	6.20	0.433	0.683	59.16	2.07	0.145
0.283	63.15	6.06	0.423	0.692	59.10	2.02	0.141
0.292	63.02	5.94	0.414	0.700	59.06	1.98	0.138
0.300	62.83	5.74	0.401	0.708	59.03	1.95	0.136
0.308	62.73	5.64	0.394	0.717	58.99	1.91	0.133
0.317	62.60	5.52	0.385	0.725	58.95	1.87	0.130
0.325	62.48	5.39	0.376	0.742	58.88	1.80	0.125
0.333	62.31	5.23	0.364	0.758	58.82	1.73	0.121
0.342	62.16	5.07	0.354	0.775	58.74	1.66	0.115
0.350	62.06	4.98	0.347	0.808	58.62	1.53	0.107
0.358	61.95	4.87	0.339	0.858	58.46	1.38	0.096
0.367	61.82	4.74	0.330	0.942	58.24	1.16	0.081
0.375	61.74	4.66	0.325	1.108	57.92	0.84	0.058
0.383	61.62	4.53	0.316	1.275	57.70	0.62	0.043
0.392	61.53	4.45	0.310	1.525	57.50	0.41	0.029
0.400	61.42	4.34	0.302	2.025	57.33	0.24	0.017
0.408	61.33	4.24	0.296	2.525	57.24	0.16	0.011

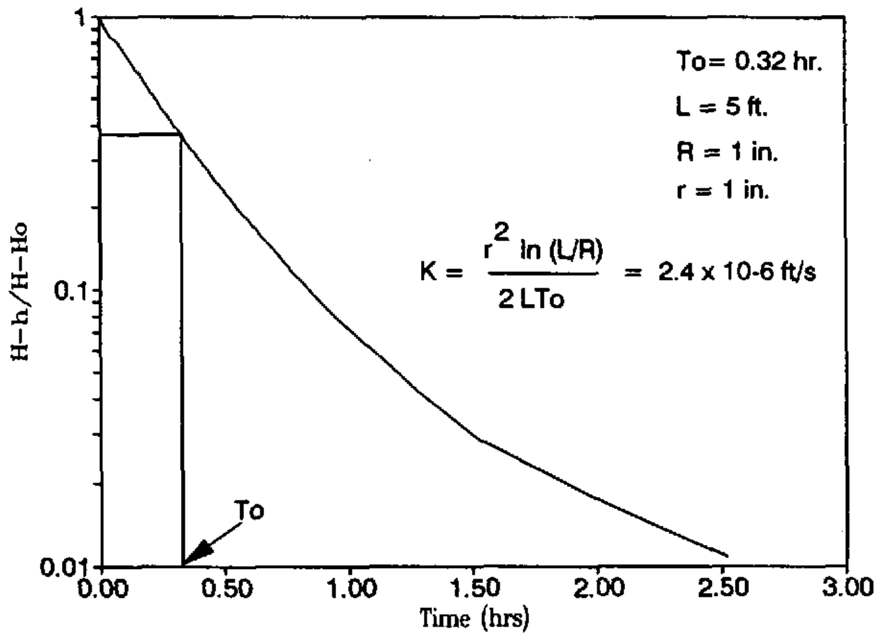


Figure 48. Plot of bail test data for MW-6 (Hvorslev, 1951).

APPENDIX V

WATER COMPOSITION DATA

Analytical techniques used to determine water composition:

Furnace Atomic Absorption (2500°C)	Flame Atomic Absorption	Inductively Coupled Argon Plasma	Ion Chromatography
Arsenic (As)	Chloride (Cl)	Aluminum (Al)	Calcium (Ca)
Silver (Ag)	Fluoride (F)	Barium (Ba)	Iron (Fe)
Cadmium (Cd)	Nitrate (NO_3)	Boron (B)	Magnesium (Mg)
Chromium (Cr)	Sulfate (SO_4)	Manganese (Mn)	Potassium (K)
Lead (Pb)		Molybdenum (Mo)	Sodium (Na)
Selenium (Se)		Silicon (Si)	
		Vanadium (V)	

Mercury (Hg): Cold Vapor Generation
TDS: laboratory method (not calculated)
pH and conductivity: Digital meter

All Measurements are in mg/l unless noted otherwise.

	Field Temp. (°F)	Lab pH	Conductivity (mmhos)	Hardness	Total Alkalinity	TDS	Organic Carbon
MW-1	44.0	6.90	1.83	999	542	1700	88.2
MW-2	45.0	6.80	1.65	961	559	1570	21.6
MW-4	45.0	6.85	1.97	1253	456	2072	33.4
MW-6	44.0	7.51	1.98	732	803	1750	34.4
MW-7	44.0	6.94	2.98	1912	539	3360	30.9
MW-9	46.0	6.69	2.78	2168	497	3320	28.3
MW-11	46.0	*	*	370	*	*	*
MW-12	44.0	7.21	1.58	892	434	1400	33.2
GP-1	34.0	7.95	1.89	1188	291	2000	47.4
GP-2	34.0	6.71	2.28	1555	327	2500	39.4

	Ca	Fe	Mg	Mn	K	Si	Na
MW-1	227	4.1	105	0.48	13	7.8	99
MW-2	215	2.0	103	0.23	11	7.7	105
MW-4	276	5.9	137	0.79	13	9.9	68
MW-6	158	1.5	82	0.4	12	5.0	300
MW-7	426	5.5	206	1.4	16	10	135
MW-9	512	6.2	216	2.9	14	12	60
MW-11	81	0.3	41	0.09	2.6	6.8	22
MW-12	204	1.1	93	1.3	13	9.6	96
GP-1	220	<.2	155	0.023	19	3.3	55
GP-2	362	0.7	158	2.2	12	12	73

* no non-acidified samples
(+) units are micrograms/l

	HCO_3	Cl	F	NO_3	SO_4	Al	As (+)	Ba (+)	B
MW-1	542	2.4	1.0	0.33	859	4.30	8.50	0.05	0.71
MW-2	559	2.5	1.0	1.2	806	4.00	7.00	0.04	0.57
MW-4	456	3.8	1.2	0.25	1066	4.80	26.00	0.13	0.93
MW-6	803	2.4	1.3	0.79	757	2.70	<2	0.04	0.65
MW-7	539	9.5	2.3	0.5	1963	5.90	<2	0.19	0.90
MW-9	497	2.6	2.7	<.2	1919	7.60	17.00	0.06	1.20
MW-11	*	*	*	*	*	2.30	<2	0.30	<0.5
MW-12	434	2.0	1.0	0.6	804	4.20	<2	0.25	0.75
GP-1	291	9.7	1.2	1.7	1098	3.80	<2	0.08	<0.5
GP-2	327	4.6	1.6	0.2	1333	5.30	<2	0.07	0.98

	Cd	Cr	Pb (+)	Hg (+)	Mo	Se (+)	Ag (+)	V
MW-1	<.02	<.02	<10	<3	<.02	<2	<1	0.03
MW-2	<.02	<.02	<10	<3	<.02	<2	<1	0.02
MW-4	<.02	<.02	<10	<3	<.02	<2	<1	0.03
MW-6	<.02	<.02	<10	<3	<.02	<2	<1	0.02
MW-7	<.02	<.02	<10	<3	<.02	<2	<1	0.04
MW-9	<.02	<.02	<10	<3	<.02	<2	<1	0.10
MW-11	<.02	<.02	<10	<3	<.02	<2	<1	0.04
MW-12	<.02	<.02	<10	<3	<.02	<2	<1	0.05
GP-1	<.02	<.02	<10	<3	<.02	<2	<1	0.03
GP-2	<.02	<.02	<10	<3	<.02	<2	<1	0.03

* no non-acidified samples
(+) units are micrograms/l

APPENDIX VI

WELL COMPLETION SUMMARIES

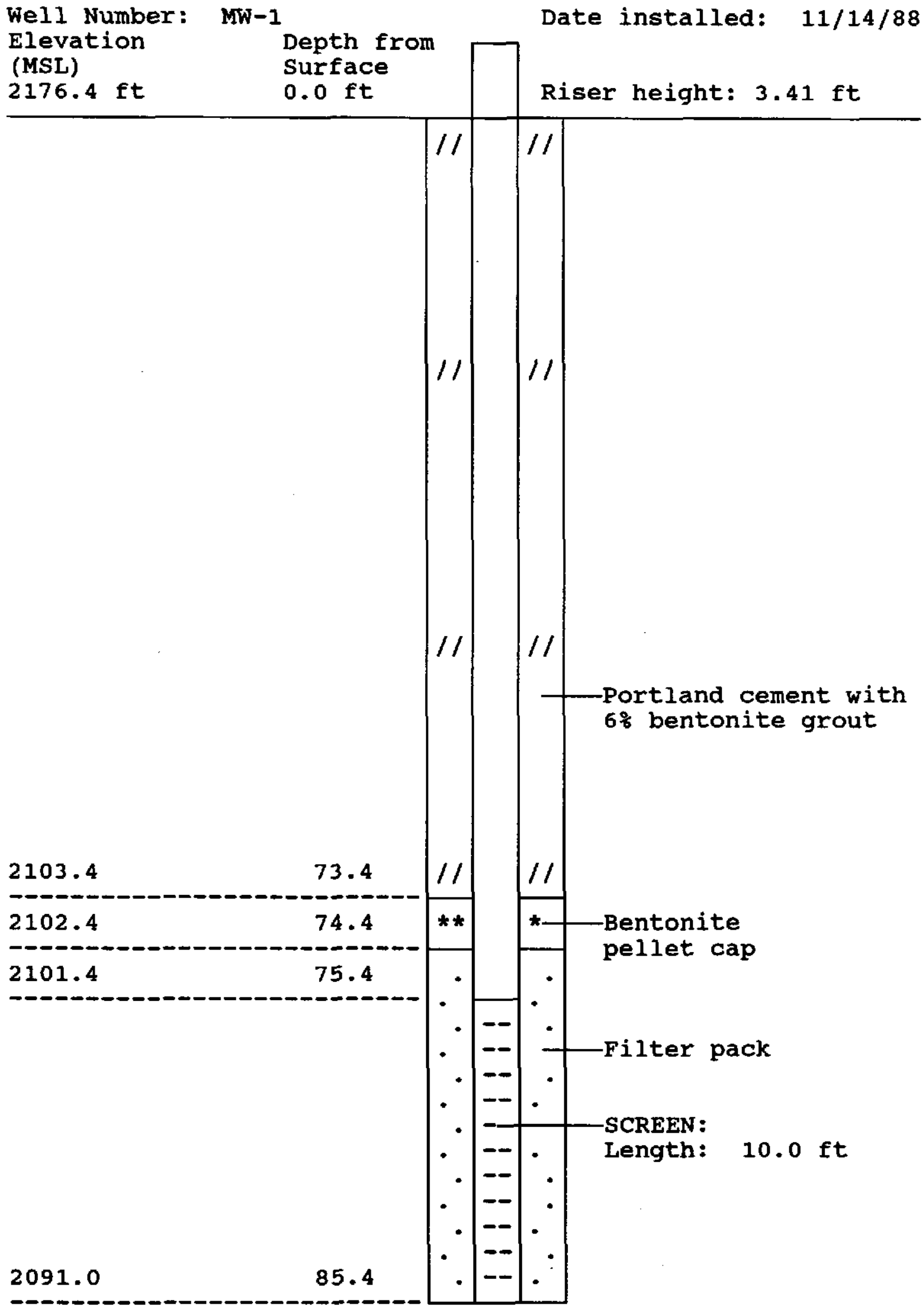
The following drilling information is applicable to all monitoring wells installed at the Wilton site for this study.

DRILLING SUMMARY:

DRILLER:	Mohl Drilling, Beulah North, Dakota
DRILLING METHOD:	air rotary, with mist as needed
DIAMETER OF BOREHOLES:	5 5/8 inches
SAMPLE COLLECTION:	cuttings at 5-foot intervals unless otherwise specified

WELL DESIGN:

CASING:	2", schedule 40, flush-joint, threaded PVC
SCREEN:	2", 0.010 (#10) continuous slot PVC, threaded bottom plug
FILTER PACK:	12/30 commercial grade silica sand
SCREEN SEAL:	commercial bentonite pellets
WELL SEAL:	portland cement with 6% bentonite grout
WELL CAP:	locking well cap (with exception of MW-4, which has PVC cap)

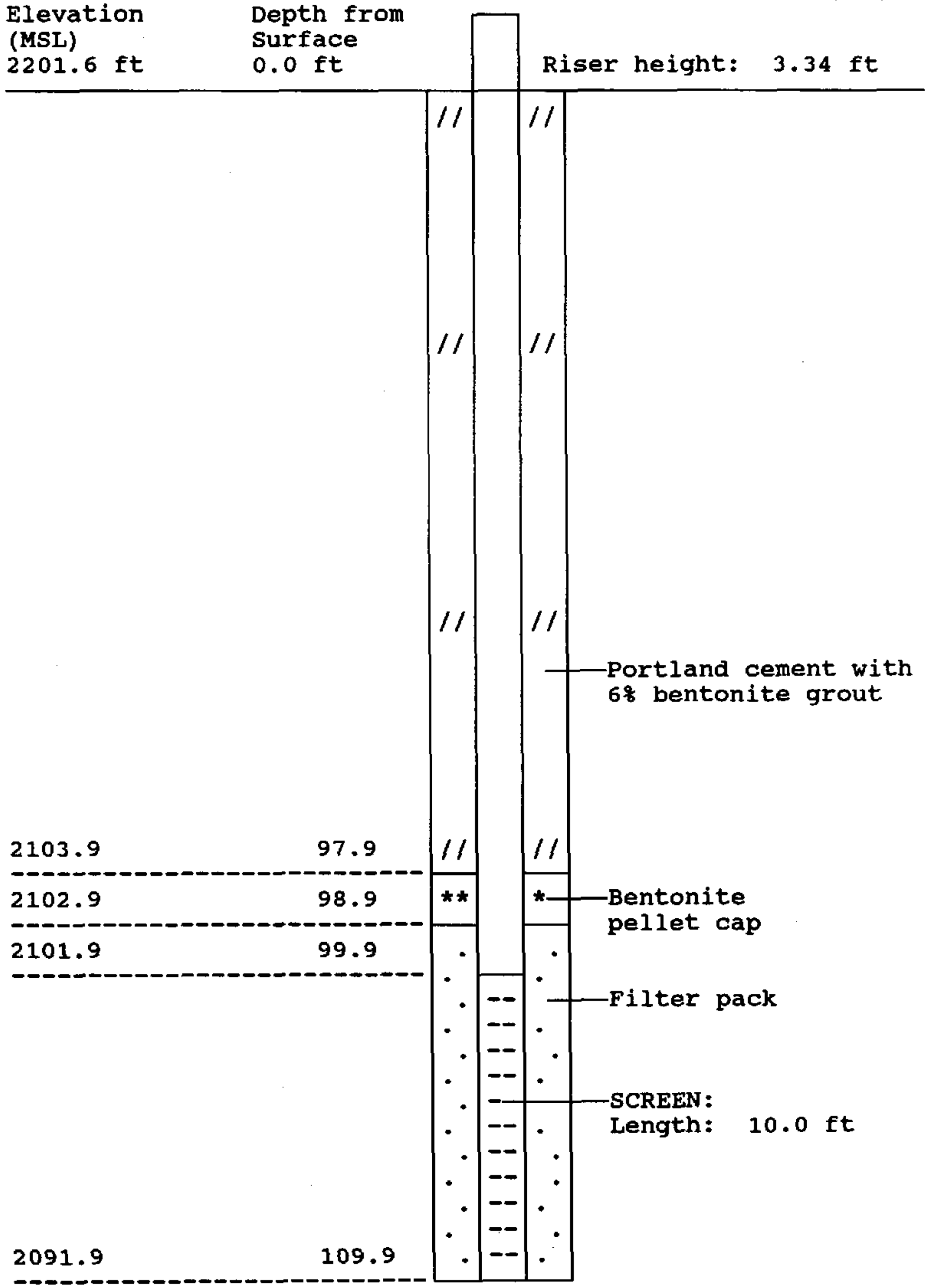

Well Number: MW-1
Date installed: 11/14/88
Elevation (MSL)
Depth from Surface
2176.4 ft
0.0 ft
Riser height: 3.41 ft
Portland cement with 6% bentonite grout
2103.4
73.4
2102.4
74.4
Bentonite pellet cap
2101.4
75.4
Filter pack
SCREEN: Length: 10.0 ft
2091.0
85.4

Well Number: MW-2 Date installed: 11/14/88

Elevation (MSL) 2201.6 ft

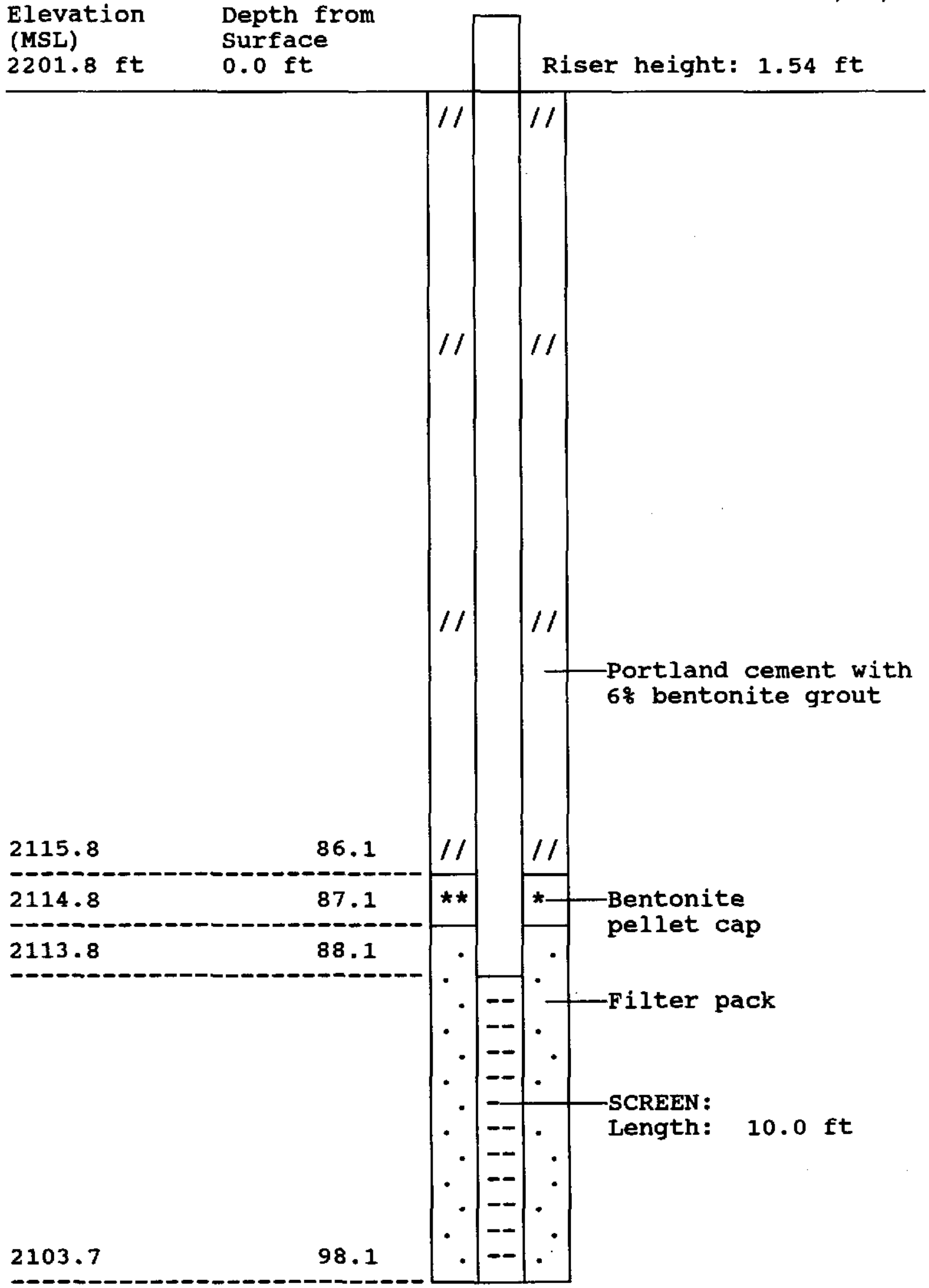
Depth from Surface 0.0 ft

Riser height: 3.34 ft

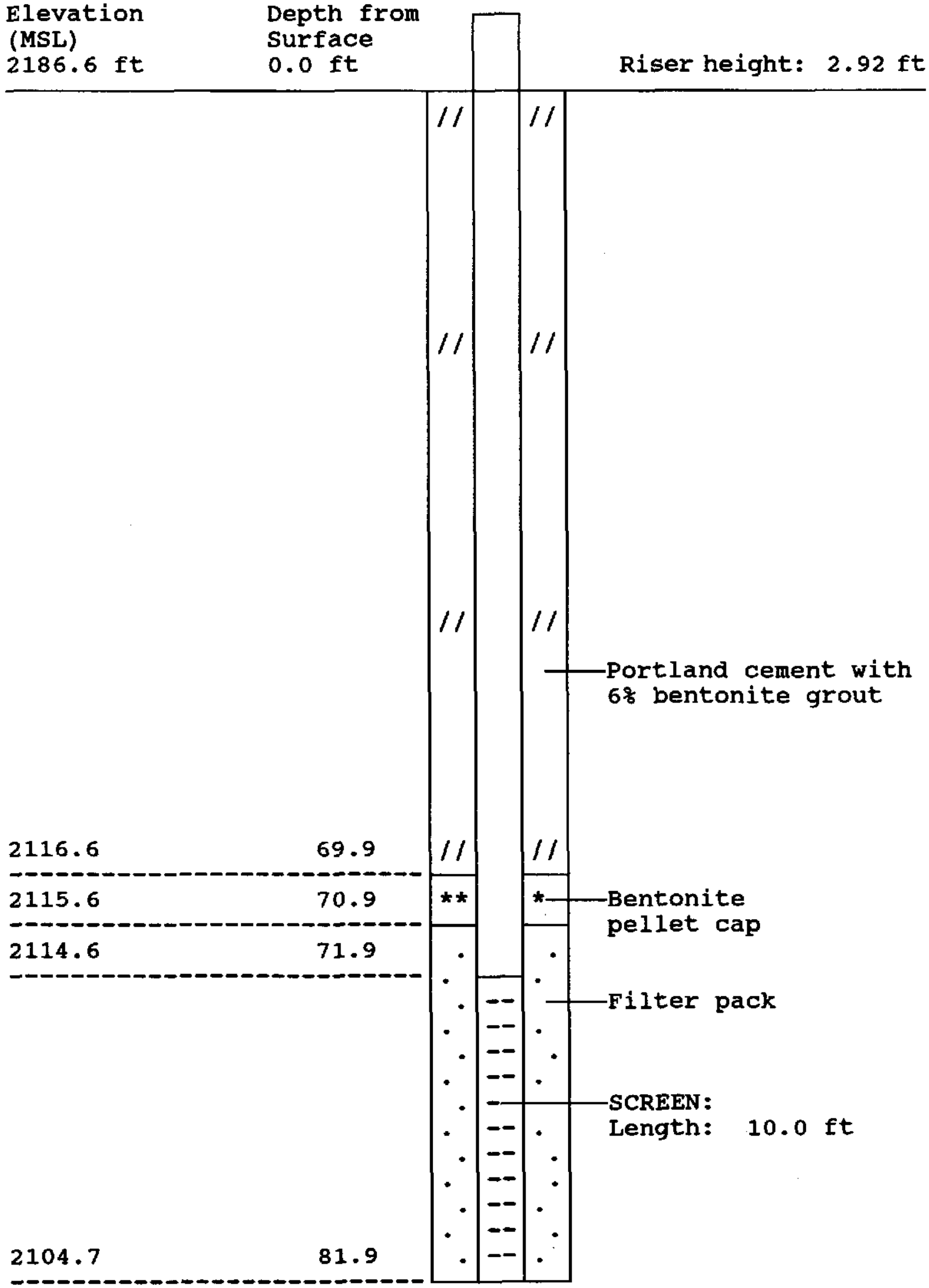


Well Number: MW-3 | Date installed: 11/15/88

Elevation (MSL) 2201.8 ft | Depth from Surface 0.0 ft | Riser height: 1.54 ft



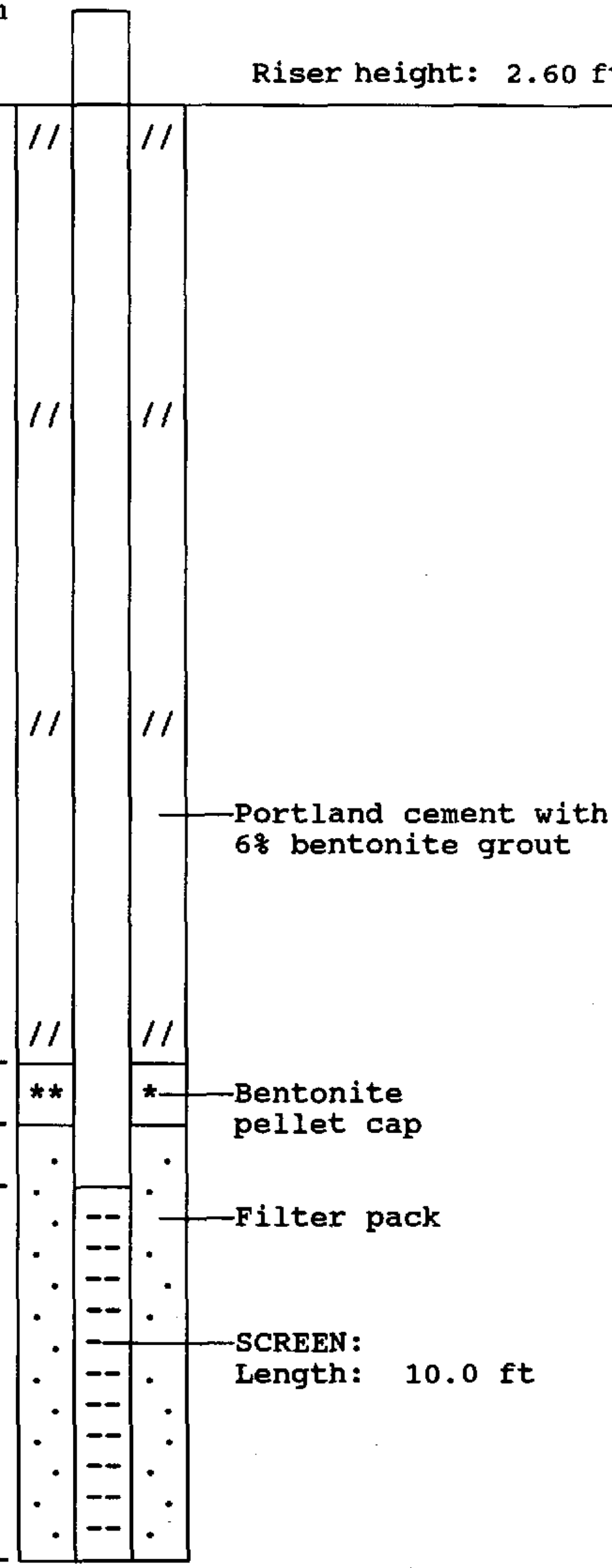
Well Number: MW-4 Date installed: 8/1/89



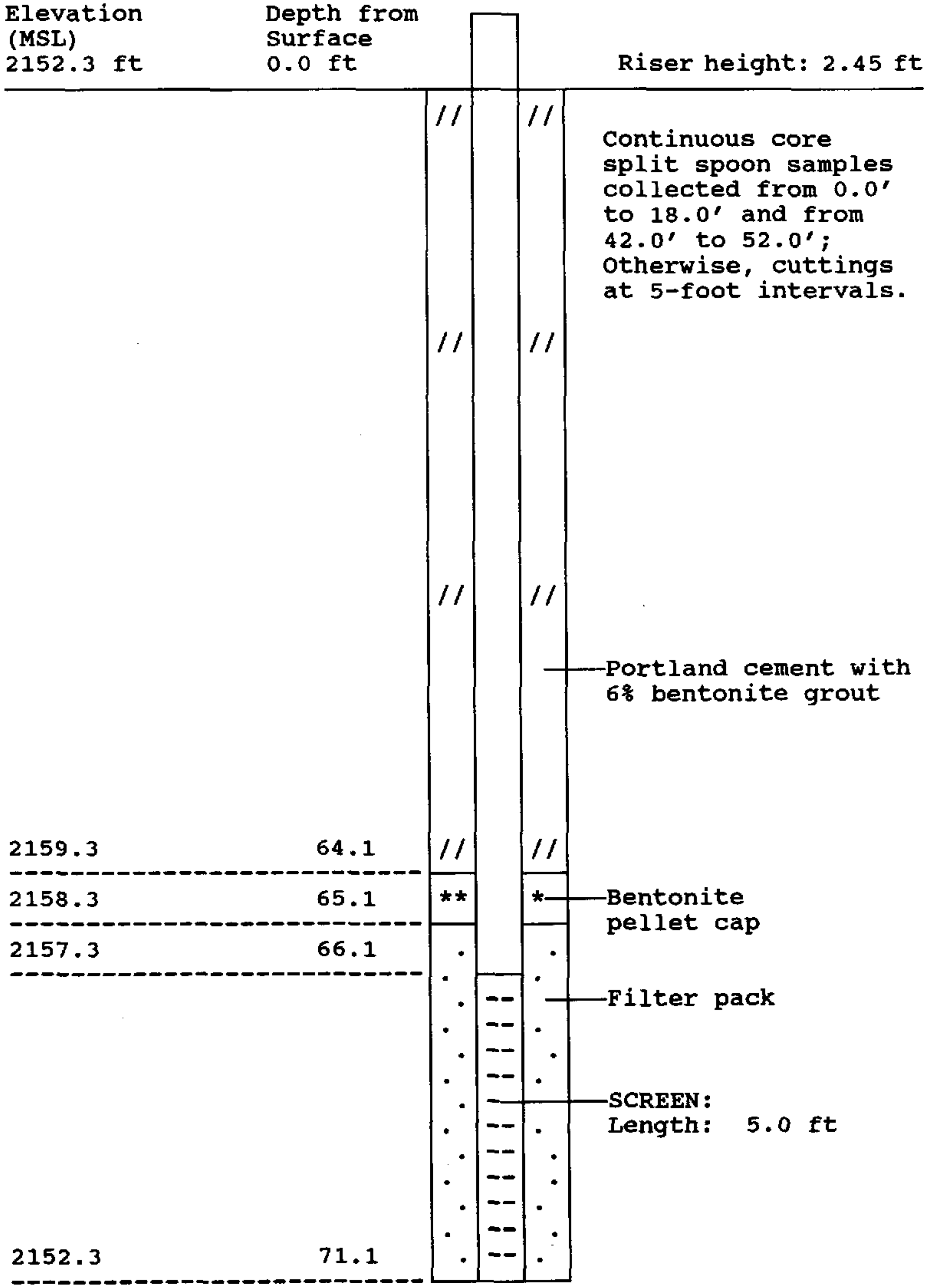
Well Number: MW-5   Date installed: 8/1/89

Riser height: 2.60 ft

Elevation (MSL)	Depth from Surface
2182.5 ft	0.0 ft
2128.0	54.5
2127.0	55.5
2126.0	56.5
2116.0	66.5

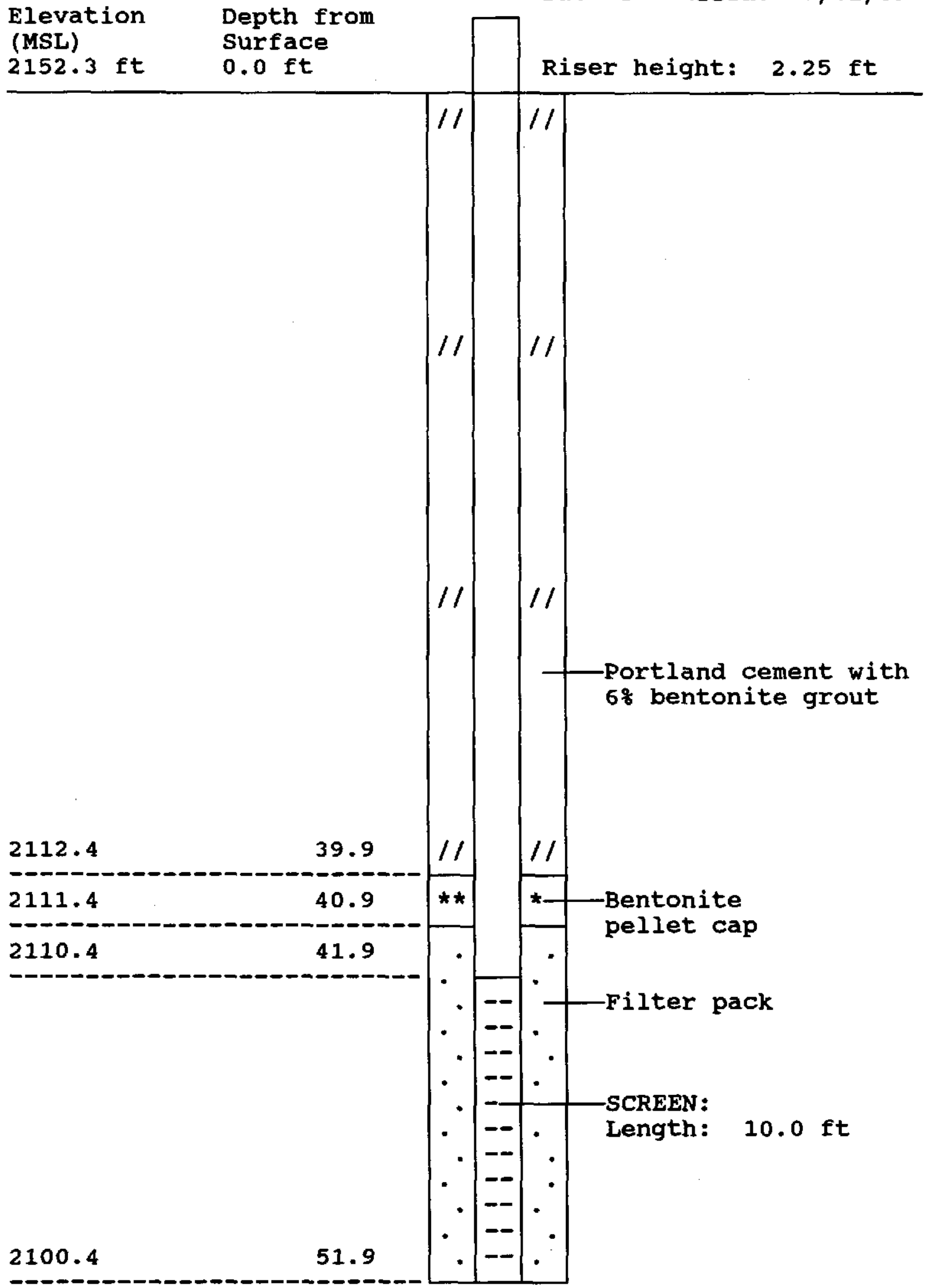


Well Number: MW-6   Date installed: 7/31/89



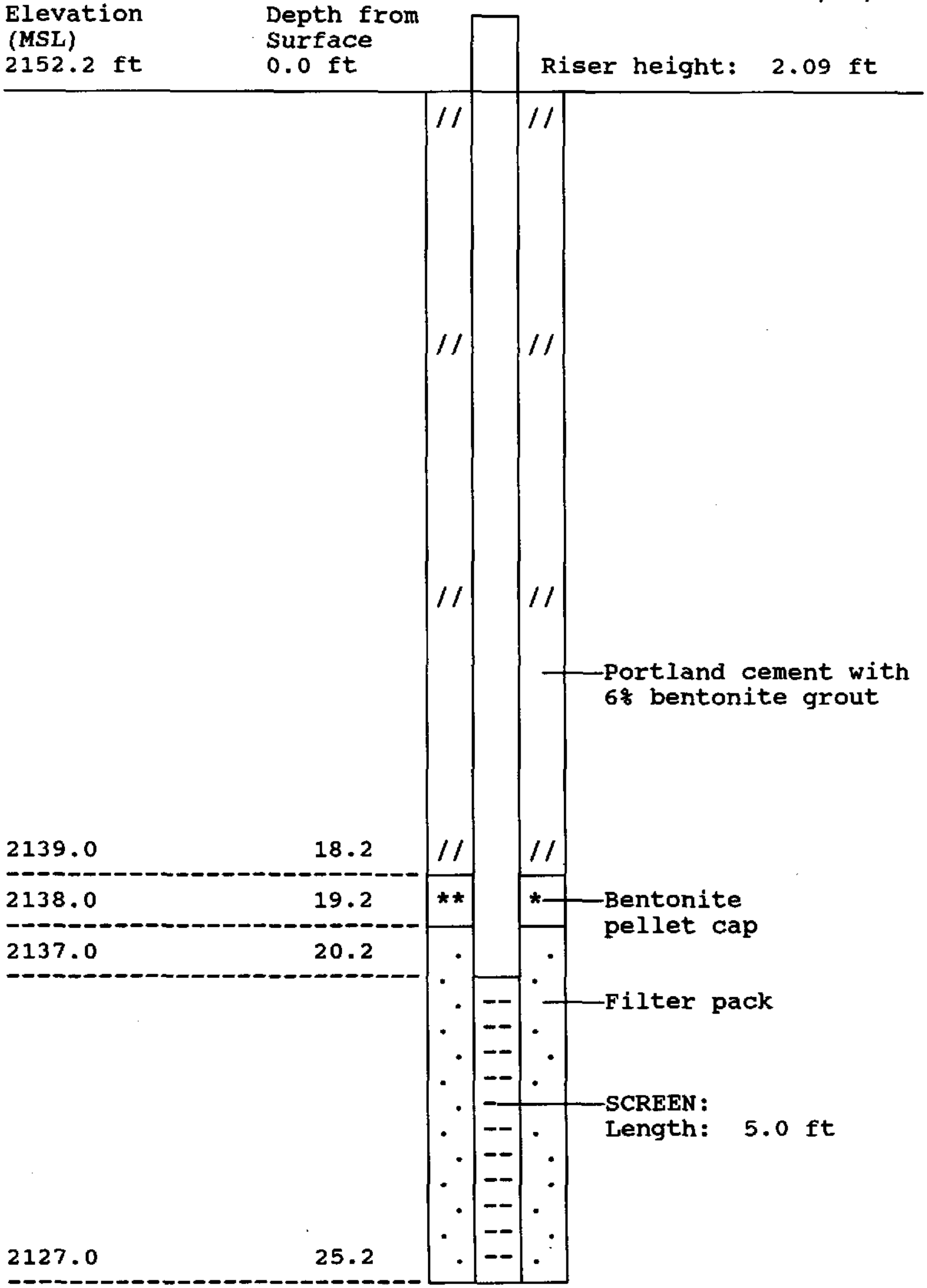
Well Number: MW-7

Date installed: 7/31/89

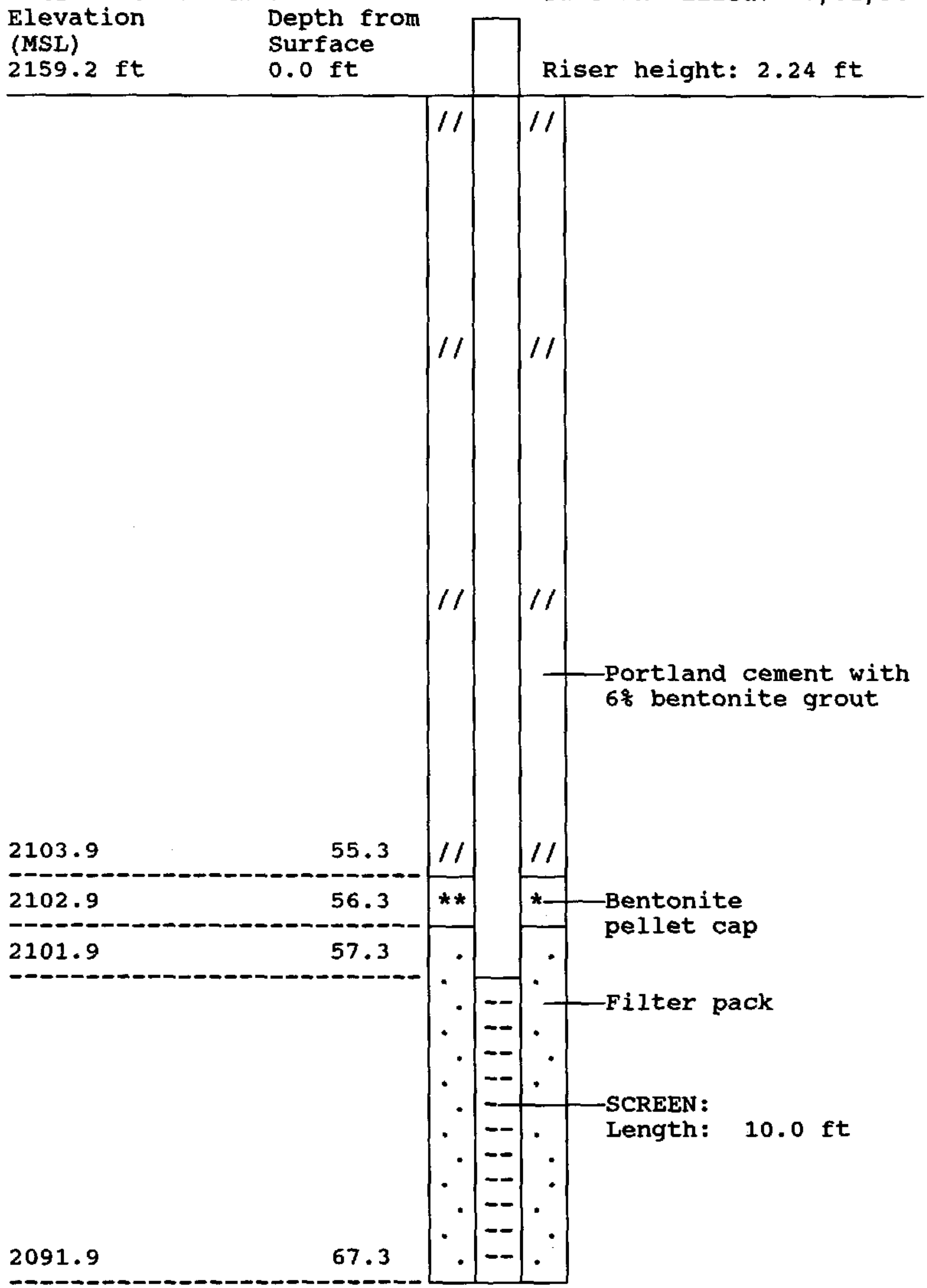


Well Number: MW-8

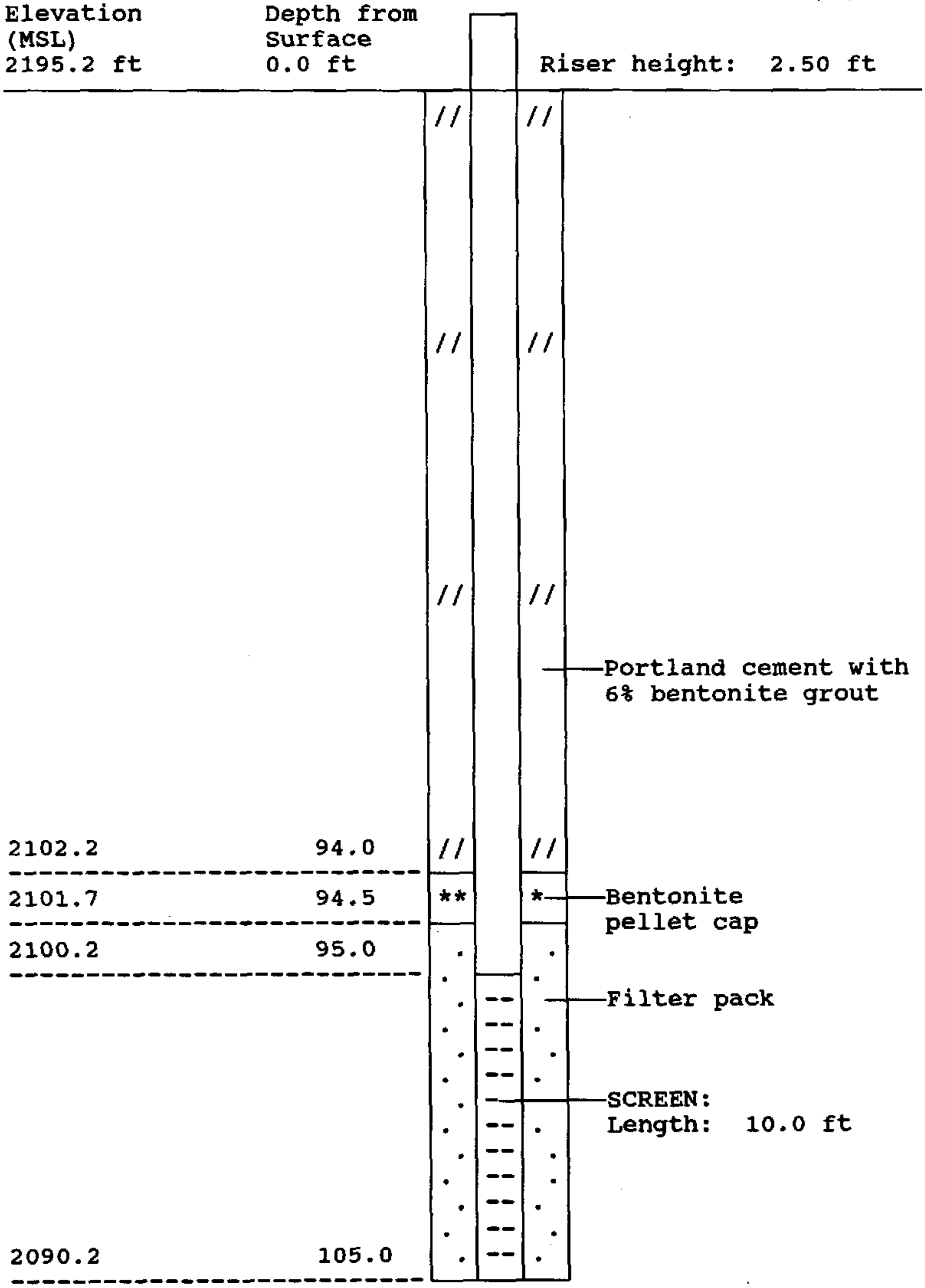
Date installed: 7/31/89



Well Number: MW-9 Date installed: 7/31/90



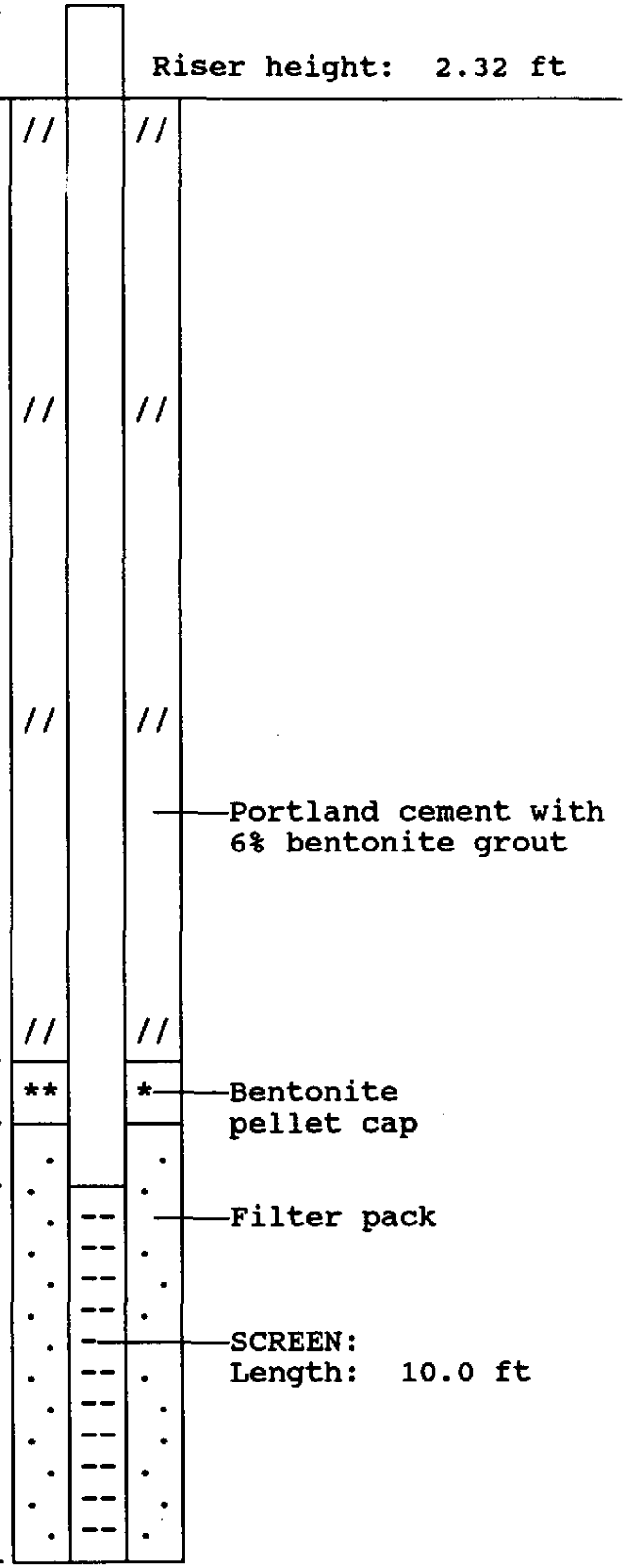
Well Number: MW-10 Date installed: 8/1/89



Well Number: MW-11 Date installed: 8/1/89

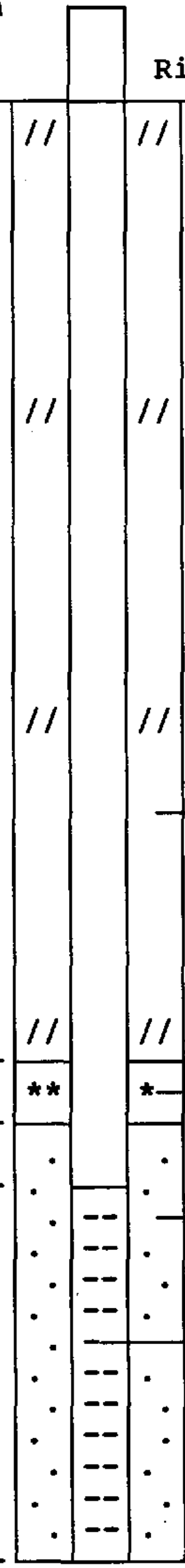
Elevation (MSL)	Depth from Surface
2133.1 ft	0.0 ft
2117.1	15.5
2116.6	16.0
2116.1	16.5
2106.6	26.5

Riser height: 2.32 ft



Well Number: MW-12 Date installed: 7/31/89

Elevation (MSL) 2180.4 ft | Depth from Surface 0.0 ft | Riser height: 2.03 ft



Continuous core split spoon samples from 10.0′ to 12.0′ and from 20.0′ to 22.0′; Otherwise, cuttings at 5-foot intervals.

Portland cement with 6% bentonite grout

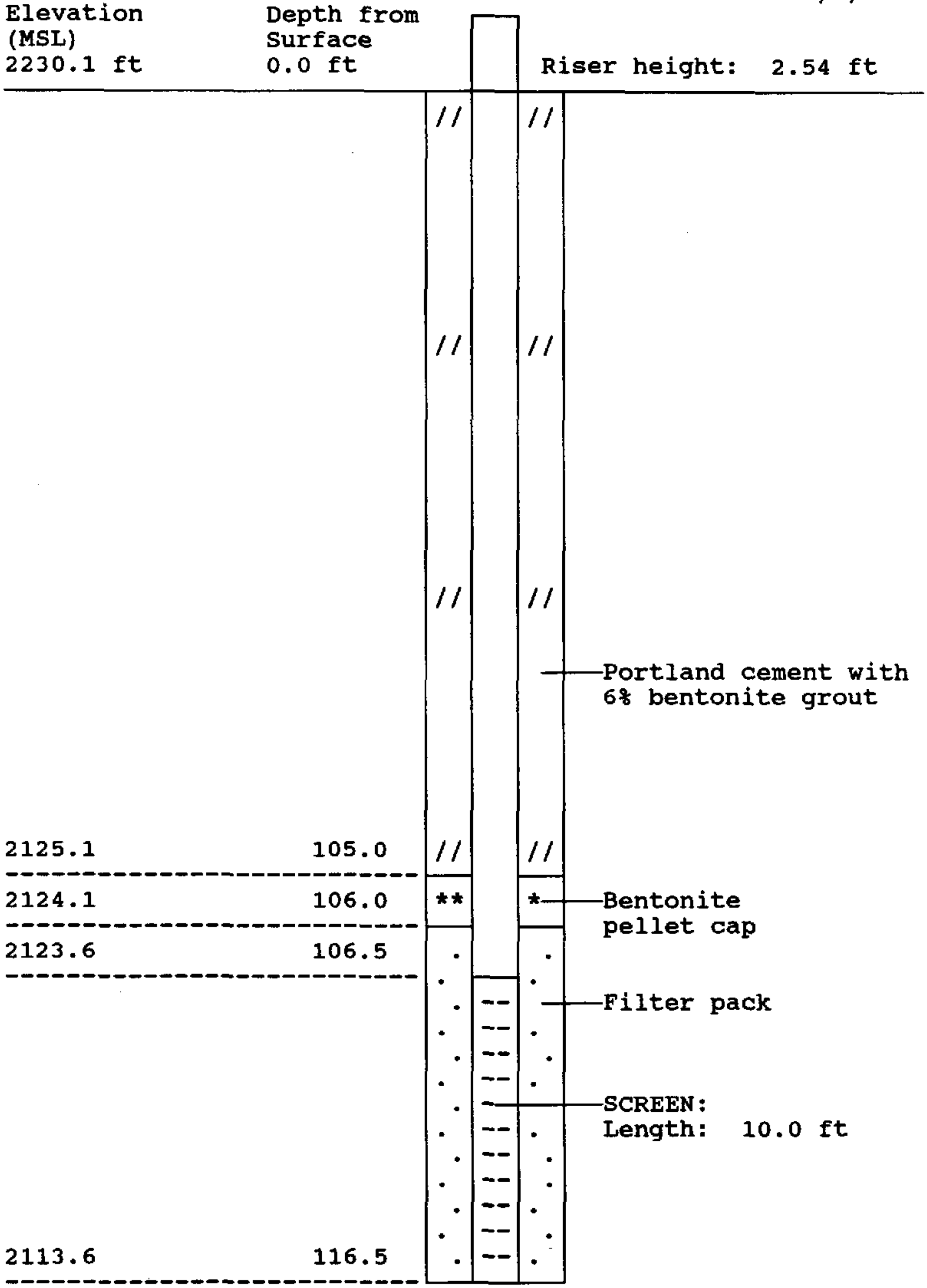
Elevation (MSL)	Depth from Surface
2107.2	72.2
2106.2	73.2
2105.7	74.7
2095.7	84.7

Bentonite pellet cap

Filter pack

SCREEN:
Length: 10.0 ft

Well Number: MW-13 Date installed: 8/1/89



APPENDIX VII

LITHOLOGIC LOGS OF BOREHOLES

All measurements on the lithologic logs are in feet. Included with the logs are the top-of-casing (TOC) elevations.

The abbreviations under the column labeled ASTM are after the American Society for Standards and Testing Standard Test Method for the Classification of Soils for Engineering Purposes (1983). Listed below is an abbreviated legend of terms used in the lithologic log descriptions.

SC: Clayey sands, sand-clay mixtures

ML: Inorganic silts, very fine sands, rock flour, silty or clayey fine sands

CH: Inorganic clays of high plasticity, fat clays

CL: Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays

OL: Organic silts and organic silty clays of low plasticity

Log of Well No.: MW-1 Surface Elev.: 2176.4 TOC Elev.: 2179.8
Logged by: MMS Well Depth: 85.4 Riser ht.: 3.41

MSL Elev.	Depth from surface	AS TM	Description of Material (all measurements in feet)
2176.4	--0	CL	(0-26.0) till; coarse sand, silt, clay, pebbles, gravel, brown, calcareous, some iron staining, calcareous, low plasticity
2171.4	-- 5	CL	same as above
2166.4	--10	CL	same as above
2161.4	--15	CL	same as above
2156.4	--20	CL	same as above
2151.4	--25	CL	
		SC	(26.0-27.0) sand, clayey, silty, medium-grained
			(27.0-29.0) coal
		CL	(29.0-45.0) clay, silty; brown, blocky, medium plasticity
2146.4	--30		
2141.4	--35	CL	same as above
2136.4	--40	CL	same as above
2131.4	--45		(45.0-46.0) coal
		CL	(46.0-74.0) clay, silty; gray, blocky, medium plasticity
2126.4	--50	CL	same as above

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2121.4	--55	CL	same as above
2116.4	--60	CL	same as above
2111.4	--65	CL	same as above
2106.4	--70	CL	same as above
2101.4	--75	CL	(74.0-75.0) coal (75.0-77.0) clay, silty; brown, carbonaceous, low plasticity (77.0-85.0) coal
2196.4	--80		
2191.4	--85	CL	(85.0-85.4) clay
			end of boring
	--90		
	--95		
	--100		
	--105		
	--110		

Log of Well No.: MW-2 Surf. Elev.: 2201.9 TOC Elev.: 2179.4
Logged by: MMS Well Depth: 109.7 Riser ht.: 3.4

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2201.9	--0	CL	(0-10.0) clay, silty; mottled, brown/gray, calcareous, low plasticity
2196.9	-- 5	CL	same as above
2191.9	--10	OL	(10.0-13.0) clay, carbonaceous; brown, low plasticity
		CL	(13.0-29.0) clay, silty; brown, blocky, some iron-staining, medium plasticity
2186.9	--15		
2181.9	--20	CL	same as above
2176.9	--25	CL	same as above
			(29.0-30.0) limestone
2171.9	--30	CL	(30.0-49.0) clay, silty, some sand, gray, blocky
2166.9	--35	CL	same as above
2161.9	--40	CL	same as above
2156.9	--45	CL	same as above
			(49.0-51.0) coal
2151.9	--50		
		CL	(51.0-99.0) clay, silty, some sand; gray, blocky, medium plasticity

MSL Elev.	Depth from surface	AS TM	Description of Material (all measurements in feet)
2146.9	--55	CL	same as above
2141.9	--60	CL	same as above
2136.9	--65	CL	same as above
2131.9	--70	CL	same as above
2126.9	--75	CL	same as above
2121.9	--80	CL	same as above
2116.9	--85	CL	same as above
2111.9	--90	CL	same as above
2106.9	--95	CL	same as above
			(99.0-109.0) coal
2101.9	--100		
2096.9	--105		same
2091.9	--110		end of boring

Log of Well No.: MW-3 Surface Elev.: 2201.8 TOC Elev.: 2203.3
Logged by: MMS Well Depth: 98.1 Riser ht.: 1.5

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2201.8	--0	CL to SC	(0-20.0) till, clay to coarse sand, pebbles to gravel, with some boulders; brown, unbedded; calcareous
2196.8	-- 5		
2191.8	--10	CL to SC	same as above
2186.8	--15		same as above
2181.8	--20		(20.0-21.0) sandstone; brown, medium-grained
	-	CL	(21.0-33.0) clay, silty; gray, blocky, medium plasticity
2176.8	--25	CL	same as above
2171.8	--30	CL	same as above
	-	OL	(33.0-37.0) carbonaceous clay and lignite
2166.8	--35		
	-	CL	(37.0-86.0) clay, silty, some sand; gray, blocky, medium plasticity
2161.8	--40		
2156.8	--45	CL	same as above
2151.8	--50	CL	same as above

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2146.8	--55	CL	same as above
2141.8	--60	CL	same as above
2136.8	--65	CL	same as above
2131.8	--70	CL	same as above
2126.8	--75	CL	same as above
2121.8	--80	CL	same as above
2116.8	--85	CL	(86.0-97.0) coal
2111.8	--90		same as above
2106.8	--95	CL	(97.0-98.1) clay; gray, thick, medium --plasticity------------------------------------ end of boring
2101.8	--100		
	--105		
	--110		

Log of Well No.: MW-4 Surface Elev.: 2186.6 TOC Elev.: 2189.4
Logged by: MMS Well Depth: 81.9 Riser ht.: 2.85

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2186.8	--0	CL to SC	(0-35.0) till, clay to coarse sand, with some pebbles through gravel; brown, calcareous, iron-stained, low plasticity
2181.8	-- 5		
2176.8	--10	CL to SC	same as above
2171.8	--15		same as above
2166.8	--20	CL to SC	same as above
2161.8	--25		same as above
2156.8	--30	CL to SC	same as above
2151.8	--35	CL	(35.0-42.0) clay, silty; dark brown, blocky, iron-stained, medium plasticity
2146.8	--40	CL	
	-	CL	(42.0-45.0) clay, silty; gray, blocky, medium plasticity
2141.8	--45	OL	(45.0-46.0) carbonaceous clay-lignite stringer
	-	CL	(46.0-73.0) clay, silty, some sand; gray, medium plasticity
2136.8	--50	CL	

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2131.8	--55	CL	same as above
2126.8	--60	CL	same as above
2121.8	--65	CL	same as above
2116.8	--70	CL	
	-	OL	(73.0-81.0) coal
2111.8	--75		
2106.8	--80		
	-	CL	(81.0-81.9) clay; gray
	-		end of boring
	--85		
	--90		
	--95		
	--100		
	--105		
	--110		

Log of Well No.: MW-5 Surface Elev.: 2182.5 TOC Elev.: 2185.1
Logged by: MMS Well Depth: 66.5 Riser ht.: 2.60

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2182.5	--0	CL to SC	(0-6.0) till; clay to coarse sand; pebbles, brown, iron-stained, calcareous, low plasticity
2177.5	-- 5		
		CL	(6.0-9.0) clay; dark brown, iron-stained, calcareous, medium plasticity
		SC	(9.0-18.0) sand, clayey; light brown, medium-grained, calcareous
2172.5	--10		
2167.5	--15	SC	same as above
			(18.0-19.0) limestone
2162.5	--20	SC	(19.0-26.0) sand, clayey; light brown, medium-grained
2157.5	--25		
		CL	(26.0-30.0) clay; brown, blocky, iron-stained, calcareous, medium plasticity
2152.5	--30		(30.0-30.5) coal stringer
		CL	(30.5-35.0) clay; gray, medium plasticity
2147.5	--35	OL	(35.0-36.0) carbonaceous clay and lignite
		CL	(36.0-48.0) clay, silty; gray, medium plasticity
2142.5	--40		
2137.5	--45	CL	same as above
		OL	(48.0-56.0) clay; brown to carbonaceous
2132.5	--50		

MSL Elev.	Depth from surface	AS TM	Description of Material (all measurements in feet)
2127.5	--55		
	-		(56.0-65.5) coal
	-		
	-		
	-		
2122.5	--60		same as above
	-		
	-		
	-		
	-		
2117.5	--65		
	-	CL	(66.0-66.5) clay
	-		--
	-		end of boring
	-		
	--70		
	-		
	-		
	-		
	-		
	--75		
	-		
	-		
	-		
	-		
	--80		
	-		
	-		
	-		
	-		
	--85		
	-		
	-		
	-		
	-		
	--90		
	-		
	-		
	-		
	-		
	--95		
	-		
	-		
	-		
	-		
	--100		
	-		
	-		
	-		
	-		
	--105		
	-		
	-		
	-		
	-		
	--110		

Log of Well No.: MW-6 Surface Elev.: 2152.2 TOC Elev.: 2154.7
Logged by: MMS Well Depth: 71.1 Riser ht.: 2.45

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2152.2	--0	CL	(0-6.0) till, clay to coarse sand; pebbles,
	-	to	light brown, calcareous, iron-stained
	-	SC	
	-		
	-		
2147.2	-- 5		
	-	CL	(6.0-7.5) clay; mottled brown and gray,
	-		extensive iron-staining, manganese oxide,
	-		medium plasticity
	-	OL	(7.5-11.5) carbonaceous clay interbedded with
2142.2	--10		brown clay, iron-stained
	-	CL	(11.5-13.5) clay, silty; brown, iron-stained,
	-		medium plasticity
	-	OL	(13.5-14.5) carbonaceous clay
	-		
2137.2	--15	CL	(14.5-23.5) clay; brown, blocky, iron-stained
	-		medium plasticity
	-		
	-		
	-		
2132.2	--20		
	-		
	-		
	-	CL	(23.5-28.5) clay,silty; brown with interbedded
	-	to	carbonaceous clay
2127.2	--25	OL	
	-		
	-		
	-	CL	(28.5-35.0) clay, silty; gray, blocky, medium
	-		plasticity
2122.2	--30		
	-		
	-		
	-		
	-		
2117.2	--35	OL	(35.0-42.0) carbonaceous clay, low plasticity
	-		
	-		
	-		
	-		
2112.2	--40	OL	same as above
	-		
	-		(42.0-52.0) coal
	-		
	-		
2107.2	--45		
	-		
	-		
	-		
	-		
2102.2	--50		same as above
	-		
	-	CL	(52.0-59.0) clay, silty; gray, thick, medium
	-		plasticity
	-		

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2097.2	--55	CL	same as above
	-		
	-		
	-		
	-	CL to CH	(59.0-64.0) clay; gray, thick, medium to high plasticity
2092.2	--60		
	-		
	-		
	-		
	-	CL	(64.0-69.0) clay, silty; gray, medium plasticity
2087.2	--65		
	-		
	-		
	-		
	-	CL	(69.0-71.1) clay, sandy; gray, low to medium plasticity
2082.2	--70		
	-		end of boring
	-		
	-		
	-		
	--75		
	-		
	-		
	-		
	-		
	--80		
	-		
	-		
	-		
	-		
	--85		
	-		
	-		
	-		
	-		
	--90		
	-		
	-		
	-		
	-		
	--95		
	-		
	-		
	-		
	-		
	--100		
	-		
	-		
	-		
	-		
	--105		
	-		
	-		
	-		
	-		
	--110		

Log of Well No.: MW-7 Surface Elev.: 2152.2 TOC Elev.: 2154.5
Logged by: MMS Well Depth: 51.9 Riser ht.: 2.25

MSL Elev.	Depth from surface	AS TM	Description of Material (all measurements in feet)
2152.2	--0	CL	(0-6.0) till, clay to coarse sand; pebbles,
	-	to	light brown, calcareous, iron-stained
	-	SC	
	-		
	-		
2147.2	-- 5		
	-	CL	(6.0-7.5) clay; mottled brown and gray,
	-		extensive iron-staining, manganese oxide,
	-		medium plasticity
	-	OL	(7.5-11.5) carbonaceous clay interbedded with
2142.2	--10		brown clay, iron-stained
	-	CL	(11.5-13.5) clay, silty; brown, iron-stained,
	-		medium plasticity
	-	OL	(13.5-14.5) carbonaceous clay
	-		
2137.2	--15	CL	(14.5-23.5) clay; brown, blocky, iron-stained
	-		medium plasticity
	-		
	-		
	-		
2132.2	--20		
	-		
	-		
	-	CL	(23.5-28.5) clay,silty; brown with interbedded
	-	to	carbonaceous clay
2127.2	--25	OL	
	-		
	-		
	-	CL	(28.5-35.0) clay, silty; gray, blocky, medium
	-		plasticity
2122.2	--30		
	-		
	-		
	-		
	-		
2117.2	--35	OL	(35.0-42.0) carbonaceous clay, low plasticity
	-		
	-		
	-		
	-		
2112.2	--40	OL	same as above
	-		
	-		(42.9-51.9) coal
	-		
	-		
2107.2	--45		
	-		
	-		
	-		
	-		
2102.2	--50		same as above
	-		
	-	CL	--
	-		end of boring
	-		

Log of Well No.: MW-8 Surface Elev.: 2152.2 TOC Elev.: 2154.3
Logged by: MMS Well Depth: 25.1 Riser ht.: 2.09

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2152.2	--0	CL to SC	(0-6.0) till, clay to coarse sand; pebbles, light brown, calcareous, iron-stained
2147.2	-- 5		
	-	CL	(6.0-7.5) clay; mottled brown and gray, extensive iron-staining, manganese oxide, medium plasticity
	-	OL	(7.5-11.5) carbonaceous clay interbedded with brown clay, iron-stained
2142.2	--10		
	-	CL	(11.5-13.5) clay, silty; brown, iron-stained, medium plasticity
	-	OL	(13.5-14.5) carbonaceous clay
2137.2	--15	CL	(14.5-23.5) clay; brown, blocky, iron-stained medium plasticity
2132.2	--20		
	-	CL to OL	(23.5-25.1) clay,silty; brown with interbedded carbonaceous clay
2127.2	--25		--
2122.2	--30		
	--35		
	--40		
	--45		
	--50		

Log of Well No.: MW-9 Surface Elev.: 2159.2 TOC Elev.: 2161.4
Logged by: MMS Well Depth: 67.3 Riser ht.: 2.24

MSL Elev.	Depth from surface	AS TM	Description of Material (all measurements in feet)
2161.4	--0	CL to SC	(0-15.5) till;clay to coarse sand, pebbles, iron-stained, calcareous
2156.4	-- 5		same as above
2151.4	--10	CL to SC	same as above
2146.4	--15		
	-	SC	(15.5-21.0) sand, clayey, silty; brown
2141.4	--20		
	-	CL	(21.0-24.0) clay, sandy; brown, low plasticity
	-	CL	(24.0-31.0) clay; mottled brown and gray, iron-stained, low to medium plasticity
2136.4	--25		
2131.4	--30		
	-	CL	(31.0-52.0) clay, silty; gray, medium plasticity
2126.4	--35	CL	same as above
2121.4	--40	CL	same as above
2116.4	--45	CL	same as above
2111.4	--50	CL	same as above
	-	OL	(52.0-56.0) carbonaceous clay

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2106.4	--55		
	-		(56.0-66.0) coal
	-		
	-		
	-		
2101.4	--60		same as above
	-		
	-		
	-		
	-		
2096.4	--65		
	-	CL	(66.0-67.3) clay; gray, medium plasticity
	-		
	-		end of boring
	-		
	--70		
	-		
	-		
	-		
	-		
	--75		
	-		
	-		
	-		
	-		
	--80		
	-		
	-		
	-		
	-		
	--85		
	-		
	-		
	-		
	-		
	--90		
	-		
	-		
	-		
	-		
	--95		
	-		
	-		
	-		
	-		
	--100		
	-		
	-		
	-		
	-		
	--105		
	-		
	-		
	-		
	-		
	--110		

Log of Well No.: MW-10 Surface Elev.: 2195.7 TOC Elev.: 2197.7
Logged by: MMS Well Depth: 105.0 Riser ht.: 2.03

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2195.7	--0	SC	(0-5.0) sand, clayey, silty; brown fine to
	-		medium grained
	-		
	-		
	-		
2190.7	-- 5		(5.0-8.0) sandstone; fine-grained
	-		
	-		
	-	SC	(8.0-22.0) sand, silty, clayey; brown, fine-
	-		grained
2185.7	--10		
	-		
	-		
	-		
	-		
2180.7	--15	SC	same as above
	-		
	-		
	-		
	-		
2175.7	--20		
	-		
	-	CL	(22.0-24.0) clay, silty; brown, low to medium
	-		plasticity
	-		(24.0-25.0) limestone
2170.7	--25	CL	(25.0-26.5) clay; gray, medium plasticity
	-		
	-	CL	(26.5-36.0) clay, silty; brown, medium plas-
	-		ticity
	-		
2165.7	--30		
	-		
	-		
	-		
	-		
2160.7	--35		
	-	CL	(36.0-37.0) clay; gray, medium plasticity
	-		(37.0-38.0) coal
	-	OL	(38.0-41.0) carbonaceous clay
	-		
2155.7	--40		
	-	CL	(41.0-46.0) clay; gray, medium plasticity
	-		
	-		
	-		
2150.7	--45		
	-	CL	(46.0-52.0) clay, sandy; gray, medium plas-
	-		ticity
	-		
	-		
2145.7	--50		
	-		
	-	CL	(52.0-55.0) clay; gray, medium plasticity
	-		
	-		

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2140.7	--55		(55.0-55.5) coal
	-	CL	(55.5-85.0) clay; gray, medium plasticity
	-		
	-		
	-		
2135.7	--60	CL	same as above
	-		
	-		
	-		
	-		
2130.7	--65	CL	same as above
	-		
	-		
	-		
	-		
2125.7	--70	CL	same as above
	-		
	-		
	-		
	-		
2120.7	--75	CL	same as above
	-		
	-		
	-		
	-		
2115.7	--80	CL	same as above
	-		
	-		
	-		
	-		
2110.7	--85	OL	(85.0-94.0) carbonaceous clay
	-		
	-		
	-		
	-		
2105.7	--90	OL	same as above
	-		
	-		
	-		
	-		(94.0-104.5) coal
2100.7	--95		
	-		
	-		
	-		
	-		
2095.7	--100		same as above
	-		
	-		
	-		
	-		(104.5-105.0) clay; gray
2090.7	--105		--
	-		end of boring
	-		
	-		
	-		
	--110		

Log of Well No.: MW-11 Surface Elev.:2133.0 TOC Elev.: 2135.4
Logged by: MMS Well Depth: 27.2 Riser ht.: 2.32

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2133.0	--0	CL	(0-5.0) clay, sandy; brown, low plasticity
2128.0	-- 5	CL	(5.0-11.0) clay, silty; brown, medium plasticity
2123.0	--10		
		CL	(11.0-17.0) clay, sandy; brown, low plasticity
2118.0	--15	CL	same as above
			(17.0-27.0) coal
2113.0	--20		same as above
2108.0	--25		same as above
		CL	(27.0-27.5) clay; gray
			end of boring
2103.0	--30		
	--35		
	--40		
	--45		
	--50		

Log of Well No.: MW-12 | Surface Elev.: 2180.4 | TOC Elev.: 2182.4
Logged by: MMS | Well Depth: 84.6 | Riser ht.: 2.03

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2180.4	--0	CL	(0-12.0) clay; brown, iron-stained, calcareous,
2175.4	-- 5	CL	same as above
2170.4	--10	CL	same as above
			(12.0-13.0) limestone
		CL	(13.0-15.0) clay; brown, calcareous, medium plasticity
2165.4	--15		(15.0-15.5) coal
		CL	(15.5-28.0) clay, silty; brown, iron-stained, calcareous, medium plasticity
2160.4	--20	CL	same as above
2155.4	--25		same as above
		CL	(28.0-29.0) clay; gray, medium plasticity
			(29.0-32.0) coal
2150.4	--30		
		CL	(32.0-49.0) clay; gray, medium plasticity
2145.4	--35		
2140.4	--40	CL	same as above
2135.4	--45	CL	same as above
			(49.0-50.0) coal
2130.4	--50	CL	(50.0-68.0) clay; gray, blocky, medium plasticity

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2125.4	--55	CL	same as above
2120.4	--60	CL	same as above
2115.4	--65	CL	same as above
	-	OL	(68.0-73.0) carbonaceous clay
2110.4	--70		
	-		(73.0-84.0) coal
2105.4	--75		
2100.4	--80		same as above
	-	CL	(84.0-84.6) clay; gray
2095.4	--85		end of boring
	--90		
	--95		
	--100		
	--105		
	--110		

Log of Well No.: MW-13 Surface Elev.: 2230.1 TOC Elev.: 2232.6
Logged by: MMS Well Depth: 116.5 Riser ht.: 2.54

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2230.1	--0	CL	(0-10.0) clay; mottled brown and gray, iron stained, calcareous, low plasticity
2225.1	-- 5	CL	same as above
2220.1	--10	CL	(10.0-18.5) clay; gray, blocky, iron-stained, calcareous, low plasticity
2215.1	--15	CL	same as above
			(18.5-20.0) claystone, calcareous
2210.1	--20	CL	(20.0-50.0) clay, silty; gray, blocky, some iron staining, medium plasticity
2205.1	--25	CL	same as above
2200.1	--30	CL	same as above
2195.1	--35	CL	same as above
2190.1	--40	CL	same as above
2185.1	--45	CL	same as above
2180.1	--50	OL	(50.0-52.0) carbonaceous clay
		CL	(52.0-55.0) clay; gray, medium plasticity

MSL Elev.	Depth from surface	ASTM	Description of Material (all measurements in feet)
2175.1	--55	SC	(55.0-62.0) sand, clayey, silty; gray
2170.1	--60	SC	same as above
	-	CL	(62.0-66.0) clay; gray, blocky, medium plasticity
2165.1	--65		
	-		(66.0-67.0) coal
	-	CL	(67.0-104.0) clay; gray, medium plasticity
2160.1	--70		
2155.1	--75	CL	same as above
2150.1	--80	CL	same as above
2145.1	--85	CL	same as above
2140.1	--90	CL	same as above
2135.1	--95	CL	Same as above
2130.1	--100	CL	same as above
	-		(104.4-116.0) coal
2125.1	--105		
2120.1	--110		same as above

MSL Elev.	Depth from surface	AS TM	Description of Material (all measurements in feet)
2115.1	--115		coal
	-	CL	(116.0-116.5) clay; gray
	-		--
	-		end of boring
	-		
2110.1	--120		
	-		
	-		
	-		
	-		
	--125		
	-		
	-		
	-		
	-		
	--130		
	-		
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