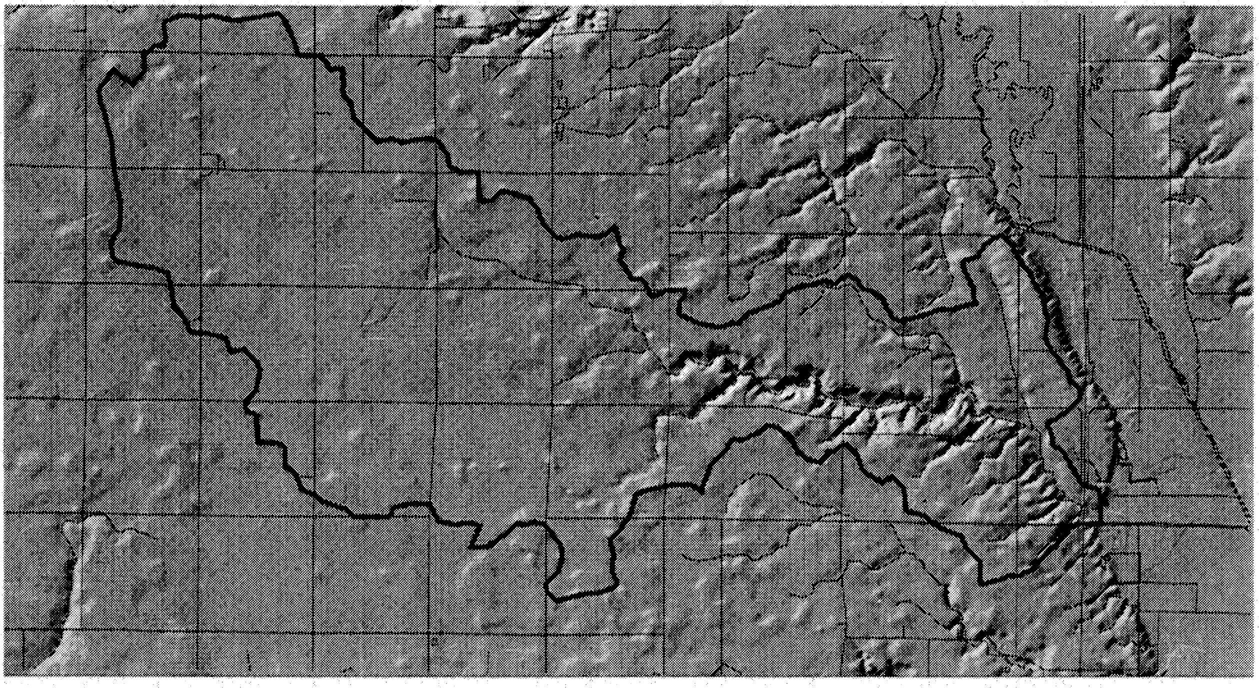
# HYDROGEOLOGY AND WATER QUALITY OF THE WALNUT CREEK WATERSHED

Geological Survey Bureau
Guidebook Series No. 20



Iowa Department of Natural Resources
Larry J. Wilson, Director
May 1996

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## Geological Survey Bureau
## Guidebook Series No. 20

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## North-Central Section Annual Meeting
## Geological Society of America
Iowa State University
Ames, Iowa

## Field Trip No. 3

May 1996

**Iowa Department of Natural Resources**
**Larry J. Wilson, Director**

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# INTRODUCTION

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Welcome to the Walnut Creek watershed and central Iowa! You are in a typical agricultural watershed within the low-relief landscape of the Des Moines Lobe. Land within the watershed is under corn-soybean rotation, continuous corn, and some corn-soybean-grain-legume rotation, and it contains some large seed-farming operations as well as smaller family farms. Conventional, ridge-tillage, and no-till practices are used and nitrogen fertilizer, manure, and pesticides are applied on the fields. The upper reaches of the watershed have poor natural drainage and are drained by tile drain networks. Tile drains are absent in the lower reaches of the watershed where the surface drainage is more integrated.

Concerns about human health and environmental degradation by agricultural practices in areas such as Walnut Creek initiated the U.S. Department of Agriculture Water Quality Initiative in 1989. The three principles of this initiative were (USDA, 1994):

- to protect of the Nation's ground water resources from contamination by fertilizers and pesticides without jeopardizing the economic vitality of U.S. agriculture:
- to initiate water quality programs that address the immediate need to halt contamination and the future need to alter fundamental farm practices; and
- to recognize the ultimate responsibility of farmers for changing production practices to avoid contaminating ground and surface waters.

The Management Systems Evaluation Area (MSEA) program grew out of the Water Quality Initiative. The Midwest region was chosen for the initial study because it produces more than half of all the corn and soybeans in the United States and uses more than half of the nations pesticides and fertilizers; hence, groundwater and surface water were thought to be at risk in this area (USDA, 1994).

On this field trip, you will see the results of nearly 6 years of interdisciplinary research in one of the 3 MSEA in Iowa - the Walnut Creek watershed. The focus of our trip is to show how scientists that are not traditionally involved in agriculture - namely, geologists and hydrogeologists - have contributed to a study that is primarily agricultural in scope. We will demonstrate how important our geological contribution has been to this research and show how this project has helped us forge new interdisciplinary linkages for the future.

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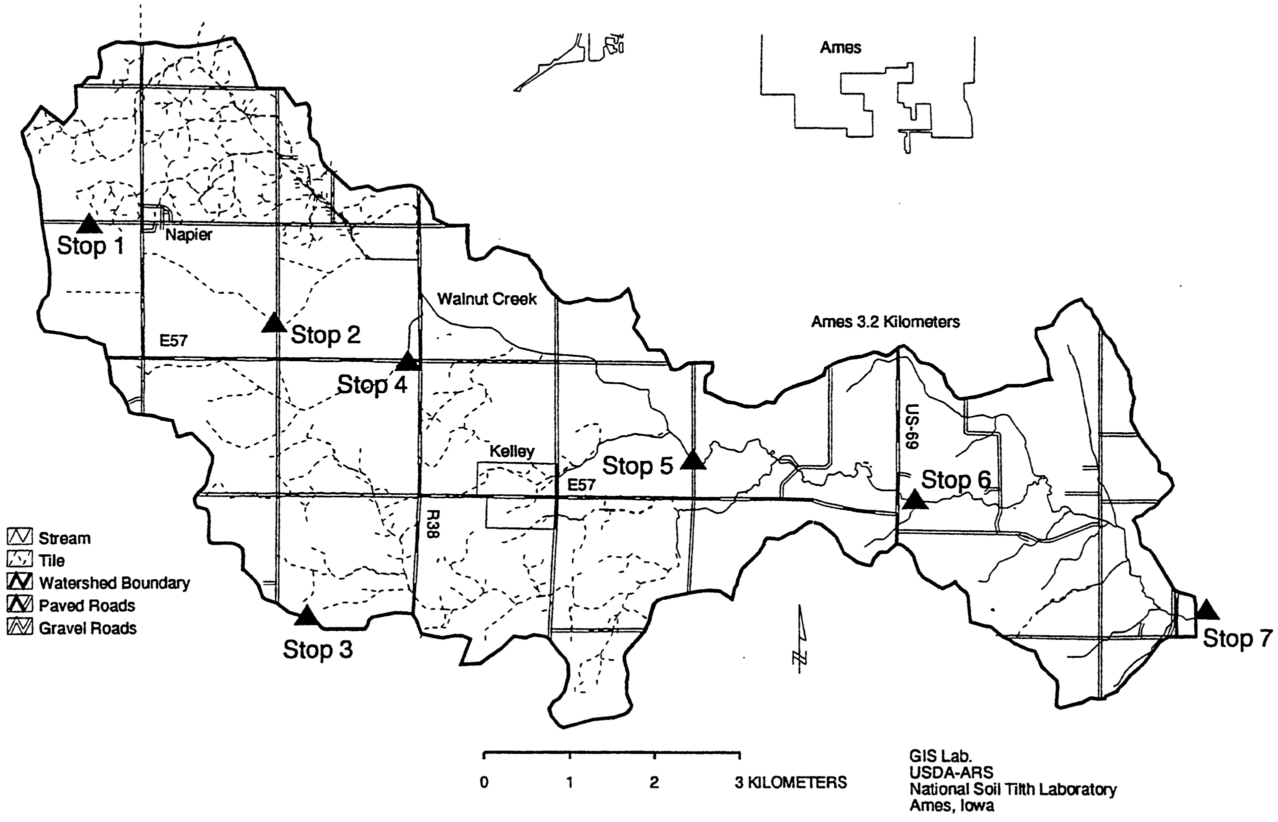

**Figure 1.** Map of the Walnut Creek watershed showing location of stream channels and the tile drainage network. Locations of monitoring stations for stream and tile drain discharge are also shown.

# OVERVIEW OF HYDROLOGIC INVESTIGATIONS IN THE WALNUT CREEK WATERSHED

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## INTRODUCTION

Walnut Creek, one of three MSEA project areas in Iowa, was selected to represent hydrologic conditions associated with the Des Moines Lobe landform region (Fig. 1). In addition, the eastern end of the watershed flows atop a large alluvial aquifer associated with the valley of the South Skunk River. The presence of this aquifer affords an opportunity to study the impact of agricultural management systems on a particularly vulnerable groundwater flow system. Walnut Creek is one of 10 areas in the Midwest being investigated within the Management Systems Evaluation Area (MSEA) program (Fig. 2). 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.

The Walnut Creek watershed is a typical agricultural watershed in central Iowa. More than 85 percent of the 5,600 ha in the watershed is in a corn-soybean rotation. Soils in the watershed are characterized by the Clarion-Nicollet-Webster association that are poorly to moderately well drained. Yield potentials 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 the most productive area of the Midwest corn and soybean producing region.

Four components of the hydrologic system are under investigation in the watershed: groundwater; artificial subsurface (tile) drainage; runoff; and the interaction of Walnut Creek with the alluvial aquifer in the South Skunk River valley. The hydrologic setting of the research area affords an opportunity to study the interactions between groundwater and surface water and the processes by which they both become contaminated with $NO_3$-N and herbicides.

## GROUNDWATER

Farming activities in the watershed have not directly impacted aquifers west of the alluvial aquifer of the South Skunk River valley (Simpkins et al., 1993). Groundwater in the till and soil is the primary focus of this study because agrichemicals occur there and because water and chemicals flow to (and from) an artificial subsurface (tile) drainage system in the watershed. Since 1990, water levels and water quality has been measured in more than 100 piezometers, generally less than 10 m deep, installed adjacent to actively-farmed fields. Water samples from these piezometers during 1991-1994 showed consistent $NO_3$-N infiltration to depths where tiles may intercept water (1 to 3 m deep), but they showed that few herbicides had leached to these depths. The data also show that transport of agricultural chemicals is minimal to the depths below most tile drains. The percentage of samples exceeding 10 mg/L $NO_3$-N decreased with depth from 75 percent at 0 to1 m to only 10 percent at depths greater than 3 m. Herbicide concentrations were below the quantitation limit of 0.2 $\mu$g/L in most samples. Atrazine, the most commonly detected herbicide, was detected in 15 percent of the groundwater samples taken from depths less than 3 m and only 2 percent of the samples taken from below 3 m (Jaynes and Hatfield, 1994). Atrazine concentrations exceeded the maximum contaminant level of 3 mg/L in only one of 1700 groundwater samples obtained from this piezometer network.

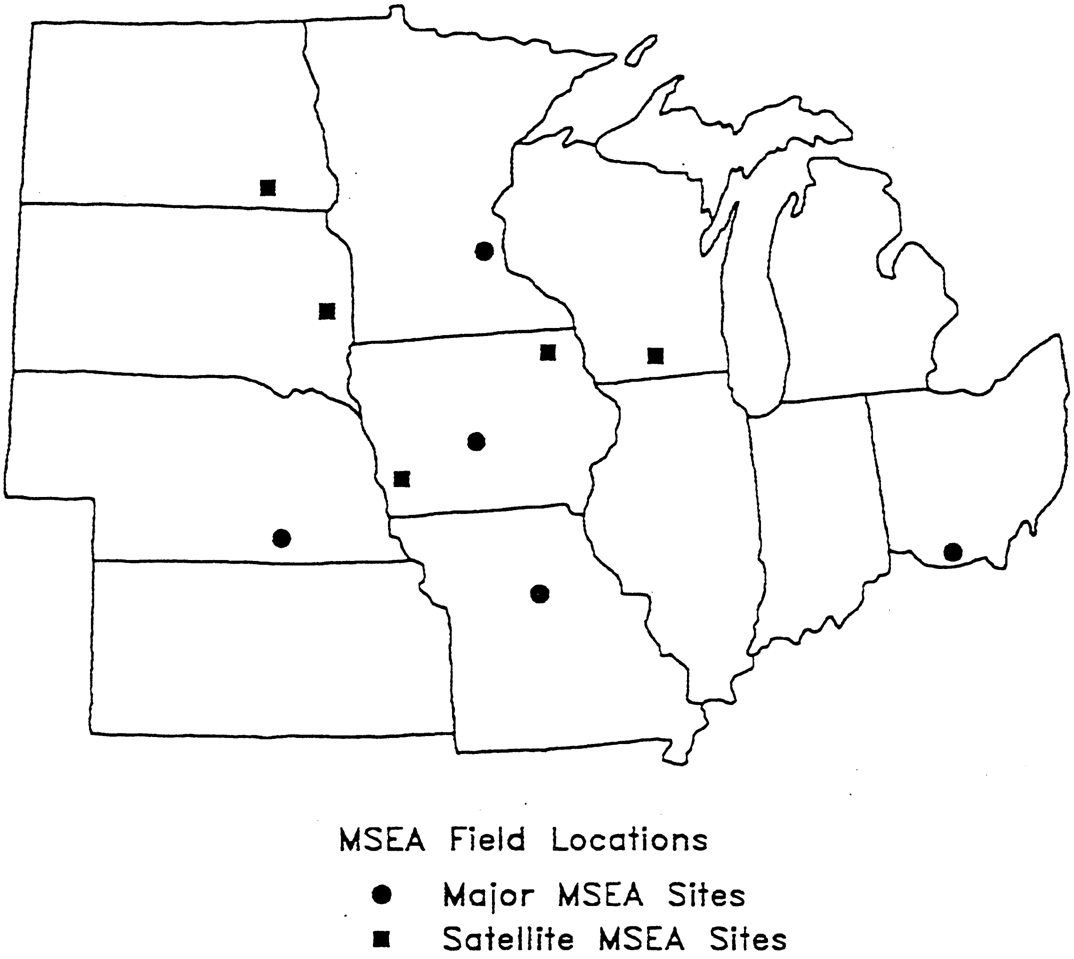

**Figure 2.** Location of the USDA Management System Evaluation Areas in the Midwest (adapted from USDA, 1994).

## ARTIFICIAL SUBSURFACE (TILE) DRAINAGE

Artificial subsurface (tile) drainage represents one of the more interesting aspects of the hydrologic system in the watershed. During the last 70 to 80 years, farmers and county governments have collaborated in the construction of subsurface tile drainage systems. These systems drain closed depressions with a combination of surface inlets and lateral tile drains that maintain the water table at a depth of 1.5 to 2 m throughout much of the growing season (Fig. 1). Field tile drains are characterized by a herringbone pattern. These are connected to county tile drains which form a dendritic pattern that resembles a stream drainage network. A series of field tile drains and an intermediate point in a county tile drainage system will be seen at Stop 2. We will see one of the larger tile drains that forms the headwaters of Walnut Creek at Stop 4.

Flow in the tile drains includes water from surface inlets, rapid infiltration following rainfall, and sustained infiltration of soil (vadose zone) water. $NO_3$-N concentrations in tile water do not vary greatly throughout the year, and concentrations generally exceed 10 mg/L. Concentrations of $NO_3$-N less than 10 mg/L frequently coincide with peak discharges, which are presumably the result of direct infiltration and preferential flow through the vadose zone. This relationship suggests that surface inlets contribute contain smaller concentrations to drainage water than does infiltration of soil water. Atrazine in tile drains is detected at concentrations generally close to or less than the quantitation limit of 0.2 µg/L at most times during the year and soil water and surface intake water are not distinguishable. Cumulative loads of atrazine and $NO_3$-N in tile drainage water indicate that the infiltration of soil water to tile drains contributes considerably more agrichemicals to the stream than does runoff immediately following storms. Given this interpretation, the load of agrichemicals passing the gaging station at Stop 7 (Fig. 1) may be attributed to tile drainage. Farming systems designed to improve water quality in this environment may need to address tile drainage systems, rather than runoff, as the principal mechanism of agrichemical transport.

## RUNOFF

Runoff is a relatively minor contributor to stream flow except: 1) in areas of high-relief in the eastern one-third of the watershed, and 2) during periods of extreme hydrologic conditions such as the 1993 floods. The contribution of runoff to stream discharge can be seen at Stop 7. The area contributing to this station is 5,130 ha and includes a large area with subsurface tile drains. Water contributing to stream discharge at this station can come from three sources: runoff from storm flow; tile drainage flow from surface inlets; and subsurface tile drainage flow from infiltration of soil water. Runoff is represented by the peaks on the hydrograph (Fig. 3). It is not surprising to find that runoff peaks are common and very large on the hydrograph in 1993. Tile drainage flow from surface inlets contributed to the larger sustained stream discharges during 1993; however, tile drainage flow from the infiltration of soil water is the main contributor during the 1991-94 period. If not for tile drainage flow, discharge in Walnut Creek would be unmeasurable during much of the growing season and during the later fall and winter months.

Concentrations of agrichemicals show interesting relationships to stream discharge. $NO_3$-N concentrations were measureable during periods of sustained tile drainage, even into the winter months. Concentrations of $NO_3$-N were often greater than 10 mg/L and generally decreased with an increase in discharge. Except for 1993, $NO_3$-N concentrations decreased from July through September. Large concentrations that persisted in the summer of 1993 despite the nearly continuous precipitation probably resulted from release and transport of nitrogen stored in soil and in the vadose zone. In fact, the load of N removed as $NO_3$ in 1993 was 150 percent of the nitrogen fertilizer applied to the watershed during that year. The fractions removed in 1991 and 1992 were 36 and 50 percent of the nitrogen fertilizer applied, respectively. These relatively large losses of $NO_3$-N, even during normal rainfall years, suggest that tile drainage systems have substantially modified the natural stream hydrology and have accelerated the removal of agrichemicals in the watershed. In contrast, atrazine concentrations increased (Fig. 3) during the typical spring runoff events and they were particularly large during events in the early summer that followed herbicide application. The annual atrazine load to Walnut Creek was more than 2 percent of that applied in 1991, less than 1 percent in 1992, and more than 7 percent in 1993.

## GROUNDWATER/SURFACE WATER INTERACTION

Investigation of groundwater/surface water interaction is occurring in the tile-drained, upland part of the watershed (Stop 6) and in eastern end, where an abrupt decrease in relief occurs as Walnut Creek flows onto the floodplain of the South Skunk River (Stop 7). In this section of Walnut Creek, the channel was artificially deepened and straightened for a distance of 2,000 m to the river. The bed of the channelized creek consists of about 1 m of medium sand. The alluvial aquifer, composed of sand and gravel that is 10 to 15 m thick, lies about 4 m beneath the floodplain surface. Initial hydraulic head measurements confirmed the hypothesis that the creek loses water to the

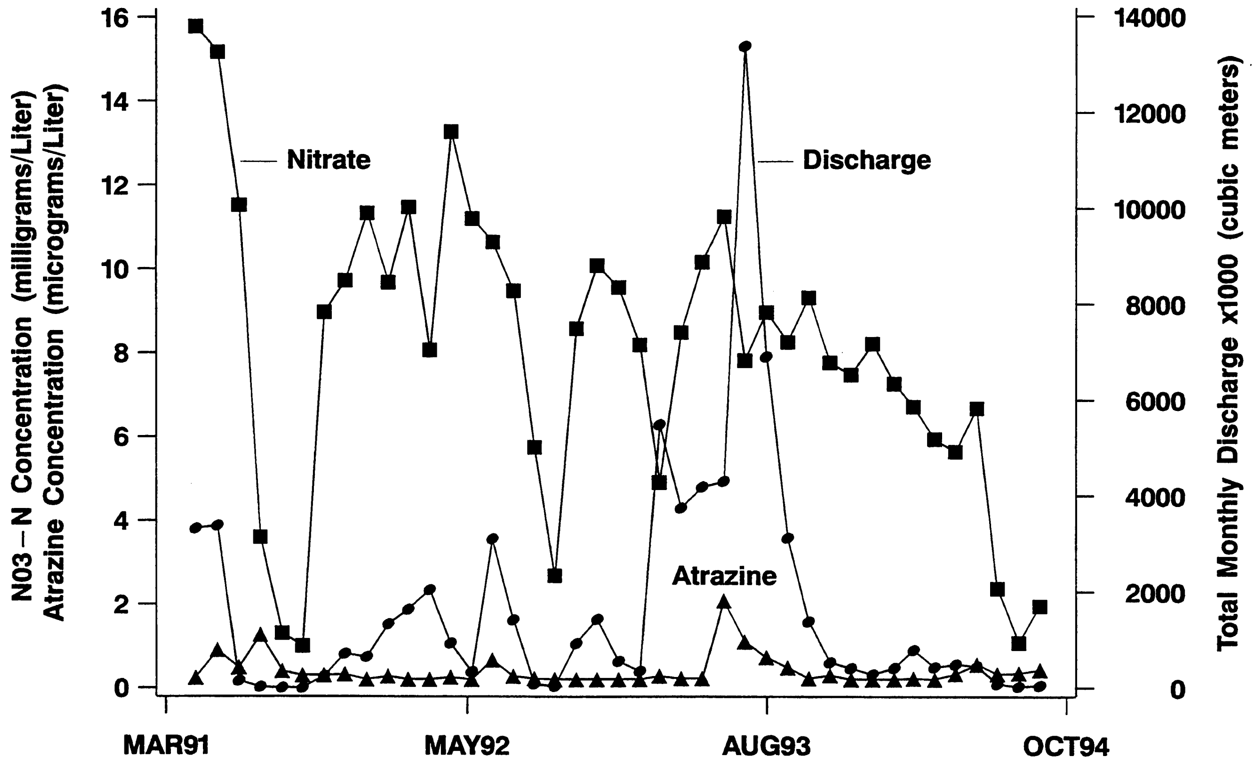

**Figure 3.** Total monthly discharge and average monthly concentrations of NO$_3$-N and atrazine at the point where Walnut Creek flows onto the floodplain of the South Skunk River (Stop 7).

underlying alluvial aquifer. The data suggested that the observed increases in the herbicide concentrations in the aquifer may be the result of vertical recharge from the creek. In 1995, we initiated a more extensive project to determine the seasonal variation in hydraulic gradients, the volume of stream discharge lost or gained in this section, and the concentrations of NO$_3$-N, metolachlor, cyanazine, alachlor, atrazine and its metabolites in the creek and the piezometers. The details of this investigation will be discussed at Stop 7.

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# GEOLOGICAL AND HYDROGEOLOGICAL SETTING OF THE WALNUT CREEK WATERSHED AND CENTRAL IOWA

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## INTRODUCTION

The Walnut Creek watershed lies within a hydrogeological setting typical of the Midwest - aquifers and confining units composed of Paleozoic bedrock that are overlain by glacial deposits and Holocene alluvium. The purpose of this paper is to introduce the reader to the major geological units in the region, with special reference to their function as confining units and aquifers.

Bedrock in central Iowa consists of Pennsylvanian, Mississippian, Devonian, Silurian, Ordovician, and Cambrian age units (Anderson, 1983). Bedrock units strike northwest to southeast and dip to the southwest into the Forest City (structural) Basin. The topography on the bedrock surface in central Iowa (which may be on the top of either Mississippian or Pennsylvanian rock) varies considerably in the region, and ranges from 198 m above mean sea level in the valley floors to 274 m above sea level on bedrock highs. The depth to bedrock (and thickness of Pleistocene sediment) in the region may vary anywhere from 0 to 115 m.

## BEDROCK AQUIFERS AND CONFINING UNITS

### Mississippian Aquifer

Rocks of Mississippian age comprise the major bedrock aquifer in central Iowa (Horick and Steinhilber, 1973), although a deeper and potentially larger groundwater source in central Iowa is the Cambro-Ordovician aquifer (Burkart and Buchmiller, 1990). The most prevalent rock type is limestone, although shale, sandstone, and siltstone are also common. The Mississippian lithostratigraphy is subdivided into three major Series, which are commonly divided into the following formations:

**Meramecian Series**
  St. Louis Formation (limestone, sandstone, evaporites)
  Warsaw Formation (dolomitic limestone and shale)
**Osagian Series:**
  Keokuk Formation (limestone and chert)
  Burlington Formation (dolomite and chert)
  Gilmore City Formation (limestone)
  Hampton Formation (dolomite)
**Kinderhookian Series**
  Prospect Hill Formation (siltstone)

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. Horick and Steinhilber (1973) suggested that groundwater flows from the north to the southeast in the aquifer; however, the recharge areas for the Mississippian formations are not well defined. Simpkins (1993) suggested that recharge to the St. Louis Formation occurs in localized outcrops in central Iowa and that recharge to the deeper Gilmore City aquifer occurs in the subcrop area near the northern limits of the formation in Hardin and Franklin Counties. High $SO_4$ concentrations in the Mississippian aquifer south of Ames suggest that some vertical recharge may also occur through Pennsylvanian shales and sandstones. Based on their interpretation of the potentiometric surface,

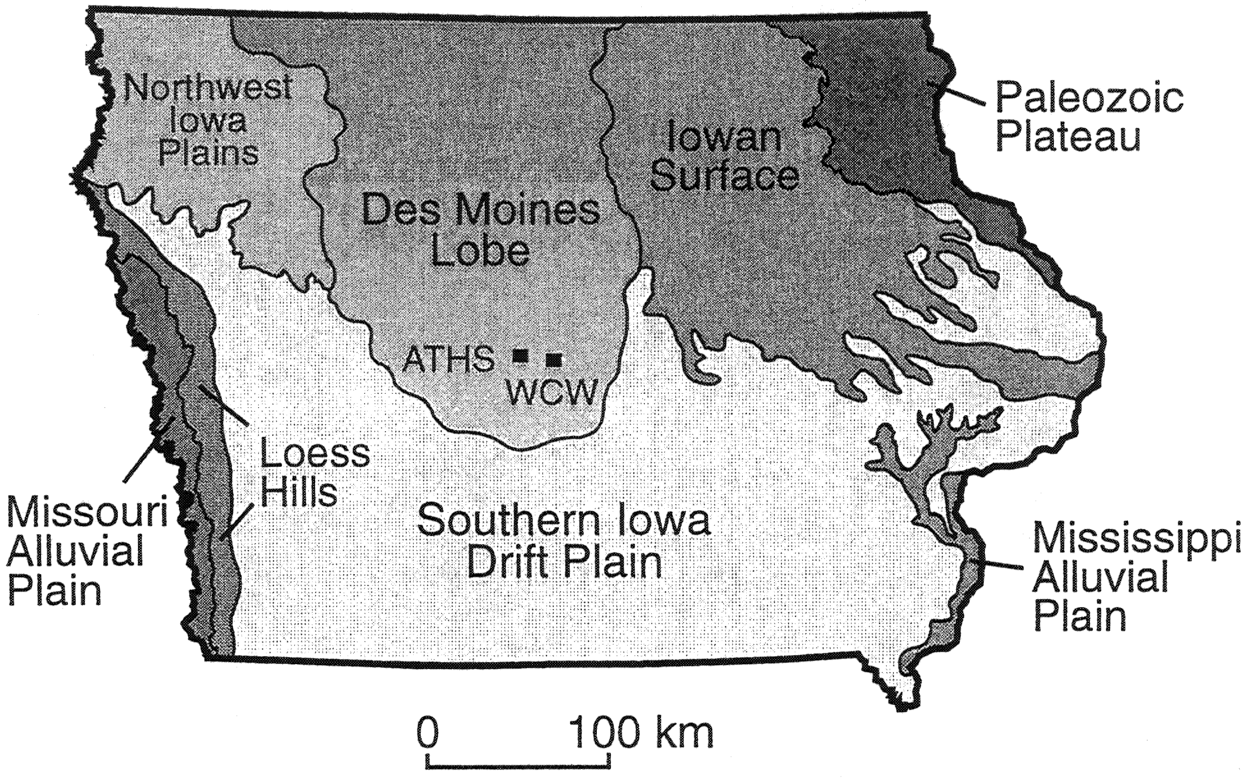

**Figure 4.** Landforms regions of Iowa and location of the Walnut Creek watershed (WCW), (map modified from Prior, 1991). ATHS = Ames Till Hydrology Site.

Horick and Steinhilber (1973) suggested that the Mississippian aquifers discharge into major streams such as the South Skunk River. In areas of shallow bedrock in northern Story County, the St. Louis limestone aquifer can discharge into creeks that are nearly the same size as Walnut Creek (Caron, 1994). Gibbons (1995) suggested that discharge from the Mississippian aquifers to buried valley aquifers was also significant. There appears to be no hydraulic connection between Mississippian aquifer and Walnut Creek, mostly because of the great thickness of glacial sediment that lies between the bedrock aquifer and the creek.

Hydraulic conductivity (K) data for the Mississippian aquifer are sparse. Gibbons (1995) calculated a geometric mean value of $9 \times 10^{-6}$ m/s for 30 wells in the aquifer (log transformed standard deviation = 0.87); however, these values are probably most representative of the St. Louis limestone. Chemical analyses of groundwater in the Mississippian aquifers in this area and in northern Story County indicate no detections of $NO_3$-N or pesticides. Most of the groundwater is a Ca-$HCO_3$ or $CaSO_4$ type water (Simpkins et al., 1993a). Many samples in northern Story County contain significant amounts of dissolved Fe and $CH_4$, but lack $SO_4$ (Simpkins and Parkin, 1994). These data suggest that low redox potentials exist in the aquifer and that $NO_3$-N species would probably be denitrified if it entered the aquifer. Long residence times are another characteristic of the aquifer. Tritium analyses suggest that groundwater in this

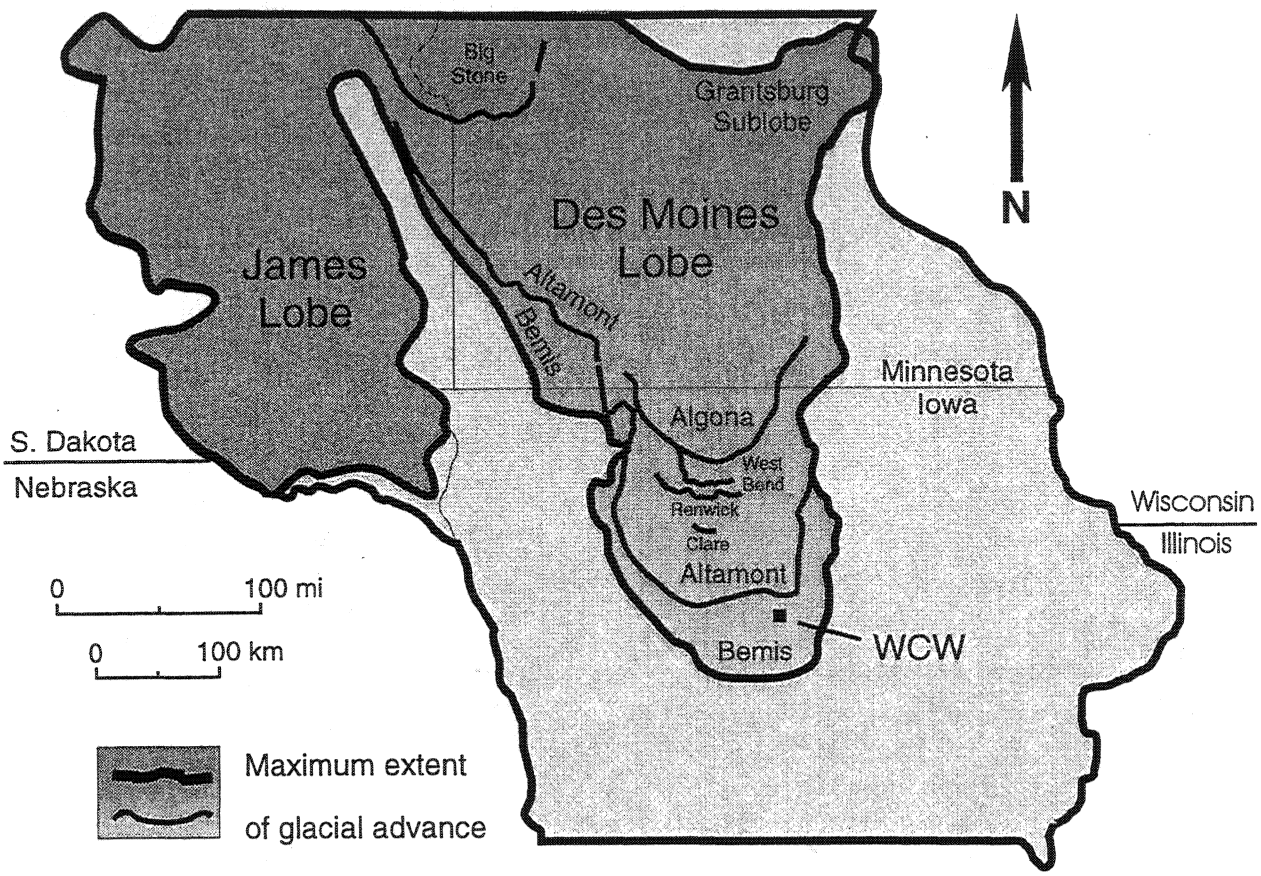

**Figure 5.** Extent of the Des Moines Lobe showing location of the watershed (WCW) and major end moraines (adapted from map by D. Quade, Geological Survey Bureau, 1995).

aquifer in Story County is older than 1953. Unpublished and uncorrected $^{14}$C dates on dissolved inorganic carbon in groundwater suggest that water in the upper part of the St. Louis Formation and in the Gilmore City Formation in northern Story County is less than about 5,000 years old. In contrast, corrected $^{14}$C dates on groundwater in these aquifers beneath Walnut Creek show it to be greater than 30,000 years old (Qiu, 1993). Based on these ages and the low redox potentials in this aquifer, there appears to be little chance of contamination from surface agricultural activities.

## Pennsylvanian Aquifer

Rocks of Pennsylvanian age in central Iowa are represented by a subdivision of the Desmoinesan Series known as the Cherokee Formation (Howes, 1993). These rock units are only present in central Iowa south of the Pennsylvanian subcrop line and are therefore absent in the central part of the Walnut Creek watershed. The unit contains primarily carbonaceous shale and siltstone units, and secondarily sandstone, coal, and freshwater limestone units. The shale units in this formation are an important regional confining unit (aquitard) and probably isolate the limestone from significant vertical recharge. Sandstone units provide water to some domestic wells in the area; however, bad taste of the water and the non-contiguous nature of the channel sandstone deposits preclude its wide usage as an aquifer. Data on K values for this aquifer are also sparse. Gibbons (1995) estimated a geometric mean K value from 3 wells at $1 \times 10^{-5}$ m/s (log transformed std. dev. = 0.98).

No significant $NO_3$-N or pesticide detections have been seen in groundwater samples from this aquifer (Simpkins et al., 1993a). Most groundwater from this unit has a high $SO_4$ concentration and lies within the Ca-$SO_4$ hydrochemical facies. Corrected $^{14}C$ dates suggest that most water in this unit is > 30,000 years old and, in some cases, beyond the range of $^{14}C$ dating (Qiu, 1993). The groundwater recharge and discharge areas for this unit in this region are not well known. Sandstone outcrops occur to the west along the Des Moines River valley and these could function as either recharge or discharge zones for this aquifer.

## UNLITHIFIED AQUIFERS AND CONFINING UNITS

### Pleistocene Stratigraphy and Landforms

The Walnut Creek watershed lies within the Des Moines Lobe Landform Region (Fig. 4) in which the primary landform feature is the Des Moines Lobe. Three major ice advances of the Des Moines Lobe, the Bemis, the Altamont, and the Algona advances and moraines of the same name, are recognized to have occurred in Iowa about 14,000 to 12,500 years B.P. during late Wisconsinan time (Prior, 1991) (Fig. 5). The shortness of time between advances and the formation of a "linked depression" landscape has suggested that the advances were surges (Kemmis, 1991; Prior, 1991).

Till and associated glacial sediment are classified formally within the Dows Formation, which is composed primarily of two members: the Alden Member (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. Both till units appear light yellowish brown (2.5 Y 6/4) where oxidized (weathered) to depths of about 4 m in upland areas. Oxidized till generally contains organic carbon concentrations of about 0.3 percent. 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 4 m of the weathered till and show a preferred orientation approximately 30 to 45 degrees from the ice-flow direction (Lee, 1991). Unweathered (unoxidized) Alden Member basal till is dark gray (2.5 Y 4/0), more cohesive and higher in bulk density than the weathered till above. In general, this till contains organic carbon concentrations > 0.5 percent. The carbon is derived from the buried spruce forest in the underlying loess. Fractures have been recognized to depths of 10 m in this zone.

The till landscape in central Iowa consists of low-relief (< 2 m high) arcuate ridges that trend transverse to ice flow and parallel to the former ice margin and end. Their direction is approximately east-northeast to west-southwest in the watershed. These features have been identified and described as corrugation ridges or minor moraines by Kemmis et al. (1981) and numerous others. They are grouped within the "plains with well-defined lineated ridge patterns" (PL3; Kemmis, 1991). Stewart et al. (1988) suggested that they formed by the squeezing of basal till and meltwater sediment into crevasses at the base of an active ice margin, although Kemmis (1991) found many to contain resedimented diamicton in the upper sections suggestive of supraglacial deposition. Colgan (1995) suggests that these features are more properly termed "aligned hummock tracts" that form in a zone 5 to 40 km wide that detaches from the ice margin after a surge. 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 together they form a connected drainage network during periods of high runoff.

The late Wisconsinan till in central Iowa overlies a Wisconsinan (Peoria) loess unit, deposited between 14,000 and 17,000 years B.P., that consists primarily of silt and some clay (Ruhe, 1969; Prior, 1991). Coring at Walnut Creek and Ames Till Hydrology projects suggests that the contact between the loess and the overlying till is sharp and that an increase in silt is often noted near the bottom of the till and near the contact. The genesis of loess deposits in the watershed is not clear in all instances and is discussed in more detail in a later section.. Johnson (1995) distinguished two distinct types of loess: Type I (eolian and colluvial) and Type II (primarily eolian). Type I loess is "till-like" in character and is technically a diamicton. It was probably affected by mass movement and deposited into a wetland environment. Type I loess also contains unusually large organic carbon percentages (> 0.5 percent) that consist of whole spruce wood chips as well as disseminated carbon. These percentages, as well as those in the overlying unoxidized till, are 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. Organic carbon in these units drive denitrification, Fe-reduction, $SO_4$ reduction and methanogenesis reactions (Simpkins and Parkin, 1993; Parkin and Simpkins, 1995; Simpkins et al., 1993b). A paleosol of earlier Wisconsinan age, known as the basal loess paleosol or Farmdale Soil, occurs below the Wisconsinan loess in the watershed. This soil is developed in what is known as the Pisgah Formation in Iowa (Bettis, 1990; Forman et al., 1992).

A period of landscape instability occurred between 21,000 and 16,500 years B.P. during the maximum cold period of the late Wisconsinan (Prior, 1991). During this period, solifluction removed materials from slopes, particularly in the area of the Iowan Erosion Surface in northeast Iowa (Fig. 4). In central Iowa, these processes removed parts of the Yarmouth-Sangamon paleosol and the Farmdale Soil from upper landscape positions and deposited them in topographic lows on the landscape. These materials are termed Wisconsinan colluvium in this guidebook.

Beneath the loess or colluvium unit is a thick (~ 80 m), Pre-Illinoian glacial sequence consisting of paleosols, multiple till units, and sand 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 and Kemmis, 1986). Palmquist et al. (1974) identified two Pre-Illinoian till units in the vicinity of Ames. Gibbons (1995) recognized as many as three Pre-Illinoian till units separated by sand and gravel units. Pre-Illinoian till units are somewhat finer-grained than the late Wisconsinan till units above them and averages (N=7) 36 percent sand (std. dev.=4.7), 39 percent silt (3.3), and 25 percent clay (3.6) at the Ames Till Hydrology Site (Simpkins and Parkin, 1993). A Yarmouth-Sangamon paleosol is commonly found at the top of the uppermost Pre-Illinoian unit (Hallberg, 1986). Recent work by Woida and Thompson (1993) has shown that this paleosol is formed in both Pre-Illinoian till and in the Loveland loess of Illinoian-Sangamonian age.

## Pre-Illinoian Sand and Gravel Aquifers

Central Iowa contains an extensive network of bedrock valleys (Fig. 6) that have been identified and studied for nearly 100 years (Twenter and Coble, 1965; Hansen, 1985; Iowa DNR, unpub-

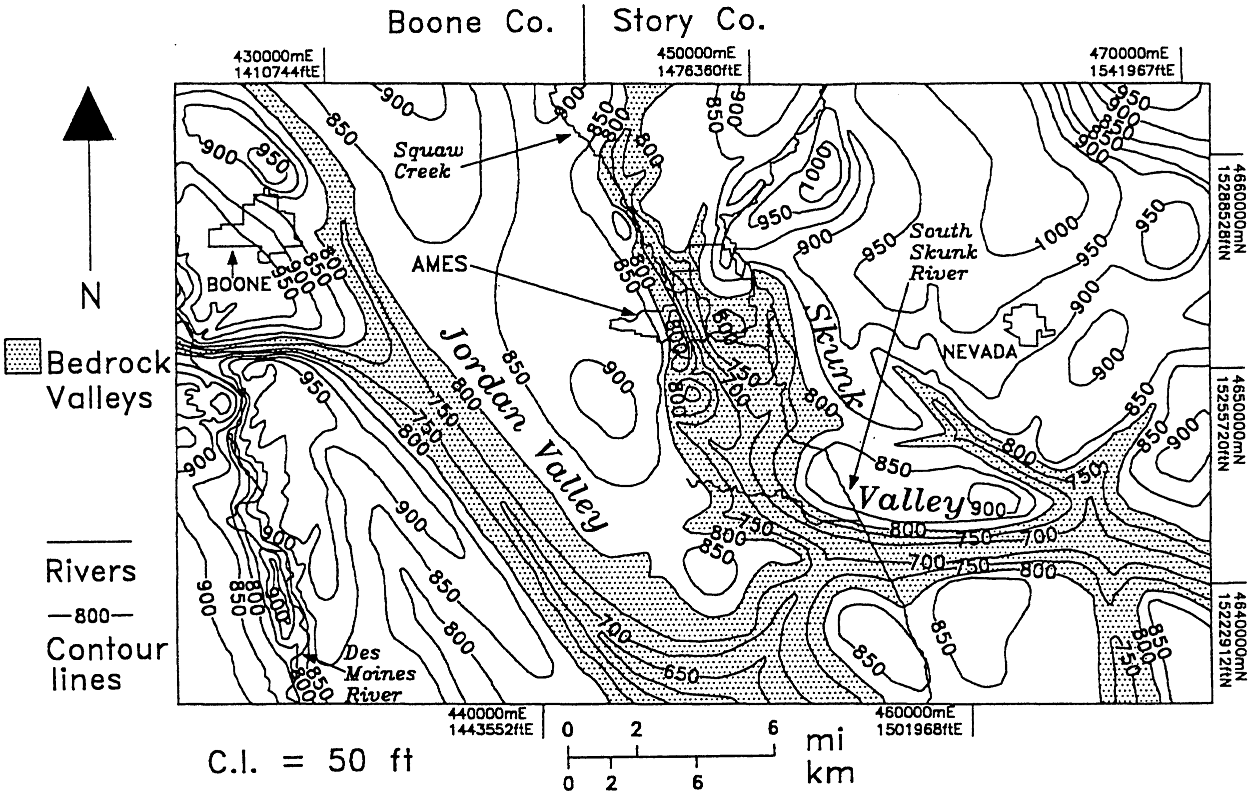

**Figure 6.** Bedrock valleys of central Iowa (from Gibbons, 1995). The Walnut Creek watershed is underlain by part of the buried Skunk Valley.

lished). The exact placement of the valleys in the subsurface involves considerable geologic interpretation of sparse well data; hence, the positions of the valleys are continuously updated as new data are received. Most recently, the buried valleys have been investigated as potential sources of groundwater for municipal supply. A large buried valley just south of Ames, comprising part of what is known as the "Ames Aquifer", provides nearly 70 percent of the water supply for that city. The buried valleys were probably pre-glacial stream valleys that later served as meltwater channels during the Pre-Illinoian glaciations and, in some cases, late Wisconsinan glaciations. For example, the present course of Squaw Creek and the Skunk River within and just north of Ames lie above the bedrock valleys (Fig. 6); these bedrock valleys are known as the Squaw and Skunk channels, respectively (Hansen, 1985). The two major bedrock valleys shown on Figure 6 are the Jordan Channel, which trends northwest-southeast across the Boone-Story county line, and the Skunk Channel, which officially begins south of Ames and then swings eastward towards the Story-Marshall county line. The Skunk Channel underlies the eastern edge of the Walnut Creek watershed.

Although it is generally thought that most of the buried valleys contain coarse sand and gravel, in fact, they mostly contain thick sequences of Pre-Illinoian till. (Fig. 7). Collectively, the sand and gravel units supply most of the landowners in the Walnut Creek Watershed and environs with drinking water (Simpkins et al., 1993a). Two recognizable sand and gravel units occur within the Pre-Illinoian section generally at depths of 34 to 38 m and about 69 to 76 m below the ground surface. These aquifers were termed the buried valley aquifer (BVA) and the upper sand and gravel aquifer (USGA) by Gibbons (1995).

The BVA is closely associated and aligned

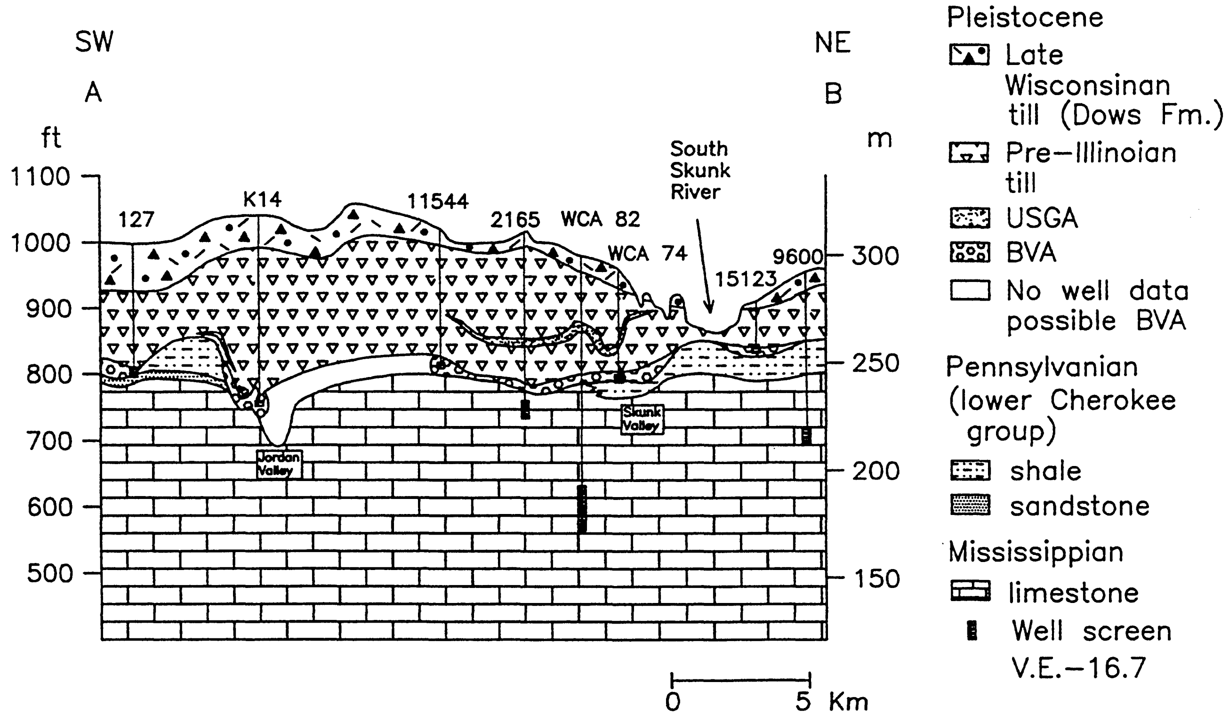

**Figure 7.** Southwest to northeast trending cross section of major geological units in central Iowa (from Gibbons, 1995).

with the buried bedrock valleys and it is usually absent on subsurface bedrock highs. The lateral continuity of the units suggest that they probably represent outwash deposits and outwash terraces. K values have been estimated for 18 wells in the USGA by Gibbons (1995). He found that geometric mean $K = 4 \times 10^{-4}$ m/s (log transformed std. dev. = 0.86), which is the highest K value of any aquifer in the region. Chemical samples indicate that this aquifer contains a Ca-HCO$_3$ to CaSO$_4$ type water with significant concentrations of dissolved Fe (Simpkins et al., 1993a), which suggests that Fe-reduction is occurring. Overall, the concentrations of ions in this water suggest a composition that is most like the adjacent limestone aquifer.

The USGA shows very little spatial relationship to the buried valleys and is more laterally discontinuous; it may represent outwash deposits that have been subsequently eroded or that were deposited on a surface that contained melting ice. No K data are available for this aquifer, although it can be presumed that the values would be similar to the BVA. Groundwater in the USGA shows high concentration of dissolved Fe and CH$_4$ and low to non-detectable concentrations of SO$_4$, all of which suggest the geochemical processes of Fe-reduction, SO$_4$-reduction and methanogenesis are occurring in the aquifer (Simpkins et al., 1993a; Simpkins and Parkin, 1994). This hydro-geochemistry is most like that found in the overlying late Wisconsinan till and loess units.

The locations of groundwater recharge and discharge for the USGA and BVA are not well known. Direct vertical recharge may occur through the overlying till, and some may come from unknown recharge areas further to the north where the units may lie at shallower depths. Gibbons (1995) also suggested that recharge to the BVA comes from the adjacent Mississippian bedrock aquifers, based in part on the much higher K values in the BVA and the similarity of the hydrogeochemistry between the BVA and adjacent bedrock aquifers. Corrected $^{14}$C dates from the buried valley aquifers suggest that the water is generally less than 15,000 years old (Qiu, 1993), which is considerably younger than groundwater in the adjacent bedrock aquifer. Stewart et al. (1988) suggested that these valleys carried subglacial meltwater from the Des Moines Lobe. The "younger" age of these waters could perhaps be accounted for if there was still a large volume of glacial meltwater in the aquifer.

## Hydrogeologic Properties of Confining Units

Quaternary sediment has always been considered to be an effective confining unit (aquitard) overlying the major bedrock aquifers in central Iowa and a barrier to contamination. However, recent studies (Kross et al., 1990) have shown showed that $NO_3$-N can be detected in about 18 percent and pesticides in about 14 percent of the domestic wells in the state. Contamination routes through till units are not clear; however, recent studies in central Iowa suggest that contaminants may be transported through till fractures or poor well construction. The till itself is probably more permeable than we originally assumed. K values of the oxidized late Wisconsinan till are on the order of $10^{-4}$ to $10^{-5}$ m/s, which approaches the K values of some aquifers (Simpkins and Parkin, 1993; Seo and Simpkins, 1995). Recently-recharged groundwater is common in this unit (Qiu, 1993). The potential for contamination of the underlying aquifers is greatest where oxidized till directly overlies bedrock. The oxidized till is also the major water-bearing unit in contact with Walnut Creek and could transport contaminants into the creek.

Unoxidized till and loess comprise a greater thickness of sediment underlying the watershed. K values for unoxidized late Wisconsinan till of the Dows Formation are much lower ($10^{-8}$ to $10^{-9}$ ms) than those for oxidized till. K values for the Wisconsinan loess are similar to those in unoxidized till (see discussion in Seo et al., this guidebook). Average vertical linear velocities are on the order of cm/year through these units (Simpkins and Parkin, 1993), groundwater is old (Qui, 1993), and the redox potentials are unfavorable for preservation of $NO_3$-N (Parkin and Simpkins, 1995); therefore, unless the till is thin, no significant contamination of underlying aquifers should occur. K values of the unoxidized Pre-Illinoian till are less than the till units above and approach $10^{-11}$ m/s (Simpkins and Parkin, 1993). The bulk density of this material is often greater than 2 g/cm$^3$, probably a result of compression by later ice advances in the region and perhaps some diagenetic changes. Although vertical hydraulic gradients are often large in this unit (> 1.0), vertical velocities are less than 1 cm/yr. Redox conditions, although not as severe as those in the Wisconsinan units, are probably unfavorable for preservation of $NO_3$-N.

## Holocene Stratigraphy and Landforms

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 Ames Till Hydrology Site 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 12,500 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 sand and gravel (deposits of the Noah Creek Formation) and Holocene alluvium of the DeForest Formation. 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 (part of the DeForest Formation). Further modifications of the channel were made (by humans) during recent times and perennial streamflow is maintained by tile drains that empty into the creek.

## SUMMARY AND CONCLUSIONS

The geological and hydrogeological setting of the Walnut Creek watershed and central Iowa consists of Paleozoic bedrock aquifers and confining units overlain by Pleistocene till, loess, colluvium, and paleosol units that act as effective confining units. Pre-Illinoian sand and gravel aquifers of Pre-Illinoian age also supply water to many residents in the watershed. Hydraulic, hydrogeochemical, and groundwater age data suggest that the potential for contamination of the bedrock and sand and gravel aquifers from agricultural activities is minimal. Contamination of Holocene units and the oxidized late Wisconsinan till of the Dows Formation can be expected because of their proximity to the land surface, higher K values, and, in the case of till, the existence of fractures.

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# STOP 1

# QUATERNARY STRATIGRAPHY OF THE WALNUT CREEK WATERSHED

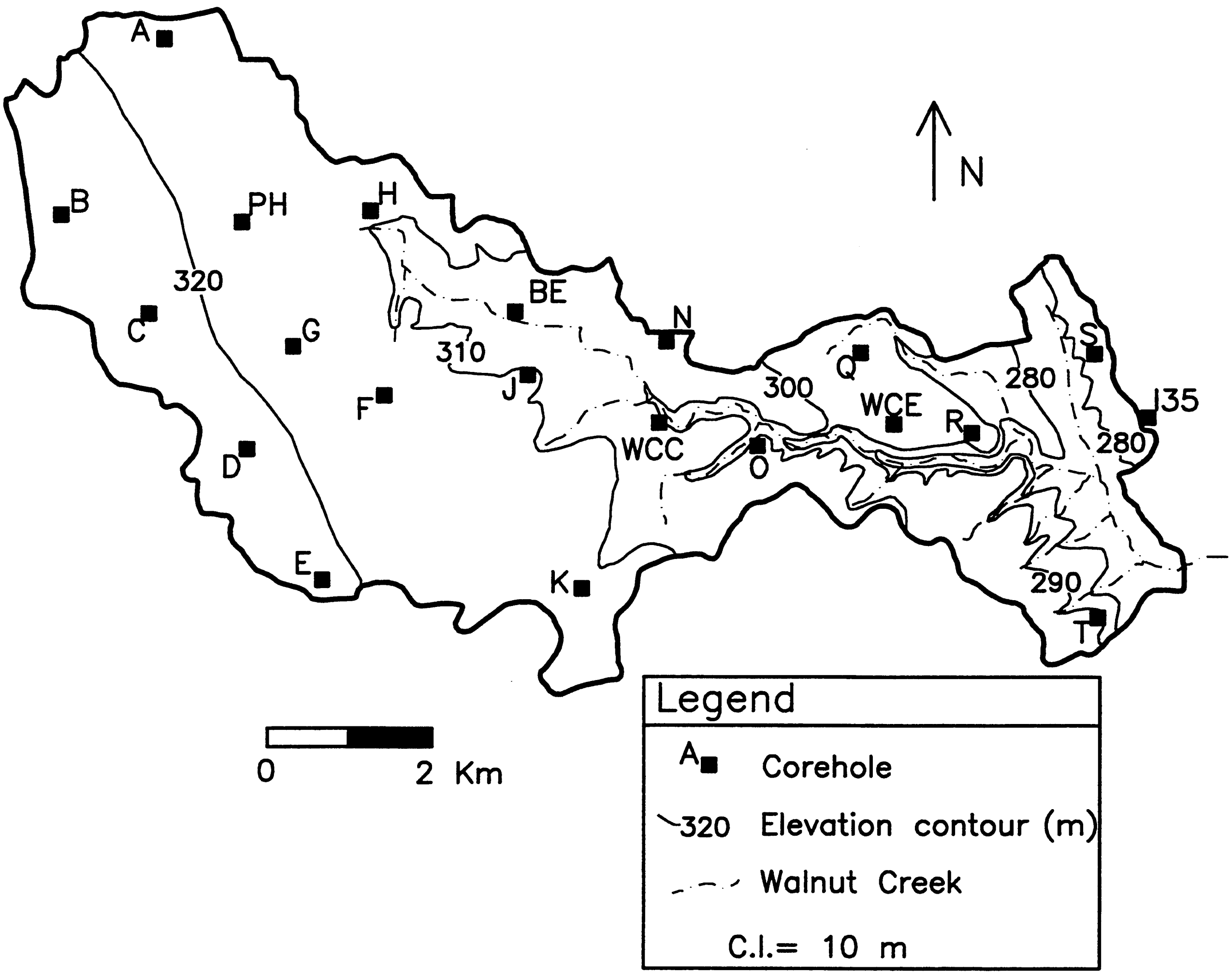

Figure 8. Location of coreholes and generalized surface topography in the Walnut Creek watershed.

# QUATERNARY STRATIGRAPHY OF THE WALNUT CREEK WATERSHED

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## INTRODUCTION

Quaternary stratigraphic units comprise the major water-bearing strata in the Walnut Creek watershed. Their physical and chemical properties likely control the groundwater flow, recharge rate, hydrogeochemistry, and groundwater quality. The purpose of this article is to describe the Quaternary stratigraphy in the watershed, characterize the major units, and interpret their lateral and vertical distribution. The relationship of the units to groundwater flow is discussed at Stop 3.

## METHODS

Seventeen continuous core samples were collected at sites located throughout the watershed during the fall of 1994 (Fig. 8). Upon retrieval, each core was measured, described, and wrapped with plastic wrap and foil in the field. In the lab, Munsell color, reaction to HCl, fractures, mottling, consistency, clast mineralogy, and depth to lithologic contacts were recorded. Units were classified using the standard weathering zone terminology for Quaternary sediments in Iowa (e.g., oxidized (O), unoxidized (U), reduced (R), jointed (J), and leached (L) or unleached (U); Hallberg et al., 1978). Core descriptions from previous (Johnson, 1995; Parkin and Simpkins, 1995) and unpublished studies in the watershed were used along with the descriptions of new core. Each lithologic unit was subsampled for particle size analysis (sand: 0.063 to 2 mm; silt: 0.002 to 0.063 mm; and clay: < 0.002 mm) and analyzed by the pipette method (Walter et al., 1978). We used a Global Positioning System (GPS) unit to locate corehole locations. Absolute elevations (relative to mean sea level) were surveyed, using a total station, from local U.S. Geological Survey benchmarks.

## RESULTS AND DISCUSSION

### Characterization of Stratigraphic Units

Our investigation has identified at least 4 time-stratigraphic units, 6 lithostratigraphic units, and 2 pedostratigraphic units underlying the Walnut Creek watershed. The youngest unit, consisting of alluvial deposits of the DeForest Formation of Holocene age (<10,500 years B.P.; Bettis, 1990; Prior, 1991) occupies areas immediately adjacent to Walnut Creek and are a minor part of the surficial material within the watershed. This stratigraphic unit was not examined in detail for this investigation and will not be discussed further here. Diamicton (till) of the Dows Formation of late Wisconsinan age (deposited 14,000 to 12,500 years B.P. in Iowa; Prior, 1991) comprises the dominant surficial unit in the Walnut Creek watershed. Particle size percentages of the diamicton average (standard deviation in parenthesis; N=42) 48 percent sand (4.1), 36 percent silt (3.5), 16 percent clay (2.6). Percentages are extremely consistent with depth (Fig. 9a-c), which suggests that this diamicton is basal till of the Alden Member. This interpretation is consistent with previous work on landform and sediment genesis in the region (see discussion in the previous section; Kemmis et al., 1981). The average thickness of the unit in the watershed is 7.2 m. The maximum thickness of 12.2 m occurs at site J and the minimum thickness of 3 m occurs at site S (Fig. 8). Drilling data support the hypothesis that the thickness of the oxidized till is related to the present landscape position. Hillslope summits have the thickest oxidized zones, whereas footslopes near drainages often lack an oxidized zone.

The late Wisconsinan till is fairly uniform in characteristics throughout the study area. The

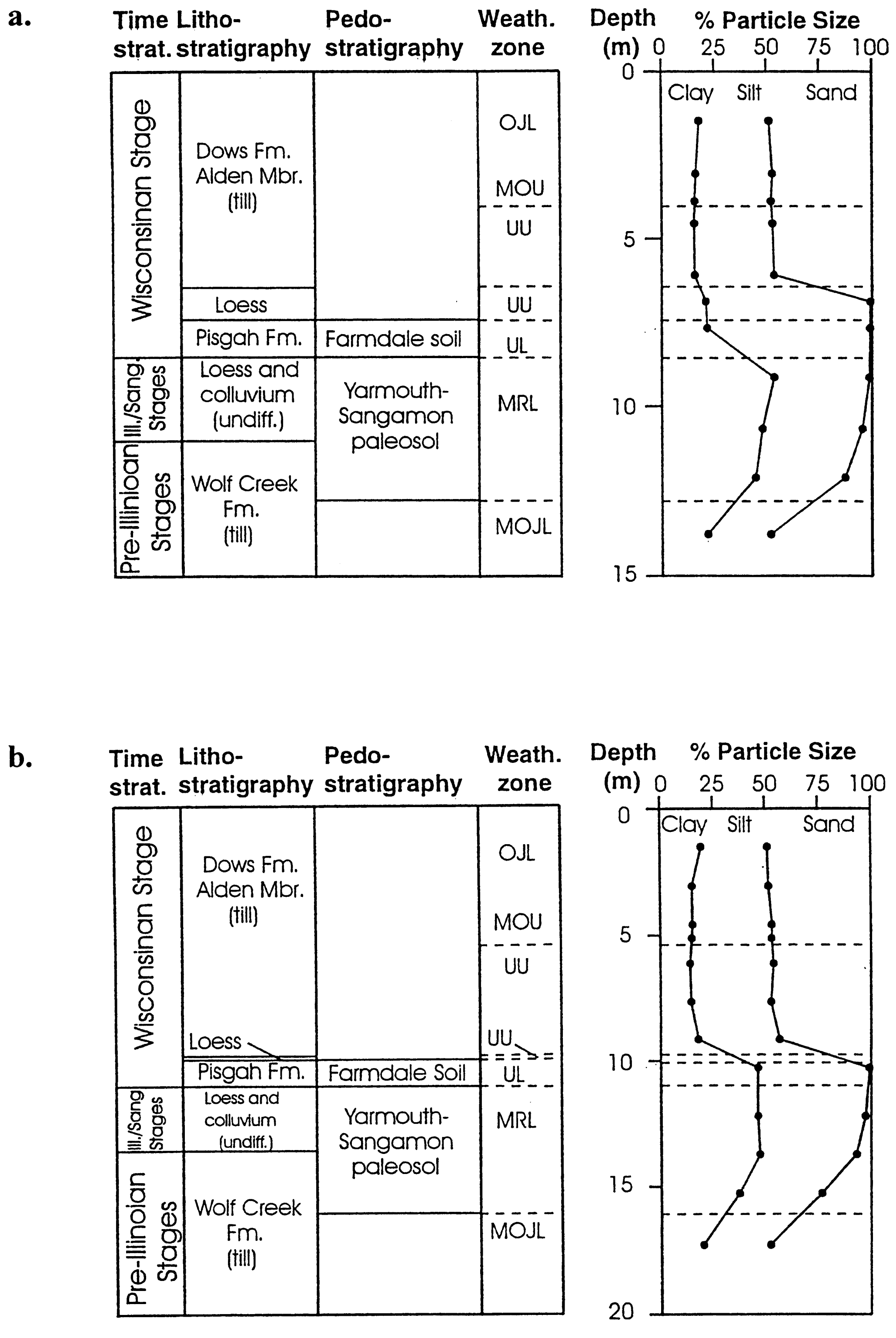
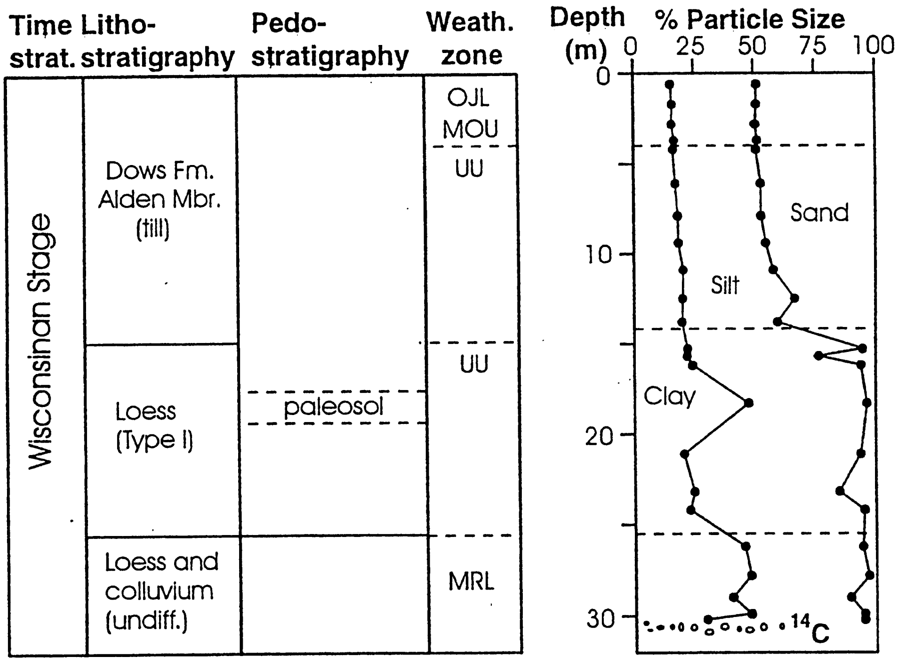


**Figure 9.** Quaternary stratigraphic nomenclature, particle-size data, and weathering zone terminology for a) Corehole B, b) Corehole D, and c) Corehole WCC (see Figure 8 for location). The $^{14}C$ date on organic carbon near the bottom of WCC is 21,900 ± 180 years B.P.

c.



upper 3 to 5 m is generally weathered (oxidized) and bulk densities are approximately 1.7 to 1.8 g/cm$^3$ (Lutenegger, 1990). The oxidized till exhibits matrix colors from light olive brown (2.5 Y 5/4) to dark yellowish brown (10 YR 3/6) and it is generally leached of carbonate (OL) to a depth of 1.5 m. Dominant pebble lithologies consist of Precambrian granite, Cretaceous shale, and Mississippian limestone. Yellowish-brown (10 YR 5/8), Fe-oxide stained zones and light brownish gray (2.5 Y 6/2) zones of Fe-depletion and calcite accumulation are common at depths < 3 m and suggest water movement along fracture planes (Fig. 10a). Fractures coated with thicker coatings of Fe-oxide, mottles, and manganese occur more frequently at depths > 3 m. A transition zone occurs between the oxidized and unoxidized zone and averages 0.5 m thick. It is characterized by light olive brown (2.5 Y 5/3) to grayish brown (2.5 Y 5/2) colors. Reduced colors (RJU) are often seen in this transition zone. Fractures are predominantly subvertical in orientation and are coated with yellowish brown (10 YR 5/6) Fe-oxide; however, the fractures here are not as densely spaced as in the oxidized till above. The underlying unoxidized, unleached (UU) till is very dark gray (2.5 Y 4/1 to 3/1) and its average thickness in the watershed is 3.6 meters. Bulk density of the till unit is usually greater than 1.9 and the unit is overconsolidated and compact (Lutenegger, 1990). Fractures commonly occur only in the upper 1.5 m of this unit; however, a subhorizontal fracture stained with Fe-oxide and associated with 18-cm-wide, light-gray, oxidation halo was encountered at a depth of 13 m at Site J (Fig. 10b).

Wisconsinan loess (equivalent to the Peoria loess in Illinois) underlies the late Wisconsinan till unit in much of the watershed. This unit ranges in age from 17,000 to 14,000 years BP based on previous radiocarbon dates on wood at the nearby Ames Till Hydrology Site (Simpkins and Parkin, 1993) and in the literature (Ruhe, 1969; Kemmis et al., 1981). The loess is dark gray (2.5 Y 4/0), calcareous (UU), and attains a maximum thickness of 4.7 m. Previous drilling data show the presence of two distinct types of loess deposits within the Walnut Creek watershed. Type I loess (Johnson, 1995) contains organic horizons (organic C > 0.5 percent), abundant spruce wood, terrestrial snail shells, small pebbles and generally shows the greater thicknesses. Particle size percentages (N=8) at the Walnut Creek Central Transect (WCC in Fig. 9c) average 9 percent sand (7.0), 66 percent silt (9.9), and 25 percent clay (8.9), and the unit contains up to 5 percent gravel clasts. Visual examination of this sediment in addition to the particle size analysis suggest that it is a diamicton. Although we believe this deposit was eolian in origin, it has been reworked and deposited as colluvium along with till in a wetland environment (Johnson, 1995). Parkin and Simpkins (1995) concluded that organic matter in Type I loess provides a carbon source which stimulates the microbial production of methane ($CH_4$). Johnson (1995) also showed that Type I loess has significantly higher ability to denitrify than other geologic units in the watershed. In contrast, Type II loess is fine grained, massive, homogeneous, and generally has less organic C (< 0.4 percent) than Type I loess. The unit is thinner and averages (N=7) 1 percent sand (0.42), 79 percent silt (1.2), and 20 percent clay (1.2), which is a textural composition closer to the 1 percent sand, 81 percent loess, and 18 percent clay composition typically cited for the Wisconsinan loess (Kemmis et al., 1981).

The Pisgah Formation (Bettis, 1990; Forman et al., 1992), a stratigraphic equivalent to the Roxana silt unit in Illinois, is also present in the watershed. It is represented by a pedostratigraphic unit known in Iowa as the basal (Wisconsinan) loess paleosol or Farmdale Soil. The unit is black (5 Y 2/1) in color and leached of carbonate. The Farmdale Soil averages (N=2) 1 percent sand, 65 percent silt and 34 percent clay in the watershed. We identified the Farmdale Soil in core samples taken from Sites B, C, D, E, H, Q, and T (Fig. 8).

At the Walnut Creek Central Transect (WCC in Fig. 8), a sample from an organic accumulation at 30 m depth and within what appears to be Yarmouth-Sangamon paleosol material (Fig. 9c) yielded a $^{14}$C date 21,900 ± 180 years B.P. (Beta-85923). This date is consistent with dates on the Farmdale Soil in the region (Woida and Thompson, 1993), but the sediment averages (N=5) 5 percent sand (3.6), 52 percent silt (9.3) and 43 percent clay (7.7) - a textural composition closer to that cited for the Yarmouth-Sangamon paleosol. The date on the organic material is probably correct and its appearance within Yarmouth-Sangamon paleosol material may be the result of erosion and re-deposition of the Farmdale and Yarmouth-Sangamon paleosols into lower paleo-landscape positions before loess deposition began in earnest during the late Wisconsinan. This will be discussed again in the next section.

A thick clay-rich unit, attaining thicknesses up to 5.7 m, was encountered primarily in the western reaches of the watershed. Based on its stratigraphic position, particle size distribution and gradation into the Pre-Illinoian till unit below, we interpret this pedostratigraphic unit to be the Yarmouth-Sangamon paleosol. This unit is a composite soil which formed at the land surface from about 600,000 years B.P. into the period of loess deposition that began about 31,000 years B.P. The paleosol is generally gray (2.5 Y 5/0), contains krotovinas, and is mottled and leached of carbonate (MRU). Although the unit averages (N=15) 11 percent sand (10.4), 46 percent silt (10.4), and 43 percent clay (7.9) (see Fig. 9a, b), the parent material of this paleosol is not the same throughout the watershed. The above particle size distribution reflects a parent material of Pre-Illinoian till of the Wolf Creek Formation; thus, the lower part of the paleosol is probably stratigraphically equivalent to Depositional Unit 4 (DU-4) of Woida and Thompson (1993). In contrast, the Loveland loess, which was deposited during the Illinoian and Sangamonian Stages (Ruhe, 1969), was probably the parent material for the upper part of the paleosol found in Coreholes B and D (Fig. 9a, b); hence, this part of the unit would be stratigraphically equivalent to Depositional Unit 3 of Woida and Thompson (1993).

A loamy diamicton unit was encountered stratigraphically beneath the Wisconsinan loess and the Yarmouth-Sangamon paleosol and it showed a yellowish-brown (10 YR 5/6) color and contained pebbles and a dense network of fracture zones and coatings. We interpret this diamicton unit to be till of Pre-Illinoian age. It is probably equivalent to the loam facies of Hickory Hills Member of the Wolf Creek Formation (Hallberg et

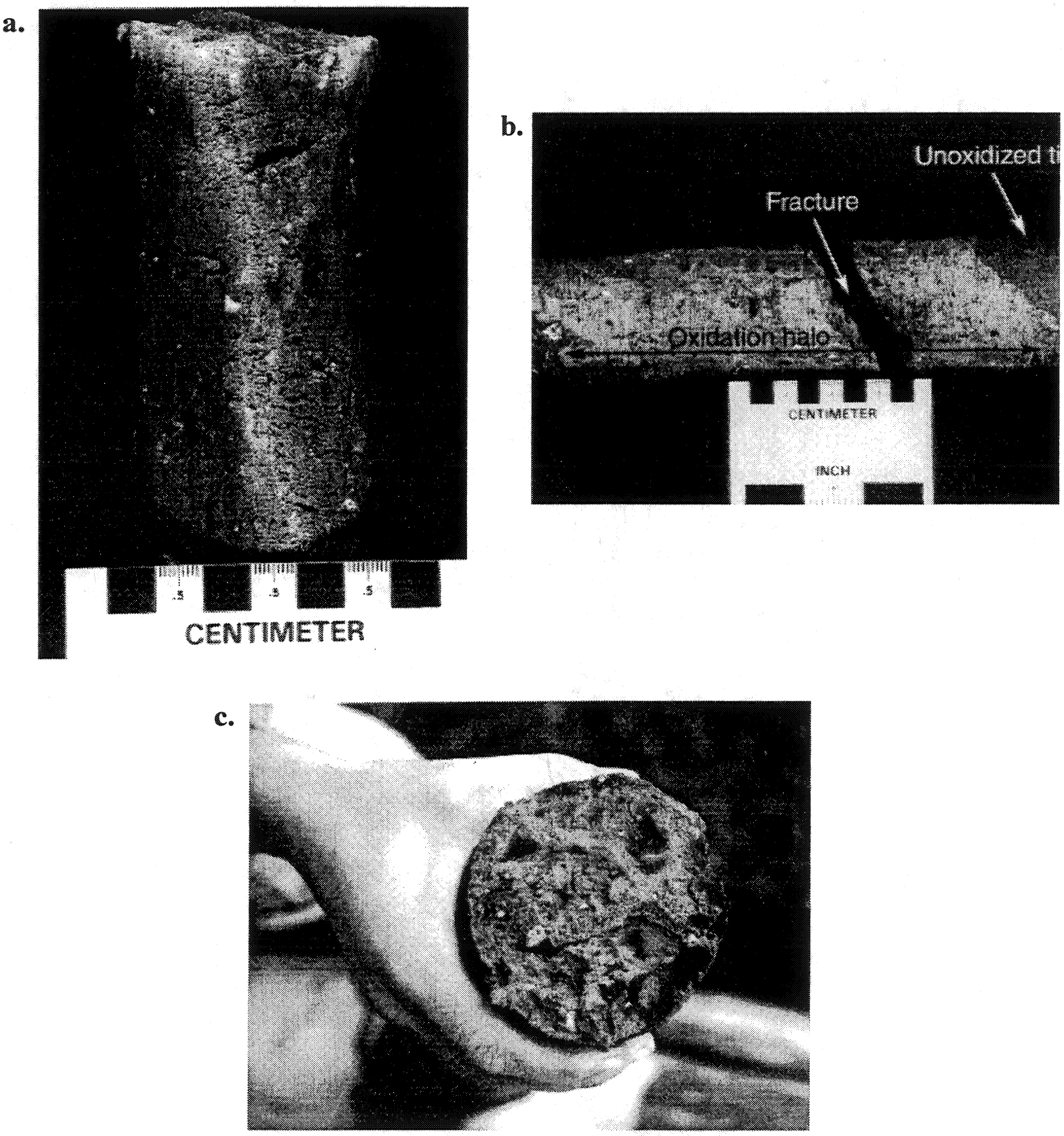


**Figure 10.** Photos of fracture zones encountered in the watershed. (a) Fractures in oxidized till of the Dows Formation at 2.7 m at Corehole PH (see Figure 8); (b) Fracture zone encountered at 14.4 m in unoxidized till of the Dows Formation at Corehole J. Oxidation "halo" emanates 8 cm outward from the fracture surface into the surrounding unoxidized till; (c) Fractures encountered in Pre-Illinoian till at ~ 4.5 m at Corehole WCE. Raised surfaces on core are fracture planes.

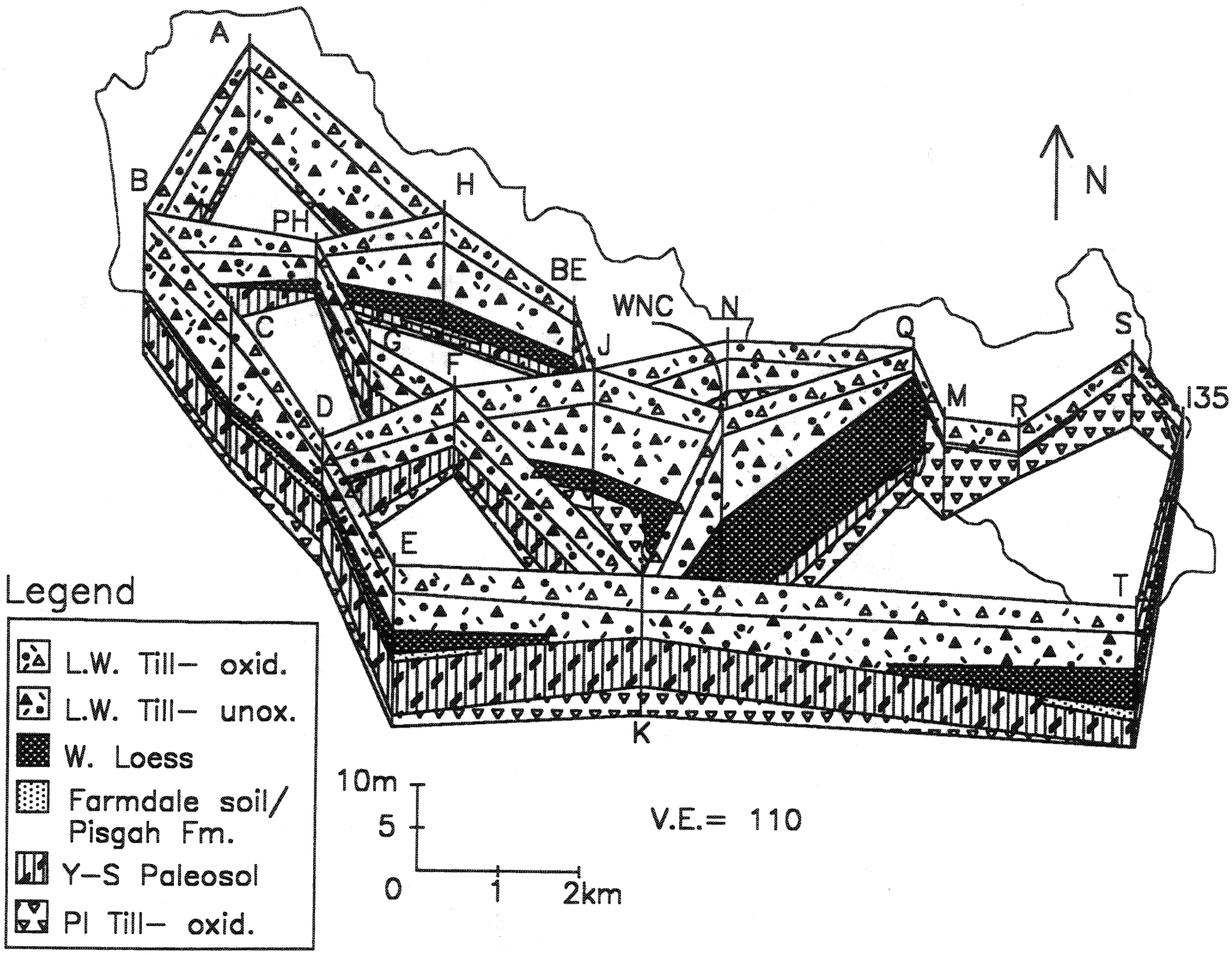


**Figure 11.** Fence diagram showing the distribution of Quaternary stratigraphic units in the Walnut Creek watershed.

al., 1991). Particle size distribution of the till matrix in the watershed averages (N=6) 47 percent sand (3.0), 32 percent silt (4.3), 21 percent clay (1.9) and thus is slightly clayier than the late Wisconsinan till unit. Krotovinas, fractures coated with Fe-oxide, Fe-depleted zones, secondary accumulations of $CaCO_3$, and discontinuous sand units are abundant in the upper 3 m of this unit (Fig. 10c). In contrast to the late Wisconsinan till which shows a maximum of 4 m of oxidation, the upper 15 m of the Pre-Illinoian till unit is generally oxidized - a reflection of a longer period of weathering at the land surface.

## Distribution of Stratigraphic Units in the Watershed

Quaternary stratigraphic units can be traced throughout the watershed and they appear to thicken and thin in a systematic fashion. Corehole data suggest that thickest deposits of Wisconsinan loess and of the oxidized and unoxidized till of the Dows Formation occur near the middle of the watershed in coreholes J, WCC, and Q (Fig. 11). These same units, particularly the Wisconsinan loess, appear to thin towards the margin of the watershed, while the Yarmouth-Sangamon paleosol appears to

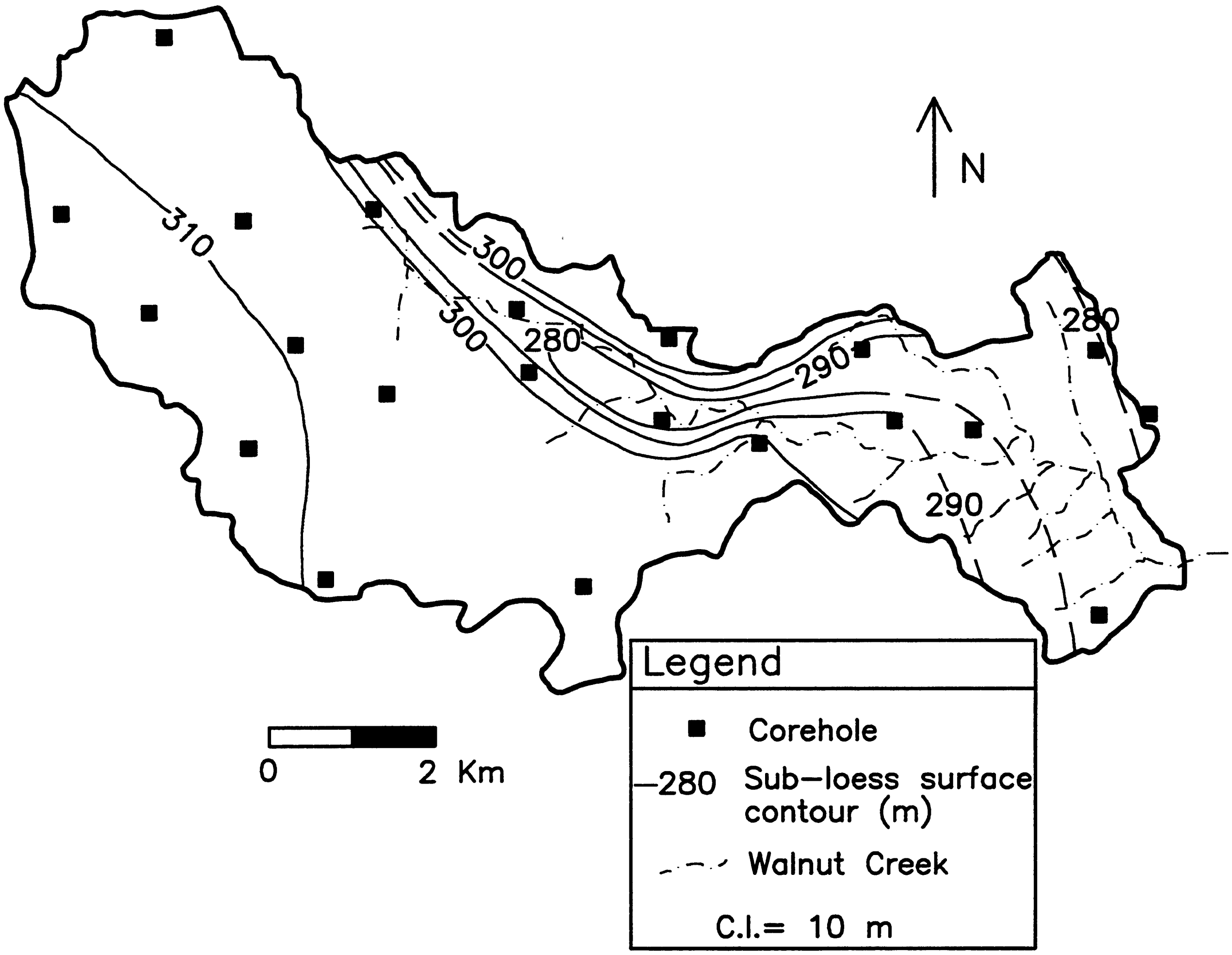


**Figure 12.** Topography on the base of the Wisconsinan loess (Yarmouth-Sangamon-Wisconsinan surface) in the Walnut Creek watershed.

thicken in the same direction (see coreholes Sites B, C, D, E, K and T in Fig. 11). In addition, the Farmdale Soil occurs only atop the Yarmouth-Sangamon paleosol in coreholes C, D, and E on the southern margin of the watershed and does not occur in the central part of the watershed. Finally, the late Wisconsinan till, Wisconsinan loess, and Yarmouth-Sangamon paleosol overlie Pre-Illinoian till in the western part of the watershed. In contrast, oxidized late Wisconsinan till directly overlies oxidized Pre-Illinoian till in the northeastern portion of the watershed.

These relationships suggest to us that paleotopography and subsequent erosion have controlled the distribution the Quaternary stratigraphic units in the watershed. The primary paleotopographic control appears to be a paleo-valley that trends nearly northwest to southeast and is actually aligned along the upper sections of the present Walnut Creek (Fig. 12). The paleo-valley is defined at the top of the composite Yarmouth-Sangamon (and Wisconsinan) geomorphic surface or, in this case, by the depth to the bottom of the Wisconsinan loess unit (the sub-loess surface of Fig. 12). Presence of the Farmdale Soil in the paleo-valley suggests that the valley existed prior to the late Wisconsinan. Similar valleys were recognized by Kemmis et al. (1981), who mapped the Pre-Wisconsinan surface from borings in a 15 township study area just to the east (including the northeast corner of the Walnut Creek watershed). The most prominent paleo-valley trends southward from Ames through eastern part of the Walnut Creek watershed and beneath the present floodplain of the South Skunk River.

Based on our knowledge of the paleo-valley's position, we hypothesized that paleosol units would not be as thick in the central part of the paleo-valley and that they would thicken towards the paleo-divide. The relationships shown in the fence diagram support this hypothesis (Fig. 11); however, the thinning of the Wisconsinan loess near the paleo-divides and thickening into the paleo-valley to thicknesses greater than 10 m (Fig. 13) is somewhat problematic. In addition, the Type I loess (diamicton) of Johnson (1995) occurs primarily in the paleo-valley and not on the paleo-divides. Ruhe (1954; 1969) investigated the effects of paleotopography on loess deposition in southwestern Iowa and other Midwestern states and found that loess deposits thickened on ridge crests and thinned along the ridge flanks. At a study site in Ohio, Hock et al. (1973) found that the thickest loess accumulations occurred in topographic lows that received sediment from adjacent uplands - a setting that is similar to ours in the Walnut Creek watershed. We suggest that the thickness of Type I loess in the paleo-valley is the result of colluvial sediment deposition as well as direct eolian deposition of loess into wetlands that must have existed in this paleo-valley. The valley may have been a groundwater discharge zone for water recharging at the adjacent uplands. We hypothesize that erosion of sediment from the sideslopes and into this valley began to occur during the permafrost conditions that are known to have existed in this region during the glacial maximum at 21,000 years B.P. (Prior, 1991). Erosion removed some of the Farmdale paleosols and deposits of the Pisgah Formation from the sideslopes, mixed them in with the older Yarmouth-Sangamon paleosol and Pre-Illinoian sediments, and then redeposited them. This scenario explains how sediment with a 21,900 years B.P. date (a Farmdale Soil date) can occur within a deposit that looks like a Yarmouth-Sangamon paleosol. Wisconsinan loess deposition began in earnest at about 17,000 years B.P. and the climate began to warm enough by 16,500 years B.P. to support the growth of coniferous forests. Loess continued to be eroded from the topographic highs and blown into wetlands, where it accumulated along with organic carbon.

The paleo-valley may still have existed when Des Moines Lobe ice advanced into central Iowa. It is unlikely that the surging Des Moines Lobe did much erosion of the paleo-valley based on the widespread preservation of paleosols at the top of the Wisconsinan loess (Kemmis et al., 1981; E.A. Bettis III, verbal comm., 1996). The presence of thicker till in topographically low spots suggests that either deposition was greater in low areas or that the till was better preserved there (Fig. 14). Significant erosion of the till probably occurred during the mid-Holocene (Walker, 1966). In addition, the alignment of the present drainage of Walnut Creek with the paleo-valley suggests a relationship between them, although data are insufficient at this time to substantiate this hypothesis. A summary of the Quaternary geologic events in the watershed is given in Figure 15.

## SUMMARY AND CONCLUSIONS

Six Quaternary lithostratigraphic units (within 4 time-stratigraphic units) underlie the Walnut Creek watershed. They consist of Holocene alluvium of the DeForest Formation, the late Wisconsinan till of the Dows Formation, the Wisconsinan (Peoria) loess, a basal Wisconsinan loess (Pisgah Formation), Loveland Loess (as parent material), and Pre-Illinoian till. Two pedostratigraphic units, the Farmdale Soil within the Pisgah Formation and the Yarmouth-Sangamon paleosol, are formed in loess and till units. The thickness and spatial distribution of the units were controlled by: 1) development of a paleo-valley in Pre-Illinoian time or during the development of the Yarmouth-Sangamon paleosol, 2) erosion of loess and paleosol material off paleo-hillslopes during

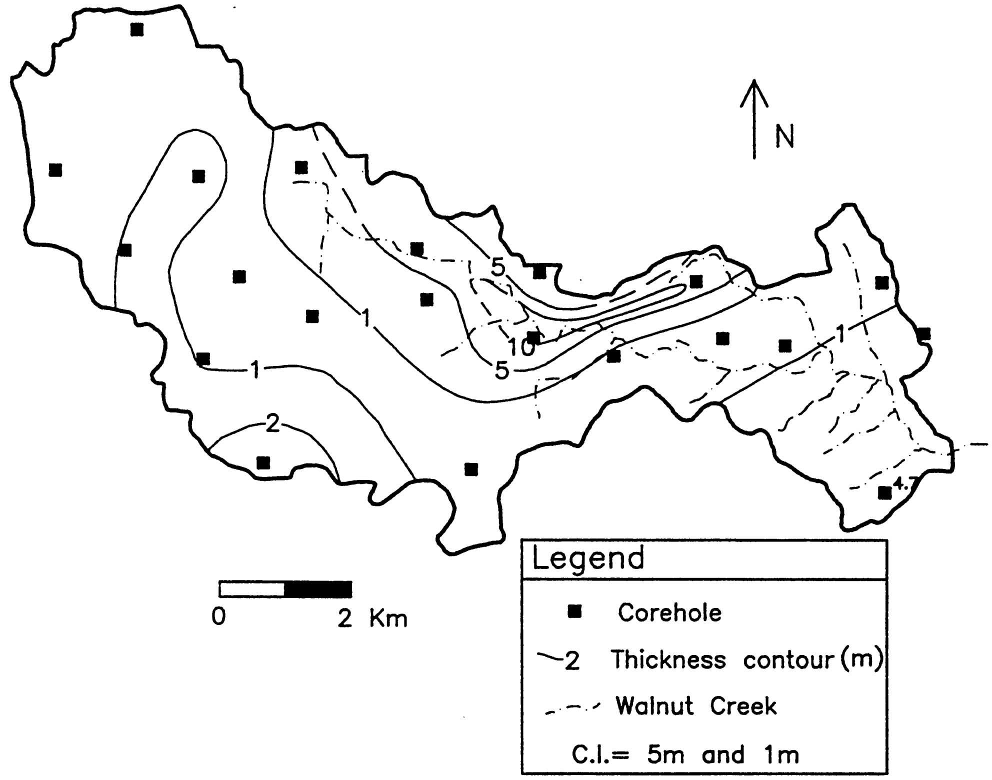


**Figure 13.** Map showing the thickness of the Wisconsinan loess in the Walnut Creek watershed. Dashed contour lines indicate estimated extent of the loess.

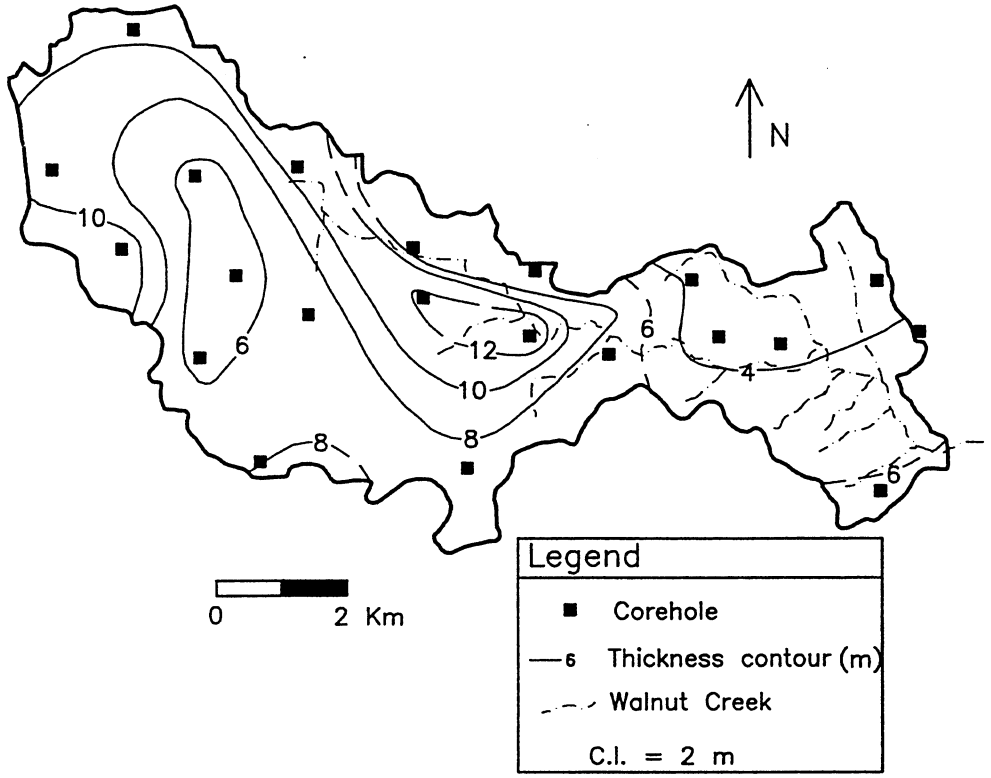


**Figure 14.** Map showing the thickness of till of the Dows Formation in the Walnut Creek watershed. Dashed contour lines indicate estimated extent of the till.

periglacial conditions that occurred between 21,000 and 16,500 years B.P., and 3) deposition of colluvium and loess into the paleo-valley between 17,000 and 14,000 years B.P. The Des Moines Lobe ice advanced into the area at about 14,000 years B.P., deposited late Wisconsinan till, and covered over the paleo-landscape.

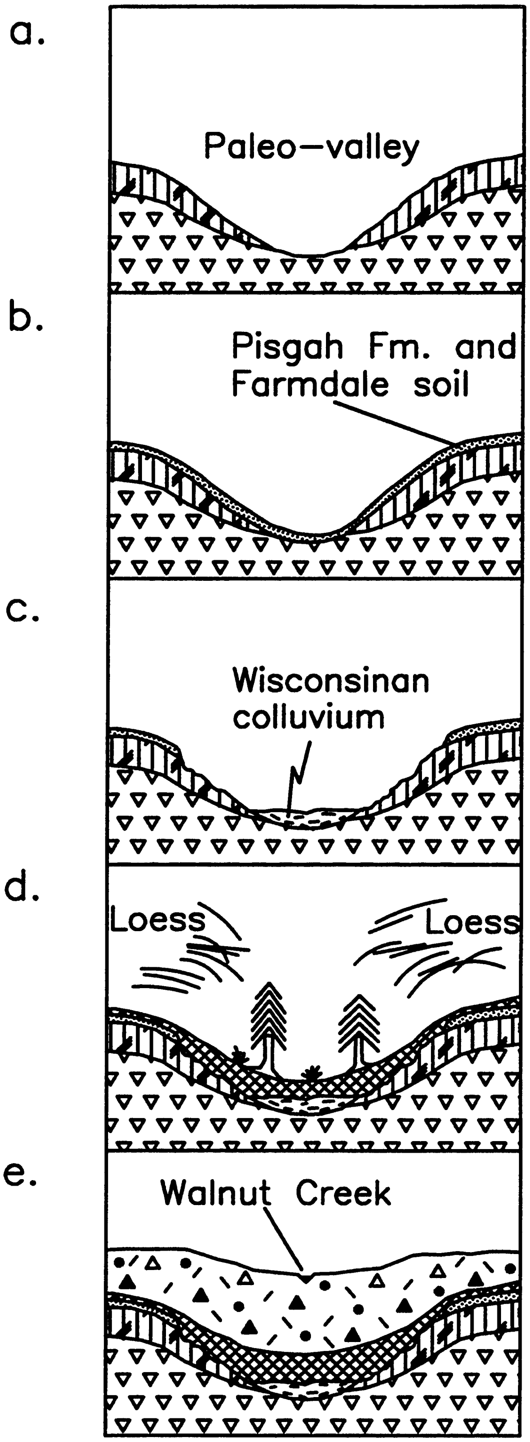


**Figure 15.** Hypothesized sequence of events that produced the stratigraphic relationships in the Walnut Creek watershed: a) development of paleo-valley and the Yarmouth-Sangamon paleosol on the Pre-Illinoian till and Loveland loess; b) deposition of the Pisgah Formation and development of the Farmdale soil at about 22,000 years B.P.; c) accelerated landscape erosion on topographic highs beginning after the glacial maximum at 21,000 years B.P.; d) Wisconsinan (Peoria) loess deposition on uplands, continued erosion, deposition of colluvium and loess into the valley, and wetland/spruce forest development; and e) advance of the surging Des Moines Lobe, deposition of the Dows Formation during Wisconsinan time, and development of Walnut Creek during the Holocene.

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# STOP 2

# HYDROLOGY AND WATER QUALITY OF SUBSURFACE TILE DRAINAGE

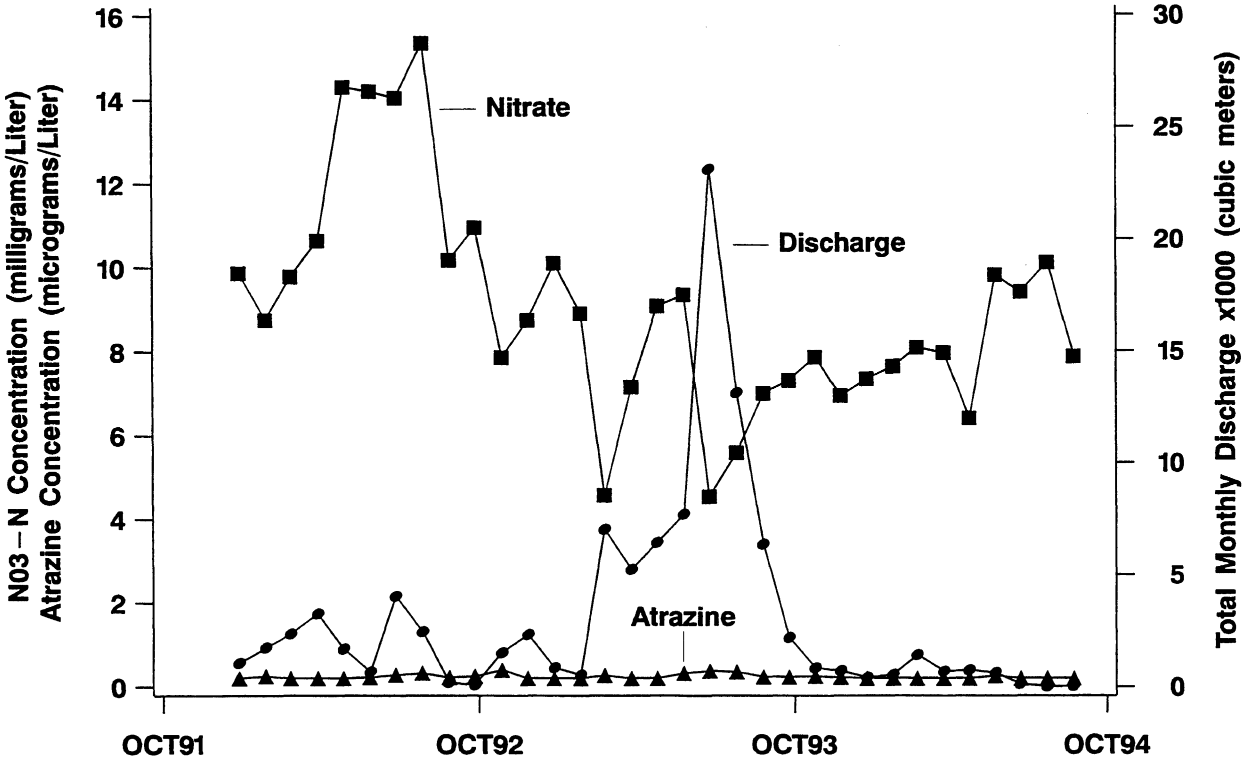

**Figure 16.** Total monthly discharge and average monthly concentrations of $NO_3$-N and atrazine from a tile draining a closed depression in the watershed.

# HYDROLOGY AND WATER QUALITY OF SUBSURFACE TILE DRAINAGE

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## INTRODUCTION

Subsurface tile drainage is an integral part of the hydrology and water quality of the Walnut Creek watershed. At this stop, we will view a tile drain that has been monitored since 1990. The tile drains a closed depression (a "prairie pothole") of 8.5 ha that is located just over the small hill to the southwest. We will see the depression as we drive through the road intersection south of this stop. There are two tile drainage systems of interest. One tile drains the depression and it has no surface inlet; hence, flow in this tile drain is dependent on moisture conditions in the pothole. A larger county tile drainage system, which is the receptor of discharge from many smaller tile drains, is represented by the surface inlet in the ditch. The inlet is covered with a slotted cast iron sieve. Discharge through the county tile drain occurs during most of the year.

## METHODS

Instruments for measuring discharge and automatically sampling tile water are somewhat different than for a standard stream-gaging station. All the instruments here are set inside the corrugated steel cylinder. An inverted siphon has been installed in the 20-cm-diameter tile drain to assure a continuously submerged portion of the tile for discharge measurements and water sampling. A Marsh-McBirney Flotote® instrument has been installed in the siphon to measure velocity. A pressure transducer measures the head in the siphon and the head is calibrated to the depth of water in the tile. Both velocity and head measurements are recorded at 5-minute intervals on a datalogger and converted to discharge values. A water sampling line is connected to an ISCO™ automatic sampler so that a 1 L sample is collected after 57 $m^3$ of discharge have passed through the tile drain. A sample of tile drainage water is also taken by hand on a weekly basis. Discharge is measured and water quality samples are obtained further down the tile drain where it comes to the surface (see Stop 4).

## RESULTS AND DISCUSSION

Data from the tile draining the depression are typical of tile drains with no surface inlets. In general, discharge peaks, when they occur, are more subdued than their surface inlet counterparts. This tile drain showed a nearly-continuous record of discharge during the 1991-1994 monitoring period (Fig. 16). A long period of standing water in the depression resulted in larger discharges during 1993 than in previous years. $NO_3$-N concentrations generally increased with increases in discharge, which was not the case at some other tile and stream sites in the watershed. This relationship suggests there is still enough $NO_3$-N stored or produced in the system that water moving through shallow subsurface flow or through groundwater can transport it to the tile drain. In contrast, the March and July discharge peaks in 1993 corresponded to a decrease in $NO_3$-N concentration, which may indicate that the flux of water passing through the soil was sufficiently great to dilute NO -N concentrations.

Atrazine concentrations were close to or less than the quantitation limit of 0.2 µg/L during 1991 to 1994. In contrast to the $NO_3$-N data, however, an increase in discharge in 1993 was accompanied by a slight increase in atrazine concentrations. This relationship may be the result of soil water from infiltration mobilizing atrazine that had been sorbed on solid particles. It is significant to note that small but discernible increases in atrazine concentration occurred in February and November 1992 and in March 1993. These dates are several months after the spring period of chemical application. Although the concentrations and loads of atrazine were not large at this site, it is clear that this chemical can persist for several months in the soil and in concentrations sufficient for quantitation.

## STOP 3

# GROUNDWATER FLOW AND WATER QUALITY IN THE WALNUT CREEK WATERSHED

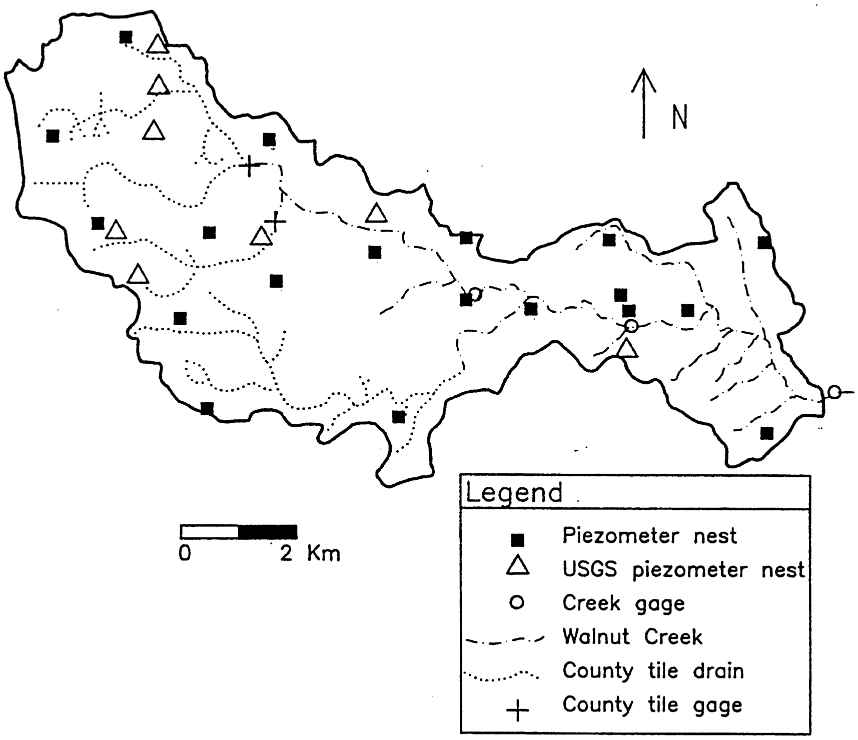

**Figure 17.** Location of piezometer sites, creek and tile gaging stations, and county tile drains in the Walnut Creek watershed.

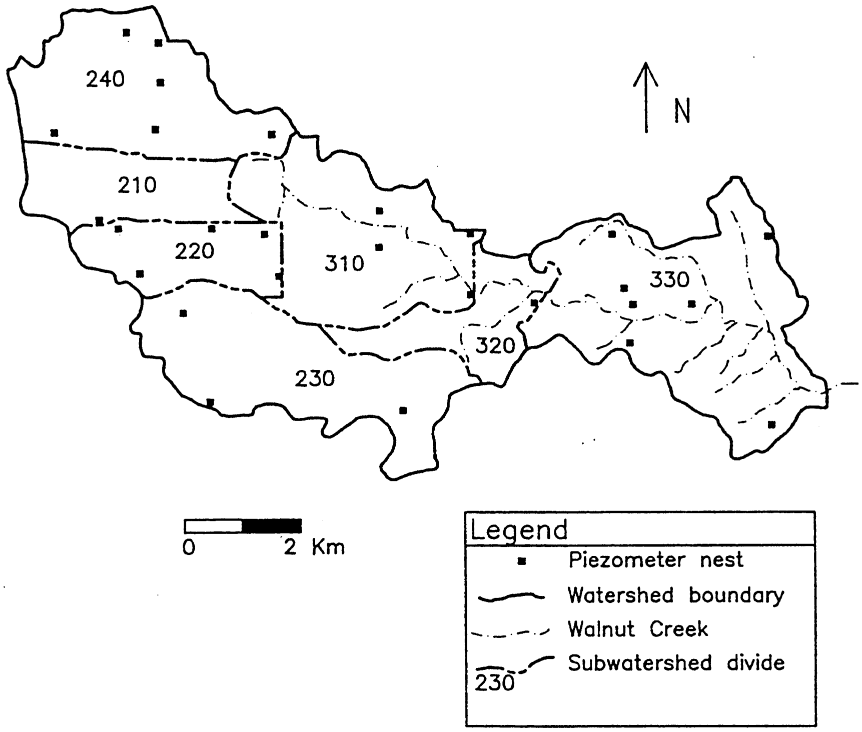

**Figure 18.** Subwatersheds delineated within the watershed.

# GROUNDWATER FLOW AND WATER QUALITY IN THE WALNUT CREEK WATERSHED

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## INTRODUCTION

In contrast to many earlier studies that emphasized field-scale or "plot" research, a major focus of the Walnut Creek watershed project is to examine the effects of agricultural practices on water quality at the "watershed" level. Recent articles have suggested that the watershed scale is perhaps the most appropriate one at which to investigate water quality and to implement land use changes that will improve water quality (Hallberg, 1995). The objective of this study is to characterize the groundwater flow in and water quality of the Walnut Creek watershed.

A study of groundwater flow and water quality in the Walnut Creek watershed presents a unique challenge. First, the "watershed" is set within the very low-relief topography of the Des Moines Lobe in central Iowa, where surface-water divides are nearly invisible on the landscape. Given the scope and level of funding for our study, it was necessary to assume that the surface-water divide approximates the position of the groundwater divide. Second, the effect of tile drains on "watershed-scale" groundwater flow constitutes a large hydrologic unknown. Tile drains, most of which cannot be located with certainty, totally dominate the hydrology in the upper parts of the watershed (Fig. 17). In fact, tile drain networks define the subwatershed boundaries (Fig. 18). The effect of tile drains at the watershed scale are not well documented. The working concept in Iowa is that an efficient tile drainage system will lower the water table to a depth of 1.5 to 2 m over the entire landscape. Instead of attempting to show the possible effect of all tile drains on groundwater flow, we chose to show the effect of only the larger county tile drains (those fed by smaller field tile drains) and their subwatershed boundaries on the configuration of the water table. The effects of smaller field tile drains were too small to map. Recent studies have suggested that the effect of tile drainage at the watershed scale can be seen only by modeling groundwater flow using an "effective" K that is higher than the "real" K value estimated from field test. The effective K accounts for the infinite permeability of the tile drain and the artificial lowering of the water table (Haitjema et al., 1993). We plan to simulate groundwater flow in the watershed and test this hypothesis in the near future.

Finally, it could be argued that a water table map should not be attempted in a dual-porosity medium such as till. Recent research has suggested that the elevation of the water table and hydraulic potentials in till will be a function of proximity to a fracture (D'Astous et al., 1989; Ruland et al., 1991; Harrison et al., 1993). Quaternary units in this watershed are probably fractured to some degree and those fractures may also transport contaminants differently than porous media (see Helmke and Simpkins, this guidebook). Despite the uncertainties involved, we constructed a water-table map as a means of understanding groundwater flow at the watershed scale. We hypothesized that if a water-table surface could be mapped, then it would tell us something about the groundwater flow systems at that scale. Our water-table map does not imply that fractures are ineffective at the local scale - they certainly are!

**Table 1.** Fertilizer and herbicide applications in 1994 on fields up gradient of piezometer nests specifically discussed in this study. Data for 1995 were not available at the time of this writing. Assume that fields in corn and soybeans in 1994 would have rotated to the alternate crop in 1995. NA = not available.

| Piez. nest | Crop | Fertilizer or pesticide | Application rate | Application method |
|---|---|---|---|---|
| B | corn | anhydrous $NH_3$ | 180 lbs/ac | 25-65-110 (N:P:K) |
| | | Buctril/Atrazine | 2 pt/ac | broadcast |
| | | Harness | 2 x 1 pt/ac | broadcast |
| D | soybeans | NA | NA | NA |
| E | soybeans | Pursuit | 4 oz/ac | broadcast |
| | | Treflan | 1.5 pt/ac | broadcast |
| F | corn | anhydrous $NH_3$ | 178 lbs/ac | 2-150-150 (N:P:K) |
| | | Dual | 2 pt/ac | broadcast |
| | | Extrazine | 4 qt/ac | banded |
| | | Pounce | 6 oz/ac | banded |
| J | soybeans | Assume | 8 oz/ac | broadcast |
| | | Basagran | 1 qt/ac | broadcast |
| | | Blazer | 1 qt/ac | broadcast |
| | | Roundup | 2 oz/ac | broadcast |
| N | corn | N | 100 lbs/ac | 28% liquid |
| | | 2,4-D | 0.5 pt/ac | broadcast |
| | | Banvel | 0.5 pt/ac | broadcast |
| | | Dual | 2 pt/ac | banded |

In summary, we took on a difficult task to produce a water-table map and to understand the groundwater quality of the Walnut Creek watershed. It was, however, a necessary task that will form the scientific framework for understanding the hydrogeological and geochemical processes in the watershed and the basis for future land-use management decisions.

## METHODS

Previous research from the Walnut Creek watershed and the Ames Till Hydrology Site (ATHS) (Simpkins and Parkin, 1993) indicates that agrichemicals occur primarily in the oxidized till of the Dows Formation. Hydraulic head gradient data (Johnson, 1995) and the difference in K between the oxidized and unoxidized till at two transects in the watershed (Seo and Simpkins, 1995) and at the ATHS also suggest that groundwater flows laterally in this oxidized zone and to the creek or tile drains.

Based on this information, we installed piezometer nests consisting of two 3.2 cm ID, Schedule 40, PVC standpipes in the oxidized portion of the late Wisconsinan till at 17 locations in the Walnut Creek watershed (Fig. 17). We determined the depth of the oxidized-unoxidized till boundary in the field from continuous cores that went to depths of 20 m. Boreholes were refilled with bentonite pellets to the bottom of the oxidized till, then filled with gravel after which a 0.9 m long factory slotted screen with 0.025 cm slots was installed at the base of the oxidized zone. A silica sandpack was emplaced to a distance of approximately 0.2 m above the slots. A minimum of 0.6 m of bentonite pellets were used on top of the sandpack to seal the screened interval and to provide a separation between the deeper piezometer and a second piezometer of the same screen dimensions that was installed above it in the same borehole. After emplacement of the second piezometer, the borehole was filled with bentonite to the surface and a protective steel casing was installed with cement. The piezometers were bailed at least 3 times with a inertial pump and then developed again with a peristaltic pump prior to monitoring hydraulic head and water quality. We also performed falling and rising-head slug tests in each piezometer and analyzed the data using the Hvorslev method (1951). These results are discussed in a separate article (see Seo et al., this guidebook).

Elevation control and location of hydraulic head measurements were essential parts of this investigation. To construct a water-table map, all piezometer nests were surveyed to absolute mean sea level and hydraulic head was measured to within 0.002 m with an electric tape. The geographic locations of piezometer nests, creek gaging stations, and county tile drains (Figs. 17 and 18) were determined with a Global Positioning System (GPS) unit and stored in a Geographic Information System (GIS) database (Oersterreich, 1994). Water level measurements from 10 existing piezometers (Buchmiller, 1994) were also used to map the water-table surface (See Fig. 17).

Data on crop type, fertilizer/pesticide use, application rate and method were assembled for areas adjacent to the piezometers in order to examine pathways of groundwater contamination (Table 1). Some sites were in corn and used anhydrous ammonia and herbicide, while other sites were in soybeans and used only herbicide (Table 1). Water quality samples were obtained three times during this study - in March, June, and October 1995. Several liters of standing water were purged from the piezometers prior to sampling with a peristaltic pump and dedicated polyethylene tubing. Samples for $NO_3$-N and $NH_4$-N were acidified in the field with 4.5 N $H_2SO_4$ and kept at ~ 4° C until they were analyzed on a Lachat system. Pesticide samples were collected in 1 L, amber, glass bottles, cooled to ~ 4° C, and analyzed by mass spectrometry for the herbicides of atrazine, alachlor, metolachlor, and metrabuzin that are frequently used in the watershed. Cl samples were filtered with a 0.45 μm filter and analyzed by ion chromatography. Dissolved oxygen (D.O.) samples were collected with a downhole sampling apparatus and analyzed with a portable spectrophotometer in the field. Tritium ($^3H$) activities were determined by direct liquid scintillation counting at the Environmental Isotope Laboratory (EIL) at the University of Waterloo. Activities are expressed in tritium units (TU) where 1 TU is equal to 1 $^3H$ atom per $10^{18}$ hydrogen atoms. The detection limit and precision for direct counting are 6 TU and ± 8 TU, respectively. Rain-equivalent precipitation data for 1995 was recorded at Walnut Creek meteorological station 702 at the WCC nest (Fig. 8). Tile drain discharge and creek stage data were collected by automated gaging stations maintained by the National Soil Tilth Laboratory.

The effects of surface topography, county tile drains, and subwatershed boundaries were considered in mapping the water-table surface. In areas of the watershed where data are sparse, the position of the water table was estimated by subtracting an average depth to the water table of 0.8 m (spring) or 2.7 m (fall) from the elevation of the land surface. Localized water-table mounds probably exist beneath the isolated hills and ridges in the watershed, but these could not be shown at the scale of the water-table map. We assumed that shallow groundwater flows into county tile drains and thus water-table contours "point" up gradient in the vicinity of those tile drains. Subwatershed boundaries (Fig. 18) were treated as local groundwater divides for groundwater flow in the oxidized till. It is not known whether groundwater flow at greater depths is affected by these divides.

## RESULTS AND DISCUSSION

### Groundwater Flow

Our hypotheses concerning hydraulic head relationships in the oxidized till were tested during the first year of observation in 1995. Hydraulic head measurements indicated that the elevation of the water table fluctuates vertically up to 3.5 m during the year. The water table rises in the spring as a result of snowmelt and increased precipitation (Fig. 19) and it may be within 1 m of the ground surface. At the point of maximum elevation, the vertical hydraulic head gradients observed between the upper and lower piezometers are on the order of 0.002 downward - a gradient which is barely detectable under most conditions. We conclude from this relationship that groundwater flow

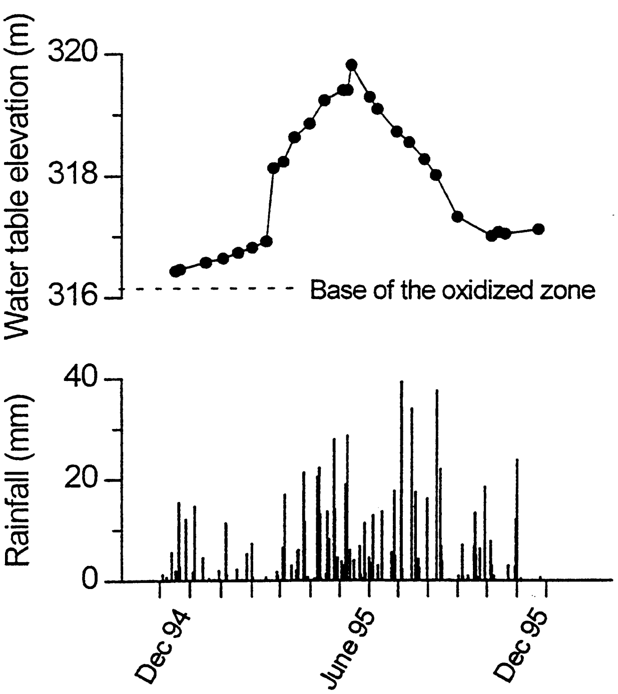

**Figure 19.** Hydrograph of water table fluctuations at Site E in relation to precipitation events in the watershed.

is primarily horizontal in the oxidized till even under groundwater recharge conditions. These results are consistent with those found by Simpkins and Johnson (this guidebook) and Helmke and Simpkins (this guidebook).

Although it is affected locally by subsurface tile drains (Fig. 20), the water table surface slopes towards Walnut Creek during most of the year. Estimated horizontal hydraulic gradients are 0.02 near the creek and tile drains and 0.005 in the upland areas that are away from tile drains. Although precipitation events continue into the summer months, the elevation of the water table steadily declines until the end of the corn and soybean growing season (Fig. 19). This decline, which is coincident with periods of crop growth, is probably the result of water loss through plant transpiration. Groundwater discharge from direct evaporation is not significant mechanism of discharge during these periods, based on isotopic evidence ($\delta^{18}$O and $\delta^{2}$H; see Hendry, 1988) from groundwater both here and at the ATHS.

A watershed-wide drop in the water-table elevation can be seen in late summer and on into fall and winter, where the water table is at a depth of 2.5 to 4 m (Fig. 21). By mid-August, flow in the county tile drains is minimal, suggesting that the water-table surface has fallen below the elevation of the field tile drains. In addition, our initial assumption that the elevation of the water table would fluctuate only in the oxidized till proved incorrect. At sites A, N, O, and T the water table fell below the oxidized/unoxidized contact and saturated conditions did not return to the oxidized till until the following spring. At site C, the water table remained in the unoxidized till during the entire year. We installed a deeper piezometer at this location in the summer of 1995 and found that the water table lay just below the oxidized zone.

Tritium data from the groundwater have been useful in assessing whether the typical spring water-table mounding seen in Figure 19 is the result of vertical infiltration or lateral dissipation of recharge in the groundwater system. Tritium activities ranged from <6 TU to 47 TU and averaged 15 TU. Most groundwater that is in the upper piezometer and nearest the water table shows $^{3}$H activities that are consistent with the modern input value of 11.02 (Simpkins, 1995) for central Iowa (Fig. 22). These data suggest that vertical infiltration occurs quickly in this upper zone every spring and causes this rise in the water table. The existence of recent recharge throughout the watershed and not just at the divides suggests that recharge is distributed, probably unevenly, across the entire watershed. The upper oxidized zone is also the one that shows the most fractures in core and the highest K values (see Seo et al., this guidebook; Seo and Simpkins, 1995). Fractured sediments usually possess very low effective porosities (see Helmke and Simpkins, this guidebook) and low specific yield values (see Seo et al., this guidebook), which could help explain the magnitude of water-table fluctuation.

In addition to containing modern $^{3}$H activities, groundwater shows higher $^{3}$H activities at depth (Fig. 22). These data suggest that groundwater at

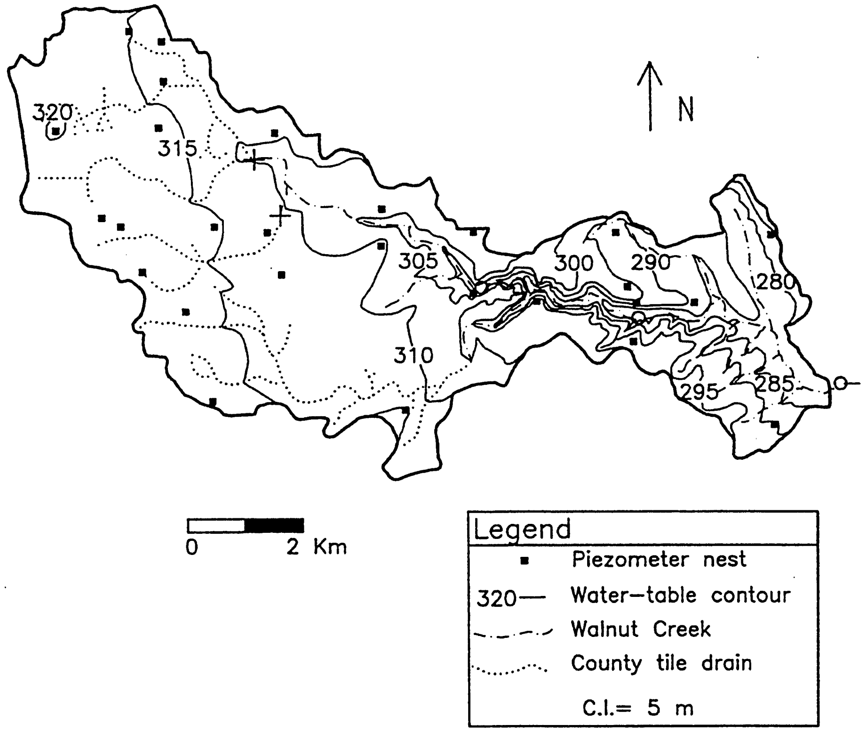

**Figure 20.** Spring 1995 (May) water-table surface in the watershed.

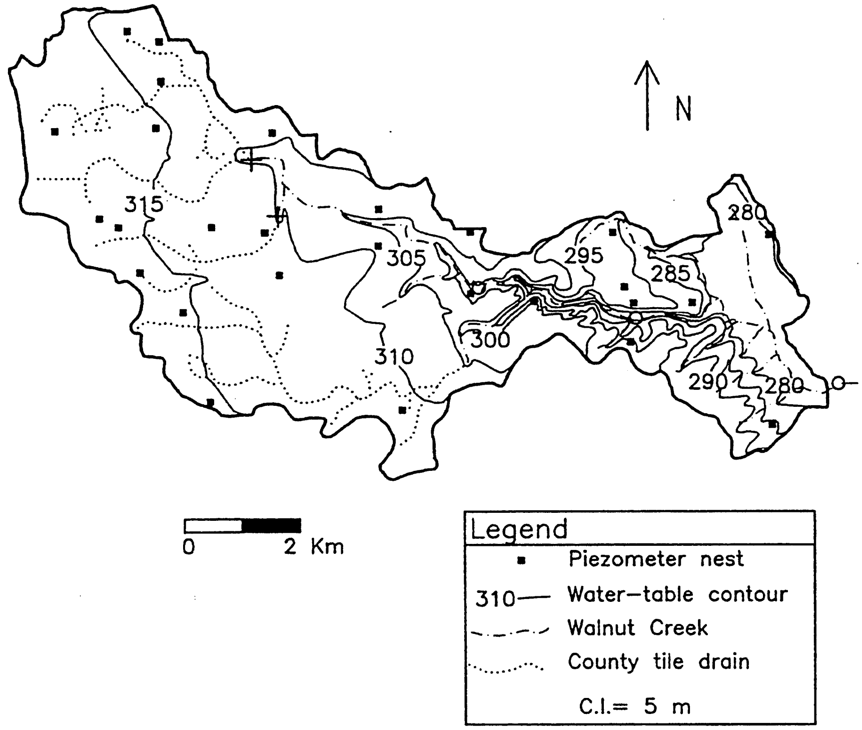

**Figure 21.** Fall 1995 (September) water-table surface in the watershed.

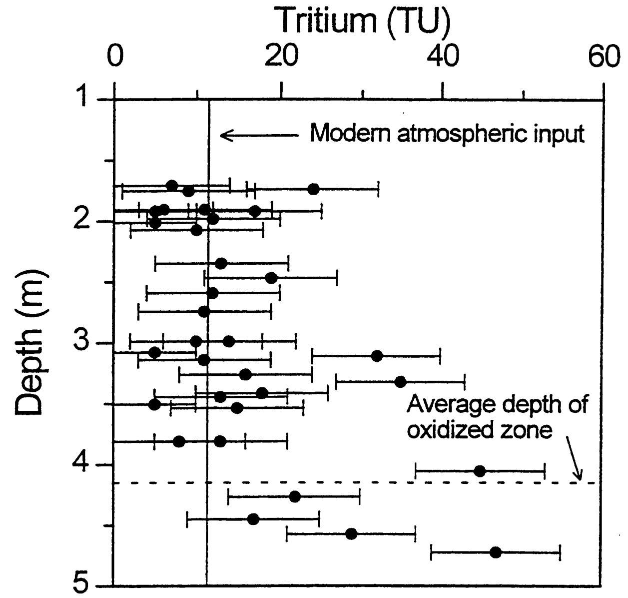

**Figure 22.** Vertical profile of all $^3$H activities in the oxidized till. Error bars show analytical precision. Modern $^3$H activity value is from Simpkins (1995).

the base of the oxidized zone is older than groundwater in the upper part of the oxidized zone. The most straightforward interpretation of data is that the water probably entered the system during the 1980's (assuming the radioactive decay of input concentrations to 1995) and has not moved much since then. Simpkins (1995) demonstrated that it is possible to have modern precipitation in Iowa with $^3$H activities up to 44 TU, so this water may be recent as well. The distribution of the higher activities at the bottom of the oxidized zone and below recent recharge also suggests the deeper water represents the point in time marked by the 1953 "bomb spike." These conclusions are speculative however, because any interpretation is clouded by the problem of matrix diffusion of $^3$H into the till matrix (Ruland et al, 1991). Quantification of the daughter product, $^3$He, and calculation of the original input activity of $^3$H would help resolve this problem. We plan to sample these piezometers for $^3$H/$^3$He and estimate the age of groundwater by this method.

One check on the validity of the $^3$H interpretations can be accomplished by calculating the length of time that groundwater resides in the flow system. We calculated average linear (advective) velocity from Darcy's Law where:

$$v_x = \frac{-K\,i}{n_e}$$

and

K = hydraulic conductivity
i = hydraulic gradient
$v_x$ = average linear velocity
$n_e$ = effective porosity

Estimates of effective porosity range from 0.25 for a bulk till matrix to 0.01 for fracture or mobile porosity (see later article by Helmke and Simpkins, this guidebook). Using a K = 1 x $10^{-5}$ m/s for oxidized till (see Seo and Simpkins, this guidebook) and a horizontal gradient of 0.01 (average from spring and fall), the average linear velocity (horizontal) could range from 12.6 to 315 m/yr. If we use a hypothetical flow line from piezometer nest N to Walnut Creek (distance of 642 m), it would take 2 to 51 years for water entering the flow system at the nearest subwatershed divide to discharge into Walnut Creek. These calculations appear to support our groundwater $^3$H ages and conceptual model of groundwater flow in the watershed.

## Water Quality

Groundwater in the oxidized till has been impacted by agricultural practices in the watershed. Samples collected in 1995 show above-background concentrations of $NO_3$-N, herbicides, and Cl (from KCl fertilizer) and $NH_4$-N has not been detected. The most common contaminants were $NO_3$-N and Cl. Fifty-five percent of the groundwater samples showed $NO_3$-N concentrations > 10 mg/L - the EPA Maximum Contaminant Level for this compound. Highest concentrations occurred during high water table conditions in the spring and early summer, although the seasonal differences in con-

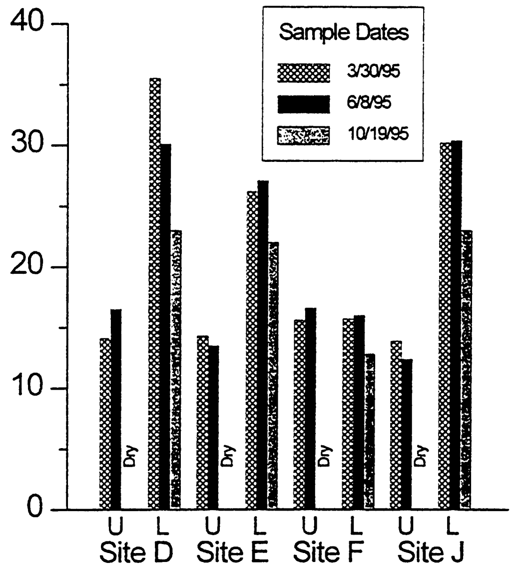

**Figure 23.** Seasonal variation of $NO_3$-N concentrations at selected piezometer sites

centrations were not significantly different in most cases and concentrations were consistently high (Fig. 23). D.O. is present in the oxidized till and shows the highest concentrations in the uppermost piezometer during spring recharge. There is no identifiable trend linking $NO_3$-N concentrations in groundwater with their location in the watershed, so it is likely that $NO_3$-N concentrations are controlled by the proximity of the piezometer to agricultural fields (Table 1) that have received anhydrous $NH_3$ or urea fertilizer. Interestingly, of the sites shown in Figure 23, Sites D, E, and J were in corn, and Site F was in soybeans in 1995.

It is interesting to note that $NO_3$-N concentrations are often higher in the deeper piezometer of the nest than in the shallower one (Fig. 23). This is in contrast to the findings of Johnson (1995), who noted a decrease in $NO_3$-N with depth at her piezometer nests in the watershed. In fact, we found that the higher concentrations of $NO_3$-N in groundwater are often associated with the higher $^3H$ activities and elevated Cl concentrations (Figs. 24a and b). One interpretation of these trends might be that older and slower-moving groundwater at the base of the oxidized till contains more

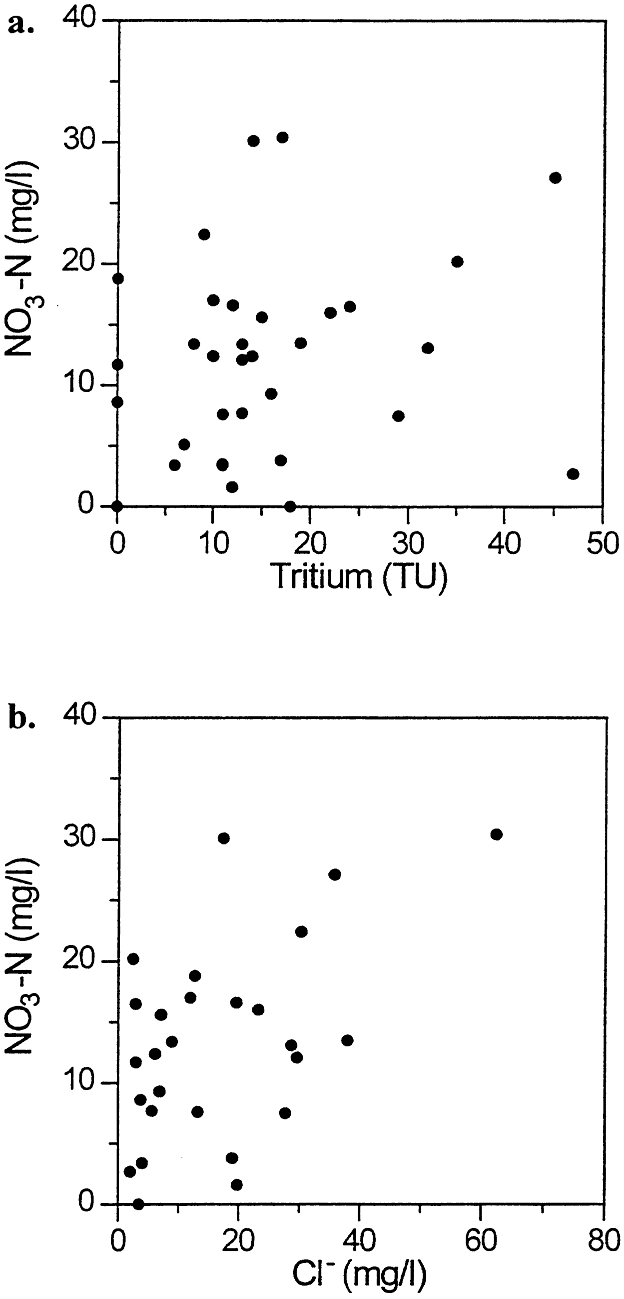

**Figure 24.** Plots of (a) $^3H$ activity versus $NO_3$-N concentration and (b) Cl concentration versus $NO_3$-N concentration. In general, high $NO_3$-N values are associated with higher than modern $^3H$ activities and above-ambient Cl concentrations.

agrichemical contamination that reflect higher application rates in the past. Until we can obtain firmer ages dates on the groundwater, however, this conclusion remains speculative.

Measurable amounts of the herbicides were detected only at Sites N and T out of 45 samples during the study period. At Site N, atrazine (2.9 µg/L) and metolachlor (Dual; 0.8 µg/L) were detected adjacent to a soybean field where only metolachlor had been applied. At Site T, metolachlor was seen at the quantitation limit of 0.2 µg/L, but no application or crop data were available for this field. This percentage is typical of the percent of detections of herbicide found in groundwater within the watershed (see article by Burkart et al. in guidebook).

## SUMMARY AND CONCLUSIONS

Data from a network of 17 nested piezometer sites completed within oxidized till in the Walnut Creek watershed suggest that groundwater recharge is distributed across the basin and that flow is primarily horizontal towards tile drains and towards Walnut Creek. Agrichemicals have significantly impacted the groundwater quality of the till unit. The primary contaminants appear to be $NO_3$-N and Cl; herbicides are infrequently observed. The timing of fertilizer application is generally coincident with the period of maximum groundwater recharge and water-table rise in the spring; thus, recharge water is an effective carrier of chemicals to the groundwater system in the till. Based on preliminary $^3H$ data and average linear velocity estimates, groundwater in the oxidized till is probably no older than 50 years old and may be less than a year old in some parts of the watershed.

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# STOP 4

# HYDROLOGY AND WATER QUALITY OF THE "HEADWATERS" OF WALNUT CREEK

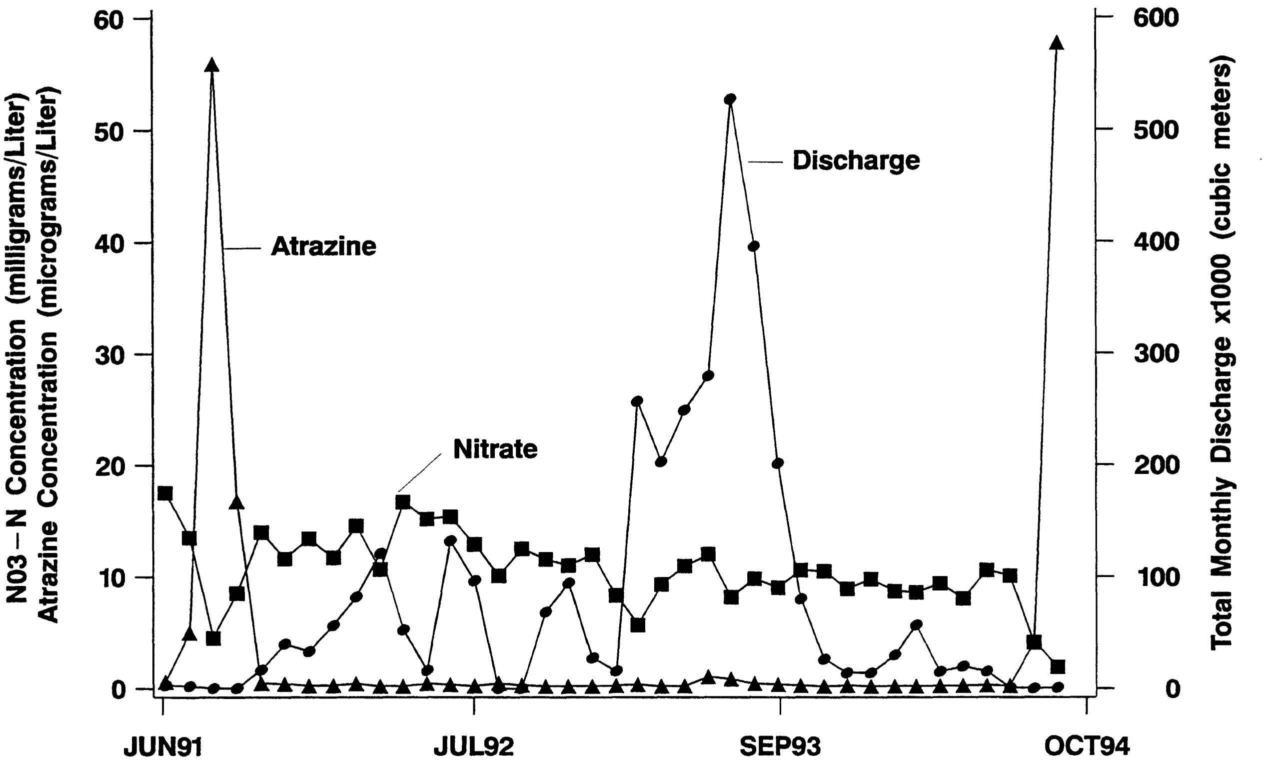

**Figure 25.** Total monthly discharge and average monthly concentrations of $NO_3$-N and atrazine at a tile that drains both field tile drains and surface inlets.

# HYDROLOGY AND WATER QUALITY OF THE "HEADWATERS" OF WALNUT CREEK

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## INTRODUCTION

One of the most unique aspects of the Walnut Creek watershed is that the upper 1/3 of the "watershed" is defined solely on the basis of an integrated network of subsurface tile drains. At this stop, one such tile drain emerges on the north side of the road through the small culvert to become the "headwaters" of a branch of Walnut Creek. A second and larger culvert seen on both sides of the road provides a drain for runoff on the part of the watershed lying south of the road. The record of discharge and water quality from the tile drain, culvert, and stream will be investigated at this location.

## METHODS

This site was instrumented in order to define the discharge and water quality of both tile drainage water and runoff from a subbasin of 366 ha. A 45-cm-diameter tile was fitted with a plastic sleeve to provide a continuously submerged tube in which discharge measurements can be made and water samples obtained. A Marsh-McBirney Flotote™ instrument was installed in the plastic sleeve to measure velocity and a pressure transducer measures the hydraulic head in the sleeve. Both velocity and hydraulic head measurements are recorded at 5-minute intervals on a datalogger and converted to discharge. A water sampling line is connected to an ISCO™ automatic sampler and a 1 L sample is collected after 1,800 $m^3$ of discharge has passed through the tile drain. The stage in the runoff culvert is measured with two float gages and potentiometers installed on the north and south ends of the culvert. An ISCO automatic sampler is programmed to collect a sample for every 9-cm increment of stage change and to collect a sequence of samples throughout runoff events.

## RESULTS AND CONCLUSIONS

Although the larger culvert carries occasional runoff from rainfall and snowmelt, continuous discharge emanates from the tile drain (Fig. 25). Infiltration of soil water presumably sustains flow in the tile throughout most of the year; relatively large discharges follow rainfall or snowmelt events and may include water from surface inlets. $NO_3$-N concentrations generally stayed above the 10 mg/L EPA-MCL and did not vary much between 1991 and 1994. Decreases in concentration to less than 10 mg/L generally coincided with periods of rainfall. This may suggest that soil water was diluted by surface inlet water that contained smaller concentrations of $NO_3$-N than did infiltration; however, note that $NO_3$-N concentrations did not decline appreciably under the large peak discharges experienced during 1993. One reason for the lack of decline may be the mobilization of older $NO_3$-N from the soil or the vadose zone. Evidence supporting this hypothesis comes from a comparison of the 1993 fertilizer application amounts to the total $NO_3$-N load discharged from this subbasin during 1993. The 1993 data indicate that the $NO_3$-N load exiting the subbasin was 150 percent of the total N applied as fertilizer.

Concentrations of atrazine and other herbicides (not shown here) in water from tile drainage water were generally close to or less than the quantitation limit of 0.2 μg/L. The anomalously large atrazine concentrations observed during August 1991 and 1994 were associated with extremely small discharges; these atrazine spikes may reflect the input of small volume point sources associated with surface inlets.

# STOP 5

# HYDROGEOLOGY AND WATER QUALITY AT THE WALNUT CREEK CENTRAL TRANSECT

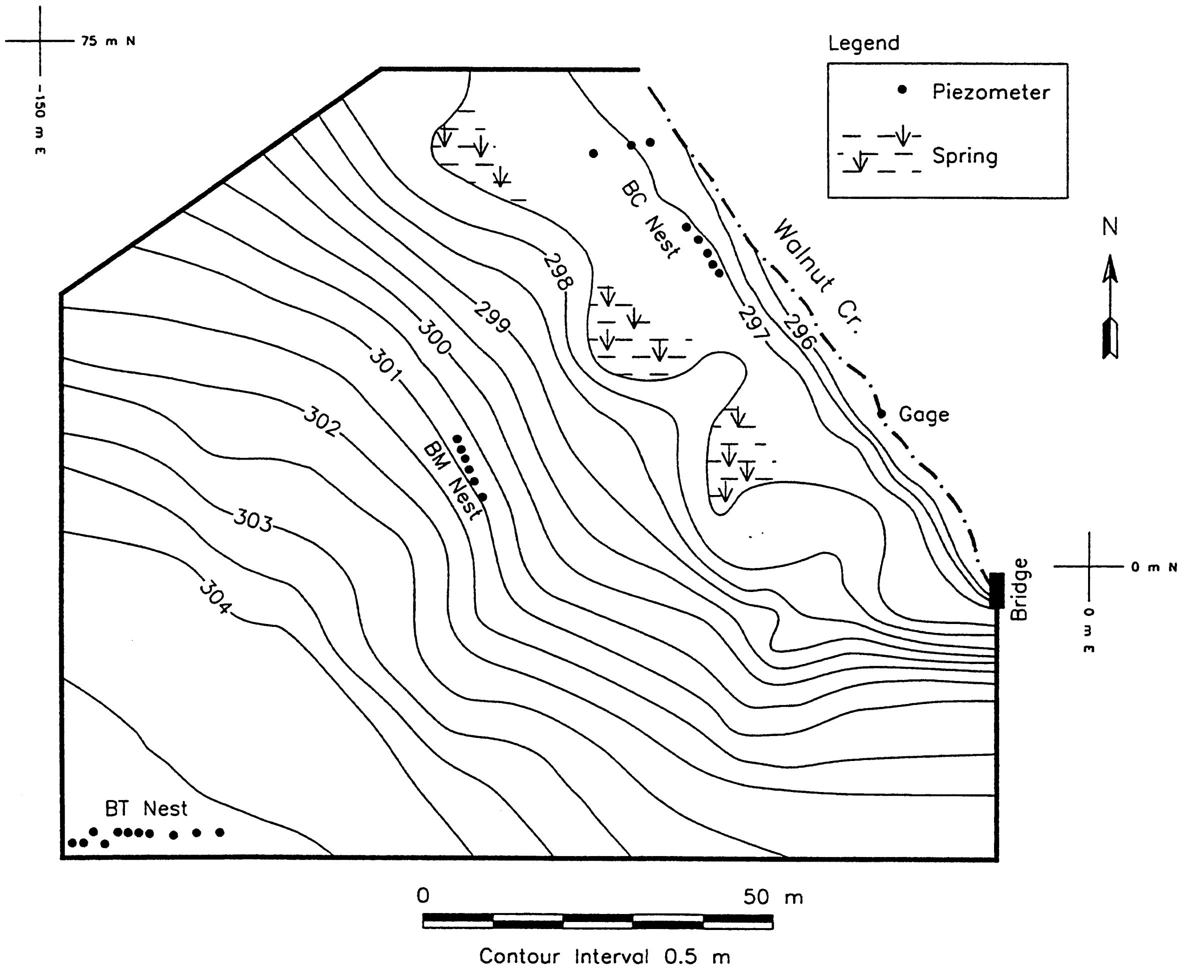

**Figure 26.** Plan view of the Walnut Creek Central Transect site. Topographic contours in meters.

# GEOLOGY AND GROUNDWATER FLOW AT THE WALNUT CREEK CENTRAL TRANSECT

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## INTRODUCTION

Hydrogeological investigations in the Walnut Creek watershed started prior to the installation of the watershed-wide piezometer network discussed by Eidem et al. (this guidebook, Stops 1 and 3). The initial investigation began in the summer of 1993 with the construction of two transects of piezometer nests adjacent to Walnut Creek. The objective was to examine groundwater flow and hydrogeochemical processes at a smaller, more-detailed level and then generalize the results to the watershed.

## METHODS

### Construction of the Central and Eastern Transects

Two sites in the watershed were chosen for detailed investigation. They will be referred to here as the Walnut Creek Central Transect and the Walnut Creek Eastern Transect. At each transect, we characterized the Quaternary stratigraphy, delineated the groundwater flow system, and investigated water quality. The Walnut Creek Central Transect is located in the central portion of the watershed north of Kelley, Iowa, and on the south bank of Walnut Creek (WCC in Fig. 8). The land use at this site is pasture and it is adjacent to a field cropped with continuous corn. We hypothesized a groundwater flow path to the creek and three piezometer nests, installed at the top slope (BT) and midslope (BM) positions and adjacent to Walnut Creek (BC), are aligned along that flow path (Fig. 26). The transect contains 26 piezometers, ranging in depth from 1.5 to 30 m. A 40-m-deep piezometer was installed north of Walnut Creek in order to investigate the hydraulic head relationships in the Pre-Illinoian till and the potential for vertical transport of $CH_4$ in that unit.

The Walnut Creek Eastern Transect is located 2 km east of the Central Transect on the north side of Walnut Creek (WCE in Fig. 8). The transect was constructed in the eastern part of the watershed where Walnut Creek has incised into the Pre-Illinoian till. Deposits of the Holocene DeForest Formation are found within the floodplain in this section. Four piezometer nests were installed at the top slope (VF) and midslope (VM) positions and on the floodplain adjacent to Walnut Creek (VAN and VAS). The entire piezometer transect is aligned along a hypothesized groundwater flow path to the creek. The piezometer nests contain 30 piezometers that range in depth from 1.5 to 30 m. The land is used primarily as pasture for livestock at the farm. The field immediately up gradient from the VF nest is cropped in corn and soybean rotation and receives annual applications of fertilizers and/or herbicides based on the crop for that year. The pasture land containing the VM, VAN, and VAS nests receives applications of manure from the farm. The Walnut Creek Eastern Transect will not be discussed in detail in this guidebook, except for the interaction of groundwater and surface water that is discussed at Stop 6.

### Piezometer Installation

We constructed the piezometer transects during the Fall of 1993 using the overcored Shelby tube method, a non-traditional piezometer installation technique designed to minimize perturbation of the microbial environment and to avoid smearing of fractures in the screened interval (McKay et al., 1993) (Fig. 27). Six angled (45°)

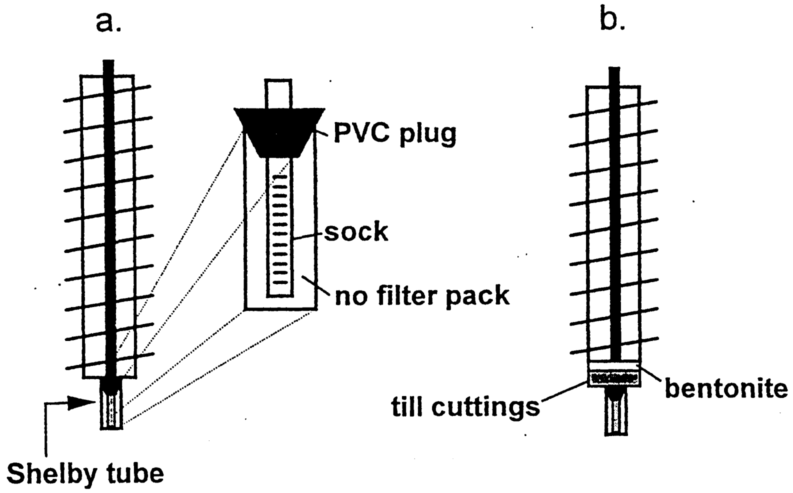

**Figure 27.** Schematic diagram depicting the overcored Shelby Tube piezometer installation technique. Description of (a) and (b) given in text.

piezometers were also installed using the overcored Shelby method at each transect. Three angled piezometers were installed 1.5, 3, and 4.5 m underneath cropped fields at each transect in order to intersect vertical fractures in till. Three were also installed 1.5, 3, and 9 m below the bottom of Walnut Creek at each site in order to determine hydraulic gradients between the creek bed and underlying geologic units.

Boreholes were drilled using 11 cm ID hollow stem augers. A continuous core was obtained at the deepest piezometer at most piezometer nests to identify the geologic units present. Core samples were retrieved with a 1.5 m long, 7.6 cm ID split core barrel and wrapped in plastic wrap and aluminum foil for storage in core boxes. Auger flights and core barrels were washed and decontaminated with water of known composition between boreholes. No drilling fluids were used. Piezometers were installed by augering 1.5 m above the desired piezometer depth, at which point a standard 7.6 cm ID, Shelby tube, either 75 or 90 cm in length, was pushed into the screened interval area (Fig. 27a). The sample was retrieved and sealed with paraffin in the Shelby tube. Next, an outward flared (0.3 cm flare) Shelby tube was sent down the inside of the auger to ream and scrape the original Shelby tube hole. The flared Shelby tube was pushed an additional 0.15 to 0.3 m in order to collect the scraped cuttings.

Piezometers consisted of 3.2 cm ID, Schedule 40, flush threaded, PVC pipe with Timco Deka-Seal™ threads and O-rings. Factory slotted (0.05 cm slot), flush-threaded, 0.76 m long Schedule 40 screens were wrapped in nylon geotextile socks prior to installation. The socks were used in place of a filter pack. A specially designed 8.9 cm diameter PVC plug was attached between the screen and riser pipe (Fig. 27a). This plug was placed into the top of the Shelby tube hole to create a barrier between the screened interval and the bentonite seal. Approximately 0.3 to 0.5 m of dried till cuttings were placed above the plug creating an additional barrier between the bentonite seal and the screened interval (Fig. 27b). The cuttings were dried on portable propane stoves during the drilling process. Approximately 1 m of bentonite pellets or chips was placed above the till cuttings. A bentonite grout mixture was pumped into the remaining annulus with a tremie pipe to the ground surface. Grout was spiked with KBr to assess the long term integrity of the piezometer

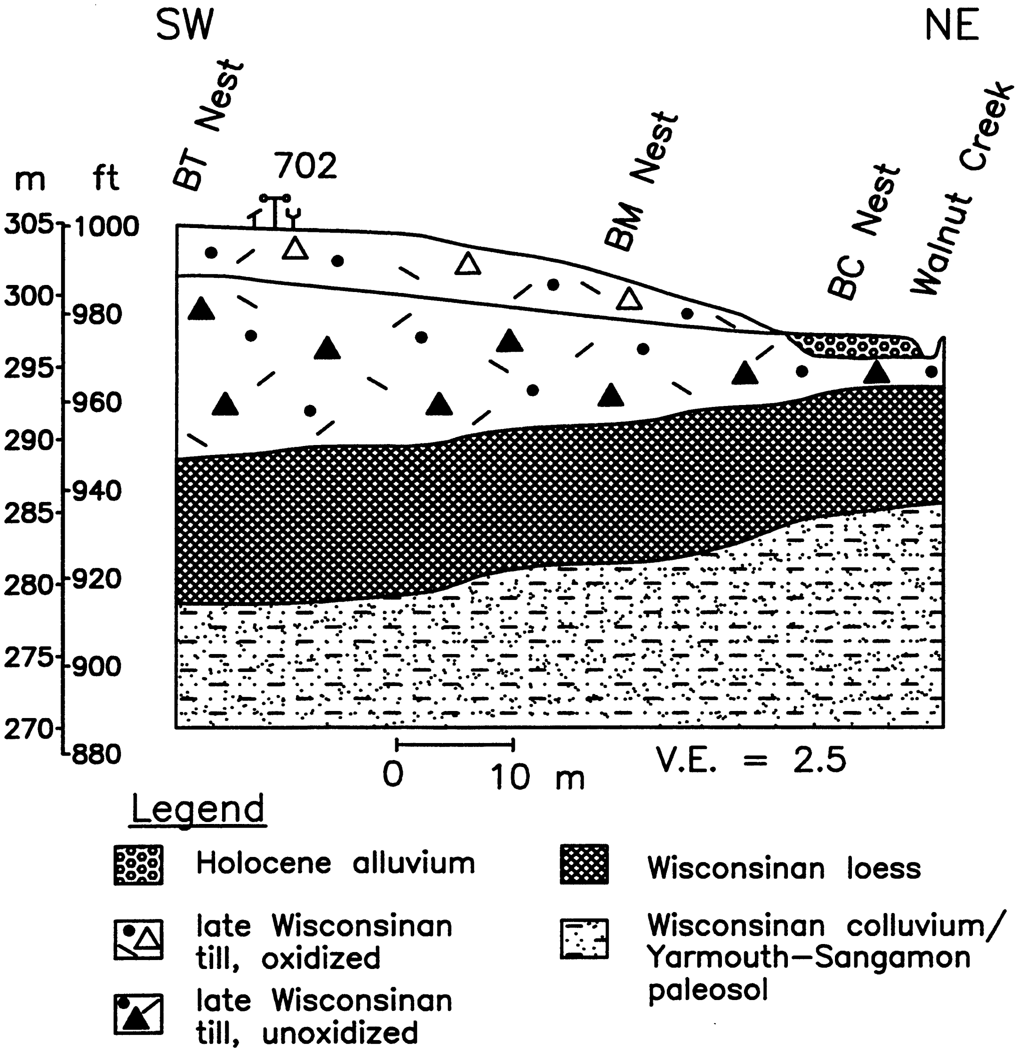

**Figure 28.** Cross section showing Quaternary stratigraphy at the Walnut Creek Central Transect.

casing. Piezometers were fitted with lockable metal casings and cemented in place.

Piezometers were developed with an inertial pump or peristaltic pump and surveyed to absolute mean sea level. Ongoing field investigation at the transects includes measurement of hydraulic heads at bimonthly to monthly intervals. Measurements are made to the nearest 0.002 m using an electric tape. Falling and rising head slug tests and pumping tests were performed at this site and the results are discussed later in this guidebook (see Seo et al., this guidebook).

## RESULTS AND DISCUSSION

### Geology

The stratigraphy at the Central Transect is similar to Pleistocene stratigraphy encountered in the watershed and in central Iowa (Fig. 28). The surficial unit is late Wisconsinan till of the Dows Formation (Alden Member). At this transect, 3 to 4 m of oxidized till overlies 14 m of unoxidized till. The oxidized till is light olive brown (2.5Y 5/3),

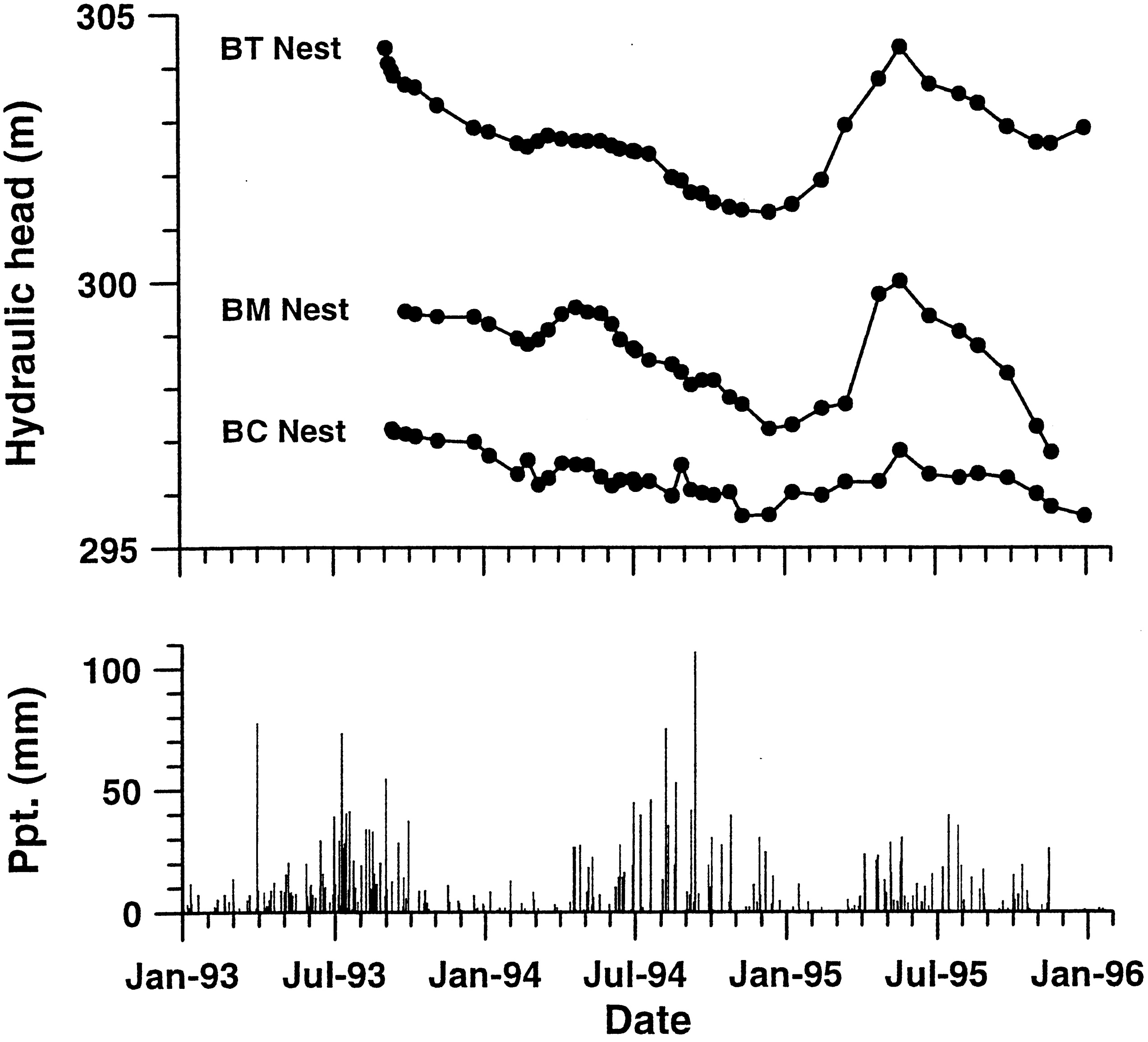

**Figure 29.** Water-table fluctuations at the 3 nests in response to precipitation at the Walnut Creek Central Transect.

calcareous, and contains numerous sedimentary pebbles. It also contains abundant rootholes and subvertical fractures exhibiting gray, iron-depleted zones or iron oxide coatings. There is a sharp transition zone (< 0.5 m) between the oxidized and unoxidized till. It consists of a dark yellowish brown (10YR 4/6) horizontal Fe-oxide band (10 cm) overlying approximately 30 cm of gleyed, dark greenish gray (5G 4/1) till. The unoxidized till below is dark gray (2.5 Y 4/0), calcareous, and also contains pebbles. Only fractures coated with Fe-oxide are present in this part of the unit, but their number is less than that in oxidized till. Particle size data for the BT Nest at this transect are given in Figure 9c.

Wisconsinan loess occurs below late

Wisconsinan till (Fig. 28). It is typically unoxidized and dark gray (2.5Y 4/0) and contains sand, pebbles, and block inclusions of unoxidized late Wisconsinan and Pre-Illinoian till (Fig. 9c). This 8-m-thick unit is more accurately described as a diamicton and is the Type I loess of Johnson (1995). Portions of this loess exhibit a gleyed appearance (5G 4/1) and contains organic horizons (paleosols) and terrestrial snail shells. Wood and disseminated organic material are present in this unit and at the base of late Wisconsinan till. Because of its textural heterogeneity, Wisconsinan loess at the Central Transect is interpreted to be colluvial in origin.

The oldest unit encountered in the Central Transect is colluvial sediment of Wisconsinan age. The unit contains pieces of the Farmdale Soil and the Yarmouth-Sangamon paleosol (Fig. 9c) and is approximately 8 m thick at the Central Transect. We encountered a black (2.5Y 2/0) organic-rich horizon that is leached of carbonate and that yielded a $^{14}C$ date consistent with that of the Farmdale Soil (see earlier article in guidebook); however, it is overlain by 5 m of Yarmouth-Sangamon-like material. Remnants of organic horizons, evidenced by alternating gray (2.5Y 5/0) and light olive brown (2.5Y 5/3) zones, occur within the unit. However, most of it consists of a gray to dark gray (2.5Y 5/0 to 4/0) clayey sediment, leached of carbonate and exhibiting a blocky texture. Krotovinas (filled animal burrows), root holes, and mottling are also observed in this part of the unit.

## Groundwater Flow

Groundwater flows northeastward from higher elevations at the transect towards Walnut Creek. Depth to the water table averaged 3.0 m below the ground surface, with a minimum and maximum depth of 0.9 m and 3.7 m, respectively, between 1993 and 1995. Fluctuations of the water table at this site are similar in magnitude to those shown earlier by Eidem et al. (Fig. 19; see earlier article, Stop 3) and the water table responds to precipitation and snowmelt in the spring months (Fig. 29). The fluctuations occurred primarily in the oxidized till; however, the water table dropped into the unoxidized late Wisconsinan till during the fall of 1994.

The water-table surface responds nearly simultaneously to recharge events at different slope positions. The magnitude of water-table rise and fall is similar in the BM and BT nests, but the response is damped at the BC nest, perhaps due to its proximity to the stream. Although we have noted (qualitatively) what appear to be masses of snowmelt water moving down gradient from the BT to the BM nest, the nearly simultaneous rise and fall suggests that recharge from vertical infiltration occurs all along the slope during the recharge period.

The groundwater flow systems that occur at this transect can be illustrated using data from two contrasting measurement times of May 1995 and November 1994 (Figs. 30 and 31). Under the high water-table conditions in May 1995, when recent recharge had saturated the oxidized till, the hydraulic head distribution suggests lateral flow towards the creek. The hydraulic gradient along the water table is about 0.06 from the BT to BC nests at this time. There is virtually no head loss in the vertical direction within the oxidized till; however, a vertical gradient of about 0.2 occurs into the unoxidized till below it and suggests a potential for vertical recharge into the unoxidized till. It is surprising that groundwater flow in the unoxidized till is still predominantly lateral and appears unaffected by 3 orders of magnitude difference between the K values in oxidized and unoxidized till (see article by Seo et al., this guidebook). The most significant loss of hydraulic head in the vertical direction occurs within the clayey material of the Wisconsinan colluvium/Yarmouth-Sangamon paleosol, where K values decrease to about $10^{-11}$ m/s. We suspect that the unit is underlain by oxidized and fractured Pre-Illinoian till ($K = 10^{-5}$ to $10^{-7}$ m/s); thus, the till may be draining the bottom of the colluvium/paleosol unit and cause the very large (> 2.0) hydraulic gradient.

Groundwater appears to discharge into the creek under high water table conditions; however, a significant volume of water is lost through spring discharge at the bottom of the slope (Fig. 30). The

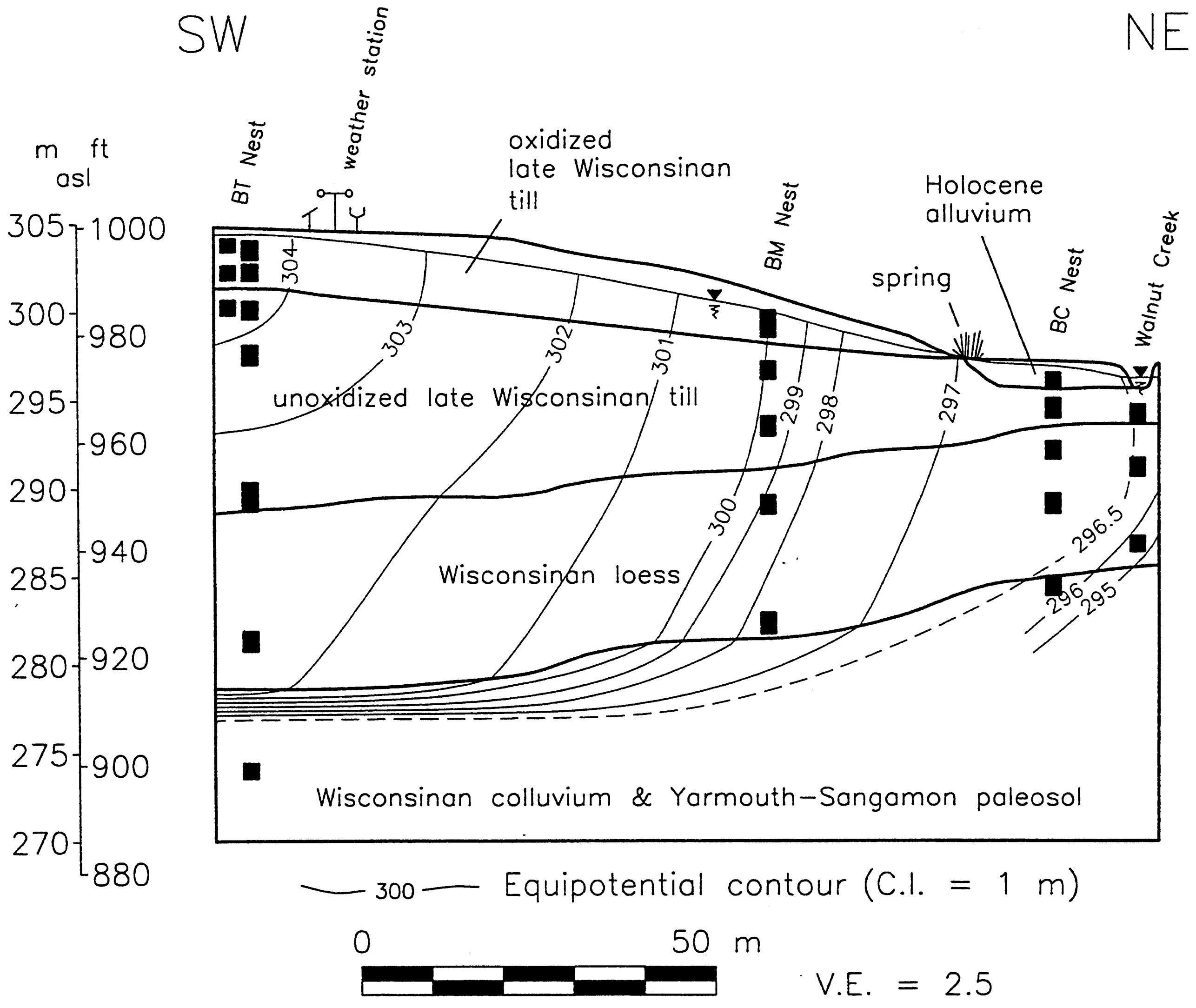

**Figure 30.** Distribution of hydraulic heads at the Central Transect for the May 1995 case. Equipotentials in meters.

discharge point lies directly on top of the unoxidized till and a seepage face likely develops there. $NO_3$-N that emerges at this point from the oxidized till either enters the creek via runoff or recharges the water table in the Holocene alluvium.

Groundwater flow conditions are much different under the low water-table conditions of November 1994 (Fig. 31). When the water table lies primarily within the unoxidized late Wisconsinan till, the hydraulic gradient at the water table becomes less steep and produces a hydraulic gradient of 0.03. Groundwater still flows toward the creek under these conditions; however, the equipotentials are nearly all vertical (except in the lower unit), the springs have all dried up (you can walk on them), and the Holocene alluvium has drained. It is during this period that there is often a potential for flow of creek water back into the alluvium and unoxidized till (Fig. 31). Discharge from tile drains upstream maintains creek discharge higher that would be

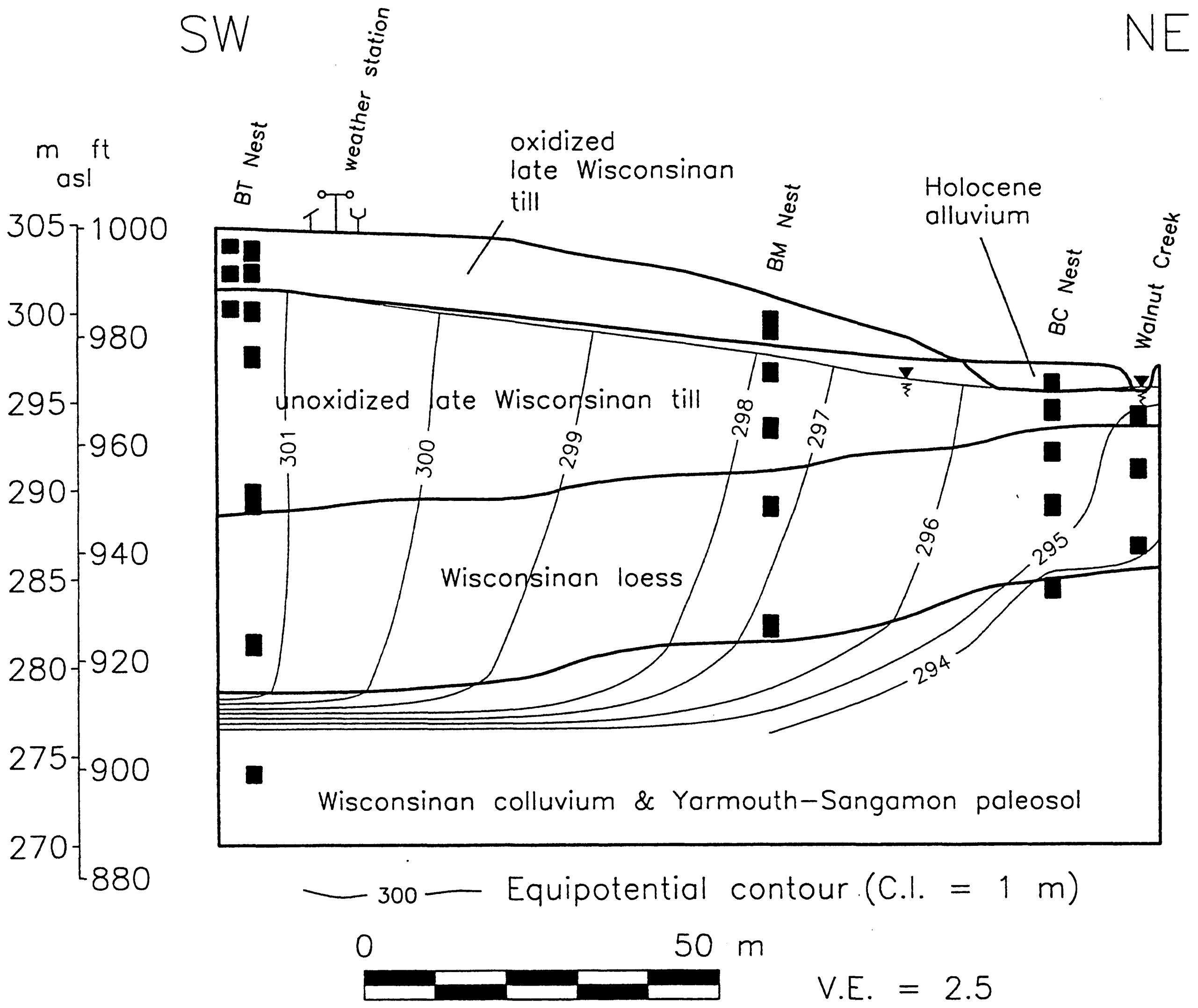

**Figure 31.** Distribution of hydraulic heads at the Central Transect for the November 1994 case. Equipotentials in meters.

normal under these conditions. A more detailed discussion of groundwater/surface water interaction is given at a later stop (see Stop 6).

## SUMMARY AND CONCLUSIONS

Detailed hydrogeological investigations at the Walnut Creek Central Transect suggest that, under high-water table conditions, groundwater flows laterally in the oxidized late Wisconsinan till toward Walnut Creek and discharges either through springs near the creek or into the creek. At low water-table conditions, flow occurs within the unoxidized till but it moves to the creek at a much slower rate. Higher stages of Walnut Creek, controlled by discharge from tile drains, can reverse hydraulic gradients and drive water back into the unoxidized till near the creek.

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# HYDRAULIC PROPERTIES OF QUATERNARY UNITS IN THE WALNUT CREEK WATERSHED

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## INTRODUCTION

Although Quaternary sediments overlie most bedrock aquifers in the Midwest, reliable and meaningful estimates of hydraulic properties in these units are difficult to obtain. Estimates of these properties are necessary for accurate prediction of point and non-point source contamination of groundwater. The purpose of this study was to use slug and pumping tests to estimate the hydraulic conductivity (K), transmissivity (T), specific yield ($S_y$), and storativity (S) of Quaternary units in the Walnut Creek watershed.

## METHODS

### Piezometer and Pumping Well Construction

A wealth of literature is available on procedures for determining hydraulic properties of confining units and aquifers (Simpkins and Bradbury, 1992; Keller et al., 1989). The approach for this research differs from previous studies in central Iowa (e.g., Jones et al., 1992; Simpkins and Parkin, 1993). First, screen lengths of piezometers are generally less than 1 m in length and are completed at depths ranging from 1.5 m to 30 m in different geological units. Second, angled wells were installed at 45° from vertical in order to intersect and examine the effect of vertical fractures on K and compare estimates to those from vertical piezometers. Finally, piezometers were completed in a non-traditional manner following the over-cored Shelby-tube method which minimizes smearing of the sidewall material in a borehole (see Simpkins and Johnson, this guidebook, Fig. 27; Simpkins et al., 1993).

A pumping well was installed at each transect site at the upper slope position and down gradient from the other piezometers at that nest. Pumping wells consisted of 5 cm ID, Schedule 40, flush-threaded, PVC pipe with factory slotted (0.10 cm slot), Timco High Flow™ well screens that spanned the entire oxidized zone of till. A filter pack of well-sorted pea gravel was placed adjacent to and 0.3 m above the screened interval. The remainder of the borehole annulus was filled with bentonite pellets. The wells were purged with a submersible pump until the effluent water was visibly clear of fine sediment.

### Slug Tests

Sixty-one slug tests were performed from October 1994 to July 1995 at the Walnut Creek Central and Eastern Transects. We used 2.5 cm-diameter, solid PVC slugs that were 0.3 m to 3.0 m long to perform the tests. Head changes during the test period were measured with an electric tape or transducer connected to a datalogger. Recovery times varied from less than 1 hour for piezometers screened in the oxidized till to several months for piezometers screened in unoxidized till, loess, and colluvium units. Slug test data were analyzed primarily by the Hvorslev method (Hvorslev, 1951), because of concerns about entrapped air in the piezometers (Keller and Van Der Kamp, 1992). Checks of K estimates calculated from the Bouwer-Rice method were found to be nearly identical to estimates from the Hvorslev analysis.

### Pumping Tests

Three pumping tests were performed in June and July of 1995 at Walnut Creek Central and

**Table 2.** Summary of (a) pumping test information and geometry for PT-1, PT-2, and PT-3, (b) data for PT-1 piezometers, (c) data for PT-2 piezometers, and (d) data for PT-3 piezometers.

**a.**

| Test no. | PT-1 | PT- 2 | PT- 3 |
|---|---|---|---|
| Site | Walnut Creek Central Transect | Walnut Creek Eastern Transect | Walnut Creek Eastern Transect |
| Type of pumping test | Constant-head | Constant-head | Constant-head |
| Duration (hours) | 72 | 72 | 36 |
| Depth of pumping well (m) | 3.66 | 12.19 | 12.19 |
| Number of piezometers | 4 | 1 | 6 |
| Initial saturated thickness (m) | 2.38 | 5.49 | 5.49 |
| Total drawdown (m) | 2.19 | 1.22 | 2.26 |
| Weighted average flow rate (L/min) | 0.561 | 0.357 | 0.669 |
| Total volume of water pumped (L) | 2418 | 1539 | 1445 |

**b.**

| PT-1 | BT-5 | BT-10 | BT-5A | BT-10A |
|---|---|---|---|---|
| Lithology | oxidized late Wisconsinan till | oxidized late Wisconsinan till | oxidized late Wisconsinan till | oxidized late Wisconsinan till |
| Depth (m) | 1.84 | 3.17 | 1.51 | 3.18 |
| r (m) | 3.33 | 4.92 | 4.27 | 6.52 |
| Drawdown (m) | 0.088 | 0.064 | 0.079 | 0.073 |

**c.**

| PT-2 | VF-25 |
|---|---|
| Lithology | oxidized Pre-Illinoian till |
| Depth (m) | 7.62 |
| r (m) | 6.22 |
| Drawdown (m) | 0.796 |

**d.**

| PT-3 | VF-5 | VF-10 | VF-5A | VF-15 | VF-15A | VF-25 |
|---|---|---|---|---|---|---|
| Lithology | oxidized late Wisconsinan till | oxidized late Wisconsinan till | oxidized late Wisconsinan till | unoxidized late Wisconsinan till | unoxidized late Wisconsinan till | oxidized Pre-Illinoian till |
| Depth (m) | 1.68 | 3.35 | 1.59 | 4.72 | 4.42 | 7.62 |
| r (m) | 1.73 | 3.14 | 4.37 | 4.65 | 8.96 | 6.22 |
| Drawdown (m) | 0.094 | 0.104 | 0.131 | 0.219 | 0.113 | 1.338 |

Eastern transects (Table 2). The piezometer nest at the Walnut Creek Central Transect was specifically designed to estimate parameters for the oxidized late Wisconsinan till and it is designated as Pumping Test 1 (PT-1) (Fig. 32). At the Walnut Creek Eastern Transect, Pumping tests 2 (PT-2) and 3 (PT-3) were designed to estimate parameters for the oxidized Pre-Illinoian till. For these tests, the pumping well penetrates the entire section of oxidized Pre-Illinoian till and VF-25 is the only piezometer which is screened within that unit (Fig. 33). Three piezometers are located within the overlying oxidized late Wisconsinan till units and two piezometers are screened within a very thin unoxidized zone (Fig. 33). In PT-2, only the change in hydraulic head in VF-25 was observed during pumping. PT-3 tested the response of the 5 piezometers that are screened in the Wisconsinan till above VF-25. All observed water level data were corrected for changes in the water table elevation that occurred prior to and during the tests.

Pumping tests were performed by lowering the static water level in the well to a specified depth and then keeping it at that depth for the remainder of the test, similar to the method used by Jones et al. (1992). This method shortens the total length of the pumping test considerably. A submersible purge pump was used for the first 5 minutes of the test, after which pumping was performed by dual-head peristaltic pump. Discharge from the pump was measured with a stopwatch and a 1000 ml graduated cylinder. Discharge decreased during the early part of the test, but remained essentially constant after about 10 hours into the test (Seo, 1996).

Two analytical methods were used to determine the hydraulic conductivity and specific yields from PT-1: the one-dimensional radial flow models of Theis (1935) and Jacob (1963) and the two-dimensional radial-vertical flow model of Neuman (1972; 1975; 1979). Water levels changed throughout the tests and hence these non-equilibrium formulas are appropriate; however, the models are based on the assumption that the medium is homogeneous and mostly isotropic. At both transects, fractures in the oxidized till probably control the groundwater flow during the pumping test and this provides a complicating factor in the analysis. For the purposes of this study, we assumed the simple homogeneous and isotropic case with the hope of gaining insight that would allow use to model a fractured system later. Data for the pumping tests were analyzed with the computer program, AQTESOLV™, which uses nonlinear least-squares parameter estimation (with Gauss-Newton iteration) to estimate T, S, and $S_y$ from the analytical solutions for transient radial flow to a well (Duffield, 1995). Values of discharge from the pump were discretized into ten time intervals in order to account for the gradual decrease of pumping rates during the tests. Partial penetration was not considered to be a significant factor in the test results.

The method of Hantush for a leaky aquifer with no storage (Hantush and Jacob, 1955) was used to analyze the results of PT-2 at the Walnut Creek Eastern Transect. The assumptions of this model are similar to the Theis solution, except that vertical leakage is considered. The early time data match the Theis type curve and then deviate from it in proportion to the leakage of overlying (or underlying) unit. This solution neglects storage in the aquitard, which may important for the evaluation of a leaky aquifer (Neuman and Witherspoon, 1969).

All the till units at the Walnut Creek Eastern Transect eventually contribute to the response in the pumping well. Thus, for PT-3, it was necessary to consider both the storage in the unoxidized till (confining unit) and the drawdown in the unpumped oxidized Wisconsinan till ("upper aquifer") in order to estimate the parameters in the underlying oxidized Pre-Illinoian till unit. Neuman and Witherspoon (1969) developed an analytical solution for this situation. Initial drawdown follows the Theis type curve until leakage from storage in the confining layer is induced by the decline in hydraulic head in the pumped aquifer. At later times, the unpumped upper aquifer also shows measurable drawdown and that data can be used for evaluation of the pumped aquifer. Eventually, the cone of depression enlarges such that discharge comes primarily from leakage of the "upper aquifer" and the type curves of Hantush and Jacob (1955) and Neuman and Witherspoon (1969) coincide.

## RESULTS AND DISCUSSION

K values show a wide range in the Quaternary materials within the watershed (Table 3a and b). Values of K from slug tests range from $6 \times 10^{-11}$ m/s in colluvium/paleosol unit to $7 \times 10^{-5}$ m/s in Holocene alluvial unit (Table 3a). K values for these units are similar to values estimated by slug tests reported elsewhere for these same units (see Simpkins and Parkin, 1993; Jones et al., 1992; Jones, 1993; Bruner and Lutenegger, 1993). Interestingly, K values from tests in other piezometers in the watershed showed different values for the oxidized and transition zone/unoxidized till units Table 3b). We hypothesize that K values for the oxidized till unit are lower for these piezometers because the construction of these piezometers in-

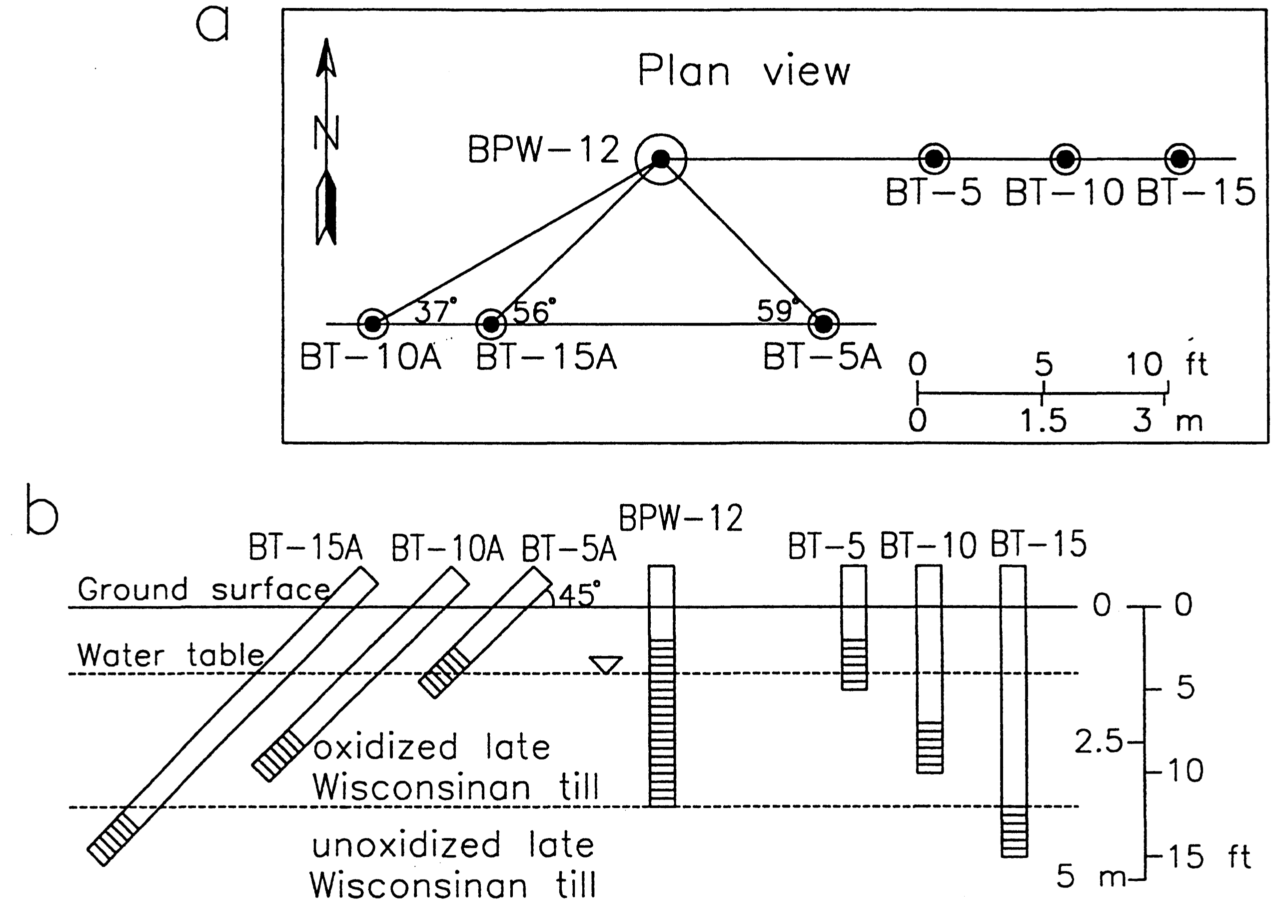

**Figure 32.** PT-1 site at the Walnut Creek Central Transect in (a) plan view and (b) schematic cross section.

volved drilling to depths of 10 m or more below the final screened interval. We suggest that cuttings from deeper, less permeable units migrated upward along the auger and smeared an impermeable "skin" on the side of the borehole. Development of the piezometers failed to dislodge this skin; hence, the K values are closer to those seen in unoxidized till elsewhere. The similarity between the K values for oxidized and unoxidized till in these piezometers suggests that the "skin" is present in the deeper piezometer as well.

Results from several piezometers in unoxidized Pre-Illinoian till are missing from Table 3, primarily because the hydraulic heads in this unit only recently achieved equilibrium. At piezometer BH-130, for example, the recovery lasted about 23 months from the time of installation (Fig. 34). Hydraulic head has recently started to decline in this piezometer. Hydraulic heads had not recovered in 9 out of 56 piezometers installed at the two sites as of mid-1995. These types of hydraulic responses, which are probably typical of the unoxidized Pre-Illinoian till and paleosol units, have hampered our ability to characterize K and to estimate groundwater flow directions and velocities in these units.

Although the evidence is not voluminous, K values from angled piezometers in the oxidized till unit appear to show higher K values than do vertical piezometers in the same unit (Table 4). This difference was hypothesized at the outset because many fractures in this unit are oriented

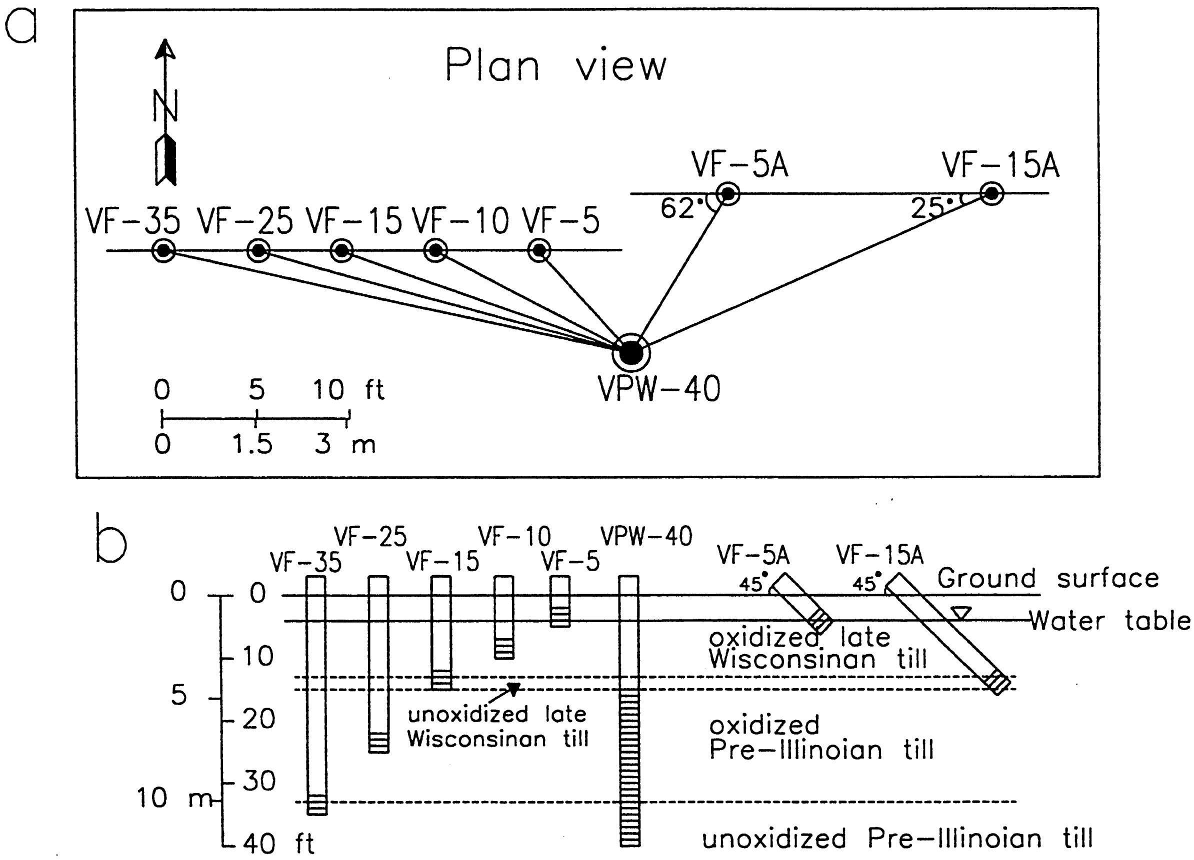

**Figure 33.** PT-2 and PT-3 sites at the Walnut Creek Eastern Transect in (a) plan view and (b) schematic cross section.

vertically; thus, angled piezometers may intersect more vertical fractures. Although we know fractures control contaminant transport in the till units (see Helmke and Simpkins, this guidebook), the K values given here are still closer to bulk K values and probably 2 orders of magnitude too low for the K of the actual fractures (Jorgensen and Spliid, 1992). Visible observations of the core indicate that fracture spacings are about 2.5 cm or greater down to depths of 3 m, so it is difficult to understand how a piezometer might "miss" one of these features. Perhaps these results indicate that not all the observed fractures are "active fractures." Differences in K between angled and vertical piezometers in the unoxidized till unit are the reverse of what we anticipated and the reasons for this are not clear.

Values of K from pumping tests results are similar to, but generally up higher than, slug test results. This is the scale effect that has been recognized elsewhere (Bradbury and Muldoon, 1990). For PT-1, estimates of T and K from the Theis Method (with Jacob correction) and the Neuman method were very close and produced identical geometric mean $K_r = 1 \times 10^{-5}$ m/s (Table 5; Fig. 35). Both analysis methods reported low values of S and $S_y$. The lowest S values occurred in till tested in angled piezometers, which may reflect the control of fractures in the till. The results suggest the units are anisotropic ($K_r/K_z$), which could be due fractures or the sedimentology of the unit.

Results for PT-2 and PT-3 at the Walnut Creek

**Table 3.** Summary of geometric mean K and log transformed standard deviation values for Quaternary units in the watershed. Values in Table 3a are from piezometers installed with the overcored Shelby Tube method. Values in Table 3b are from the dual piezometer installations done by Eidem (see description in Stop 3). All values from slug tests. NA = not applicable.

**a**

| | **Holocene alluvium** | **late Wisconsinan till (Dows Fm.)** | | **Wisconsinan loess** | **Wisconsinan colluvium/paleosol** | **Pre-Illinoian till (Wolf Creek Fm.)** | |
|---|---|---|---|---|---|---|---|
| | **oxidized** | **oxidized** | **unoxidized** | **unoxidized** | **unoxidized** | **oxidized** | **unoxidized** |
| **No. of samples** | 1 | 12 | 11 | 8 | 1 | 2 | 2 |
| **Geometric mean (m/s)** | $7 \times 10^{-5}$ | $2 \times 10^{-6}$ | $6 \times 10^{-9}$ | $1 \times 10^{-9}$ | $6 \times 10^{-11}$ | $4 \times 10^{-7}$ | $7 \times 10^{-10}$ |
| **Log trans. std. dev.** | NA | 1.4 | 0.96 | 0.56 | NA | NA | NA |

**b**

| | **late Wisconsinan till (Dows Fm.)** | |
|---|---|---|
| | **oxidized** | **transition zone to unoxidized** |
| **No. of samples** | 14 | 7 |
| **Geometric mean (m/s)** | $3 \times 10^{-8}$ | $8 \times 10^{-8}$ |
| **Log trans. std. dev.** | 0.69 | 0.70 |

**Table 4**. Comparison of geometric mean K values from vertical and angled piezometers. Log transformed standard deviation in parenthesis. Number of tests in brackets.

| **Piezometer orientation** | **late Wisconsinan till (Dows Fm.)** | |
|---|---|---|
| | **K (m/s) oxidized** | **K (m/s) unoxidized** |
| **Vertical** | $4 \times 10^{-6}$<br>(0.84)<br>[N=6] | $1 \times 10^{-8}$<br>(0.68)<br>[N=8] |
| **Angled** | $1 \times 10^{-5}$<br>(0.99)<br>[N=3] | $2 \times 10^{-9}$<br>(0.81)<br>[N=3] |

Eastern Transect yielded contrasting estimates of T and K (Table 6). The Hantush and Jacob (1955) method yielded the lower T and K values for the oxidized Pre-Illinoian till (Table 6a) and these values are also less than those for PT-1. Storativity values were also similar. Results from the Neuman and Witherspoon method (1969) were closer to, but still lower than, the values of oxidized late Wisconsinan till yielded at PT-1 (Table 6b). The reason for these differences are not entirely clear at this time and are under investigation.

**Table 5.** Pumping test results for PT-1 using (a) Theis (1935) and Jacob (1963), and (b) Neuman (1972; 1975; 1979) methods. Geometric means and log transformed standard deviations are given for K and T values only.

**a.**

| | | **Slug test** | **Theis Method with Jacob correction** | | |
|---|---|---|---|---|---|
| **Piez. no.** | **Lithology** | **K (m/s)** | **T ($m^2$/s)** | **K (m/s)** | **S** |
| BT-5 | ox. LW. till | 3E-05 | 3E-05 | 1E-05 | 0.1673 |
| BT-5A | ox. LW. till | 3E-05 | 3E-05 | 1E-05 | 0.0863 |
| BT-10 | ox. LW. till | 1E-06 | 3E-05 | 1E-05 | 0.1737 |
| BT-10A | ox. LW. till | 2E-06 | 4E-05 | 2E-05 | 0.0520 |
| Mean | | 7E-06 | 3E-05 | 1E-05 | 0.1198 |
| St. Dev. | | 0.776 | 0.062 | 0.151 | 0.0602 |

**b.**

| | | **Neuman Method for Unconfined Aquifers** | | | | |
|---|---|---|---|---|---|---|
| **Piez. no.** | **T ($m^2$/s)** | **$K_r$ (m/s)** | **S** | **$S_y$** | **$K_z$** | **$K_r/K_z$** |
| BT-5 | 3E-05 | 1E-05 | 0.1761 | 0.1752 | 1E-07 | 97.84 |
| BT-5A | 3E-05 | 1E-05 | 0.0747 | 0.0742 | 1E-07 | 80.45 |
| BT-10 | 2E-05 | 9E-06 | 0.1632 | 0.1620 | 2E-07 | 41.52 |
| BT-10A | 4E-05 | 2E-05 | 0.0525 | 0.0523 | 1E-07 | 125.08 |
| Mean | 3E-05 | 1E-05 | 0.1166 | 0.1159 | 1E-07 | 86.22 |
| St. Dev. | 0.124 | 0.160 | 0.0621 | 0.0617 | 0.151 | 35.01 |

**Table 6.** Pumping test results for PT-2 and PT-3 using Hantush and Jacob (1955) and Neuman and Witherspoon (1969) methods. Geometric means and log transformed standard deviations are given for K and T values only in (b).

**a.**

| **Piez. no.** | **Lithology** | **Slug test** | **Hantush and Jacob (1955) method** | | | |
|---|---|---|---|---|---|---|
| | | **K (m/s)** | **T ($m^2$/s)** | **K (m/s)** | **S** | **K'** |
| VF-25 | oxid. Pre-Ill. till | 4E-07 | 6E-07 | 1E-07 | 3E-05 | 8.0E-09 |

**b.**

| | | | **Neuman and Witherspoon (1969) method** | | | |
|---|---|---|---|---|---|---|
| **Piez. #** | **Lithology** | **Hydrostrat. unit** | **T ($m^2$/s)** | **K (m/s)** | **$S_s$** | **$S_sb$** |
| VF-5 | oxid. late Wisc. till | upper aquifer | 1E-05 | 2E-06 | 4E-05 | 2E-04 |
| VF-5A | oxid. late Wisc. till | | 9E-06 | 2E-06 | 4E-06 | 2E-05 |
| VF-10 | oxid. late Wisc. till | | 2E-05 | 4E-06 | 5E-06 | 3E-05 |
| VF-15 | unoxid. late Wisc. till | confining unit | 1E-05 | 3E-06 | 5E-06 | 3E-05 |
| VF-15A | unoxid. late Wisc. till | | 3E-05 | 5E-06 | 1E-05 | 7E-05 |
| VF-25 | oxid. Pre-Ill. till | lower aquifer | 3E-05 | 5E-06 | 9E-06 | 5E-05 |
| Mean | | | 2E-05 | 3E-06 | 8E-06 | 5E-05 |
| Std. Dev. | | | 0.247 | 0.183 | 0.366 | 0.358 |

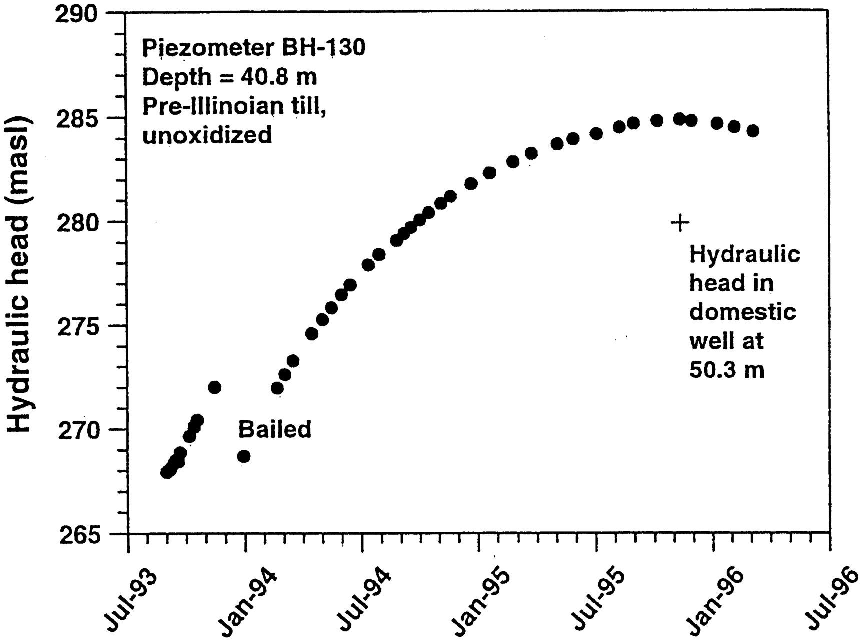

**Figure 34.** Recovery of piezometer BH-130 in unoxidized, Pre-Illinoian till at the Walnut Creek Central Transect.

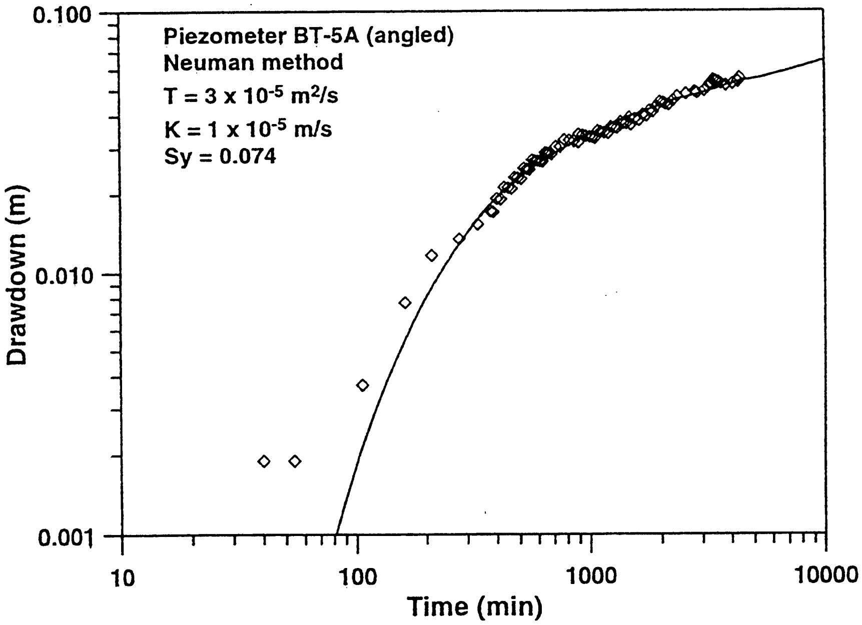

**Figure 35.** Pumping test results from PT-1 and Neuman model fit for angled piezometer BT-5A.

## SUMMARY AND CONCLUSIONS

Slug tests and pumping tests were used to estimate the T, K, S, and $S_y$ of Quaternary units in the Walnut Creek watershed. K values of units in the watershed show a range of six orders of magnitude. The Wisconsinan colluvium/Yarmouth-Sangamon paleosol unit ($K = 6 \times 10^{-11}$ m/s) shows the lowest K value and this unit should be an effective confining unit and barrier to vertical flow in the watershed. In general, pumping test results in the oxidized late Wisconsinan till yielded a K value ($1 \times 10^{-5}$ m/s) that was slightly higher than values from slug tests ($7 \times 10^{-6}$ m/s). Given these K values, the oxidized late Wisconsinan till and Holocene alluvium ($K = 7 \times 10^{-5}$ m/s) are the most permeable units and should conduct most of the shallow groundwater and contaminants in the watershed.

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**Table 7.** Fertilizer and pesticide applications in cropped fields up gradient from the Central and Eastern Transects. Application data for 1995 are not yet available; however, both transects were cropped in corn. UAN = Urea ammonium nitrate.

| Year | Crop | Fertilizer or pesticide | Application rate | Application method |
|---|---|---|---|---|
| **Walnut Creek Central Transect** | | | | |
| 1993 | corn | UAN<br>atrazine<br>metolachlor | 60 lbs/ac<br>1 lb/ac<br>3 pt/ac | 28% liquid<br>broadcast<br>broadcast |
| | pasture land (location of piezometers) | N<br>2-4,D<br>dicamba | 0.9 lb/ac<br>0.5 pt/ac<br>0.5 pt/ac | 32% liquid<br>sprayed<br>sprayed |
| 1994 | corn | UAN<br>metolachlor<br>2-4,D<br>dicamba | 100 lb/ac<br>1 qt/ac<br>0.5 pt/ac<br>0.5 pt/ac | 28% liquid<br>banded<br>broadcast<br>broadcast |
| **Walnut Creek Eastern Transect** | | | | |
| 1993 | corn | anhydrous $NH_3$<br>metolachlor | 125 lb/ac<br>2.5 pt/ac | broadcast<br>banded |
| 1994 | soybean | trifluralin<br>imazethapyr | 1 qt/ac<br>4 oz/ac | broadcast<br>broadcast |

# WATER QUALITY AND HYDROGEOCHEMISTRY AT THE WALNUT CREEK CENTRAL TRANSECT

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## INTRODUCTION

The widespread use of fertilizers and pesticides in the United States has increased the productivity of the nation's croplands. As a result, agricultural chemicals have been introduced into surface water and groundwater and have produced potential environmental and health hazards. The Midwest Corn Belt is one of the most intensively farmed areas in the U.S. It produces over two-thirds of all U.S. corn and soybeans, and uses more than half of the nation's fertilizers and pesticides (USDA, 1994). Studies conducted in the Midwest report that agricultural activities are a significant source of groundwater contamination (Spalding et al., 1978; Baker and Johnson, 1981; Madison and Brunett, 1985; Keeney 1986; Hallberg, 1987; Schepers et al., 1991; Hallberg and Keeney 1993). Current research focuses on evaluating measures that would minimize the risk of groundwater contamination, such as reducing applications of fertilizers and pesticides and implementing alternative farming practices.

In contrast to previous studies of non-point source contamination in groundwater that have addressed the "Where is the nitrate?" question, our research has focused on the processes by which contaminants move and why they disappear in groundwater systems in central Iowa. Our research suggests that the geological setting is the primary control of transport of agrichemicals in the subsurface. At the Ames Till Hydrology Site (see Fig. 4), two hydrogeochemical zones of groundwater were identified that affect the persistence of agricultural chemicals in groundwater. The shallow groundwater zone (oxidized late Wisconsinan till < 4 m deep) is characterized by large, positive Eh values, the presence of large concentrations of D.O. and $NO_3$-N, $^3H$ activities ranging from 17 to 20 T.U., and low or non-detectable concentrations of dissolved Fe and $NH_4$-N (Simpkins and Parkin, 1993). These data suggest that groundwater in the oxidized late Wisconsinan till is young in age and supports an oxidizing environment. It is likely that $NO_3$-N will persist and be transported readily within this zone, a conclusion also reached by Eidem et al. (this guidebook; Stop 3).

In contrast, the deeper groundwater zone (in unoxidized till and loess > 4 m deep) is characterized by low or non-detectable D.O. and $NO_3$-N concentrations, high concentrations of dissolved Fe and $NH_4$-N, unusually high DOC concentrations (up to 88 mg/L), above ambient concentrations of $CH_4$, and a decrease in Eh values (Simpkins and Parkin, 1993). Recent studies by Parkin and Simpkins (1995) show that $CH_4$ is produced microbially in the Wisconsinan till and Wisconsinan loess from organic carbon that is Wisconsinan in age. Tritium activities in this zone are < 1.0 TU, which suggests that the groundwater was recharged prior to 1953. These data suggest that groundwater in this zone is older than in the shallow zone and that it supports a reducing environment in which denitrification, Fe, Mn, $SO_4$ reduction and methanogenesis may occur. Because $NO_3$-N is an alternate electron acceptor that will oxidize carbon, $NO_3$-N will likely be reduced, rather than transported, in the unoxidized till and loess units.

The thickness and character of Quaternary stratigraphic units present in the Walnut Creek watershed are similar to those at the Ames Till Hydrology Site and we hypothesized that the hydrogeochemical environments should be similar. We also chose transect locations that were immediately down gradient from land where fertilizers and pesticides are applied to actively cropped fields (Table 7). The purpose of this ongoing study is to characterize the hydrogeochemistry and water quality of both the Walnut Creek Central and Eastern Transects, particularly with regard to hydrogeochemical processes such as denitrification. Work at the Central Transect has progressed faster than that at the Eastern Transect, so we will confine our discussion to the former in this article.

## METHODS

Standard techniques for water quality investigation have been used at this site. One notable exception is the piezometer installation technique discussed earlier at this stop (see Simpkins and Johnson, this guidebook). These rather elaborate methods were necessary to try to isolate the bentonite sealant or grout, which contain $SO_4$ and Cl, from entering and contaminating the screened interval. Aside from the piezometer construction, procedures such as water sampling followed established methods. Standing water in piezometers was purged before sampling. Groundwater samples were obtained with a peristaltic pump, filtered with a 0.45 µm filter, and packed with ice in the field. Samples for $NO_3$-N and $NH_4$-N were acidified with 4.5 N $H_2SO_4$ in the field and analyzed with a Lachat system. Samples for anions (F, Cl, Br, H, $PO_4$ and $SO_4$) were analyzed by ion chromatography. Samples for dissolved organic carbon (DOC) were acidified with concentrated $H_3PO_4$ and analyzed using persulfate oxidation on a carbon analyzer. Samples for cations (Ca, Mg, Na, Fe, Si, Mn, Sr, Ba, B and Li) were acidified with 8N H $NO_3$ in the field and analyzed by inductively coupled plasma (ICP). Temperature and specific conductivity were measured downhole using a YSI TLC meter, and pH and alkalinity were determined in the field. Hydrogeochemical data were speciated using the geochemical model, WATEQF, within NETPATH (Plummer et al. 1976; 1991).

Groundwater was analyzed with respect to D.O., $N_2O$, and $CH_4$. D.O. was determined using a modified Winkler titration for highly oxygenated groundwater (> 1 mg/L). For less oxygenated groundwater, D.O. concentrations were determined by the Rhodazine D colorimetric technique (White et al., 1990). Samples were analyzed by a color comparitor or a portable spectrophotometer. Groundwater samples of $N_2O$ and $CH_4$ were obtained with a downhole 20 ml syringe sampler attached to a portable vacuum pump. After retrieving the syringe sample, the groundwater was injected into evacuated 26.5 ml glass vials with butyl stoppers. Vials were packed in ice in the field, then refrigerated at the laboratory. Prior to analysis, the vials were warmed to room temperature (25°C), brought to atmospheric pressure with He, and shaken. Headspace gas concentrations were analyzed using a split loop gas chromatographic system. Nitrous oxide was analyzed using a Shidmadzu GC-Mini 2 gas chromatograph (Shidmadzu Scientific Instruments, Inc., Columbia, Maryland) equipped with an electron capture detector. Methane was analyzed with a Tracor 540 gas chromatograph (Tracor Instruments, Austin, Texas) equipped with a flame ionization detector. Peak areas were compared to $N_2O$ and $CH_4$ standards prepared from commercial gas mixtures (Scotty Specialty Gases, Troy, Michigan) to determine gas concentrations in the gas phase. The Bunsen coefficient relationship was used to determined the dissolved gas concentrations in groundwater.

Groundwater samples for direct $^3H$ and enriched $^3H$ analyses were collected in polyethylene bottles, packed in ice, and analyzed at the Environmental Isotope Laboratory (EIL) at the University of Waterloo. Activities of $^3H$ were determined by direct liquid scintillation counting and activities of enriched $^3H$ were determined following electrolytic enrichment. The quantitation limit for $^3H$ and enriched $^3H$ was < 6 TU and < 0.8 TU, respectively.

# RESULTS AND DISCUSSION

## Agricultural Chemicals and Water Quality

During the 1993 to 1996 monitoring period, $NO_3$-N and Cl (from fertilizer) were the most frequently detected agricultural chemicals in groundwater at the Walnut Creek Central Transect. Concentrations of atrazine, alachlor, metolachlor and metrabuzin were all below the quantitation limit of 0.2 µg/L during this period. $NO_3$-N was only found in piezometers screened in the oxidized till at depths less than about 3 m (Fig. 36); concentrations below the quantitation limit of 1 mg/L were noted in piezometers screened in the unoxidized till and loess below this depth (Johnson, 1995). Cl, applied as KCl, penetrated to depths below that of $NO_3$-N to about 7 m; lower concentrations of Cl below this depth do not reflect agricultural practices This pattern is most prevalent at the BT nest, which is immediately adjacent to and partially underneath a field in continuous corn rotation (Fig. 37). Tritium indicative of modern recharge and D.O. are present in the upper 3 m, while both are nearly absent in depths below 3 m (Fig. 37; Table 8). Overall, these data suggest that recharge entrains $NO_3$-N and Cl and from the adjacent field and transports them via groundwater to piezometers at the BT Nest.

Processes in piezometers at the BM and BC nests provide an interesting contrast to those at the BT nest. The water table was below the piezometers in the oxidized zone at the BM nest during much of the study period; this is due in part to a thinner oxidized zone at the midslope position (Fig. 28). Recent $^3$H activities and Cl and D.O. concentrations suggest that recent recharge has occurred in groundwater at this nest; however, $NO_3$-N concentrations have been low and often below the quantitation limit (Table 8). $NO_3$-N has never been detected in samples from the BC Nest, which lies entirely within unoxidized till and loess; however, samples contain Cl and $^3$H suggestive of modern recharge. The presence of $NH_4$-N in groundwater from each piezometer suggests that the redox conditions are not favorable for preservation of $NO_3$-N.

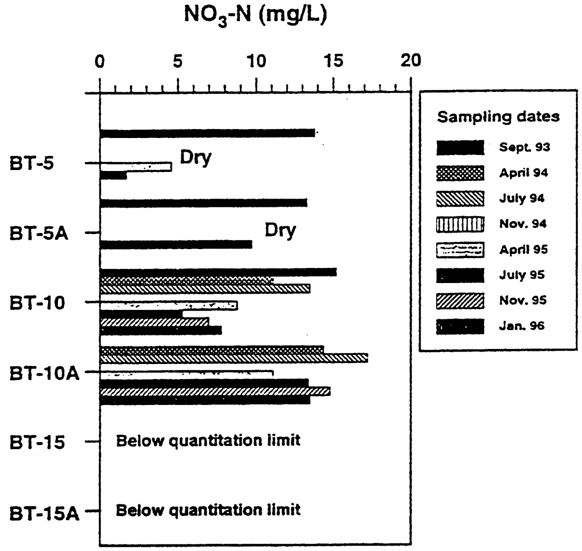

**Figure 36.** Profile of $NO_3$-N at the BT Nest from September 1993 to January 1996.

In summary, the lack of $NO_3$-N in samples from the midslope and creekside piezometers may suggest that: 1) groundwater with $NO_3$-N moves downward into the unoxidized zone before reaching these piezometers (suggested by the groundwater model; see Helmke and Simpkins, this guidebook), 2) $NO_3$-N is stored in the unsaturated zone of the till matrix, or 3) $NO_3$-N is removed by chemical or microbiological processes as it moves toward Walnut Creek. Denitrification is a possible sink for $NO_3$-N and it will be discussed later in this article.

## Hydrogeochemistry

Hydrogeochemical evidence suggests that conditions in the oxidized zone are mostly favorable for $NO_3$-N and that conditions in the unoxidized sediments are not favorable for $NO_3$-N. Similar to earlier findings in central Iowa (Simpkins and Parkin 1993), groundwater in the deeper sediments contain significant concentrations of $CH_4$ (Table 8; Fig. 38). It is likely that $CH_4$ is produced

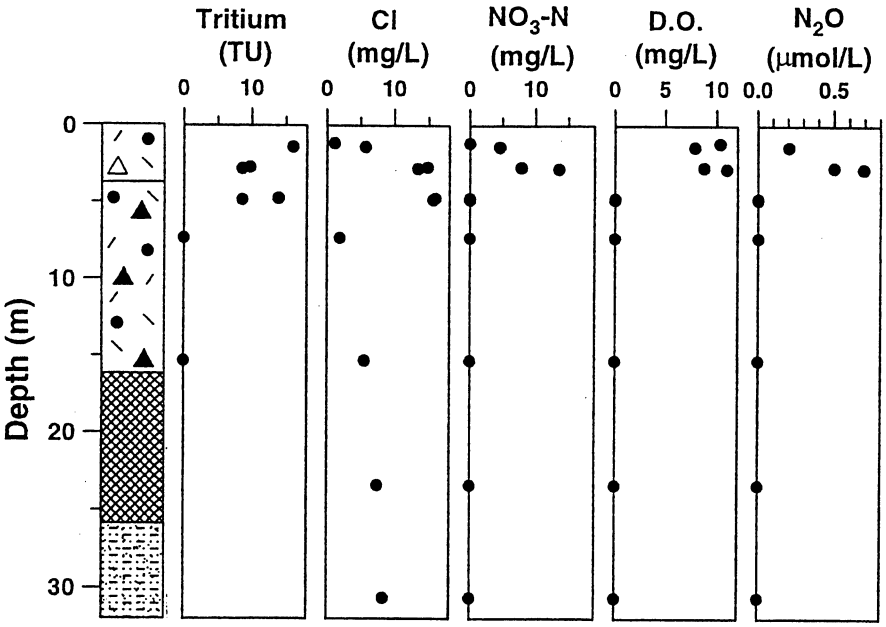

Figure 37. Vertical profile of $^3$H, Cl, $NO_3$-N, D.O., and $N_2O$ at the BT Nest.

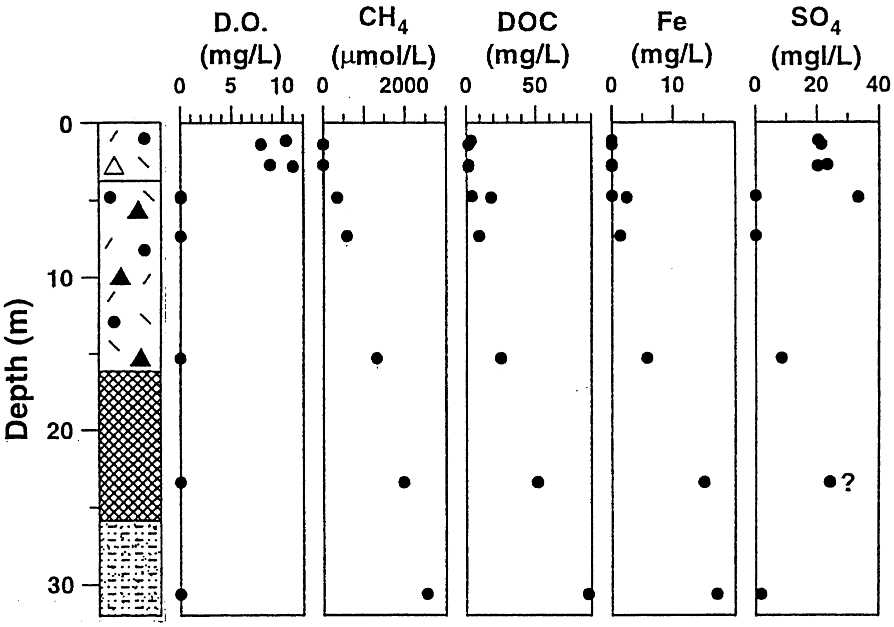

Figure 38. Vertical profile of D.O., $CH_4$, DOC, Fe, $SO_4$ at the BT Nest.

at the depths where it is found (Parkin and Simpkins, 1995); thus, redox conditions (pE) must be low enough to support methanogenesis. $NO_3$-N, an electron acceptor, utilizes organic C at much higher redox potentials, so it would be rapidly reduced in this environment. The higher Mn concentrations and the very high Fe concentrations (up to 17.1 mg/L) at depth, particularly in the loess, suggest that this is dissolved $Fe^{2+}$ and that the loess is a Fe source (Table 9). Geochemical modeling suggests that the system is in near equilibrium with $FeCO_3$ (siderite) (Table 10). Sulfate concentrations are low in some instances (BT-15A, BT-25) , but not in others (BC-10) (Table 9); the higher concentrations are likely from the bentonite seal or the grout and are not ambient concentrations. High $SO_4$ concentrations indicate that our exotic piezometer installation techniques were not completely successful; however, based on data from the Ames Till Hydrology Site, the $SO_4$ concentrations will eventually return to near zero concentrations after bentonite contamination. Undersaturation of the groundwater with respect to gypsum and near equilibrium with FeS also suggest that $SO_4$ reduction is a major process. FeS is a common feature on the dedicated polyethylene tubing in the piezometers and it oxidized quickly when exposed to air.

Most of the redox reactions are supported by the large concentrations (up to 88 mg/L) of dissolved organic carbon (DOC), even though most of the DOC appears to consist of high molecular weight humic and fulvic acids (see Van Iten et al., this guidebook) (Table 9). Evidence for oxidation of DOC by these alternate electron acceptors and conversion to $CO_2$ is suggested by the significant increase in $PCO_2$ in loess units (Table 10). $NH_4$-N was detected in piezometers BT-50, BT-75, BT-100 and all the piezometers at the BC nest (Table 9). The source of $NH_4$-N is presumably the breakdown of organic matter into amine-like compounds. This process requires low redox potentials; thus, it not related to fertilizer application.

## Denitrification

As suggested in the previous section, the spatial distribution of $NO_3$-N and the hydrogeochemistry of groundwater are related to the Quaternary stratigraphy at this site. $NO_3$-N was detected within oxidized till at the BT and BM nests (Table 9), but was not detected at the BC nest. There is also a general disappearance of $NO_3$-N with depth. The preferential loss of $NO_3$-N relative to other constituents in groundwater, such as the conservative Cl ion, suggests that denitrification is actively occurring in groundwater. For example, the disappearance of $NO_3$-N with depth into the unoxidized till at the BT nest is associated with an increase in Cl concentrations (Fig. 37). Elevated Cl concentrations and an absence of $NO_3$-N have been observed at the BC nest (Table 9), which is further along the groundwater flow path. Howard (1985) suggested that the disappearance of $NO_3$-N vertically within a profile or down gradient along a groundwater flow path is more likely due to dilution of $NO_3$-N by the mixing of groundwater of different ages or from different flow systems. However, in the present case, the presence of both Cl and $^3H$ suggest waters of relatively young age that should contain $NO_3$-N.

The best evidence for denitrification is the presence of above-ambient concentrations of $N_2O$ in the groundwater (Fig. 37; Table 8). At the Central Transect, $N_2O$ concentrations ranged from $< 0.007$ to 1.95 µmol /L during the study period (Johnson, 1995). Groundwater is not fully saturated with respect to $N_2O$, based on theoretical solubility calculations; however, the concentrations are about 300 times greater than equilibrium concentrations in ambient air. The zone containing $N_2O$ coincides with the zone of elevated $NO_3$-N concentrations within the oxidized till and just above the boundary between oxidized and unoxidized till.(Fig. 37). High $N_2O$ and D.O. concentrations (0.13 to 0.56 µmol/L) also occur together at depths of 1.5 m immediately after recharge events (Johnson, 1995). Theoretically, $NO_3$ should not be used as an alternate electron acceptor until D.O. concentrations are very low; however, both D.O. and $N_2O$ commonly occur together in our samples (Fig. 37). The comingling of seemingly contradictory compounds has been a difficult relationship to explain. Presence of both

**Table 8.** Depth and stratigraphic unit information for piezometers and field parameters, $^3$H and dissolved gas data for groundwater samples at the Walnut Creek Central Transect.

| Piez. no. | Midpoint depth (m) | Stratigraphic unit | Temp °C | Spec. cond. (µS) @ 25°C | pH | $^3$H (TU) | Diss. $O_2$ (mg/L) | $N_20$ (µmol/L) | $CH_4$ (µmol/L) |
|---|---|---|---|---|---|---|---|---|---|
| **BT Nest** | | | | | | | | | |
| BT-5 | 1.4 | Dows Fm. till, oxidized | 8.4 | 491 | 7.4 | 16 ± 8 | 7.9 | 0.20 | 0.06 |
| BT-5A | 1.1 | Dows Fm. till, oxidized | 8.7 | 456 | 7.5 | --- | 10.3 | --- | --- |
| BT-10 | 2.7 | Dows Fm. till, oxidized | 8.9 | 644 | 7.7 | 9.7 ± 0.9 | 8.8 | 0.25 | 0.10 |
| BT-10A | 2.8 | Dows Fm. till, oxidized | 8.6 | 653 | 7.5 | 8.6 ± 0.8 | 11.0 | 0.69 | 0.09 |
| BT-15 | 4.8 | Dows Fm. till, unoxidized | 11.3 | 694 | 7.5 | 8.6 ± 0.8 | 0.004 | 0.02 | 332 |
| BT-15A | 4.7 | Dows Fm. till, unoxidized | 12.0 | 622 | 7.6 | 13.9 ± 1.0 | 0.200 | bql | 219 |
| BT-25 | 7.3 | Dows Fm. till, unoxidized | 10.7 | 659 | 7.8 | <0.8 ± 0.5 | 0.005 | bql | 783 |
| BT-50 | 15.3 | Dows Fm. till, unoxidized | 10.1 | 841 | 7.5 | --- | 0.002 | bql | 1310 |
| BT-75 | 23.4 | Wisconsinan loess | 10.4 | 1373 | 7.3 | --- | bql | bql | 1965 |
| BT-100 | 30.7 | Wisconsinan colluvium | 10.6 | 1424 | 7.3 | --- | bql | bql | 2529 |
| | | | | | | | | | |
| **BM Nest** | | | | | | | | | |
| BM-5 | 1.2 | Dows Fm. till, oxidized | 6.5 | 529 | 7.5 | 7.8 ± 0.8 | 11.5 | .05 | 0.15 |
| BM-10 | 1.7 | Dows Fm. till, oxidized | 7.3 | 558 | 7.3 | 8.9 ± 0.8 | 10.3 | .06 | 0.93 |
| BM-15 | 4.2 | Dows Fm. till, unoxidized | 12.3 | 832 | 7.5 | <6 ± 8 | bql | .01 | 150 |
| BM-25 | 7.3 | Dows Fm. till, unoxidized | 10.6 | 779 | 7.7 | <6 ± 8 | bql | bql | 392 |
| BM-40 | 11.9 | Wisconsinan loess | 10.5 | 762 | 7.6 | --- | bql | bql | 901 |
| BM-60 | 18.7 | Wisconsinan loess | 10.5 | 1294 | 7.4 | --- | bql | bql | 939 |
| | | | | | | | | | |
| **BC Nest** | | | | | | | | | |
| BC-10 | 2.7 | Dows Fm. till, unoxidized | 12.8 | 2100 | 7.3 | 15 ± 8 | 0.250 | 0.17 | 5.3 |
| BC-15 | 5.1 | Dows Fm. till, unoxidized | 11.8 | 1192 | 7.3 | <6 ± 8 | 0.015 | bql | 675 |
| BC-25 | 8.2 | Dows Fm. till, unoxidized | 10.3 | 1156 | 7.3 | <6 ± 8 | bql | bql | 915 |
| BC-40 | 12.7 | Wisconsinan colluvium | 10.2 | 1135 | 7.4 | --- | bql | bql | 582 |
| BC-5A | 2.8 | Dows Fm. till, unoxidized | 12.0 | 1447 | 7.1 | 8 ± 8 | 0.200 | 0.04 | 174 |
| BC-15A | 5.9 | Wisconsinan loess | 12.2 | 1294 | 7.2 | <6 ± 8 | bql | bql | 986 |

--- = not determined

bql = below quantitation limit

**Table 9.** Major and minor element, anion, and DOC concentrations in groundwater at the Walnut Creek Central Transect.

| Piez. no | Ca | Mg | Na | K | $HCO_3$ | $SO_4$ | Cl | DOC | $NO_3$-N | $NH_4$-N | Fe | Mn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **BT Nest** | | | | | | | | | | | | |
| BT-5 | 78.5 | 21.3 | 3.4 | 0.7 | 251 | 21.5 | 5.7 | 1.8 | 4.6 | bql | 0.017 | 0.001 |
| BT-5A | 68.0 | 18.3 | 4.0 | 0.9 | 266 | 20.5 | 1.1 | 3.5 | bql | bql | 0.001 | 0.003 |
| BT-10 | 89.9 | 26.6 | 4.5 | bdl | 370 | 23.4 | 14.8 | 1.8 | 7.8 | bql | bql | 0.001 |
| BT-10A | 87.2 | 27.2 | 4.6 | bdl | 336 | 20.3 | 13.5 | 1.5 | 13.5 | bql | bql | 0.001 |
| BT-15 | 81.2 | 28.5 | 22.5 | 2.9 | 474 | 33.3 | 14.6 | 17.5 | bql | bql | 2.42 | 0.466 |
| BT-15A | 72.4 | 24.6 | 8.0 | 1.5 | 439 | bql | 15.6 | 4.1 | bql | bql | 0.020 | 0.170 |
| BT-25 | 66.9 | 23.4 | 23.5 | 3.2 | 439 | bql | 2.0 | 9.4 | bql | bql | 1.37 | 0.730 |
| BT-50 | 85.8 | 28.0 | 49.8 | 4.3 | 573 | 8.5 | 5.6 | 25.1 | bql | 2.4 | 5.81 | 0.060 |
| BT-75 | 163.9 | 51.2 | 63.7 | 5.1 | 1019 | 24.2 | 7.5 | 51.4 | bql | 6.6 | 15.0 | 0.370 |
| BT-100 | 168.6 | 53.9 | 60.3 | 3.3 | 1119 | 1.8 | 8.3 | 87.8 | bql | 10.1 | 17.1 | 0.260 |
| **BM Nest** | | | | | | | | | | | | |
| BM-5 | 77.1 | 21.9 | 4.8 | 0.6 | 320 | 16.2 | 2.5 | 16.6 | bql | bql | 0.011 | 0.004 |
| BM-10 | 88.8 | 24.6 | 7.7 | 1.1 | 343 | 32.7 | 8.0 | 1.8 | bql | bql | 0.003 | 0.001 |
| BM-15 | 103.4 | 36.9 | 15.4 | 3.2 | 455 | 113.4 | 5.3 | 6.0 | bql | bql | 1.97 | 0.130 |
| BM-25 | 78.3 | 28.6 | 33.5 | 4.4 | 481 | 43.9 | 3.1 | 10.6 | bql | bql | 2.37 | 0.090 |
| BM-40 | 73.7 | 25.0 | 49.4 | 4.1 | 498 | 1.2 | 4.0 | 18.6 | bql | 1.8 | 6.29 | 0.100 |
| BM-60 | 94.8 | 28.7 | 197.8 | 9.6 | 814 | 158.0 | 10.6 | 76.6 | bql | 6.7 | 2.57 | 0.282 |
| **BC-Nest** | | | | | | | | | | | | |
| BC-10 | 301.8 | 86.3 | 26.0 | 4.9 | 795 | 739.4 | 12.2 | 33.7 | bql | 1.7 | 2.50 | 1.237 |
| BC-15 | 133.7 | 39.9 | 30.8 | 4.7 | 811 | 31.2 | 4.6 | 63.7 | bql | 2.8 | 10.50 | 0.111 |
| BC-25 | 126.4 | 35.7 | 37.5 | 4.2 | 795 | 15.4 | 4.1 | 61.7 | bql | 3.2 | 13.60 | 0.152 |
| BC-40 | 116.0 | 35.0 | 53.5 | 3.9 | 499 | 154.7 | 6.0 | 27.2 | 2.7 | 1.7 | 1.50 | 0.136 |
| BC-5A | 185.1 | 56.2 | 31.6 | 5.0 | 821 | 201.3 | 12.3 | 40.9 | bql | 1.8 | 0.980 | 0.189 |
| BC-15A | 149.2 | 42.5 | 43.3 | 5.2 | 824 | 105.9 | 3.7 | 48.6 | bql | 3.2 | 11.90 | 0.093 |

bql = below quantitation limit

**Table 10.** Log $PCO_2$ and saturation indices (SI) for selected mineral phases in groundwater at the Walnut Creek Central Transect.

| Piez. no | Log $PCO_2$ | SI Calcite | SI Dolomite | SI Gypsum | SI Siderite | SI FeS |
|---|---|---|---|---|---|---|
| **BT Nest** | | | | | | |
| BT-5 | -2.1 | 0.0 | -0.5 | -2.1 | N/A | N/A |
| BT-5A | -2.2 | +0.1 | -0.4 | -2.4 | N/A | N/A |
| BT-10 | -2.2 | +0.4 | +0.4 | -2.1 | N/A | N/A |
| BT-10A | -2.1 | +0.2 | +0.1 | -2.2 | N/A | N/A |
| BT-15 | -1.9 | +0.4 | +0.3 | -1.7 | +0.6 | -0.3 |
| BT-15A | -2.0 | +0.4 | +0.5 | N/A | -1.0 | -2.0 |
| BT-25 | -2.3 | +0.6 | +0.8 | N/A | +1.0 | +0.1 |
| BT-50 | -1.9 | +0.5 | +0.5 | -2.6 | +1.4 | +0.3 |
| BT-75 | -1.4 | +0.7 | +1.1 | -2.0 | +1.7 | +0.4 |
| BT-100 | -1.4 | +0.7 | +1.1 | -3.2 | +1.8 | +0.4 |
| **BM Nest** | | | | | | |
| BM-5 | -2.1 | +0.1 | -0.2 | -2.3 | N/A | N/A |
| BM-10 | -1.9 | 0.0 | -0.4 | -1.9 | N/A | N/A |
| BM-15 | -1.9 | +0.4 | +0.6 | -1.5 | +0.8 | -0.1 |
| BM-25 | -2.1 | +0.6 | +0.8 | -2.0 | +1.1 | +0.2 |
| BM-40 | -2.0 | +0.4 | +0.5 | -3.5 | +1.5 | +0.5 |
| BM-60 | -1.6 | +0.4 | +0.4 | -1.4 | +0.9 | -0.3 |
| **BC-Nest** | | | | | | |
| BC-10 | -1.3 | +0.6 | +0.8 | -0.5 | -8.1 | -9.4 |
| BC-15 | -1.5 | +0.5 | +0.7 | -1.9 | +1.5 | +0.2 |
| BC-25 | -1.5 | +0.5 | +0.5 | -2.3 | +1.6 | +0.3 |
| BC-40 | -1.8 | +0.4 | +0.4 | -1.3 | +0.7 | -0.4 |
| BC-5A | -1.3 | +0.5 | +0.6 | -1.1 | +0.3 | -1.1 |
| BC-15A | -1.4 | +0.5 | +0.6 | -1.4 | +1.5 | +0.2 |

N/A = concentrations low or below quantitation limit; SI not calculated.

D.O. and $N_2O$ together may just mean that the screened interval of nearly 1 m is too large to sample discrete redox zonation. In addition, the presence of $N_2O$ only suggests that denitrification has occurred somewhere, but it does not indicate where in the groundwater system it occurred. Alternatively, Bremner and Blackmer (1979) suggest that this relationship can occur if $N_2O$ is produced not by denitrification but by nitrifying microorganisms that reduce $NO_2^-$ to $N_2O$ during oxidation of surface-applied ammonium. Thus, $NO_2^-$ becomes the terminal electron acceptor rather than $O_2$. This is more likely to occur when the $O_2$ supply is limited. Further study is needed to investigate the origin of these $N_2O$ concentrations.

## SUMMARY AND CONCLUSIONS

Results of this study indicate that $NO_3$-N is the primary contaminant in groundwater at this transect. $NO_3$-N transport is limited to the zone of oxidized till where recharge and flow rates are the greatest and where oxidizing conditions exist. In contrast, the low redox potentials present in groundwater within the unoxidized till and loess units produce conditions of Mn, Fe, $SO_4$ reduction and methanogenesis. Above-ambient concentrations of $N_2O$ and preferential loss of $NO_3$-N relative to Cl and $^3H$ near the boundary between oxidized and unoxidized units suggest that denitrification occurs in groundwater. However, elevated $N_2O$ concentrations were detected well above this boundary after large recharge events. More data are need to determine the source of the $N_2O$.

This study has important implications for assessing the risk of groundwater contamination for in the Walnut Creek watershed. The hydrogeology and hydrogeochemistry of the Quaternary stratigraphic units (aquitard) will prevent $NO_3$-N contamination of deep aquifers and may remove $NO_3$-N before it reaches Walnut Creek. Tile drains that discharge into Walnut Creek are located above the zone of low redox potential and denitrification; thus, they bypass this potential attenuation mechanism. As a result, Walnut Creek receives agrichemicals that it would not have received under natural hydrologic conditions.

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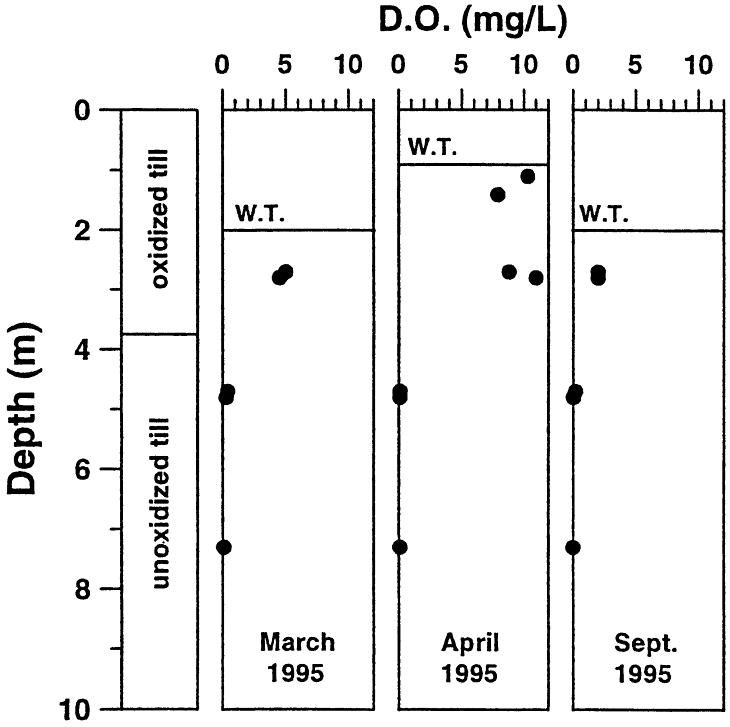

Figure 39. Vertical profiles of D.O. and position of water table in March, April, and September 1995 at the BT Nest.

# VARIABILITY OF DISSOLVED OXYGEN CONCENTRATIONS IN GROUNDWATER AT THE WALNUT CREEK CENTRAL TRANSECT

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## INTRODUCTION

Redox reactions that occur in groundwater are affected by the concentration of dissolved oxygen (D.O.). Reactions important to water quality studies, such as denitrification, can only occur if D.O. concentrations are very small; however, measurement of D.O. is frequently not an integral part of water quality investigations involving $NO_3$-N. Previous research in the Walnut Creek watershed suggests that D.O. and $NO_3$-N concentrations in groundwater are related (see Johnson et al., this guidebook). We hypothesize that groundwater recharge causes temporal variations in D.O. concentrations near the water table and that concentrations decrease with depth. The objective of our study is to test this hypothesis in shallow groundwater in the Walnut Creek watershed.

## METHODS

Hydraulic head and D.O. measurements have been made monthly in 25 shallow piezometers during a one year period. Piezometers are screened at depths between 1.5 to 8 m in oxidized and unoxidized, late Wisconsinan till of the Dows Formation and in Wisconsinan loess (see Simpkins and Johnson, this guidebook). D.O. is determined using CHEMetrics™ Indigo Carmine and Rhodazine-D ampoules installed into a self-designed, downhole sampler. The measurement range of these methods is 0 to 12 mg/L. Concentrations are obtained by both colorimetric comparison to known standards and by use of a portable spectrophotometer (White et al., 1990).

## RESULTS AND CONCLUSIONS

Based on data from our first year of monitoring, highest D.O. concentrations (up to 10.5 mg/L) occur near the water table and coincide with groundwater recharge in late spring (Fig. 39). Most of the recharge occurs in the oxidized till at this site. D.O. concentrations increase in all the piezometers in the oxidized till at the time of recharge; however, concentrations decrease thereafter presumably because of $O_2$ consumption. Concentrations decline markedly with depth and are barely detectable in samples taken below 4 m. D.O. concentrations do not vary significantly in the unoxidized till at depths to 7.3 m at this nest, suggesting that there is not much vertical $O_2$ transfer from zones near the water table. We will continue monitoring throughout 1996 to better define the temporal and spatial variability of D.O. in this groundwater system.

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# ORIGIN AND AGE OF DISSOLVED ORGANIC CARBON (*DOC*) IN GROUNDWATER IN THE WALNUT CREEK WATERSHED

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## INTRODUCTION

Groundwater contains thousands of dissolved organic compounds ranging in molecular weight from less than 100 to more than 5000 Daltons (Thurman, 1985). Referred to collectively as dissolved organic carbon, or DOC, these compounds are derived from the decay of solid organic matter (SOM) present in soils and unconsolidated sediments. Compounds that comprise DOC participate in a variety of chemical reactions critical to groundwater quality, including the chelation of heavy metals and radionuclides, and the bacterially mediated reduction of nitrate ($NO_3$-N) or denitrification. In the latter reaction, low molecular weight (< 100 Daltons) organic compounds such as acetate and formate may serve as the electron acceptors for oxidation of carbon.

Our interest in DOC stems in part from previous work on $NO_3$-N contamination of shallow groundwater in Pleistocene tills and loess in Iowa (Kross et al., 1990). This work showed that $NO_3$-N contamination is substantially less widespread in north-central Iowa than in other parts of the state. Based on previous research on the occurrence of DOC in late Wisconsinan till and loess in the Des Moines Lobe (e.g., Simpkins and Parkin, 1993), we hypothesize that geographic variation in the degree of $NO_3$-N contamination may be the result of differences in the kinds of DOC present in these materials. More specifically, we suspect that the lack of detections above the EPA-MCL of 10 mg/L $NO_3$-N in shallow groundwater in the Des Moines Lobe are the result of exceptionally high concentrations of relatively young, labile DOC derived from the decay of coniferous plant matter present in late Wisconsinan till and loess units. The more frequent occurrence of $NO_3$-N contamination of shallow groundwater in other parts of the state may reflect the fact that older, Pre-Illinoian till units at the surface have old DOC that is essentially depleted in labile organic compounds.

We have been conducting stable carbon isotope ($^{13}C/^{12}C$) and radiocarbon analyses of the humic and fulvic acid fractions of DOC isolated from groundwater samples, as part of an investigation of the ages and sources of DOC in shallow groundwater in Iowa. Samples have been taken from the Walnut Creek Central Transect and from the Ames Till Hydrology Site. Together, the humic and fulvic acid fractions account for nearly all of the high- and medium-weight dissolved organic compounds in groundwater.

Radiocarbon dating of these fractions yield their age, but it is also provides evidence bearing on their possible sources. In the Des Moines Lobe region, the most likely sources of DOC in groundwater are (1) partially decayed grasses and other plant matter in the A-horizons of modern soils, (2) organic matter associated with the Farmdale Soil, and (3) late Wisconsinan coniferous plant matter incorporated into late Wisconsinan till and loess at the time of their deposition. Additional evidence bearing on the origin of DOC in groundwater is provided by analysis of the ratios of the two stable isotopes of carbon, $^{13}C$ and $^{12}C$. This approach takes advantage of the fact that the organic tissues of $C_3$ plants such as coniferous trees are enriched in the heavier carbon isotope relative to tissues of $C_4$ plants such as certain grasses. More specifically, the stable carbon isotope ratio ($\delta^{13}C$) of $C_3$ plants averages about -26 ‰, while that of $C_4$ plants averages about -16 ‰. Differences in $\delta^{13}C$ between the major sources of DOC are reflected in the $\delta^{13}C$ of DOC (e.g., Wassenaar et al., 1992).

## METHODS

DOC must first be isolated and converted into solid form in order to analyze it for $\delta^{13}C$ and $^{14}C$. Isolation of DOC is accomplished using XAD-8 adsorption chromatography (e.g., Wassenaar et. al., 1990). Briefly, acidified groundwater samples are pumped through glass columns packed with XAD-8 resin, which sorbs both humic and fulvic acids. These fractions are desorbed and concentrated by back-pumping the columns with concentrated NaOH solution. Depending on the abundance of DOC, this step produces a concentrated solution that may range in color from straw yellow to amber or even to reddish-brown. Acidification of the concentrate causes solid humic acids to precipitate from the solution during a period of several days. The humic acid precipitate is separated from the fulvic acid solution by means of centrifugation. The separated humic and fulvic concentrates are frozen in plastic bottles (using a dry ice and methanol bath) and then freeze-dried to produce solid humic and fumic matter.

## RESULTS AND CONCLUSIONS

Our preliminary results show that DOC from groundwater in unoxidized late Wisconsinan till and loess in central Iowa has a $\delta^{13}C$ of approximately -26 ‰ and that it ranges in age from about 13,000 to 19,000 years B.P. The oldest DOC occurs in groundwater in the Wisconsinan loess. By contrast, DOC from groundwater in the oxidized late Wisconsinan till has a $\delta^{13}C \sim -20$ ‰ and is modern in age. These results corroborate the hypothesis that the principle source of DOC in unoxidized, late Wisconsinan till and loess is late Wisconsinan coniferous plant matter, and that DOC in oxidized till was derived primarily from plant matter, including $C_4$ grasses, in the A-horizon of modern soils at these sites.

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# SIMULATION OF GROUNDWATER FLOW AT THE WALNUT CREEK CENTRAL TRANSECT

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## INTRODUCTION

The interpreted distribution of equipotentials for the Walnut Creek Central Transect (see Simpkins and Johnson, this guidebook, Figs. 30 and 31) posed a number of questions about the validity of the K data and our concept of the groundwater flow system. We used a groundwater flow model to test our hypothesis about the configuration of the flow system at two different water-table conditions and to examine the possible fate of agrichemicals in the system.

## METHODS

The groundwater flow model was constructed by first extending the cross section in Figure 28 back to the nearest subwatershed divide (about 500 m). We assumed that the stratigraphy was similar out to this distance. We discretized the two-dimensional domain into 1122 grid cells. A greater density of cells was added in the area near the stream for more greater detail in hydraulic head (Fig. 40). Five separate model layers representing Holocene alluvium (Unit E) and Wisconsinan oxidized till (Unit A), unoxidized till (Unit B), loess (Unit C), and colluvium (Unit D) were assigned K values from field tests (A,C-E see Seo et al., this guidebook, Table 3; Unit D from Simpkins and Parkin, 1993). We imposed a no-flow boundary at the divide and below the creek down to the bottom of the loess unit. We specified the head at the bottom of the domain, at the sides of the colluvium/paleosol unit, and at the water table. The flow system was simulated at steady-state. We used the USGS modular finite-difference model MODFLOW (McDonald and Harbaugh, 1988) in conjunction with the particle tracking code MODPATH (Pollack, 1989) to track particles in the domain.

## RESULTS AND DISCUSSION

Model results for the high water-table condition (May 1995) predict a lateral component of flow in the oxidized till (as expected) and in the unoxidized till, even with its low K value (Fig. 41). It appears that the clayey colluvium/ paleosol unit forces the flow laterally except very near the lower boundary where flow is forced to be nearly vertical. Discharge calculated for the spring and at Walnut Creek are reasonable. Pathlines for this simulation suggest that particles entering the oxidized till further up in the recharge area move through the unoxidized till before entering the creek. This groundwater pathway would be a mechanism for removing $NO_3$-N (and pesticides).

Under the low water-table condition (November 1994), the groundwater flow system in the oxidized till disappears and particles travel totally within the unoxidized till unit (Fig. 42). As a result, more particles move vertically into the deeper units, particularly in the area nearer the imposed groundwater divide (not shown here). Although the fluxes are not large in this situation, it suggests that lowering the water table provides for the recharge of deeper units in the section. Note also that Walnut Creek becomes a losing stream in this simulation.

## SUMMARY AND CONCLUSIONS

We simulated steady-state groundwater flow at the Walnut Creek Central Transect using a finite-difference groundwater flow model. Based on the very simplified boundary conditions imposed on

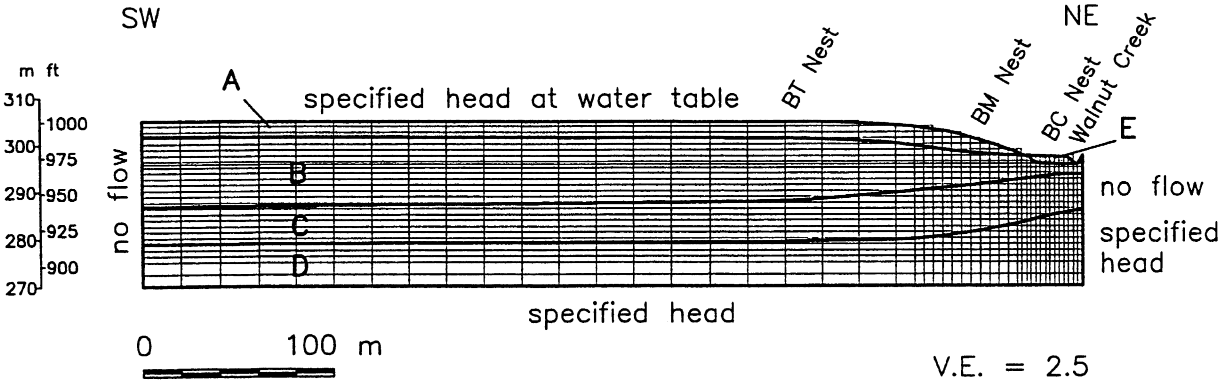

**Figure 40.** Discretized domain of the groundwater model for the Walnut Creek Central Transect. Model layers and respective K values are discussed in text.

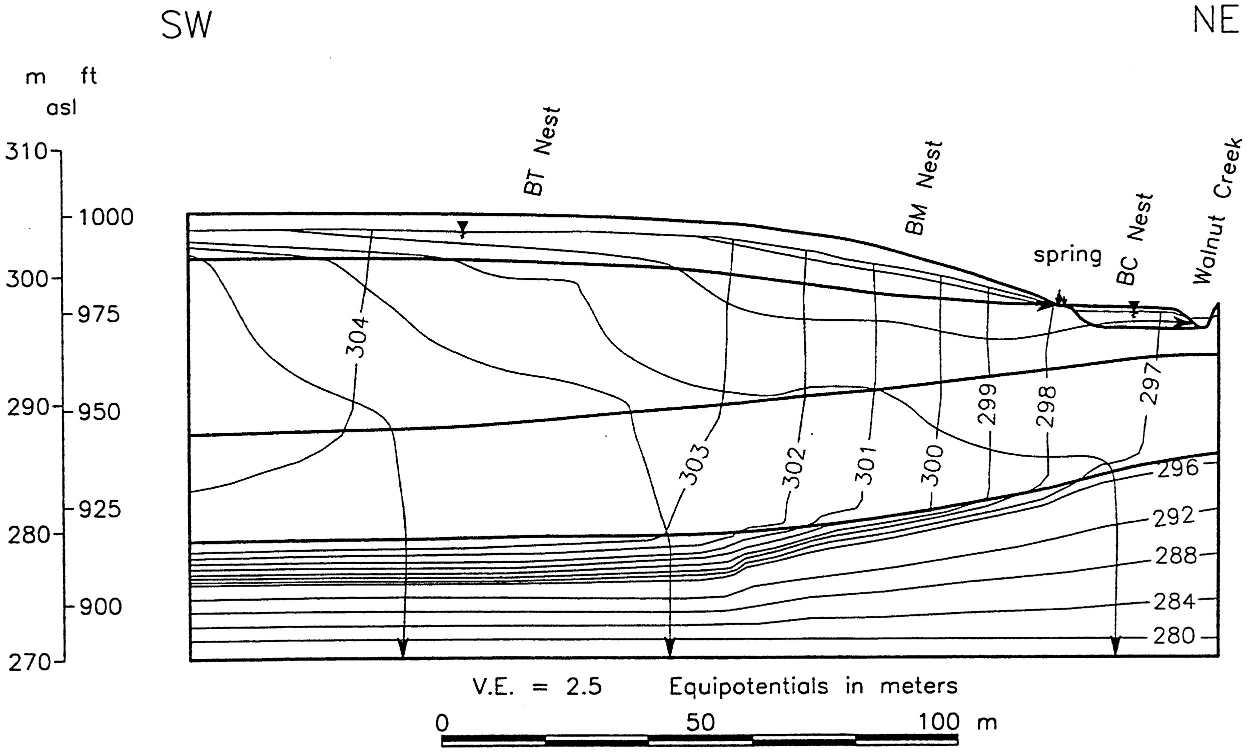

**Figure 41.** Results of simulations for the high water-table condition (May 1995).

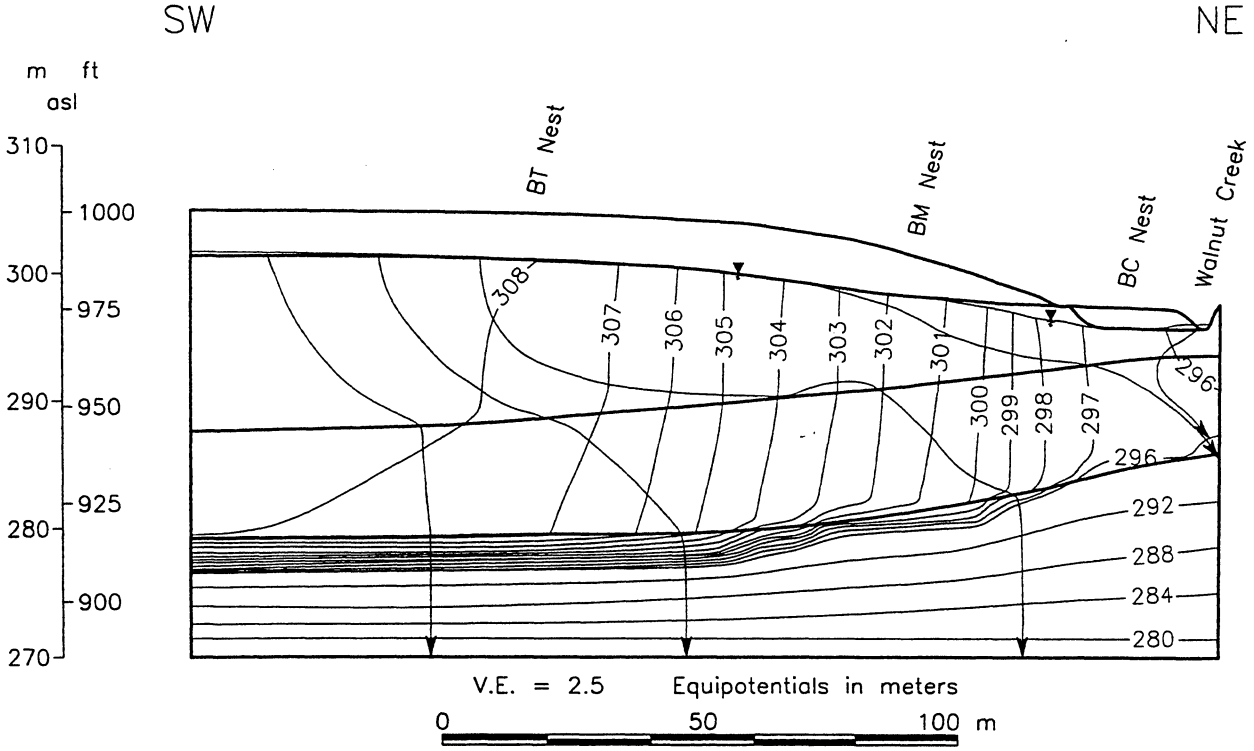

**Figure 42.** Results of simulations for the low water-table condition (November 1994).

the model, the results were similar to the hydraulic head distributions interpreted from the field data. This suggests that the field-derived data are reliable estimates. The suggestion from the model that agrichemicals are removed by vertical transport into the unoxidized till will be pursued in the next phase of research. We also plan to incorporate a head-dependent boundary at the creek, a drain node at the spring, and a specified recharge rate in order to allow the model to calculate the position of the water table.

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# LABORATORY DETERMINATION OF EFFECTIVE TRANSPORT PARAMETERS FOR FRACTURED TILL IN THE WALNUT CREEK WATERSHED

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## INTRODUCTION

Recent studies have shown that shallow aquifers in Iowa are contaminated by agricultural chemicals even though they are overlain by thick sequences of "impermeable" till. Recent surveys of private wells in Iowa suggest that 35 percent of shallow wells (< 15 m deep) contain $NO_3$-N at concentrations above the EPA MCL of 10 mg/L and 18 percent show a detection of at least one pesticide (Kross et al., 1990). Some of the more frequent detections occur in areas that are overlain by Pre-Illinoian till units containing well-documented fracture systems (see article by Simpkins, this guidebook). We hypothesize that the coincidence is not accidental and that fracture networks in the till can create preferential flow paths for the transport of contaminants to underlying aquifers. We are testing this hypothesis by conducting standard column experiments and breakthrough curve analyses on large-diameter core samples in the laboratory.

Contaminant transport through fractured media is different than transport in the standard porous media such as sand. Average linear or advective velocities are greater in fractured systems than in a bulk sample of clay, for example, because fracture porosity is often several orders -of magnitude smaller than total or bulk porosity (Jorgensen and Spliid, 1992; McKay et al., 1993). The average linear velocity of a conservative solute can be determined from the equation,

$$\mathrm{v} = \frac{\mathrm{Ki}}{n_e}$$

where v is the average linear velocity, K is the hydraulic conductivity, i is the hydraulic gradient, and $n_e$ (or $q_e$) is the effective porosity of the medium. Values of bulk porosity ($n_b$ or $q_b$) are often used where effective values are not available. This equation is useful for predicting the initial breakthrough time of a contaminant in a fractured system; however, it is not adequate for describing later parts of a solute breakthrough curve because it neglects dispersion, retardation, and matrix diffusion. The latter process retards the center of mass of the plume because, assuming a favorable concentration gradient, solute moves from the fractures into the lower-permeability matrix during transport (Foster, 1975).

A more complete model for predicting solute transport through a fractured medium has been described by Van Genuchten and Wierenga (1976). Two porosities are assumed in this model: a mobile region where advective and diffusive transport takes place, and an immobile region where transport occurs only via diffusion. The mass transfer between the mobile and immobile zones is driven by a concentration gradient and is analogous to matrix diffusion. The governing equations for this mobile-immobile model (1-dimensional, dual-porosity system with no sorption) are:

$$\theta_{\mathrm{m}} \frac{\partial c_m}{\partial t} + \theta_{\mathrm{im}} \frac{\partial c_{\mathrm{im}}}{\partial \mathrm{t}} = \theta_{\mathrm{m}} D_m \frac{\partial^2 c_m}{\partial x^2} - \theta_b \frac{\partial c_m}{\partial x}$$

$$\theta_{\mathrm{im}} \frac{\partial c_{\mathrm{im}}}{\partial t} = \alpha \left(c_m - c_{im}\right)$$

where:

$c_m$ and $c_{im}$ = solute concentrations in the mobile and immobile liquid phases
$\theta_m$, $\theta_{im}$, $\theta_b$ = mobile and immobile region porosities and bulk porosity
$D_m$ = coefficient of hydrodynamic dispersion for the mobile region
$\alpha$ = first-order rate coefficient for solute transfer from mobile to immobile region
t = time since solute introduction to column
x = length of column

This model cannot be applied in most groundwater systems since it only describes flow in one dimension; however, it can be used in breakthrough curve experiments in the laboratory to estimate mobile (effective) porosity and thus average linear velocity.

Effective porosity can also be estimated by measuring the volume of water released from a known volume of saturated material (Kluitenberg and Horton, 1990). The volume of water released with respect to the total volume of the sample is the drainable porosity ($q_d$) or specific yield ($S_y$). This value is always less than the bulk porosity and generally closer to the actual effective porosity.

For this preliminary study, we conducted solute breakthrough experiments in a large-diameter core sample of oxidized and fractured late Wisconsinan till. We used the dual porosity model to calculate $q_m$ from the breakthrough curves and measured the drainable porosity ($q_d$). Finally, we used the average linear velocity equation and our estimates of $q_b$, $q_m$, and $q_d$ to predict the arrival time of the solute at the end of the column and compared our predictions with the observed velocities.

## METHODS

The experiment was performed on a large-diameter (0.28 m diameter, 0.17 m length) sample of oxidized and fractured late Wisconsinan till that was excavated from a local borrow pit near Ames. Fracture spacing in the till was approximately 5 cm, which is similar to the spacing reported by Lee (1991) at this site. Vertical and horizontal fracture surfaces and root holes were observed in the core. The sample was placed in a polyethylene container and transported undisturbed to the laboratory. Paraffin wax was used to seal the wall of the core to prevent flow along the sidewall of the container. The core was saturated by ponding water above the sample and applying a vacuum of 15 psi to the lower end of the core. A constant hydraulic gradient of 0.905 was applied to the sample, and water was allowed to flow through the core for one week before flow rate was measured. Hydraulic conductivity (K) was calculated using Darcy's Law.

Solute breakthrough experiments were conducted with a conservative solute (1 g/L NaCl) and a non-conservative solute (1 g/L K $NO_3$). The relative effluent concentration ($C/C_0$) was determined by electrical conductance. Mobile porosity was calculated by fitting the dual porosity model to the Cl and $NO_3$-N breakthrough curve (BTC) using the computer program CXTFIT (Parker and Van Genuchten, 1984). A mass transfer coefficient ($\alpha$) of $4.57 \times 10^{-4}$ 1/s (Li et al., 1994) was assumed for simulation of the Cl BTC. Drainable porosity ($\theta_d$) was measured by draining the saturated core for a period of 12 hr and collecting the effluent in an airtight container to reduce loss by evaporation.

## RESULTS AND DISCUSSION

The measured K of the till core was $3.9 \times 10^{-7}$ m/s. This value of K is less than values measured in the field (see Seo and Simpkins, this guidebook) but greater than K values measured from laboratory measurements elsewhere (K ~$10^{-8}$ to $10^{-9}$ m/s; Lutenegger, 1989).

Breakthrough curves from the experiments are typical of a dual porosity system (Figs. 43 and 44). Arrival time of the solute front, defined as the point at which the $C/C_0$ attained a value of 0.01, was 13.2 min for Cl and 16.2 min for $NO_3$-N. In view of the low K value determined for this material, the rapid breakthrough suggests that the solute moved pri-

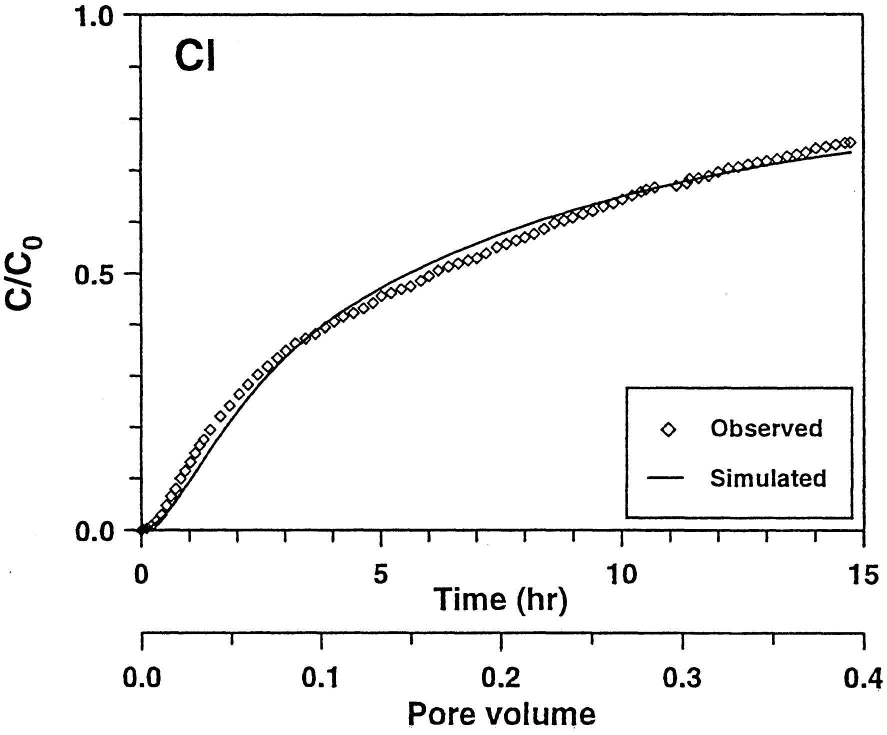

Figure 43. Observed and CXTFIT simulation ($r^2$=0.99) results from Cl experiment.

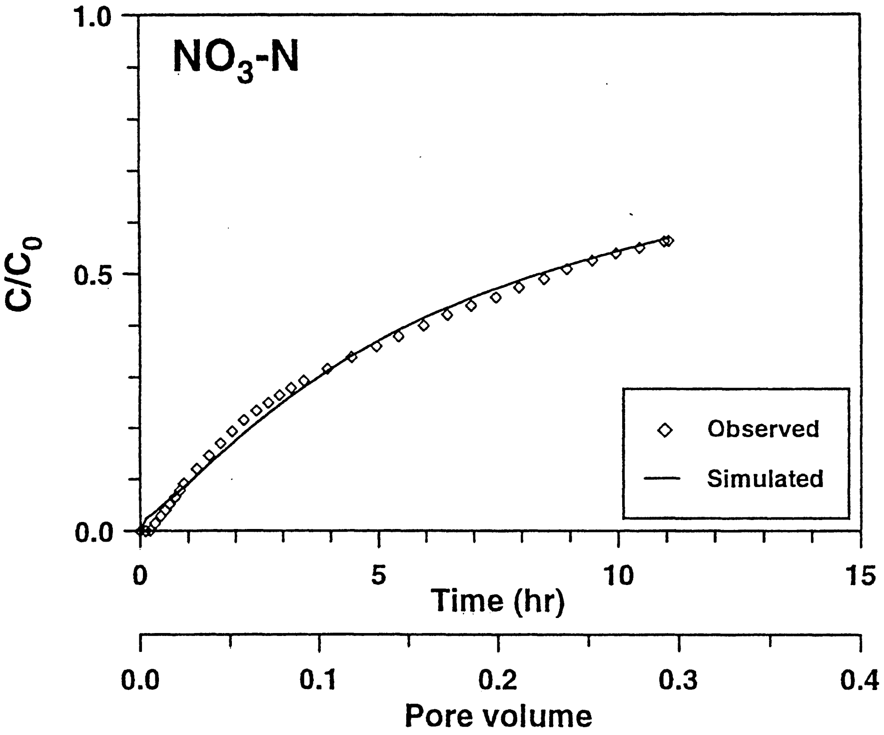

Figure 44. Observed and CXTFIT simulation ($r^2$=0.99) results from $NO_3$-N experiment.

**Table 11.** Comparison of observed and predicted groundwater velocities in the large-diameter core.

| Calculation method for velocity | Velocity, m/d |
|---|---|
| BTC Observed, Cl | 18.4 |
| BTC Observed, $NO_3$-N | 15.0 |
| Predicted, K, i, $\theta_b$ | 0.101 |
| Predicted, K, i, $\theta_m$ | 6.42 |
| Predicted, K, i, $\theta_d$ | 4.43 |

marily by fracture flow. The center of mass of the solute plume, defined at $C/C_0=0.5$, did not appear at the end of the column until 6.11 hr for Cl and 8.89 hr for $NO_3$-N. This "tailing" phenomenon is also typical of dual porosity media and is probably the result of matrix diffusion. The reason for the difference in arrival time of Cl and $NO_3$-N has not been investigated.

The model CXTFIT successfully simulated the BTCs ($r^2=0.99$). Mobile porosity, $\theta_m$, was estimated at $0.0047 \pm 0.001$ and $D = 1.2 \times 10^{-6}$ m²/s for Cl. For $NO_3$-N, the value of $\theta_m$ from the Cl simulation was used to obtain $D = 8.3 \times 10^{-7}$ m²/s and $\alpha = 1.55 \times 10^{-4} \pm 3.4 \times 10^{-5}$ 1/s. The total porosity ($\theta_b$) of the till was 0.30 (30 percent). The measured drainable porosity ($\theta_d$) was estimated to be 0.007 (0.7 percent) - a value that is similar to the value of $\theta_m$.

The average linear velocity equation was used to calculate breakthrough times using estimates of $\theta_b$, $\theta_m$, and $\theta_d$ and these values were compared to observed breakthrough velocities (Table 11). Predicted (using $\theta_m$ and $\theta_d$) and observed breakthrough velocities were within the same order of magnitude; however, velocity was two orders of magnitude lower than the observed when $\theta_b$ was used to estimate velocity.

## SUMMARY AND CONCLUSIONS

Based on our preliminary column experiment with a large-diameter core, it appears that fractures in till can increase the contaminant transport velocities significantly. Effective porosity determined by either using a dual porosity solute transport model or by measurement of drainable porosity provides a better estimate of the velocity of groundwater in fractured till environments. Movement of agricultural contaminants quickly through fractures in till may explain why shallow aquifers in Iowa have become contaminated by nitrate and pesticides. Matrix diffusion may also explain the persistence of these contaminants in groundwater through time. In the future, we plan to continue these types of experiments on larger-diameter core samples of both late Wisconsinan and Pre-Illinoian till units.

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# STOP 6

# INTERACTION OF GROUNDWATER AND WALNUT CREEK AT THE CENTRAL AND EASTERN TRANSECTS

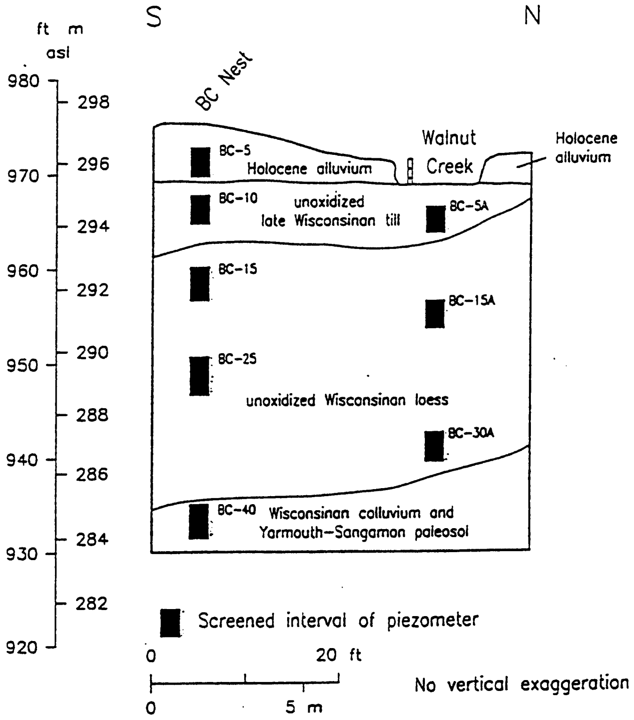

**Figure 45.** Cross section of the Walnut Creek Central Transect showing piezometer locations and stratigraphic units. Hachured stick in creek is the staff gage.

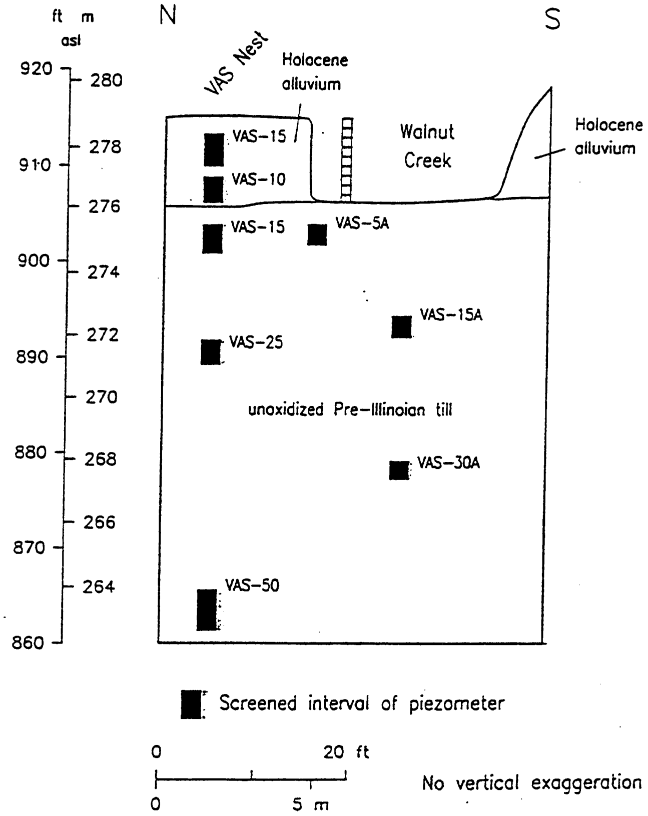

**Figure 46.** Cross section of the Walnut Creek Eastern Transect showing piezometer locations and stratigraphic units. Hachured stick in creek is the staff gage.

# INTERACTION OF GROUNDWATER AND WALNUT CREEK AT THE CENTRAL AND EASTERN TRANSECTS

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## INTRODUCTION

Results presented earlier in this guidebook indicate that Walnut Creek, like many streams draining cropland in the Midwest, is contaminated with $NO_3$-N and pesticides. Data have also suggested that tile drains provide a rapid pathway from cropped fields to Walnut Creek and thus contribute a substantial portion of that contamination. Groundwater may also carry contaminants from cropped fields to Walnut Creek; however, the flux of contaminants by this pathway is not known. Conversely, at times of peak flow, Walnut Creek may contaminate the groundwater immediately adjacent to the creek through bank storage. Contaminated water in bank storage may eventually flow back into the creek and cause additional contamination (see Squillace et al., 1993). The purpose of this preliminary study was to examine the interaction between groundwater and Walnut Creek in these fine-grained materials and to determine the magnitude and seasonal fluctuation of hydraulic head and hydraulic head gradients between the creek and groundwater.

## METHODS

This study utilized the angled and vertical piezometers at the Walnut Creek Central and Eastern Transects that are described elsewhere in the guidebook (see Simpkins and Johnson, this guidebook). Beginning in September 1995, hydraulic heads in piezometers at the BC and VAS Nests and the stage of Walnut Creek were monitored weekly or biweekly. Hydraulic heads previous to this date were affected by slug tests, water quality sampling, and recovery to equilibrium. Water levels were measured to the nearest 0.002 m using an electric tape. Stage was determined manually by reading water surface elevation from staff gages at each transect. Piezometers and staff gages were surveyed in to the nearest 0.0003 m of absolute elevation above sea level.

The stratigraphy and K values at the two transects are quite different. At the Central Transect, Walnut Creek flows on top of unoxidized late Wisconsinan till of the Dows Formation ($K = 6 \times 10^{-9}$ m/s) that overlies Wisconsinan loess ($K = 1 \times 10^{-9}$ m/s) and Wisconsinan colluvium and Yarmouth-Sangamon paleosol ($K = 6 \times 10^{-11}$) (Fig. 45). A terrace consisting of sandy Holocene alluvium ($K = 7 \times 10^{-5}$ m/s) lies immediately adjacent to the channel on both sides of the creek. At the Eastern Transect, Walnut Creek flows on top of unoxidized Pre-Illinoian till. Although K values have not been determined for these piezometers, values for this unit at this site are in the range of $7 \times 10^{-10}$ m/s (Fig. 46). A large terrace, also containing sandy Holocene alluvium, lies adjacent to the creek at this site. A mean K value for this unit has not been determined, but it is probably similar to that of the alluvium of the Central Transect.

## RESULTS AND DISCUSSION

### Central Transect

Hydraulic heads measured in piezometers at the BC Nest suggest that groundwater has the potential to flow into Walnut Creek (Fig. 47). The water table fluctuates between the alluvium and the top of the unoxidized till. Based on monitoring since September and some previous data, a hydraulic gradient and potential for groundwater flow is established from the groundwater to the creek during the spring and into the late fall. The evidence for this is a horizontal component of the gradient from the water table (either BC-5 or BC-10) to the creek and a upward-directed, vertical component of gradient from BC-5A to the creek (Fig. 47 ). Visual observations at the site and groundwater modeling have suggested that more water may discharge at springs up gradient from the creek alluvium than into the creek at this time.

Beginning in November and December, this relationship appears to reverse, such that the stage of the creek lies above the hydraulic head shown in both piezometers (Fig. 47). The creek shows a very small discharge during this period, although we hesitate to term it "baseflow" because of the contribution of water from tile drains during this time. The water table drops into the unoxidized till and there is potential for flow outward from the creek. It must be noted that measuring stage during the winter months was difficult due to freezing of the creek, so stages may have dropped further than shown in Figure 47; however, hints of this trend have occurred in previous years, so we think the relationship is valid. The trend appears to reverse itself in February and is accompanied by higher flows (due to snowmelt) in the creek (Fig. 47). The water table responds to the increase in stage and there is a lesser response in the piezometer immediately under the creek. Based on these preliminary data, we believe that piezometers BC-5, BC-10, and BC-5A represent groundwater that interacts with Walnut Creek.

The presence of waveform-like trends in hydraulic head (Fig. 47) in proximity to a fluctuating boundary condition such as the creek was unexpected. Sinusoidal wave patterns that are propagated from the surface to hydraulic heads at depth are a commonly observed phenomenon in fine-grained sediments. The vertical propagation of this wave downward and its attenuation with depth are described by the vertical hydraulic diffusivity, $K_v/S_s$ of the material (see Keller et al., 1989). In addition, a "loading effect" due to snow and changes in the water content occurs seasonally and results in a second sinusoidal wave variation in piezometers that are probably too deep to be realistically affected by the propagation of a surface waveform (Maathuis and van der Kamp, 1985). In our case, the hydraulic heads in the BC Nest follow the general sinusoidal pattern shown earlier for the up gradient BM and BT Nests at this site, although some damping is evident in the BC Nest waveform (Fig. 29). The relationship between the nests may suggest that these variations are in response to recharge through infiltration at the site and responses to creek stage. Increases in creek stage, however, do appear to affect a response (Fig. 47), so perhaps it is a combination of both processes.

Deeper piezometers in the BC Nest (BC-15, BC-15A, and BC-25) also show this sinusoidal pattern of hydraulic head; however, they are offset in time from shallow piezometers by at least 2 months and do not respond directly to increases in creek stage (Fig. 48). This phase lag is consistent with propagation of a surface wave, particularly because the lag time increases as K values decrease - as they do with depth at this site. Based on the distribution of the equipotential field at this site, it appears that groundwater in the unoxidized loess and below does not interact with Walnut Creek. Deeper piezometers (BC-40 and BC-30A) showed very little fluctuation during the monitoring period and are probably "unaware" of Walnut Creek.

## Eastern Transect

Hydraulic heads at piezometers at the VAS Nest also suggest that groundwater flows towards Walnut Creek along the water table (Fig. 49). An upward-directed vertical gradient from VAS-15 to VAS-10 suggests flow up into the creek. Hydraulic heads increased quickly with an increase in stage in February 1996 and suggest a temporary reversal of gradient at that time. The seasonal variation seen at the Central Transect is not present in these data. However, deeper piezometers (VAS-15A and VAS-25) suggest some very long-term sinusoidal variation that is similar to that at the Central Transect (Fig. 50). Although the hydraulic head in VAS-25 indicates a potential for vertical flow to the creek, this relationship may not reflect current hydraulic conditions because of the time lag and the long period of the sinusoidal waveform. The hydraulic head measured in January 1996 was first true static reading in this piezometer. Based

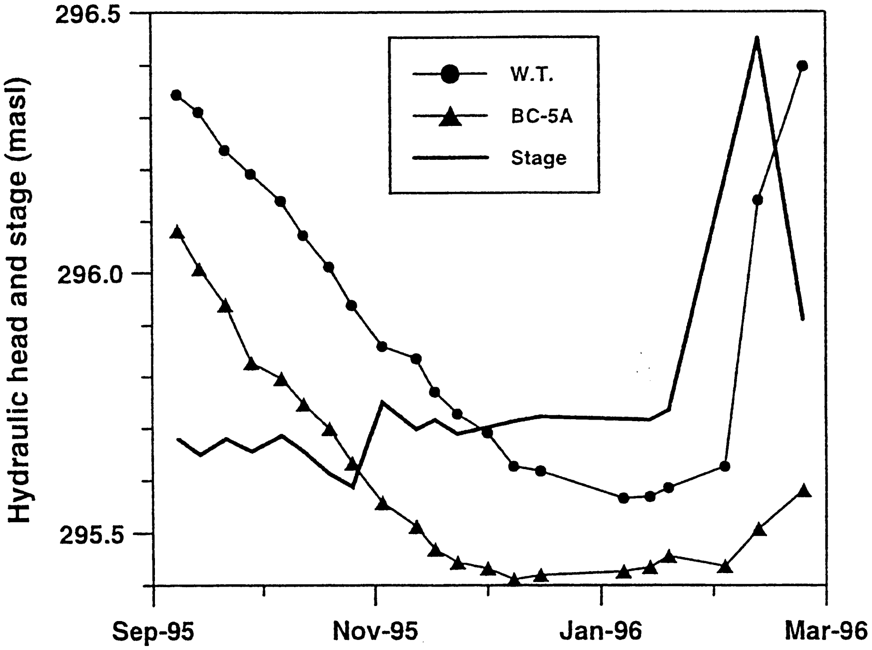

**Figure 47.** Variation of stage and hydraulic head for piezometers at the water table (BC-5 or BC-10) and BC-5A (below creek) at the Walnut Creek Central Transect since September 1995.

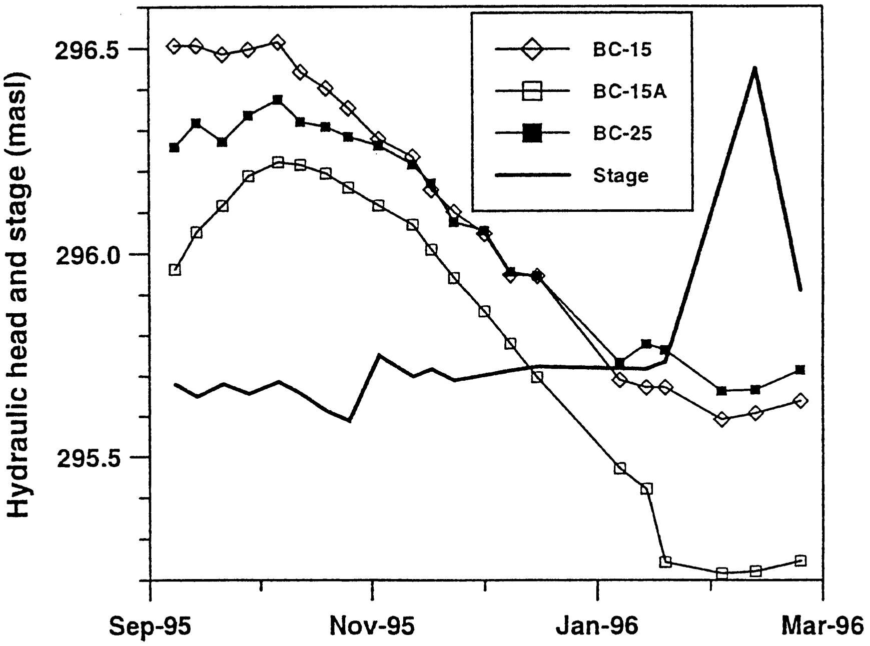

**Figure 48.** Variation of stage and hydraulic head for piezometers BC-15, BC-15A (below creek), and BC-25 at the Walnut Creek Central Transect since September 1995.

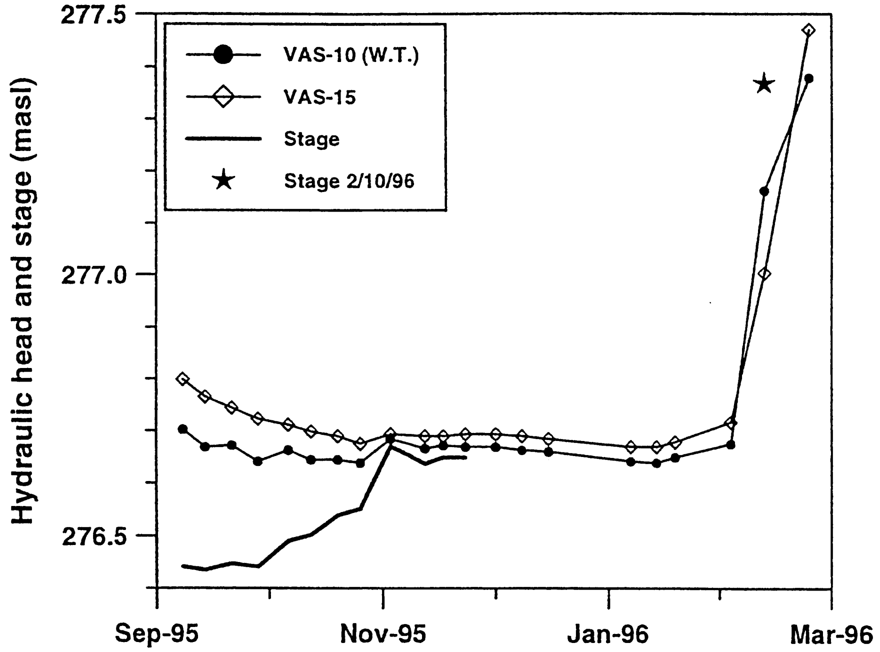

**Figure 49.** Variation of stage and hydraulic head for piezometers at the water table (VAS-10) and VAS-15 at the Walnut Creek Eastern Transect since September 1995. Peak flow on February 10, 1996, was preceded by a period of no data due to a frozen creek.

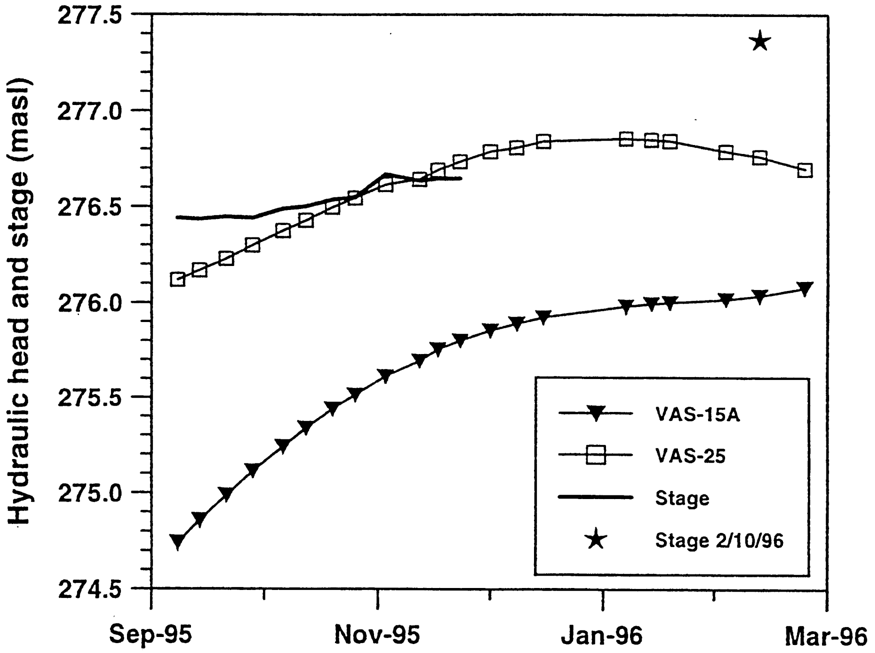

**Figure 50.** Variation of stage and hydraulic head for piezometers VAS-15A (below creek) and VAS-25 at the Walnut Creek Eastern Transect since September 1995. Peak flow of February 10, 1996, was preceded by period of no data due to a frozen creek.

on these data, we hypothesize that that only groundwater measured in VAS-10 and VAS-15 is interacting with Walnut Creek at this transect. Piezometers VAS-15A, VAS-25, and deeper piezometers are responding to boundary conditions other than Walnut Creek and on much longer time scales.

## Groundwater Flux into Walnut Creek

Although there appears to be good evidence for groundwater discharge into Walnut Creek, the total contribution of that flow is generally small and depends on the contributing unit. For example, at the Central Transect, using a horizontal hydraulic gradient at the water table of 0.07 and a $K = 7 \times 10^{-5}$ m/s (alluvium), the groundwater discharge is $4.8 \times 10^{-6}$ $m^3/s$ through a 1 $m^2$ cross section. For comparison, discharge calculated in the groundwater model (see earlier section) was $5.9 \times 10^{-5}$ $m^3/s$ through a 1 $m^2$ cross section. Flux is reduced if the water table falls to an elevation within the unoxidized till. Using a horizontal hydraulic gradient at the water table of 0.095 and $K = 6 \times 10^{-9}$ m/s (unoxidized till), discharge is limited to $5.7 \times 10^{-10}$ $m^3/s$ for a 1 $m^2$ cross section. At the Eastern Transect, the horizontal hydraulic gradient at the water table in alluvium is 0.09. Using a $K = 7 \times 10^{-5}$ m/s (alluvium), the discharge of groundwater to the creek is $6.1 \times 10^{-6}$ $m^3/s$ per 1 $m^2$ cross section. We expect that the contribution of the unoxidized till at the Central Transect will be much less than this value, given that the K values are much lower for that unit. Comparison of all these values to the average discharge of Walnut Creek of 0.2 $m^3/s$ at the Central Transect, suggests that groundwater contributes only a small part of the discharge of the creek and that tile drains supply most of the creek flow.

## SUMMARY AND CONCLUSIONS

Our preliminary study of the interaction of groundwater and Walnut Creek at the Central and Eastern Transects suggests that groundwater discharges into Walnut Creek, probably from zones within a few meters below and adjacent to the creek. The amount of groundwater discharge is small in comparison to the total creek discharge. The hydraulic head relationships and thus the direction and magnitude of groundwater flow between the units are complicated by slow response times in the low K units at the two transects. Because $NO_3$-N and pesticides have not been found in piezometers adjacent to the creek, we assume that the net flux of contaminants to the creek from groundwater is also very small or non-existent. Future work at these transects will include installation of piezometers directly into the creek bed to better define hydraulic head relationships (similar to those described at Stop 7), seepage meter studies to quantify flux into the creek, transducers and dataloggers to continuously monitor hydraulic head and stage relationships, and computer simulation of the groundwater flow system to predict value of flux into and out of the creek.

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# STOP 7

# LOSS OF STREAM DISCHARGE AND IMPLICATIONS FOR WATER QUALITY IN AN ALLUVIAL AQUIFER

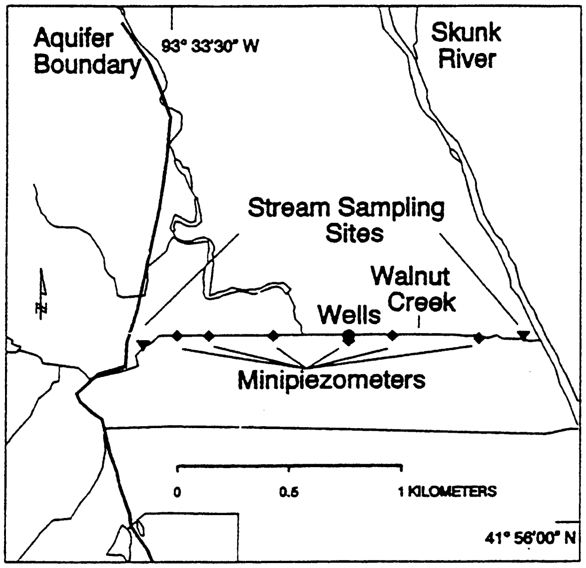

**Figure 51.** Map of the alluvial reach of Walnut Creek.

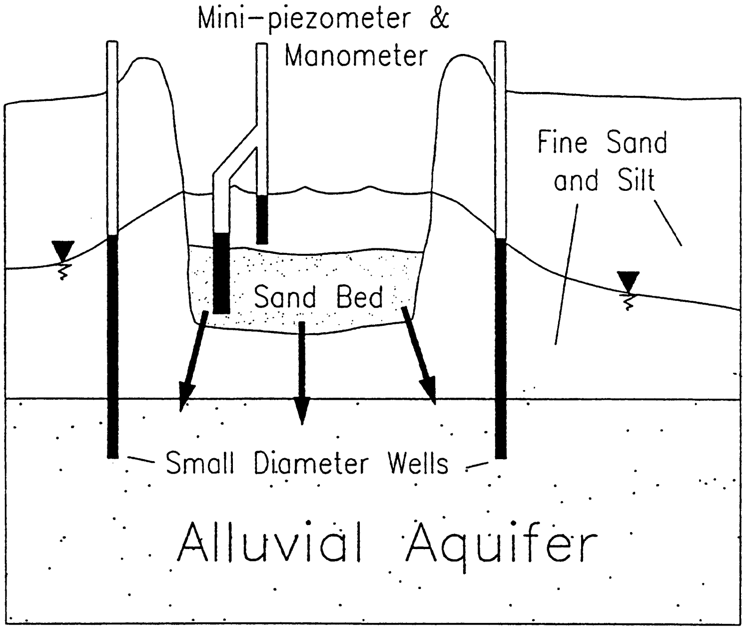

**Figure 52.** Schematic diagram showing the relationship of groundwater, hydraulic heads, and sediments beneath Walnut Creek.

# LOSS OF STREAM DISCHARGE AND IMPLICATIONS FOR WATER QUALITY IN AN ALLUVIAL AQUIFER

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## INTRODUCTION

Alluvial aquifers and other unlithified (unconsolidated) aquifers have been shown to be among the most susceptible to agrichemical contamination in the Midwest (Burkart and Kolpin, 1993). Leaching of chemicals by precipitation or irrigation water through soils has been the most studied process contributing to such contamination. However, preliminary studies in the channelized lower reach of Walnut Creek have suggested to us that the infiltration of agrichemicals downward through the creek bed and into the underlying alluvial aquifer may also be a significant mechanism for contamination. The potential for this process to occur was noted during an earlier study of Walnut Creek and the South Skunk River alluvial aquifer, where atrazine was detected in piezometers installed beneath cropped fields (Buchmiller, 1994). The appearance of atrazine in groundwater samples from the piezometers was noteworthy because this herbicide had not been applied on the overlying field for several years. Investigators also observed a decrease in discharge in the creek to nearly zero as the creek passes from the upland till area onto the South Skunk River alluvium; this phenomenon suggests that at least this part of Walnut Creek is a losing reach. Together, these observations led us to investigate vertical infiltration of creek water as a mechanism for atrazine contamination of the alluvial aquifer.

## METHODS

In 1994, a preliminary study was conducted to define the hydraulic head relationships between the creek and the alluvial aquifer and to estimate the flux of agrichemicals through the stream bed. Two flow conditions were selected for the preliminary analysis. First, a period of sustained tile-drain and creek discharge was selected in April 1994 before the late spring application of herbicides and when agrichemical concentrations in the creek were hypothesized to be at a minimum. Next, a period after the spring herbicide application was selected when stream discharge was higher than normal and associated with runoff after a rainfall event in June. At both times, the differences among hydraulic head in the creek, creek bed, and aquifer were measured and water samples for analysis of $NO_3$-N, triazine and acetanelide herbicides, atrazine metabolites (deethylatrazine and deisopropylatrazine) and ethanesulfonic acid (an alachlor metabolite) were collected.

Stream discharge measurements were made at two points about 1,300 meters apart in order to quantify the loss of stream discharge to the aquifer (Fig. 51). At the midpoint in the studied reach of

**Table 12.** Concentrations of agrichemicals in Walnut Creek, the creek bed sediment, and the South Skunk River alluvial aquifer.

| | **Concentrations During April 1994** | | | **Concentrations During June 1994** | | |
|---|---|---|---|---|---|---|
| **Chemical Name** | **Creek** | ***Creek Bed*** | **Aquifer** | **Creek** | ***Creek Bed*** | **Aquifer** |
| Nitrate | 6.3 mg/L | 6.0 mg/L | 5.6 mg/L | 7.1 mg/L | 5.7 mg/L | 2.4 mg/L |
| Atrazine | 0.11 mg/L | 0.16 mg/L | 0.08 mg/L | 2.44 mg/L | 3.37 mg/L | 0.16 mg/L |
| Cyanazine | <0.05 mg/L | <0.05 mg/L | <0.05 mg/L | 3.28 mg/L | 0.48 mg/L | <0.05 mg/L |
| Deethylatrazine | 0.11 mg/L | 0.14 mg/L | 0.10 mg/L | 0.21 mg/L | 0.32 mg/L | 0.14 mg/L |
| Deisopropylatrazine | <0.05 mg/L | <0.05 mg/L | <0.05 mg/L | 0.24 mg/L | 0.30 mg/L | 0.12 mg/L |
| Ethanesulfonic acid | 0.76 mg/L | 0.76 mg/L | 0.74 mg/L | 0.59 mg/L | 0.65 mg/L | 0.65 mg/L |
| Metolachlor | 0.13 mg/L | 0.12 mg/L | 0.07 mg/L | 1.42 mg/L | 2.54 mg/L | 0.11 mg/L |

the creek, a transect of small diameter (3.6 mm) wells was installed beneath and on either side of the creek with a portable electric jackhammer in order to obtain access to the aquifer and the stream bed material (Fig. 52). Hydraulic head differences between the creek and creek bed were measured using a portable potentiomanometer (Winter and others, 1988).

## RESULTS AND DISCUSSION

The aquifer at this location consists of sand and gravel that coarsens with depth. It is generally 10 to 15 m thick, although the specific thickness in this location is not known. The aquifer is separated from the creek bed by 2 to 4 m of silt and fine-grained sand. The creek bed material consists of less than 1 m of well-sorted medium sand.

During both measurement periods, the creek stage was higher than the hydraulic head in the creek bed at six measurement points (Figs. 51 and 52). The difference in hydraulic head was only 7 to 8 mm over a vertical distance of 70 cm, but it indicates the potential for vertical flow from the creek to the creek bed. Similarly, hydraulic head measurements in the creek and aquifer at the transect (Fig. 51) showed that the creek stage was 114 mm above the hydraulic head in the aquifer in April and 144 mm above it in June. These difference in hydraulic head were measured over a vertical distance of 4 m between the creek and the top of the aquifer. It is clear from these measurements that the creek has the potential to lose water during the two conditions sampled.

The water quality obtained from creek bed sediments was similar to that of the creek water (Table 12). Concentrations of atrazine, two atrazine metabolites (deethylatrazine and deisopropylatrazine), cyanazine, and metolachlor were substantially larger in June than in April. Note that the concentrations of atrazine, metolachlor, and atrazine metabolites in the June samples from the creek bed are larger than those found in the creek. This difference probably reflects previous recharge to the creek bed which contained larger concentrations of these compounds. Concentration of $N0_3$-N did not vary in water in the creek or the creek bed between the two seasons, a finding consistent with long term monitoring of the creek at this point and further upstream.

The concentration of atrazine in the aquifer beneath the creek nearly doubled between April and June and metolachlor increased by more than

50 percent. The smaller concentration in the aquifer compared to the creek and the creek bed may result from dilution when herbicide-charged water recharges the aquifer. Herbicide sorption and degradation may also reduce concentrations in water beneath the creek. The relatively consistent concentrations of ethanesulfonic acid (ESA) in the creek, creek bed, and aquifer in both sample periods is noteworthy. ESA is a first-order degradation product of alachlor, an herbicide not currently used in the watershed. Its presence in the creek indicates there may be residual concentrations stored in soils and mobilized by tile drainage throughout the watershed. Similar concentrations in the aquifer indicate this compound may be present in many parts of the hydrologic system of the area.

Chemical flux from the creek to the alluvial aquifer was calculated as the product of the stream discharge lost per unit area of the creek bottom and the concentrations of atrazine. For comparison, an estimate of atrazine flux via leaching through a field was made assuming an annual residue of 10 mg/L atrazine (1 percent of the normal application rate) at 2 m depth and an annual recharge rate of 150 mm. The estimated 1 percent residue at 2 m is relatively large when compared to leaching model estimates in the area. Despite this overestimate of field leaching rates, estimates of atrazine flux through the creek bed from this study are generally 2 to 3 orders of magnitude greater than field leaching estimates. The flux rates of chemicals from Walnut Creek to the aquifer were 60 mg/d/$m^2$ in April and 8,700 mg/d/$m^2$ in June. The large seasonal difference reflects the larger concentrations and larger creek discharge in June. Conditions in April represent sustained tile-drain discharge conditions near the end of the annual cycle of herbicide application and flushing through the hydrologic system. By comparison, fluxes from field leaching were estimated to be only 4 mg/d/$m^2$; hence, even if we assumed that the residual atrazine at 2 m depth was 10 percent of the field application rate, the resulting flux from leaching would still be less than the vertical flux to the aquifer derived from pre-application tile-drain discharge in Walnut Creek.

## CONCLUSIONS

Preliminary results from this study illustrate that vertical leakage from a tributary stream (i.e. Walnut Creek) into an alluvial aquifer (i.e., South Skunk River alluvium) can substantially exceed field leaching, which has traditionally been considered the main process for delivering herbicides to groundwater. If this process of vertical leakage occurs in many hydrologic settings, it may be necessary to reexamine the utility of using field-leaching models to explain groundwater contamination by agricultural chemicals.

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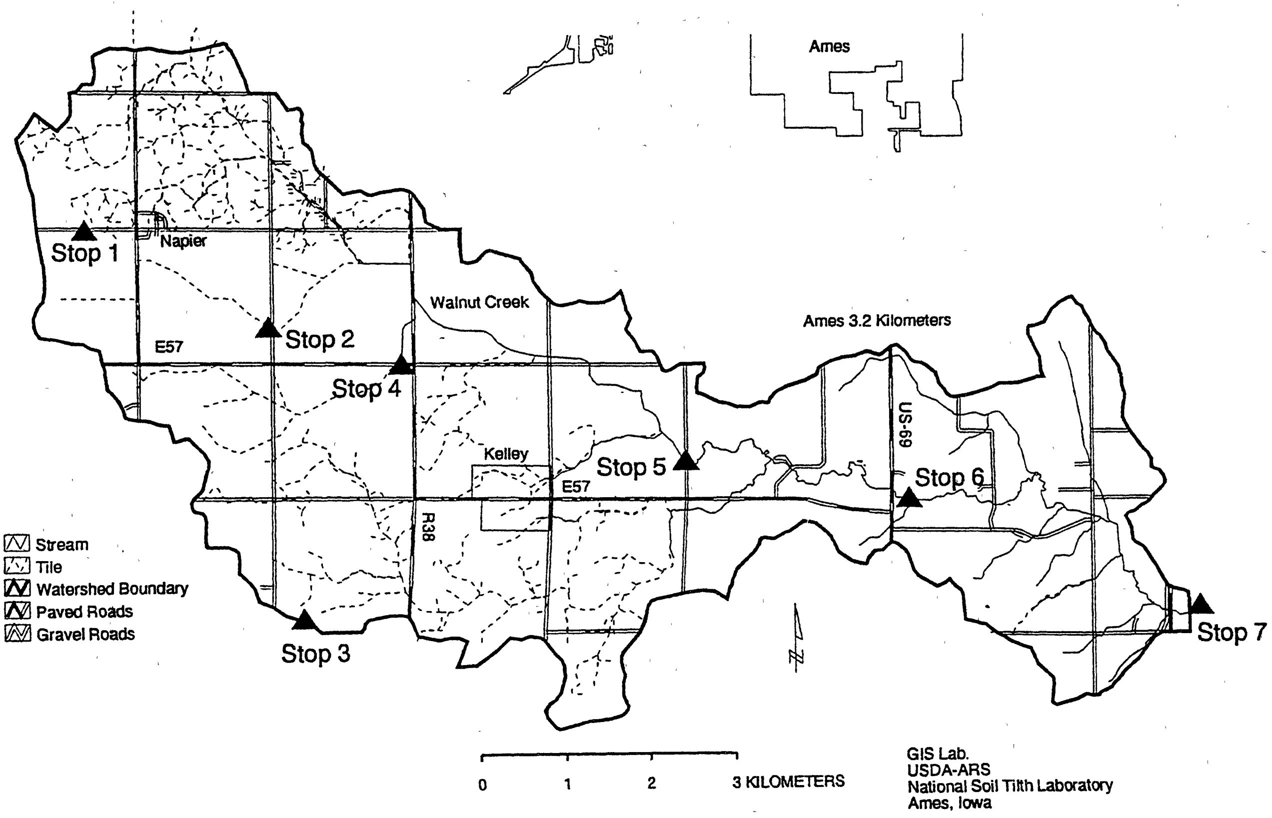

Map of the Walnut Creek watershed showing locations of the field trip stops.

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