"WATER, WATER, EVERYWHERE..."

57th ANNUAL
TRI-STATE GEOLOGICAL FIELD CONFERENCE
IOWA STATE UNIVERSITY
AMES, IOWA

October 8-10, 1993

co-sponsored by

Department of Geological and Atmospheric Sciences
Iowa State University
and
Geological Society of Iowa

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Guidebook 58

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ACKNOWLEDGMENTS

We wish to thank the many people involved in the preparation and production of this guidebook. First, I wish to acknowledge the efforts by the many authors who worked hard to prepare their materials in time to meet guidebook publication deadlines. They are listed on the guidebook title page and the sections they authored. Thanks also to the staff of the Geological Survey Bureau of the Iowa Department of Natural Resources who prepared the manuscripts for publication. These people include Mary Pat Heitman (word processing), Greg Ludvigson (editing), Bill Bunker (reformatting and layout), Patricia Lohmann (final publication layout), and Ray Anderson (publication coordinator). Additionally, we would like to thank the field trip stop land owners for their cooperation, including the U.S. Army Corps of Engineers at Saylorville Lake (Jerry DeMarce, Park Manager), the I.S.U. Agronomy and Agricultural and Biosystems Engineering Research Farm (Jon Bahrenfus and Rich Van DePol, farm manager), Larry Black (owner of the Walnut Creek research site), the U.S.D.A.- A.R.S. National Soil Tilth Laboratory (for demonstrating their instrumentation), and Ron and Sandy Risdal (owners of the location of the Sunday trip stop). Finally, I wish to thank the students from the I.S.U. Geology Graduate Student Organization and Geology club who assisted in many of the logistical aspects of the registration, field trips, and banquet.

INTRODUCTION

by

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The theme of this year's joint *Tri-State Geological Field Conference* and *Geological Society of Iowa Fall Field Trip*, "**Water, Water, Everywhere...**" reflects the record-breaking rainfall in Iowa and many other areas of the Midwest in 1993. By the end of August, Iowa records had been set for the most rain in one, two, three, four, five, seven, eight, nine, ten, 11, 12, 18, 24, 36, and 48 months. Iowa State Climatologist Harry Hillacker noted that "virtually every conceivable maximum precipitation record (in Iowa) has been broken in 1993. The past ten months in particular have been far wetter than any other November through August period since Iowa records began in 1873." In fact, new precipitation records were set in each of the past 10 months. A total of 47.50 inches of rain fell on Iowa from November of 1992 through August of 1993. This total was 20.75 inches above the normal average for that period and an amazing 11.92 inches more that the previous record, set in 1950-51. By the end of August, 41.20 inches of rain had fallen on Iowa, making this the sixth-wettest year on record even without a single additional drop for the remaining four months. This total is only 2.96 inches below the yearly record precipitation of 44.16 inches set in 1881.

Flooding of Iowa's rivers and creeks began early in the Spring of 1993. By mid-August thirty-three U.S. Geological Survey surface water gaging stations had recorded peak records of stage and/or discharge. Of these, fifteen stations recorded water levels indicative of 100 year or greater floods. The flooding completely destroyed three of the gaging stations, partially inundated nine others damaging equipment, and produced minor damage in eleven more. Record outflows were recorded at three of the four U.S. Army Corps of Engineers reservoirs in Iowa, with flows over the emergency spillway of all three, two for the first time since their construction.

The rains and associated floods inflicted billions of dollars of damage and great hardships on thousands of Iowans. When the Raccoon River basin received an 8 inch rainfall in an area already saturated from earlier storms, a 500 year flood crest descended on the State Capitol of Des Moines, inundating the town's water treatment plant and leaving 250,000 people without a public water supply for 19 days.

This increased rainfall and flooding has "spilled" into other geologic areas as well. Water tables and potentiometric surfaces throughout central Iowa have risen to unprecedented levels.

Standing water has been present in most potholes and other depressions on the Wisconsinan glaciated area of the Des Moines lobe for most of the year. High water tables have put excessive stress on house foundations, resulting in collapsed basements and basement flooding from seepage. In addition, mass movement of water-saturated slopes has been common this year, resulting in flows and slides onto major highways and the movement of expensive homes on steep slopes.

Concentrations of contaminants from agricultural activities have also been affected by the rainfall. Concentrations found in shallow wells in agricultural areas were generally less than are normal in Iowa, in part due to the excess water and "dilution" and partly due to non-application of fertilizers and pesticides in some areas due to wet fields. In contrast, the concentration of pesticides in streams including the Mississippi River appears to have reached very high levels, perhaps due to actual erosion and transport of soil particles containing pesticides.

Despite the soggy weather, geologists should be and are involved in investigations of all of these water-related phenomena. The focus of the 1993 Tri-State Geological Field Conference / GSI Field Trip is to illustrate the roles that geologists have played regarding each of these problem areas, from basic stratigraphy and sedimentology and the erosive power of water, to dam building and the interaction between groundwater and surface water, and finally to water quality investigations in till.

STOP 1

SAYLORVILLE LAKE EMERGENCY SPILLWAY

INTRODUCTION

by

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The Des Moines River begins its southward journey from Lake Shetek in southwest Minnesota's Murray County. As the West Fork of the Des Moines River, it enters Iowa in Emmet County northwest of Estherville. The East Branch of the Des Moines River begins in southern-most Minnesota just over the Iowa boarder north of Estherville. The rivers flow in a southeasterly direction, converging in south-central Humboldt County, south of the city of Humboldt. The river continues south through Fort Dodge, joining the Boone River in eastern-most Webster County, and down the axis of the Des Moines Lobe (the till sheet deposited by the most recent advance of glacial ice into Iowa) through the cities of Boone and Des Moines. From there, the Des Moines River is joined by the Raccoon and Middle Rivers as it flows in a southeasterly direction, eventually ending at the Mississippi River just south of Keokuk, about 380 miles from its headwaters. The river began its life about 12,000 years ago, sourced by melt water from the retreating Des Moinesian glacier.

Although flooding has no doubt always affected the Des Moines River, the first large recorded flood in the reach of the river between Des Moines and Boone occurred in 1947 when 500 people were forced from their homes and two persons drowned. On June 24, 1954, flows of 60,200 cubic feet per second (cfs) forced 1,800 people from their homes, and in 1965 the river experienced a flow of 47,400 cfs. In 1953 the U.S. Army Corps of Engineers studied nine potential dam and reservoir sites in central Iowa, six sites on the Des Moines River, two sites on the Raccoon River, and one site on the South Raccoon River. The study led to the construction of the Saylorville Dam and Reservoir, with construction beginning in 1966 and completed in 1977. The Saylorville Dam is about one mile long and 105 feet high (its maximum elevation is 915 feet above mean sea level). With a normal pool level of 836 feet the Saylorville Reservoir covers 5,950 acres; at a maximum flood pool elevation of 890 feet it covers 16,700 acres and contains 190,948,100,000 gallons of water. The maximum outflow through the dam's control structure is 21,000 cfs. The Saylorville Dam and Reservoir were designed to contain handle a Hypothetical Probable Maximum Flood that included a lake level of 907 feet and a flow of 162,000 cfs.

A series of floods in the 1980's and 1990's filled Saylorville Lake to capacity and beyond. Erosion from water flowing over the emergency spillway of the lake produced spectacular exposures of Quaternary materials and Pennsylvanian rock strata. In 1984 flooding led to the first use of the Emergency spillway. The lake reached a maximum level of 889.53 feet on June 22, 53 feet above the conservation pool level of 836 feet. Water flowed over the spillway (elevation 884 feet) for 14 days between June 18 and July 4. During this period, Saylorville Lake experienced a maximum inflow of 38,000 cfs (on June 21), a maximum outflow of 29,000 cfs (on June 22). In the fall of 1985, the Geological Society of Iowa led a field trip (Bettis et al., 1985) to examine the geological materials exposed by flooding in the Emergency Spillway, nicknamed "Saylorville Canyon".

In 1991, water once again flowed over the spillway, this time for 11 days between June 6 and June 17. On June 9, Saylorville Lake reached a maximum level of 889.26 feet, again 53 feet above the conservation pool level. Maximum inflow of 45,000 cfs was reached on June 6, maximum outflow of 26,000 cfs on June 10 and 11.

The multiple episodes of heavy rainfalls that marked the Summer of 1993 produced flooding in many areas of Iowa, including the Des Moines River. Two major episodes of flooding again forced utilization of the Saylorville Reservoir's Emergency Spillway. The first event included an increase in the pool level from 836 feet on March 25 to 882 feet on April 12, a rise of 46 feet in just 18 days. Water flowed over the spillway for nine days between April 22 and May 1, reaching a maximum pool level of 886 feet on April 27, fifty feet above the normal pool level. During this event the maximum inflow was 45,000 cfs, the maximum outflow was 21,000 cfs.

The level of Saylorville Lake had lowered to 865 feet by June 3, 1993, before new heavy rains again began to fill the reservoir. By June 17 water was again flowing over the Emergency Spillway, this time continuing for 42 days, until July 29. During this episode water in the lake reached 892.02 feet, 55 feet above the conservation pool level. Inflows reached 61,000 cfs and outflow 43,000 cfs, with outflow in excess of 21,000 cfs for about 46 days.

The Saylorville Lake Emergency Spillway is 430 feet wide with an elevation of 884 feet at the dam, and drops in elevation about 80 feet from the dam to its junction with the Des Moines River less than a mile away. Comparing this slope to normal stream gradients in the region, about 2.5 feet per mile, gives a measure of the force and velocity with which water moved through the spillway. At maximum flow the spillway was conducting 21,000 cfs of water, up to eight feet deep. The earthen spillway was designed to cut its own channel when in use, and performed as expected.

A spectacular suite of geologic materials was exposed by the cumulative effects of the four spillway events. Quaternary materials exposed in the southern end of the spillway range in age from pre-Wisconsinan to Holocene and include glacial, glaciofluvial, eolian, alluvial, and colluvial sediments. In the northern end of the spillway, Middle Pennsylvanian materials are exposed including strata of the Floris and overlying Swede Hollow Formations of the Cherokee Group. Materials exposed include sandstone, shaly limestone, shale (including the Oakley Black Shale), and the Whitebreast Coal. Fossils are abundant, including brachiopods, cephalopods, trace fossils, and wood. At Stop 1 you will be able to examine the variety of materials present in the Saylorville Canyon, however ***NO FOSSIL OR ROCK COLLECTING IS PERMITTED.***

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UPPER CHEROKEE GROUP (PENNSYLVANIAN) EXPOSURES SAYLORVILLE EMERGENCY SPILLWAY

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INTRODUCTION

A thick sequence of Middle Pennsylvanian strata was exposed by rapid downcutting as floodwaters surged through the emergency spillway of Saylorville Dam during June, 1984 and again during the Summer of 1993. These strata, part of the Cherokee Group, range upward from the mid-Floris Formation through strata above the Ardmore Limestone Member of the Swede Hollow Formation (Fig. 1). Ravn et al. (1984) presents the Pennsylvanian stratigraphic nomenclature of Iowa used in this report.

The exposure at the Saylorville Lake emergency spillway is the most extensive (and most accessible) exposure of this stratigraphic interval in Iowa. It presents an excellent opportunity to view several interesting facets of the Pennsylvanian geology of Iowa. First, two distinct depositional regimes are represented in this exposure. The sequence of strata exposed here represent the transition from fluvial-deltaic dominated depositional regimes of the older Pennsylvanian to deposition more influenced by marine environments. The clastic units of the Floris Formation are primarily nonmarine, fluvial-deltaic sediments. Marine units are confined to thin limestones and fossiliferous shales, often overlying coal seams. In contrast, the Swede Hollow portion of the outcrop is a transgressive-regressive marine sequence closely resembling the cyclic repetitions (cyclothems) of marine and non-marine units in the younger Marmaton Group (Heckel, 1979).

Second, the lower part of the Swede Hollow Formation, including the Whitebreast Coal, Oakley Shale, and Ardmore Limestone Members, form the most widely traceable sequence of units in the Pennsylvanian of North America. Correlative units extend across much of the midcontinent region into Missouri, Kansas, Illinois, Indiana, and possibly as far east as Ohio.

Third, Oakley-Ardmore deposition marked the first complete marine inundation of the Iowa area during the Pennsylvanian. Although older marine units are known from the Pennsylvanian of Iowa, none are as thick or laterally persistent as those in the lower Swede Hollow Formation.

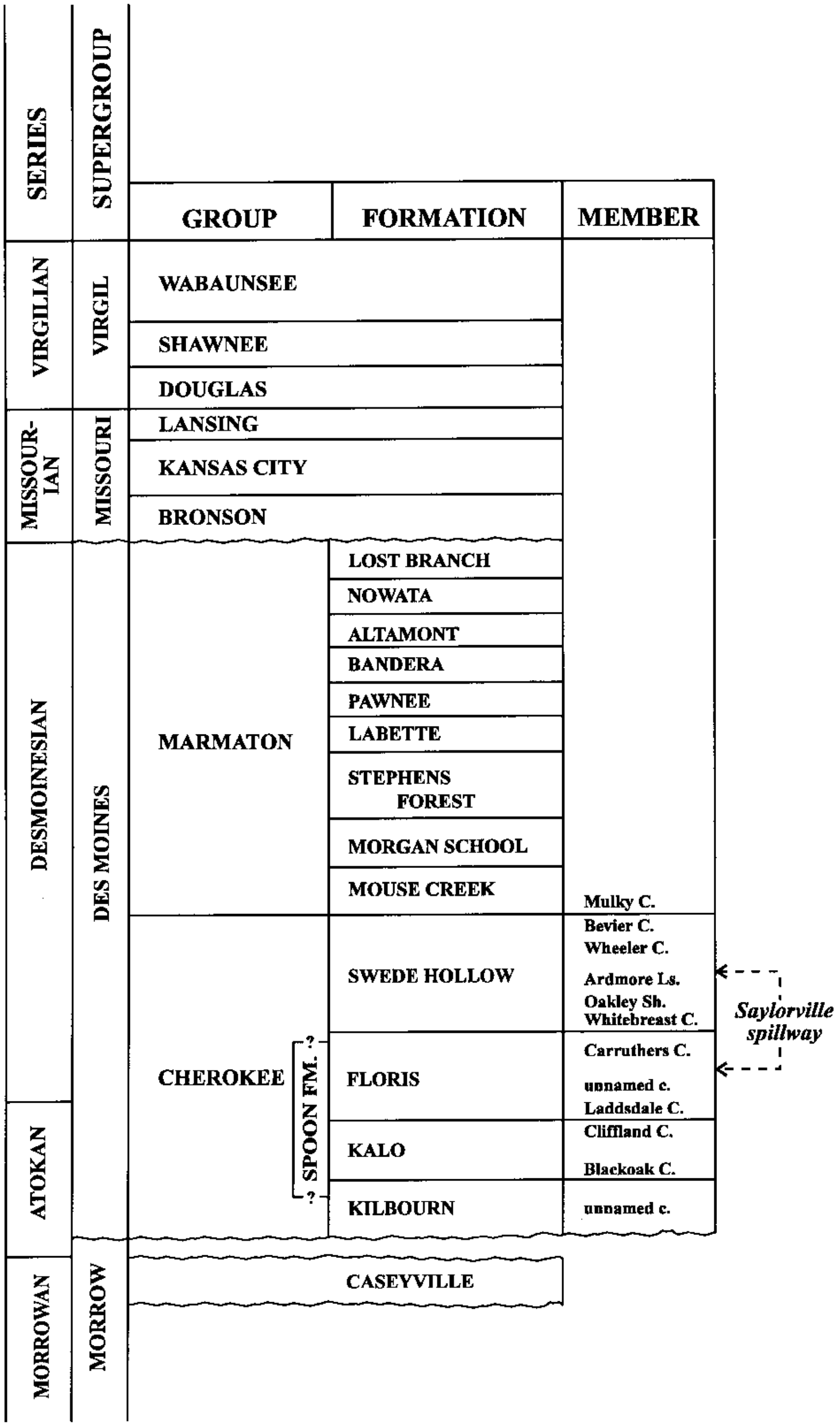

Figure 1. Stratigraphic nomenclature of Pennsylvanian strata in Iowa (after Ravn et al., 1984). The range of strata exposed at the Saylorville spillway is indicated.

INTERPRETATION AND DISCUSSION OF PENNSYLVANIAN STRATIGRAPHY

Pennsylvanian strata in Iowa are highly variable, both laterally and vertically. Much of the variability is cyclic in nature, related primarily to changes in base level on a local or regional scale. The portions of the Swede Hollow and Floris formations exposed at the Saylorville spillway are quite different in character. Nevertheless, the variability within each of the two units is cyclic. The differences in the two units can be attributed to factors such as position relative to the shoreline, the amount of local topographic relief at the time of deposition, and the amount of sediment being carried by the system.

Floris Formation

The oldest Pennsylvanian units exposed at the emergency spillway are part of the Floris Formation. Here, as elsewhere in Iowa, the Floris is dominated by nonmarine, fluvial-deltaic deposits. Thin marine units present in the Floris probably originated from brief incursions of marine water into otherwise nonmarine environments. The thin, fossiliferous limestone near the base of the exposure probably originated in this way. Similar limestone beds have been observed at this stratigraphic position elsewhere in Iowa. In the past they have been correlated with the Seville Limestone of Illinois; however, Ravn et al. (1984) stated that this correlation was incorrect and discouraged the use of the name in Iowa.

The nonfossiliferous gray-green shale with dark red mottling and maroon nodules that makes up the lower part of the exposure is typical of the middle Floris Formation. This shale may have been deposited in a lower delta plain environment or in a transitional zone between upper and lower delta plains. The red mottling and nodules are products of partial oxidation brought about by a minor influx of oxygen-bearing water (Horne et al., 1979).

The Carruthers Coal formed from peat accumulated in a swamp created by a gradual rise in base level that allowed widespread development of abundant vegetation and preservation of peat. Rooting in the mudstone underlying the coal suggests a local source of peat. The Carruthers Coal is laterally persistent, but quite variable in thickness and character ranging from a few inches thick to approximately three feet. The abundant fusain noted in the Carruthers Coal at this exposure is typical of this coal bed and is further evidence of oxidation due to the influx of oxygen-bearing water suggested above or brief subaerial exposure of the peat.

As the local base level continued to rise the area was briefly inundated by marine water. Peat deposition terminated and the thin limestone and fossiliferous shale which overlie the Carruthers Coal were deposited. A return to fluvial-deltaic conditions and a lowered local base level are indicated by subsequent deposition of non-marine shales and a coal streak (also assigned to the Carruthers Coal Member).

The shale overlying the coal streak becomes increasingly silty upward and contains calcareous nodules which may be related to rooting. A single cycle of deposition, perhaps from a crevasse splay is suggested for this unit. The shale/mudstone at the top of the Floris Formation which forms the seatrock for the Whitebreast Coal marks the point of maximum regression in the depositional cycle.

The lower portions of the Floris Formation (not exposed at the spillway) are characterized by great lateral and vertical variability so that few lithologies are traceable beyond a short distance. It was not until biostratigraphic techniques using fossil palynomorphs were developed that it became possible to correlate coal beds across the region (Ravn, 1986). Local base levels were changed in part due to differential compaction of the sediments being deposited and to tectonic adjustments. The large channel systems represented by the thick sandstone bodies exposed along Red Rock Lake and at Ledges State Park are thought to be a product of this relatively unstable environment. The sandstone channel-fills probably originate in the Floris Formation below the Carruthers Coal and locally cut downward as far as the Pennsylvanian-Mississippian contact. At a large number of localities to the west and south the Carruthers Coal is overlain by a phosphatic, black shale and fossiliferous limestones

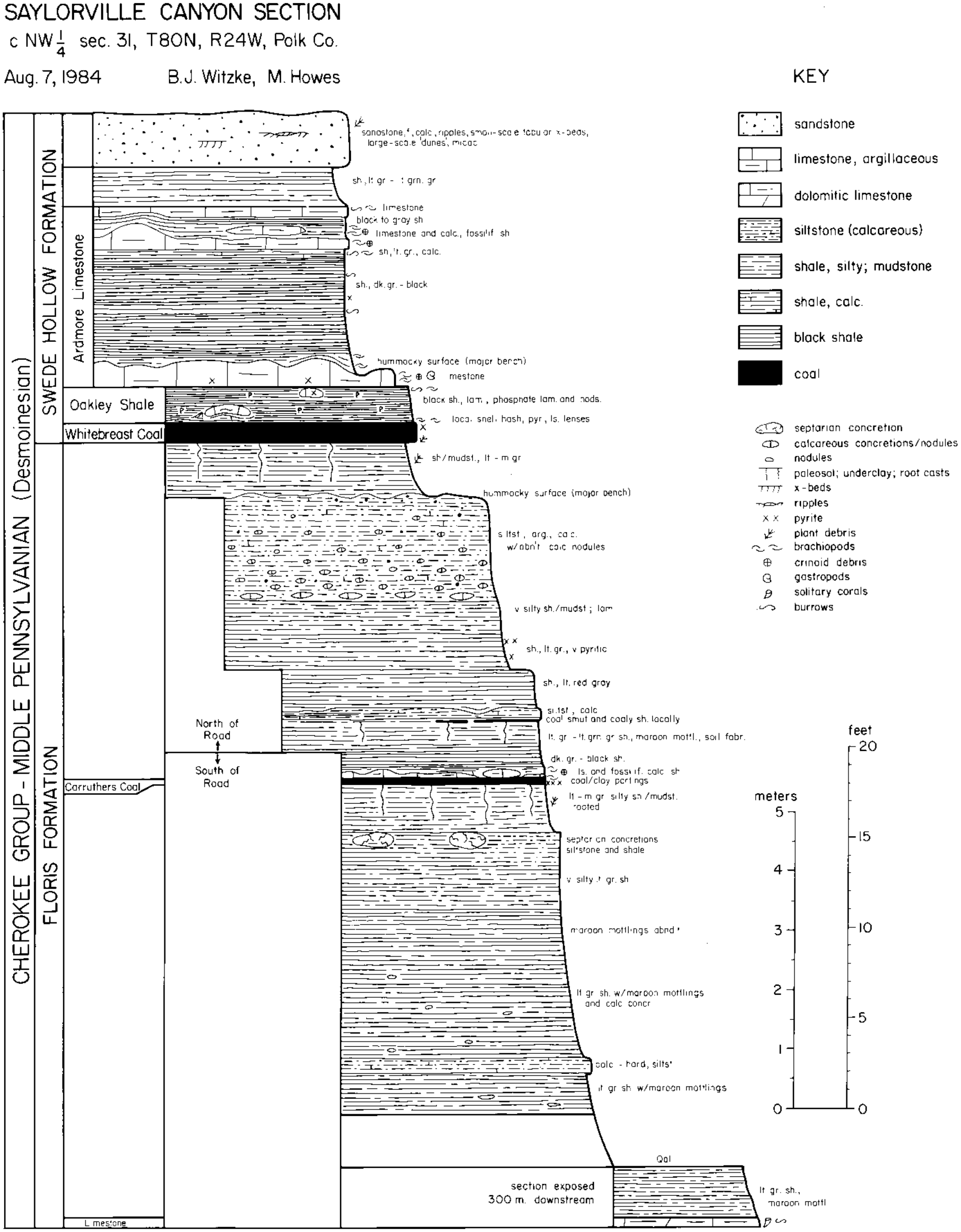

Figure 2. Pennsylvanian deposits exposed at the Saylorville spillway.

DESCRIPTION OF STRATA

SWEDE HOLLOW FORMATION

unnamed bed

Sandstone -1 m (3.1 ft), light brown, fine-grained, calcareous, jointed and very resistant forming a prominent bench around the top of the exposure. Tool marks are visible on the upper surface of the bed. Ripple-drift cross-lamination and cross-bedding are visible on edges of broken slabs and the top of the bed is marked by dunes on the east side of the exposure. The lower contact is sharp and fairly planar with sole marks visible locally. Plant fossils, some quite large, are common especially log casts of *Lepidodendron* and *Sigillaria*.

Shale -0.7m (2.2 ft), gray-green, silty.

Ardmore Limestone Member

"upper limestone unit" -0.7 m (2.2 ft), consists of two to three thin, slightly shaley, irregular limestone beds which vary in thickness from 0.05 to 0.5 m (0.2 to 1.7 ft), interbedded with light to dark gray, calcareous shales. The uppermost limestone bed is sparsely fossiliferous, with productid brachiopods and burrows noted. The limestone overlies a 0.15 m (0.5 ft) shale which varies from medium gray to black and contains scattered phosphate nodules. The lower portion of this unit is extremely fossiliferous, and loose brachiopod valves weather out of the shales. Brachiopods include productids (*Desmoinesia muricata*), strophomenids (*Derbyia crassa*), and athryids (*Composita subtilita*). Scattered crinoid debris is also present.

Shale -1.8 m (5.8 ft), very dark gray, with weak laminations in the upper half, becoming distinct downward. Burrows common throughout, but most apparent near the upper contact with pyritized in-filling common. Common to abundant brachiopods (mostly *Desmoinesia*) occur in the lower few centimeters.

Limestone -0.05 to 0.5 m (0.2 to 1.7 ft), medium gray, fine-grained, argillaceous, fossiliferous and hard forming a resistant single bed with a very irregular (hummocky) upper contact which locally appears nodular. Fossils include brachiopods (*Desmoinesia muricata*, other productids, *Derbyia crassa, Composita subtilita, Mesolobus mesolobus*), scattered crinoid debris, and gastropods. Pyrite-lined fractures and rinds are common especially near the lower contact which is sharp and fairly planar

Oakley Shale Member -0.6 m (1.8 ft), dark gray, burrowed with brachiopods in the upper 8 cm (3 in.). Rare calcareous nodules were observed near the upper contact. The shale grades to black, fissile with scattered small phosphatic nodules in the upper portion which become more abundant downward to form laminations. A pyritic "shell hash" with abundant productid brachiopods or irregular limestone nodules and concretions are found locally at the lower contact.

Whitebreast Coal Member -0.25 m (0.8 ft), fine alternating bright and dull bands, with rare, thin fusain bands, cleated with calcite, pyrite, and kaolin cleat fills. Yellow, white, or gray efflorescences of iron sulfate minerals develop on surfaces where coal is weathered. The lower contact is sharp and regular.

FLORIS FORMATION

unnamed beds

Shale -0.9 m (3.0 ft), light to medium gray, weakly laminated in the upper half with common root traces.

Siltstone/Shale -3.7 m (12.1 ft), siltstone, light gray, argillaceous, with abundant, small calcareous nodules, well indurated to form a prominent hummocky bench which marks the upper contact. Grades downward to shale -light gray, very silty grading to slightly silty. Abundant pyrite was noted near the middle of the unit and minor light red mottling in the lower part.

Siltstone -tr. to 0.2 m (tr. to 0.7 ft), calcareous with irregular upper contact.

Coal -tr., discontinuous [assigned to ***Carruthers Coal***].

Mudstone/Shale -2.0 m (6.7 ft), silty, rooted mudstone grades to dark gray, calcareous shale which is fossiliferous in the lower few centimeters.

(The access road crossed the exposure in this interval prior to the recent flooding.)

Limestone -0.15 m (0.5 ft), argillaceous, nodular with *Desmoinesia muricata*, *Composita subtilita*, and ambocoeliid brachiopods, and crinoid debris.

Carruthers Coal Member -0.1 m (0.3 ft), very pyritic with abundant fusain (a fibrous, friable coal lithotype which has a silky luster.

Mudstone -0.8 m (2.7 ft), light to medium gray, silty with common root traces.

Shale -7.4 m (24.7 ft), light gray to light gray green, very silty decreasing downward with extensive maroon and yellowish mottling in the lower half. A zone of scattered 0.1 to 0.3 m (0.3 to 1 ft) diameter septarian concretions occurs at the upper contact. Bands of maroon concretions are present in the lower half. A 0.3 m (0.8 ft) light gray, calcite cemented siltstone is present near the base of the unit. Portions of this unit are only poorly exposed.

Limestone -0.1 m (0.3 ft), light gray, weathered to light brown, dolomitic, bioturbated with sparse solitary corals and brachiopods.

similar to those found in the overlying Swede Hollow Formation, providing evidence of large areas of marine inundation at the end of Floris deposition. Thus, the portion of the Floris Formation exposed at the spillway records leveling of the irregular topography created by the extensive channelization characteristic of the earlier parts of the Floris Formation. The lateral persistence of the Carruthers Coal is evidence of a region wide rise in base level and consequent development of widespread swamps. A few topographic highs remained accounting for the discontinuities in the Carruthers Coal and associated units.

Swede Hollow Formation

The lower portion of the Swede Hollow Formation contains strata similar to the marine-dominated portion of the younger Marmaton Group and Missouri Supergroup strata of Iowa, and may represent a transition to marine-dominated depositional regimes (Ravn et al., 1984).

Swede Hollow deposition began with a slow rise in the water table, in response to a eustatic rise in base level on a broad, relatively stable shelf with very little apparent relief. The peat that accumulated in the resulting region-wide swamps became the Whitebreast Coal. This coal is characterized by its lateral persistence and uniform thickness. The low diversity in the assemblage of miospores recovered from the Whitebreast Coal serves as further evidence of its lack of variation (Ravn, 1986).

Marine inundation ended peat accumulation and initiated marine deposition. The Oakley Shale Member, a fissile, black, phosphatic shale is in direct contact with the Whitebreast Coal over most of the region. It is analogous to younger Pennsylvanian "core" shales such as those described by Heckel (1977). The "shell hash" and limestone nodules found sporadically at the base of the Oakley Shale are the sole record of deepening marine water and are the equivalent of the transgressive limestones of younger Pennsylvanian cyclothems in the Midcontinent. However, the lack of well-developed transgressive limestone strongly resembles the Middle Pennsylvanian cyclothems of Illinois. Swade (1985) speculated that near absence of a transgressive limestone in Illinois-type cyclothems may have been due to the limited development of calcite precipitating benthic algae in close proximity to a peat deposit. The shale and phosphorite nodules were deposited when water depth was sufficient for establishment of stratification of the water by temperature, i.e., a thermocline. The thermocline halted vertical circulation in the water body and ended the small amount of carbonate precipitation represented by the shell hash and nodules. Below the thermocline oxygen in the water was consumed by bacterial activity, setting up reducing conditions which facilitated the accumulation of phosphorite and preserving the large quantity of organic matter characteristic of the Oakley shale.

The Ardmore Limestone Member was deposited following the restoration of open marine circulation that allowed a marine biota to colonize the area. The lower limestone bed of the Ardmore was deposited in this environment. Ravn et al. (1984) suggested an episode of rapid deposition in a prodeltaic setting with decreasing water depth as the source of the overlying dark gray shale. The extensive burrowed zones and sparse fauna of low diversity are consistent with a prodeltaic environment. The extensive burrowing at the upper contact of the shale probably marks the end of the influx of clastic sediment. The uppermost limestone was deposited during a brief stabilization of sea level or minor transgression which allowed the open marine biota to become established. This limestone is typically split into two or more thin beds by small prodeltaic clastic pulses. Additional biostratigraphic and depositional aspects of the Oakley-Ardmore interval are discussed by Swade (1985).

The Ardmore Limestone Member is overlain by a non-marine shale and sandstone deposited after withdrawal of the sea and return to fluvial-deltaic deposition. The near absence of scouring at the base of the sandstone, uniform thickness, and sedimentary structures suggest a distributary mouth bar origin.

A NOTE ON COAL RESOURCES AND MINING

Des Moines Iowa, a few miles to the south was the site of the earliest coal mining in the state in 1840. Landis and Van Eck (1965) estimated original resources for the county at 750 million tons. Polk County was the second largest coal producer in the state when mining ceased there in 1947. The state of Iowa was the largest coal producer west of the Mississippi River prior to the development of the major coal deposits in Colorado after the turn of the century. Most of the coal production in Iowa was used to fuel the railroads and so played a vital role in their westward expansion and in the settlement of the state.

The coals mined in the Des Moines area are older than those exposed at the Saylorville spillway. They were primarily the Blackoak and Cliffland coals of the Kalo Formation and to a lesser degree the Laddsdale Coal found in the lower part of the Floris Formation. The Carruthers and Whitebreast coals have been mined in Iowa where they are thicker than at this exposure and where the thicker coals of the Kalo and lower Floris formations were not available (Howes et al., 1989).

Resources have been estimated for the Whitebreast and Carruthers coal beds in Dallas, Davis, Decatur, Guthrie, Lucas, Monroe, Wapello, and Warren counties (Landis and Van Eck, 1965).

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THE QUATERNARY DEPOSITS OF THE SAYLORVILLE EMERGENCY SPILLWAY: *HERE TODAY.......GONE TOMORROW!!*

by

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After The Great Flood, Exposures in the Emergency Spillway, Saylorville Dam
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INTRODUCTION

by
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Detailed investigations were completed during the Late Summer and Fall of 1984 on Quarternary exposures in the Saylorville Emergency Spillway. A cursory examination of the post-*'July Flood of 93'* exposures revealed an exposed section very similar to that described following the 1984 overflow event. Unfortunately, on this field trip we will not have an opportunity to closely examine the Quaternary exposures. The new exposures that were present immediately following the *'July Flood of 93'* are now covered by nests of rotational slump blocks. Large rotational landslides have and are still occurring on both banks of the emergency spillway as the Army Corp of Engineers continues to lower Saylorville Lake and the Quarternary exposures continue to de-water. We feel this is a potentially hazardous situation therefore we will view the Quaternary section from the road and discuss the history and stratigraphic relationships of the Quaternary sequence.

As you look Southeast (down) the emergency spillway you can see a thin, resistant ledge of Pennsylvanian limestone. The limestone is overlain by oxidized (brown) and reduced (gray) pre-Wisconsinan alluvium exposed at the base of slumped exposures. These sediments accumulated in a small tributary valley of the paleo-Des Moines River (presently Beaver Creek) prior to development of the Sangamon Soil. Several buried soils are present in the pre-Wisconsinan alluvium indicating a complex aggradational history analogous to that documented at the St. Charles Site in Madison County south of Des Moines (Baker et al., 1991).

Farther down the spillway the Pennsylvanian limestone is absent and late Wisconsinan deposits make up the entire exposed section. Most of the section consists of unoxidized (gray), fossiliferous (plant macrofossils, beetles, gastropods) alluvium that accumulated in a large wetland as the paleo-Des Moines Valley aggraded during advance of the Des Moines Lobe. The alluvium is overlain by Des Moines Lobe glacial diamicton with basal ages averaging 13,500 B.P. The fossil record preserved in this alluvium provides us with a detailed picture of the period between 16,200 and 13,500 B.P. when the Des Moines Lobe advanced into northcentral Iowa. The general scenario is one of at first rapid, then continued steady warming as the glacier advanced to the terminal position. The record here is consistent with other, shorter paleoenvironmental records from Iowa, all indicating that advance of the Des Moines Lobe occurred during a warming climatic interval and this lobe's behavior was therefore out of phase with the regional climate.

OVERVIEW OF THE QUATERNARY DEPOSITS

Authors note: *The following section, taken from GSI Guidebook 43, provides a detailed discussion of the five Quaternary stratigraphic units exposed in the emergency spillway. These exposures provided an excellent opportunity to view deposit geometry by examining the lateral occurrence of several stratigraphic units. These exposures are unique because they afford a rare view of Wisconsinan and older fine-grained alluvial deposits. The emergency spillway sequence includes deposits of glacial, glaciofluvial, eolian, alluvial and colluvial origin and is an excellent site to discuss the primary sedimentologic properties and facies relationships of these units.*

The Saylorville Emergency Spillway occurs along the western margin of the present Des Moines River valley. Natural valley incision and artificial grading of the original emergency spillway channel have progressively truncated portions of the Quaternary sequence, exhuming older Quaternary deposits and Pennsylvanian-age bedrock. At present, the Quaternary deposits occupy a buried bedrock valley which is cut successively through the Pennsylvanian-age Swede Hollow and Floris Formations. This bedrock valley includes roughly the lower one-half of the emergency spillway channel shown on Figure 1.

Five different Quaternary stratigraphic units occur in the emergency spillway exposures, from youngest to oldest: 1) Holocene-age alluvium and colluvium; 2) late Wisconsinan-age glacigenic deposits (Des Moines Lobe deposits); 3) late Wisconsin-age alluvium; 4) late Wisconsinan-age loess; and 5) pre-Wisconsinan age alluvium. Three of these five stratigraphic units, the Holocene-age alluvium and colluvium, late Wisconsinan-age glacigenic deposits (Des Moines Lobe deposits), and pre-Wisconsinan age alluvium, are each comprised of multiple fills or deposit types.

There are a number of unusual aspects of the Quaternary sequence in the Saylorville Emergency Spillway. First, the geometry of the stratigraphic units is not the typical 'pancake layer' stratigraphy where simple vertical superposition relationships can be used to determine the relative age of the different stratigraphic units. Instead, many of the stratigraphic units lie lateral to one another, and cross-cutting relationships must be analyzed to determine relative age.

Secondly, the Quaternary sequence in the emergency spillway is a sequence dominated by alluvial fills, rather than the more typically preserved upland sequences . The pre-Wisconsinan and Wisconsinan-age alluvial fills are hardly ever encountered (preserved) in stratigraphic section across the state.

Thirdly, the pre-Wisconsinan age alluvial fills are dominated by fine-grained, and in some cases, poorly-sorted deposits which can at times be difficult to distinguish from loess or glacial till. In such cases analysis of primary sedimentary properties and lateral facies relationships is essential for the correct identification of the deposits' origin.

Finally, time-stratigraphic classification of the deposits (as Holocene, Wisconsinan, pre-Wisconsinan) can be made here in lieu of radiocarbon dates if stratigraphic relationships (superposition, cut-and-fill relationships) and secondary properties (soil and weathering-related properties) are analyzed.

To study the extensive Saylorville Spillway exposures, the channel walls on both sides of the spillway were examined. Representative sections were drawn, the sections were described, and vertical profiles were sampled for standard particle-size and clay mineralogic data (Hallberg, ed., 1978). It should be noted that this sampling was reconnaissance sampling in which the purpose was to provide a gross characterization of the strata present; more rigorous sampling and description for detailed sedimentologic studies could still be done. Table 1 and the following sections summarize the properties of the various Quaternary stratigraphic units exposed

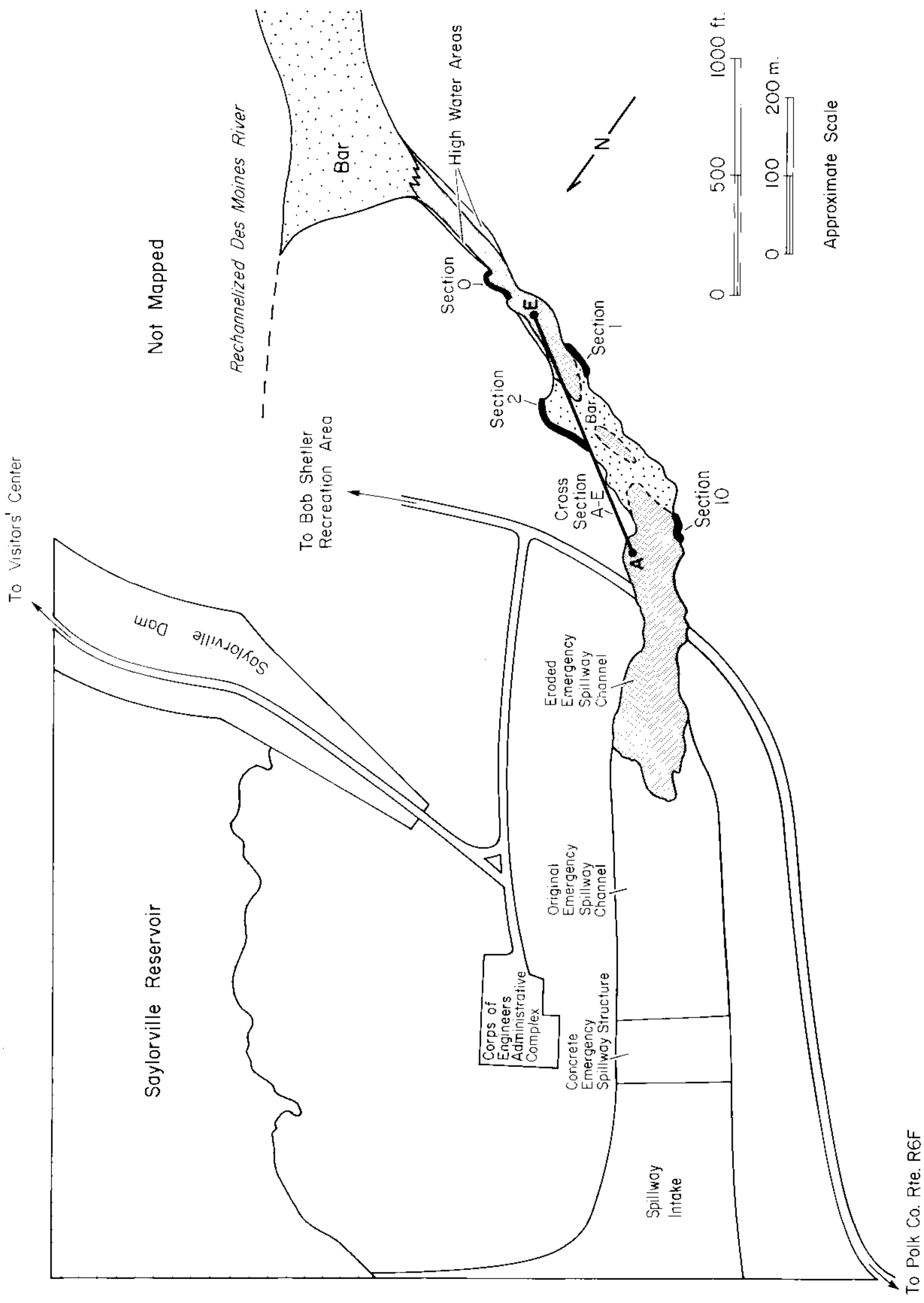


Figure 1. Sketch map of the Saylorville Emergency Spillway area.

Table 1. Summary of properties of Quaternary stratigraphic units exposed at the Saylorville Emergency Spillway.

STRATIGRAPHIC UNIT	PRIMARY PROPERTIES		GEOMETRY	CARBONATE CONTENT	SECONDARY PROPERTIES		
	texture	bedding structures			Pedogenic (Soil) features	Weathering zone changes	Jointing
HOLOCENE ALLUVIUM AND COLLUVIUM	1. Fine-grained sediments range from silt loam to sandy loam. 2. Basal channel fills consist of bedded sands and pebbly gravels.	1. Weak to continuous stone line at base. 2. Faint stratification at base grading upward to massive fine-grained sediments. Thinly-bedded sands and pebbly gravels at base of low-order drainage channels with finer-grained sediments at top.	Unconformably overlies older deposits forming low-order modern drainageways; In drainageway this unit may consist of many fills, indicating punctuated erosion and filling during the Holocene; upper surface disturbed by clearing and grading in many areas.	Non-calcareous	Modern soil profile developed in top: 1. Systematic soil horizonation with depth (A-E-B-C or A-B-C horizons) 2. Organic matter accumulation--development of A horizon. 3. Development of secondary soil structure. 4. Development of discontinuous cutans-- secondary clay coatings-- in B horizon. 5. Buried soil evident in some areas.	Where the sediments are thicker than the modern soil, reduced and mottled reduced, grayish colors predominate.	Absent
WISCONSINAN GLACIGENIC DEPOSITS							
1. Main diamicton unit	Variable between sections; section 1: massive, uniform pebbly silt loam diamicton. Section 10, massive, variable pebbly clay loam diamicton. Section 0;pebbly silt loam diamicton with common imbricated block inclusions of loess; a few small-scale channel-fill inclusions.	Massive or with imbricated block inclusions of loess; weakly bimodal pebble fabric with main mode dipping to W-NW in some direction as imbricated block inclusions.	Slightly undulating, irregular lower boundary filling in low areas on the surface of the underlying Wisconsinan loess and alluvium; planar, erosional contact where it overlies associated glaciofluvial sands and fine gravels; upper surface truncated either by grading for the original emergency spillway channel.	Generally calcareous below modern soil profile; leached at Section 10.	Surface truncated; soil horizons absent.	In most sections, unoxidized, unleached; only 1 to 2 ft. (0.3 - 0.6 m) below truncated surface and secondary oxidation along numerous, closely-spaced, sub-horizontal joints. Section 10 is near the original ground surface, with mottled oxidized , reduced, leached horizons present, the weathering enhanced by the decomposition of locally derived, easily -weathered, pyrite-containing Pennsylvanian bedrock.	Occasional, If any, sub-vertical joints with little or no secondary alteration along them. Upper 1 to 2 ft. (0.3 - 0.6m) of truncated sections commonly have numerous closely-spaced sub-horizontal joints which break up into plates 2 cm or less in thickness, and several cm in length.
2. Associated glaciofluvial deposits	Variable from fine sand to pebbly gravel	Irregularly bounded beds of planar - bedded and cross-bedded sands and fine gravel or incised small-scale channel fills.	Where present, unconformable on underlying Wisconsinan alluvium; upper surface is an abrupt planar erosional surface with the overlying diamicton.	Calcareous	Unaffected by soil formation processes.	Unoxidized, unleached, but readily weathers to oxidized upon exposure.	Absent
WISCONSINAN ALLUVIUM	Dominantly fine-grained silt loam alluvium with thin, discontinuous sand lenses; abundant mollusc shells and fragments of organic matter (wood, twigs, etc.)	Laminated to thinly-bedded fine-grained sediments with thin (up to 1 cm thick) discontinuous (lenticular) wavy sand lenses.	Base generally covered; at Section 0-D appears to overlie loess. Occurs to south of low-order Holocene drainageway that formerly crossed the emergency spillway area prior to construction ; top truncated by construction along part of the spillway, infilled with Des Moines Lobe glacigenic deposits elsewhere.	Calcareous	Unaffected by soil formation processes.	Unoxidized, unleached, but coarser sediments weather to oxidized upon exposure.	Absent
WISCONSINAN LOESS	Fine-grained silt loam; occasional mollusc shells.	Massive.	Overlies Pre-Wisconsinan alluvial fills; at Section 2, fills small valley incised into pre-Wisconsinan alluvium.	Section 2: calcareous; common secondary concretions. Section 10: lower portion leached with some organic matter accumulations.	Occurs below modern soil profile.	1. Deoxidized, unleached ; reduced at Section 10. 2. Infrequent sub-vertical joints. 3. few hard, common soft secondary carbonate concretions. 4. common 'pipestems' (secondary iron oxide concretions)	Infrequent sub-vertical joints with secondary oxidation rinds.
PRE-WISCONSINAN ALLUVIUM (multiple alluvial fills and buried soils)	Dominantly fine-grained, poorly sorted loam, silt loam, clay loam sandy loam alluvium; lag gravels and sand beds commonly mark the base of individual fills; occasional graded, fining upward beds.	Multiple alluvial fills; base of indiviual fills commonly marked by gravel lags and sand lenses; fine-grained sediments generally massive, poorly sorted, occasionally stratified or fining upward.	Unconformably overlies Pennsylvanian - age bedrock; fills in valley on bedrock surface. Unconfromably overlain by Wisconsinan loess, Holocene alluvium, and Wisconsinan till of the Des Moines Lobe at various locations along the emergency spillway channel.	Non-calcareous	Multiple buried soils within the unit, each developed at the top of one of the alluvial fills; most of the buried soils are truncated. Pedogenic features found among the buried soils include: 1. systematic soil horizonation 2. organic matter accumulation--A horizon development 3. development of secondary soil structure 4. development of thin, discontinuous to thick, continuous cutans-- secondary clay coatings in B horizons 5. common secondary iron and manganese oxide coatings and concretions.	1. Below buried soils oxidized and reduced colors present 2. Secondary, sub-vertical jointing with common secondary weathering changes. 3. common secondary iron and mangenese oxide coatings and concretions (including 'pipestems').	Secondary, sub-vertical joints present; secondary iron oxide staining along joints.

in the emergency spillway exposures.

Quaternary Strata in the Emergency Spillway

Holocene Alluvium and Colluvium

General. Pre-Saylorville Late Holocene alluvium is exposed along the north-eastern wall (left bank) of the emergency spillway channel (Fig. 2, cross-sections A-D). The Holocene alluvium and colluvium consists of thin, reworked sediments (colluvium and pedisediment) on hillslopes (some of these are now paleohillslopes, buried by fill placed during construction of the original emergency spillway channel) which descend into low-order drainageways that occur (or occurred) on the modern land surface. Alluvial fills in these low-order drainageways may consist entirely of fine-grained alluvial fills or of fining-upward sequence composed of basal sands or gravels overlain by fine-grained alluvium. Some drainageways contain multiple fill units. Section 2 shows many of the characteristic features of the Holocene alluvium and colluvium in the emergency spillway exposures. The following discussion details properties of the alluvium there. In this area (Section 2) the top of the exposure approximates the original land-surface. At the southeastern edge of Section 2 a wedge of man-made fill composed of abundant clasts of Pennsylvanian rocks in a loamy matrix buries a former small northwest- to southeast trending tributary to the Des Moines River (Fig. 2, cross-section C-D). Prior to grading of the emergency spillway area this tributary ran transversely across what is now the emergency spillway and extended north-westward at the location where the access road (Fig. 1) crosses the emergency spillway today.

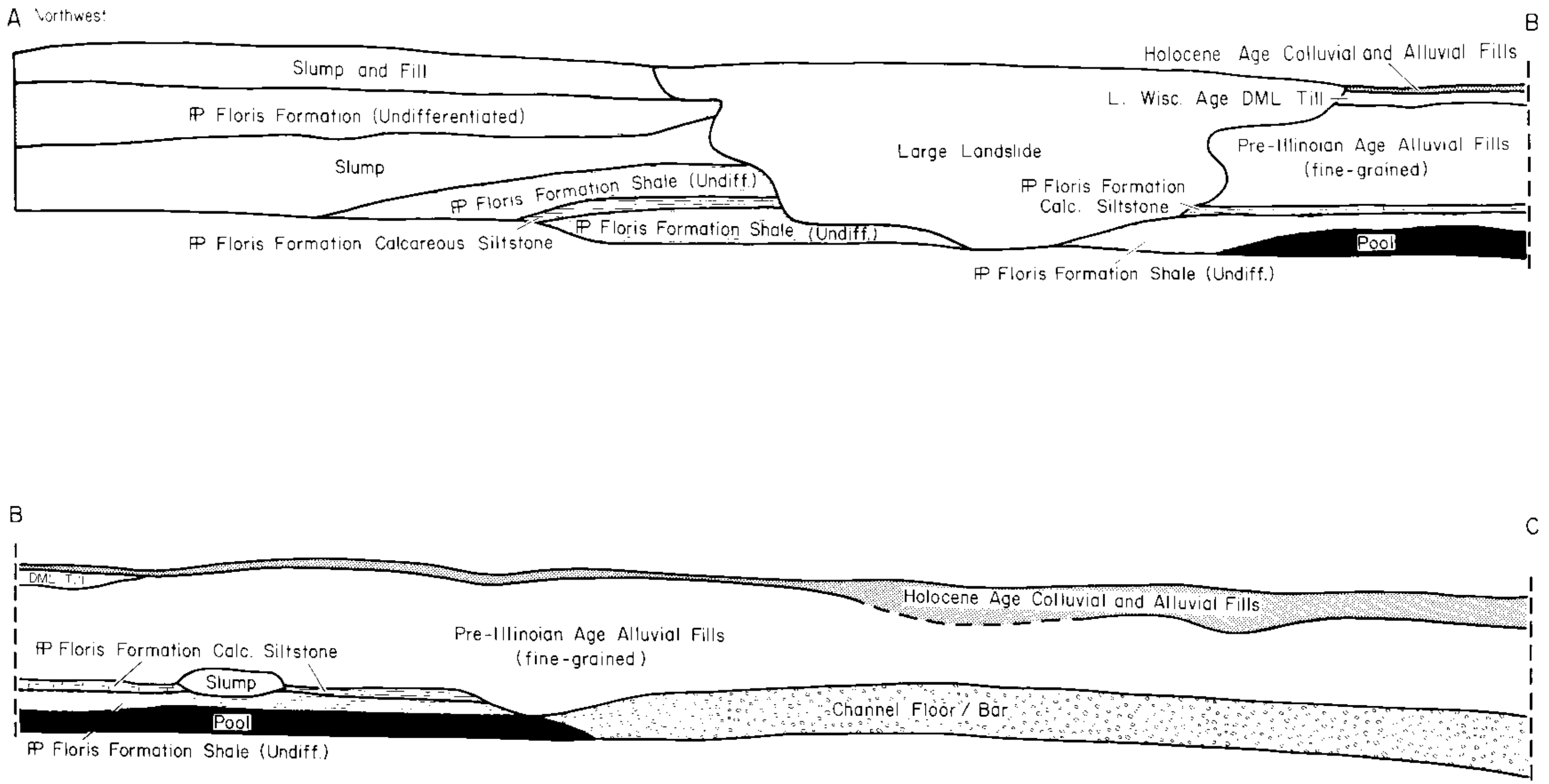
The pre-dam Holocene alluvium occurs as a wedge of deposits paralleling the former tributary course. The Holocene alluvium rests unconformably on Pre-Wisconsinan alluvium on the north end of Section 2 and on Wisconsinan loess in the central and southern portions of this area.

Although no datable material was recovered from the upper alluvial deposits at this section, two lines of evidence indicate that the alluvium is Holocene in age: 1) the superposition of the alluvium on the Wisconsinan-age loess indicates that the alluvium is younger than the loess and 2) previous experience with Holocene alluvium in the Des Moines River valley and its tributaries indicates that this alluvium has primary and secondary features comparable to Holocene alluvium in the area. These properties are discussed below.

Primary Properties. Holocene alluvium in Section 2 has been extensively modified by post-depositional pedogenic (soil) processes, and therefore few primary depositional features are evident. The alluvium has a silt loam to loam texture, having originated from erosion of loamy Des Moines Lobe glacial deposits and pre-Wisconsinan alluvium as well as silty late Wisconsinan-age loess. In some places where the Holocene deposits are cut into the Pre-Wisconsinan alluvium, a stone line occurs at the base of the Holocene deposits. This stone line is a log deposit derived from erosion of the older alluvium. In a few parts of the section, the lowermost part of this unit exhibits faint stratification consisting of thinly-bedded pebbly sands and gravels.

Two distinct Holocene alluvial fills are present at Section 2A. The distinction between the two is easiest to recognize on the basis of secondary alteration features, which will be described below, but the two are also slightly different in texture. The uppermost alluvial unit contains significantly more sand and then the underlying unit.

Secondary Properties. Secondary alteration (soil) features have extensively modified the Holocene alluvium in Section 2. All these alterations fall in the category of pedogenic—those associated with soil development. Small valley alluvial units, especially those deposited marginal to a channel, usually accumulate slow enough so that they are influenced by pedogenic (soil) processes during, as well as subsequent to their accumulation (Riecken and Poetsch 1960). Soils developed in these situations are referred to as 'cumulic' and are characterized by relatively thick soil horizons. In addition, since soil development is occurring during accumulation of the unit, the soil profile tends to "grow upward" and former surface (A) horizons become


A Northwest
B
Slump and Fill
IP Floris Formation (Undifferentiated)
Slump
IP Floris Formation Shale (Undiff.)
IP Floris Formation Calcareous Siltstone
IP Floris Formation Shale (Undiff.)
Large Landslide
IP Floris Formation Calc. Siltstone
IP Floris Formation Shale (Undiff.)
Holocene Age Colluvial and Alluvial Fills
L. Wisc. Age DML Till
Pre-Illinoian Age Alluvial Fills (fine-grained)
Pool
B
C
DML Till
IP Floris Formation Calc. Siltstone
Slump
Pool
IP Floris Formation Shale (Undiff.)
Pre-Illinoian Age Alluvial Fills (fine-grained)
Holocene Age Colluvial and Alluvial Fills
Channel Floor / Bar

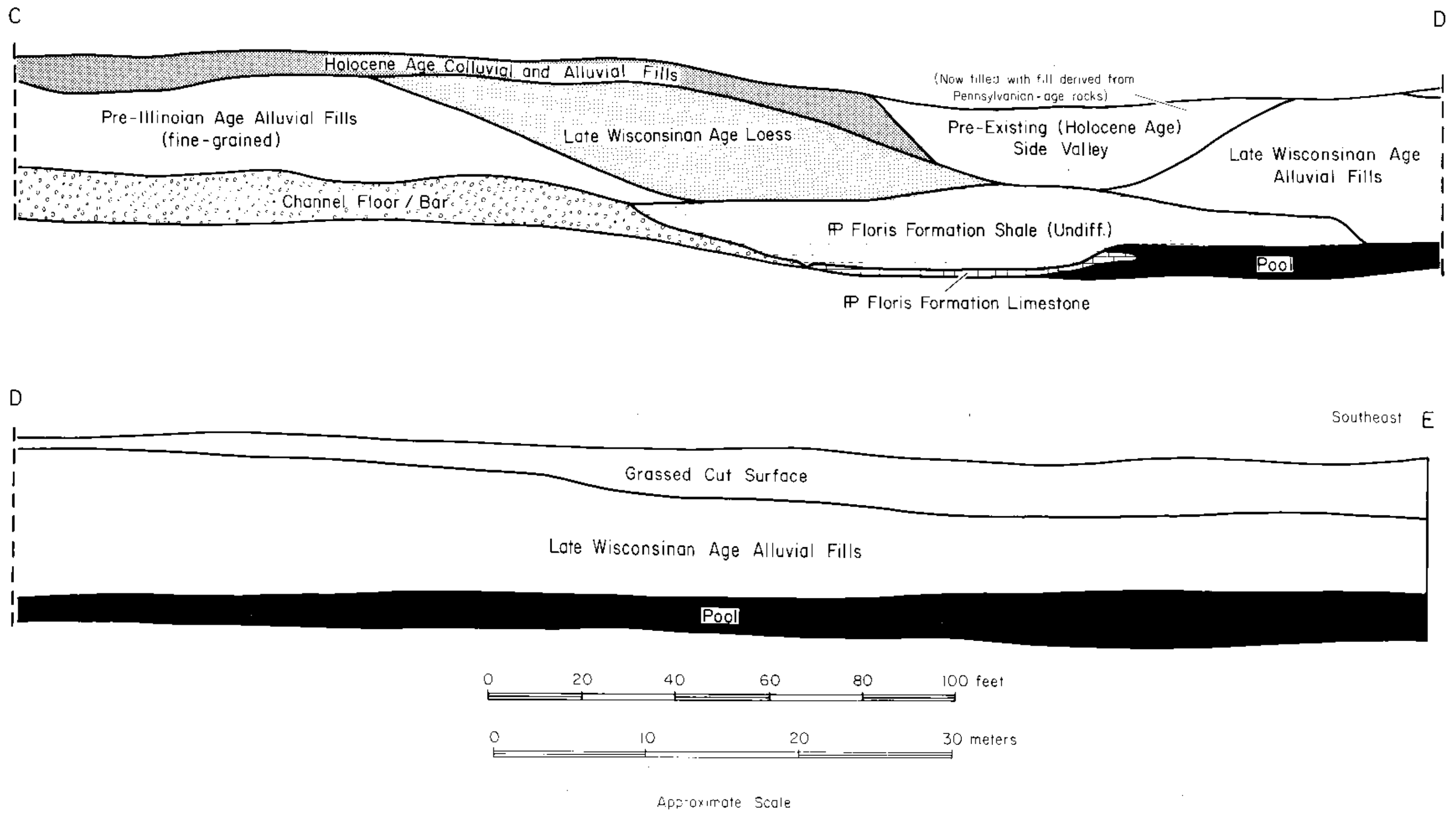


Figure 2. Cross-section along the left (northeast) bank of the emergency spillway beginning approximately at the access road (Station A). Redrawn from a photo mosaic.

subsurface (B) horizons as the deposit continues to slowly accumulate.

Forty-six centimeters of fill bury the pre-construction surface at the described section (2A). Underlying the fill, the uppermost Holocene alluvial fill is marked by the secondary development of E and Bt soil horizons (for a general discussion of soil horizon characteristics and nomenclature see Bettis, 1984; Guthrie and Witty, 1982). An E horizon is a soil horizon usually associated with forest vegetation on the landscape, and is a horizon of eluviation in which iron oxides, organic matter and clay are stripped from the soil matrix giving the materials a characteristic grayish brown color and platy secondary soil structure. The stripped iron oxides, clays and organic matter are transported to the underlying B soil horizon where they accumulate as secondary coatings or concretions. The textural analysis of this zone shows that it is depleted in clay relative to the remainder of the alluvium. An E horizon is a subsurface soil horizon; that forms beneath darker, relatively organic-rich A or O topsoil horizons. The absence of A or O horizons at this site probably resulted from removal of the upper few centimeters of alluvium prior to or during construction of the original emergency spillway.

An argillic (Bt) soil horizon (a type of secondary clay-enriched B horizon, Soil Survey Staff, 1975) is present beneath the E horizon in the uppermost alluvial fill. This is the zone where clay, iron oxides, and other compounds leached from the overlying horizons accumulate. This horizon has the blocky structure and secondary clay accumulations (cutans) along ped (secondary soil structural units) faces that is characteristic of Bt horizons.

The top of the second Holocene alluvial fill occurs at a depth of 96 cm in Figure 3. The contact between fills is marked by lithologic and pedologic discontinuities. The top of the second alluvial fill has a buried soil developed in it which, in turn, has been modified by later soil-forming processes in the overlying thin alluvial fill. The difference between the upper and lower alluvial fills is marked as the lower alluvium becomes much darker, the soil structure changes for subangular blocky to angular blocky, and the cutans (secondary clay coatings) change from thin and discontinuous to thick and continuous. These changes, as well as stratigraphic relations across the outcrop (Fig. 3), indicate the presence of a buried soil developed in the lower alluvium. The dark color of this horizon just below the contact suggests that it originally was the A (surface or topsoil) horizon of the soil developed in the basal Holocene alluvial unit prior to burial by the uppermost alluvium. The thickness of the dark horizon suggests that this was an overthickened (cumulic) A horizon and that the soil originally developed under the influence of grass vegetation, a change in vegetation from that influencing soil development in the modern surface soil.

This original soil has been extensively modified by subsequent burial and pedogenesis. As the soil surface was buried, the former A horizon became the Bt horizon of the modern surface soil developing in the thin overlying alluvium. Iron oxides, clay, and other materials moving through the overlying alluvium accumulated in the buried A horizon as a result of a change in porosity and the complexing and flocculating properties of organic matter in the buried A horizon.

Below a depth of 156 cm the lower Holocene alluvium is less altered pedogenically than above. Several pedologic features such as cutans and soil structure are still discernible however. This zone is the lower portion of the buried solum and the place where the few remaining primary features in the Holocene alluvium can be observed. The colors of the Holocene alluvium in this section indicate that the soils here are well-drained. The iron compounds in these deposits are oxidized. Mottles within the buried A horizon indicate that at times in the past this zone became saturated for short intervals, allowing free iron in the deposits to migrate to areas where it accumulated as mottles. The change in porosity and soil structure from the overlying Bt1 horizon to the buried A horizon (2Ab) may have been sufficient to promote saturation of the 2Ab horizon.

Depositional Environments. Several properties of the Holocene alluvium at this site give us insights about its environment of deposition. The pebble lag or sandier zone at the base of the unit

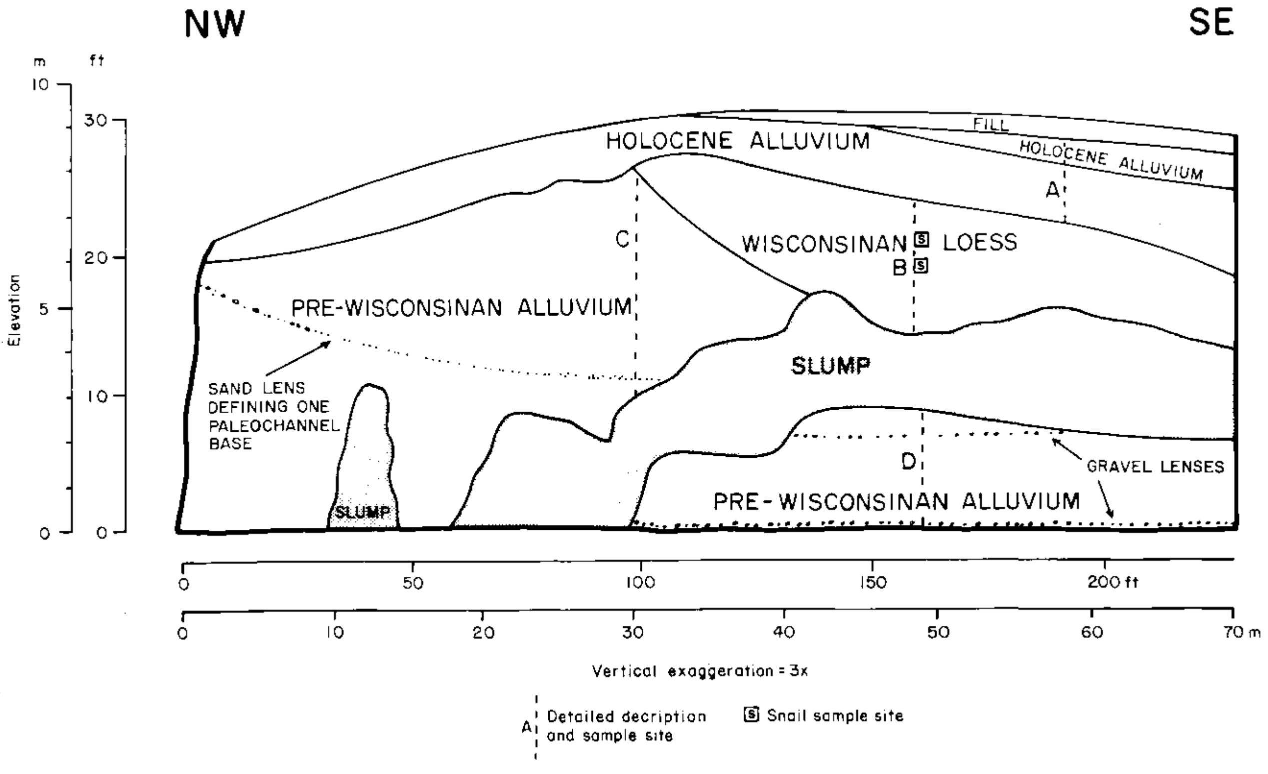


Figure 3. Cross-sectional sketch of the generalized stratigraphy at section 2.

indicates an erosional episode preceded deposition of the rest of the unit. The general lack of bedding features and the thinness of the unit suggest that this alluvium was deposited marginal to a channel, probably near the edge of the valley. The buried soil, as well as the properties of the surface soil indicate that alluvium accumulated episodically. All these features are consistent with the interpretation that this is alluvium associated with a small tributary valley. The alluvium probably accumulated in the footslope or toeslope position at the base of the former valley slope.

The oxidized colors of the deposits and the presence of an argillic soil horizon indicate that the alluvial deposits are early to middle Holocene in age. These properties are characteristic of alluvium of this age in the Midwest (Bettis, 1983). Dry conditions and resultant lowered water tables during the middle Holocene promoted oxidation of alluvial deposits throughout the region.

Late Wisconsinan-Age Glacigenic Deposits (Des Moines Lobe deposits)

General. The Saylorville Emergency Spillway is located a scant 9 miles (15 km) north of the southern terminus of the Des Moines Lobe of the Wisconsinan-age Laurentide ice sheet. Because of the plethora of radiocarbon dates from the base of the Des Moines Lobe in this immediate vicinity (Ruhe, 1969; Kemmis et al., 1981), no wood from the Des Moines Lobe basal till was submitted for radiocarbon dating. Dates from the area consistently range around 14,000 RCYBP.

It appears Quaternary glaciers in much of the Midwest carved a flat bed on easily eroded substrate materials (such as older Quaternary deposits) by eroding off subglacial highs and filling in subglacial lows. Thin ice and a considerably short time for ice occupation led to the inability of the Des Moines Lobe ice to erode a flat bed in the Saylorville

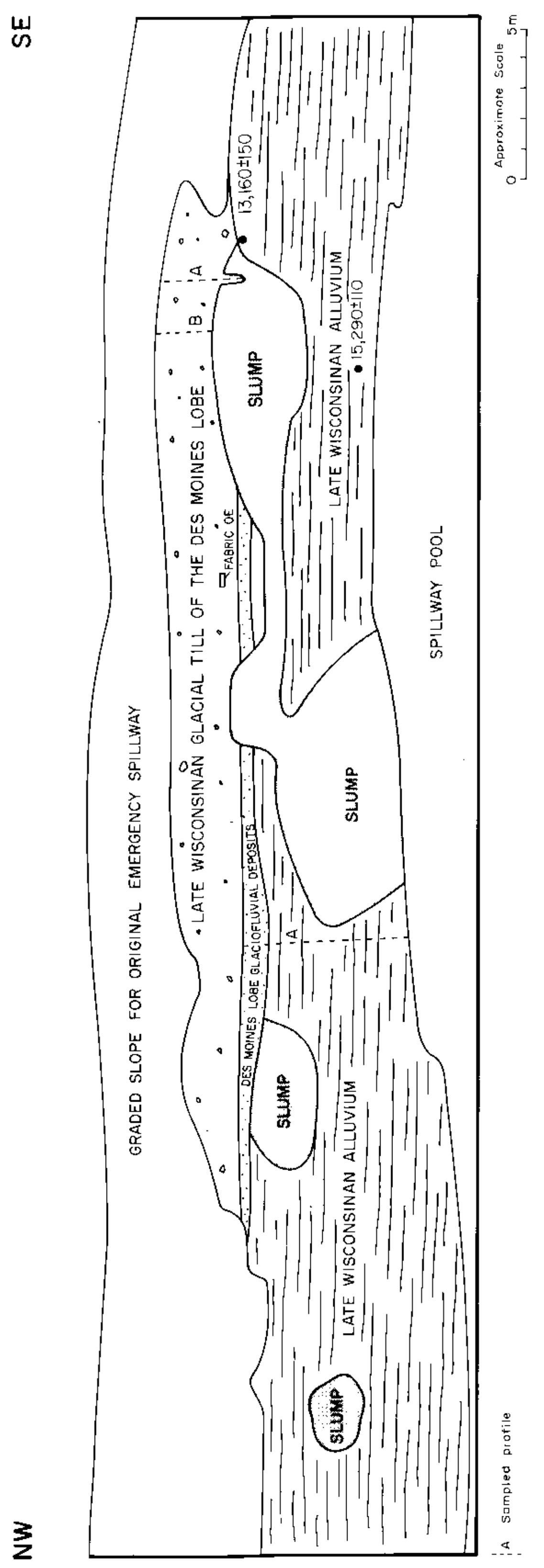


Figure 4. Cross-sectional sketch of the generalized stratigraphy exposed at Section 0. Redrawn from a photo mosaic.

area. The result is greater local relief on the sub-Des Moines Lobe surface than farther to the north. This greater local relief on the sub-Des Moines Lobe surface can be seen, on the small scale, in the emergency spillway exposures where Des Moines Lobe deposits are locally preserved in broad, shallow lows on the top of older Quaternary deposits (Section 0, Fig. 4; Section 1, Fig. 5; Fig. 2, cross-sections A-C).

Truncation of the surface of the Des Moines Lobe deposits resulted both from subaerial erosion as the Des Moines River valley periodically downcut and from grading during construction of the original emergency spillway. Comparing elevations of adjacent divides on both the east and west sides of the valley surrounding the emergency spillway suggests that on the order of 15 to 20 m (50 to 60 ft) of the Des Moines Lobe deposits have been removed.

The Des Moines Lobe deposits present in the Saylorville Emergency Spillway are variable. The bulk of the deposits are diamictons; that is, poorly-sorted, pebbly silt loam, clay loam, and loam. These diamictons vary in composition and character between the locations where they are exposed in the spillway. However the various sedimentologic properties of the diamictons exposed in the emergency spillway all suggest that the diamictons were deposited subglacially. The diamictons are thus interpreted to be 'basal tills,' following the terminology of the Dreimanis (1976).

The Des Moines Lobe deposits also include thin glaciofluvial deposits which occur beneath the basal tills at Section 0 (Fig. 4) and Section 1 (Fig. 5). The following sections describe the properties and depositional environments of these various late Wisconsinan-age Des Moines Lobe properties.

Primary and Secondary Properties: Diamicton deposits. The Des Moines Lobe diamicton deposits still remaining in the emergency spillway exposures are thin, ranging from 1.75 to 3 m (5 to 10 ft) in thickness. Basal tills of the Des Moines Lobe are generally massive and uniform in composition (Kemmis et al., 1981), whereas those exposed in the emergency spillway are highly variable in nature, and will be discussed section by section.

Section 1B (Fig. 5) is the simplest section, and resembles "typical" Des Moines Lobe basal tills. Except for the upper half meter (1 to 2 ft), the Des Moines Lobe diamicton is a classic matrix-dominated diamicton: a massive, poorly sorted, non-stratified deposit in which various sized pebbles are individually inset in a fine-grained silt loam matrix. This massive diamicton, like massive basal tills from many other portions of the Des Moines Lobe (Kemmis et al., 1981), has extremely uniform matrix texture. This diamicton is considerably lower in sand content than is typical for basal tills of the Des Moines Lobe (Kemmis et al., 1981). This lower sand content, with a corresponding increase in silt content, is likely the result of the Des Moines Lobe incorporating the local Wisconsinan-age loess substrate and mixing it in with farther-traveled debris. Kemmis and Lutenegger (unpublished) have found a systematic increase in silt content southward (and corresponding decrease in sand content) in massive Des Moines Lobe basal tills near the southern terminus of the Des Moines Lobe. From Ames south, Wisconsinan-age loess becomes the dominant substrate material beneath the Des Moines Lobe deposits. The massive Des Moines Lobe diamicton at Section 1B is unweathered: unoxidized (dark gray), unjointed (massive) and unleached. No secondary oxidation or various concretions or coating occur. Wood fragments are common throughout the diamicton. The diamicton has an undeformed, planar, erosional lower contact with late Wisconsinan-age alluvium or channel fills of glaciofluvial deposits incised into the late Wisconsinan-age alluvium (Fig. 5).

The upper half meter (1 to 2 ft) at Section 0 is also a diamicton, but it is extensively jointed with sub-horizontal joints spaced at 1 to 3 m intervals (1/3 to 1 1/3 in) and occasional vertical joints spaced several centimeters (2 to 6 in) apart. The diamicton matrix is unoxidized (dark gray), while the joints are oxidized and have some secondary iron oxide coatings along them. it is uncertain what has cause this sub-horizontal jointing. Three possibilities include: shearing related to lodgment depositional processes (Dreimanis, 1976, among many others); vertical stress relief resulting from removal of overlying material, perhaps enhanced by residual,

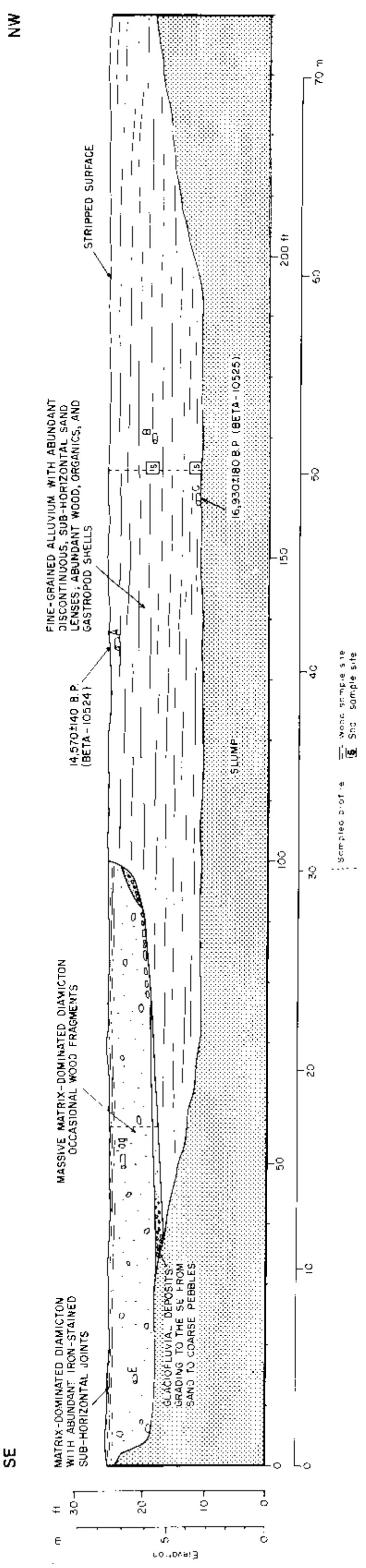


Figure 5. Cross-sectional sketch of the stratigraphy exposed at Section 1.

glacially-induced stresses within the till; or disturbances caused by stripping and grading of original emergency spillway channel floor.

As at Section 1B, the Des Moines Lobe diamicton at Section 0 also has a sub-horizontal, planar, erosional lower contact on Des Moines Lobe glaciofluvial deposits. However, the character of the diamicton is wholly different form that at Section 1B. An indistinct, sub-horizontal horizon of individual cobbles occurs 0.15 to 0.5 m (0.5 to 1.5 ft) above the base of the diamicton across much of the exposure. The diamicton includes extremely abundant wood fragments of all sizes up to log size. This section, in fact, probably contains as much or ore woos and log fragments than any other till exposure in the Midwest. The diamicton also includes abundant inclusions of fine-grained sediment, much of which appears to be loess. When this exposure was originally studied in the Fall of 1984, all of the deposits were unoxidized, dark gray. Tracing (seeing) the contacts between the fine-grained, loess-like deposits and the fine-grained diamicton was extremely difficult. By the Fall of 1985, differential oxidation of the deposit types on the outcrop face has made identification and delineation of the units possible. Many of the fine-grained deposits occur as large, lenticular, imbricated block inclusions 1 to 2.5 m (3 to 8 ft) long, 0.15 to 0.3 m (0.3 to 1 ft) thick, dipping to the W-NW (roughly parallel to the paleovalley crossing the emergency spillway channel) at 25 to 25 degrees.

Small-scale channel fills, up to 0.2 m (8 in) wide and 0.15 m (6 in) deep, occur interbedded in the diamicton at a few locations along the exposure; 2 occur along the left (NW) side of the outcrop. These channel fills appear virtually undeformed, but they have been rotated somewhat from their original depositional orientation.

The upper half meter of diamicton across the outcrop, like that at Section 1B, is extensively jointed with numerous, closely-spaced, sub-horizontal joints. The rest of the diamicton body includes conjugate sets of dipping joints, most of which appear to have slickensides developed along them. On the original outcrop, the diamicton and associated inclusions were all unweathered, unoxidized (dark gray), unleached. During the past year and a half the deposits have begun to oxidize.

The diamicton at Section 10 was poorly exposed, but it was entirely different than those at Section 0 and 1B. It appeared to be a massive, matrix-dominated diamicton. The matrix texture of the diamicton was very variable, however, and ranged from clay loam to loam. These textures are anomalous for Des Moines Lobe diamictons, and include some of the highest clay percentages yet encountered. The Des Moines Lobe diamicton at this site is also anomalously weathered, the high degree of secondary alteration being similar to that found in weathered Pre-Illinoian age tills. At the described section, the diamicton is leached throughout. The upper part of the unit is jointed, and oxidized; abundant secondary mottles are present. The described section must have been near the original land surface, accounting in part for the observed weathering. The relatively high degree of secondary alteration at this site may also be related to the high content of locally-derived Pennsylvanian clasts. Decomposition of pyrite from these clasts may account for the oxidation, leaching, and abundant mottling. This section is located nearest the highest portions of the Pennsylvanian subcrop, and the high proportion of Pennsylvanian clasts is probably related to the local incorporation of these lithologies. The high clay content of the diamicton at this section may also be related to local incorporation of Pennsylvanian mudstones, and perhaps to weathering-related decomposition of these mudstone clasts in the diamicton. Observations to confirm these contentions could not be made because of the poorly-exposed nature of the upper part of this section, but these explanations do at least provide a believable cop out.

Primary and Secondary Properties: Glaciofluvial deposits. Des Moines Lobe glaciofluvial deposits occur in Section 0 and 1. They are thin, less than 1 m (3 ft) thick, incised into late Wisconsinan-age alluvial deposits, and are truncated by planar erosion surfaces of overlying Des Moines Lobe diamicton deposits. At Section 0 the glaciofluvial deposits consist of thin, lenticular beds of planar-stratified and low-angle cross-stratified sands and silty sands. The top of this bedding has been truncated by the planar, sub-horizontal base of the Des Moines Lobe diamicton.

At Section 1B the glaciofluvial deposits consist of small-scale channel fills. These fills are characterized by simple vertical accretion with planar bedding mimicking the channel geometry. Like the glaciofluvial deposits at Section 0, these deposits are undeformed, but erosionally truncated by the planar base of the overlying Des Moines Lobe diamicton. At both sections, the Des Moines Lobe glaciofluvial deposits are unoxidized and unleached (i.e., unweathered)

Depositional Environment: Diamicton deposits. In recent years geologists have become aware of the great complexity of sedimentation in glacial environments (note the complexity shown in Boulton, 1971, 1972; Sugden and John, 1976; Lawson, 1979a; Eyles and Miall, 1984, for example). This complexity, unfortunately, can lead to problems in interpretation. There can be considerable overlap in facies between different glacial depositional environments, and in those cases where facies or structures indicative of deposition in a single depositional environment are absent, a unique, unequivocal interpretation may not be possible (Kemmis et al, 1985). Such a situation exists for the Des Moines Lobe diamicton deposits exposed in the emergency spillway. Primary depositional features present allow us to confidently interpret the diamictons as 'basal till,' deposits formed subglacially, although more refined interpretations of precise depositional processes, such as lodgment (by actively moving ice at the pressure melting point) or melt out (by passive melt-out from stagnant ice) remain problematic.

Four primary features of the Des Moines Lobe diamicton deposits suggest deposition in a subglacial environment: 1) planar erosion surfaces at the base of the deposits; 2) imbricated inclusions of local substrate materials (such as loess) and associates joint (fault) structures in the diamicton; 3) consistently oriented wood fragments and pebble fabrics in the diamictons; and 4) uniform matrix textures in the massive diamictons. Planar erosion surfaces are indicative of erosion by an actively moving, rigid ice mass. The imbricated block inclusions of local substrate are typical of compressional flow regime which can occur either in basal ice near a glacier terminus or against the stoss (upstream) side of an obstacle on the glacier bed.

Consistently-oriented wood fragments and pebble fabrics were found in the Des Moines Lobe diamicton at Section 0. The 'fabric' orientation of particles in a deposit may be a useful indicator of depositional process or environment. The pervasive stress field in glaciers imparts a preferred orientation to particles in the deposit (till) depending on flow conditions (compressive and extending) and particle shape (Holmes, 1941; Boulton, 1971; Drake, 1974; Lawson, 1979b; among many other studies). Resedimentation processes in the glacial environment such as sediment gravity (debris) flows, spall collapse, etc., lackthe strength or pervasive stress field to promote a consistent, well-oriented fabric in the deposits (Lawson, 1979b; Boulton, 1971; among others).

The fabrics of wood fragments and prolate-shaped (elongate) pebbles in the diamicton at Section 0 are in the range of those characteristic of subglacially-deposited diamictons (basal tills.). Fabric measurements on wood fragments were made because wood was so abundant in Section 0 (58 fragments were measured across the outcrop) and because twigs and logs are of ideal elongate, 'prolate' shape. The fabric for the wood fragments is roughly biomodal with a dominant W-NW-E-SE mode and weak N-S mode. The dominate mode is parallel to the axis of the paleovalley crossing the emergency spillway channel and is in the same direction as the imbricated block inclusions of loess. It is uncertain why there is a bimodal fabric for the wood fragments. Perhaps some of the fragments were rolled along transverse to the direction of greatest stress while others were 'streamlined' parallel to the greatest stress direction.

Just one pebble fabric was taken in the diamicton. This fabric was measured over a small area near the center of the outcrop (Fig. 4), 0.5 m (1.5 ft) above the base of the Des Moines Lobe diamicton and approximately 0.5 m 91.5 ft) below one of the imbricated block inclusions of loess. Twenty-five elongate, prolate pebbles were measured. The pebble fabric is very similar to that of the wood fragments, suggesting that both had been oriented by the same pervasive stress field.

Finally, the massive, textural homogeneity of the Des Moines Lobe diamictons at Section 1B and 0 are also typical of basal tills on the Des Moines Lobe (Kemmis et al., 1981). Various resedimentation processes (e.g., Lawson, 1979a, 1982) cause some resorting and the development of a host of sedimentary structures (basal tractional gravels, winnowed horizons, water-escape structures, graded bedding, load structures, etc., are all possible) none of which are present in the massive, texturally-uniform diamictons.

Diamictons deposited subglacially (basal tills) may be deposited either by 'lodgment' from actively moving ice at the pressure melting point or passively by melt-out from stagnant ice. As yet, the authors have not observed any structures clearly definitive of deposition solely by one or the other of these processes. A melt-out origin might be favored because there is a planar, undeformed lower contact even though large-scale, high-angle deformation structures (the imbricated block inclusions) occur less than a meter (3 ft) above the contact. Such deformation could occur in debris-rich basal ice unrelated to glacial erosion at the spillway exposure; subsequent melt-out from the debris-rich basal ice would later preserve the imbricated structures. In any case, at this time there are few structures present in the emergency spillway exposures which indicate specific depositional processes for the basal tills.

Depositional Environment: Glaciofluvial deposits. Des Moines Lobe glaciofluvial deposits are preserved at Section 1B and 0. At section 1B the glaciofluvial deposits are dominantly small-scale channel fills less than one meter (3 ft) deep and from 1 to a few meters (3 to 15 ft) wide incised into the underlying late Wisconsinan-age alluvium. The channel fills are dominantly simple vertical-accretion fills in which the stratification mimics the channel geometry. The fills are dominated by planar-bedded sands and silty sands, suggesting deposition in relatively low energy glaciofluvial channels.

At Section 0 the edges of the glaciofluvial deposits are not exposed, and thus it is not possible to know the geometry and scale of the channel there. The total sequence preserved is 1 meter (3 ft) or less in thickness, and consists of thinly-bedded sands and silty sands. These strata suggest deposition by vertical accretion on the channel floor and migration of small-scale sand waves. This sequence, too, does not appear to have been a very high energy glaciofluvial environment. It is uncertain if the glaciofluvial deposits at either Section 0 or 1B were proglacial or subglacial deposits.

Wisconsinan Alluvium

General. Fine-grained late Wisconsinan-age alluvium is extensively exposed in the central and downstream portions of the emergency spillway (Section 0, Fig. 4; and Section 1, Fig. 5). At section 1 the alluvium is buried by Des Moines Lobe basal till (Dows Formation, Alden Member). Prior to grading of the emergency spillway, Des Moines Lobe till probably covered the alluvium over the entire area. At Section 0D the late Wisconsinan-age alluvium buries Wisconsinan-age loess. The base of the alluvium is buried by slump at the other sections. Four radiocarbon dates from wood buried within the alluvium at Section 0 and Section 1 indicate that the alluvium accumulated between about 17,000 and 14,000 years ago (Figs. 4 and 5).

Primary Properties. This unit consists of laminated to thinly-bedded fine-grained (dominantly silt loam) alluvium with thin (up to 1 cm thick) discontinuous (lenticular), wavy lenses of fine to medium sand. On fresh exposure the unit is unoxidized and unleached (UU). The fine-grained parts of the deposit are dark gray (N 4/0) while the sand lenses are gray (N5/0). We interpret these colors and the oxidation state indicated by them to be primary features of the deposit. The unit also contains wood and other plant macrofossils, mollusc shells, and fossil insects.

Secondary Properties. Few secondary alteration features are evident in the late Wisconsinan-age alluvium. As a result of the recent exposure of this unit to the atmosphere, portions of it are oxidizing. Oxidation is most pronounced in and around the sand lenses. Fine-grained portions of the deposit also oxidize to an olive brown color. These color changes are surficial and the original, unoxidized colors of the deposit can be observed by scraping and digging into the exposure.

Depositional Environment. Sedimentary structures (bedding features) indicate that this deposit is alluvium. The absence of coarse grains and channel forms indicate that this is not an active channel deposit. The nearly planar bedding, fine texture, and thin, discontinuous lenses of fine to medium sand suggest a relatively low energy fluvial environment. The features observed in this unit in the emergency spillway exposures are consistent with a rapidly aggrading floodplain environment. The thin sand lenses are interpreted as small-scale splay deposits originating during flood events.

The geometry of this unit is very poorly understood. The northern valley wall is present north of the Holocene drainageway which crossed the emergency spillway prior to construction. The southern part of the deposit is unknown, but occurs farther south than the southernmost emergency spillway exposure (Section 0). We suggest that the late Wisconsinan-age alluvium was deposited in a backswamp area associated with a high-order stream valley.

This is the only locality in the state where such fine-grained late-Wisconsinan floodplain alluvium has been observed and described. Fossil plants, molluscs, and insects associated with this deposit provide us with a unique picture of a relatively large, high-order stream environment just prior to the Des Moines Lobe glacier advance in central Iowa.

Wisconsinan Loess

General. Wisconsinan-age loess is exposed at Section 2 and 10 in the emergency spillway (Fig. 1). This deposit is buried by either Holocene alluvium (Section 2) or by Des Moines Lobe Dows Formation (Alden Member) glacial tills (Section 10). The loess, in turn, buries pre-Wisconsinan age alluvium in these exposures.

Loess beneath Des Moines Lobe glacial deposits is a common occurrence in the southern portion of the Des Moines Lobe landform region (Ruhe, 1969; Kemmis et al., 1981). Numerous radiocarbon dates indicate that ice of the Des Moines Lobe glacier buried the loess around 14,000 years ago. In Illinois, Wisconsinan loess found in a similar stratigraphic position (buried by Wisconsinan-age Wedron Formation) is rock-stratigraphically classified as a formation, the Morton Loess. The loess began accumulating in south-central Iowa around 21,000 years ago. Loess buried beneath the Des Moines Lobe till is equivalent to portions of the loess that form the surficial deposit outside the margins of the Des Moines Lobe.

Primary Properties. Loess exposed in the emergency spillway has properties typical of that found beneath Des Moines Lobe glacial deposits elsewhere. The deposit is silt loam in texture with low sand content (less than 5 percent here). The loess is massive, unbedded. The matrix is calcareous and mollusc shells are common.

Secondary Properties. Post-depositional alteration of the loess has produced many of the morphologic features observable in the deposit today. Most of these alterations are weathering-related, but are not called pedogenic here since they have not resulted in the development of soil horizons and secondary soil structure. Some of the most obvious features of the loess here are its grayish brown color with brown mottles and secondary, vertically elongate iron concretions (pipestems). The grayish brown colors, mottles, and pipestems are genetically related. When loess is this color and has mottles and/or secondary accumulations of iron oxides (pipestems or tubules) associated with it, it is referred to as deoxidized (Hallberg et al., 1978). Loess exhibiting these colors has been found to have low total free iron content relative to loess exhibiting yellow and browner "oxidized" colors (Daniels et al., 1961; Bradbury et al., 1977; Hallberg et al., 1978). Originally the loess, since it is a windblown deposit, was probably in an oxidized state. Shortly after its deposition, or following burial by Des Moines Lobe glacial deposits, the loess became saturated. Iron compounds were mobilized and migrated toward macropores or other areas where a change in Eh (oxidation potential) caused precipitation as mottles or concretions. In the lower portion of Section 10 the loess exhibits a dark greenish gray color (5GY 4/1). When loess is this color it is referred to as unoxidized (Hallberg et al., 1978). Iron ions in this zone tend to be dominated by the ferrous (Fe2+) form. Also associated with the unoxidized zone of the loess in Section 10 are smudges of organic material. The presence of these organics may promote the unoxidized state of the loess here as microbial decomposition of the organic matter consumes any oxygen reaching this zone. This would retard segregation of the soluble iron compounds under the saturated conditions existing in the deposits.

Soft secondary accumulations of carbonate minerals (calcite) are abundant in the loess at Section 2. Carbonate concretions are ubiquitous in unleached loess section in Iowa. The mobilization (dissolution and movement in with the soil solution) of carbonate ions in the loess is primarily produced by weathering associated with soil development at the land surface. The secondary carbonate concretions form when carbonate in solution segregates and precipitates lower in the weathering zone profile as the soil water solution becomes saturated with respect to calcium carbonate. Accumulation of secondary carbonates is indicated in standard weathering zone terminology in the descriptions by the arabic numeral 2 at the end of the weathering zone designation; for example MRU2 (Hallberg et al., 1978).

Section 10 also exhibits secondary properties associated with soil development in the lower 84 cm of the loess. The organic smudges in this part of the deposit accumulated when this deposit formed at the land surface during the Wisconsinan. These are equivalent to O or A (topsoil) horizons which develop at or near the present land surface as result of the accumulation of litter, shallow roots and other organic matter. Another indication that his zone has been altered by pedogenic activity is the fact that it is noneffervescent (leached). Loess is originally calcareous when deposited. This zone was probably leached of primary carbonates when it was near the land surface.

This lower zone at Section 10 is correlative with the 'basal loess sediment,' an informal recognized in the lower portion of the Wisconsinan loess throughout Iowa. This zone accumulated during the onset of loess deposition in Iowa when the rate of loess deposition was slow enough that the deposit was often leached before being buried. In many areas a paleosol, the 'basal loess paleosol,' is developed into the basal loess sediment. The Farmdale Soil is in this identical stratigraphic position in Illinois (Follmer, 1983).

Another phenomena often associated with the basal loess sediment is a mixing zone at the base of the deposit where subjacent material is mixed with lower portions of the basal loess sediment. Such a mixing zone is evident in the particle-size plot of Section 10. The lower approximately 25 cm of the "loess" contains much more sand than the overlying loess because of mixing with underlying pre-Wisconsinan deposits. This mixing probably resulted from biogenic activity and slopewash when this part of the section constituted the land surface at the beginning of loess deposition.

Depositional Environment. Late Wisconsinan-age loess was deposited in south-central Iowa on an eroded landscape with surface relief similar to that present south of the Des Moines Lobe today. Soils of variable morphology were developed on that landscape. At the time loess deposition began the landscape was occupied by a spruce-larch forest (Baker et al., 1980). Based on pollen studies in eastern Iowa the forest was probably closed at the onset of loess deposition, then began to open as loess deposition rates increased (Baker et al., 1980; R. G. Baker, personal communication). As the loess fell, it accumulated in several environments on the land surface. Three of these are represented in the emergency spillway. Loess at Section 2 feel on a well or moderately well-drained portion of the landscape, while that at Section 10 fell on an adjacent, poorly-drained area. Both Sections 10 and 2 are located on the northern margin of a pre-Des Moines Lobe valley. Aspects of the paleotopography will be discussed in a following section. The third environment in which loess fell in this area is on an actively aggrading Wisconsinan-age floodplain discussed previously.

Pre-Wisconsinan Age Alluvial Fills

General Aspects. Another unique feature of the Quaternary exposure in the emergency spillway is the presence of relatively fine-grained pre-Wisconsinan age alluvium. The alluvium fills a valley cut into the Pennsylvanian rocks south of the access road crossing the emergency spillway (Fig.1). Wisconsinan-age loess, Des Moines Lobe till and glaciofluvial deposits, and Holocene alluvium/colluvium bury the pre-Wisconsinan alluvium. Various unconformities (erosion surfaces and/or soils) separate the pre-Wisconsinan and Holocene deposits.

Primary Properties. This unit is the most variable of the Quaternary deposits exposed in the emergency spillway, ranging from fine-grained clay loam to pebbles. Numerous primary sedimentary features are preserved in these sediments. Several fining-upward sequences are present. These usually consist of sand or pebbly loam grading upward to clay loam or silt loam. Often 10-20 cm thick troughs of clast- or matrix-supported pebbles and cobbles occur at the base of a fining-upward sequence. They truncate underlying deposits. The troughs are greater than 10 m (30 ft) in lateral extent. Pebbles and coarser clasts are dominated by local Pennsylvanian lithologies, although erratic clasts are also present.

Secondary Properties. Post-depositional alterations have extensively modified the pre-Wisconsinan alluvium. Paleosols are developed into the upper portion of the pre-Wisconsinan deposits at both Sections 2 and 10. The buried soils are morphologically well expressed. The uppermost paleosol at Section 10 developed on a poorly-drained landscape position. This is indicated by the gray and dark greenish gray matrix colors (5Y 4/1 and 5GY 4/1-5G 4/1) and greenish gray mottles. Slickensides are common in the clay loam textured Bg1b and Bg2b (subsoil) horizons of this paleosol. The slickensides develop as a result of shrink-swell phenomena induced by wetting and drying and/or freezing and thawing. The Cg horizon material beneath this soil also has a dark, reduced color indicative of poor drainage.

In contrast to the soil developed at Section 10, the buried soil developed in the upper portion of the pre-Wisconsinan alluvium at Section 2 is moderately well-drained. The lighter colored brown matrix colors, in conjunction with yellowish brown mottles in the B horizon, indicate that it developed on a moderately well-drained landscape position. This soil also has a Btb horizon (zone where significant secondary accumulation of clay has occurred). The 3Eb and 3EBb horizons above the 3Btb are the zones from which the clay eluviated (moved). The 3EBb horizon also exhibits thin discontinuous silans, zones where the icon and/or clay has been stripped from the sand and silt grains and or where clay- and silt-size quartz has accumulated on the ped faces (Brewer, 1964). From a distance these zones appear as grayish brown patches.

The marked clay bulges in these soils are probably depositional in origin. The profile at Section 2 does show evidence of clay translocation in the form of cutans, but the overlying 3EBb is also clay loam texture. Heavy-textured soils developed into the upper portion of fining-upward sequences are common occurrences on floodplains. Soils developed in heavy-textured deposits also tend to exhibit finer size and stronger grade soil structure than do soils formed under similar conditions in lighter-textured deposits. This phenomena can lead to erroneous interpretations of the relative degree of soil profile development (which is often equated with length of weathering) when comparing soils developed in alluvium of differing textures.

Another buried soil is developed lower in the pre-Wisconsinan alluvial sequence at Section 10 between a depth of 551 and 590 cm. This soil has an AM soil profile and would be classified as an Entisol (soil classification is discussed in a publication by the Soil Survey Staff, 1975). Soils such as this can develop in a very short time in floodplain environments. Mottles are a common feature in the pre-Wisconsinan alluvium. These developed during periods of alternate saturation and aeration as outlined in the discussion of mottles in the loess. Subvertical joints are evident in the lower 4m (13 ft) of Section 10. These may have been produced during dry periods prior to the late-Wisconsinan. Iron oxides have accumulated along the joint faces. The original carbonate status of the pre-Wisconsinan alluvium is unknown. Today the deposit is noncalcareous throughout.

Depositional Environment. Bedding structures, texture of the deposits, presence of fining-upward sequences, and superimposed paleosols all indicate that his is an alluvial deposit. The size of channels observed suggest that this alluvium was deposited in a large valley. The fine texture and general absence of bedding structures in the bulk of the deposit suggest that these are overbank deposits.

The valley was incised into Pennsylvanian bedrock, and its northern valley wall was located at approximately the location of the access road crossing the emergency spillway today. Similar pre-Wisconsinan alluvial deposits are exposed north of the Visitor Center along the eastern shoreline of Saylorville Lake (Bettis and Hoyer, in preparation). The northern valley wall is exposed along the eastern shoreline. In that area Pre-Illinoian age glacial till forms the valley wall. A 'Late Sangamon' Paleosol is developed on the till surface. That paleosol descends into the pre-Wisconsinan alluvium and bifurcates into several, superimposed paleosols developed into the alluvium.

The Latest Holocene: features of the 1984 and 1993 emergency spillway channel ('Saylorville' Canyon)

Besides the spectacular geology exhumed along the floor and walls of the emergency spillway, the channel itself displays a variety of interesting erosional and depositional features. The Pennsylvanian strata have locally influenced channel erosion in a number of ways. The stepped longitudinal profile in the Pennsylvanian-age rocks results from the differing erodability of the various Pennsylvanian strata. Related to this lithologic control is the undercutting of more competent rocks (such as the Swede Hollow Fm. sandstone) as softer underlying rocks (such as Swede Hollow Fm. shales) were eroded away.

In map view, the erosion of the Pennsylvanian rocks takes on a V-shape widening down channel. Presumably this shape results from greater velocities, and hence greater erosion, in the center of the emergency spillway channel.

In the uppermost reaches of the emergency spillway channel, above where the Swede Hollow Fm. sandstone is breached, both a main and side channel system were cut in the overlying fill materials. Downstream of the area of bedrock control in the channel, two pools, part of a pool-and-bar sequence, were scoured in the Quaternary deposits (Fig. 1). Also downstream, the valley widens in two loops along the left bank at described Section 0 and 2 (Fig. 1). In both cases, the widening resulted where flows in the spillway were able to easily excavate cohesionless materials in the emergency spillway walls: at Section 0 stratified glaciofluvial sands between the Des Moines Lobe till and fine-grained late Wisconsinan-age alluvium (Figure 4) were excavated; at Section 2 cohesionless mad-made fill of Pennsylvanian rock fragments (which infilled the former side valley crossing the site) were eroded (Figure 2, cross-section C-D).

Depositional features in the emergency spillway channel include joint-bounded blocks of sandstone left as lagged-out remnants in the upper reaches. Downstream, where the channel is cut in Quaternary deposits, 2 bars, megaforms, were deposited as part of a pool-and-bar sequence. The bars are conspicuously composed of imbricated 'gravel clusters' (Brayshaw, 1984, 1985), macroforms consisting of large blocks of Pennsylvanian bedrock oriented with their long axes transverse to flow (i.e., rollers, oriented across the valley) upon which other bedrock blocks are progressively imbricated.

It should be noted that neither the erosional nor depositional features were deposited by a stream in equilibrium. Flooding in the emergency spillway was a very short-term, high-magnitude event where features rapidly evolved, but full channel equilibrium, which would have resulted from continued flow, was never achieved. Because of this disequilibrium condition, relating various erosional and depositional features to observed flow conditions (stream power, etc.) would be incorrect.

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STOP 2

AMES TILL HYDROLOGY SITE

			North-central Iowa	Southeastern Iowa		North-central Iowa	Southeastern Iowa
MISSISSIPPIAN	Meramecian		Ste. Genevieve	Ste. Genevieve	0-85	Red, green and gray calcareous shales; minor limestones, dense and fossiliferous.	Limestone and greenish-gray shale; the limestone may be very dense locally. Commonly fossiliferous.
			St. Louis	St. Louis	0-135	Limestone, very dense in some zones, and dolomite, usually sandy; commonly much sandstone; minor chert, locally thin shale.	Upper part limestone and sandstone; limestone commonly very dense. Lower part dolomite, sandy, minor chert; also gypsum-anhydrite beds in parts of Dallas, Marion, Mahaska, Monroe, Appanoose, Davis, and Van Buren Counties.
			Spergen	Spergen			
	Osagean		Warsaw	Warsaw	0-75	Dolomite and limestone with much chert; locally contains shale in upper part; glauconite near top and base of Burlington. Many beds consist largely of fossil fragments.	Dolomite and shale; usually small amount of chert and chalcedony; geode zone locally at base.
			Keokuk	Keokuk	0-125		Limestone and dolomite containing much chert; glauconite usually at top and near base of Burlington. Many beds consist largely of fossil fragments. Upper part of Keokuk contains a thin shale unit locally.
			Burlington	Burlington	0-140		
	Kinderhookian		Gilmore City		0-160	Limestone, generally partly oolitic, but may be nearly all oolitic in some places; locally some beds consist predominately of fossil fragments; commonly very dense at top.	
		Hampton Formation	Iowa Falls		0-160	Dolomite, often calcareous; generally dense, may be saccharoidal.	
			Eagle City			Limestone, partly oolitic and very dense.	
			Maynes Creek	Wassonville	0-130	Dolomite, calcareous; usually contains considerable chert in lower part.	Dolomite, calcareous; or dolomite and limestone, cherty; thin oolite locally at top in northwest part of this district; usually minor chert in lower part.
		North Hill Group	Chapin	Starrs Cave	0-90	Limestone and dolomite, partly oolitic.	Limestone, locally oolitic, especially at base; commonly fossil fragments.
			Prospect Hill	Prospect Hill	0-95	Siltstone, dolomitic, and becoming more dolomitic toward the north.	Siltstone, dolomitic; some shale.
				McCraney	0-70		Limestone to dolomite, locally very dense.

Figure 1. Stratigraphic section for the Mississippian in Iowa (Horick, 1973).

GEOLOGICAL AND HYDROGEOLOGICAL SETTING OF CENTRAL IOWA

by

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INTRODUCTION

The focus of this joint field trip is water in central Iowa. Water in the subsurface, i.e. groundwater, occurs in a variety of geologic units ranging in age from Mississippian to late Pleistocene. An understanding of the hydrogeology in this region necessitates a discussion of the major geologic units and aquifers. The purpose of this article is to give a general summary of the geologic units, their water-bearing potential, and other relevant properties.

BEDROCK UNITS

The bedrock geology in central Iowa consists primarily of Pennsylvanian, Mississippian, Devonian, Silurian, Ordovician, and Cambrian age units. Bedrock units strike northwest to southeast and dip to the southwest and into the Forest City (structural) Basin. The topography on the bedrock surface in central Iowa (which may be on the top of either the Mississippian or Pennsylvanian rock) varies considerably in the region, due to the presence of two north-south trending buried bedrock valleys. Elevations vary from 213 m (700 ft) above mean sea level in the valley floors to 274 m (900 ft) above sea level on bedrock highs; thus, the depth to bedrock (and thickness of Pleistocene sediment) in the region may vary anywhere from 30 to 100 m (100 to 330 ft). These valleys were probably preglacial stream valleys that may have also served as meltwater channels during the Pre-Illinoian glaciations.

The deepest usable groundwater source is the Cambro-Ordovician aquifer: however, rocks of Mississippian age comprise a major aquifer in central Iowa. The most prevalent rock type is limestone, although shale, sandstone, and siltstone are also common. The Mississippian is subdivided into three major Series, which are commonly divided into the following formations (Anderson, 1983; see also Fig. 1):

In central Iowa, the most productive Mississippian aquifers are found in the Gilmore City and Hampton Formations (Horick and Steinhilber, 1973), although production rates (< 100 gpm) are still well below those from most alluvial aquifers (1000 gpm) in Iowa. Domestic wells supplying less than 10 gpm are commonly located within the Burlington-Keokuk and the St. Louis Formations in central Iowa. Recharge areas for the Mississippian Formations are not well defined, although some may occur in localized outcrops in central Iowa. High SO_4 concentrations in the Mississippian aquifer south of Ames suggest that some recharge may occur through Pennsylvanian shales and sandstones. It has been suggested that all the Mississippian aquifers discharge into major streams such as the South Skunk River (Horick and Steinhilber, 1973). This is certainly true of Bear Creek in northern Story County, but it is not known whether the aquifer discharges into smaller tributaries such as Walnut Creek.

Rocks of Pennsylvanian age in central Iowa are represented by the Cherokee Group. As we have seen in the Saylorville Canyon, the unit contains primarily carbonaceous shale and siltstone units, and secondarily sandstone, coal, anhydrite/gyp-

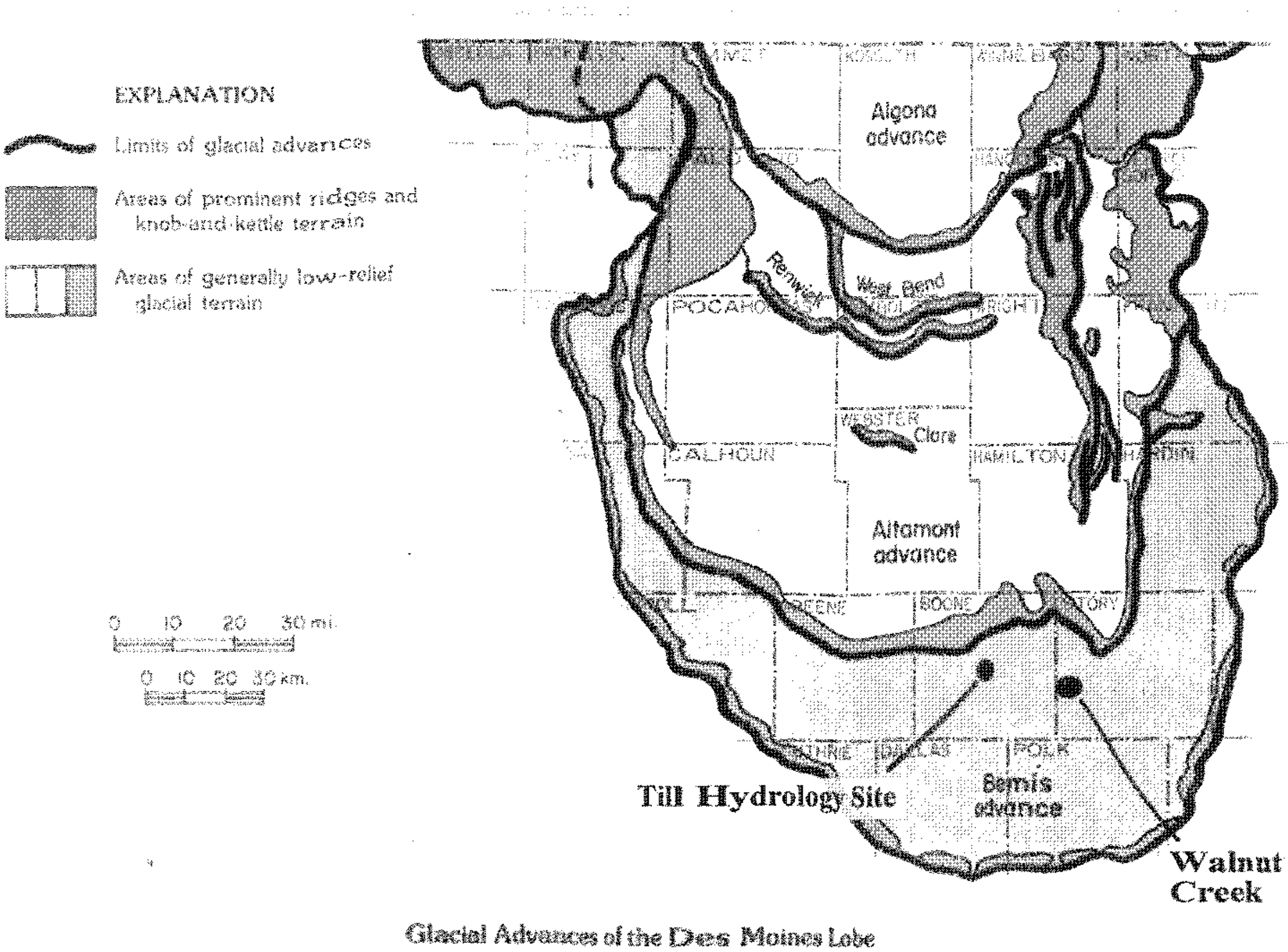

Figure 2. Extent of the Des Moines Lobe (Prior, 1991). The Ames Till Hydrology Site and the Walnut Creek Watershed are between the Altamont and Bemis moraines and in Boone and Story counties, respectively.

sum, and freshwater limestone units. The shale units in this formation are an important regional confining unit (aquitard) and may isolate the limestone from signficant vertical recharge. Sandstone units provide water to some domestic wells in the area; however, high SO_4 concentrations and the non-contiguous nature of the channel sandstone deposits preclude its wide usage as an aquifer. In addition, the unit is absent in part of and to the north of the Walnut Creek watershed. The groundwater recharge and discharge areas for this unit are not well known.

PLEISTOCENE UNITS

Three major ice advances of the Des Moines Lobe are recognized to have occured in Iowa during late Wisconsinan time (14,000 to 12,000 years B.P.): the Bemis, the Altamont, and the Algona (Fig. 2). On this field trip, we will view only those deposits left by the Bemis phase which advanced southward about to the City of Des Moines. Till and associated glacial sediment are classified formally within the Dows Formation, which is primarily composed of two Members: the Alden Member

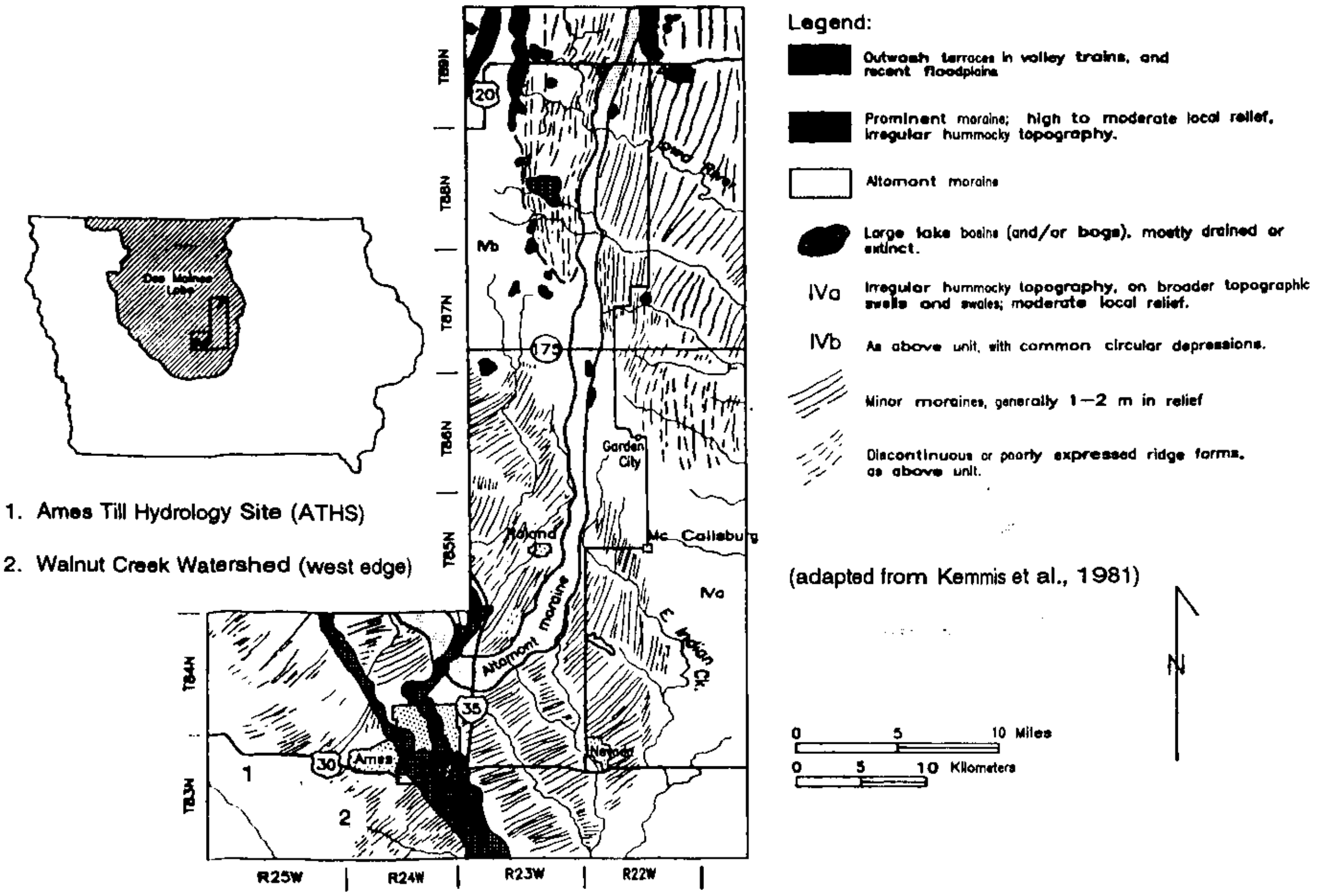

Figure 3. Map showing major and minor landforms of the Des Moines Lobe in central Iowa. Map adapted from Kemmis et al. (1981).

(basal till) and the Morgan Member (supraglacial sediment)(Kemmis et al., 1981). Other members of the Dows Formation recognized in Iowa include the Lake Mills, Pilot Knob, and Noah Creek Formations (Kemmis et al., 1981; Quade, 1992). Supraglacial sediment of the Morgan Member is variable in composition and averages 44 percent sand, 42 percent silt, and 14 percent clay in Iowa. Where present, it is frequently the surficial unit on the landscape and may contain discontinuous sand lenses. The Alden Member is compositionally more uniform and averages 48 percent clay, 37 percent silt, 16 percent clay in Iowa (Kemmis et al., 1981). Most of this unit was deposited either by lodgement or melt-out processes. The thickness of this unit ranges from 4.5 to 25 m (15 to 80 ft). Both till units appear light yellowish brown (2.5 Y 6/4) where weathered (oxidized) to depths of about 4 m (13 ft) in upland areas - probably a result of water table lowering during the mid-Holocene. The weathered zone is absent in topographic lows and near creeks, partly due to removal by erosion and also due to a lesser degree of Holocene weathering in lower topographic positions. Fractures containing precipitated iron oxides are commonly seen in the upper 5 m (13 ft) of the weathered till and show a preferred orientation approximately 30 to 45 degrees from the ice-flow direction (Lee, 1990). Unweathered (unoxidized) Alden Member till is dark gray (2.5 Y 4/0), and more cohesive and higher in bulk density than the weathered till above. It is primarily basal till. Fractures have been recognized to depths of 10 m in this zone.

The till landscape in central Iowa Iowa consists of low-relief (< 6 ft or 2 m high) arcuate-shaped ridges that are parallel to the former ice margin (ENE to WSW in this area) and to the end moraines (the Bemis moraine to the south near Des Moines and the Altamount moraine near Gilbert). These features (Fig. 3) have been identified and described as corrugation ridges or minor moraines (Kemmis et al., 1981; Stewart et al., 1987). They were apparently formed from basal till and meltwater sediment squeezed into crevasses at the base of the ice. The numerous topographic lows ("Prairie Potholes") can be found in between these ridges and many drainages, such as Walnut Creek, probably formed parallel to the ridge trends during the Holocene. These topographic lows have been the locus of sedimentation during the Holocene for sand and silt deposits of colluvial origin (Walker, 1966). Most of these potholes were filled to capacity with water due to the abnormally high precipitation experienced in 1993, and many formed connected drainageways across the landscape.

The late Wisconsinan till in central Iowa overlies a Wisconsinan (Peoria) loess unit, deposited between 14,000 and 17,000 years B.P., which consists primarly of eolian silt and clay and is a maximum of 8 m (25 ft) thick in this area. Coring in association with both the Walnut Creek and Ames Till Hydrology Projects suggests that the contact between the loess and the till is often sharp and that an increase in silt is often noted near the bottom of the till and near the contact. Coring in the Walnut Creek watershed has suggested, however, that a thick zone of a chaotically-interbedded diamicton, consisting of late Wisconsinan till, loess, and even Pre-Illinoian till, may exist at this contact. Our preliminary interpretation is that this material was incorporated as blocks of sediment when the ice overrode the landscape, and then was not homogenized, perhaps due to a short distance of transport. Another unique characteristic of the loess is that it has unusually large organic carbon percentages (near 1 percent). The carbon content is the result of a spruce forest that grew on the land surface prior to the advance of the Des Moines Lobe. The forest was buried and incorporated into the ice, which later deposited its debris as till. This is an important part of the geochemical story in central Iowa and it will be discussed in detail at the Ames Till Hydrology stop.

Beneath the loess unit is a thick (100m), Pre-Illinoian glacial sequence consisting of multiple till units and gravel. Pre-Illinoian deposits in Iowa are known to be older than 500,000 years, and are equivalent to the previously described Nebraskan and Kansan units in this region. Pre-Illinoian units recognized in eastern Iowa consist of the Wolf Creek Formation and the Alburnett Formation, both of which are thought to be more than 500,000 years old (Hallberg, 1986). Till members of the Wolf Creek Formation, the most likely Pre-Illinoian Formation present in central Iowa, are the Hickory Hills, the Aurora, and the Winthrop (Hallberg et al., 1984; Hallberg and Kemmis, 1986). The pre-Illinoian till unit is somewhat finer-grained than the late Wisconsinan till unit above it and averages (standard deviation in parentheses; N=7) 36 percent sand (4.7), 39 percent silt (3.3), and 25 percent clay (3.6) at the Ames Till Hydrology Site. A Yarmouth-Sangamon paleosol exists at the top of the uppermost Pre-Illinoian unit (Hallberg, 1986). Palmquist et al. (1974) identified two Pre-Illinoian till units in the vicinity of Ames.

Two major sand and gravel units of unknown origin (although probably outwash) occur within the Pre-Illinoian section generally at depths of 34 to 38 m about 69 to 76 m below the ground surface. These units may be associated with bedrock valleys that trend through the region and are usually absent on subsurface bedrock highs. These units supply most of the landowners in the Walnut Creek Watershed and environs with drinking water. The zones of groundwater recharge and discharge for these units are not known. Some recharge may come from direct vertical recharge through the overlying till, and some may come from further to the north where the units may be shallower.

The Pleistocene sediment in Iowa has always been considered to be an effective confining unit (aquitard) overlying the major bedrock aquifers in central Iowa, therefore protecting them from contamination. However, recent studies (Kross et al., 1990) showed that NO_3-N can be detected in about

18 percent of the domestic wells in the state. The routes of this contamination through till units are not clear; however, recent studies in central Iowa suggest that contaminants may be transported via alternate routes such as fractures or poor well construction. The till itself may also be more permeable than we once thought. Heterogeneity (sand) and fractures cause the hydraulic conductivity of the weathered (oxidized till) to be quite high (10^{-3} to 10^{-5} ms^{-1}) and it approaches that of some aquifers. The weathered till generally contains NO_3-N concentrations of about 10 mg L^{-1}. However, the weathered zone is thin in many areas and is definitely not a uniform unit in the landscape. By far the greatest thickness of till belongs to the unweathered (unoxidized) till, and its hydraulic conductivity is much lower (10^{-8} ms^{-1}). Overall vertical hydraulic gradients in this unit average about 0.05 and average vertical linear velocities are on the order of cm per year; therefore, unless the till is thin, no significant contamination of underlying aquifers should occur within our lifetimes. As we will see later on this field trip, redox potentials in the till are incompatable with large concentrations of NO_3-N. The hydraulic conductivity of the Pre-Illinoian till is considerably less than the till units above and approaches the K values seen elsewhere only in shale (10^{-11} ms^{-1}). The bulk density of this material is generally greater than 2, probably a result of compression by later ice advances in the region and perhaps some diagenetic changes. Although vertical hydraulic gradients are large in this unit (> 1.0), velocities are less than 1 cm yr^{-1}. Redox conditions in this uint are also unfavorable for preservation of NO_3-N.

Holocene Units

The Holocene history of central Iowa is marked by a period of decreased rainfall, higher temperature, and increased prairie vegetation between about 8,000 and 3,000 years B.P. (Van Nest and Bettis, 1990; Dorale et al., 1992). Recharge decreased significantly during this interval, as evidenced by a decline in lake levels as much as 9 to 10 m below present levels in northwestern Iowa (Van Zant, 1979). Depth to the water table in central Iowa probably increased, perhaps to 5 m, allowing oxidation of minerals and organic carbon in the till. Following the dry period, rainfall increased and a period of erosion began at about 3,000 years B.P. which stripped sediment from the high points in the landscape and deposited them in the low points, such as in the numerous bogs and potholes in central Iowa (Walker, 1966; Ruhe, 1969). Tributaries such as Worrell Creek at the ATHS probably eroded headward during this period by taking advantage of existing low spots in the landscape.

Walnut Creek is a fairly recent arrival on the landscape of central Iowa. During wastage of the Des Moines Lobe at about 12,000 years B.P., the South Skunk River was a meltwater channel that incised and widened its valley through the Alden Member till unit, older Pre-Illinoian till units, and Mississippian bedrock. The channel has since been filled by late Wisconsinan (deposits of the Noah Creek Formation) and Holocene alluvium. The incision produced very steep valley walls and tributaries such as Walnut Creek eroded headward to the west. Based on analogies with the Buchanan Drainage, a tributary on the east side of the South Skunk River, basal dates in alluvial fill sequences in Walnut Creek should be about 10,000 years B.P. (Van Nest and Bettis, 1990); thus, Walnut Creek probably evolved through several episodes of entrenchment, headward erosion, and alluviation during the Holocene. Further modifications of the channel were made (by humans) during recent times.

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HYDROGEOLOGIC INVESTIGATIONS OF FINE-GRAINED GLACIAL TILL:
THE AMES TILL HYDROLOGY SITE

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INTRODUCTION

The Ames Till Hydrology Site is the major component of Iowa's Aquitard Hydrology Study. The elaborate instrumentation at this site is the result of coordination among many different projects to develop a facility where investigators can collaborate on the difficult problems of understanding water and chemical transport in fine-grained materials. The site is known by many names — dependent upon what project is under discussion, but formally this is Field 5 of the Agricultural and Biosystems Engineering Research Center farm.

The Till Hydrology Project was designed to develop improved methods for characterizing the hydrogeologic properties of fine-grained tills and to compare new, innovative technologies and techniques with traditional ones. This paper provides a brief historical overview of the problem and the development of the Till Hydrology component of the Ames Site.

Till Hydrology? Some History

Till hydrology. To many this sounds like an oxymoron — how can you study the hydrology of something as 'impermeable' as till? In years past, too many geologists, engineers, and well drillers, often referred to till in Iowa and surrounding areas, as 'impermeable,' as a 'tight' clay, as 'blue' clay (or brown clay), or 'stiff' clay.

Over the past 30 years or so, as society has moved from waste 'dumps' to landfilling to contain our wastes, upland sites, underlain by relatively thick till deposits, have often been the preferred locations for waste disposal. We have counted on the 'impermeable' till to act as a container for leachate that might issue from the wastes, preventing the leachate from getting into aquifers. Traditional site investigations would often use standard, small soil cores (1-3 inches in diameter, 3-6 inches long) to determine laboratory permeability-saturated hydraulic conductivity (K) for these materials, and commonly measured K values of 10^{-9} cm/sec — *verrry slowly* permeable — but not impermeable! Under the prevailing notions, it was not uncommon to discuss sampling with consultants and find that some core segments, or the data from some cores, had been discarded as unrepresentative because they had a "crack" in them and the K values were much too high — and *obviously* something was wrong with the sample. Also, it was not uncommon to read in a site report that a borehole had been left open in the till to assess the depth to the water table, but that, after 24 or 48 hours, no appreciable water was in the hole, and hence there was no water table, or even that the deposits were "unsaturated" because they were 'impermeable'. Hydraulic estimates using such data suggested that there would not be any seepage problems and that what leachate was generated would move so slowly through such materials that it would be 100s of years before it might possibly reach an aquifer, and even then the delivery rate of contaminants would be so low that it would not have any significant effect.

While these conclusions seemed consistent with the preconceptions of the day regarding till, problems arose at many waste disposal sites. Also a variety of research was beginning to indicate: that while till may be an aquitard, it isn't 'impermeable;' till stratigraphic and depositional studies suggested that it may not be a nice homogeneous substance, prone to such generalizations; and that standard techniques of determining hydraulic properties may not be adequate to characterize the hydraulic properties of such materials (e.g., Hughes et al., 1971; Johnson and Cartwright, 1980). Examples: most till in the midwest is not 'clay,' and in fact the clay content (as properly defined by grain-size analysis) is often rather low. While it may be 'stiff,' or more properly firm, consolidated, or cohesive, not all till even fits this description. Problems that arose — chemical contaminants from landfills began to appear in nearby wells — in a period of years — not hundreds. At some sites the water table rose, or seeped right into the facility causing drainage problems and leachate generation problems. Field investigations began to show that *field* measured responses indicated K values 2 to 3 orders of magnitude greater than small cores had estimated (e.g., Lutenegger, Kemmis, and Hallberg, 1983).

Cracks, Joints, and Wormholes

Studies of till genesis showed that some glacial deposits evolved in a supraglacial environment while others were deposited subglacially, imparting very different material properties (e.g., Kemmis, Lutenegger, Kemmis, and Hallberg, 1983; Kemmis, Hallberg, and Lutenegger, 1981). Supraglacial deposits may include a myriad materials — from till, to sand and gravel — imparting a very different hydrologic condition than the 'stiff' clay of yesteryear! The subglacial till exhibited many of the properties generalized — it was often a 'stiff' deposit, and relatively uniform. The 'stiff' nature evolved because it had been loaded and/or overridden by ice; pressure that consolidated the deposit. But just because it was consolidated did not mean it was uniformly 'impermeable.' These processes, as well as subsequent weathering, imparted other structural considerations to the material. Diagenetic and structural processes impart fractures and joints in lithified materials such as sandstone or limestone — so why not till? Field investigations, particularly into the stratigraphy and properties of older, pre-Wisconsinan tills showed that they were 'jointed.' And that such joints often extended downward from structural features in the soil — likely related to both stress release and desiccation. These joints were the cracks in the core samples that used to be thrown out. In field exposure, after a rain, water could be seen 'running down' these cracks and freely moving out of these joints, sometimes 30-40 feet below the landsurface. Such observations, as well as water-quality studies clearly indicating that modern land-applied chemicals or nutrients were penetrating the till and entering aquifers over fairly widespread areas (e.g., Libra et al., 1984), helped to unveil a new concept — now often referred to as preferential flow. The flow of water and solutes (chemicals in solution) through preferential paths in the soil and geologic materials (ranging from worm burrows in the soil, to joints in the till); flow that takes place much more rapidly than flow through the matrix, and may even occur when the material is not saturated (i.e., when there is no gradient for flow through the matrix).

In brief, this outlines the need for the till hydrology study, and the reasoning behind the development of the till hydrology field site. It is imperative that we develop refined concepts of the hydrology of such deposits — and define better field methods of investigation to characterize the real hydrologic properties. We need to refine our knowledge of the integration of the hydraulic characteristics, of water and solute transport through such materials, to improve site design for waste disposal — particularly for hazardous materials. The site was developed here at Field 5, because of some of the preexisting instrumentation, and to provide a permanent installation that Iowa investigators could continue to use as a resource on such needed research for many years to come.

As part of the Iowa Groundwater Protection Act of 1987, special funding was dedicated to these studies. Further support by Iowa State University, the Leopold Center, and grants to several co-investigators besides the authors (particularly Dr. Ramesh Kanwar and Dr. James Baker, Agricultural and Biosystems Engineering; Dr. William Simpkins, Geology Department; and Dr. LaDon Jones, Civil Engineering; Iowa State University) have facilitated the extensive instrumentation and development of this research site.

AN OVERVIEW OF THE AMES SITE

The field investigation at the Ames site began with a detailed description of the till sequence / stratigraphy derived from continuous cores collected at the top, mid-slope, and toe of the hillslope. This was found to be one of the most important pieces of information collected at this site. Unfortunately, It is also one the least complete pieces of information collected at many ground water investigation sites. These borings were completed as monitoring points with standard construction practices. This is typically two-inch, flush-threaded PVC pipe, connected to a 2.5 foot factory-slotted PVC screen. A sandpack is put around the screen and is extended approximately one foot above the slots. A one foot seal of bentonite chips is placed above the sandpack and a cement-bentonite grout is tremmied from the seal to the surface. Protective steel housings are set in a concrete surface plug to protect the above ground PVC pipe. Shelby tube samples were collected from the zone to be screened in every piezometer.

At sites 1 and 4, at the top of the hill, piezometers are nested in individual borings throughout the Wisconsinan till, Pre-Illinoian till, and into the bedrock. Site 3, at the base of the hill, is similar to site one. The other sites all have well nests that monitor both the oxidized and unoxidized Wisconsinan till. The effects of borehole diameter, well/screen material, and screen slot-size were studied at site 7. Borehole diameters ranged from three inches to eleven inches. Materials included PVC, Teflon, and 304 stainless steel. Slot sizes included 0.01 inch to 0.1 inch with a geotextile wrap. These borings were all about 20 feet deep. There were no significant hydraulic or chemical effects related to these variables.

Electronic transducers were nested in single borings and wired to a datalogger at sites 1 and 3. The transducers measure in situ pressure that can be related to the hydraulic head — i.e., the water-level, or potentiometric surface, in each hole. The transducer ports are matched to the midscreen elevations of the piezometers at each site. While the piezometer sampling frequency varies from twice a week in the summer to monthly in the winter, the dataloggers collect measurements every 15 minutes and calculate an average every hour. This provides a nearly continuous record of water-level elevations at each site. Water level trends measured by each system (piezometers vs. transducers) are very similar. However, piezometers have a dampened response to changes in water level. Relatively short-term reversals in vertical gradients were detected by the transducers, but these were not apparent in the piezometer data. Hydraulically pushed transducers were also matched to both piezometers and transducers buried in a boring. These transducers also performed very well compared to the buried transducers. The installation of the push-in transducers was very easy and very fast. There are the obvious tradeoffs using these instruments, no soil samples or groundwater samples can be collected. However, ease of installation and their ability to be reused may make their use attractive in certain settings.

The shelby tube samples that had been collected from each piezometer had one or more permeameter tests conducted on each sample. Single-well hydraulic tests (bailer tests) have been conducted at least once on all of the piezometers. The test results fall into two general groups; the first group has a larger hydraulic conductivity and are piezometers finished in the oxidized Wisconsinan till. The other group has a smaller hydraulic conductivity and are the piezometers finished in the unoxidized

Wisconsinan till. Although variations of about an order of magnitude were noted within the groups, this is not unusual or significant with respect to the test method and materials. Several field tracer tests were conducted in the field in both the oxidized and unoxidized Wisconsinan till. The results of all these different tests indicate an apparent scale dependency for hydraulic conductivity, with the lab permeameter tests on core samples resulting in the smallest, and field tracer tests yielding the largest, hydraulic conductivities. The greater the "radius" or dimensions of the material tested, the more "joints" or other preferential flow paths the test can actually involve, resulting in a greater effective conductivity. This has important implications for site design, particularly related to past inadequacies of standard 1-2 inch core samples.

Spatial variability of unsaturated hydraulic conductivity has also been measured in surface soils at this site. Infiltration studies are also being conducted with the installation of a 10 foot diameter borehole to a depth of approximately 14 feet. The boring is cased, sealed, and instrumented with suction lysimeters and transiometers in a radial pattern around the borehole and with depth. Artificial rainfall experiments using various chemical tracers have documented how rapidly water and surface applied chemicals can travel through the fine-grained till and reach the water table.

The groundwater chemistry has been characterized for the major cations and anions (moderately hard water), dissolved heavy metals (generally iron and manganese above the minimum detection levels), selected agricultural chemicals and volatile organic compounds. Analyses of natural radioactive and stable isotopes with depth has indicated the relative "age" of the groundwater with depth, and has shed some light on apparent local flowpaths. Tritium (^{3}H) concentrations are generally below minimum detection levels in samples collected deeper than about 20 feet - - showing that the water at these depths is older than 1955. Deuterium, oxygen-18, and carbon-14 will be discussed in more detail in an article in this guidebook by Dr. William Simpkins. The information collected at this site has highlighted the need for detailed geologic, hydrogeologic, and groundwater chemistry investigations to provide the information necessary to accurately characterize the hydrogeology of fine-grained tills.

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SUMMARY OF HYDROGEOLOGICAL AND HYDROGEOCHEMICAL RESEARCH AT THE AMES TILL HYDROLOGY SITE

by

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INTRODUCTION

The purpose of this research at the Ames Till Hydrology Site (ATHS) was to use hydraulic head, hydraulic gradient, hydraulic conductivity data in several geologic units, in addition to isotopic dating techniques, particulary Carbon-14, to determine the potential for groundwater contamination of underlying aquifers. A total of 46 piezometers were installed in late Wisconsinan till, Wisconsinan loess, Pre-Illinoian till and gravel, and Pennsylvanian sandstone starting in 1988. Depths of these piezometers range from 3 to 128 m (10 to 421 ft) below land surface.

Hydraulic heads were measured monthly in piezometers and hydraulic conductivities of the units were determined in order to estimate the velocity of groundwater at the site. We also used a some atmospherically derived tracers - tritium (^3H), $\delta^{18}O$ ($^{18}O/^{16}O$), and δD (D/H), and Carbon-14 (^{14}C) and $\delta^{13}C$ ($^{13}C/^{12}C$) of the dissolved organic carbon (DIC), to determine the age of groundwater. During the course of that investigation, we found that the till and loess at the site contained dissolved methane (CH_4) gas, which provided a very interesting, but complex, geochemical environment for study.

In this article, we present the results of hydrogeological and geochemical studies at the ATHS in central Iowa. We will discuss the hydrogeology of the site, discuss the origin of the dissolved CH_4, describe the hydrogeochemical environment in which it occurs, and present ideas concerning the role topography and groundwater recharge may play in affecting the vertical distribution of CH_4. The age of groundwaters in central Iowa will be discussed in a separate article . The results of this study suggest that both hydrological and geochemical barriers exist in groundwater systems that preclude the vertical migration of agricultural chemicals.

BACKGROUND

Pre-Illinoian units recognized in eastern Iowa consist of the Wolf Creek Formation and the Alburnett Formation, both of which are thought to be more than 500,000 years old (Hallberg, 1986). Till members of the Wolf Creek Formation, the most likely Pre-Illinoian formation present in central Iowa, are the Hickory Hills, the Aurora, and the Winthrop (Hallberg et al., 1984; Hallberg and Kemmis, 1986). A Yarmouth-Sangamon paleosol exists at the top of the uppermost Pre-Illinoian unit (Hallberg, 1986). Two distinct loess units are common in Iowa: 1) an "early Wisconsin" or "basal Wisconsin" loess, which is correlative to the Roxana silt in Illinois, the Gilman Canyon Formation in Nebraska, and has now been included within the newly proposed Pisgah Formation, and 2) the "Wisconsin" or "upper Wisconsin" loess, which is correlative to the Peoria Loess elsewhere in the Midwest (Ruhe, 1969, 1976, 1983; Hallberg, 1986; Bettis, 1990). The radiocarbon age of the Pisgah loess ranges from greater than 31,000 years B.P. to about 18,000 years B.P. Radiocarbon dates within the Wisconsin loess in Iowa range from about 29,000 years B.P. to 14,000 years B.P. Dates at the base of the loess range from 29,000 years B.P. to 17,000 years B.P. and decrease in age with distance from the Missouri River, which was probably the source of much of the fine-grained sediment (Ruhe, 1976, 1983; Hallberg, 1986).

Full-glacial and periglacial conditions of the late Wisconsinan occurred between approximately 21,000 years to 16,500 years B.P. in Iowa and most of the upper Midwest. At the time of the Des Moines Lobe ice advance at about 14,000 years B.P., a coniferous forest, consisting of *Picea* (Spruce) and *Fraxinus* (Hemlock), had established itself on the Wisconsin loess (Baker et al., 1986; Baker 1992). The subsequent advance by Des Moines Lobe ice buried that forest and entrained particulate organic material which was later deposited in till. Spruce logs and blocks of organic material are common at the top of the loess and in the overlying late-Wisconsinan till (Kemmis et al., 1981). The wood dates indicate that the age of the Wisconsin loess in central Iowa is between 17,000 and 14,000 years old (Kemmis et al., 1981; Hallberg, 1986). Eight radiocarbon dates from coniferous wood in the lower part of the till or upper part of the underlying loess range from 14,700 years B.P. to 13,680 years B.P.; these bracket the date of the Des Moines Lobe ice advance in the region. The ATHS lies within the Des Moines Lobe, the depositional area of the last glacial advance into Iowa during late Wisconsinan time between 14,000 and 12,000 years ago (Hallberg and Kemmis, 1986). The water table generally occurs 1 to 3 m below land surface in the late Wisconsinan till.

Research for this study was conducted at the Ames Till Hydrology Site (ATHS), which is located in Field no. 5 on the Iowa State University, Agronomy and Agricultural and Biosystems Engineering Research Farm, approximately 7 km west of Ames, Iowa (Fig. 1). Two contrasting topographical and hydrogeological settings, represented by Piezometer Nests 1 and 4 and Piezometer Nest 3, were chosen for this investigation. Elevations at the site decline from a high of 339 m, in the north near Nests 1 and 4, to 334 m, in the south near Nest 3, over a distance of 357 m. The slope declines to Worrell Creek, whose headwaters begin just to the northwest of the ATHS.

RESULTS

Geology

Data from this study confirm that the ATHS is underlain by late Wisconsinan till, a Wisconsinan loess unit, Pre-Illinoian till, and Pennsylvanian sandstone (Fig. 2). In Core 1 (see Fig. 1 for location), the upper till unit is massive, leached of carbonate in the upper 1 m, and oxidized to a light yellowish brown color (10YR 5/4) in the upper 3.4 m. Below that depth, it is unoxidized and exhibits a dark gray color (5Y 4/1 to 3/1). The late Wisconsinan till unit averages (standard deviation in parentheses) 46 percent sand (1.4), 40 percent silt (1.6), and 14 percent clay (1.2) is extremely uniform with depth (N=21)(Fig. 3). Silt percentage increases at about 20 m, just above the loess contact at this site. Mississippian limestone, Pennsylvanian sandstone and coal, and Cretaceous age sider-

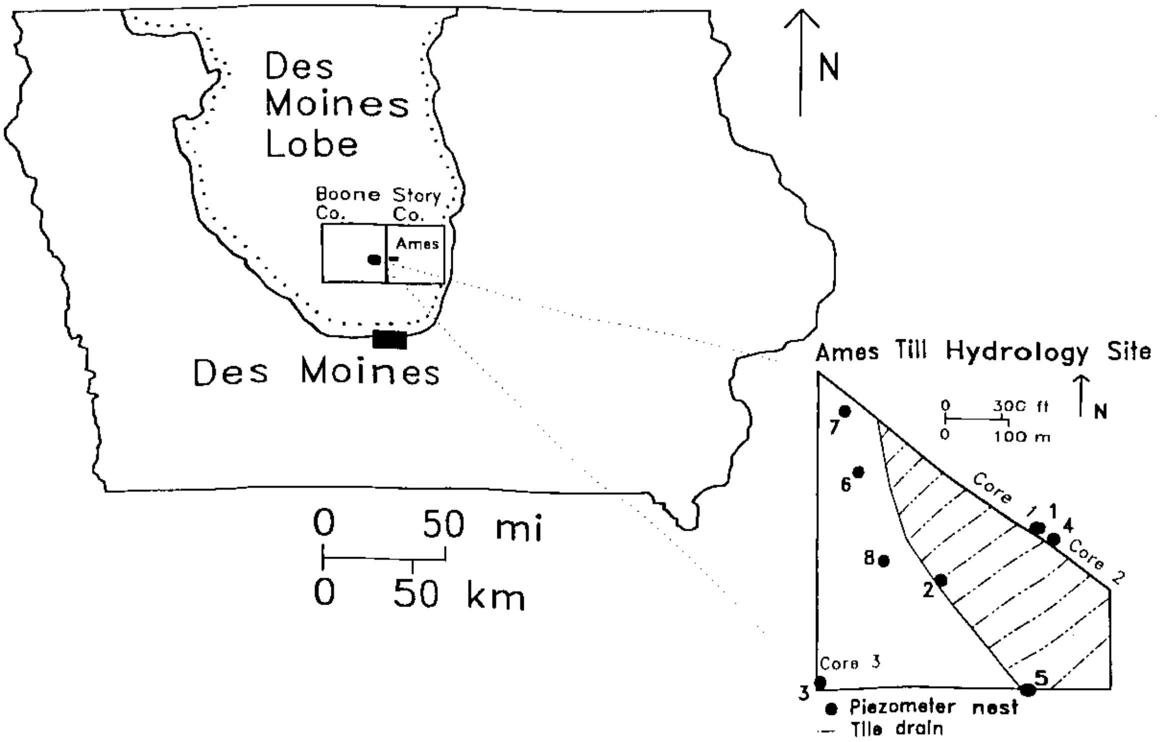


Figure 1. Map showing the location of the Ames Till Hydrology Site (ATHS) within Boone County, Iowa, and the Des Moines Lobe.

ite and shale are the common clast lithologies found in the till. Pyrite is also present, and although mostly disseminated in the till matrix, one sample from Core 3 at 30 m depth showed a pyrite crystal of cubic form, approximately 0.5 cm wide and rimmed by an oxidation "halo." Oxidation may have occurred between the time that the core was retrieved in 1989 and the present. The core exhibits horizontal and sub-vertical, iron-oxide coated fractures which occur to a depth of 13 m (E.A. Bettis III, written comm., 1991).

The stratigraphy in Core 3 consists of 2.8 m of silt loam and loamy sand alluvium, which is leached of carbonate and only slightly oxidized to a light olive brown color (2.5Y 5/4). This unit overlies the late Wisconsinan till unit, which is massive, unleached, unoxidized and exhibits a dark gray color (5Y 4/1). The till from Core 3 is not significantly different than Core 1 and averages 45 percent sand (2.2), 40 percent silt (1.2), and 15 percent clay (1.4)(N=20). Grain size percentages are extremely uniform with depth, except for an increase in the silt percentage at a depth of 13 m, which may suggest proximity to the loess contact.

The Wisconsinan loess unit below the till is unoxidized, dark gray (5Y 4/1), and mostly unleached and averages 6 percent sand (6.3), 73 percent silt (9.7), and 21 percent clay (7.7) (N=10). Terrestrial snail shells (gastropods) are common. There are suggestions of bedding in the unit which may indicate that part of it is waterlain or reworked as slopewash. The Pre-Illinoian till unit beneath the loess unit is unoxidized and dark gray (5Y 5/1). The till unit is somewhat finer-grained than the late Wisconsinan till unit above it and averages (N=7) 36 percent sand (4.7), 39 percent silt (3.3), and 25 percent clay (3.6). These grain size percentages are consistent with till members of the Wolf Creek Formation (Hallberg, 1986). A remnant of a Yarmouth-Sangamon interval is suggested at the

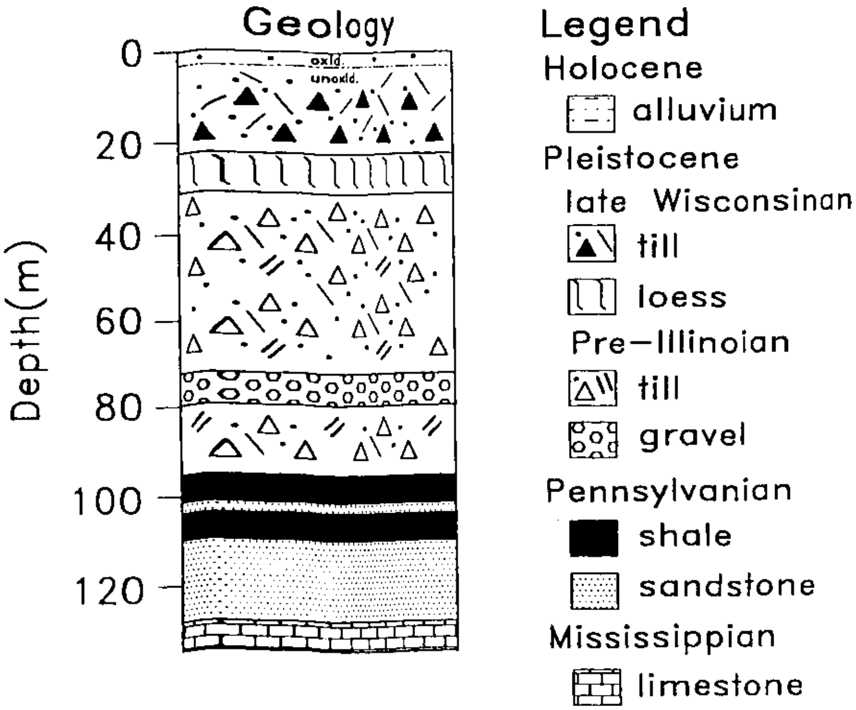


Figure 2. Stratigraphic section and legend for the ATHS.

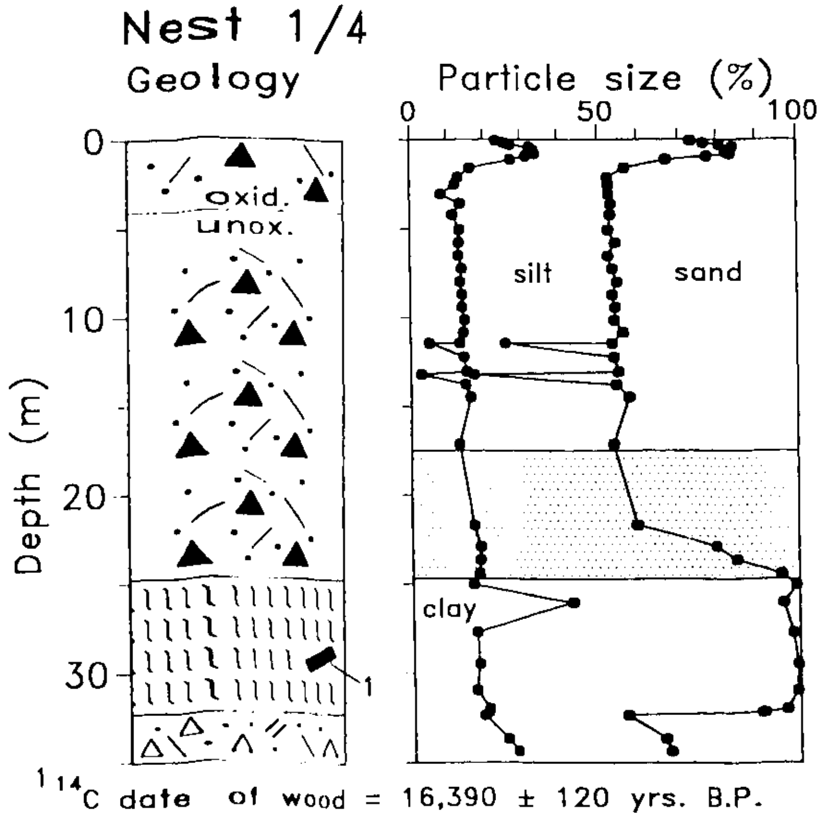


Figure 3. Particle size distribution of sediments at the ATHS. Shaded area indicates zone of local loess incorporation into the till.

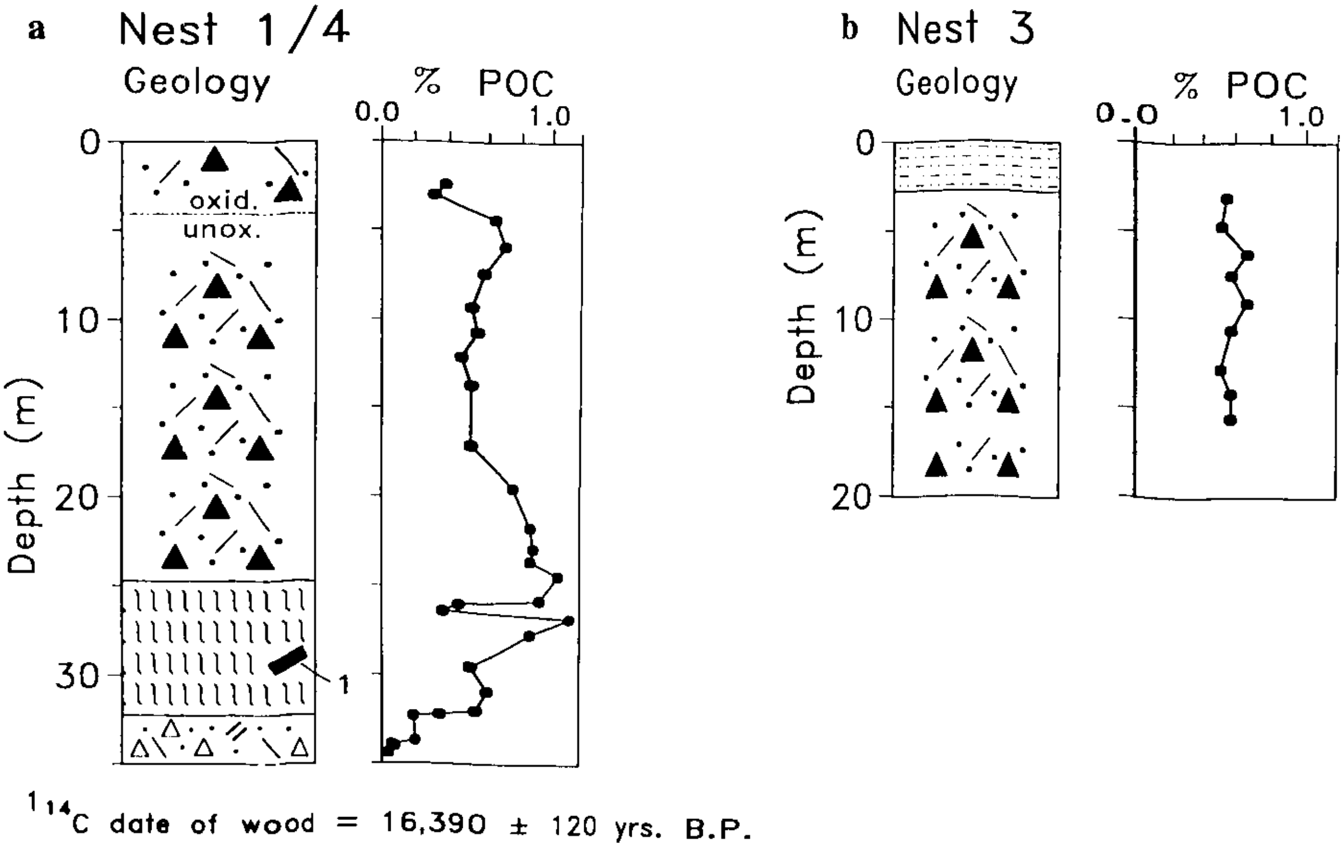


Figure 4. Profiles of (POC) percentage with depth at (a) Nest 1/4 and (b) Nest 3. In general, values in the late Wisconsinan till unit are homogeneous and increase with depth towards the loess unit. ^{14}C date from wood at Core 2 (Nest 1/4) is shown.

top of the Pre-Illinoian section by a color change to a dark gray (2.5Y 4/0) and a slight increase in clay percentage. Iron-oxide coated (7.5YR 4/4), subvertical fractures were observed in the core; these are consistent with the extensive fracturing seen in surface exposures of Pre-Illinoian till in eastern Iowa (Kemmis et al., 1992). A strong H_2S odor was noted during unwrapping of the core and suggested a reducing environment.

Wood and disseminated organic material (charcoal) are prominent in the core and are manifested in the unusually high percentage of particulate organic carbon (POC) in the unit (Figs. 4a and b). Three distinct zones of organic carbon occur in the late Wisconsinan till from Cores 1 & 2. Values in the oxidized, upper part average (standard deviation in parentheses) 0.35 percent POC (0.03), a typical value for parent material in till in central Iowa (Soil Conservation Service, 1978). POC increases abruptly in the unoxidized zone; values in the upper 17 m average 0.56 percent (0.07). Below 17 m, POC increases to its highest value of 1.05 percent; the average value in this zone is 0.89 percent (0.09) (Fig. 4a). A large (2 cm) wood fragment was extracted from the late Wisconsinan till at 22.3 m. The POC in Core 3 averages 0.58 percent (0.05) and is very homogeneous with depth (Fig. 4b). Coniferous wood and disseminated organic material (charcoal) are more apparent in the loess unit, particularly below 27 m. Large (2 cm) wood samples were extracted from depths of 23.7 m, 27.7, and 28.6 m - the latter sample was processed for radiocarbon dating and yielded a ^{14}C date of 16,390 ± 120 years RCYBP (Beta-50160).

The $\delta^{13}C$ value of the wood sample was determined to be -25.7 o/oo. The ^{14}C date and the stratigraphic setting suggests that the entire loess unit is of late Wisconsinan age. POC in the loess averages 0.64 percent (0.26), which is not significantly greater than values in the till unit immediately above it; however, the variability in the percentages and the visible abundance of wood fragments stand in contrast to the overlying till (Fig. 4a). We believe this relationship provides good evidence for incorporation of the organic carbon into the till as ice overrode the loess (see Kemmis et al., 1981). POC in the loess decreases gradually to values near 0.1 percent at its base (Fig. 4a). Wood fragments and disseminated charcoal are visually absent in the upper part of the Pre-Illinoian till unit and POC percentages there are near zero.

A bouldery, sand and gravel unit was encountered within the Pre-Illinoian section at about 73 to 79 m below land surface. The origin of this unit is unknown, but it is commonly found outside the ATHS is presumably the remnants of an outwash deposit. Pennsylvanian sandstone and shale of the Des Moines Series were encountered at 95.4 m below land surface (Fig. 2).

Hydrogeology

Based on water levels measured at the ATHS and recorded from well construction reports, hydraulic gradients are primarily downward in the region; thus, a potential exists for downward groundwater flow through the Pleistocene units towards the underlying aquifers. Hydraulic conductivity (K) varies with depth and with the specific geological units measured (Fig. 5). K values shown in the upper 3 m at Nests 1/4 reflect the influence of coarse-textured Holocene sediment and/or fractured, supraglacial sediment containing stratified sand units (Vondra, 1993). Hydraulic conductivity (K) decreases significantly in the underlying unoxidized till, where the geometric mean K = 3 x 10^{-8} ms^{-1} (log transformed standard deviation = 0.6)(Table 1). Below the late Wisconsinan till unit, hydraulic conductivities in the upper part of the loess (K = 3 x 10^{-8} m s^{-1}) and in the lower part of the loess (K = 4 x 10^{-8} m s^{-1}) are similar to those in the overlying late Wisconsinan till (Table 1). Hydraulic conductivity decreases to 2 x 10^{-11} m s^{-1} in underlying Pre-Illinoian till, which is presumably the cause for the steepening of hydraulic gradient there to values near 1.0 (Simpkins et al., 1992a). K values are highest in the Pre-Illinoian gravel and in the Pennsylvanian sandstone (Fig. 5).

Hydraulic heads measured in the piezometers between 1989 and 1992 indicate both lateral and vertical (downward) components of hydraulic gradient through the late Wisconsinan till. Maps of the water-table surface (Kanwar et al., 1990) indicate a water table depth of 2 m or less and a horizontal component of flow with a hydraulic gradient of about 0.01 in the upper 3 to 4 m of sediment. The hydraulic gradient is induced by the decline in surface elevation of about 5.8 m between Nests 1/4 and Nest 3. Under the present conditions, groundwater flow in the upper, more permeable zone may conduct most of the groundwater laterally toward surface waters or it may be intercepted by drainage tiles (Jones et al., 1992).

Vertical recharge through the till is suggested by a consistent, downward vertical hydraulic gradient of 0.06 at Nest 1/4 in the upland topographic setting. In contrast, hydraulic gradients at the base of the slope at Nest 3 are at the limit of detection and average 0.002 during most of the year. These data suggest that there is much less potential for vertical recharge at Nest 3; groundwater may have a significant horizontal flow component there. Assuming a bulk porosity of 0.28 and the geometric mean K given above, the average vertical linear velocity at Nest 1/4 is 27 cm yr^{-1}; thus, 130 pore volumes should have passed vertically through the till here since the retreat of the Des Moines Lobe. The average vertical linear velocity at Nest 3 is only 0.9 cm yr^{-1}; thus, only 4 pore volumes have been transmitted vertically there since ice retreat. The differences in vertical velocities are supported by the tritium data (Table 1), which suggest a deeper penetration of tritium into the till at Nest 1/4 than at Nest 3. Groundwater at the base of the loess could only be about 300 years old, based on these velocity estimates.

In contrast, the vertical hydraulic gradient through the Pre-Illinoian till approaches 1.2 (Fig.

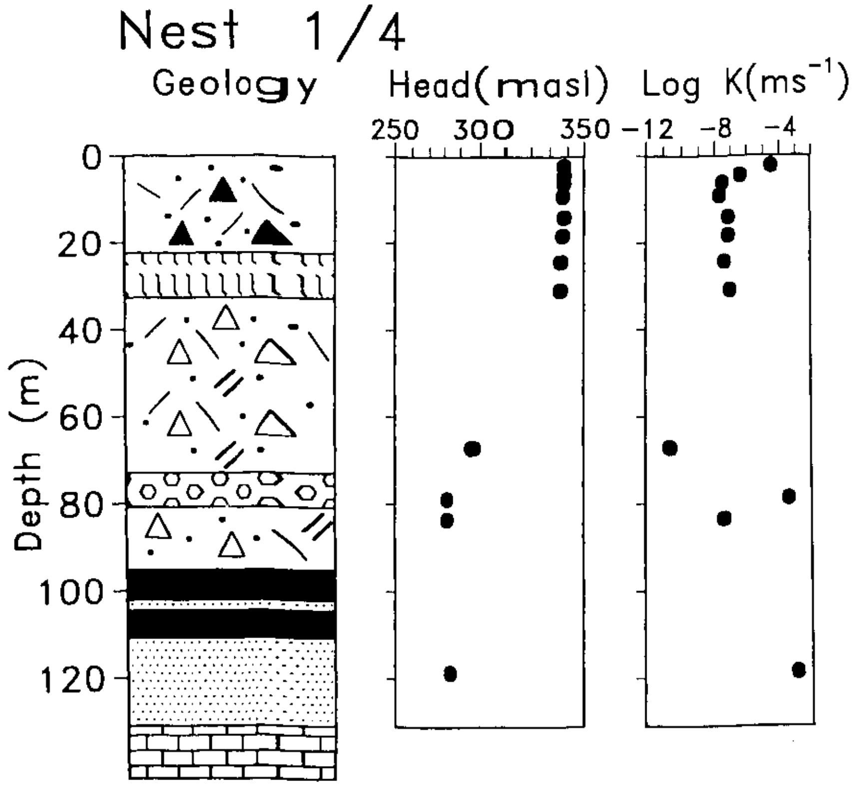


Figure 5. Variation of hydraulic head and hydraulic conductivity (K) with depth at the ATHS. Low hydraulic vertical head gradients exist in the late Wisconsinan till and loess; however, the Pre-Illinoian till produces vertical hydraulic gradients > 1.0.

4), which is an unusually high gradient for groundwater environments. This may indicate that the Pre-Illinoian section has not completely recovered from the hydraulic stress imposed by the advance of the Des Moines Lobe into the region. Using a K value of 3 x 10^{-11} ms^{-1} (a suspect value because the head in this 2-inch piezometer is still recovering after 2 years) and a bulk porosity of 0.22, average vertical linear velocities should be only 0.4 cm yr^{-1} through the Pre-Illinoian section. Using these calculations, groundwater in the Pre-Illinoian gravel unit may be 14,000 years old.

Hydrogeochemistry

The hydrogeochemistry of groundwater sampled at Nests 1/4 and Nest 3 is similar with respect to major ions, PCO_2 values, and saturation indices of calcite, dolomite, and gypsum (Table 1 and 2). Log PCO_2 values range from -1.3 to -2.0, and groundwater is near saturation with respect to calcite and dolomite. These values are similar to those calculated for groundwater till in Saskatchewan (Keller et al., 1991), Alberta (Hendry et al., 1986) and in southeastern Wisconsin (Simpkins, 1989). In contrast to the Canadian and Wisconsin studies, groundwater at the ATHS is very undersaturated with respect to gypsum. Although the Des Moines Lobe ice advanced over gypsum deposits 50 km north of the ATHS and probably incorporated gypsum into the till, gypsum undersaturation is apparently the result of anaerobic microbial SO_4 reduction.

Differences in redox hydrogeochemistry can be used to distinguish two hydrochemical zones of groundwater: shallow groundwater (< 4 m) and deep groundwater (> 4 m)(Table 1). Groundwater

Table 1. Summary of geochemical analyses. Concentrations in mg L^{-1}. $\delta^{13}C$ in per mil relative to PDB. δD in per mil relative to SMOW

Piez. no.	Depth (m)	^3H (TU)	pH	HCO_3	Eh (vlts)	Diss. O_2	NO_3^--N	NH_4^--N	Diss. Fe	SO_4	CH_4	DOC	$\delta^{13}C$-DIC	$\delta^{13}C$-CH_4	δD-CH_4
Nest 1/4															
1-10	2.2	17.6	7.4	304	0.459	3.1	0.4	<0.1	0.05	26.2	0.003	4.5	-14.07	----	----
1-15	4.4	10.1	7.5	451	0.405	0.6	<0.1	0.6	0.06	<0.2	4.4	3.2	-11.21	-68.63	----
1-25	6.1	2.0	7.5	488	0.195	<0.1	<0.1	1.8	0.83	81.5	13.6	3.0	-9.99	-64.81	----
1-30B	9.1	2.7	7.6	506	0.145	<0.1	0.1	1.3	0.30	42.9	30.3	3.4	-7.85	-81.10	-234.5
1-45	14.0	3.1	7.4	459	0.315	<0.1	<0.1	1.0	1.20	30.1	34.8	6.6	-7.28	-75.00	-194.0
1-60A	18.3	<0.8	7.6	465	0.145	<0.1	0.5	2.5	3.00	<0.2	42.4	5.8	-2.78	-72.83	-216.1
4AH-1B	24.3	<1.0	7.2	634	0.075	<0.1	<0.1	8.5	14.00	<0.2	41.3	15.3	+3.35	-74.15	-239.9
4AH-1A	30.9	<1.0	7.1	459	0.095	<0.1	0.5	11.3	16.00	<0.2	43.0	34.7	+8.10	-73.87	-212.6
Nest 3															
3-9A	2.5	20	7.4	437	0.358	4.1	17.4	2.2	0.02	45.0	0.001	4.6	-12.22	----	----
3-15B	4.3	9	7.4	492	0.132	<0.1	<0.1	1.9	8.00	2.2	29.9	18.6	-9.60	-74.06	-213.0
3-25D	7.0	<0.8	7.7	547	0.105	<0.1	<0.1	2.2	3.60	17.5	41.6	45.6	+3.66	-69.35	-222.6
3-36E	10.4	<0.8	7.5	587	0.145	<0.1	0.8	3.8	3.70	22.3	33.3	50.3	+4.45	-69.25	-210.1
3-51F	15.7	<0.8	7.4	659	0.145	<0.1	<0.1	5.8	4.60	0.5	37.9	54.3	+6.35	-69.97	-225.0

---- = not determined

Table 2. CO_2 partial pressures (log PCO_2) and saturation indices (log SI) calculated by WATEQF.

Piezometer no.	**log PCO_2**	**log SI Calcite**	**log SI Dolomite**	**log SI Gypsum**	**log SI Siderite**
Nest 1/4					
1-10	-2.0	0.0	-0.4	-2.1	-11.9
1-15	-1.9	+0.3	+0.3	-4.5	-11.5
1-25	-1.9	+0.2	+0.2	-1.7	+0.1
1-30B	-2.0	+0.4	+0.5	-2.0	-0.2
1-45	-1.8	+0.2	+0.1	-2.1	+0.2
1-60A	-2.0	+0.4	+0.4	NC	+0.8
4AH-1B	-1.5	+0.3	+0.1	NC	+1.2
4AH-1A	-1.3	+0.3	+0.2	NC	+1.2
Nest 3					
3-9A	-1.8	+0.4	+0.3	-1.8	-12.1
3-15B	-1.8	+0.3	+0.2	-3.1	+1.0
3-25D	-2.0	+0.6	+0.8	-2.3	+1.0
3-36E	-1.8	+0.5	+0.6	-2.2	+0.9
3-51F	-1.6	+0.4	+0.5	-3.8	+0.9

NC = SO_4 concentration below detection limit; SI not calculated.

in the shallow zone in Nests 1/4 and 3 is characterized by tritium activities of 17-20 TU, large positive Eh values, dissolved O_2 and NO_3-N, and low NH_4-N concentrations (Table 1)(Figs. 6a and b). NO_3-N concentrations are particularly high (16 mg L^{-1}) in piezometer 3-9A at Nest 3. SO_4 concentrations in the shallowest piezometers are similar to those found in precipitation (13 mg L^{-1}), but lower than that found at 1 m depths in tile drainage water (61 mg L^{-1}) at this site and region (Baker et al., 1975; Tabatabai and Laflen, 1976). Fe concentrations are near the detection limit. Saturation indices in the upper 4 m suggest that groundwater is oversaturated with respect to the oxidized form of Fe-minerals, such as goethite (not shown). Thus, the hydrogeochemical data suggest that the groundwater is recently recharged and exists in an oxidizing environment.

In the deep groundwater zone below 4 m, the hydrogeochemical environment changes to a more reducing one. Tritium activities decrease to near the detection limit, dissolved O_2 and NO_3-N are not detectable, NH_4-N increases, and Fe increases (particularly in Nest 3). SO_4 values are also near the detection limit and Eh values decrease sharply at 4 m, then gradually reach minima in the loess (Table 1) (Figs. 6a and b). Although the absolute values of most of the Eh values suggest an oxidizing environment throughout the till and loess section, the relative values in conjunction with the geochemical data suggest the onset of a reducing environment at depths greater than 4 m. Low SO_4 concentrations suggest that SO_4 reduction may occur, although actual H_2S concentrations are 0.2 mg L^{-1} in 4AH-1B and 0.1 mg L^{-1} in 3-15B - all other samples showed concentrations below the detection limit of 0.1 mg L^{-1}.

Groundwater at the ATHS also contains some unusually high concentrations of DOC. Whereas values of DOC concentrations in Nest 1/4 average 4.4 mg L^{-1} (S.D.=1.4) and are within the normal range for groundwater (Thurman, 1985), DOC concentrations in samples from Nest 3 average 34.7 mg L^{-1} (S.D.=19.6) and generally exceed all values shown in Nest 1/4 (Figs. 7a and b). The highest DOC concentration of 54.3 mg L^{-1} occurs at 15.7 m depth at Nest 3, which greatly exceeds concentrations measured from soil A-horizon extracts at the ATHS (T.B. Moorman, verbal comm., 1992); this suggests that the origin of this material is not downward percolation of modern soil organic matter. DOC values from Nest 3 also exceed those in the underlying loess unit.

We also discovered methane (CH_4) in the till and loess at this site. Some background information on CH_4 is provided here for the reader to help understand the significance of this discovery. Methane (CH_4) can be derived from abiogenic sources (inorganic reactions) and biogenic sources (from biologically-formed organic matter) and can be produced in a number of different near-surface and subsurface terrestrial and marine environments. Abiogenic CH_4 has been identified in groundwater in the Canadian Shield (Sherwood et al., 1988) and in mid-ocean ridges (Welhan, 1988). Biogenic CH_4 has been documented in marine environments (Reeburgh, 1976; Martens and Berner, 1977; Schoell, 1988) and anaerobic groundwater environments, including peat bogs, lignite deposits, glacial, lacustrine, and eolian sediment (Meents, 1960; Wasserburg et al., 1963; Coleman, 1976; Barker and Fritz, 1981; Coleman et al., 1988; Grossman et al., 1989; Romanowicz et al., 1991). Conditions favorable to CH_4 production may be found in anaerobic and low Eh (pE) environments where a useable substrate exists to provide energy. Methanogenesis represents the last of a series of reactions (the "ecological succession" suggested by Claypool and Kaplan, 1974) where electron acceptors such as O_2, NO_3^-, Mn^{4+}, Fe^{3+}, and SO_4^{2-} are used sequentially to oxidize organic matter. Methanogenesis is constrained to sediment intervals where the electron acceptors preceding SO_4^{2-} in the thermodynamic reduction sequence are absent, and generally where SO_4^{2-} concentrations have been reduced to < 1.0 mmol L^{-1} (Martens and Berner, 1977; Reeburgh, 1980; Whiticar et al., 1986). Methanogenic bacteria may co-exist with sulfate-reducing bacteria, but the latter will "outcompete" methanogens for hydrogen (Winfrey and Zeikus, 1977; Abram and Nedwell, 1978a, 1978b; Lovley et al., 1982).

"Biogenic" CH_4 is produced from microbial activity or thermocatalysis related to petroleum

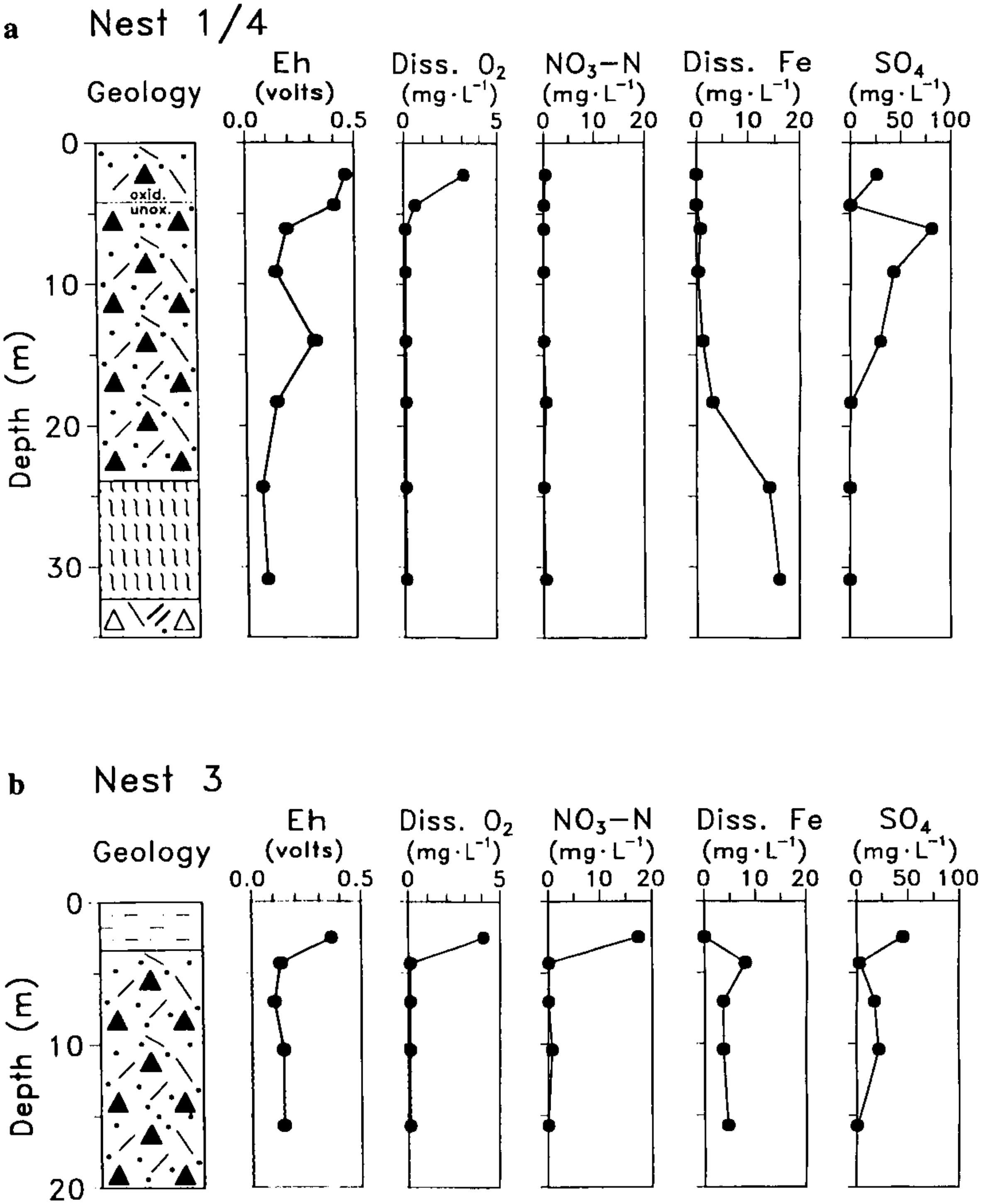
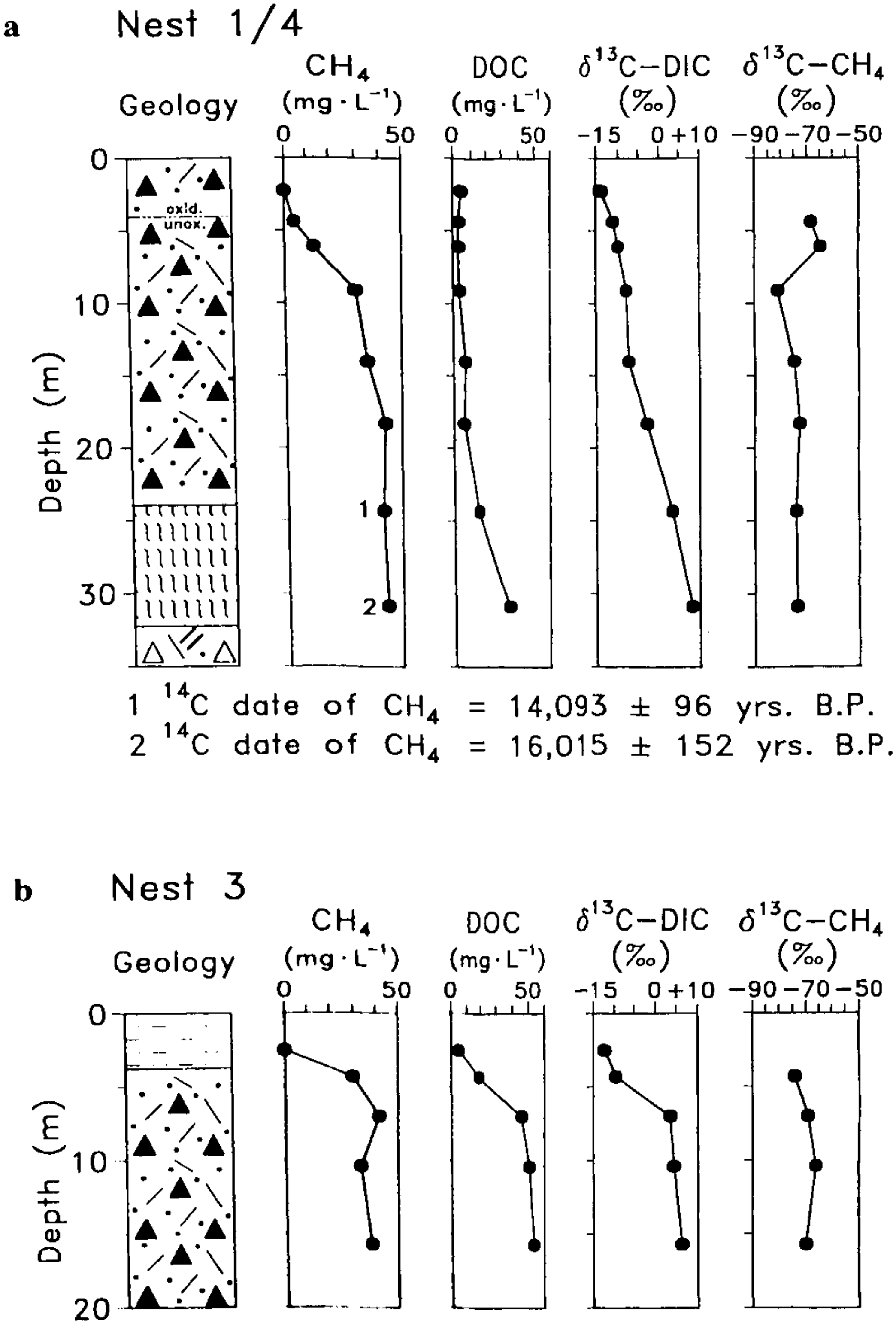


Figure 6. Profiles of Eh, dissolved O_2, and major redox species at (a) Nest 1/4 and (b) Nest 3. Oxidizing conditions occur down to about 4 m at Nest 1/4 and Nest 3. Reducing conditions occur below about 4 m.



1 ^{14}C date of CH$_4$ = 14,093 ± 96 yrs. B.P.
2 ^{14}C date of CH$_4$ = 16,015 ± 152 yrs. B.P.

Figure 7. CH$_4$, DOC, δ^{13}C-DIC, and δ^{13}C-CH$_4$ profiles with depth at (a) Nest 1/4 and (b) Nest 3. Trends of CH$_4$, DOC, and δ^{13}C-DIC at Nest 3 (b) suggest that the original CH$_4$ profile is preserved below depths of about 7 m.

formation. Microbial CH_4 predominates in most freshwater lakes and swamps (Rudd et al., 1974; Strayer and Tiedje, 1978) and in deep ocean basins (Barnes and Goldberg, 1976; Reeburgh, 1980). Thermocatalytic or "thermogenic" CH_4 is associated with petroleum reservoirs or natural gas fields and also with their storage and distribution systems (Coleman et al., 1977; Barker and Fritz, 1981). Kinetic fractionation of hydrogen and carbon isotopes accompanies the biogenic production of CH_4, and the degree of fractionation can be used empirically to differentiate a microbial versus thermogenic source for the gas (Fuex, 1977; Schoell, 1980; Barker and Fritz, 1981). In general, the $\delta^{13}C$-CH_4 of microbial CH_4 is less than -58 ± 5 o/oo and for thermogenic CH_4 is greater than -58 ± 5 o/oo (Fuex, 1977). Microbial CH_4 rarely contains hydrocarbons higher than ethane (Barker and Fritz, 1981). Zones of methanogenesis show high dissolved inorganic carbon (DIC) or bicarbonate (HCO_3) concentrations and enriched $\delta^{13}C$-DIC values. Methanogenesis, which can produce both CH_4 and CO_2 by acetate fermentation (see below), preferentially depletes ^{12}C and enriches the CO_2 in ^{13}C. The CO_2 promotes dissolution of carbonate minerals present in the aquifer, which, in turn, causes an increase in the DIC and HCO_3 concentrations in the groundwater.

Methanogenesis is a complex process and can proceed via several possible metabolic pathways and use several possible substrates. The two major metabolic pathways are acetate fermentation:

$$CH_3COOH \rightarrow CH_4 + CO_2$$

and CO_2 reduction:

$$CO_2 + 4H_2 \rightarrow 2H_2O + CH_4.$$

Schoell (1980), Whiticar et al. (1986), and Whiticar and Faber (1986) showed theoretically that crossplots of $\delta^{13}C$-CH_4 and δD-CH_4 values and crossplots of δD-CH_4 and δD-H_2O values separate acetate fermentation and CO_2 reduction pathways into two separate fields. Whiticar et al. (1986) used plots of published $\delta^{13}C$-CH_4 and δD-CH_4 values to show that microbial CH_4 produced in freshwater environments, including groundwater, can follow either the acetate fermentation or CO_2 reduction pathway. Laboratory experiments suggest that the dominant metabolic pathway in recent freshwater sediments is acetate fermentation (Lovley and Klug, 1986). CO_2 is produced from the breakdown of organic acids prior to the production of CH_4, but it may be reduced subsequently to CH_4. Thus, acetate fermentation occurs primarily in younger sediment and under warmer temperatures. It will precede CO_2 reduction, which is dominant in older and colder sediment (Schoell, 1988).

CH_4, at above-ambient atmospheric concentrations, occurs in all groundwater sampled in Nests 1/4 and 3 (Table 1; Figs. 5a and b). The gas extracted from the water samples contains mostly CH_4, CO_2, N_2O, and N_2; there are no hydrocarbons other than CH_4 in the gas phase. CH_4 concentrations in groundwater range from less than 1 ug L^{-1} in the near surface piezometers to a maximum of 43 mg L^{-1} in the loess; however, not unlike the other geochemical data, concentration profiles differ considerably between Nest 1/4 and Nest 3. At Nest 1/4, concentrations increase gradually to near the maximum value of 43 mg L^{-1} at 18.3 m and do not vary significantly below that depth. In contrast, high concentrations of 29.9 mg L^{-1} occur within 4.3 m of the land surface in Nest 3. No CH_4 data are yet available for the top of the Pre-Illinoian sequence immediately below the loess unit.

$\delta^{13}C$-CH_4 values in Nests 1/4 and 3 range from -64.81 o/oo to -81.10 o/oo and values of δD-CH_4 range from -194.0 to -239.9 o/oo (Table 1)(Fig. 7a and b); these are typical ranges for CH_4 produced by microbial systems (Barker and Fritz, 1981; Whiticar et al., 1986), especially those that produce CH_4 from CO_2 reduction (Schoell, 1988). $\delta^{13}C$-DIC values increase systematically with depth in both nests from a minimum of -14.07 o/oo in a shallow piezometer in Nest 1/4 to a maximum value of +8.1 o/oo in the deep piezometer in the loess (Fig. 7a and b). Trends of $\delta^{13}C$-DIC values appear unrelated to trends of $\delta^{13}C$-CH_4 values; but, $\delta^{13}C$-DIC values show a much closer relationship to CH_4 concentrations (Table 1). For example, higher CH_4 concentrations and more enriched $\delta^{13}C$-DIC values occur at shallower depths in Nest 3 than in Nest 1/4. The first positive $\delta^{13}C$-DIC values occur at 24.3

m depth in the loess in Nest 1/4; the first positive δ^{13}C-DIC values occur at 7 m depth in Nest 3. The depth at which the first positive δ^{13}C-DIC values occur may indicate the depth of penetration of recent CO_2 and DIC from the soil zone. This hypothesis will be discussed later in the paper.

We took samples from our original cores and placed them into evacuated tubes to evaluate their CH_4 production potential. Amended samples from Core 2 produced showed CH_4 production in the laboratory during a two-week incubation period. These results suggest that methanogens are indigenous to at least the lower part of the till and throughout the loess unit. In general, rates were highest in the loess materials and in materials from the lower part of the late Wisconsinan till where POC was greatest. Production rates were 1.73 ng CH_4-C/g/d (21.3 m; Wisconsinan till), 1.33 ng CH_4-C/g/d (25.9 m; loess), 1.77 ng CH_4-C/g/d (28.9 m; loess), and 0.68 ng CH_4-C/g/d (32.9 m; Pre-Illinoian till). Because the core samples were amended with nutrients and CH_4 was produced under ideal conditions, these rates should be considered only as estimates of the CH_4 production potential in these units. This shows that methanogens are present in these units and suggest that they are active *in situ*.

Carbon-14 dates of CH_4 gas and wood in the loess suggest that CH_4 is produced from the organic carbon *in situ*. The ^{14}C activity of the CH_4 gas sample taken from the piezometer in the upper part of the loess at 24.3 m is 17.30 ± 0.21 PMC, corresponding to a ^{14}C date of 14,093 ± 96 years B.P. Likewise, the ^{14}C activity of the CH_4 gas sample taken from the piezometer in the lower part of the loess at 30.9 m is 13.62 ± 0.26 PMC, which corresponds to a ^{14}C date of 16,015 ± 152 years B.P. These ^{14}C dates are in excellent agreement with the ^{14}C age of the organic material sampled at 28.6 m at the ATHS (16,390 120 years B.P.), as well as published ^{14}C dates (Kemmis et al., 1981) from the top of the buried Wisconsinan loess in central Iowa.

DISCUSSION

Origin of CH_4

CH_4 in groundwater at the ATHS was produced by microbial processes. Evidence for this conclusion consists of δ^{13}C-CH_4 values in CH_4 that are more depleted than -58 o/oo (Fuex, 1977) and the absence of hydrocarbons higher than CH_4. Additional evidence for microbial production of CH_4 is provided by the positive δ^{13}C-DIC values found in groundwater, which are typical values for microbial fractionation of carbon isotopes (Baedecker and Back, 1979a, b). The age of the CH_4 confirms a geologically recent substrate for methanogenesis, and not one tied to thermogenic processes may be associated with coal-bearing Pennsylvanian strata in the region. δ^{13}C-CH_4 and δD-CH_4 data also suggest that the primary metabolic pathway for the CH_4 is reduction of CO_2 gas, not acetate fermentation.

Recent laboratory studies have demonstrated that CH_4 can be produced in both the till and loess without amendents of any kind. In fact, the predominant CH_4 producers are wood chips within the till and loess. A complicating factor is that little is also known about the spatial variability of CH_4 production from site to site. Variability could result from an unequal distribution of POC in the till and loess, or perhaps an unequal amount of useable substrate. For example, it is possible that the large volume of biomass in the loess has allowed it to produce CH_4 for 12,000 years and still produce it today, while the useable substrate in the till has since been depleted and CH_4 production is declining or has ceased.

We hypothesize that the differences in the shape of the CH_4 and DOC concentration profiles between Nest 3 and in Nest 1/4 reflect differences in vertical groundwater velocities and recharge rates. Higher vertical groundwater velocities in the upslope recharge position (Nest 1/4) not only enable dissolution and transport of more DOC from the till, but they transport more electron acceptors deeper in the profile than at Nest 3 (Fig. 8). O_2 is consumed by oxidation of CH_4, and alternate electron acceptors, such as NO_3, Fe^{3+}, and SO_4^{2-}, oxidize carbon and

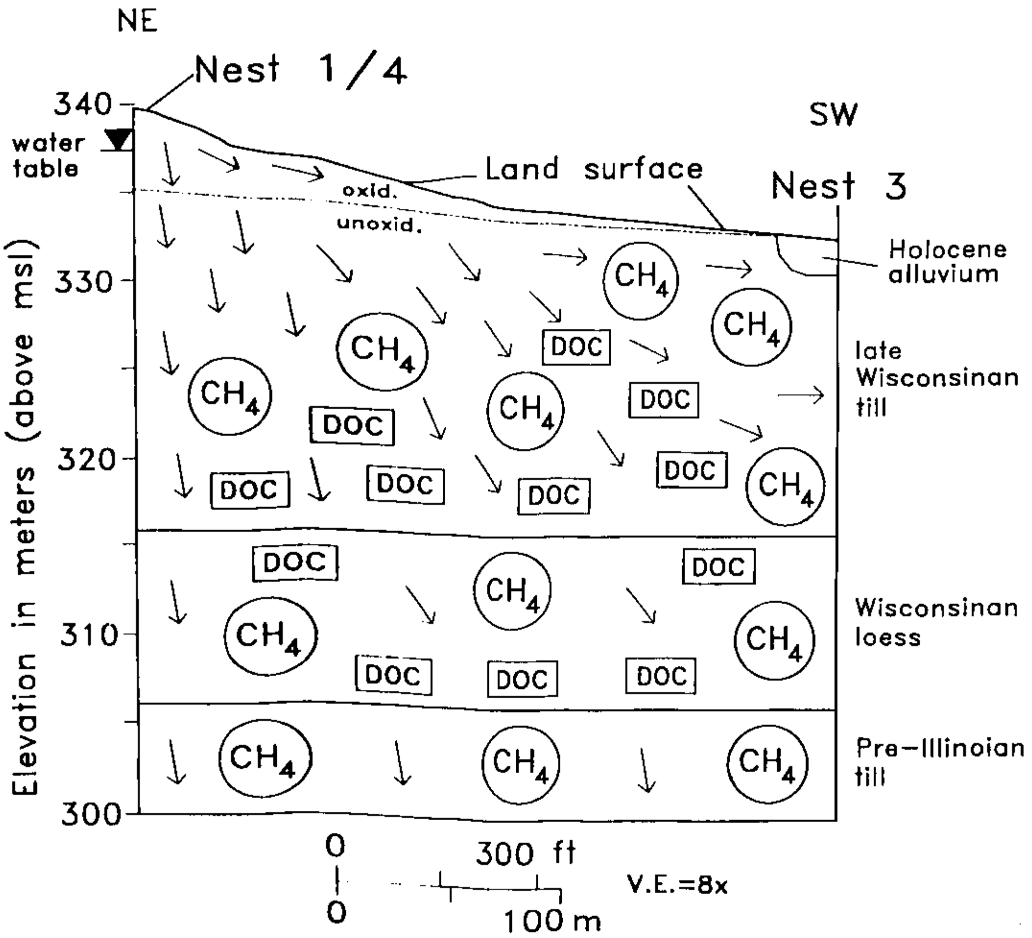


Figure 8. Conceptual model of the hydrogeology and hydrogeochemistry at the ATHS. Arrows indicate generalized direction of groundwater flow. High CH_4 and DOC concentrations occur near the ground surface at Nest 3 where average vertical linear velocities are low or non-existent; concentrations are depressed downward at Nest 1 where average vertical linear velocities are higher.

are reduced at the top of the CH_4 profile to N_2O gas, Fe^{2+}, and S^{2-}, respectively. In contrast, the relatively low vertical velocities in the downslope position at Nest 3 provide an ideal environment for the accumulation or preservation of DOC and CH_4; Nest 3 has been insulated from deep penetration of electron acceptors that could oxidize CH_4 (Fig. 6).

Redox Geochemistry

Our evidence suggests that low redox conditions exist today below 4 m in the till and are favorable for the production of CH_4; however, the system does not exhibit the typical redox zonation described elsewhere (Champ et al., 1979; Jackson and Patterson, 1982). Redox zonation in groundwater occurs because microorganisms need energy from organic carbon and will oxidize a carbon substrate anaerobically using a specified order of alternate electron acceptors (Stumm and Morgan, 1981). Redox zones are identified by the disappearance of an electron acceptor or an increase in the concentration of the reduced form of the electron acceptor. At the ATHS, however, electron acceptors, in particular O_2, NO_3, and SO_4, disappear at relatively the same depth. For example, after O_2 is used to oxidize carbon in the upper 4 m or so, the next possible electron acceptor, NO_3, also disappears (Figs. 6a and b). At this same depth, we have also measured above-ambient concentrations of N_2O, a product of denitrification, in groundwater. At Nest 3 in particular, NO_3 disappears where CH_4 concentrations increase abruptly (Figs. 6b and 7b), suggesting that CH_4 may provide the carbon substrate for denitrification.

Based on the first disappearance of SO_4 in the concentration profiles, SO_4 may also be utilized as an alternate electron acceptor at about 4 m. If this is the case, then SO_4 concentrations should be below the detection limit in all the piezometers screened below 4 m; however, some groundwater shows SO_4 concentrations up to 81.5 mg L^{-1} (Figs. 6a and b; Table 1). Concentrations are less than 1 mmol L^{-1} (Table 1), the threshold value which would still allow methanogenesis to predominate over SO_4 reduction; therefore, the presence of SO_4 alone does not preclude SO_4 reduction or methanogenesis. Additional data are consistent with the hypothesis of SO_4 reduction below 4 m. H_2S odors are ubiquitous in deep piezometers and tests for presence or absence of SO_4 reducing bacteria have shown them to be present in most groundwater below 4 m. Preliminary results of $\delta^{34}S$-SO_4 analyses also indicate that the $\delta^{34}S$ in the residual SO_4 show values as high as +10.60 o/oo, which suggests enrichment due to microbial processes.

Considerable evidence exists for the presence of an amorphous FeS precipitate in the till and loess. Fe^{2+} activities calculated by WATEQF suggest that groundwater may be saturated with respect to FeS at HS^{-1} concentrations less than 0.03 mg L^{-1} - a value that is consistent with our observation of very low H_2S concentrations. FeS precipitate was identified on permanent inertial pumps in piezometers 1-30, 1-45, 3-25D, and 3-36E. In core samples, H_2S gas was detected when HCl was placed on fresh core samples - a common laboratory test for the presence of FeS precipitate in soil (Doner and Lynn, 1989). In addition, the results of SO_4 determinations (not shown) performed under aerobic conditions on unoxidized till in Core 1 showed SO_4 concentrations up to 300 µg g^{-1}, a value that is not consistent with the measured aqueous concentrations (Table 1). We have performed similar analyses on unoxidized till and extracted SO_4 under completely anaerobic conditions. These samples produced little extractable SO_4 (< 10 µg g^{-1}); this evidence suggests that the additional SO_4 seen in the aerobic extractions was due to the oxidation of an unstable sulfide mineral, presumably FeS precipitate. Perhaps the increase in Fe^{2+} concentrations with depth reflects the removal of Fe^{2+} at shallow depths by FeS precipitation; future studies will examine the role of Fe in this system in more detail.

The detectable SO_4 concentrations in groundwater observed under these redox conditions could be artifacts related to piezometer construction and the piezometer environment. SO_4 concentrations in piezometers 1-30B (9.1 m) and 3-25D (7.0 m) have declined by about 75 percent since they were first sampled in 1989, while groundwater in the remaining piezometers has maintained similar SO_4 concentrations during the same time period. This trend suggests that oxidation of FeS in the immediate vicinity of the piezometer screen caused an initial spike in SO_4 concentration, which then has decayed with time due to SO_4 reduction. The decrease in SO_4 may also be due to groundwater flushing of indigenous SO_4 in the bentonite seal (Keller et al., 1991). We are monitoring SO_4 concentrations at the site over time in order to assess the temporal variability of this parameter, to determine the ultimate source of the SO_4, and to determine if a redox zonation exists in this system.

SUMMARY AND CONCLUSIONS

We investigated the hydrogeology and hydrogeochemistry of till and loess at the ATHS in central Iowa. From the hydrogeological studies, we determined that the groundwater within the weathered (oxidized) late Wisconsinan till is quite young, and that groundwater at the base of the Wisconsinan loess is no older than 300 years. Groundwater ages increase markedly in the Pre-Illinoian till and are about 14,000 years old there. In short, based on an examination of the hydrogeology, the highest potential for groundwater contamination appears to exist in the near surface, oxidized till environment.

We also presented evidence that the late Wisconsinan till and loess sequence in two hydrogeological settings at the ATHS are characterized by high concentrations of CH_4 produced by microbial processes. The data are consistent with the hypothesis that methanogens utilized particulate organic carbon (POC) and dissolved organic carbon (DOC) derived from a coniferous forest growing on the loess at the time Des Moines Lobe ice advanced into the region 14,000 years ago. The overriding ice incorporated wood into the till that was then deposited and buried the forest remnant of the loess. Carbon-14 dates on CH_4 and laboratory data indicate that CH_4 is produced in groundwater in the loess at present, and recent laboratory experiments have shown us that it is produced in the till as well. We interpret the differences in the vertical profiles of CH_4 concentrations to be due mainly to differences in the topographic setting and the magnitude of vertical recharge at the piezometer nests. The role of spatial variability of CH_4 production and consumption in the till landscape, also an important factor, has not been evaluated and will be the subject of future work.

The results of this research have important implications for evaluating the water quality impacts of agriculture in the Midwest and specifically to the area of the Des Moines Lobe. In addition to the hydrologic barriers to the vertical migration of contaminants that we have shown, till units that conform to our hydrogeochemical model will produce low redox conditions. Unless recharge rates are unusually high, the till units will promote denitrification, Fe^{3+}, Mn^{4+}, and SO_4^{2-} reduction and perhaps methanogenesis. If CH_4 provides the carbon substrate for denitrification under these redox conditions, it is unlikely that NO_3-N derived from agricultural practices can be transported through ***any*** thickness of till and contaminate an underlying aquifer.

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STOP 3

"HEADWATERS" OF WALNUT CREEK

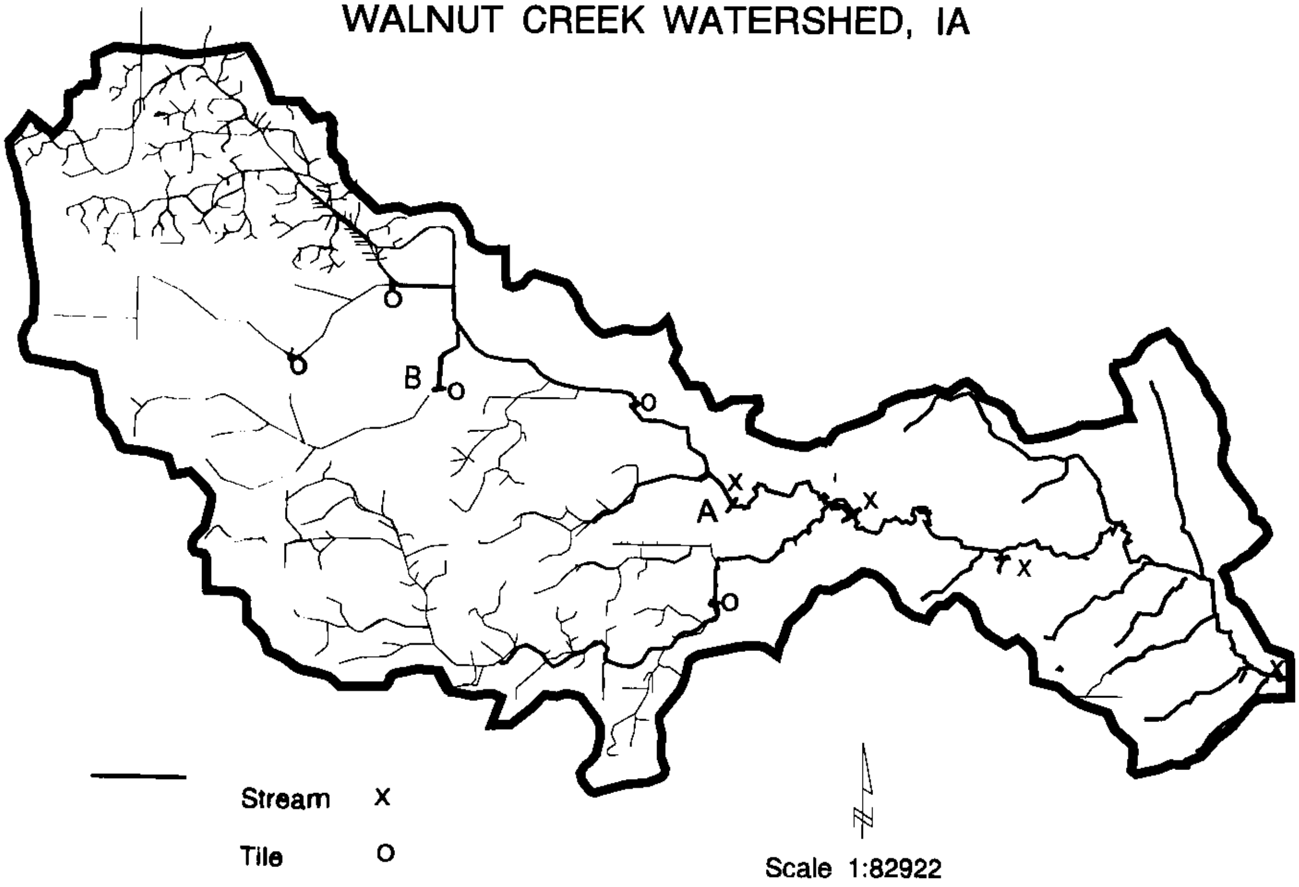

Figure 1. Map of Walnut Creek watershed showing location of stream channels, drainage tile systems and stream and tile monitoring stations.

DISTRIBUTION OF AGRICHEMICALS IN WATER RESOURCES OF THE WALNUT CREEK WATERSHED, MANAGEMENT SYSTEMS EVALUATION AREA

by

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Research in the Walnut Creek watershed is a result of collaboration among the U.S. Department of Agriculture, Agricultural Research Service, U.S. Environmental Protection Agency, U.S. Geological Survey, and faculty from Iowa State University. Walnut Creek is one of 10 areas in the midwest being studied in the Management Systems Evaluation Areas (MSEA) program. Some results of preliminary research are available from the watershed, however, most projects are in a phase of reconnaissance, methods development, or initial data acquisition.

The goal of the MSEA program is to understand the effect of current agricultural management systems on water resources and to develop alternative systems to improve water quality. Three MSEA projects exist in Iowa; in the Loess Hills of the southwest; in the area with thin Pre-Illinoisan till of the northeast; and Walnut Creek. Walnut Creek was selected to represent hydrologic conditions associated with Wisconsinan till and poorly dissected terrain. In addition, the adjacent Skunk River alluvial aquifer affords an opportunity to study the impact of management system on an aquifer which is particularly vulnerable to contamination from agricultural chemicals.

Walnut Creek drains 5,600 ha (Fig. 1) of mostly cropland dominated by corn and soybeans. The soils in the watershed are characterized by the Clarion-Nicollet-Webster association and are formed on late Wisconsin drift. The permeability of most soils allows relatively rapid vertical drainage although horizontal drainage is limited to local depressions under natural conditions. Yield potential for crops on these soils are quite high because of the deep soil profiles, high water holding capacity, and high fertility levels. Consequently, this watershed represents some of most ideal land for crop production in the midwest corn and soybean producing region.

There are four aspects of the hydrologic system being actively studied in the watershed. These include: natural ground water contributions to streams; runoff; artificial subsurface drainage; and stream recharge to an alluvial aquifer. The transport of agrichemicals is the principal focus of the hydrologic research with herbicides and nitrate of greatest interest. The hydrologic setting of the research area offers an opportunity to study a complex set of interactions between ground and surface water and the resulting effects on nitrogen and herbicide contamination.

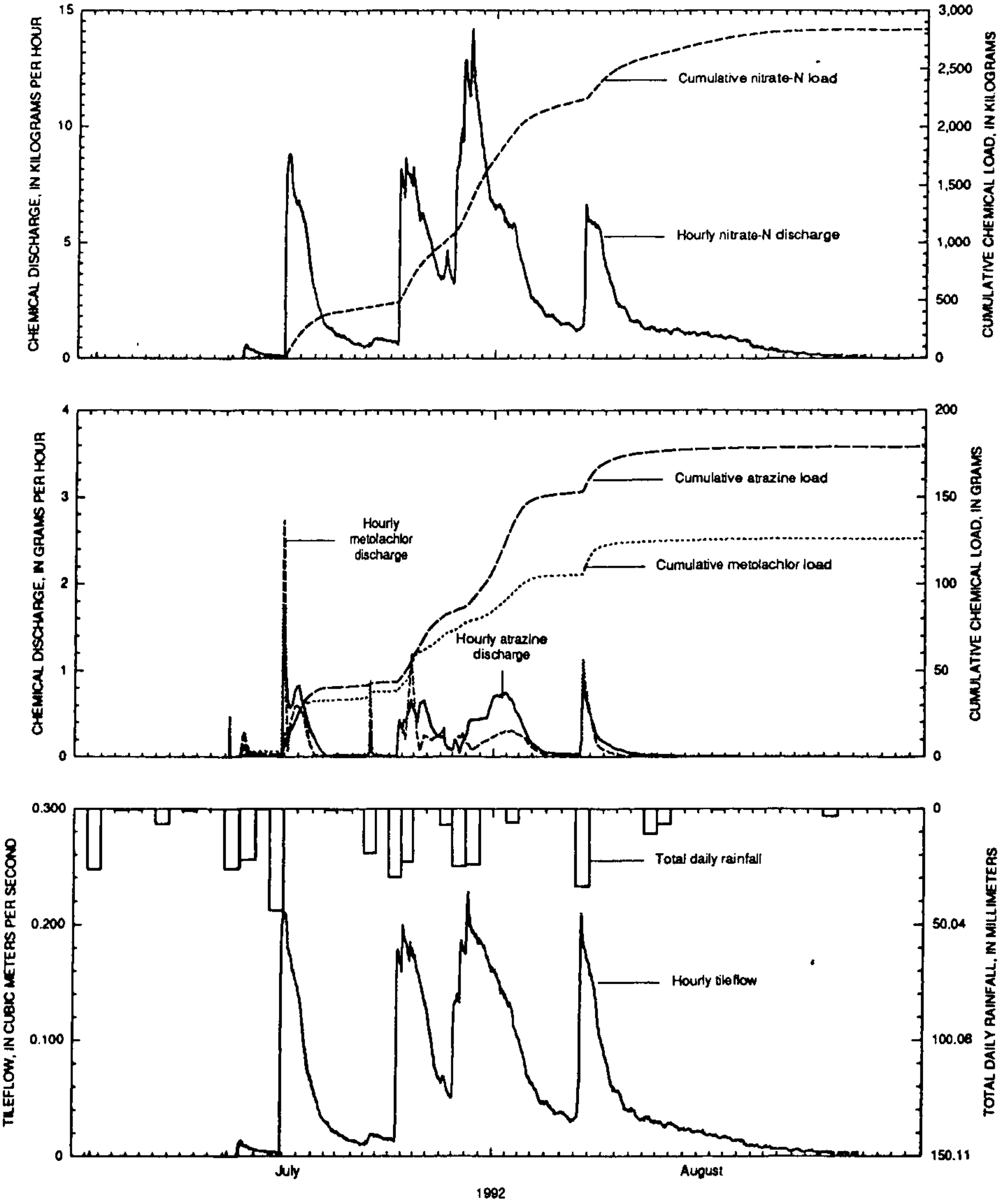

Figure 2. Daily and cumulative loads of nitrate, atrazine, and metolachlor and mean daily stream discharge at site A (from Soenksen et al., 1993)

Runoff is hypothesized to constitute a relatively minor contribution to stream flow except under extreme conditions such as those encountered in 1993. Preliminary data from the most upstream open-channel monitoring station (A on Fig. 1) illustrates the discharge of water and selected chemical loads in the stream. The area contributing to this station is 2,540 ha and includes a large area with subsurface tile drains. The cumulative loads for the illustrated period (Fig. 2) were 150,000 kg (58 $kgha^{-1}$) of NO_3-N; 11,000 g (4.5 gha^{-1}) atrazine and 19,000 g (7.3 gha^{-1}) metolachlor (Soenksen, et al., 1993). All chemical loads increased during stormflow, particularly the herbicide loads. However, NO_3-N loads also increased during base flow periods, even in winter months. Most of the herbicide load was transported during storm flow periods in May and early June, 1991 shortly after chemical application. In 1992, storms were less frequent and the herbicide load was less than in 1991.

Natural ground water contributions to streams is actively being researched. A series of well nests at the stop labeled A (Fig. 1) are being installed as one of several profiles being studied by William Simpkins and others at Iowa State University. That research is expected to increase understanding of the rate and timing of ground water flow and resulting transport of chemicals to the stream. Because there is no aquifer directly in contact with the stream in the area shown on Figure 1, discharge is not likely to be large enough to measure through stream-channel seepage methods. Consequently, well nests will be used to define hydraulic gradients and hydraulic conductivity necessary to calculate the potential discharge to the stream.

Artificial subsurface drainage represents one of the more interesting aspects of the hydrologic system in the watershed. Over the last 70 to 80 years, farmers and County governments have collaborated to develop extensive underground drainage systems in large areas of the midwest (Fig. 3). These systems are designed to drain the closed depressions and maintain a water table depth of 1.5 to 2 meters throughout much of a typical growing season. Tile drains in this watershed are installed in fields and connected to larger drains (Fig. 1) beneath topographically low areas of each field. These in turn are connected to county tiles, one of which forms the headwaters of Walnut Creek. An intermediate size drainage system is being monitored at site B (Fig. 1), also a stop on the field trip. At this station a tile surfaces in a pool maintained by a contributing area of 320 ha. Cumulative NO_3-N loads were 22 kg (0.06 $kgha^{-1}$) during stormflow periods when direct surface inlets to the drainage network are active and 2,800 kg (7.9 $kgha^{-1}$) in tileflow derived from infiltration through soil (Fig. 4; Soenksen, et al., 1993). Cumulative loads of atrazine were 3.5 g (0.010 gha^{-1}) from stormflow and 180 g (0.50 gha^{-1}) from tileflow. The cumulative load of metolachlor load was 2.6 g (0.010 gha^{-1}) in stormflow and 130 g (0.35 gha^{-1}) in tileflow.

These results indicate that water which has infiltrated soil contributes considerably more herbicides and nitrate to the stream than does surface flux immediately following storms. If this is the general case in the watershed, the load of chemicals passing the stream station A (Figs. 1 and 2) may also be largely attributed to subsurface drainage. The implications of this conclusion for designing systems to improve water quality are quite different from those which would address problems associated with overland runoff as a principal transport mechanism.

Stream recharge to an alluvial aquifer occurs east of the area mapped in Figure 1. Before discharging into the Skunk River, Walnut Creek flows across the floodplain for a distance of more than 2000 meters. It has often been observed that during periods of base flow in Walnut Creek little or no discharge reaches the Skunk River. Plans for 1994 are to establish well nests and stream monitors to measure the loss of water from Walnut Creek to the Skunk River alluvial aquifer. These measurements will be used to determine the potential for introducing agrichemicals to a type of aquifer among the most vulnerable to surface contamination in the region. Much previous research in similar aquifers was based on the hypothesis that agrichemicals were introduced from a non-point, areally distrib-

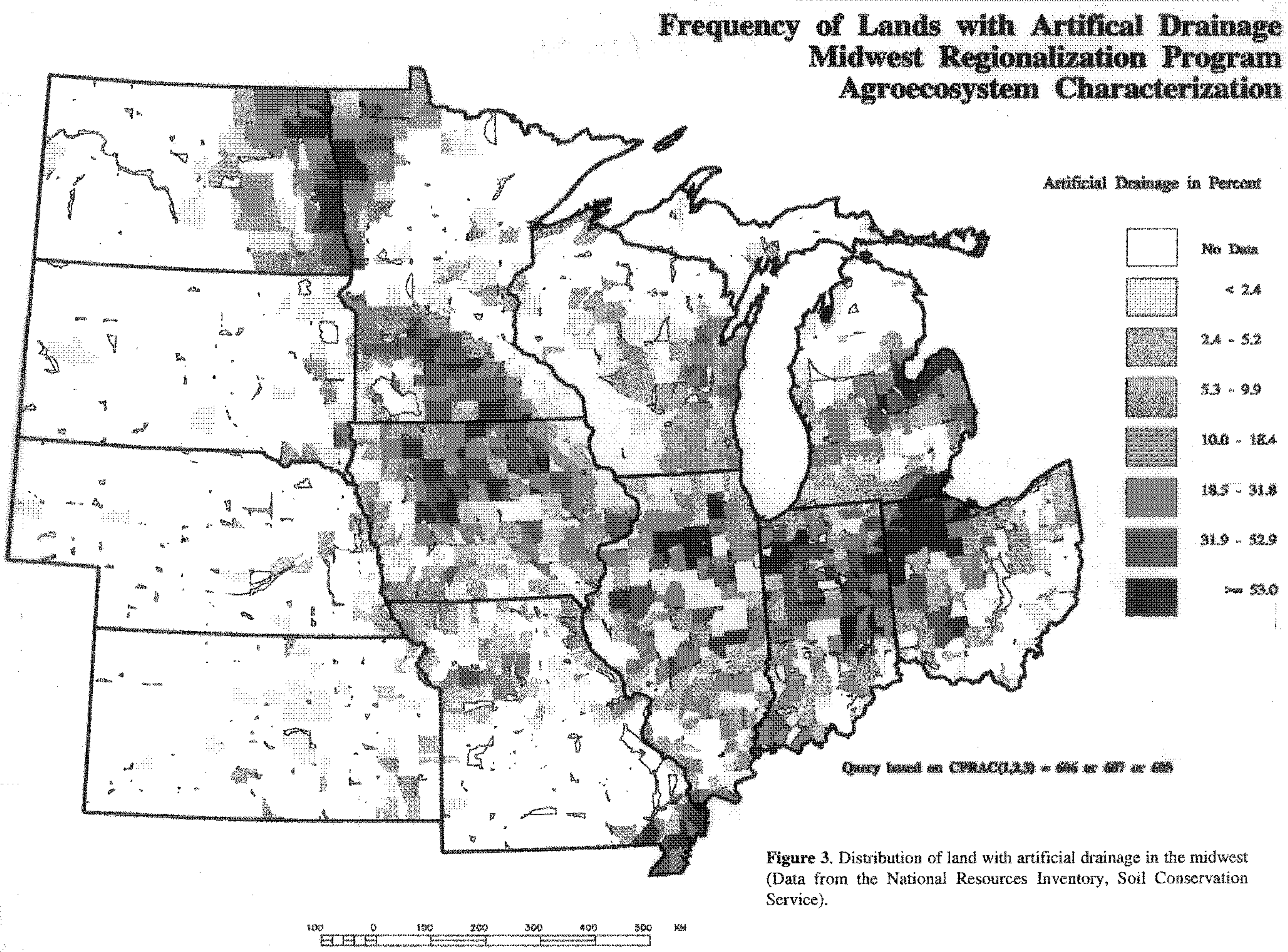

Figure 3. Distribution of land with artificial drainage in the midwest (Data from the National Resources Inventory, Soil Conservation Service).

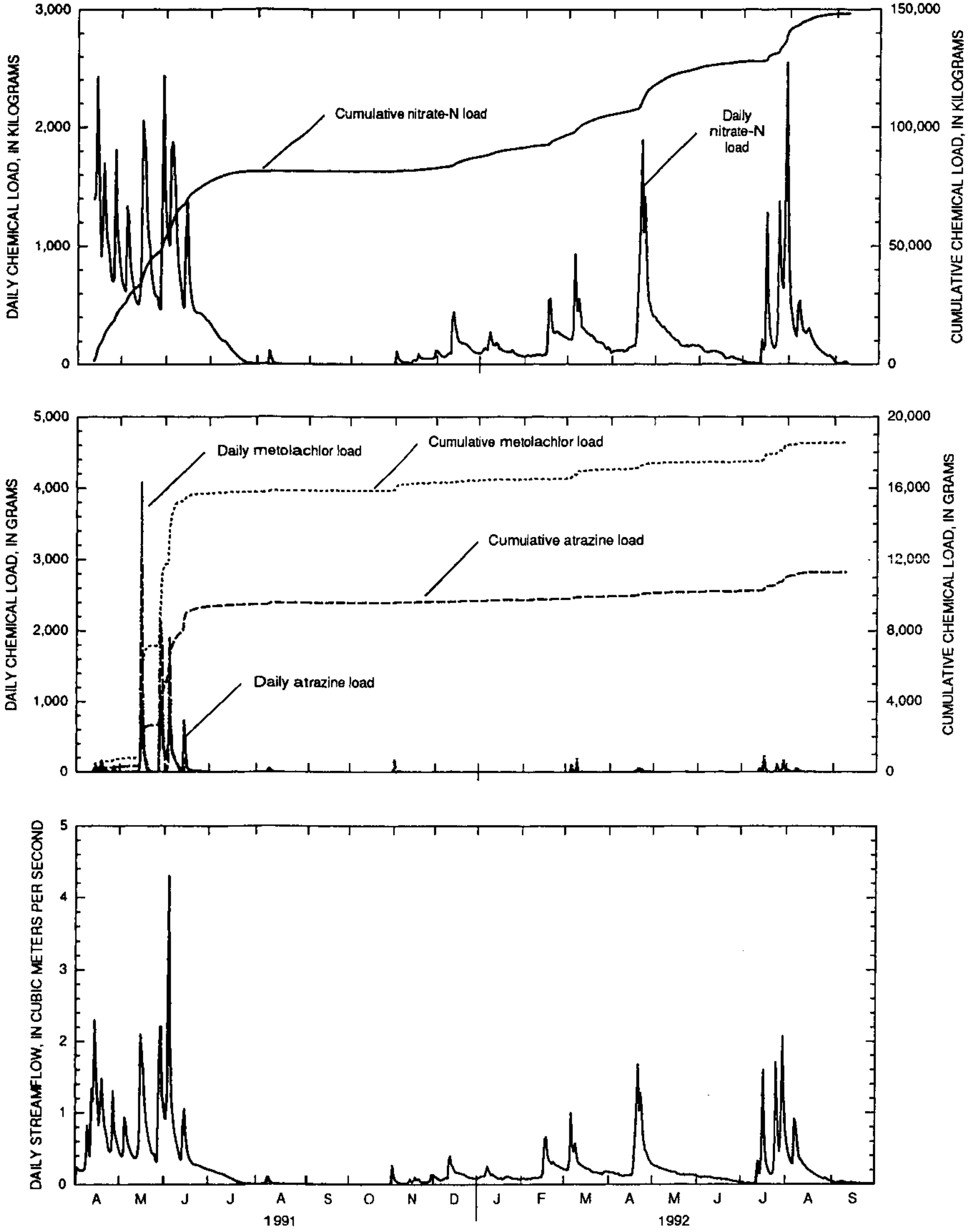

Figure 4. Daily concentrations of atrazine and nitrate with daily total discharge at tileflow station B (from Soenksen et al., 1993).

uted source. It will be critical to determine the potential load of agrichemicals from linear sources such as small tributary loss to aquifers. Plans also include research to identify the fate and transport of contaminants within the alluvial aquifer to determine the relative contribution of direct contaminant infiltration and that from the losing stream. If stream loss constitutes a major source of contamination, the implications for land-use and management systems design may extend beyond managing land immediately overlying vulnerable aquifers.

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STOP 4

BLACK'S GAGE, WALNUT CREEK

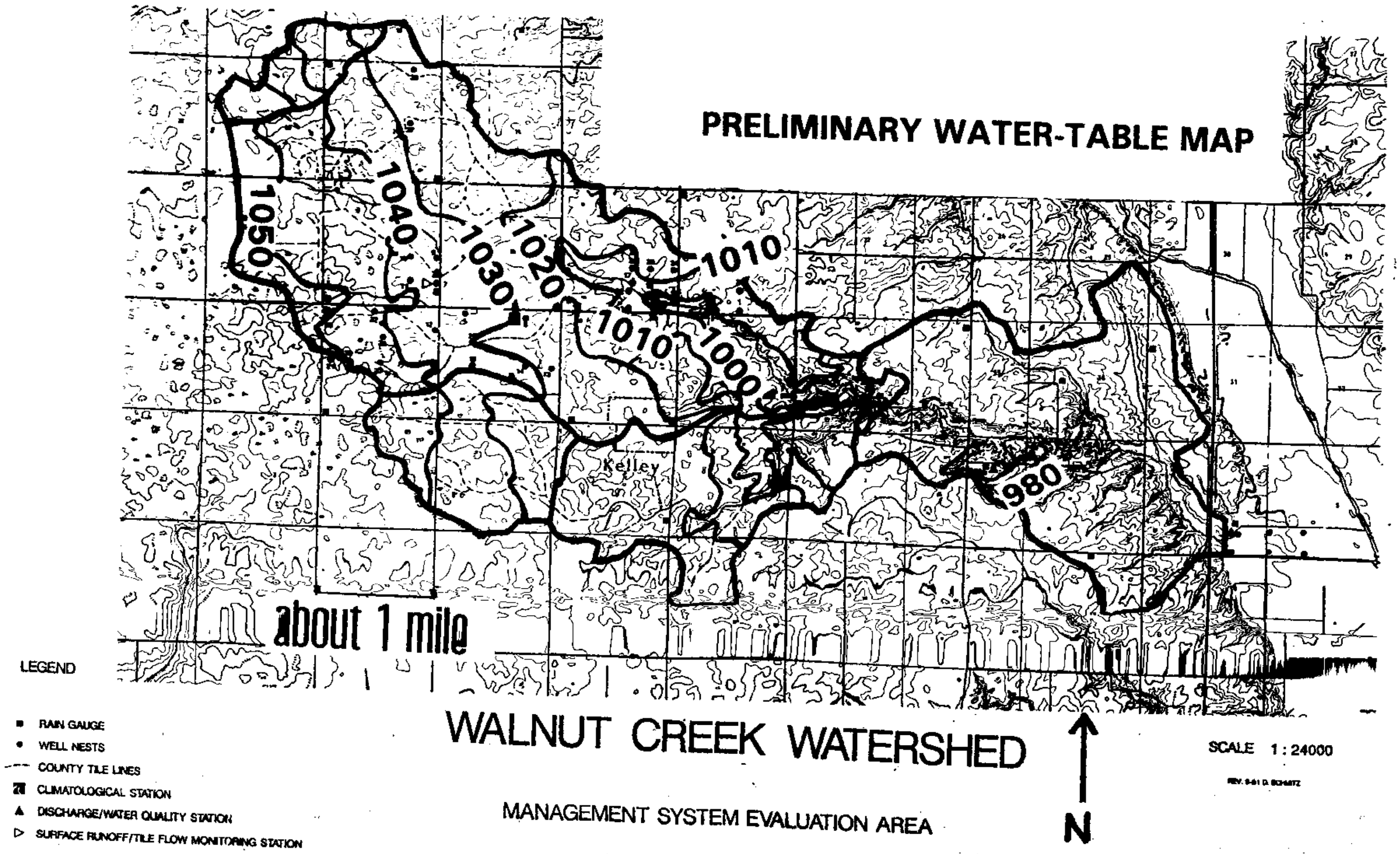

Figure 1. Preliminary water-table map of the Walnut Creek Watershed.

GROUNDWATER / SURFACE WATER INTERACTION AND HYDROGEOCHEMISTRY IN THE WALNUT CREEK WATERSHED

by

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INTRODUCTION

Combined funding from the U.S. Department of Agriculture - Cooperative State Research Service (CSRS) for the Walnut Creek MSEA Project and from the U.S. EPA MASTER (Midwest Agrichemical Surface/Subsurface Transport and Effects Research) Program have allowed us to investigate the hydrogeology and water quality within the Walnut Creek watershed. Prior to this work, 80 piezometers were installed under the auspices of the U.S. Geological Survey in Iowa City primarily for collection of water quality data and some hydraulic head measurements. The data from these piezometers allowed us to construct a very crude water table map (Fig. 1) for the watershed and outline critical areas for further study.

Perhaps the greatest unknown factor in the Walnut Creek watershed is the interaction between groundwater and the creek itself. It seems reasonable to assume that this interaction may be affected by the different geological environments in the watershed. For example, the creek is channelized in its upper reaches (the western part), where it also receives mostly tile outflow. In the central part of the watershed, the creek is cut into till and some alluvium is present. Incision is greatest in the eastern part, where the creek could be flowing on Pre-Illinoian till units (Fig. 1). Finally, Walnut Creek enters into the Skunk River via a channelized reach cut into the Skunk River alluvium (Fig. 1). Each of these areas probably has a slightly different hydrogeological environment, which, in turn, may affect the amount of groundwater discharge and the water quality input into Walnut Creek.

Because of the large area covered by the watershed, it would be financially impractical to put in hundreds of piezometers and then continue to monitor them through time. Instead, we identified what we thought were parts of the creek that were typical of the larger system, with the idea that we would instrument and monitor these reaches very intensely and then extrapolate the results to larger areas of the creek. As a result, we identified several transects in the watershed that would be used for research sites during the next few years of the study. Presently, the Black's Gage site (26 piezometers) and the Highway 69 site (30 piezometers) are the only transects under investigation. Other transects have been identified but have been put on hold pending additional funding and evaluation of the results of the first two transects. Bids for drilling and piezometer installation at the two transects ranged from $24,000 to $56,000, and the low bid was accepted. Drilling started in mid-August 1993 - delayed considerably by abnormally high summer precipitation. After these piezometers are in place, we plan to drill a continuous corehole in each section (18) to determine the glacial stratigraphy and vertical hydraulic gradients throughout the watershed. This will hopefully give us a better idea of the boundaries of the groundwater "watershed" and help us to refine the water-table map in Figure 1.

The purpose of this article is to discuss some of the preliminary hydrogeological investigations at the Black's Gage site. A separate article discussing our non-traditional piezometer installation techniques is also included in the guidebook.

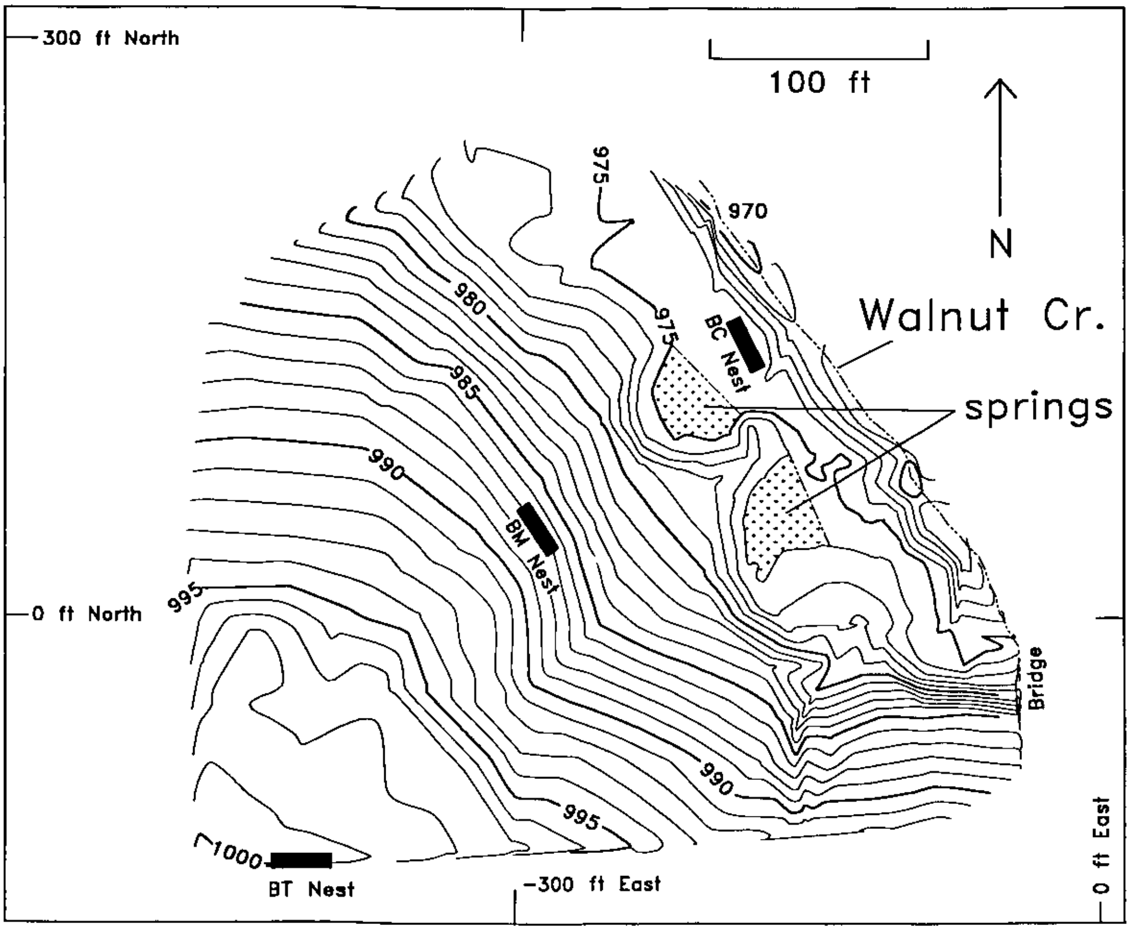

Figure 2. Site topography and piezometer locations for the Black's Gage Transect.

METHODOLOGY AND PRELIMINARY RESULTS

The Black's Gage site consists of 26 piezometers set at depths between 0.6 and 40 m. The piezometers are grouped into three nests (BT, BM, and BC) on the south side of the creek (Fig. 2). The piezometers were installed in these positions so that both horizontal and vertical components of groundwater flow into Walnut Creek could be analyzed. A single 40 m deep piezometer was installed on the north side of the creek adjacent to the private well at the house for the purpose of investigating CH_4 transport in the Pre-Illinoian till. Some new and non-traditional methods were used during the installation process (see accompanying article). Note that perennial springs have located themselves at the bottom of the slope at the contact with the alluvium (Fig. 2).

The location for this site was chosen partly because of the existing hydrologic instrumentation and the weather station, and partly because the geology appeared to be straightforward. In January 1993, as part of the MASTER program, EPA drilled a corehole approximately 1.6 km northwest of this site. The units identified in that core indicated nearly 2.6 m of alluvium and colluvium overlying late Wisconsinan diamicton (till). Wisconsinan loess, complete with gastropod shells, was encountered at 7.3 m. Although we did not drill

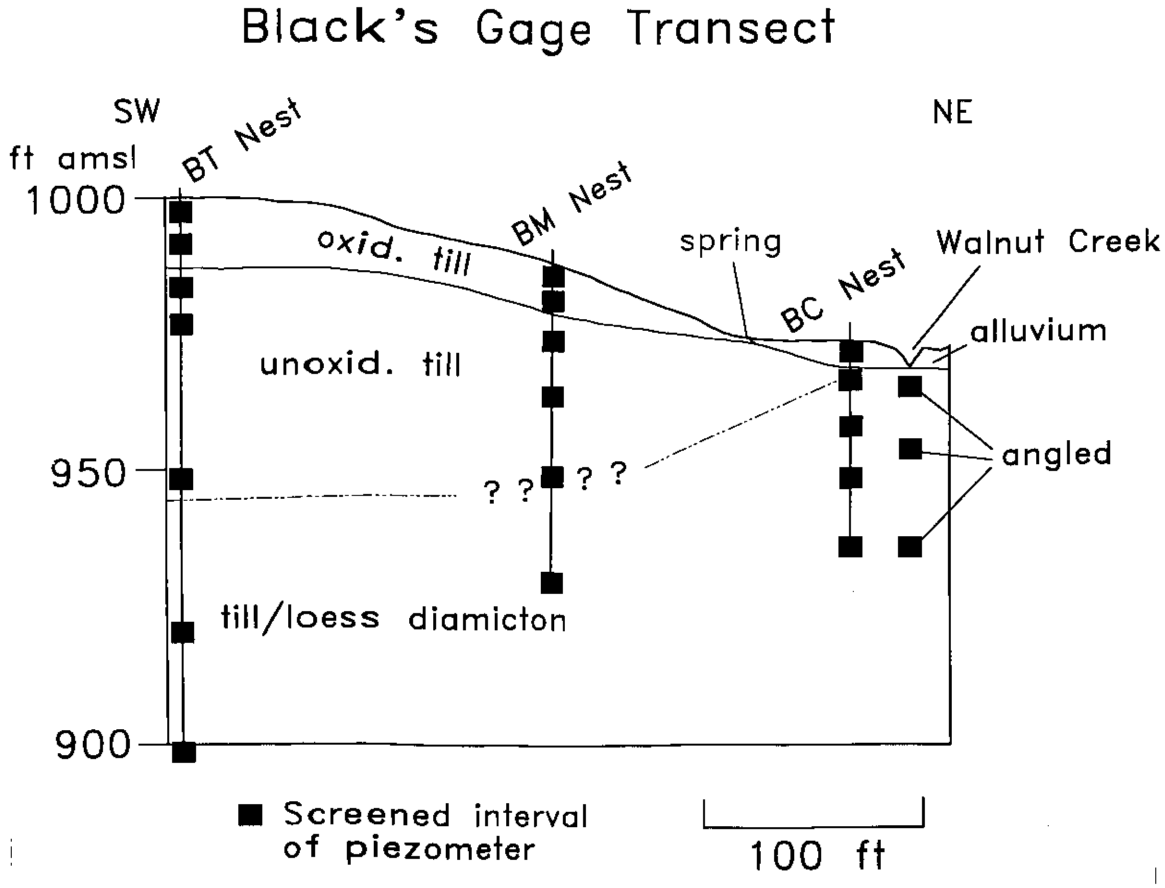

Figure 3. Cross-section showing depths of piezometers and preliminary stratigraphy at the Black's Gage transect.

further than 7.6 m, we assumed that loess would be 8 m thick or less, and that the Pre-Illinoian till would probably lie just below the loess; however, when we initiated coring at Black's Gage at the BT Nest (30.5 m continuous corehole), we found that the upper 17 m here was composed completely of very homogeneous late Wisconsinan till. Furthermore, the interval from 17 to 30.5 m contained a diamicton composed of a mixture of loess, pebbly loess and till, and Pre-Illinoian till in random stratigraphic sequence (Fig. 3). Coring near the stream at the BC Nest indicated that this diamicton, including some large 10 cm wood chips which from studies at the ATHS actually produce CH_4, begins almost immediately below the present creek bed. The contact with this material at the BM Nest is unclear, although the Shelby tube sample indicated till at 18 m. We interpret this mixture to consist of blocks of substrate that were incorporated by the ice as it overrode the area. The blocks were, perhaps due to a short distance of transport, not homogenized to the degree that the Alden Member generally appears elsewhere. In contrast to this heterogeneous mixture on the south side of the creek, drilling for the 40 m piezometer by the farm house indicated a possible stone line at 12.8 m, a possible paleosol (Yarmouth-Sangamon gumbotil) at 13.7 m, yellowish-brown Pre-Illinoian till from there to 23.7 m, a sandy zone from 23.7 to 26.5 m, and finally, unoxidized, Pre-Illinoian till from 26.5 to 40 m.

Table 1. Major cation and anion analyses for the Black's Gage Transect.

Piez. no.	**Depth (m)**	**Unit**	**Temp (C)**	**pH**	**Spec. Cond. @ 25C**	**Diss. O2**	**Ca**	**Mg**	**Na**	**K**	**HCO3**	**SO4**	**Cl**	**Fe**	**Mn**	**NO3-N**
BT-5	1.5	oxid. till	16.9	7.50	672	ND	108	28	5	0.3	342	25	4.8	0.005	0.007	13.8
BT-10	3.1	oxid. till	14.5	7.45	687	3.15	104	28	5	0.2	327	27	6.7	0.026	0.058	15.2
BT-15	5.2	unoxid. till	11.6	7.55	1582	0.83	259	72	20	6.6	355	654	11.0	5.3	1.1	BDL
BT-25	7.6	unoxid. till	10.2	7.80	694	0.86	93	28	19	4.3	443	12	5.1	0.7	1.24	BDL

This is the sequence that we had suspected to see at our other piezometer nests, and illustrates how heterogeneous these sediments can be over relatively short lateral short distances. At this time, only the hydraulic heads in the shallowest piezometers have achieved static equilibrium, and heads in the deeper piezometers, particularly the 40 m one, are still recovering. We hope to present some preliminary hydraulic head data at the time of the field trip. Samples for microbiological analysis have been taken from all parts of the core and are being stored in sterile Mason jars inside an anaerobic hood.

Recent geochemical analyses confirm our suspicions that NO_3-N occurs primarily in the oxidized zone of the till and are absent from the unoxidized zone (Table 1). This fits with our hydrogeochemical model of the Ames Till Hydrology Site. The water chemistry in BT-15 is very interesting and needs further investigation, although the Fe and Mn are consistent with our geochemical model. We do not know at this time whether CH_4 is present in this system. It is a bit worrysome that we still find dissolved O_2 fairly deep in the profile, but this along with Cl could represent remnants of shallow groundwater that leaked into deeper zones during the drilling process. We will monitor these parameters over time to determine when ambient water chemistry is re-established in this system.

USE OF NON-TRADITIONAL PIEZOMETER INSTALLATION TECHNIQUES FOR HYDROGEOLOGICAL STUDIES IN THE WALNUT CREEK WATERSHED

by

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INTRODUCTION

Research at the Ames Till Hydrology Site suggested that traditional piezometer installation techniques were inadequate to unambiguously determine the hydraulic gradients and geochemical processes in the late Wisconsinan till, loess, and Pre-Illinoian till. The problems concern four subject areas: 1) standard 2-inch diameter piezometers (wells) have a very slow response time and do reflect static equilibrium quickly, 2) standard drilling techniques smear the borehole annulus and seal off fractures in till, 3) rotary rigs add drilling fluid and contaminate the test formation and 4) the bentonite seals used to isolate the testing interval in the piezometer also add Na and SO_4 to the water, which perturbs the geochemical and microbiological environment. To solve these problems, we adapted some installation techniques patterned after those used by the Centre for Groundwater Research at the University of Waterloo. Based on the results of our initial installations, these new techniques appear to be as good as the standard ones, and may even be more cost effective in some instances.

METHODOLOGY

The standard well installation method is shown in Figure 1. In general, a drill rig uses a hollow-stem auger or rotary rig to access the desired depth. When the interval is reached, the center plug of the hollow-stem is withdrawn and a 2-inch diameter pipe is placed in the borehole. Sand or gravel (filter pack) is placed around the pipe screen to about 1 ft above the top of the screen. Then bentonite chips or a slurry are pumped on top of the sand and into the center of the hollow stem augers as they are withdrawn from the hole. While these methods may work well for very permeable aquifers, they create problems for low permeability formations. First, we discovered through studies at the ATHS that drilling fluid that is forced into the low permeability formation through the use of a rotary rig, and it is impossible to retrieve that fluid in a reasonable amount of time. Therefore, we specified the use of an auger rig only for the Walnut Creek piezometers. Second, we specified a smaller pipe diameter at Walnut Creek. If the hydraulic conductivity (K) of the till is 10^{-8} ms^{-1}, it could take several months for a static hydraulic head to be achieved in the piezometer. If it is 10^{-11} ms^{-1}, you could wait for over 1 year! We used 1.25 inch diameter piezometers to decrease the response time and to be able to calculate hydraulic gradients accurately at any one time. The small diameter pipe also enables us to sample more frequently for water quality and still allows time for the hydraulic head in the piezometer to equilibrate completely before the next measurement period.

The installation of the piezometers themselves was a bit more tedious. First, we specifed that drilling start with hollow stem augers that have been washed and decontaminated with water of known composition between boreholes. At 3 ft above the desired depth (Fig. 2; Step 1), a standard

3 inch diameter, 3 ft long Shelby tube was pushed (using drill rod and a centralizer) 3 ft into the desired piezometer interval using the tophead, and the sample was retrieved and sealed in the Shelby tube at the surface (Step 2). Next, an outward-flared (0.125 inch outward flare) Shelby tube was attached to the drill rod and sent back down the original 3 inch tube hole. The flared Shelby tube will ream the tube hole diameter to 3.25 inches and open potential fracture surfaces (Step 3). The flared Shelby tube was then pushed an additional 0.5 ft beyond the original tube hole to allow the cuttings (from scraping the tube hole) to stay in the tube and be brought to the surface.

The piezometers consisted of 1.25 inch diameter, Schedule 40 PVC pipe, with O-rings. Screens were factory .020 inch slot, 3 ft long, and were fitted with a Geotextile sock in place of a filter pack. At the top of the screen, a specially-designed, 3.5 inch diameter PVC plug was screwed onto the pipe (Fig. 3; Step 4). The purpose of this plug was to fit into the top of the Shelby Tube hole and separate the screened interval from the bentonite seal above (see attached diagram). In order to maintain an additional physical barrier between the screened interval and the bentonite, 1 ft of till cuttings (dried and crushed) were placed down the hole above the plug using a tremie pipe. The cuttings were "cooked" on site using two portable propane stoves, crushed by hand, and then passed through a funnel to make sure they would fit into the tremie pipe. We were optimistic in thinking that we could cook 3 ft of cuttings with two people and two propane stoves in the time it took to drill the borehole, so we had to revise our estimate down to 1 ft of cuttings. Three ft of bentonite pellets or chips were then placed on top of the dried cuttings (Fig. 3; Step 5) and the remainder of the borehole annulus was sealed with a pumpable bentonite grout mixture to avoid bridging. The grout was also laced with a bromide tracer from a water tank containing approved water from the City of Kelley (Fig. 4; Step 6). The purpose of the bromide was to help determine the long-term integrity of the well casing. Protective casing was installed at the top of the pipe with concrete to protect against curious bovines.

We also experimented with a number of angled piezometers in order to examine fracture flow in the till (Fig. 5) and also to measure hydraulic potentials beneath Walnut Creek (Fig. 6). Because many fractures are vertical, an angled piezometer will theoretically intersect more fractures than a vertical piezometer. Three angled piezometers will be installed at depths of 5, 15 and 30 ft beneath Walnut Creek for the purpose of determining hydraulic gradients to the creek (Fig. 6). These piezometers were drilled at an angle of 45 degrees and required a special shoe on the bottom of the drill rig mast in order to support the augers.

RESULTS AND CONCLUSIONS

How did these installation techniques work? Water analyses from 11 piezometers are shown in Table 1. Based on these analyses, it appears that no bromide has been artificially introduced into the piezometers; however, some SO_4 is present in all piezometers and high SO4 concentrations are present in BT-15 and BC-40, which could be due to bentonite contamination. On the other hand, by drilling into the till we have allowed O_2 into zones that are anaerobic, so we might expect some initial spike in SO_4, as we saw at the ATHS (see previous article). The two high SO_4 piezometers also show higher than average Cl values, which may indicate that groundwater that is high in Cl (such as from the oxidized till) is leaking down into the screened interval, perhaps before final screen emplacement. The background concentration of Cl in the grouting water is 1.2 mg L^{-1}, so that is not a likely source of contamination. Note that only the shallow piezometers have both significant NO_3-N and Cl concentrations; these are both derived from agricultural activities.

Although it is too early to make a final judgement, the non-traditional installation techniques appear to be working better or at least as well as the standard installation techniques. Hopefully, the extra work put into these installations will benefit us by providing excellent data in the years to come. At least if contamination is suspected or identified, we will know the source and perhaps be able to remediate it.

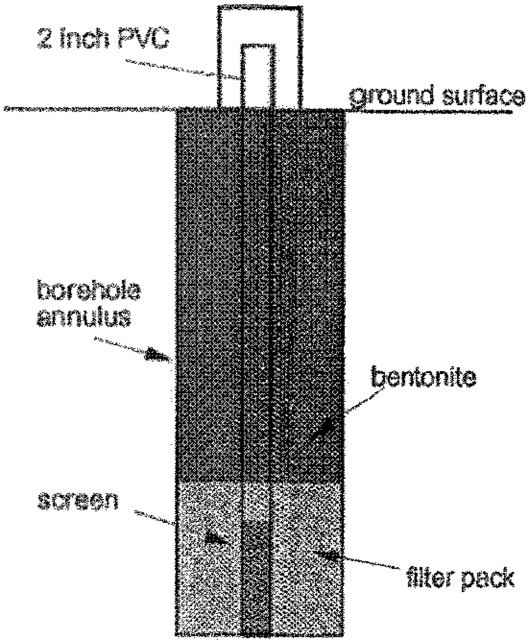
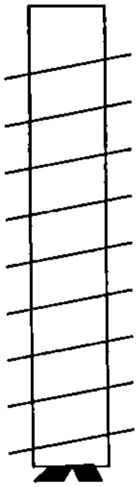


Figure 1. Diagram showing the standard piezometer or monitoring well installation.

Piezometer Installation

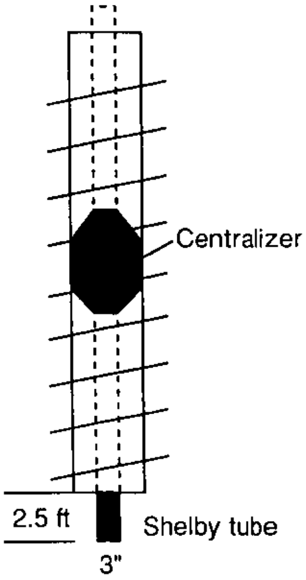
Step 1

Drill to 3 ft above depth
with 4.25" ID hollow stem



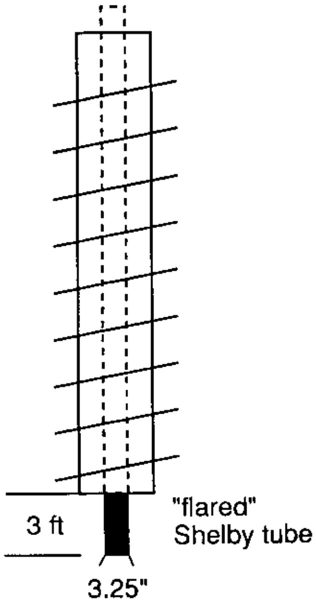
Step 2

Push 3" Shelby tube 2.5 ft
beyond hollow stem and
retrieve



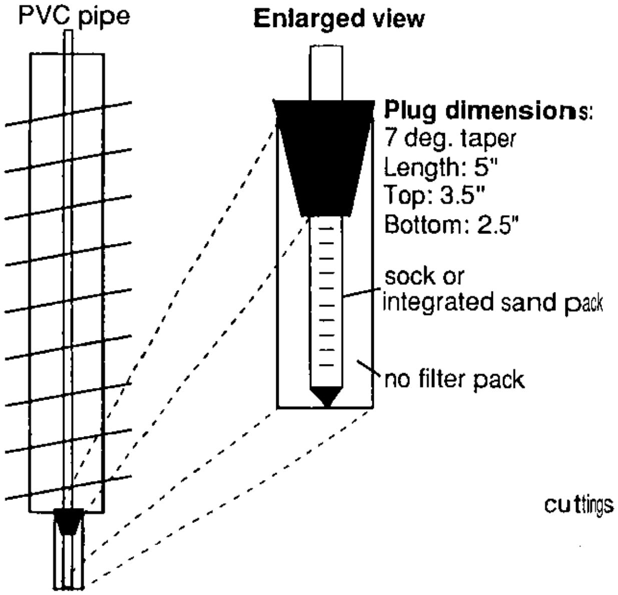
Step 3

Push 3" Shelby tube with
0.125" outward flare
into hole and 5" beyond end



Step 4

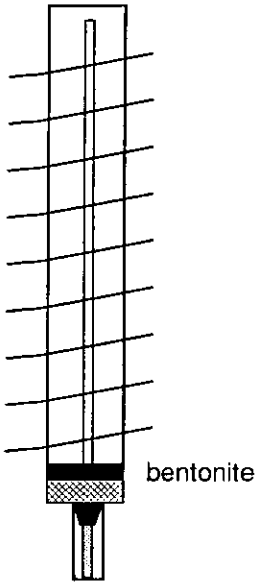
Emplace 1.25" pipe with
2.5 ft screen and 5" plug
into Shelby tube hole

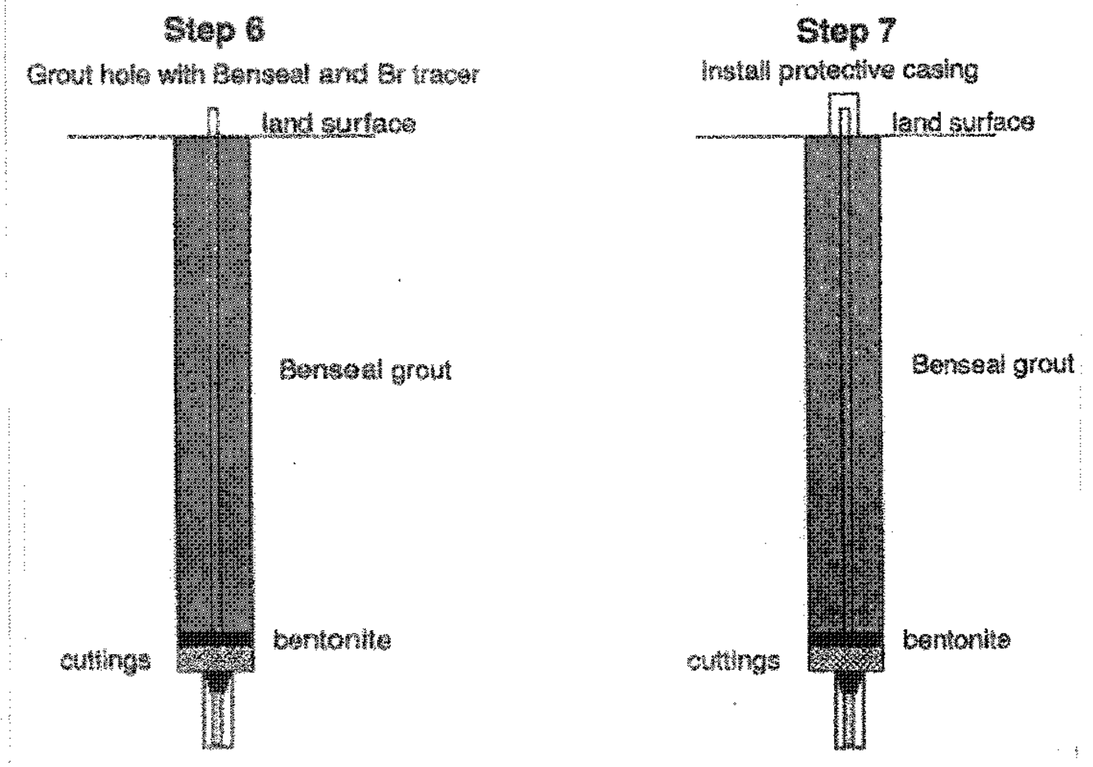


Plug dimensions:
7 deg. taper
Length: 5"
Top: 3.5"
Bottom: 2.5"

Step 5

Heat cuttings on stove to dryness
and emplace to 3 ft above plug, then
add 3 ft bentonite pellets on top





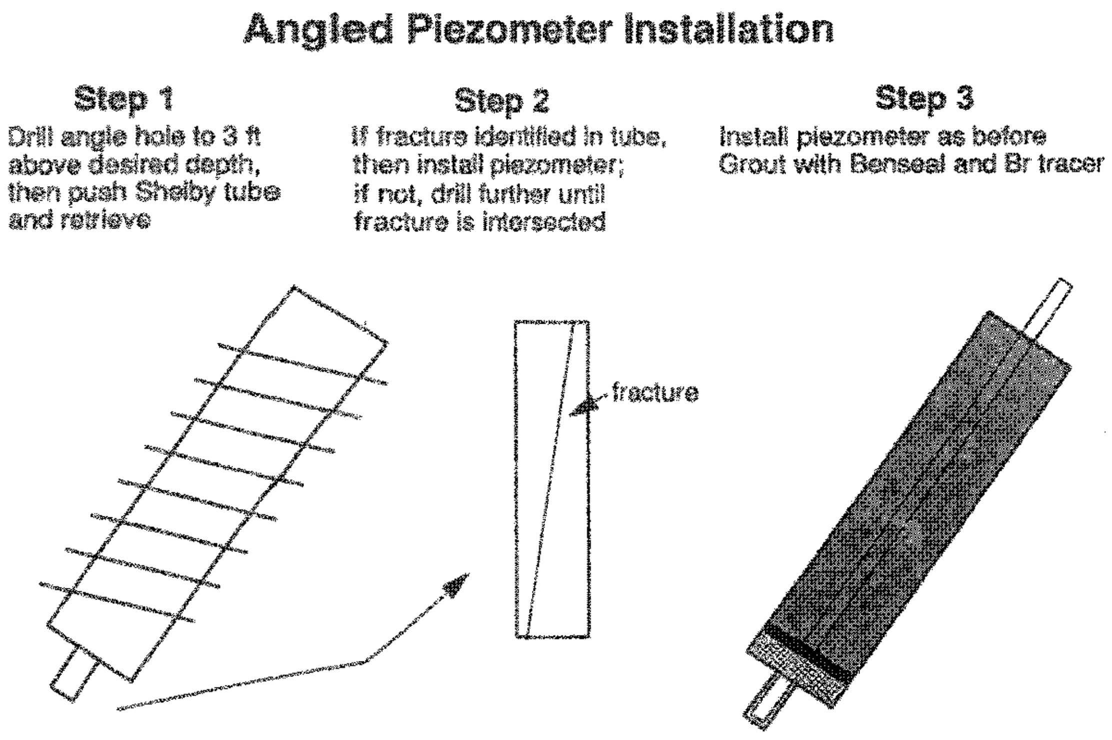
Step 6

Grout hole with Benseal and Br tracer

Step 7

Install protective casing

Figures 2 to 4. Installation technique used for vertical piezometers in the Walnut Creek Watershed.



Angled Piezometer Installation

Step 1

Drill angle hole to 3 ft above desired depth, then push Shelby tube and retrieve

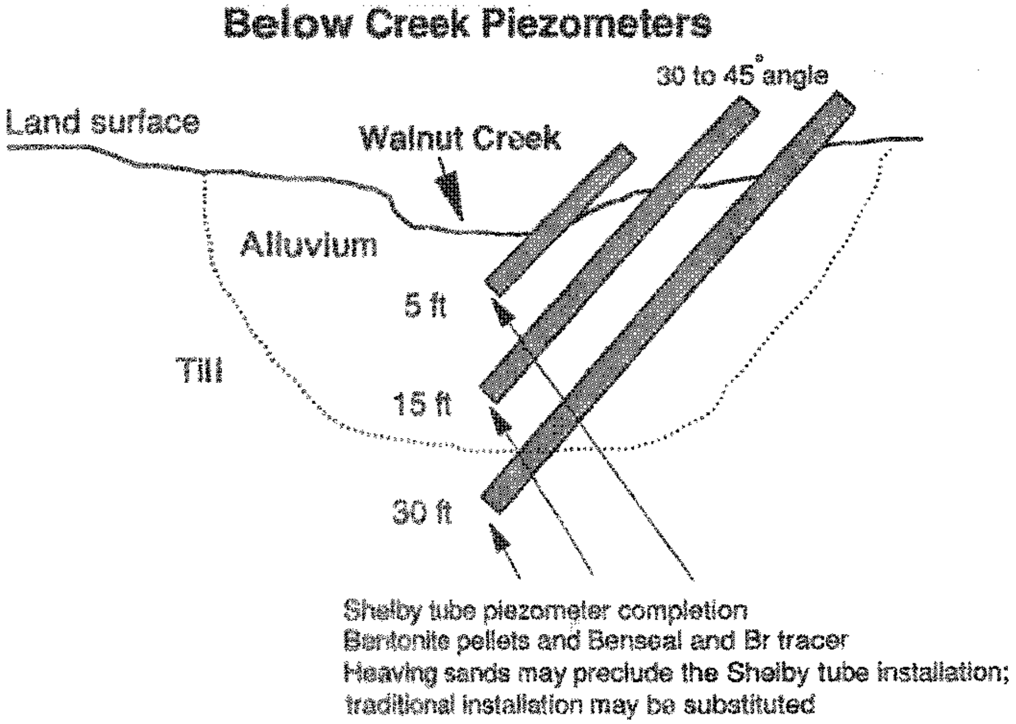
Step 2

If fracture identified in tube, then install piezometer; if not, drill further until fracture is intersected

Step 3

Install piezometer as before
Grout with Benseal and Br tracer

Figure 5. Angled borehole installation technique used in the Walnut Creek Watershed.



Below Creek Piezometers

Shelby tube piezometer completion
Bentonite pellets and Benseal and Br tracer
Heaving sands may preclude the Shelby tube installation; traditional installation may be substituted

Figure 6. Placement of angled piezometers below Walnut Creek to measure vertical hydraulic gradients.

Table 1. Major anions sampled from piezometers at the Black's Gage Transect.

Piez. no.	Br	Cl	SO4	NO3-N
BT-5	<0.6	4.8	24.5	13.8
BT-5 ang	<0.6	3.7	19.9	13.3
BT-10	<0.6	6.7	27.0	15.2
BT-15	<1.2	11.0	654.0	BDL
BT-15 ang	<0.6	16.2	6.6	BDL
BT-25	<0.6	5.1	11.6	BDL
BC-5	<0.6	6.6	19.4	BDL
BC-15	<0.6	2.9	7.8	BDL
BC-25	<0.6	<0.2	7.8	BDL
BC-40	<0.6	10.2	409.2	BDL

BDL = below the detection limit

WATER QUALITY IN PRIVATE WELLS WITHIN THE WALNUT CREEK WATERSHED

by

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INTRODUCTION

There is great interest in the water quality of private wells in agricultural areas of Iowa. As part of our studies in the Walnut Creek watershed, we sampled 47 private wells for the traditional water quality parameters of NO_3-N and pesticides (atrazine, alachlor, metolachlor, and metribuzin). In addition, we sampled wells for parameters that would indicate recent contamination (tritium and Cl) and that would yield information about the redox state of the groundwater (Fe, Mn, SO_4, CH_4, and $\delta^{13}C$-DIC). The purpose of this article is to demonstrate that conjunctive use of these parameters can yield information about the contamination potential and geochemical processes in the aquifers underlying the watershed.

RESULTS

Samples were obtained during the Summer and Fall of 1992 and many wells were resampled in 1993. Methods for this sampling are detailed in the article on the Ames Till Hydrology Site. The composite results are shown in Table 1. In general, there are four major aquifers that are used within the watershed: an upper and lower gravel unit in the Pre-Illinoian, sandstones in the Pennsylvanian or the upper part of the Mississippian, and Mississippian limestones, primarily of the Burlington and Gilmore City Formations. The results of all our sampling indicate that concentrations of pesticides that are used in the watershed were below the detection limit in all wells, and that NO_3-N was near the detection limit, with the exception of a few wells. These data are corroborated by the tritium and chloride data, which generally suggest that no recent water has migrated into the well. It should be noted that high Cl concentrations in the Pennsylvanian and Mississippian units are naturally-occuring and do not indicate contamination.

More interesting from a geochemical perspective are the redox indicators in the system. Most groundwater from the wells show high Fe concentrations, which suggests a redox environment conducive to Fe reduction. CH_4 is also found, but it is constrained primarily to the upper gravel unit. Carbon-14 dates on the gas (provided by a Grant from the Iowa Science Foundation) indicate that it is 14,000 to 17,000 years old; thus, the gas was formed in the Wisconsinan loess above and has migrated vertically into the gravel. It makes sense that most of the gas has only made it 20 to 30 m below the source horizon, and not into deeper units. In addition, where large amounts of CH_4 are present, SO_4 is generally absent. This relationship may indicate a SO_4 reduction-CH_4 oxidation process known previously only in oceanic sediments. SO_4 reduction processes are suggested by the very depleted ^{13}C concentrations of dissolved inorganic carbon, which are very close to that for the particulate organic carbon that may be present in the Pre-Illinoian units. SO_4 concentrations increase in deeper units, and CH_4 concentrations there are barely above ambient air levels. This suggests either that CH_4 has not migrated to these depths (perhaps inhibited by the Pennsylvanian shale) or that all the loess-derived CH_4 has been oxidized to CO_2 by SO_4 and much SO_4 still remains. We are presently investigating this relationship and hope to report on our findings soon.

SUMMARY AND CONCLUSIONS

Based on our sampling of private wells in the Walnut Creek watershed, we found that none of them showed evidence of substantial contamination. In addition, we found that the hydrogeochemical environment of the groundwater is so reducing that the preservation of NO_3-N is unlikely. These findings, along with Carbon-14 dates of the groundwater showing very old water, suggest that where large concentrations of NO_3-N are found in a well in this region, it is far more likely that contamination has come from a breach in the casing or through the well pit.

Table 1. Analyses of major cations, anions,tritium and pesticides for private wells within the Walnut Creek Watershed. All values in mg/L unless otherwise noted.

		Contamination indicators				Redox indicators							
Well no.	Depth (ft)	Tritium(TU)	Cl	Pest.(ug/L)	NO3-N	NH4-N	SO4	Diss. Fe	Diss. Mn	CH4(umol/L)	CH4(mg/L)	DOC	C13-DIC (o/oo)
Pre-Illinolan gravel (upper unit)													
WCA-5a	100	<6	0.7	<0.2	1.9	NS	3.2	0.54	0.02	2417.49	38.68	11.6	-11.83
WCA-8	100	<6	0.0	<0.2	0.0	0.0	0.0	1.80	0.14	549.60	8.79	5.3	-14.92
WCA-103	110	<6	2.9	<0.2	0.0	P	0.0	1.09	0.04	2574.30	41.19	P	P
WCA-11	125	<6	0.9	<0.2	0.0	1.7	108.0	1.41	0.03	0.46	0.01	1.7	-17.28
WCA-5b	130	10	0.0	<0.2	NS	NS	2.1	0.59	0.02	3130.10	50.08	9.8	NS
WCA-81	134	<6	0.0	<0.2	1.0	NS	71.8	1.39	0.03	799.14	12.79	6.2	-18.50
WCA-12a	161	<6	1.3	<0.2	0.0	NS	168.8	1.93	0.04	0.58	0.01	3.7	-18.68
WCA-95	165	<6	1.2	<0.2	3.6	3.0	0.0	3.33	0.16	2438.00	39.01	20.1	-2.90
WCA-74	167	<6	1.6	<0.2	0.0	8.6	98.3	2.24	0.05	2.08	0.03	P	-19.11
WCA-6	180	<6	0.0	<0.2	1.3	1.8	7.8	0.73	0.02	56.30	0.90	7.4	-24.68
Mean	137	<6	0.9	<0.2	0.9	3.0	46.0	1.50	0.05	1196.81	19.15	8.2	-15.99
Pre-Illinolan gravel (lower unit)													
WCA-41	190	16	0.9	<0.2	2.6	1.4	150.7	2.95	0.06	0.86	0.01	3.4	-17.47
WCA-55	190	<6	3.3	<0.2	0.6	NS	153.0	1.22	0.02	0.69	0.01	9.3	-18.67
WCA-18	210	<6	0.0	<0.2	1.2	0.0	9.0	1.66	0.04	4.02	0.06	2.9	-26.88
WCA-13	214	<6	0.9	<0.2	0.0	1.0	109.8	1.25	0.04	0.47	0.01	4.8	-22.20
WCA-92	218	<6	1.2	<0.2	2.8	2.0	158.7	1.24	0.04	1.23	0.02	3.5	-17.20
WCA-31	220	<6	1.2	<0.2	1.3	0.0	14.8	1.71	0.03	1.38	0.02	4.4	-20.19
WCA-34	220	<6	1.2	<0.2	1.4	1.6	16.4	1.22	0.02	12.26	0.20	5.0	-18.11
WCA-91	220	<6	1.4	<0.2	0.9	1.9	56.4	1.49	0.03	0.95	0.02	0.8	-22.62
WCA-93	220	<6	0.4	<0.2	3.0	2.2	161.2	1.91	0.03	1.27	0.02	4.7	-20.20
WCA-28	223	<6	1.4	<0.2	1.3	1.0	59.1	1.13	0.04	2.07	0.03	4.9	-23.67
WCA-102	225	<6	4.7	<0.2	0.0	P	268.8	0.65	0.10	0.69	0.01	P	P
WCA-24a	227	<6	0.0	<0.2	1.2	1.4	124.7	2.37	0.04	0.86	0.01	1.5	-24.24
WCA-71aa	231	<6	5.3	<0.2	1.2	8.7	280.3	2.03	0.03	126.12	2.02	1.1	-11.12
WCA-12	240	<6	1.9	<0.2	0.0	1.6	126.2	2.14	0.03	0.48	0.01	3.5	-19.15
WCA-49a	240	<6	0.0	<0.2	0.0	NS	511.0	2.41	0.07	3.74	0.06	2.9	-16.08
WCA-25	250	<6	2.2	<0.2	0.0	NS	336.2	1.79	0.03	0.45	0.01	3.6	-22.35
WCA-61	250	<6	0.0	<0.2	2.0	4.6	320.4	2.72	0.02	0.61	0.01	0.7	-17.45
WCA-22a	254	<6	1.0	<0.2	1.2	1.2	159.4	1.75	0.06	6.25	0.10	5.7	-24.01
WCA-21	260	<6	1.9	<0.2	1.1	0.0	145.3	1.60	0.03	0.55	0.01	4.1	-21.70
WCA-73	260	<6	10.2	<0.2	1.1	NS	358.2	0.74	0.13	0.42	0.01	2.5	NS
WCA-69a	279	<6	13.0	<0.2	3.7	1.5	368.3	3.77	0.07	0.53	0.01	0.7	-5.78
WCA-15	???	<6	0.0	<0.2	3.5	NS	0.0	0.00	0.02	2.68	0.04	6.4	-26.20
WCA-46	???	<6	0.0	<0.2	1.3	2.8	385.0	3.25	0.06	0.55	0.01	1.8	-15.19
Mean	231	<6	2.3	<0.2	1.4	1.9	185.8	1.78	0.04	7.35	0.12	3.6	-19.55
Pennsylvanian or Mississippian St Louis sandstones													
WCA-20	260	<6	1.8	<0.2	1.3	4.7	533.8	1.79	0.03	1.07	0.02	4.1	-18.50
WCA-45	200	7	4.2	<0.2	0.0	3.0	734.8	2.71	0.06	1.40	0.02	0.9	-15.33
WCA-47	285	<6	3.5	<0.2	0.0	NS	603.5	2.68	0.05	0.59	0.01	2.4	-15.82
WCA-64	???	<6	9.3	<0.2	0.0	9.7	985.2	3.80	0.06	0.47	0.01	0.6	NS
WCA-72	286	<6	9.3	<0.2	1.9	9.1	762.1	5.94	0.15	2.24	0.04	1.1	-13.11
WCA-98	285	<6	9.8	<0.2	0.0	9.0	882.0	4.55	0.07	1.11	0.02	0.8	-13.42
WCA-100	255	<6	1.9	<0.2	10.7	12.9	453.5	2.20	0.12	1.33	0.02	1.6	-17.30
Mean	262	<6	6.3	<0.2	2.1	8.7	736.9	3.65	0.08	1.19	0.02	1.2	-15.00
Mississippian limestones (Burlington and Gilmore City)													
WCA-3	360	<6	1.7	<0.2	1.0	1.7	83.4	4.88	0.04	5.83	0.09	3.4	-17.25
WCA-36	361	<6	13.3	<0.2	1.3	1.5	543.3	1.05	0.02	0.60	0.01	0.5	-11.77
WCA-44	380	<6	52.3	<0.2	0.0	NS	884.9	2.08	0.03	0.38	0.01	0.9	-3.60
WCA-71ab	298	<6	9.8	<0.2	1.2	7.9	416.4	0.46	0.02	2.37	0.04	1.0	-10.18
WCA-82	415	<6	0.0	<0.2	1.0	NS	191.6	2.51	0.05	0.70	0.01	4.4	-20.06
WCA-90	442	<6	35.8	<0.2	1.0	5.0	645.9	2.10	0.02	0.60	0.01	P	-4.70
WCA-101	300	<6	3.7	<0.2	3.9	2.5	410.4	0.13	0.05	P	P	0.8	-18.80
Mean	365	<6	16.7	<0.2	1.3	3.7	453.7	1.89	0.03	1.75	0.03	1.8	-12.34

P = analysis pending, NS = not sampled.

STOP 5

A CONSTRUCTED MULTI-SPECIES RIPARIAN BUFFER STRIP ON BEAR CREEK NEAR ROLAND, IOWA

revised 12/29/93

CONSTRUCTED MULTI-SPECIES RIPARIAN BUFFER STRIPS IN IOWA

by

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Iowa State University

INTRODUCTION

Iowa is a mosaic landscape of agricultural crops, pasture lands, native woodlands, and a network of streams and creeks for drainage of abundant rainfall. The soil on this landscape produces some of the world's best crop yields. Settlement of the land and the increased mechanization of agriculture caused removal of many natural woodland corridors along streams and creeks. Loss of this permanent riparian ecosystem resulted in the movement of agrichemicals from millions of hectares of farmland into surface water and groundwater. Restoration of riparian buffer strips is a Best Management Practice (BMP) that can that can function similarly to natural riparian communities and thus reduce agricultural impacts on surface water.

AGROFORESTRY AND BUFFER STRIPS

Combinations of trees, shrubs, and grasses can be developed that contribute to sustainable agriculture by functioning as nutrient and sediment sinks for non-point source (NPS) pollutants. Innovative designs that use specially selected fast-growing tree species can be grown as short-rotation woody crop (SRWC) systems. SRWC systems produce fiber products or biomass-for-energy in 5-8 years and timber products in 15-20 years. The selected species reproduce vegetatively by stump or root sprouts. As a result, sites need only be planted every 3 to 4 harvests. The large root systems allow very rapid regrowth that provides continuity in water and nutrient uptake and physical stability of the soil throughout the life of the stand. Trees combined with shrubs and native prairie grasses increase biodiversity and thus improve wildlife habitat and aesthetics. To date, however, there is little research-based information on the design, technical capabilities, and appropriate management approaches for reconstructed riparian communities.

The Iowa State Agroforestry Research Team (IStART), along with researchers from the Departments of Forestry, Agronomy, Geological and Atmospheric Sciences, and Animal Ecology at Iowa State University, has established a riparian buffer strip management system on the Risdal farm along Bear Creek north of Roland, Iowa. The impact of agriculture on the surface water quality of the whole watershed is being studied by the Agroecology Issue Team of the Leopold Center for Sustainable Agriculture at Iowa State University. The goal of this project is to develop a riparian management system and study its ability to trap sediment and to function as a nutrient and pesticide sink. At the same time the buffer strip should provide wildlife habitat and potential economic returns for the landowner, generally in the form of biomass for energy. Funding for this project has come from the Leopold Center for Sustainable Agriculture, the Iowa Department of Natural Resources, and the U.S. EPA Region 7 in Kansas City. The strips are 66 ft wide in order to qualify for the set-aside width for the Conservation Reserve Program (CRP). In this paper, the study site will be known as the Constructed Multi-Species Riparian Buffer Strip site or CMRBS.

PHYSICAL SETTING OF THE CONSTRUCTED MULTI-SPECIES RIPARIAN BUFFER STRIP (CMRBS) SITE

by

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INTRODUCTION

The study site is located on a privately-owned farm that supports a typical soybean and corn rotation. The CMRBS was constructed on a 66-ft-wide (20-m-wide) strip adjacent to Bear Creek north of Roland, Iowa. The physical setting of and farming practices on the site are typical of central Iowa; thus, the results of this study could be extrapolated to areas that exhibit similar geological, soil, and agronomic settings.

PHYSICAL SETTING

The Bear Creek Watershed is located in north-central Iowa north of Roland, and lies within the Des Moines Lobe - the depositional remnant of the late Wisconsinan glaciation in Iowa (Figure 1). On its eastern margin, the watershed is constrained by the Altamont moraine, which trends nearly north-south in this area and which lies several miles west of the terminal Bemis moraine (Figure 1). The total length of Bear Creek is 21.6 mi (34.8 km) and it intersects 17.2 mi (27.8 km) of major tributaries before it empties into the Skunk River south of Story City. The watershed drains 17,180 acres (7160 ha) of farmland, most of which has been subjected to tile-drainage during the last 40 years. About 85% of the watershed is devoted to corn and soybean agriculture. Prairie vegetation originally dominated most of the gently undulating topography except for the forests that lie near the mouth end of the creek. Soils are well-drained to poorly drained and formed in till or local alluvium and colluvium derived from till. Roland, a town of 1,100 people, is the only community in the watershed and there are no major recreational areas.

The site lies along a 3300 ft (1000 m) reach of Bear Creek on a privately-owned farm that is approximately 1.5 mi (2.4 km) north of Roland. Until 1988, livestock were allowed to graze down to the present stream bank, which caused severe stream bank erosion. The farmer, Ron Risdal, having expressed concern about the erosion of his stream banks, allowed construction of the CMRBS on his property beginning in 1990. Corn, soybeans, alfalfa hay, oats, and "Christmas trees" are grown on the farm and the corn and soybeans are rotated on an annual basis. During the past four years, pesticides applied on the farm have included Commence (chlomazone) in 1989 and 1991, Extrazine (atrazine and cyanazine) in 1990, 1992, and 1993, and Eradicane (EPTC) in 1990 and 1992. During the past twelve years, impregnated urea pellets have been applied at the rate of 120 lb ac^{-1} (134 kg ha^{-1}). On legume fields, 80 lb ac^{-1} (90 kg ha^{-1}) of 120-60-60 (N-P-K) are applied annually.

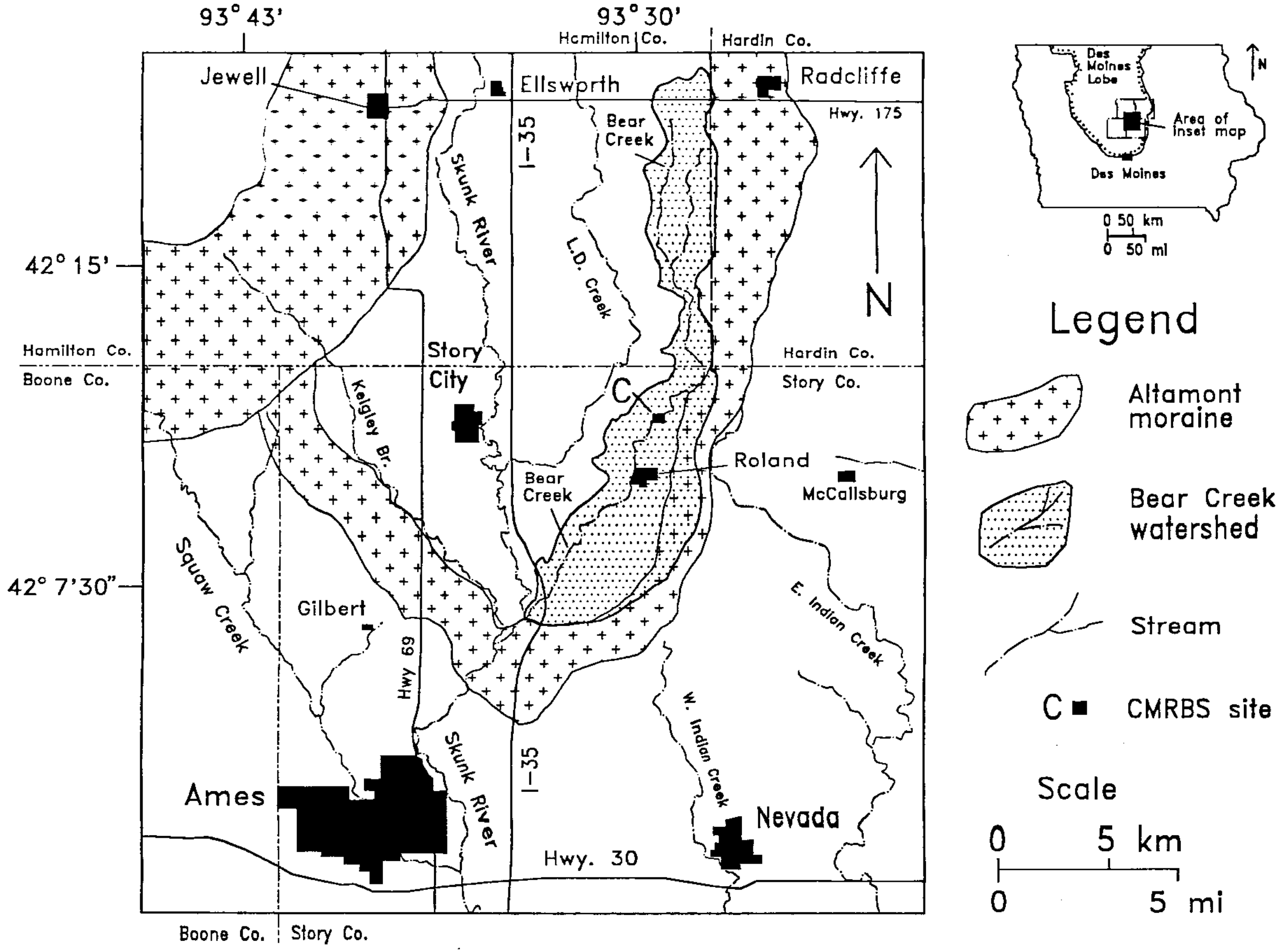

Figure 1. Location of the Bear Creek watershed and the CMRBS site.

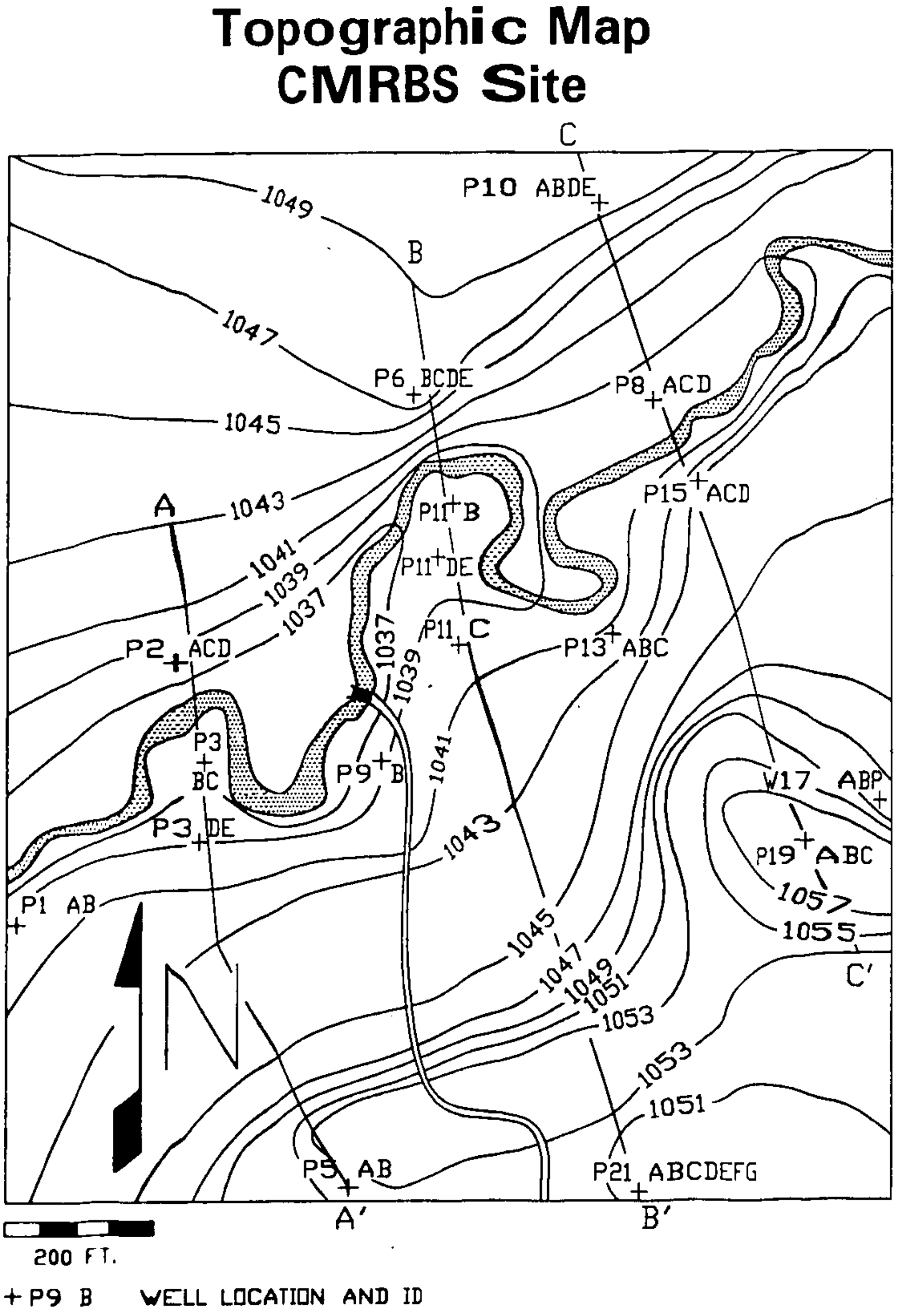

Figure 2. Preliminary topographic map of the CMRBS site showing location of piezometer nests.

Ground elevations at the farm decrease gradually down to the creek (Figure 2). Pleistocene deposits of the Des Moines Lobe (Alden and Morgan Members) and Holocene age sediment dominate the surficial materials, and overlie Mississippian age bedrock, composed of primarily limestone, dolomite, sandstone and shale (the Mississippian units are described in a next article in the guidebook by Witzke and Bunker). The most surprising feature of the geology at the site was the depth to bedrock. Although maps provided by the Iowa Department of Natural Resources - Geological Survey Bureau (IDNR-GSB) indicated that the Pleistocene sediment was probably less than 100 ft (30 m) thick and there were no visible bedrock outcrops, bedrock was encountered at depths of 22 ft (6.7 m) near the entrance to the farm and at depths of 12 to 15 ft (3.7 to 4.6 m) below the alluvium and adjacent to the present channel. Excavations of the creek bed for the weir installations indicated that weathered limestone and siltstone lie less than 5 ft (1.5 m) below the channel. The presence of bedrock at shallow depths complicates the hydrogeology of the site and provides a route for groundwater that bypasses the CMRBS. As a result, much of the hydrogeological research has been directed towards distinguishing groundwater flow in the shallow unconfined and the deeper bedrock aquifer.

EXPERIMENTAL DESIGN

In order to provide an objective evaluation of the CMRBS, sections of the Bear Creek reach were divided up according to a split block statistical design. The reach of the creek under study was divided into three blocks: inside bend, outside bend, and straight reaches (Figure 3). Five 300 ft (90 m) plots were located within each block. Treatments consisting of three combinations of planted trees, shrubs, grass, and two controls, were randomly assigned to the plots within each block. The planted treatments consisted of five rows of trees planted closest to and parallel to the creek at a 4 x 6 ft (1.2 x 1.8 m) spacing. Different species of trees were used in each of the three treatments. One treatment consisted of a poplar hybrid (*Populus* X *euramericana* 'Eugenei') which has been extensively tested and is readily available in Iowa. The second treatment contained green ash (*Fraxinus pennsylvanica* Marsh.) and the third treatment contained a mixture of four rows of silver maple (*Acer saccharinum* L.) with a center row of black walnut (*Juglans nigra* L.). Upslope from the trees a row of red-osier dogwood (*Cornus stolonifera* Michx.) and a row of ninebark (*Physocarpus opulifolius* L.). The shrubs were planted at a 3 x 6 ft (0.9 x 1.8 m) spacing. Finally, a 24 ft wide (7.3 m) strip of switchgrass (*Panicum virgatum*) was planted upslope from the shrubs. Controls consist of pasture grasses similar to those that were present on the previous grazing areas. Most trees are being grown on a 6- to 8-year rotation, depending on the species. Black walnut is being grown on a 45- to 55-year rotation. Views of the site in 1990, 1991, and 1993 are shown in Figure 4.

REFERENCE

Ryan, W.J., 1993. A preliminary hydrogeological assessment of a constructed multispecies riparian buffer strip near Roland, Iowa. unpubl. M.S. thesis, Department of Geological and Atmospheric Sciences, Iowa State University, 147 pp.

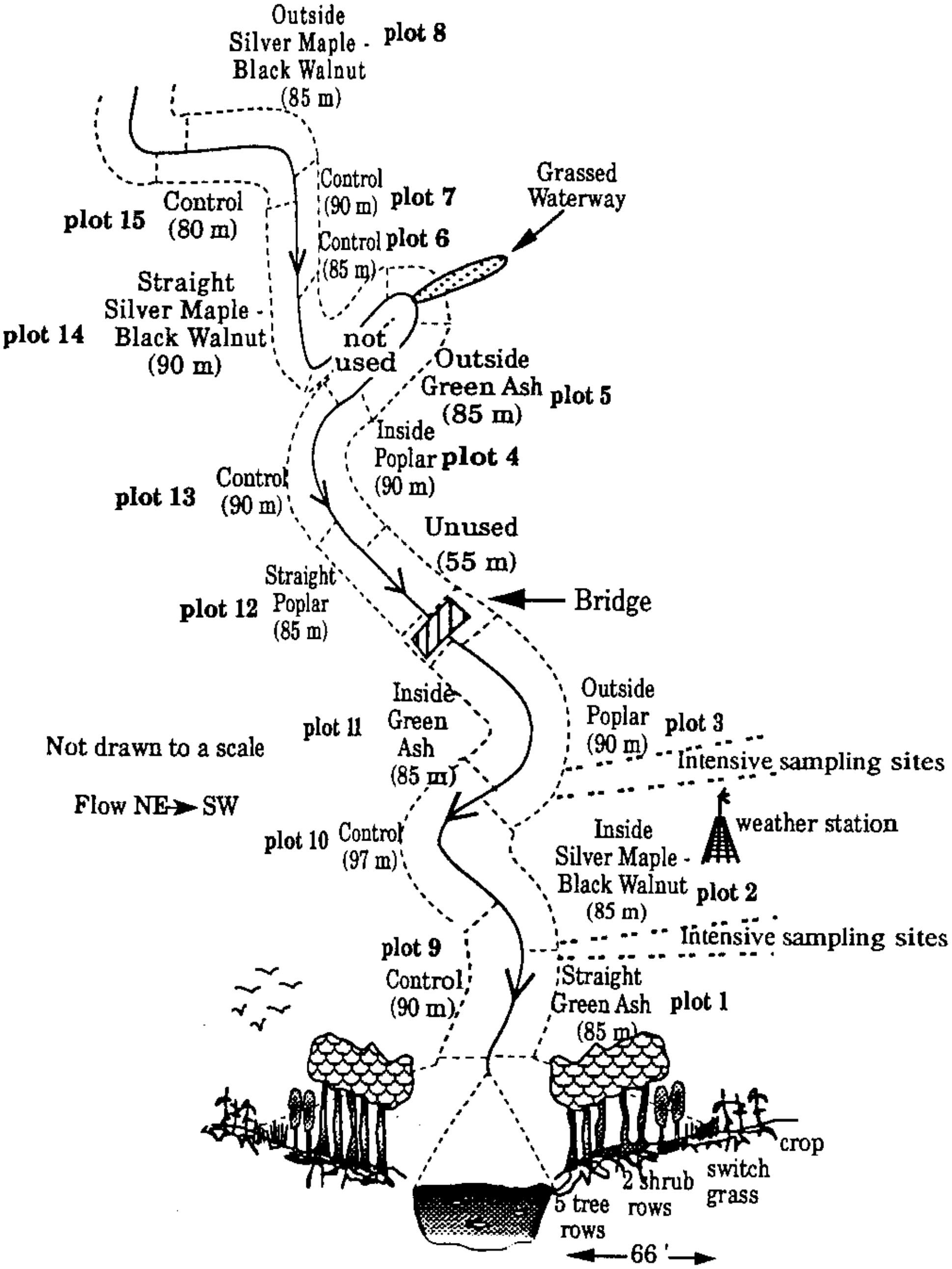

Figure 3. Experimental design and configuration of the CMRBS.

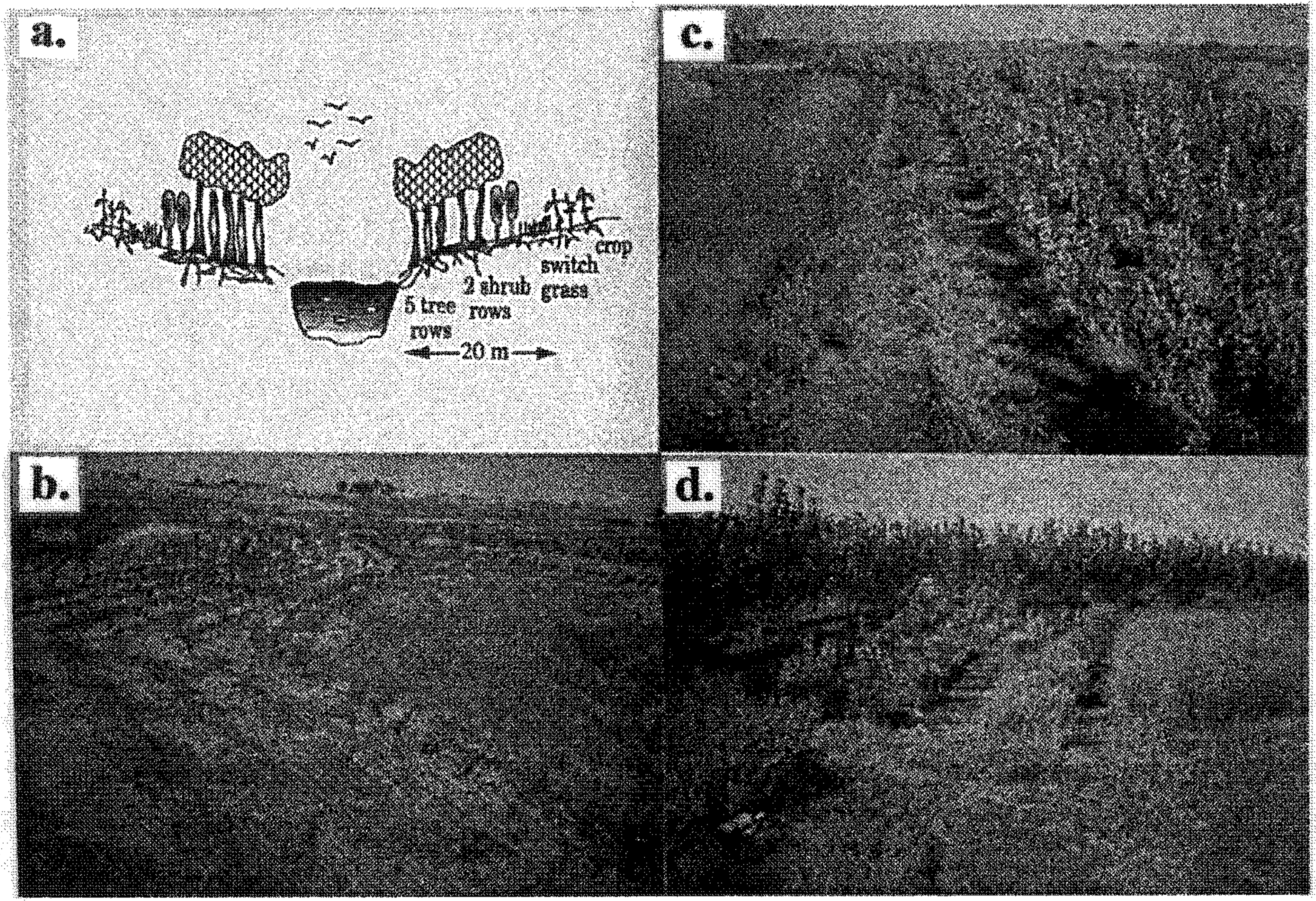

Figure 4. Layout of the CMRBS (a) and photographs of the site in (b) 1990, (c) 1991, and (d) 1993.

DESCRIPTION OF BEDROCK CORE FROM THE CMRBS SITE

by
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Geological Survey Bureau

INTRODUCTION

Bedrock core obtained from the CMRBS has aided the stratigraphic and hydrogeologic studies at the site. The core occupies a very important location between two predominant facies of the Mississippian in Iowa and it may provide the necessary link to document the transition between the two facies. Shales and chert units seen within the limestone should provide effective aquitards or confining units for groundwater flow in different parts of the Mississippian aquifer and prevent transport of agrichemicals into the deeper parts of the aquifer.

CORE DESCRIPTION AND INTERPRETATIONS

As part of the hydrogeological investigations at the CMRBS site, the IDNR-GSB was contracted in May 1991 to drill and obtain a bedrock core in order to characterize the general stratigraphy of the site and to help install piezometers into this corehole. The core has the notable distinction of being the last one drilled by the GSB outside of the Manson Impact Structure; the GSB's drilling program was terminated shortly thereafter due to state budgetary pressures. The core penetrated the entire thickness of Mississippian strata (260 feet or 79.3 m)(Figure 1). Geographically speaking, the core occupies a critical region in which important facies transitions occur within the Mississippian sequence of Iowa. It is equidistant between the seemingly disparate Mississippian stratigraphies of southeastern and north-central Iowa. Prior to this core, little subsurface information was available to document the transition between the large-scale facies belts of these areas; as such, it constitutes a possible link between facies of the Burlington Formation to the south and Gilmore City Formation to the north and may help unravel that particular relationship.

The lowest interval in the core is assigned to the Maynes Creek Formation, which is characterized by dolomite, cherty in part (Figure 1). Porous, fossil-moldic intervals occur near the base, and calcite-filled vugs and stylolites are scattered through the formation. Two prominent irregular hardground or discontinuity surfaces are noted, one of which is tentatively used to mark the top of the formation. A similar surface bounds the contact of the Burlington and Wassonville formation in southeast Iowa (the Maynes Creek and Wassonville formations are stratigraphically equivalent). A dolomite interval at 237.3 to 255.7 ft (72.3 to 78.0 m) - above the upper surface and below the oolite unit - resembles the Maynes Creek in part, but lacks chert and includes dolomitized packstone lithologies. The interval is tentatively included with the lower "Gilmore City" facies, pending further biostratigraphic study.

Limestone and dolomitic limestone strata above the Maynes Creek unit are provisionally labeled as "Gilmore City" Formation; however, these units include a mixture of carbonate lithologies not typically seen in the classic Gilmore City exposures. The interval contains carbonate facies that closely resemble strata of the lower Burlington Formation (Dolbee Creek Member) of southeast Iowa. In particular, the limestone units display crinoidal packstone to grainstone fabrics and very common stylolites

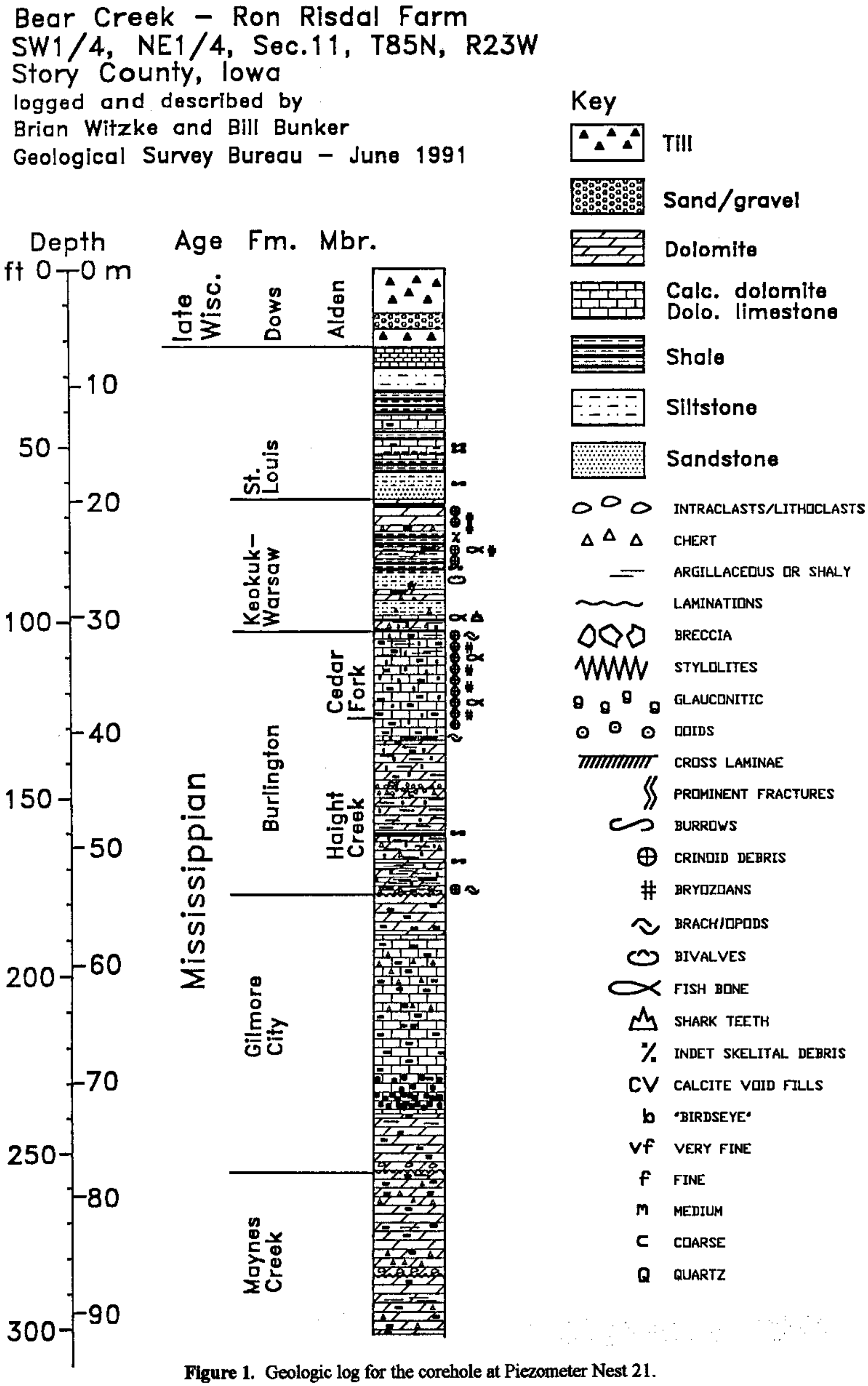

Figure 1. Geologic log for the corehole at Piezometer Nest 21.

that are typical of the lower Burlington Formation. However, the oolitic limestones within the core are uncharacteristic of lower Burlington strata, are more typical of Gilmore City Formation in northern Iowa. Thus, we tentatively suggest that the core is transitional between northern Gilmore City and southern Burlington facies, and that the two formations are correlative in part. The top of this interval in the core is marked by a prominent, irregular surface that is probably a hardground or discontinuity surface.

We assign the next higher interval at 128.4 to 177.2 ft (39.1 to 54.0 m)(Figure 1) more assuredly to the Haight Creek Member of the Burlington Formation. The Haight Creek in southern Iowa is characterized by faintly laminated cherty dolomite strata with a prominent glauconitic zone at the base. These lithologies are also seen in this core, although the cored interval is exceptionally glauconitic and unlike anything seen in typical Haight Creek strata to the south. This interval in the CMRBS core is the most glauconitic interval yet recognized anywhere in the entire Mississippian section of Iowa, and in some beds, much of the interval reveals a prominent dark green color. The CMRBS site occurs near the northern extent of the Haight Creek Member in Iowa, and the exceptional glauconite enrichment in this core may be due to its position at the margin of a proposed shelf break of the peritidal facies of the Gilmore City Formation to the north. The prominent shales and shaly strata in the lower part of this interval should be of interest to hydrogeologists, because they should be a major aquitard or confining unit in the hydrostratigraphic sequence. Brecciation occurs in the middle part of the Haight Creek member, and it is probably related to karst development.

Limestone strata of the Cedar Fork Member (Upper Burlington Formation) are also identified in the core (Figure 1). These strata are dominated by crinoidal packstone and grainstone lithologies, glauconitic in part, and are typical of the Cedar Fork Member in southeast Iowa; however, unlike classic Cedar Fork exposures, the beds are recrystallized and dolomitized to varying degrees. A prominent bone bed with blackened fish bone material occurs regionally at the top of the Burlington Formation across southern Iowa and adjacent parts of Illinois and Missouri; a similar bone bed is recognized in the CMRBS core at 97.5 ft (29.7 m)(Figure 1).

The units overlying the Burlington Formation strata (to 64.2 ft or 19.6 m) are included in an informal "Keokuk-Warsaw" interval (Figure 1). The interval is characterized by shales with interbedded, porous, fossil-moldic dolomite. The interval is notably shalier than that seen in typical Keokuk strata of southeastern Iowa. Siltstone, which is only known from high elevations in the Warsaw Shale of southeastern Iowa, occurs at the bottom of the interval. Megaquartz void-linings or geodes, typical of Keokuk and Warsaw strata in southeastern Iowa, are also seen in the core. As in most of southeastern Iowa, a prominent erosional unconformity that truncates the top of the Keokuk and Warsaw strata beneath the so-called "St. Louis" Formation across southeast Iowa, can be seen in the core. Again, the shale units probably function as effective confining units between the Keokuk and Burlington aquifers and the "St. Louis" aquifer at this site.

The uppermost bedrock unit of the core and the site is assigned to the "St. Louis" Formation, a probable correlate of the type St. Louis Formation in Missouri (Figure 1). The basal interval shows a fining-upward sequence starting from sandstone and ending in shale. This interval is capped by an interbedded argillaceous calcitic dolomite and shale interval. Shales found within the "St. Louis" intervals in the core may serve as a aquitards of confining units for the St. Louis or underlying Burlington aquifers. Based on the drilling logs from piezometers installed at this site, shale units within the St. Louis Formation may be laterally discontinuous, and thus may affect the extent of confined and unconfined conditions in the aquifer.

Recommended references for the Mississippian stratigraphy of southeast and north-central Iowa include the following:

Woodson, F.J., 1989, An excursion to the historic Gilmore City quarries: Geological Society of Iowa, Guidebook 50, 41 p.

Witzke, B.J., McKay, R.M., Bunker, B.J., and Woodson, F.J., 1990, Stratigraphy and paleoenvironments of Mississippian strata in Keokuk and Washington counties, southeast Iowa: Iowa Department of Natural Resources, Geological Survey Bureau, Guidebook Series no. 10 (54th Tri-State Geological Field Conference), 105 p.

PLEISTOCENE AND HOLOCENE GEOLOGY OF THE CMRBS SITE

by

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INTRODUCTION

A description of the Pleistocene and Holocene geologic units at the CMRBS has been integral part of the hydrogeological investigations at the site. Although the CMRBS site lies within the Des Moines Lobe, the "overburden" was considerably thinner and more complex than at sites west and south of Ames that were described earlier in this guidebook (see Simpkins, W.W., *Geological and Hydrogeological Setting of Central Iowa*, p. 37). Some differences between the CMRBS and other previously-discussed sites are as follows: 1) the diamicton is thin and is mostly oxidized, 2) there is a significant amount of sand consistently interbedded with the diamicton, and 3) the oxidized diamicton is somewhat less dense and sandier than it is to the south and west of this site. Groundwater flow in and the hydrologic function of the till units (e.g., an aquitard?) here at this site may be different than the conceptual models presented earlier in the guidebook.

PLEISTOCENE GEOLOGIC UNITS

Glacial sediment from auger grab samples and from coreholes at the CMRBS was analyzed for particle size according to the methods described in Walter et al. (1978). The results for the corehole are shown in Table 1 below. Diamicton at the CMRBS (standard deviation in parentheses) averages 53 percent sand (5.8), 30 percent silt (3.9), and 17 percent clay (3.4). In general, these values show a much higher sand percentage than is typical for till of the Dows Formation. Kemmis et al. (1981) showed that till of the Alden Member of the Dows Formation (basal till) in central Iowa averages 48 percent sand, 37 percent silt, and 15 percent clay. The Morgan Member, which consists of supraglacial sediment or diamicton, averages 44 percent sand, 42 percent silt, and 14 percent clay; however, the Morgan Member exhibits enough variability in particle size percentage that the samples above would probably fall within one standard deviation of the means given by Kemmis et al. (1981). The presence of the diamicton between significant thicknesses of sand (up to 6 ft or 1.8 m), the sandier nature of the diamicton, and the close proximity of the site (1 mi or 1.6 km) to the Altamont moraine (Figure 1) suggest that the uppermost diamicton and sand in the upper 11 to 15 ft (3.4 to 4.6 m) comprise the Morgan Member and likely indicate a supraglacial origin. In contrast, the unoxidized diamicton in this core and elsewhere on the site shows particle size percentages much closer to those cited by Kemmis et al. (1981). With reference to the corehole, oxidized diamicton and sand belongs to the Morgan Member. Oxidized diamicton at 17.3 and 19.4 ft (5.3 and 5.9 m) is likely basal till of the Alden Member (Dows Formation).

In addition to the heterogeneity within the Pleistocene section, there are a number of areas at the site where sand and gravel predominate at or near high surface away from the creek, e.g. at Piezometer Nests 6, 17, 19, and 21. These could represent fluvial surfaces that were active during or shortly after deglaciation (Noah Creek Formation?). A lower terrace system above the present floodplain occurs at Piezometer P11C and extends eastward at about the same elevation along the slope. Some of the coarse gravel here has been mined previously for aggregate and the farmer is now growing Christmas trees on these deposits. The terraces are significant features at the site because the gravel and sand have a significantly higher hydraulic conductivity than the till. Because the terraces lie directly downgradient from fields where agrichemicals are applied, samples from the groundwater often show significant quantities of NO_3-N and metabolites of atrazine.

Table 1. Particle size distribution of glacial sediment in the P21 corehole.

Depth in ft (m)	Sediment description	Percent sand (< 2mm)	Percent silt	Percent clay
4.5 (1.4)	diamicton, oxid.	56	26	18
5.5 (1.7)	diamicton, oxid.	63	20	27
6.3 (1.9)	diamicton, oxid.	52	30	18
8.1 (2.5)	diamicton, oxid.	59	28	13
9.9 (3.0)	diamicton, mixed	52	33	15
11.3 (3.4)	diamicton, unoxid.	55	33	12
14.0 (4.3)	sand, med. wl-srtd	94	0	6
17.3 (5.3)	diamicton, oxid.	46	30	24
19.4 (5.9)	diamicton, oxid.	50	31	19

HOLOCENE GEOLOGIC UNITS

The flood plain of Bear Creek consists of loamy alluvial sediment with some organic material. Much of it may be post-settlement alluvium. Two particle size analyses of the upper part of the material showed 49 and 56 percent sand, 31 and 23 percent silt, and 20 and 21 percent clay; these analyses suggest that most of this sediment is reworked till of the Dows Formation and may be partly colluvial in origin. Sandy and gravelly zones, presumably channel lag deposits, often occur at the base of the organic upper unit and both generally rest immediately on till - both oxidized and unoxidized. Although it fairly coarse-grained and piezometers within it produce large amounts of water, samples of groundwater from the alluvium generally have not shown high concentrations of NO_3-N or metabolites of atrazine.

REFERENCES

Kemmis, T.J., Hallberg, G.R., and Lutenegger, A.J., 1981. Depositional environments of the Des Moines Lobe, Iowa, *Iowa Geological Survey Guidebook Series no. 6,* 132 pp.

Walter, N.F., Hallberg, G.R., and Fenton, T.E., 1978. Particle-size analysis by the Iowa State University Soil Survey Laboratory *in* G.R. Hallberg, ed., *Standard Procedures for Evaluation of Quaternary Materials in Iowa, Iowa Geological Survey, Technical Information Series no. 8,* p. 61-74.

HYDROGEOLOGY AND HYDROGEOCHEMISTRY OF THE CMRBS SITE

by

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INTRODUCTION

Unlike many previous buffer strip projects cited in the literature, the CMRBS project has from the beginning supported a significant hydrogeological and hydrogeochemical research component. This emphasis is due primarily to three factors listed below:

1. Previous buffer strip studies have failed to understand completely the groundwater flow system beneath the buffer strip and have failed to document important groundwater geochemical processes both inside and outside the buffer strip.

2. Many previous studies have examined the role of buffer strips in presumed single aquifer systems predominated by horizontal groundwater flow. In Iowa and in other parts of the Midwest, vertical components of flow occur in groundwater systems associated with streams, and many groundwater systems consist of thin till overlying a bedrock aquifer (such as the CMRBS). Evaluations of buffer strips in likely geological and agronomic settings are necessary to provide the justification for increased construction of these strips.

3. Although the Mississippian aquifer is considered susceptible to groundwater contamination, relatively little is known about the location of its recharge and discharge areas. This study will contribute to our understanding of local to regional groundwater flow systems and the hydrogeochemistry in the Mississippian aquifer.

The purpose of this article is to provide a status report on the hydrogeological and hydrogeochemical research at the CMRBS and to demonstrate the importance of geology to the evaluation of the buffer strip at this site and elsewhere.

METHODOLOGY

The original conceptual model of groundwater flow at this site assumed that groundwater flowed primarily through the till and discharged into the stream; however, drilling in the Fall of 1990 indicated that bedrock was much shallower - less than 12 ft (3.7 m) in some areas - than had been expected at the site. This "new" aquifer impacted the buffer strip evaluation considerably, because groundwater in the bedrock aquifer would never "see" the buffer strip and it could discharge unaffected into Bear Creek. Thus, in addition to the local groundwater flow system developed in the till and alluvium, the hydrogeological investigations expanded in 1990 to look at the local and regional flow system developed in the Mississippian limestone aquifer.

To date, 46 standpipe piezometers and 27 minipiezometers have been installed on land and in the creek for the purpose of monitoring hydraulic head and calculation of hydraulic gradients and for obtaining water samples both for water quality and geochemical research. Ten piezometers were installed into till, alluvium, and sand in the Fall of 1990 and Spring of 1991. The drilling suggested that the till contained many thick sand units within it (see discussion in earlier guidebook article) and that the alluvium in the floodplain rested on both till and bedrock. In 1991, we engaged in a joint venture with the IDNR - GSB to delineate the bedrock units at the site and install piezometers to get a better idea of the hydrogeology of the bedrock aquifer. The first part of this effort was the corehole shown earlier. After coring, 4 piezometers were emplaced in the corehole separated by bentonite (Figure 1). Twenty three piezometers and a pumping well were installed at that time, along with 1 water table piezometer in the till. In August 1992, twelve piezometers were installed at or near the water table in till, sand, and alluvium. In 1993, 12 drive-point minipiezometers were been installed in the creek bottom and 15 drive-point minipiezometer were installed in the intense monitoring area in the southwestern part of the CMRBS.

Data collection activities at the site consisted of monthly and bimonthly water level measurements using an electric water level tape. Water quality samples were obtained monthly from the piezometers, tiles, and Bear Creek. NO_3-N and NH_4^+-N were determined initially with a Lachat system and then with a ion specific electrode and ion chromatography. Water samples were analyzed for atrazine using the ELISA (Enzyme-linked immunosorbent assay) developed by Ohmicron Corporation. Duplicate samples from specific piezometers, tiles, and Bear Creek were sent to the University of Iowa Hygienic Laboratory in Iowa City for analysis of common pesticides (including atrazine) and the two common metabolites of atrazine - desethylatrazine and deisopropylatrazine. Cations were analyzed by ICP-MS and Atomic Absorption. Anions were analyzed by ion chromatography. Tritium was analyzed by electrolytic enrichment and standard scintillation counting at the Environmental Isotope Laboratory at the University of Waterloo. ^{14}C dating of dissolved inorganic carbon was done by Tandem Accelerator Mass Spectrometry (TAMS) at IsoTrace Laboratories at the University of Toronto. Slug tests were conducted using a solid PVC slug (Ryan, 1993). A Campbell Scientific weather station was also installed at the site in 1992 and has recorded weather data on a daily basis until the present.

PREVIOUS WORK

The geology and hydrogeology of till and the Mississippian aquifer in Iowa have been discussed both in this guidebook and in the literature (see previous article on p. 47). The investigations into the hydrogeology of till at the Ames Till Hydrology Site have focused mainly on basal till of the Alden Member. The site is between the Bemis and Altamont moraines and in the area of minor moraines or corrugation ridges that consist mainly of basal till. Supraglacial sediment of the Morgan member is sometimes present in the upper 10 ft (3 m) or so in the Walnut Creek watershed. In contrast, the CMRBS site is much closer to the Altamont moraine and appears to contain a greater percentage of supraglacial sediment. Little is known about the organic carbon content and the nature of groundwater flow systems that develop in this type of heterogeneous material; hopefully, this investigation will shed some light on the subject.

Probably the most useful compendium of information on the Mississippian aquifer is the publication by Horick and Steinhilber (1973) (*Mississippian Aquifer of Iowa*). In that publication, the authors suggest that vertical recharge occurs in all of the aquifer (Gilmore City through the St. Louis) near groundwater divides and that groundwater discharges into major rivers in the region. The potentiometric surface map of the Mississippian aquifer, which, necessarily lumps the St. Louis, Burlington, and Maynes Creek - Gilmore City aquifers into one unit because of a lack of unit-specific head data, suggests that groundwater flow is generally from northwest to southeast along the strike, except where discharge occurs, presumably in major drainages such as the Iowa and Skunk Rivers.

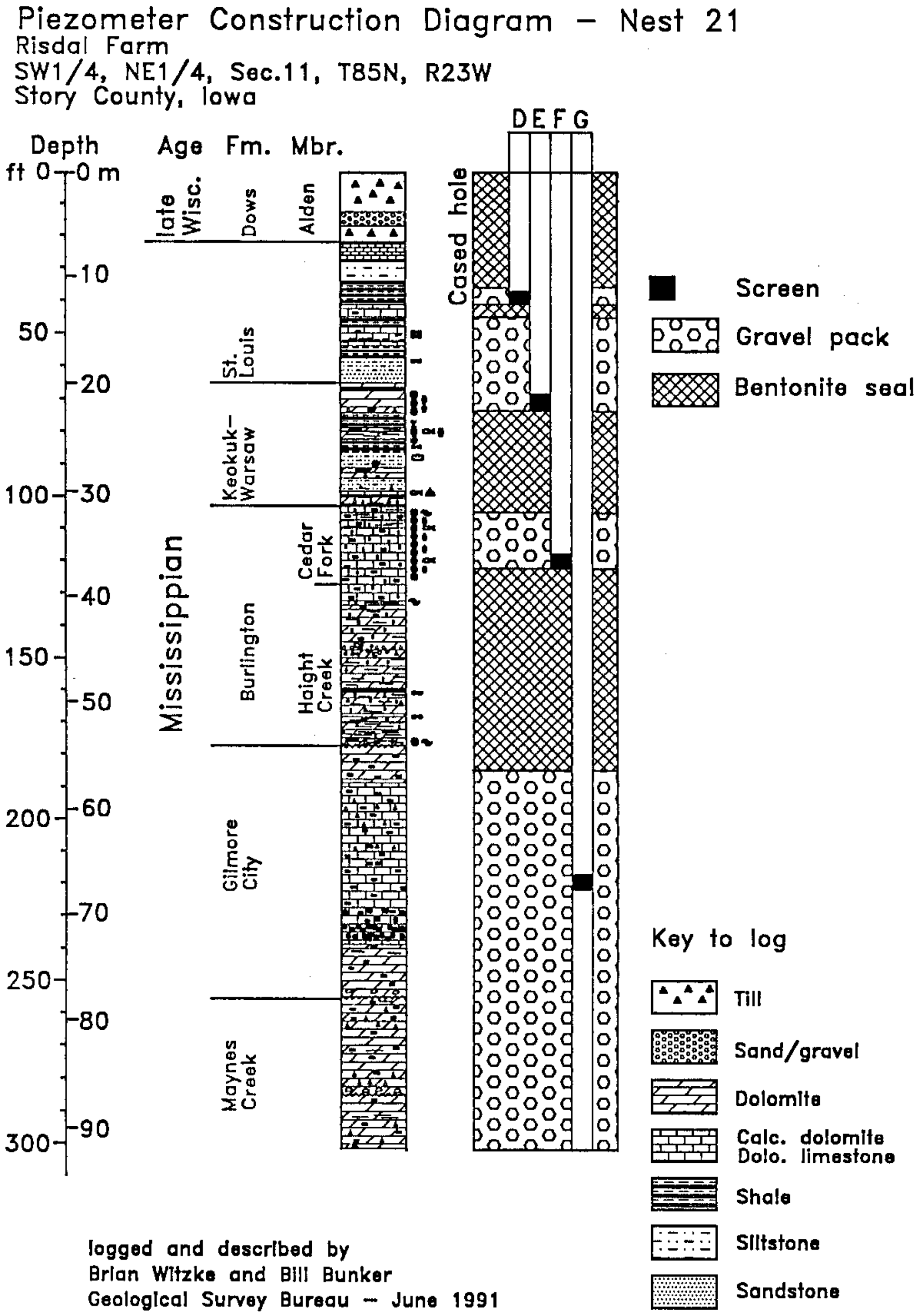


Figure 1. Depths and screened intervals of piezometers at Nest P21.

The CMRBS site is located approximately 4.5 mi (7.2 km) east of the Skunk River; thus, groundwater flow in the bedrock at the CMRBS site is likely either horizontal towards the river or slightly upward indicative of discharge to the Skunk River.

RESULTS AND DISCUSSION

Precipitation

The years 1992 and 1993 have been two of the wetter years in the recent record in central Iowa (Figure 2). Rainfall at the CMRBS in 1992 was near normal at 32.4 in (822.5 mm); however, in 1993, the CMRBS station had recorded 50.7 in (1286.5 mm) by the end of August 1993. This precipitation was in contrast to the drier than normal years that had preceded 1992. Major flooding of Bear Creek occurred at the CMRBS during the July and August rainfall periods.

Hydraulic Conductivity

Twenty-six slug tests were conducted at the site to determine the hydraulic conductivity of the different units (Table 1). In general, bedrock units at the site showed similar K values, with the exception of shale, which shows a considerably lower values. K values for till are typical for oxidized till of the Des Moines Lobe in central Iowa (Simpkins and Parkin, 1993).

Local Groundwater Flow Systems

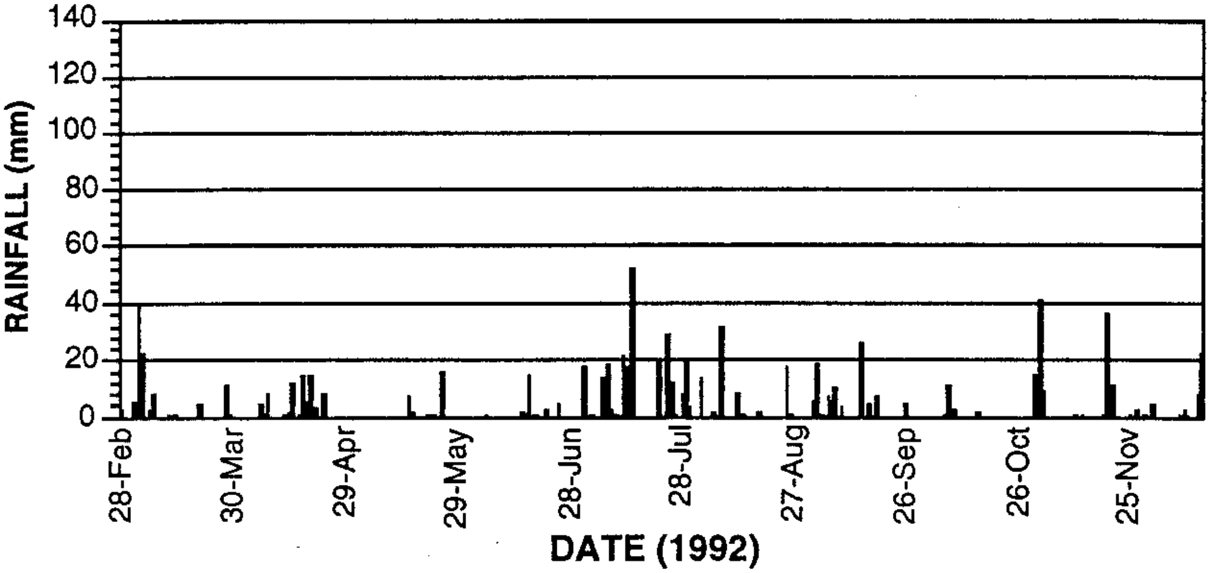
The conceptual model of groundwater flow towards Bear Creek is shown in Figure 3. Based on this conceptualization, which assumes an unconfined groundwater flow system and a separate, always-confined bedrock groundwater flow system, Ryan (1993) constructed preliminary water table and potentiometric surface maps from average water-level measurements taken in the latter part of 1991 and all of 1992 (Figure 4). The contours suggest that both the unconfined and the confined groundwater flow systems flow laterally towards Bear Creek and eventually discharge into it. Some shallow groundwater may be lost to tile drainage, although the small number of tiles and the steepness of the topography may negate that effect. Although it is an attractive conceptual model of groundwater flow, it appears to be overly simplistic; this will be discussed in the next few paragraphs.

Table 1. Geometric mean hydraulic conductivities (K) for geologic units at the CMRBS site.

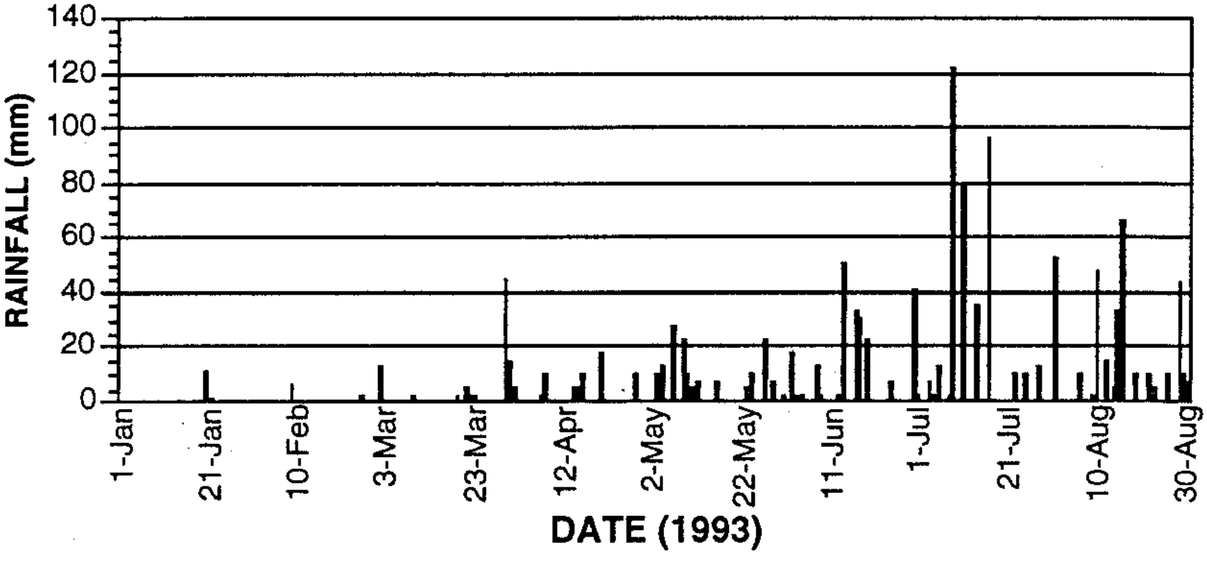
Unit	K (ms^{-1})
St. Louis Fm. limestone	6×10^{-6}
St. Louis Fm. sandstone	5×10^{-6}
St. Louis Fm. shale	1×10^{-7}
Dows Fm. diamicton (till)	3×10^{-6}
Noah Creek (?) gravel	1×10^{-6}

The unconfined groundwater flow system appears to be recharged at the site. Evidence for this includes hydrographs for piezometers screened at the water table that respond quickly to major precipitation events (Figure 5). Many of the highest heads were seen during periods of abnormally high precipitation in Summer 1993. Hydraulic gradients at the site taken from nested piezometers suggest vertical components of groundwater flow in the unconfined system. The vertical component is slightly downward in the upland parts of the site, and may be slightly upward directly adjacent to the stream. Even piezometers within 50 ft (15.2 m) of the stream have shown a downward vertical gradient for most of the study period (Figure 5a).

The relationship between the unconfined flow system and the bedrock (confined?) flow system is less clear at the site and may vary



1992 daily precipitation inputs at the CMRBS.



1993 daily precipitation inputs at the CMRBS.

Figure 2. Precipitation at the CMRBS in 1991 and 1992.

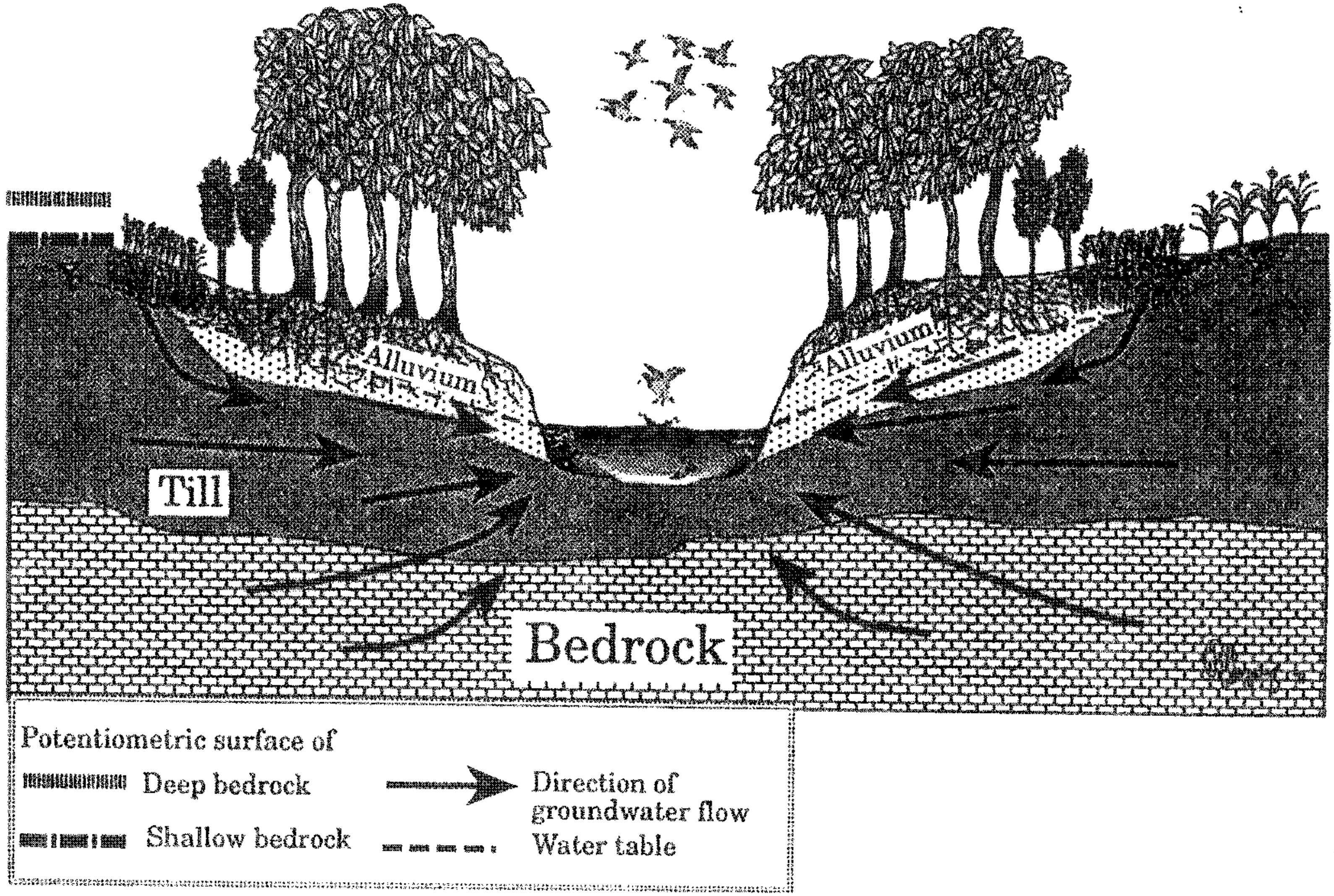
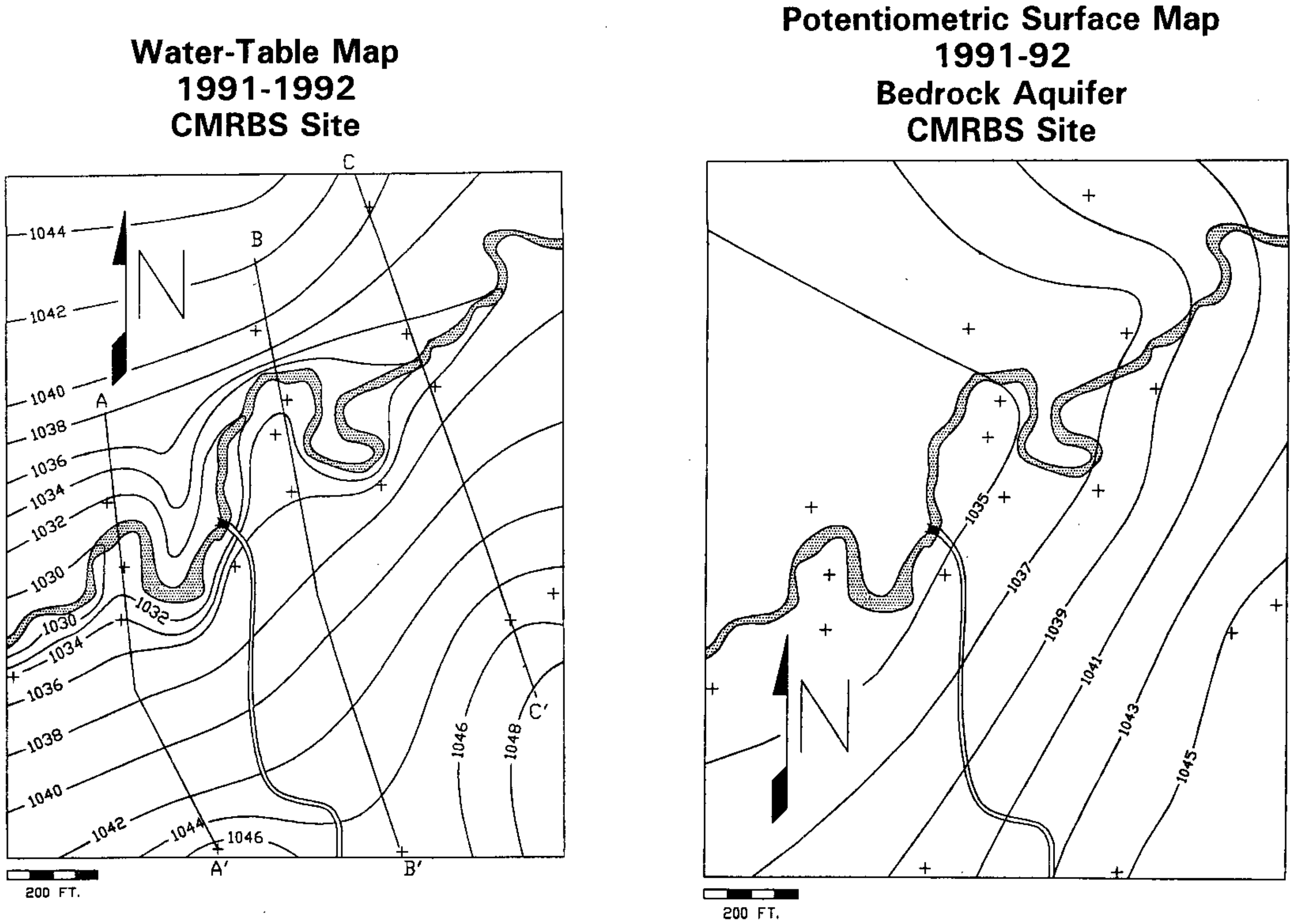


Figure 3. Conceptual model of groundwater flow at the CMRBS.



Water-Table Map
1991-1992
CMRBS Site

Potentiometric Surface Map
1991-92
Bedrock Aquifer
CMRBS Site

Figure 4. Preliminary water-table and potentiometric surface maps (from Ryan, 1993).

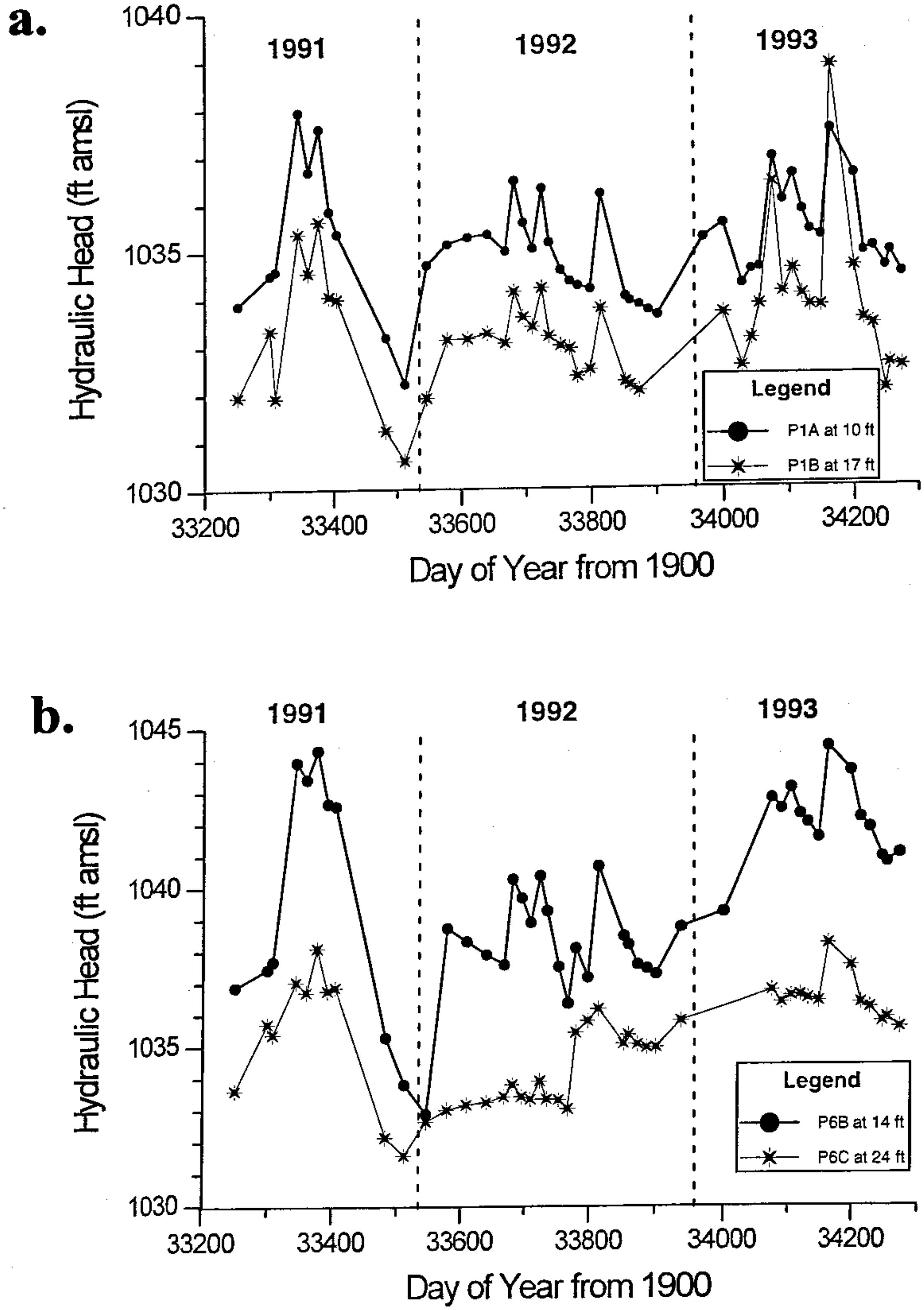


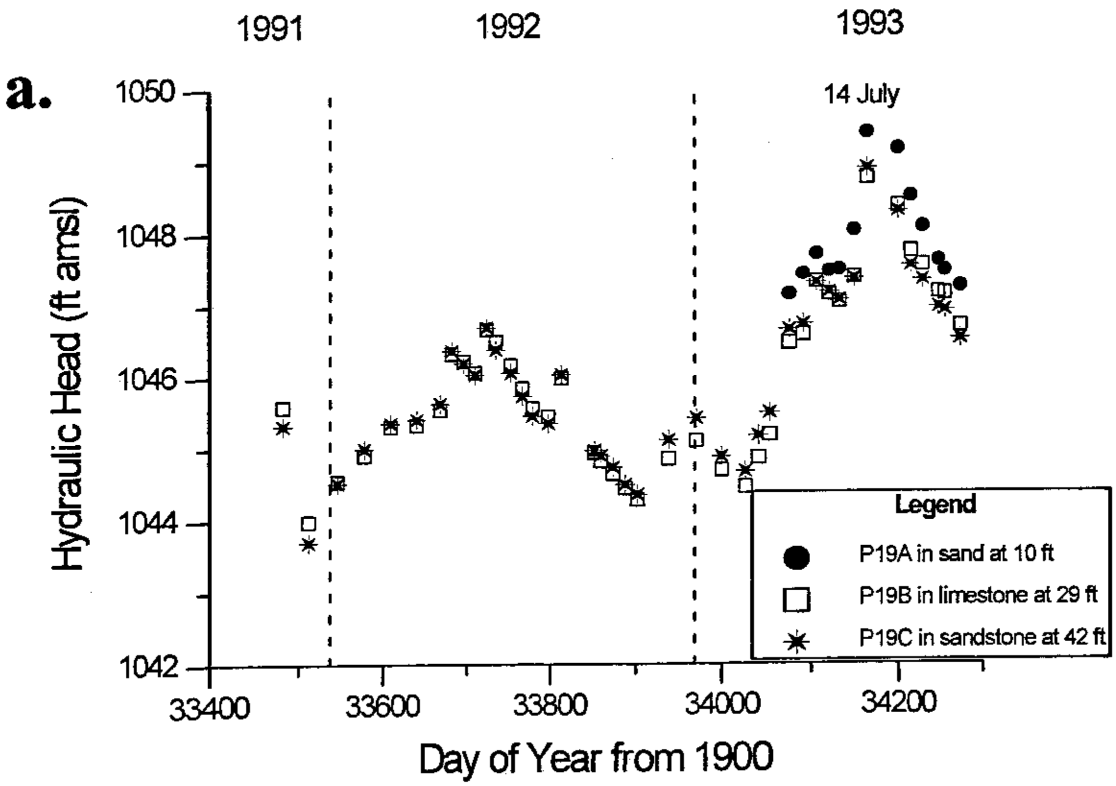
Figure 5. Hydrographs for piezometer nests (a) P1 (b) P6.

considerably. Data from Piezometer Nest 19 (Figure 6a) suggests a downward vertical gradient between the piezometer in sand (P19A) and the piezometers in bedrock. This would indicate that the bedrock aquifer could be recharged by groundwater at the site; thus, the bedrock aquifer could be contaminated by activities at the site. The head in the water table piezometer (in sand) and in both bedrock piezometer rise and fall in sink with each other; this suggests a good hydraulic connection between all three piezometers. In contrast, data from Piezometer Nest 21 (Figure 6b), which is some distance from the creek, indicated that heads in the bedrock aquifer (P21E) were above the water table (P21A) during 1993. In fact, artificially high heads at P21A during 1992 were caused by discharge of water on the ground surface from P21G (the flowing well) until March 1993. It appears that the natural condition at this nest is for heads in the bedrock aquifer to be higher than the water table; thus, this part of the bedrock aquifer cannot then be recharged from above at this location.

Within the bedrock aquifer itself, flow appears to be nearly horizontal in the upland areas, and upward directed in the bedrock at stream level. The magnitude of the hydraulic gradient is not constant across the site and this indicates the effect of heterogeneity and the presence or absence of confining units. Away from the creek in Nest P19, there is a noticeable lack of a vertical gradient over 32 ft (9.8 m) distance in the bedrock (Figure 6a) and a predominantly horizontal gradient in bedrock is hypothesized for this nest. In contrast, bedrock piezometers near the stream consistently show an upward-directed vertical hydraulic gradient, suggesting that groundwater is discharging into the stream from the bedrock aquifer. One "end member" situation occurs at Piezometer Nest 3 adjacent to Bear Creek, where it can be seen that water levels in the deeper bedrock piezometer are at least 1 ft higher than those in the shallow bedrock piezometer (Figure 7a). The vertical hydraulic gradient is about 0.05. The small head gradient would be expected because there is not much resistance to flow in the limestone and sandstone bedrock.; the shale unit becomes more of a hydrologic factor east of this nest. For example, in Piezometer Nest 13, there is a about a 9 ft difference in head over a distance of about 10 ft between the screened intervals, resulting in a vertical head gradient of 0.9 (Figure 7b). Flowing artesian conditions occur here, and also at Nest 8, because hydraulic head must build-up beneath the shale between the bedrock piezometers in order to discharge water into the creek. It is likely that a shale unit is the predominant bedrock unit beneath the creek on the eastern one half of the site. We inadvertently tested that hypothesis by putting in drive-point minipiezometers into this unit under the creek bottom - these produced no water in 4 months. The drive-point minipiezometers produce water at the other two nests to the west, primarily because at those locations they are in weathered limestone.

The previous discussions highlight a particularly important hydrogeologic problem at the site, namely whether there exists a continuous confining unit (aquitard) to maintain confined conditions in the bedrock aquifer. What are the potential confining units? Ordinarily, till units that overlie bedrock aquifers are assumed to function as confining units or aquitard (see earlier article by Bruner and Hallberg, p. 43); however, the Pleistocene section here contains enough sand that a true confining unit may be absent or very thin in some parts of the site. In addition to K values from sandstone, limestone, and till units that are quite similar (Table 1), true confined aquifers would probably not show hydrographs such as those shown in Figure 6a. It is tentatively concluded on the basis of very little data that, at best, the till at the site provides a very discontinuous confining unit for the bedrock aquifer.

Other confining units exist atop and within the bedrock units. For example, shale units sit at the alluvium/bedrock interface and directly underlie the creek on the eastern edge of the site. A sample of this material at Nest 10 showed a particle size percentage of 10 percent clay, 45 percent silt, and 45 percent clay. These may act to separate the unconfined groundwater flow system in the till/alluvium from the confinedbedrock flow system. Where the shale



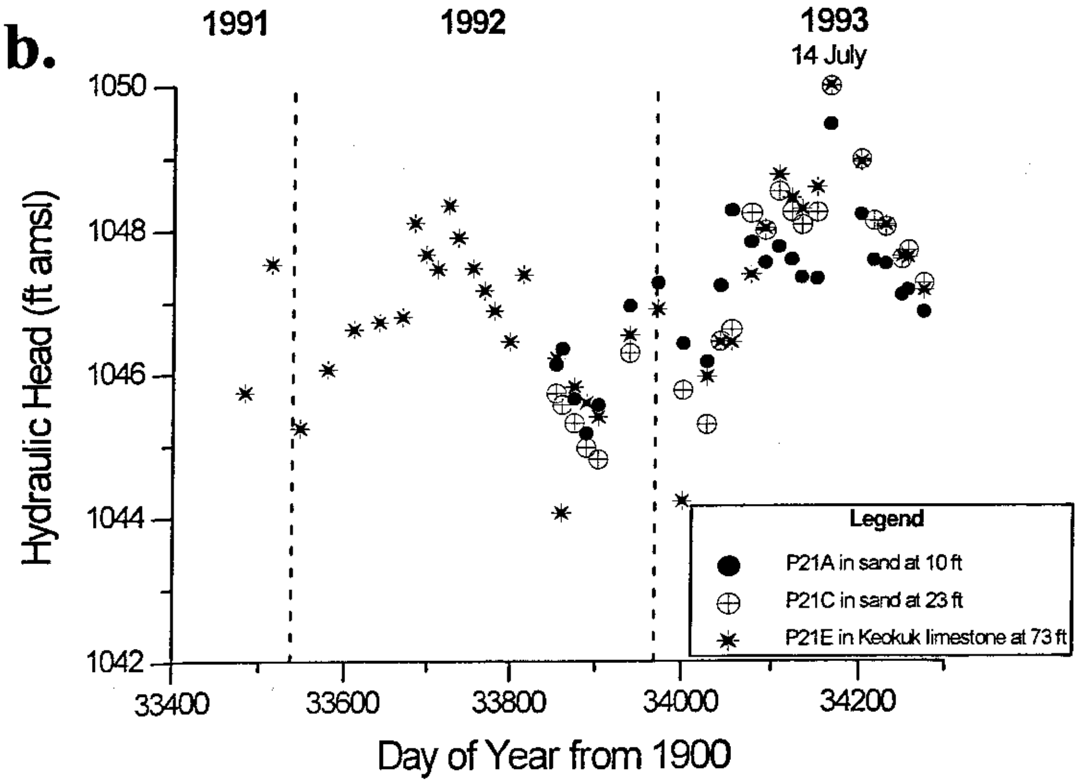


Figure 6. Hydrographs for piezometer nests (a) P19 and (b) P21.

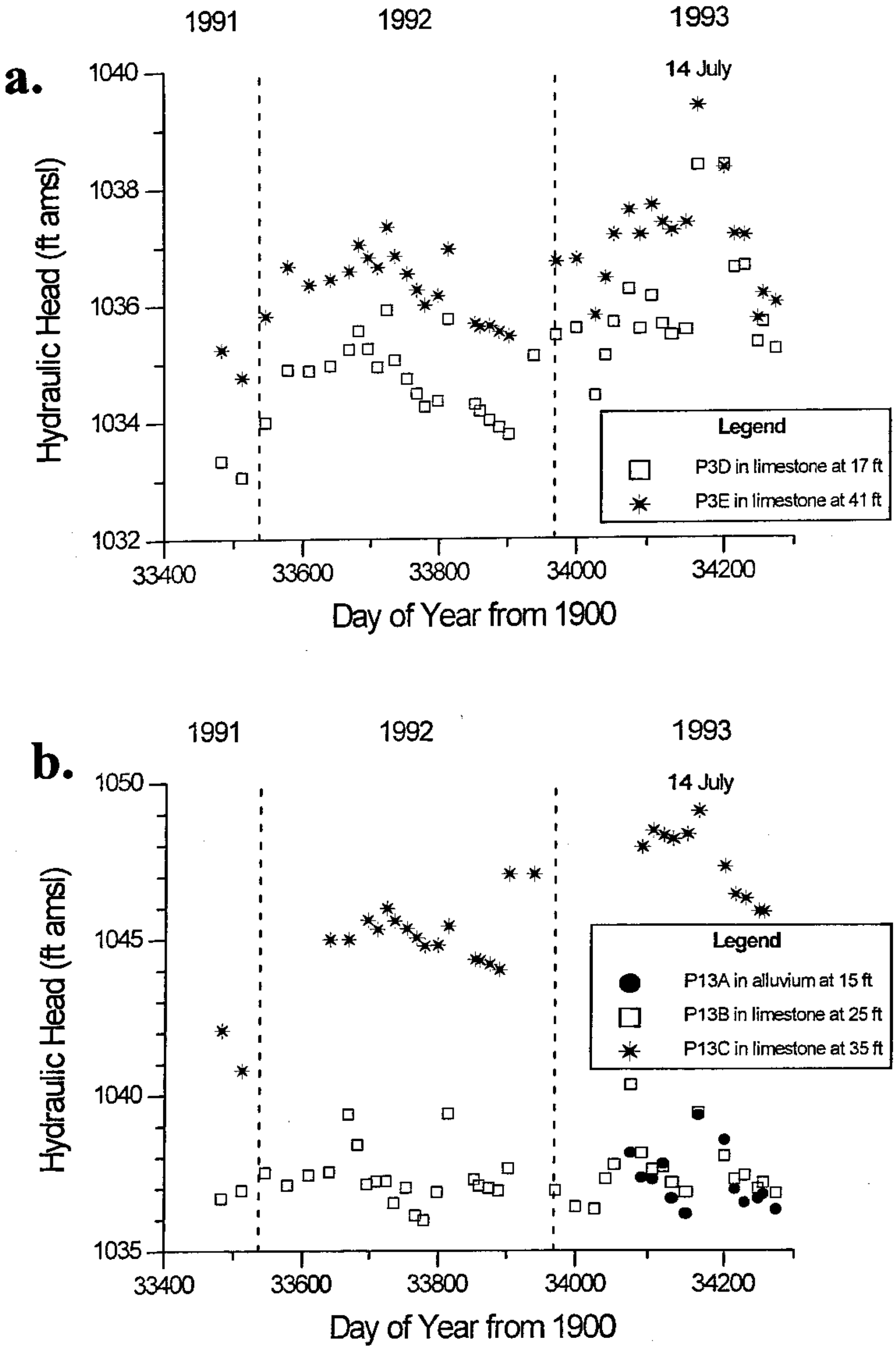


Figure 7. Hydrographs for piezometer nests (a) P3 and (b) P13.

unit is absent, the till/alluvium and bedrock aquifers belong to the same flow system. In addition, thick shale units occur within the bedrock sequence and act as a local confining unit on some parts of the site (e.g., Nest 13) and not in others (e.g., Nest 19). Depending on their location relative to the creek, shale units can either impede downward flow to deeper parts of the aquifer or cause large upward-directed head gradients near the creek. In addition to the shale units, pre-glacial weathering on the limestone bedrock surface seems to have produced some residuum that was often encountered at the bedrock surface. Cuttings from such units may be what the driller called "tan shale" in the geological logs . Particle size analysis of one sample of this material at Nest 13 yielded 3 percent sand, 48 percent silt, and 49 percent clay. The extent of this residuum is not known, although excavations of the creek bottom on the west end of the site during emplacement of the weirs showed mainly a weathered limestone, but not a distinct weathering horizon.. Bear Creek may have eroded this unit during downcutting of the channel.

In summary, the hydrogeology at the CMRBS is quite complex. In general, an unconfined groundwater flow system exists in the till/sand/alluvium that recharges at the site and discharges into Bear Creek. Where shale units are absent atop or within the bedrock, this unconfined system may include bedrock units within the St. Louis limestone. Till units are not continuous enough to support a confined aquifer condition in the bedrock. A separate groundwater flow system exists in the bedrock and it generally exists under confined conditions either due to shale units at the top of the bedrock, or shale units within the bedrock, or both. Upward hydraulic gradients near the stream suggest that this flow system also discharges into Bear Creek. Where contiguous shale units are present, they provide a confining unit may result in the sealing off of the bedrock units from recharge at the site. In many instances, heads in the bedrock aquifer are higher than the water table, indicating a non-recharge condition at the site.

Geochemical data (see later discussion) support these interpretations. Tritium activities in groundwater suggest that groundwater in the alluvium and shallow bedrock is similar in age; hence, there is effectively no confining unit where the alluvium rests on bedrock. Similarly, the water from the deeper piezometers below shale units show ages greater than 50 years; this age suggests that the water has migrated here from somewhere off the site. The chemical composition of the groundwater also provides "markers" for the separation of these waters and that topic is discussed in a later section.

Regional Groundwater Flow Systems

Hydraulic head relationships in Piezometer Nest 21 have provided insight into the nature of regional groundwater flow in the St. Louis (P21D), Keokuk (P21E), Burlington (P21F), and Gilmore City/Maynes Creek (P21G) aquifers (Figure 8). Upward-directed hydraulic gradients occur throughout the piezometer nest installed in the corehole. For example, heads in Keokuk limestone (P21E) are always 1 ft (0.3 m) higher than those in the St. Louis shale unit (P21D) above it, although the latter piezometer may not be giving a true head reading due to some problems in its installation. It may be better to use P21C as (Figure 6b) as the representative head at the top of the St. Louis aquifer. Groundwater from the deeper two piezometers, set in the Maynes Creed/Gilmore City and the Burlington units, have even higher potentials and flow at the land surface (Figure 8). Flowing wells in this part of Story County are not unusual, and there are numerous such wells that occur just south of Story City near the now defunct "Artesian Service" gas station on Highway 69, and along the Keigley Branch, a tributary to the Skunk River which is just north of and trends parallel to the northwest to southeast-trending Altamont moraine. However, most of the flowing wells are not more than 125 ft (38 m) deep and they all occur in a topographically *low* area near the Skunk River. This relationship suggests that the hydraulic head drive that produces the flowingwells is due to

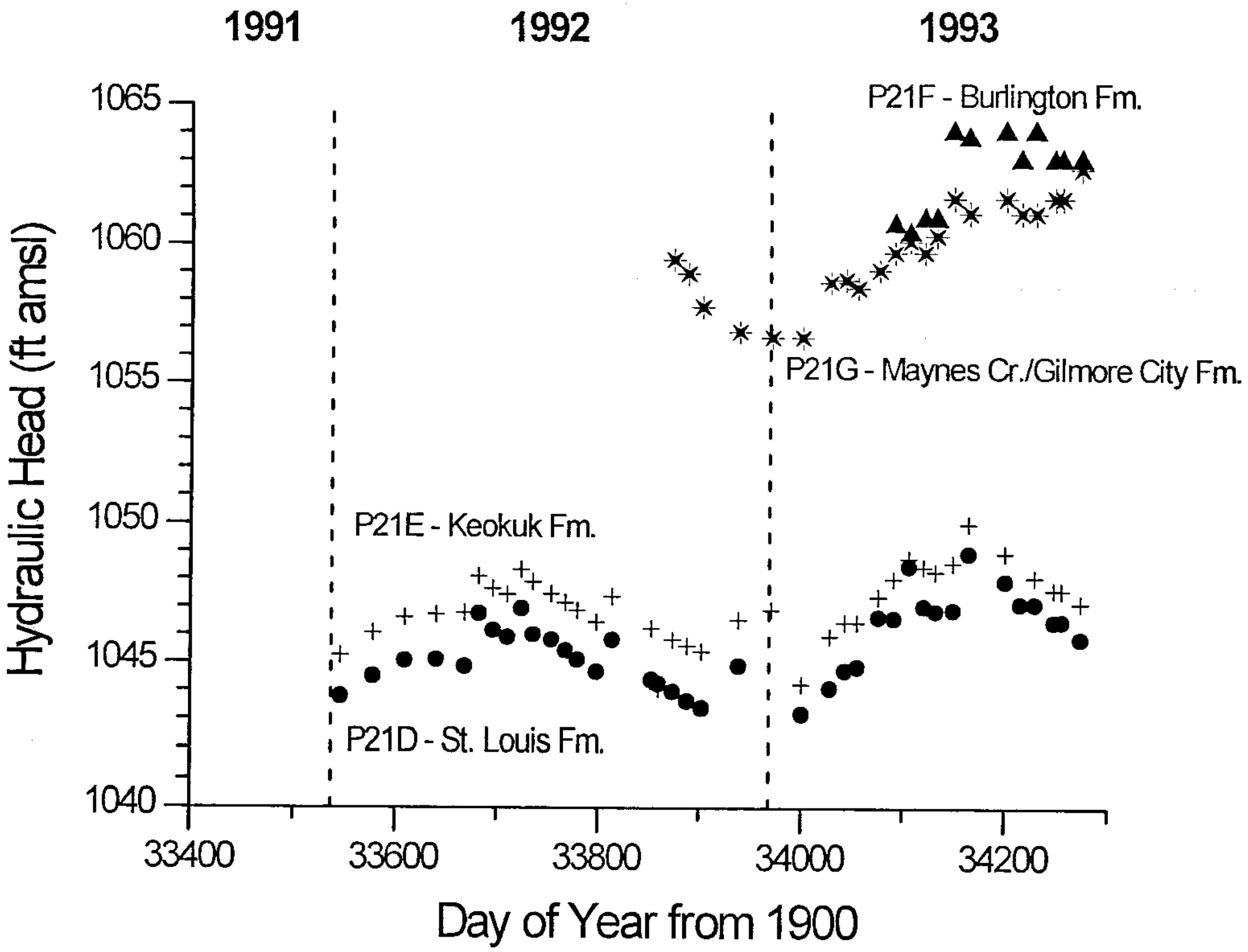


Figure 8. Hydrographs for piezometer nest P21.

some adjacent topographic high, such as the Altamont moraine. Flowing (artesian) conditions also occur in the city well at Story City. The well lies just above the floodplain of the Skunk River and is completed in the Gilmore City Formation.

Because flowing wells at the CMRBS site occur on what appears to be a topographically *high* area, this phenomenon proposes some interesting questions about regional groundwater flow systems in the Mississippian aquifer. During the first few months of monitoring, the head gradients in the piezometers were all upward directed, suggesting that Bear Creek is actually a groundwater discharge point for the entire Mississippian aquifer (Figure 8). However, the physical nature of the bedrock units suggest this is unlikely. Shale units such as those in the Warsaw Formation are excellent confining units, and it would be unlikely that much discharge is moving through them. So, what causes the upward hydraulic gradients? Two hypotheses are proposed here. First, they could represent a regional groundwater discharge to the nearby Skunk River, some 4.5 mi (7.2 km) to the west. At Story City, the surface elevation of the city well in the Gilmore City Formation is about 970 ft (280.5 m). Thus the hydraulic head (it flows in Story City at +12 ft) is nearly 100 ft (30 m) lower than the head in piezometer P21G at the CMRBS. A decline in head in the aquifer towards the west would consistent with groundwater discharge into the Skunk River, so it is possible that the Gilmore City/Maynes Creek aquifer discharges into the Skunk River, and that the conditions seen at Nest 21 are indicative of that discharge. This evidence supports the conceptual model of groundwater flow of Horick and Steinhilber (1973). However, because nested piezometers do not exist within *each aquifer*, it is difficult to prove with certainty that a groundwater discharge condition exists *in each aquifer*.

Because of the ambiguity introduced by a lack of vertical gradient data in each aquifer, a second possible explanation must be considered - that heads in the aquifers only represent heads carried from their respective recharge areas and that groundwater discharge is not occurring. For example, in order for any head to be at a position 12 ft (3.7 m) about the ground surface in P21G, the recharge area must also be that high or probably higher in elevation. Higher ground surface elevations up to 1200 ft asl (366 m asl) only occur northeast of the site in Hardin County. Bedrock maps also suggest that the subsurface elevation of the Gilmore City Formation rises to elevations of 1100 ft (335 m asl) in northern Hamilton and Hardin counties to the north of the site. In either case, the heads measured in P21G are likely due to a regional-scale, confined groundwater flow system where water is flowing south to this site from recharge areas in the north or northeast. Similar relationships would hold for the Burlington and Keokuk aquifers at the site.

The relationship between P21F and P21G complicates confirmation of either of the interpretations given above. During the Summer of 1993, piezometer P21F was evacuated with nitrogen gas to see if the screen was clogged, thus causing an inaccurate head reading. Shortly after purging, head values in this piezometer increased by almost 10 ft (3 m), to a total elevation of about 1062 ft (323.8 m), and we began to measure heads at that time. Unfortunately, the head rise was also coincident with the abnormally wet summer of 1993; the effect of that precipitation is definitely seen in the head values from P21G (Figure 8). At the end of the summer, the Burlington aquifer possessed a higher hydraulic potential than the Maynes Creek/Gilmore City aquifer; thus, the former had the potential to vertically recharge the latter and not vice-versa as had been the case in the previous two years of monitoring at this site. Downward directed, vertical heads between the Burlington and the Gilmore City aquifers support the Horick and Steinhilber (1973) model conceptual model, which suggests that groundwater in the Burlington aquifer should recharge the underlying Gilmore City/Maynes Creek aquifer where the two are both present - *except, of course, near discharge areas where the gradients should be upward.* It is also curious that towards the end of 1993, the heads in the two piezometers are nearly equal and may be returning to the pre-1993 conditions. Why would this occur? One possibility is that the Burlington aquifer has responded faster to the 1993 recharge than has the Gilmore City/Maynes Creek aquifer. This seems counter-intuitive to observations of a lower flow rate (i.e. lower K) from the Burlington aquifer than the Gilmore City/Maynes Creek aquifer. Another possible, and perhaps more intriguing, explanation is that heads in the Burlington aquifer are responding to stage fluctuations in the Skunk River; i.e., when the Skunk River rose to record levels this summer, so did the heads in the contributing aquifer. This phenomenon is known as the "back pressure" or "backwater effect". Elevation and geological data appear to support this hypothesis. Geological maps indicate that the Skunk River has downcut to the Burlington aquifer (see Horick and Steinhilber, 1973) and the channel of the Skunk River at Story City (about 950 ft msl or 289.7 m) and the elevation of the Burlington aquifer at the CMRBS (about 940 ft msl or 286.6 m) are similar. Some "backpressure" effect would also be shown in the underlying Gilmore City/Maynes Creek aquifer, although the magnitude of response would likely be much less. The effect would not be as great in the St. Louis aquifer, because it may unconfined in areas to the west of the CMRBS.

In summary, hydraulic heads in the Keokuk, Burlington, and Gilmore City/ Maynes Creek aquifers have the hydraulic potential to discharge upwards into the St. Louis Formation aquifer and ultimately to Bear Creek; however, this probably does not occur because of thick shale confining units between the aquifers. It is more likely that the Burlington and Gilmore City/ Maynes Creek aquifers discharge into the Skunk River to the west of this site and that the upward-directed heads somehow reflect a regional groundwater discharge condition. The bedrock aquifer that really affects the CMRBS site is the St. Louis aquifer, which as mentioned earlier, may not be recharged on the site and may only be recharged near drainage divides. The St. Louis aquifer supplies the farm well and most of the neighboring farms that have not yet connected to rural water systems.

Groundwater Age

Groundwater at the CMRBS site is between about 11,000 years old and recent, according to both enriched tritium and ^{14}C-DIC dating techniques (Table 2). Based on an interpretation of the site drilling logs and the tritium data, groundwater in the deeper confined aquifer at the site has values <0.8 T.U. (the detection limit) and is definitely older than 30 years - probably older than 50 years. Groundwater at the water table shows values close to modern input value of 10 T.U. in this region. Below the water table in the unconfined system, some groundwater appears to have entered the system in the early to mid-1980's (30 to 32 T.U.).

Tritium was not detectable in any piezometers in the P21 Nest. Uncorrected ^{14}C ages of dissolved inorganic carbon (DIC) indicate that groundwater in the Burlington aquifer is 11,164 years old. Groundwater in the Gilmore City/Maynes Creek aquifer is 6,667 years old. This is an age relationship that is consistent with a predominantly upward gradient found at the site. Corrected ^{14}C-DIC ages will probably be younger for both of these aquifers, based on dates calculated for similar units in central Iowa by this author. A ^{14}C-DIC date for groundwater in P21E is pending and may shed some light on the age relationships.

Hydrogeochemistry

One of the main research tasks in this project is to determine what effect buffer strips may have on water quality. To that end, a considerable effort has been made to understand the hydrogeochemistry of the groundwater at the site with special regard for water quality parameters such as NO_3 and pesticides. Complete geochemical analyses of 24 samples submitted in July and September 1993. Tritium samples were taken in 1992.

Groundwater can be divided into three groups based on the hydrogeochemistry. In Group 1, groundwater in piezometers that are screened near the water table (i.e., P1A or P17A) show higher temperatures, more dissolved O_2, more Cl (fertilizer?), and more NO_3-N than deeper piezometers (Table 2). They also show very low dissolved Fe concentrations, which suggests that oxidizing conditions prevail there. Tritium activities near recent input values occur in these waters and suggest the groundwater is very young. The water also contains trace amounts of pesticides. In short, these hydrogeochemical characteristics suggest that groundwater has been recently recharged and that contamination of the groundwater has occurred due to recent agricultural practices at the site.

In Group 2, piezometers in the unconfined groundwater flow system (i.e., P1B or P6C) show temperatures that are near the mean annual temperature of 10 C, no dissolved O_2, little or no NO_3-N or pesticides, and large concentrations of dissolved Fe (Table 2). The groundwater also shows some tritium activities that are not modern values and some of these waters may be 5 to 10 years old. The high concentrations of Fe combined with little or no NO_3-N suggest a redox environment favorable for denitrification; this is a topic of future research at this site. In short, groundwater in these piezometers is older and if contamination has occurred in the past, most of the contaminants have probably undergone significant transformation.

Finally, Group 3 piezometers in the confined bedrock aquifer show the same characteristics as the second group above, but tritium activities are all below the detection limit of 0.8 T.U.(Table 2). Not only is this water significantly older than any water on site, but the slightly lower SO_4 concentrations suggest that SO_4 reduction has occurred. This is definitely true in groundwater in the Gilmore City/Maynes Creek aquifer (P21G) where SO_4 concentrations are below the detection limit and CH_4 concentrations of 2 mg L^{-1} are present. The CH_4 detected here is presumably of the same age as that discussed for the Ames Till Hydrology Site (*see Simpkins et al., this guidebook, p. 47*). CH_4 is also present in groundwater in the Burlington aquifer (P21F) at this site and it may have arrived there with downward recharge or via upward discharge from the Gilmore City/Maynes Creek aquifer.

Water Quality

In addition to piezometers, waters from Bear Creek and the tile drains were routinely sampled and analyzed for pesticides, NO_3-N, and Cl. In general, the water quality of Bear Creek is typical of surface water in Iowa. It routinely carries NO_3-N concentrations above the EPA-designated MCL value of 10 mg L^{-1} and atrazine concentrations ranging between 0.10 and 0.25 μg/L. Concentrations of atrazine have increased to values near 2.0 μg/L during storm events. Tile drains show similar concentrations. The greatest increases in NO_3-N and atrazine concentrations occur soon after they are applied to the fields and during rainfall events. These relationships, as well as evidence from other studies in Iowa, suggest that most agrichemical enter surface water through tile drainage and runoff - not groundwater discharge.

Concentrations of NO_3-N above the MCL are commonly found in shallow piezometers (Table 2; Figure 9). Values vary according to the amount of groundwater recharge and antecedent conditions. High concentrations of NO_3-N seen at P1A and P11C in 1991 are probably the result of NO_3-N that was mobilized from the soil zone by precipitation in 1991 after drought conditions that may have encouraged storage of NO_3-N in the unsaturated zone. Concentrations of NO_3-N have declined since that time indicating removal of stored NO_3-N in the system.

Atrazine has been seen in shallow groundwater at the site throughout the project - according to the ELISA results (Table 2). Cross checks of the same samples using GC-MS indicate that the parent compound atrazine has actually never occurred in groundwater (Figure 10a and b). In piezometers P1A and P11C, it is actually the metabolites and not the parent that have been detected. This result is consistent with other studies which have shown that the ELISA method is unable to resolve the daughter from the parent compound (E.M. Thurman, verbal comm., 1993). Deisopropylatrazine, the least stable

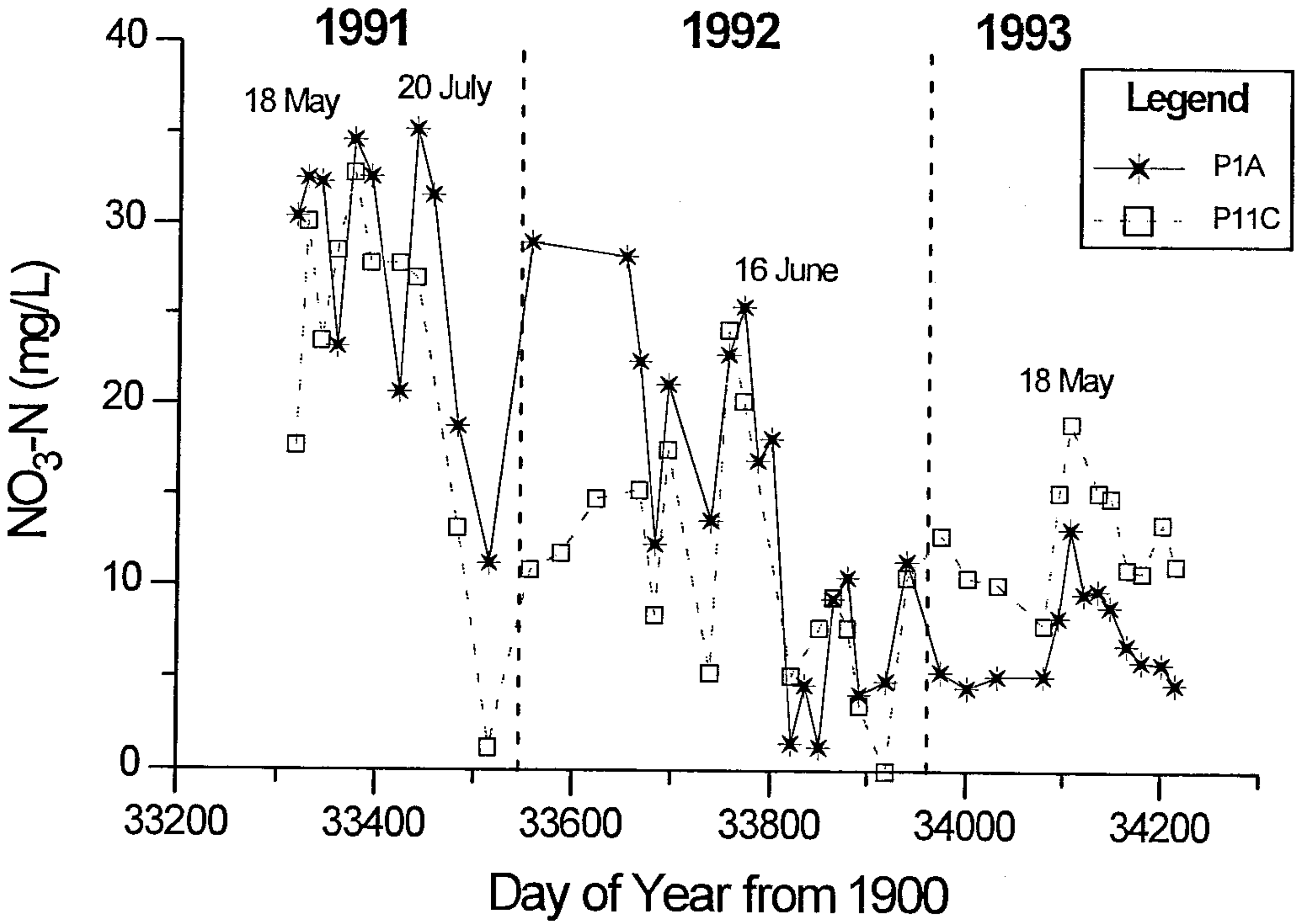


Figure 9. Variations in NO_3-N concentrations for water table piezometers P1A and P11C.

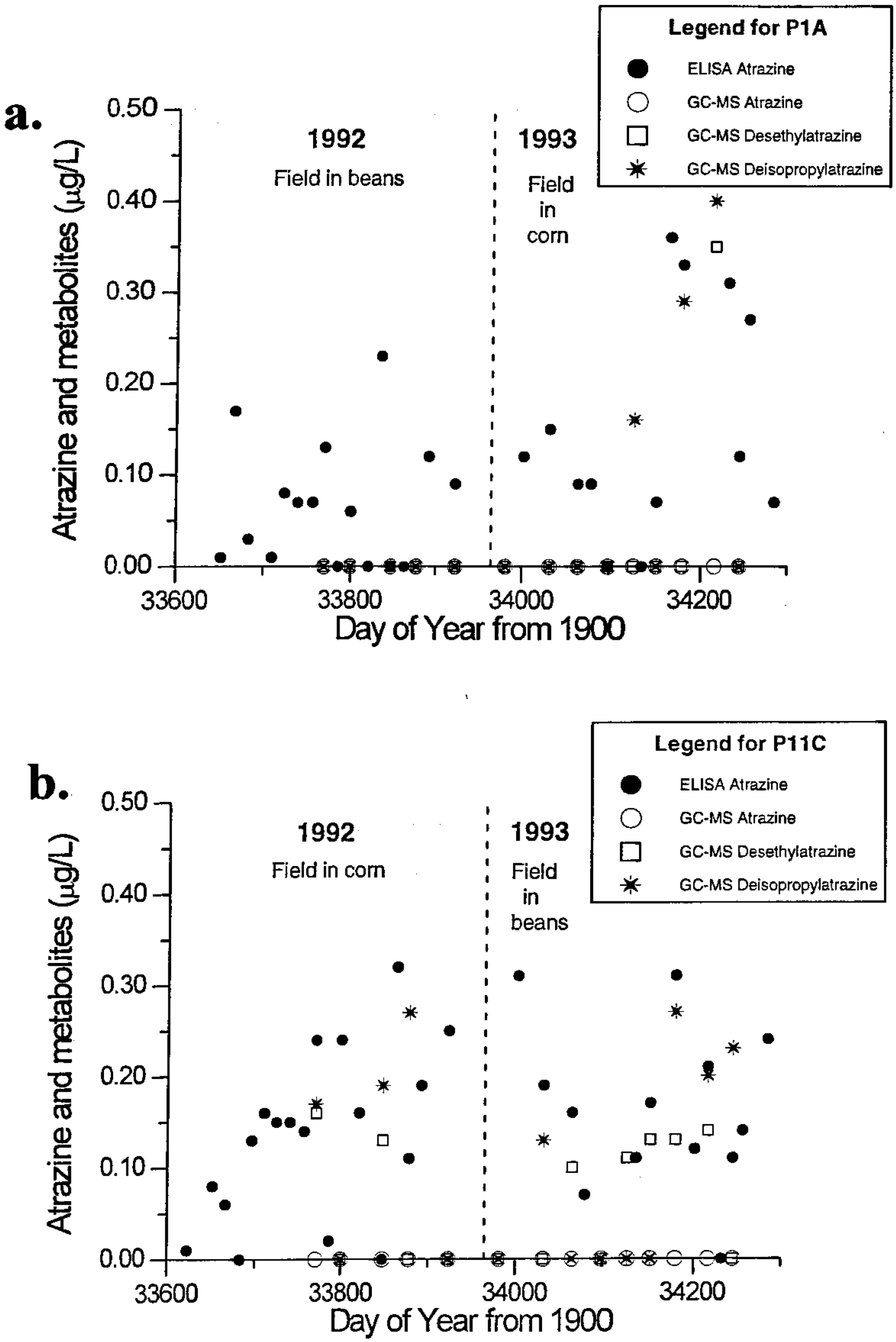


Figure 10. Comparison of ELISA atrazine analyses and GC-MS analyses of atrazine, desethylatrazine, and deisopropylatrazine, for (a) P1A, (b) P11C

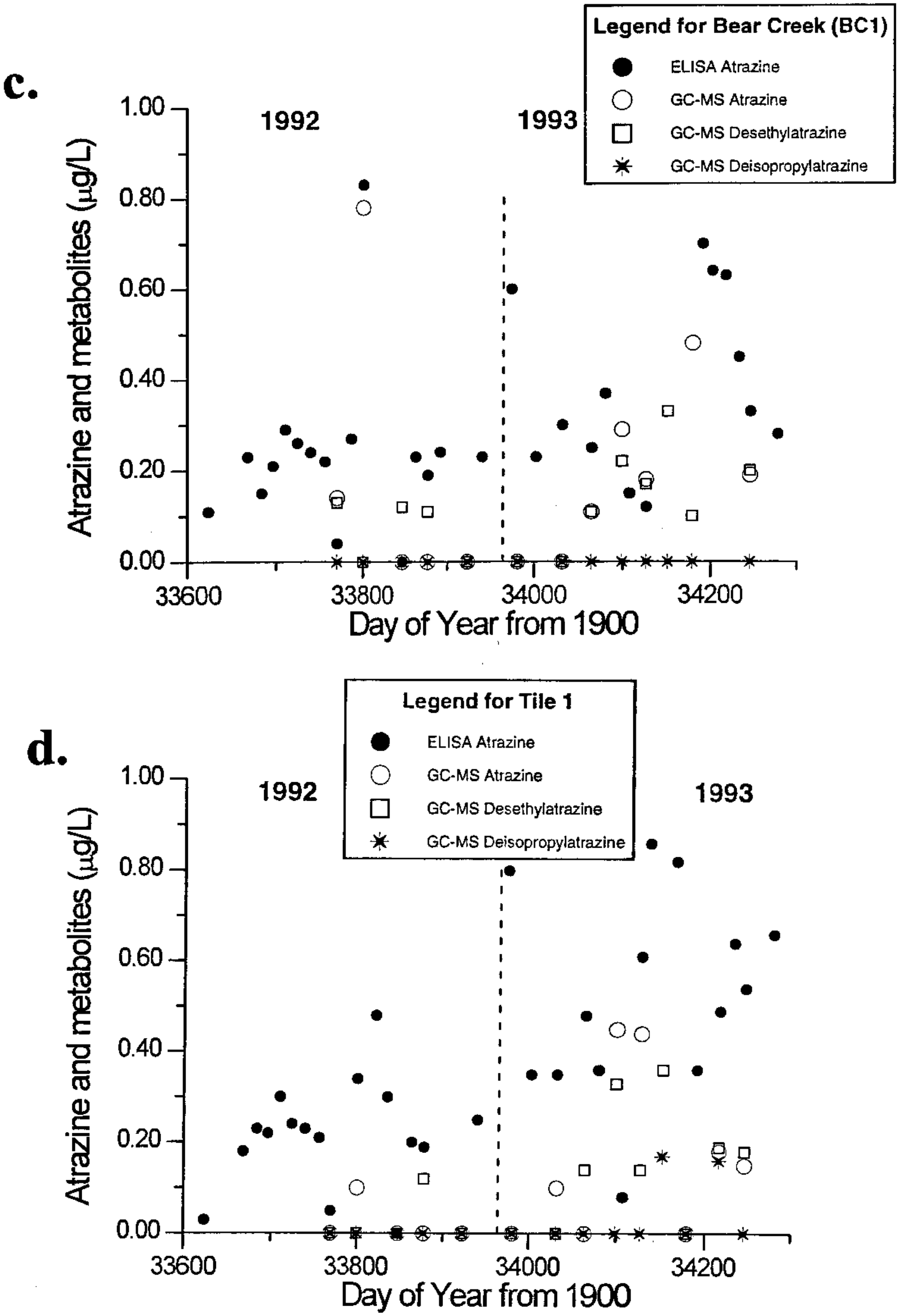


Figure 10 (cont'd.). Comparison of ELISA atrazine analyses and GC-MS analyses of atrazine, desethylatrazine, and deisopropylatrazine, for (c) Bear Creek, and (d) Tile 1.

Table 2. Hydrogeochemistry and water quality data from piezometers at the CMRBS site

Piez. no.	Depth (ft)	Lithologic unit	Temp (C)	Diss. O2 (mg/L)	Tritium (TU)	pH	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	HCO3 (mg/L)	SO4 (mg/L)	Cl (mg/L)	NO3-N (mg/L)	Fe (mg/L)	DOC (mg/L)	Atrazine (ug/L)
Group 1 - Unconfined flow system																	
P1A	10.0	diamicton	15.8	5.7	12.7	7.6	85.4	26.3	5.8	0.3	305	14.8	4.8	11.9	0.0040	NS	0.36
P5B	10.0	diamicton	15.5	5.0	8.7	7.7	74.2	21.3	2.3	0.2	289	10.8	0.7	1.5	0.0040	4.5	0.08
P6B	14.0	diamicton	11.3	<0.1	30.0	7.3	132.9	42.2	9.7	0.5	499	130.9	27.3	11.0	BDL	2.7	0.16
P11C	12.5	gravel	12.7	6.8	12.6	7.5	117.2	36.0	8.2	1.2	377	67.2	16.6	14.6	BDL	1.6	0.78
P13A	14.4	alluvium	11.6	1.8	17.5	7.3	90.7	24.8	16.6	1.7	367	51.6	7.5	BDL	BDL	1.6	BDL
P13B	25.0	shale+ls	10.1	<0.1	11.9	7.2	79.3	21.6	49.4	1.6	408	50.3	8.1	1.2	BDL	1.7	BDL
P15A	14.5	alluvium	11.7	0.9	13.2	7.7	73.8	22.7	7.5	0.5	287	51.3	7.2	13.9	BDL	1.5	BDL
P15C	23.0	till and shale	10.0	<0.1	11.2	7.7	70.4	19.3	9.3	1.3	332	37.0	4.6	1.2	BDL	1.5	0.08
P17A	14.5	diam. + sand	15.5	8.8	NS	7.9	53.7	14.2	2.4	0.1	173	19.5	1.7	9.3	0.0008	1.5	0.18
P19A	10.0	sand	14.8	9.2	12.8	7.7	58.3	15.1	4.1	0.0	137	20.8	18.3	14.9	0.0006	2.3	BDL
P21A	9.8	diam + sand	13.9	5.1	NS	7.6	108.4	27.6	5.2	0.3	294	27.2	20.0	18.0	0.0001	1.5	0.17
P21C	23.6	diamicton	12.6	<0.1	14.0	7.6	109.2	28.1	5.4	1.1	304	35.6	20.2	17.1	0.0001	1.2	BDL
Group 2 - Unconfined flow system																	
P1B	17.0	diamicton	12.7	<0.1	32.0	7.6	113.5	37.3	5.9	1.1	328	106.2	21.2	BDL	0.38	2.3	NS
P6C	27.0	sand+ls	10.0	<0.1	13.6	7.4	115.4	43.4	10.8	2.3	405	137.9	12.7	0.2	5.54	2.0	NS
P6D	28.0	sandstone	9.3	<0.1	10.4	7.5	84.6	33.9	8.4	2.9	395	22.3	4.8	BDL	3.90	1.8	NS
Group 3 - Confined flow system																	
P6E	41.0	limestone	10.0	<0.1	1.0	7.4	73.1	30.2	9.6	4.2	395	10.0	1.0	0.1	2.60	2.0	NS
P11B	9.5	alluvium/ls	12.2	<0.1	<0.8	7.5	68.2	22.7	8.1	1.6	383	10.5	1.3	BDL	2.50	2.5	BDL
P11D	21.0	sandstone	9.4	<0.1	<0.8	7.5	65.1	23.8	20.8	2.1	381	12.1	1.0	0.3	0.15	1.8	NS
P11E	41.0	limestone	9.3	<0.1	1.0	7.4	76.7	26.6	9.6	2.4	392	11.1	1.3	BDL	1.35	1.2	NS
P13C	41.0	sandstone	9.8	<0.1	<0.8	7.4	59.1	23.5	7.7	1.2	321	20.7	1.5	BDL	0.30	1.0	NS
P15D	41.0	sh,ls, sltstn	9.8	<0.1	<0.8	7.5	73.7	29.7	9.0	2.5	364	6.6	0.9	BDL	1.30	1.5	NS
P21E	45.0	limestone	10.4	<0.1	<0.8	7.5	87.1	27.5	11.1	4.1	419	6.9	0.7	BDL	0.46	1.3	NS
P21F	128.0	limestone	10.6	<0.1	<0.8	7.8	70.8	26.4	51.7	4.4	548	17.7	1.0	BDL	4.06	2.6	NS
P21G	301.0	limestone	10.9	<0.1	<0.8	7.4	72.9	28.8	10.1	3.0	373	<0.1	0.4	BDL	0.70	1.3	NS

BDL = below detection limit

P = results pending

and least persistent of the two metabolites, also appears in both piezometers. The age of groundwater in these piezometers suggests that the transformation may happen quickly but that the chemicals persist in the groundwater at least for a few years. Metabolites are not present in the older groundwater (Group 2 in Table 2) in the system, suggesting that total mineralization of the pesticide occurs within 5 to 10 years. Deeper groundwater at the site is older than the first application of atrazine in the 1960's, so it should not contain atrazine or its metabolites.

It is interesting to compare water quality data from piezometers to those in the creek and Tile 1 (Figure 10c and d). Data from creek and tile samples both indicate the presence of the parent compound atrazine and some indication of desethylatrazine - the most rapidly-formed, most stable, and most persistent compound. Only the tile drain, which is subject to inflow from the water table, shows detections of deisopropylatrazine. Thurman et al. (1991) suggested that the ratio of desethylatrazine to atrazine (the DAR ratio) of 1 or greater can be used as signature of a groundwater source of atrazine, and that values <<1 are indicative of surface runoff of applied atrazine. The results of this study show that DAR ratios > 1 always occur in groundwater and never occur in Bear Creek, which in general shows DAR ratios < 1. This also suggests that the groundwater input of chemicals in Bear Creek is much less than from other sources. Data from Tile 1 show a mix of both "end members" (creek and groundwater), which suggests that both groundwater and surface water (runoff) provide atrazine and its metabolites for the tile drains.

SUMMARY AND CONCLUSIONS

In summary, geological, hydraulic head, hydraulic gradient, water quality, hydrogeochemical, and isotopic data were used to help decipher the groundwater flow systems and to determine the processes of groundwater contamination at the CMRBS. The CMRBS supports an unconfined groundwater flow system in till, sand, alluvium, and shallow bedrock. Groundwater in this aquifer is recently recharged on the site, discharges into Bear Creek, and shows evidence of contamination from recent agricultural practices at the site. This is the only groundwater flow system at the site that will be affected by processes within the CMRBS.

A discontinuous confined aquifer within the St. Louis Formation also occurs at the site. This aquifer is confined by shale units within the formation and only recharges on site where the shale is absent at the top of the bedrock. Although groundwater in this flow system also discharges into Bear Creek, it may be considerably older and will not be impacted significantly by agricultural activities at the site. Similarly, groundwater in this aquifer will not be affected by processes within the CMRBS.

Finally, deep aquifers in the Mississippian within the Keokuk, Burlington, and Gilmore City/Maynes Creek Formations, also show upward hydraulic gradients at the site, but it is unlikely that they influence the local groundwater flow systems there. Their hydraulic head relationships may be more related to regional groundwater discharge at the Skunk River. Groundwater age in these units also suggests that water entered those groundwater flow systems well before agricultural activities began in the region.

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DETERMINATION OF THE QUANTITY AND QUALITY OF GROUNDWATER INFLOW TO BEAR CREEK

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INTRODUCTION

Delineation of groundwater flow systems and their associated water quality are important to the CMRBS project because it is important to know what effect, if any, the buffer strips will have on groundwater quality as it moves towards surface water. Questions such as: "Will all the groundwater flow systems at the site be affected by the buffer strip?" and "Do buffer strips have the ability to sequester NO_3 and pesticides from the groundwater?" come to mind in this regard. In order to answer these questions, however, it is first necessary to determine the quantity and quality of groundwater discharge to Bear Creek. If the quantity of groundwater inflow is significant and groundwater is contaminated by agrichemicals, then buffer strips may have a significant impact on stream water quality, providing that they come in contact with the groundwater from the aquifer. If groundwater inflow is small relative to stream discharge and/or if the quality of groundwater indicates no contamination, then constructed buffer strips may function primarily to decrease runoff of contaminated surface water but will not affect groundwater quality.

METHODOLOGY

The focus of much or our activity in 1993 was to install equipment at the site that will help us to determine the quantity and quality of groundwater inflow and chemical loads by several different methods. Previous studies on this creek used Darcy's Law to determine very crude estimates of groundwater inflow to Bear Creek. Preliminary estimates showed that inflow from the unconfined aquifer was about 0.105 ft^3/s (2.97 L/s) and inflow from the confined aquifer was about 0.007 ft^3/s (0.198 L/s)(Ryan, 1993). Because these estimates were based on average head, K, and hydraulic gradient data, these values were subject to a fairly large error. Nevertheless, they indicate the relative magnitude of groundwater inflow to the creek. Following that study, our approach has involved installation of drive-point minipiezometers, seepage meters, and weirs in Bear Creek and on Tile 1 to determine groundwater discharge into the creek more precisely. These methods and their preliminary results will be discussed in the next few sections.

Drive-Point Minipiezometers

Three sets of four stainless steel, drive-point minipiezometers were installed in the bottom of the channel of Bear Creek. The purpose of these minipiezometers was: 1) to measure (vertical) hydraulic gradients through the stream bottom and their variability in time and space, and 2) to provide an access point for groundwater quality samples from the stream sediment and also the underlying bedrock. Early versions of these minipiezometers were plagued with many difficulties. We first attempted to manually drive expendable points using a fence post driver and then inserting a teflon tube with a small screened section into the pipe as it was pulled out. The bedrock and unoxidized till beneath the channel proved formidable obstacles for this method, and we often bent or crushed the points. Sometimes the well seal was questionable, as well. Although we did succeed in installing a number of these minipiezometers in this manner, animals promptly destroyed the tubing. We were unaware that beavers love teflon!!! Finally, some unusually high stream flows overcame the fence posts supporting the tubing and buried the minipiezometers.

Recent work at the University of Waterloo has demonstrated the use of gasoline powered jackhammers as an inexpensive alternative to emplacing piezometers with drilling equipment. Unfortunately, there is only one company that manufactures gasoline-powered jackhammers (in Sweden). Many firms rent electric hammers, which would ordinarily work fine, except that one would have to use it while wading in the stream - not an attractive alternative. With luck, we were able to secure a Pionjar jackhammer from a local construction company. We ordered Waterloo-type drive-point piezometers containing a hose barb fitting from Solinst Canada, Inc. Polyethylene tubing (3/8 in ID) was attached to the hose barb. The stainless steel screen was screwed into a 6 inch stainless steel pipe section, which was in turn attached to several 3 ft sections of standard 3/4 inch ID black (cast iron) water pipe. The jackhammer was used to drive on the black pipe sections and set the screen. The black pipe also support the piezometer tubing and protects it from stream debris, sunlight, and large rodents.

Three locations in Bear Creek were chosen for emplacement of the drive-point minipiezometers: one below the upstream weir, one just before the bridge, and one just upstream from the downstream weir. Each nest included four minipiezometers and they were aligned perpendicular to the bank. The minipiezometers closest to the stream bank were placed only about 2 to 3 ft (0.6 to 0.9 m) beneath the sediment-water interface. These included minipiezometers GP1, GP4, GP5, GP8, GP9, and GP12. They were most likely finished in unoxidized diamicton. The innermost two minipiezometers, including minipiezometers GP2-3, GP6-7, and GP10-11, were driven to depths from 3 to 6.5 ft (0.9 to 2 m). The deeper of these piezometers were probably finished in limestone or shale bedrock. Hydraulic heads were measured and water quality samples taken on weekly basis. Water samples were analyzed for NO_3-N, atrazine by ELISA, and Cl.

Seepage Meters

Minipiezometers provide hydraulic head data, from which we can calculate a hydraulic gradient. Assuming we know the hydraulic conductivity (K) of the sediment, we can then use Darcy's Law to determine the vertical flux of water into the creek. A more direct method, however, is to measure the groundwater discharge directly. One method that we are using at the site involves seepage meters, which are 55 gallon drums driven into the stream bed. Attached to the top of the meter is a plastic bag that measures groundwater inflow. These meters yield a rough value for the amount of groundwater flux from the stream bed during a given period of time through the cross-sectional area of the drum. Values of flux from seepage meters yield reasonable seepage values, but only for a small part of the area of the stream bed.

Weirs

Another more "energy-intensive" method of determining groundwater inflow is to install permanent control structures in the stream to document the variation of stream discharge between two points in the stream. An easier method to determine stream discharge would be to use a hand-held velocity meter (such as a Pygmy meter) and an estimate of the cross-sectional area of stream. However, this method is prone to error, and it is better to have a permanent structure where discharge is measured each time so that accurate and precise data can be gathered. Our working hypothesis for this study was that the difference in discharge between the upstream and downstream weirs, minus any tile inflow, was due to groundwater inflow. We installed three control structures, or *weirs*, in Bear Creek. Weirs are an obstruction or dam built across an open channel over which (water) flows, often through a specially shaped opening or notch. Many shapes or types of weirs exist, but we chose triangular or V-notch weirs for this project (Figure 1). For any weir, the stream discharge is proportional to the height of water in the pool upstream of the weir; thus, weirs are designed to operate under the assumption that only one depth of water in the upstream pool can exist for a given discharge. In essence, the weir shapes the flow of water so as to allow a single depth of flow reading that is uniquely related to the discharge.

Standard terminology and design requirements for weirs are relatively straightforward. Triangular weirs come to a 'point' at the base of the V-notch. This is termed the *crest* of the weir. The downstream edge of the weir plate is often beveled or chamfered. This provides the essential *ventilation* for the stream of water, or the *nappe*, flowing through the notch . Water passing across the V-notch does not contact the downstream edge of the weir plate, and essentially 'springs' past it. Accurate stream discharge measurements can be calculated only under free flow conditions. If the flow beneath the weir rises to the extent that the nappe becomes submerged, the accuracy of the discharge rate is affected.

Two in-stream weirs and one tile monitoring weir have been installed at this field site. The in-stream weirs have interior angles of 150 degrees and a maximum head value of 1.75 ft (0.5 m). The equation for discharge calculations associated with flow across triangular weirs is:

$$Q = 2.5 (\tan\theta /2)(H)^{2.5}$$

where: Q = discharge in cubic feet per second (cfs)

θ = interior angle of V-notch in degrees

H = water head observed above the crest of the V-notch

At maximum head conditions:

$$Q = 2.5 (\tan 150 /2)(1.75)^{2.5}$$

and thus $Q_{max} = 37.8$ cfs.

The weir box on Tile 1 is a triangular weir that has an interior angle of 120 degrees and a maximum head value of 1 ft. So, at maximum head conditions:

$$Q = 2.5 (\tan 120 /2)(1.00)^{2.5}$$

and thus $Q_{max} = 4.33$ cfs.

We can use the weirs to determine groundwater inflow to Bear Creek in the following manner. Assuming a stream gradient in equilibrium, mass balance suggests that the components of stream discharge are:

$$Q\text{total} = Q\text{stream} + Q\text{precip.} + Q\text{runoff} + Q\text{tiles} \pm Q\text{groundwater}$$

Precipitation and runoff can be neglected in most cases, and discharge from the smaller drainage tiles can be measured as needed. A simplified mass balance equation can be developed:

$$Q\text{total} = Q\text{stream} + Q\text{tiles} \pm Q\text{groundwater}$$

and solving for the groundwater component,

$$\pm Q\text{groundwater} = Q\text{total} - Q\text{stream} - Q\text{tiles}$$

This equation says that the difference in discharge between the upstream and downstream weirs is due to gains or losses from groundwater and tiles along the reach of interest; therefore, Qtotal is represented by Q at the downstream weir, and Qstream is represented by the discharge at the upstream weir.

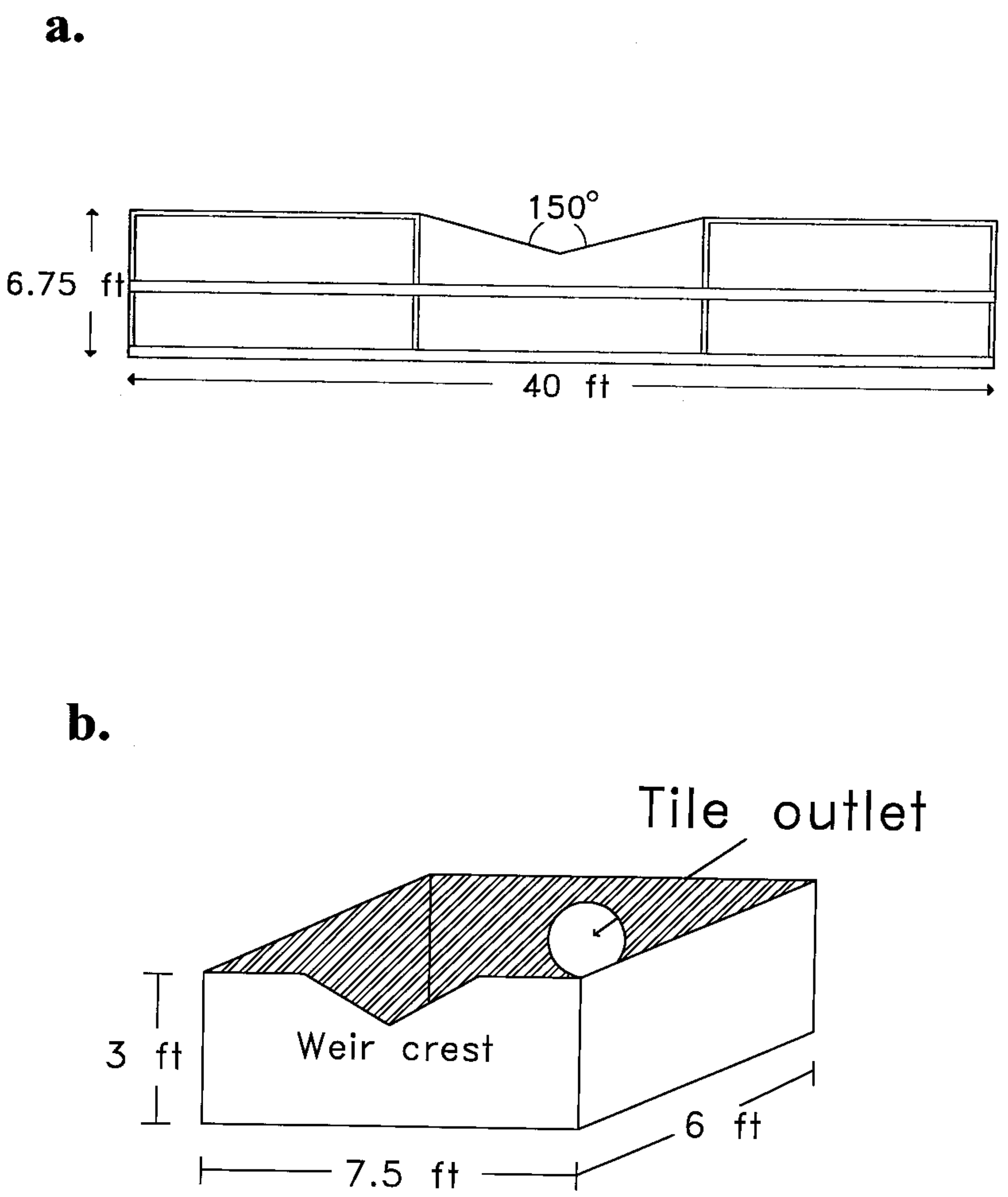

Figure 1. Scale drawings of (a) in-stream weirs in Bear Creek and (b) weir box on Tile 1.

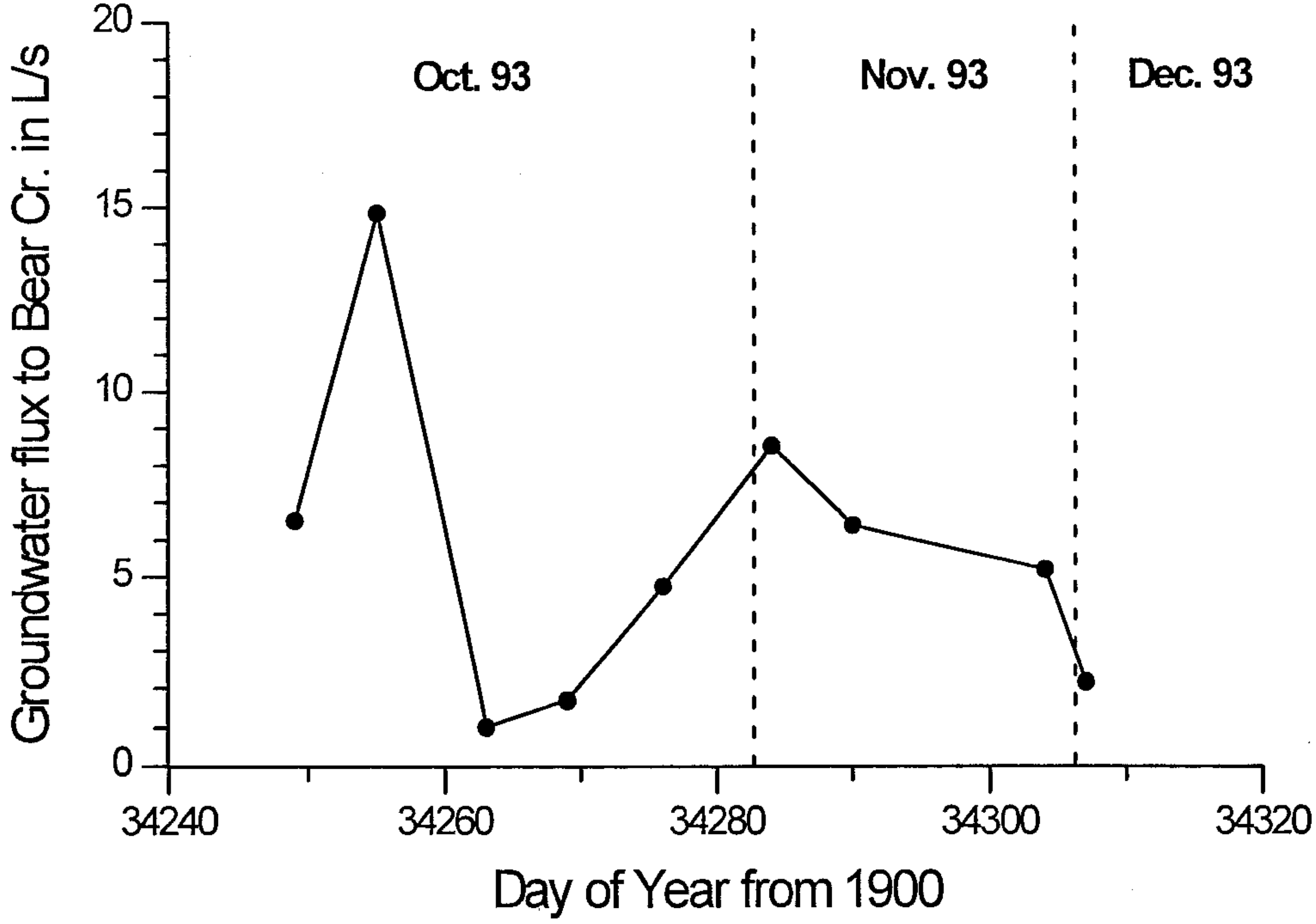

Figure 2. Variations in groundwater discharge to Bear Creek during the latter part of 1993.

RESULTS AND DISCUSSION

Based on some preliminary hydraulic head data, the minipiezometers show upward-directed hydraulic gradients in the sediment underlying the creek. This was expected, based on the upward-directed hydraulic gradients that occur in all the bedrock in the vicinity of the stream. Data could not be obtained from GP9-12, because these piezometers appear to be in shale bedrock and have not yielded very much water since their installation. We suspect that the hydraulic gradients across this unit are quite high. Water quality analyses through from September 9 to October 6, 1993, indicate no significant amounts of agrichemical contamination in the drive-point piezometers. The highest NO_3-N concentrations occurred in GP3 and GP4 at the west end of the site, where values up to 3.2 mg/L were observed. ELISA atrazine concentrations are generally < 0.1 µg/L in the drive-point piezometers. In summary, the results suggest that groundwater is not a major contributor to surface water contamination in Bear Creek.

Seepage meters were placed in various positions and sediment types (gravel, sand, and silt) within the creek bed. Approximately 0.1 to 1.0 L of discharge were captured in one hour in the meters when the measurements were taken during the Summer of 1993. Discharges were as high as 2.1×10^{-3} L/s per m^2 of stream bed. Assuming an approximate area of the stream bed of 5000 m^2 (1000 m long by 5 m wide) in this section, the cumulative discharge extrapolated from the maximum seepage flux would be 10.5 L/s - a value not too different from the original estimates of Ryan (1993). The data from the seepage meters emphasize how variable the discharge can be in a stream bed as a result of the underlying sediment type. It is quite possible that most of the discharge in the study site occurs in the western part where limestone and not shale underlies the bottom of the channel.

Weekly measurements of discharge from all three weirs at the site from October 7 to December 4, 1993 show that groundwater discharge to Bear Creek varied from 0.06 cfs (1.69 L/s) to 0.52 cfs (14.84 L/s) during that period (Figure 2). These values are of the same magnitude as those calculated by the other methods discussed above. Chemical loads of atrazine in the stream ranged from 5.2 g/day to 13.5 g/day for three dates in that period, whereas the tile only contributed from 0.75 to 0.97 g/day to the stream. Because groundwater has shown no significant NO_3-N or atrazine concentrations during the monitoring period, we assume that it does not contribute to the chemical load in Bear Creek; in fact, it may act to dilute the existing chemical concentrations in the creek. In addition, groundwater discharge is only a fraction of the total discharge in Bear Creek during non-baseflow periods (1% or less); therefore, high concentrations of contaminants in groundwater would be necessary in order for it to impact the ambient chemical concentration of the stream.

SUMMARY AND CONCLUSIONS

The quantity and quality of groundwater inflow to Bear Creek have been calculated using a variety of direct measurement methods. Although preliminary data indicate that groundwater discharge may reach in the 10's of L/s, it only amounts to a small fraction of the total stream discharge. There is also little evidence of groundwater contamination of the geological units immediately underlying the stream bed. Thus, our preliminary conclusion is that groundwater does not contribute significantly to degradation of water quality in Bear Creek.

We plan to collect data from drive-points minipiezometers and weirs during periods of baseflow this winter to determine if these relationships still hold under low flow conditions. Ultimately, we will use a groundwater flow model to simulate the groundwater flow and contaminant transport at this site; this will allow yet another estimate of groundwater inflow and contaminant flux.

REFERENCES

Ryan, W.J., 1993. A preliminary hydrogeological assessment of a constructed multispecies riparian buffer strip near Roland, Iowa. unpubl. M.S. thesis, Department of Geological and Atmospheric Sciences, Iowa State University, 147 pp.

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Location map of field trip stops.