IS-5117
UC-600

ZERO-TENSION LYSIMETERS:

AN IMPROVED DESIGN TO MONITOR COLLOID-FACILITATED CONTAMINANT TRANSPORT IN THE VADOSE ZONE

by

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Date Transmitted: April 24, 1995

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Prepared for the
Characterization, Monitoring, & Sensor Technology Crosscutting Program
Office of Technology Development
U.S. Department of Energy

*Operated by Iowa State University for the
U. S. Department of Energy under Contract
No. W-7405-ENG-82.

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ABSTRACT

There is increasing evidence that mobile colloids facilitate the long-distance transport of contaminants. The mobility of fine particles and macromolecules has been linked to the movement of actinides , organic contaminants, and heavy metals through soil. Direct evidence for colloid mobility includes the presence of humic materials in deep aquifers as well as coatings of accumulated clay, organic matter, or sesquioxides on particle or aggregate surfaces in subsoil horizons of many soils. The potential for colloid-facilitated transport of contaminants from hazardous-waste sites requires adequate monitoring before, during, and after *in-situ* remediation treatments.

A lysimeter is a device permanently installed in the soil to sample soil water periodically. Zero-tension lysimeters (ZTLs) are especially appropriate for sampling water as it moves through saturated soil, although some unsaturated flow events may be sampled as well. Because no ceramic barrier or fiberglass wick is involved to maintain tension on the water (as is the case with other lysimeters), particles suspended in the water as well as dissolved species may be sampled with ZTLs. Conventionally, ZTLs consist of shallow pans or troughs that are inserted laterally into the soil from an access pit or trench. But conventional design and installation of ZTLs leads to a number of problems. First, digging access pits or trenches to depths appropriate for sampling subsurface materials may be impractical or prohibitively costly. Second, disturbance of trench walls by digging equipment (e.g., smearing of the pit walls; fractures induced by the jarring of backhoe buckets) may alter physical conditions and limit interpretations and predictions for unsampled sites. Finally (and most importantly), the time and space required to install a conventional ZTL may place limitations on the number of replications possible at a given site and thereby limit appropriate monitoring of spatial variability.

To address these problems, a ZTL design is proposed that is more suitable for monitoring colloid-facilitated contaminant migration. The improved design consists of a cylinder made of polycarbonate or polytetrafluoroethylene (PTFE) that is placed below undisturbed soil material. In many soils, a hydraulically powered tube may be used to extract an undisturbed core of soil before placement of the lysimeter. In those cases, the design has significant advantages over conventional designs with respect to simplicity and speed of installation. Therefore, it will allow colloid-facilitated transport of contaminants to be monitored at more locations at a given site.

Zero-tension lysimeters are intended to capture samples of suspended colloids as they move in the vadose zone. The specific benefits of the proposed design are related to the simplicity of installation and the concomitant reduction of cost of monitoring. Because more ZTLs of the proposed design than of the conventional design can be installed to assess site variability, more accurate monitoring of contaminant transport before, during, and after remediation will be achieved. In addition, because of the improved spatial resolution in sampling and monitoring, if

contaminants are mobilized, their source can be more easily identified than with piezometer-based monitoring methods.

The improved zero-tension lysimeters described in this proposal have been installed at five sites contaminated with americium and plutonium at Rocky Flats Plant, Golden, Colorado. Rainfall simulation experiments have been performed to test the ability of the improved lysimeters to intercept mobile colloids and actinides and to compare their behavior with that of conventional zero-tension lysimeters.

Zero-tension lysimeters have been installed near Ames, Iowa, where colloid-facilitated transport of heavy metals (Cu, Ni, Cd, and Zn) in municipal sewage sludge amendments is monitored. In water samples collected from the lysimeters, suspended colloid concentrations, heavy metals, dissolved organic carbon, electrical conductivity, and pH are determined. Rainfall simulation experiments designed to simulate the intensity of typical summer storms will be completed along with transport simulation trials designed to identify the initial pH and ionic strength levels of soil water that are most conducive to mobilization of organic and phyllosilicate colloids and associated metals.

TECHNOLOGY NEED

Zero-tension lysimeters (ZTLs) are needed to monitor contaminant migration in conjunction with mobile colloids. They are applicable where a contaminated site is undergoing *in-situ* remediation treatment that leaves the soil physically undisturbed. Their use would be also be recommended in other contexts where colloid-facilitated transport of contaminants is suspected or must be quantified in near-surface environments, but where remediation is not actively taking place. Unfortunately, zero-tension lysimeters of the conventional design are expensive to install because they require significant excavation and disturbance of the soil.

A zero-tension lysimeter that can be installed in much less time and with less site disturbance than conventional ZTLs was developed and demonstrated in this project. The technology is most suitable where contaminants have impacted the soil surface. Where contaminants are deeply buried below the soil surface, the improved zero-tension lysimeter may be employed only if physical disturbance of the soil overlying the lysimeter is not expected to affect colloid mobility significantly (perhaps the case in fairly coarse-textured deposits).

BACKGROUND AND THEORY

Some environmental contaminants (e.g., heavy metals and certain radionuclides) have been assumed to be immobile in soils because they are strongly sorbed to soil solid phases in laboratory batch studies (e.g., McBride, 1989). However, contaminant mobility may be greatly enhanced in situations where solid-phase components are themselves mobile. There is increasing evidence that mobile colloids can facilitate the long-distance transport of soil contaminants (McCarthy and Zachara, 1989). The mobility of naturally occurring fine particles and macromolecules has been linked to the movement of actinides (Penrose et al., 1990), organic contaminants (Enfield and Bengtsson, 1988; Dunnivant et al., 1992), and heavy metals (Dunnivant et al., 1992) through soil. Devices designed to monitor the movement of colloids and associated contaminants are needed both at sites where significant levels of contaminants are present as well as at sites undergoing active *in-situ* remediation treatments to remove contaminants.

Natural colloidal materials in soils include humic macromolecules synthesized during microbial oxidation of vegetative materials (Stevenson, 1982), certain microorganisms (Corapcioglu and Haridas, 1985), precipitated sesquioxides (e.g., iron and manganese oxides), and phyllosilicate clay minerals (e.g., smectites and micas)(Hayes and Himes, 1986; Borchardt, 1989). Many environmental factors influence colloid mobilization, ranging from the pH, redox potential, and osmotic potential (related principally to ionic strength) of the soil solution (Thompson et al., 1976) to the size and continuity of pores in the soil (Beven and Germann, 1982; Thompson, 1987). The drainage regime of the soil appears to be a master variable and predictor in this regard (Scharf and Thompson, 1990).

Direct evidence for natural colloid mobility includes the presence of humic materials in deep aquifers (Thurman, 1985) as well as coatings of accumulated clay, organic matter, or sesquioxides on particle or aggregate surfaces in subsoil horizons of many soils (Bullock and Thompson, 1985). Unfortunately, relatively little quantitative information about colloid mobility is available, including identification of the near-surface conditions that initiate colloid transport as well as long- and short-term fluxes of colloids in different kinds of soil. Significant colloid transport is probably coincident with preferential flow of water in soils. Thus, it may occur under saturated soil conditions when large, continuous pores function to conduct water, solutes, and suspended particles. On the other hand, colloids may also be mobilized by preferential flow that occurs in dry, unsaturated soil.

Two kinds of colloid mobilization can be distinguished: **(1)** dispersion of organomineral colloids or discrete organic colloids containing radionuclides and metal ions and **(2)** preferential flow of suspended soil colloids and/or soluble contaminants in soil macropores.

Chemical dispersion of colloids in soil may occur **(a)** when water that has a low osmotic potential (i.e., low ionic strength) or a high pH moves through the soil (Sposito, 1984), **(b)** when water (e.g., irrigation water) with a large sodium content is added to the soil (Thompson et al., 1976; Yousaf et al., 1987),**(c)** when low-molecular-weight organic anions produced by soil microorganisms are sorbed on mineral surfaces, increasing the net negative surface-charge density (Oades, 1984), and **(d)** when iron oxides that normally act as cements between particles are dissolved by low oxidation-reduction potentials (Vepraskas, 1992). *Physical dispersion* of soil colloids typically occurs when dry soils are suddenly wet, e.g., by a rainstorm. Swelling pressures caused by imbibition of water and compression of air in soil aggregates can cause particles to be sloughed from the aggregates and carried with the moving water.

Preferential flow. Most soils contain macropores, i.e., large, continuous pores (greater than about 1 mm in diameter) through which water can move rapidly (Beven and Germann, 1981). Macropore flow may occur in either saturated or unsaturated soils, but greater quantities of water and dissolved species can move in a given period under saturated conditions. If water is applied to soil so that saturated flow occurs, dissolved species and suspended colloids may flow downward, primarily through macropores, invalidating predictions of their fate that assumed uniform mixing of solute with the soil. Such conditions may occur when high fluid rates are used, when the soil is already near saturation at the time of application, or where heavy precipitation shortly follows application of water. Alternatively, if water is applied to a dry soil surface where large cracks are present, unsaturated vertical flow may occur in the cracks. Enfield and Bengtsson (1988) have suggested that organic colloids may actually move through soil faster than small molecules because colloid movement is restricted to relatively continuous macropores.

Although there has been considerable interest recently in colloid-facilitated transport of many types of contaminants in soil (McCarthy and Zachara, 1989; Corapcioglu and Haridas, 1985; Dunnivant et al., 1992; Vinten et al., 1983a, b), many questions remain. There have been very few investigations to establish near-surface fluxes of organic and/or inorganic colloids under ambient climatic conditions. Moreover, it is not known which of the possible mechanisms of colloid transport described above are most significant in field situations. The lysimeter described in this report is a device intended to sample mobile soil water, mobilized colloids, and any associated contaminants.

DESIGN AND INSTALLATION

Design of an Improved Zero-Tension Lysimeter

Figure 1 depicts the zero-tension lysimeter's design (Thompson and Scharf, 1994). It was adapted from the ideas of Howitt and Pawluk (1985). The lysimeter consists of a cylinder that is 8 cm long, has an 8.9-cm outside diameter, and is sealed to a base at one end. The upper 1 cm of the cylinder is indented by 2 mm so that an 8.3-cm (inside diameter) ring can fit at the top. A polyester screen with 150-um openings is placed between the cylinder and the ring and bonded into place. The ring's edge is beveled at a 35-degree angle to penetrate unconsolidated soil material that overlies the lysimeter upon installation in the soil. The base plate is cut from a solid cylinder of polycarbonate the same diameter as the open cylinder. Cutting the base from a solid cylinder at a slight angle produces a sloping floor for the lysimeter. This design insures that water will be directed toward a sampling nipple at the base of the lysimeter.

A rigid sampling nipple (3.2 mm OD, 1.6 mm ID) is inserted through the wall of the cylinder at the lowest point of the sloping floor and bonded in place with epoxy. A fluorinated ethylene propylene (FEP) tube of length appropriate for the depth of lysimeter installation is attached to the sampling nipple. Near the top of the cylinder, a second rigid nipple (same size as the sampling nipple) is inserted and epoxied into the wall to provide an outlet for air as water moves into the cavity and also to allow air to enter the lysimeter during sample extraction. A flexible polyester tube leading to the soil surface is attached to the vent nipple. Tubes for both the sampling nipple and the vent nipple are attached by short (about 5 cm) piece of connecting polyethylene tubing (2.0 mm ID).

Lysimeter prototypes have been constructed of both polycarbonate and PTFE. Both materials minimize sorption of either contaminants or natural, suspended colloids by the device itself. PTFE also has excellent resistance to a very large number of chemicals and pH ranges. A PTFE base probably provides somewhat greater rigidity and durability for the lysimeter, although in the period of this study no difference between the two materials was observed.

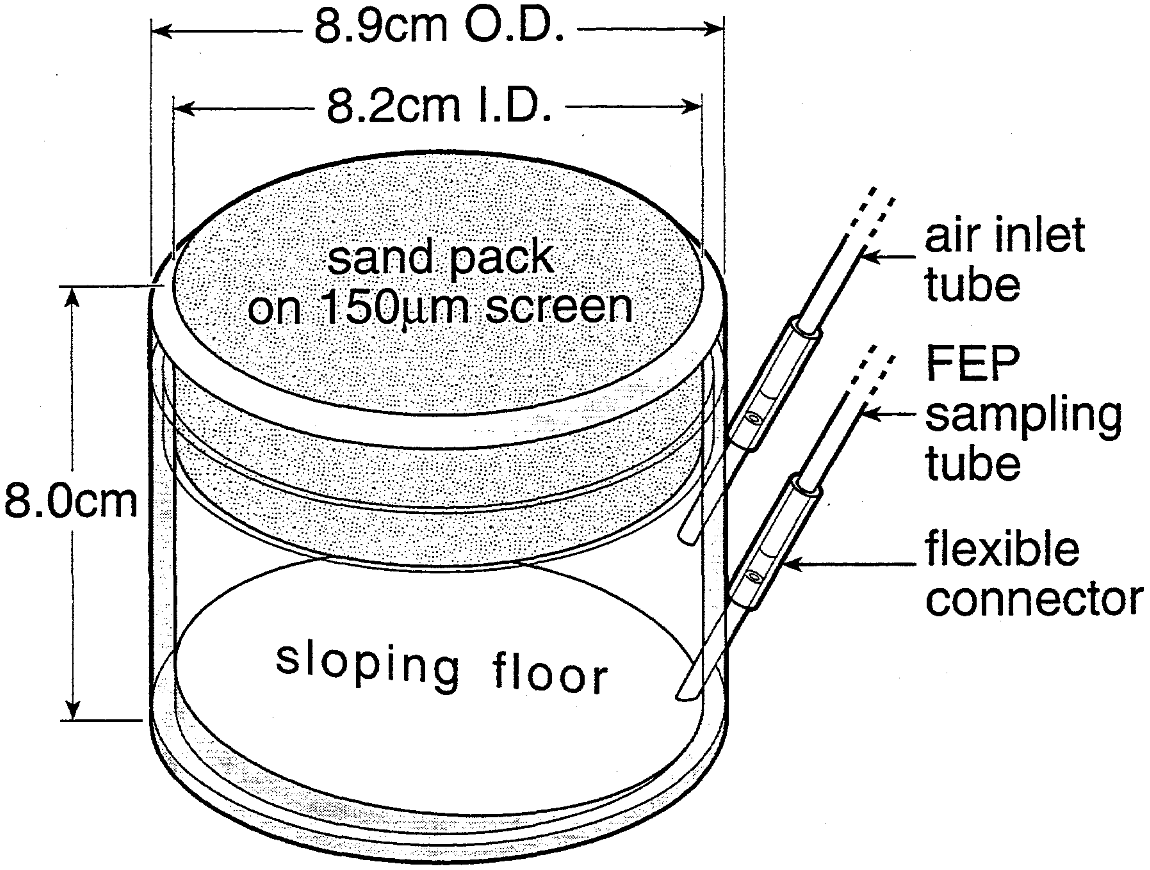

Figure 1. Design of the zero-tension lysimeter.

To insure that only undisturbed soil material directly overlies the lysimeter, it is sized to be 1.3 cm smaller than the diameter of a soil core removed with the 10.2-cm-diameter sampling tube of a Giddings hydraulic soil coring and sampling machine (Giddings Machine Company, Fort Collins, Colorado). This is the largest tube currently available and the largest tube practical for sampling most soils with the conventional Giddings soil coring machine. If other means are available to remove an undisturbed soil core of larger diameter, the lysimeter may be enlarged proportionately. Given the variabilities of pore- and aggregate-size distributions in most soils, it is not recommended that the lysimeter be made smaller.

Normal Method of Installation

The ZTL is installed when the soil is dry enough that an undisturbed core can be extruded from the sampling tube easily. The appropriate water content will vary from soil to soil, depending especially on clay content. A Giddings hydraulic soil probe is used to collect an undisturbed core about 10 cm in diameter and approximately as long as the desired depth of lysimeter placement. The Giddings unit may be mounted on a pickup, a trailer, or a tractor (Fig. 2).

The installation steps are:

(1) Remove an undisturbed core of soil to the chosen depth.

(2) Unscrew the cutting bit from the sampling tube and gently extrude a length of the core that corresponds to the length of the lysimeter (i.e., about 9.5 cm).

(3) Before placing the lysimeter in the ground, place enough acid-washed, silica sand onto the screen at the top of the cylinder to fill the cavity and provide hydraulic contact with the overlying soil. Then place the lysimeter at the base of the hole and surround it with sand for stability.

(4) Replace the core in its hole so that it seats well on the beveled cylinder of the lysimeter (Fig. 3). The core may be supported with a length of fishing line as it is lowered gently into the hole; then the line is slipped from under the core before pushing the core down onto the beveled edges of the lysimeter.

The sand at the top of the lysimeter should have a uniform size distribution, chosen to be slightly smaller than the size of the dominant conducting pores in the overlying soil (e.g., 1-2 mm). We have used tumbled sand from Granusil Corp., LeSueur, MN 56058. Depending on the roughness of the soil core's base, a thickness of about 1 cm of sand should be sufficient to provide contact between the soil and the lysimeter.

Installation Options

This installation technique has been successfully used to a depth of 50 cm in a variety of unsaturated soils in Iowa as well as at the Rocky Flats Environmental Technology Site in Colorado (see below). Deeper placements are possible in

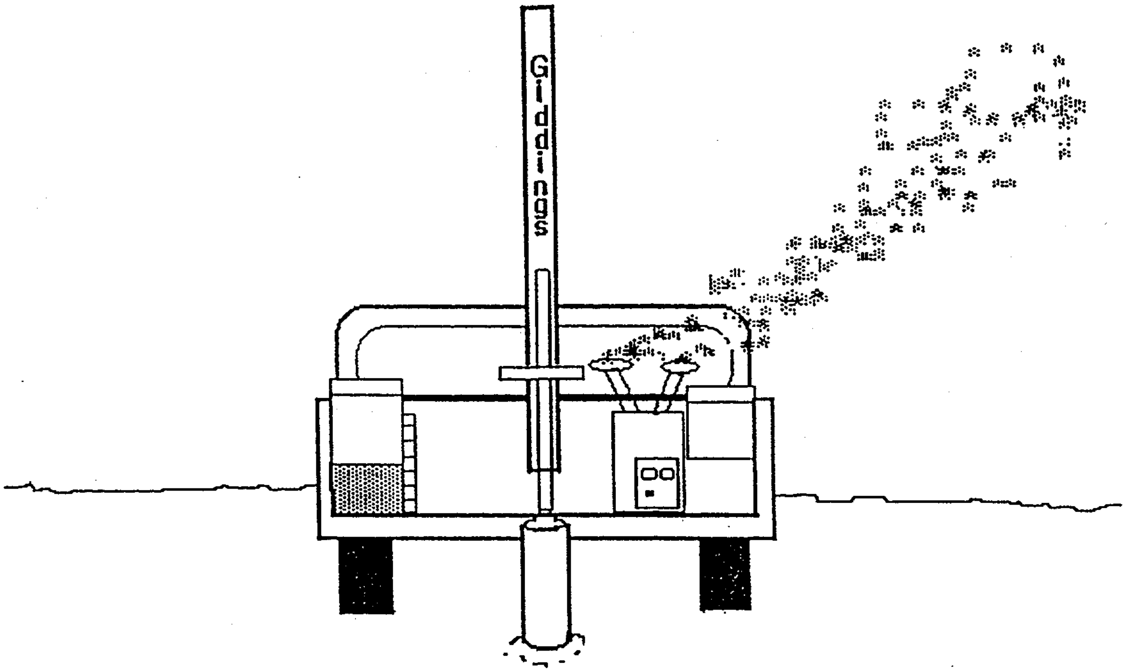

Figure 2. Truck-mounted Giddings soil probe about to pull up an undisturbed core of soil.

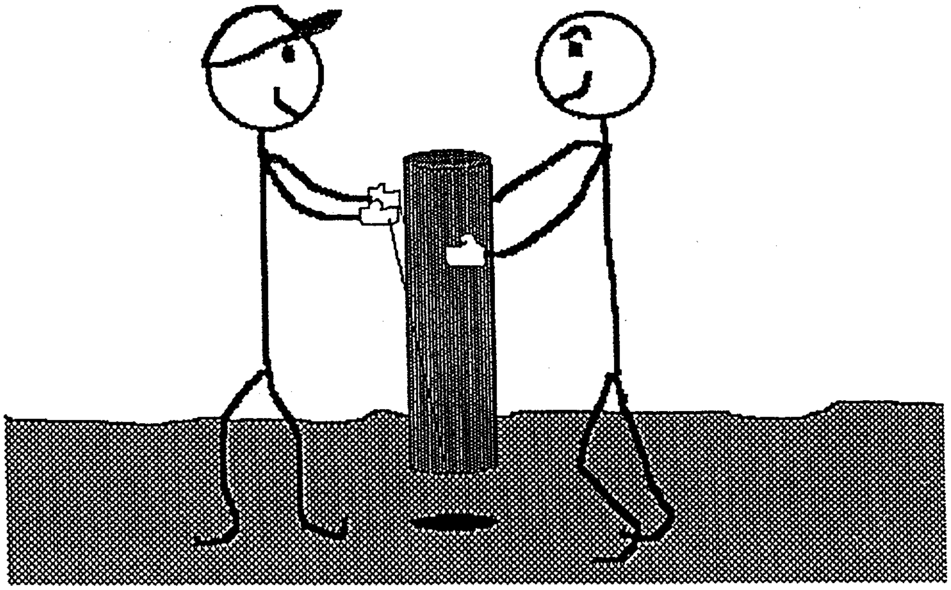

Figure 3. Lowering an undisturbed core of soil into its original hole and on top of a zero-tension lysimeter placed at the base of the hole.

principle, but the logistical problems of placing the lysimeter in the hole, of extruding an undisturbed soil core from the sampling tube, and of lowering the intact core to the lysimeter are reasons for caution. Where concerns about maintaining the physical organization of the soil are minimal (e.g., where the soil above the lysimeter depth has been recently tilled or where distributions of pore size and continuity are relatively uniform), it may not be necessary to maintain an undisturbed core above the lysimeter. In such instances, the lysimeter's hole could be excavated with a bucket auger by hand, and the lysimeter may be placed considerably deeper than 50 cm. Another scenario in which a bucket auger installation would be appropriate would be where the soil is too rocky or cemented to allow recovery of an undisturbed core by a Giddings probe.

Sampling and Maintenance

Samples of soil solution or suspension are removed from the lysimeter by applying suction to the sampling tube with a hand pump or peristaltic pump (Fig. 4). Normally, sampling will take place shortly after it is believed that saturated water flow has occurred in the soil, e.g., spring snow melt, long periods of rain in spring, heavy rainstorms, etc. Sampling interval depends upon depth of lysimeter placement as well. The lysimeter may be especially useful to monitor colloid mobilization and transport during <u>in</u>-<u>situ</u> remediation treatments that require long periods of saturation and significant fluid flux.

When there is intense rainfall on a relatively dry soil, water may enter zero-tension lysimeters under conditions of unsaturated flow. After micropores and mesopores near the soil surface fill with water, further rainfall "spills over" into macropores (Bouma and Dekker, 1977). Unsaturated flow into the lysimeter occurs when one or more conducting macropores (associated with faunal activity, root growth, or shrinkage cracks) are in direct contact with the layer of sand at the top of the lysimeter. Therefore, sampling the ZTL is recommended after each significant event, even if saturated flow was unlikely.

It is useful to place a fine mesh screen (e.g., with 150-mm openings) at the end of the vent tube and a cap at the end of the sampling tube to prevent occupation of the tubes by insects and arachnids. We have found it helpful to mark the location of sampling and air tubes where they emerge from the ground by leading them into a brightly painted polyvinyl chloride pipe placed vertically into the ground near the lysimeter. Periodically, the lysimeters may be cleaned <u>in</u> <u>situ</u> by pumping in a detergent solution which is allowed to sit for 24 hours before being flushed thoroughly by pumping with distilled water. Strongly alkaline cleaning solutions such as sodium hypochlorite may etch polycarbonate ZTLs and should be avoided.

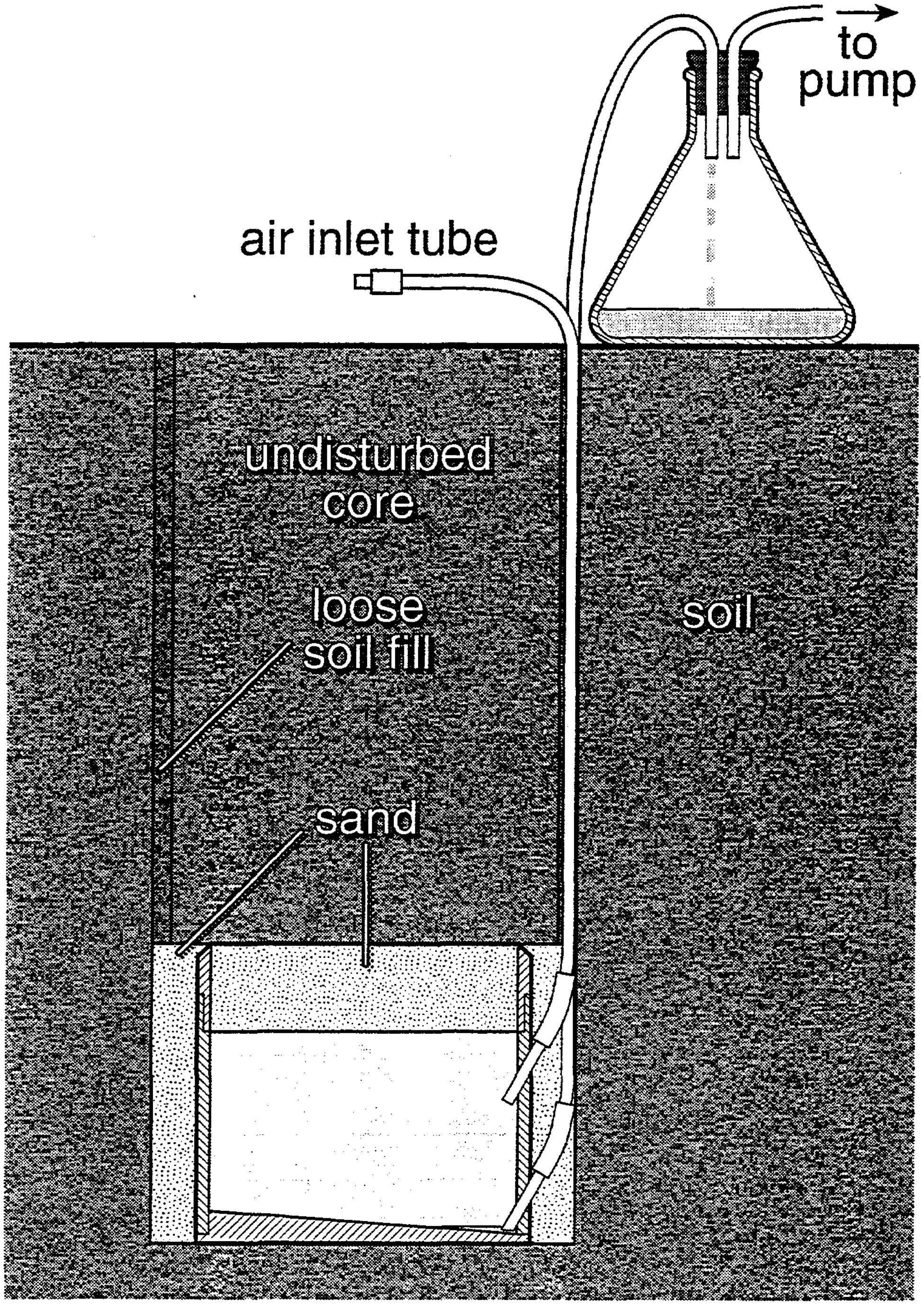

Figure 4. Retrieving water collected in the zero-tension lysimeter.

COSTS

A ZTL constructed of polycarbonate cost approximately $60 for labor and materials.

A ZTL constructed of PTFE cost approximately $200 for labor and materials.

The cost of installation includes labor and access to a Giddings soil probe. Once experience has been gained at installation procedures, each installation (at 50 cm depth in unconsolidated soil) takes two people about 45 minutes.

A trailer-mounted Giddings soil probe cost about $20,000 in 1994.

FIELD INVESTIGATIONS: ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE, GOLDEN, COLORADO

Site Context

A general description of the soils at the Rocky Flats Environmental Technology Site is found in Appendix A of this report.

Soils near the 903 Pad at Rocky Flats Plant have been contaminated as a result of leaking barrels of Pu-contaminated oil (McGehee et al. 1994) (Fig. 5). Surficial soil horizons within 1 km of the pad were subsequently contaminated by wind dispersal of Pu oxide particles during clean-up operations. Areal and vertical surveys of Pu concentration in Rocky Flats soils suggest that Pu contamination resides mainly in the upper 10 cm of the soil, but that as much as 10% of the total Pu deposit has migrated to deeper levels (Litaor et al., 1994). Elevated concentrations of Pu have also been found in filtered water samples from seeps and in stream sediments along nearby Woman Creek, suggesting that some Pu has been carried through or over the soil and has affected groundwater and surface water quality.

The mechanisms and rates of actinide migration at the site have been the focus of a study conducted by M.I. Litaor of EG&G/Rocky Flats. Transport of Pu in colloidal form or associated with natural colloids has been documented or inferred elsewhere (e.g., Penrose et al., 1990). Therefore, an important part of Dr. Litaor's Rocky Flats investigation is *in-situ* documentation of colloid mobilization. At five intensively monitored sites on a hillslope east of the 903 Pad (Fig. 6), soil solution is sampled by both tension lysimeters and conventional zero-tension lysimeters (polyvinyl chloride troughs inserted laterally in the soil) that are installed at five intensively monitored sites. In addition to sampling soil water moving under the influence of ambient precipitation and snow melt events, rainfall simulation studies have been conducted to simulate extreme storm events at each site.

Chemical, physical, and descriptive information about the monitored soils near the 903 Pad is found in Appendix B of this report.

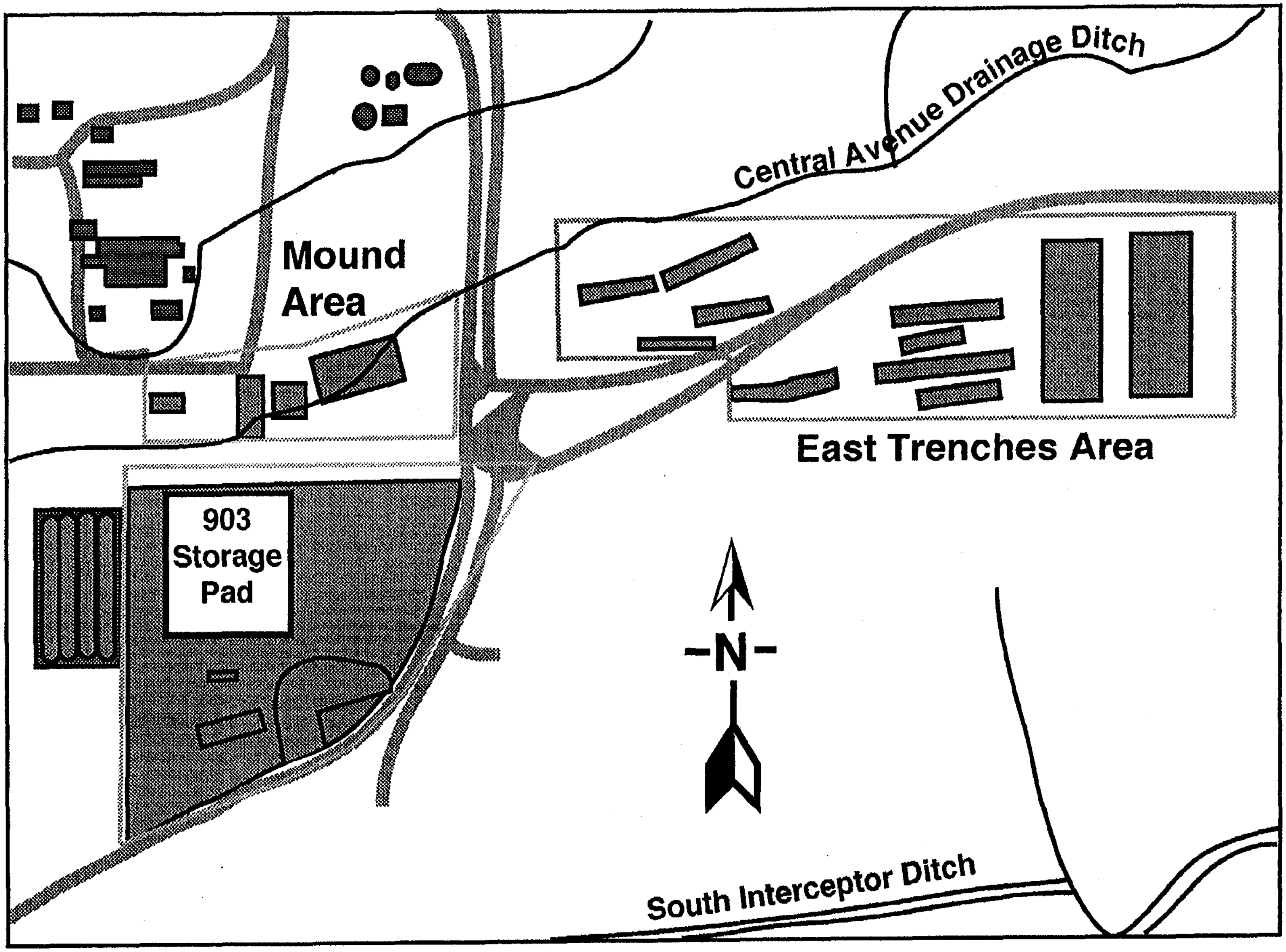

Figure 5. Location of the 903 storage pad at Rocky Flats.

Figure 1. Hillslope east of the 903 storage pad where intensively monitored soil pits and ZTLs are located.

Installation Trials and Rainfall Simulation Demonstrations at Rocky Flats

1993. The improved zero-tension lysimeters described in this report were installed near the five intensively monitored sites (Fig. 7). It was expected that installation of the lysimeters by collecting undisturbed cores would be difficult at Rocky Flats because of the potential for contamination of the pickup-mounted Giddings soil probe. In addition, the soils at the site are known to contain large amounts of coarse fragments. Finally, access to much of the site was limited by previously installed equipment. Therefore, our first attempts at ZTL installation at RFETS were by a manual method.

During the week of August 16, zero-tension lysimeters constructed of PTFE were installed by hand-digging a small access hole to the appropriate depth, placing the lysimeter under an undisturbed portion of the soil, and closing the hole (Fig. 8). The manual installation technique had worked well at a practice site in Iowa. However, installations at RFETS were slowed greatly by the compact nature of the soil. In addition, we found it very difficult to level the lysimeters in the holes and to push them up into an even contact with the roof of the excavated cavities. Finally, site work rules (e.g., requirements of personal protective clothing, worker training, lightning advisories, and limitations on permissible periods of intense labor) resulted in the installation of fewer lysimeters than had originally been planned. During the four days we were at RFETS, we were able to install one PTFE lysimeter near each of four monitored pits and one polycarbonate lysimeter near one pit. These installations required approximately 64 person-hours of labor.

During the week of September 20, we completed installation of additional zero-tension lysimeters constructed of PTFE at RFETS. The final lysimeter was installed near Pit 5 of the intensively monitored site. In August, we had encountered problems with the manual installation technique because of the dry, compacted, and clayey soil materials at the site. We devised an alternative method of installation by using a right-angle drill to auger the required lateral cavity. That approach greatly speeded installation of the lysimeters in September.

Following lysimeter installation, we set up a plot-size rainfall simulator (Bowyer-Bower and Burt, 1989) constructed for this project and conducted rainfall tests at three of the five sites (Fig. 9). The tests were intended to document that infiltrating rainwater would be intercepted by the lysimeters as well as to learn the approximate amount of water required to initiate saturated flow of water and transport of colloids in the different soils at the site. Unfortunately, water was collected only from one of the lysimeters at Pit 1, and that only after 20 cm of simulated rain (over a two-hour period) had fallen. At Pit 2 and Pit 5, not enough soil water was collected to characterize for the parameters of electrical conductivity, pH, alkalinity, turbidity, dissolved organic carbon, and actinides.

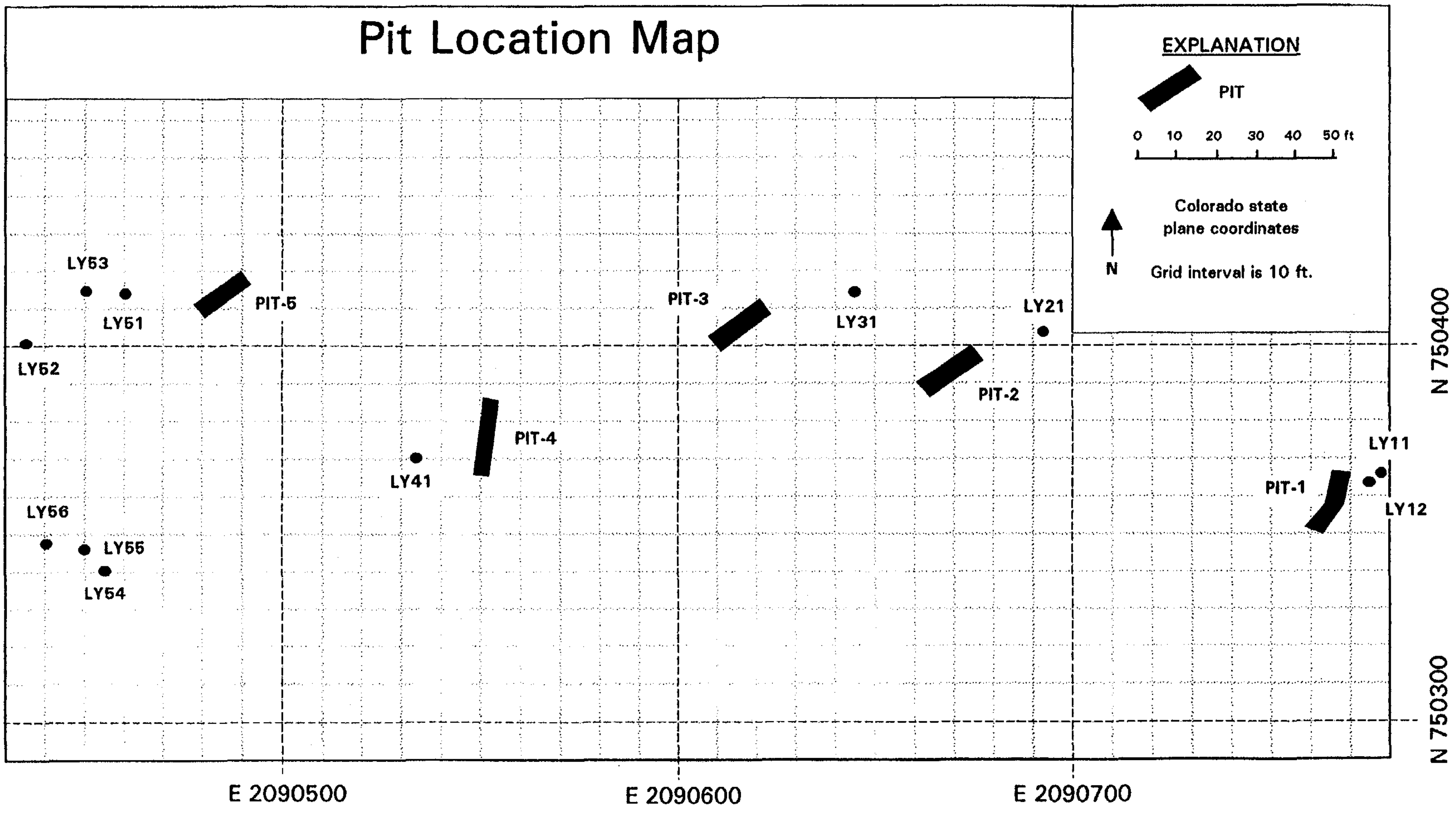

Figure 7. Placement of zero-tension lysimeters near intensively monitored soil pits.

Figure 2. Manual installation of the ZTLs required digging a small access hole and placing the lysimeter under an undisturbed portion of the soil.

Figure 3. Conducting rainfall simulation experiments at Rocky Flats.

The failure to collect water in the lysimeters installed at the Rocky Flats Plant was in direct contrast to our experience with the lysimeters installed at the Ames site, where water has been collected in the lysimeters after virtually every rain since 1992. We have developed three hypotheses to explain the results at Rocky Flats: (1) The soils at Rocky Flats have less macroporosity than the soils tested in Iowa as a result of less faunal activity. (2) Most of the Rocky Flats sites occurred on slopes of 8-13%. To the extent that lateral water flow dominated at these sites, the lysimeters would have been bypassed. (3) Installation of the lysimeters provided insufficient hydraulic contact between the sand at the top of the lysimeter and the overlying soil. Of these hypotheses, (2) and (3) seem the most likely.

1994. During the week of July 17, we installed five additional ZTLs at the Rocky Flats research site. Instead of using the manual installation method of 1993, we used a pickup-mounted hydraulic soil probe (Giddings rig) to remove cores of soil before placing the ZTLs in the soil. The approach worked well at the site when the truck was anchored to the soil. We collected undisturbed cores of soil as long as 50 cm, and the probe could have gone deeper. These cores provided excellent morphological documentation concerning the likelihood of preferential flow of water in soil macropores.

Because of physical access restraints, all the lysimeters installed in 1994 were in the vicinity of Pit 5, which is the pit nearest the 903 Pad and where contaminated soil was previously determined to occur at the surface. There was a stone line at all locations sampled; it occurred between about 13 and 20 cm depth. It consisted of stones 1-3 cm in diameter, and it probably had a significant effect on water movement to the subsoil at the site. We installed two ZTLs in place of the stone line (ZTL Sites LY53 and LY55) and two at the bottom of the stone line (ZTL Sites LY54 and LY56). One ZTL was installed at 20 cm depth and below disturbed soil material to evaluate the effect of physical disturbance of the surface horizon on colloid and actinide migration (ZTL Site LY52).

During the week of August 15, we conducted rainfall simulation experiments at the sites where ZTLs had been installed in July. Turbidity, electrical conductivity, pH, alkalinity, and temperature were determined in the field for most samples. Dissolved organic carbon in water samples was determined in Ames by Pt-catalyzed, low-temperature combustion on a Shimadzu TOC 5050. Analytical data for both simulated and subsequent natural rainfall are presented in Table 1.

We also determined that two of the five ZTLs installed during 1993 were functioning. Although the 1993 method of installation is not recommended, we continued to monitor and sample these ZTLs during the life of the project.

The simulated and natural precipitation data of Table 1 indicate that the lysimeters installed by using the Giddings soil probe to remove an undisturbed core of soil functioned well to capture water that moved through the soil in response to precipitation. The data also document the large variation both spatially and

Table 1. Simulated and Natural Preciptation Data -- Rocky Flats Environmental Techonology Site

Sampling date	Location Code	Site	Placement	Intensity	Duration	Total rainfall	Approximate return interval	Volume Collected	pH	EC	Alkalinity	Turbidity	Visual Assessment	Dissolved organic carbon	Temperature
				cm/hr	min	cm	years	mL		mS/cm	mg/L	NTU		mg/L	degrees C
Rainfall simulation															
8/18/94	LY52	94-1	At 20 cm, below disturbed soil *material*	5.5	60	5.5	100	325	6.6	0.40	0	30	lt yellow, clear	43	15
8/18/94	LY53	94-2	At 20 cm, at bottom of stone line	2.2	130	4.8	25	150	6.5	0.36	0	50	lt yellow, clear	61	23
8/17/94	LY54	94-3	At 13 cm, in place of stone line	5.4	70	6.3	100	85	7.1	0.61	57	19	lt yellow, clear	68	28
8/16/94	LY55	94-4	At 14 cm, at bottom of stone line	5.5	75	6.9	100	100	6.6	0.31	0	117	lt yellow, clear	...	28
8/16/94	LY56	94-5	At 7 cm, in place of stone line	3.6	85	5.1	50	225	6.5	0.21	0	51	lt yellow, clear	46	17
Water used for rainfall simulation									5.7	0.06	0	8	clear	6	24
Natural rainfall and snowmelt events															
8/11/94	LY21	93-2		NA	NA	NA		10	7.6	...	...	...	v. lt yellow,	...	...
8/11/94	LY31	93-3		NA	NA	NA		100	6.3	0.11	0	67	lt yellow, clear	...	27
8/11/94	LY51	93-5		NA	NA	NA		20	7.1	1.45	...	...	...	...	26
8/11/94	LY53	94-2		NA	NA	NA		150	6.4	0.32	1.2	36	v. lt yellow,	...	27
8/11/94	LY54	94-3		NA	NA	NA		10	7.2	...	...	...	clear	...	27
8/11/94	LY55	94-4		NA	NA	NA		210	7.0	0.22	17	11	v. lt yellow,	...	27
8/11/94	LY56	94-5		NA	NA	NA		190	6.2	0.16	0	25	v. lt yellow,	...	27
10/21/94	LY56	94-5		NA	NA	NA		150	7.2	0.14	21	17	lt yellow, clear	52	16
11/11/94	LY21	93-2		NA	NA	NA		100	7.7	0.20	37	6	v. lt yellow,	31	19
11/11/94	LY55	94-4		NA	NA	NA		50	7.5	0.10	35	4	clear	12	18
11/14/94	LY56	94-5		NA	NA	NA		175	7.6	0.14	35	22	yellow, clear	42	16
12/21/94	LY52	94-1		NA	NA	NA		50	8.1	1.40	...	16	lt yellow, clear	140	11
12/21/94	LY56	94-5		NA	NA	NA		200	7.9	1.70	...	7	clear	97	9
2/23/95	LY53	94-2		NA	NA	NA		245	6.1	0.12	...	5	clear	19	27
2/23/95	LY55	94-4		NA	NA	NA		70	7.6	0.11	...	24	clear	14	27
2/23/95	LY56	94-5		NA	NA	NA		170	7.7	0.12	...	27	lt yellow, clear	21	27

... = not determined
NA = not available

temporally in water movement through the soil. Finally, the data document that even water that traverses soil pores quickly in events dominated by macropore flow picks up dissolved solutes (increase in electrical conductivity over the simulated rainwater) and dissolved organic compounds (increase in DOC), some of which are likely to be "colloidal" in size (a conclusion suggested by the increase in turbidity).

FIELD INVESTIGATIONS: AMES WATER POLLUTION CONTROL FACILITY

Site Context

Zero-tension lysimeters constructed of polycarbonate were installed at the City of Ames Water Pollution Control Facility (WPCF) near Ames, Iowa, to monitor colloid transport in a soil during amendments with treated municipal biosolids.

Soil and Vegetation

The soil at the site is a fine-loamy, mixed, mesic Endoaquic Hapludoll (Coland series). To a depth of about 1 m the soil is a clay loam (about 380 g clay per kg soil). The surface horizon is massive in the upper 15 cm. From 15 cm to about 60 cm depth the soil possesses fine and medium subangular blocky structure; medium prismatic structure occurs from about 60 cm to about 1.0-1.4 m depth. The soil has a permanent cover of switchgrass (*Panicum virgatum* L.) and cottonwood-poplar hybrid trees, laid out in alternating alleys that are about 15 m wide and 365 m long. Appendix C of this report contains additional chemical and physical data for the soil at the WPCF.

Sampling Design

Twenty-four lysimeters were placed in plots associated with three levels of biosolids treatment (application rates of approximately 0, 2, and 5 dry t/ha) and two vegetation treatments. Four replicate plots for each treatment were assigned on a randomized block design. The lysimeters were placed at a depth of approximately 50-cm according to the procedures outlined above.. Half of the lysimeters (replicates 1 and 2) were installed in the fall of 1991; the other half (replicates 3 and 4) were installed in the spring of 1992. In water samples collected from the lysimeters following significant rainstorms, suspended colloids and particles were monitored by turbidimetric measurements with a ratio nephelometric turbidimeter. Heavy metals were determined by inductively coupled plasma spectrometry. Dissolved organic carbon was determined by Pt-catalyzed, low-temperature combustion on a Shimadzu TOC 5050.

Natural Precipitation

There was considerable variability in the composition of samples collected from ZTLs installed in replicate plots. In fact, in some instances, no water was found in the ZTL of one replicate but it was found in other ZTLs of the same biosolids treatment. This observation confirms the significance of the spatial variability of and solute transport and supports the use of ZTLs that can be installed quickly and cheaply in large numbers at a site.

For example, both temporal and spatial variations in dissolved organic carbon in ZTL water collected under poplar trees throughout the growing season of 1994 is shown in Fig. 10. For some sampling dates no samples were found in ZTLs of one or two biosolids treatments, but they were found in ZTLs of the other treatments (e.g., dates of 4/15, 5/2, and 6/3). Where no error bars are shown in Fig. 10 only one ZTL of four replicates collected water from a precipitation event. Similar data are shown for the switchgrass plots in Fig. 11.

Figure 12 summarizes the effect of vegetation and biosolids amendments on dissolved organic carbon concentrations in ZTL-collected soil water in 1992, 1993, and 1994. In general, dissolved organic carbon concentrations were greater in mobile water of the switchgrass plots than in water of the poplar plots. The lower levels of dissolved organic carbon in soil under poplar trees was probably related to the porosity and faunal activity in the switchgrass soil. During 1992, 1993, and 1994, biosolids were added to the plots only from the spring of 1992 through the spring of 1993. Figure 12 indicates that an effect of biosolids amendments on the concentration of dissolved organic carbon in mobile water was clearly discernible under switchgrass in both 1992 and 1993.

We found that turbidity in the soil water collected was dependent upon the levels of biosolids addition to the plot. In both 1992 and 1993, the higher the rate of biosolids addition, the less turbidity occurred in water that leached through the soil. Originally, we intended that turbidity would be used as an index of colloid concentration in the samples. The results with respect to biosolids additions suggest that greater additions of biosolids may be limiting colloid transport through the soil. Perhaps this is because organic matter in the biosolids acts to stabilize soil particles by physical linkages. On the other hand, turbidity in the water samples was negatively correlated with electrical conductivity values, suggesting that the biosolids additions resulted in soil water with relatively higher ionic strengths. Larger ionic strength in the soil solution tends to limit expansion of the diffuse layers of ions associated with soil colloids and to keep colloidal materials from dispersing.

We used stepwise multiple linear regression to identify the soil water parameters that were related to turbidity. Both electrical conductivity and Fe content of the water were strongly related to turbidity in the samples (see equation below).

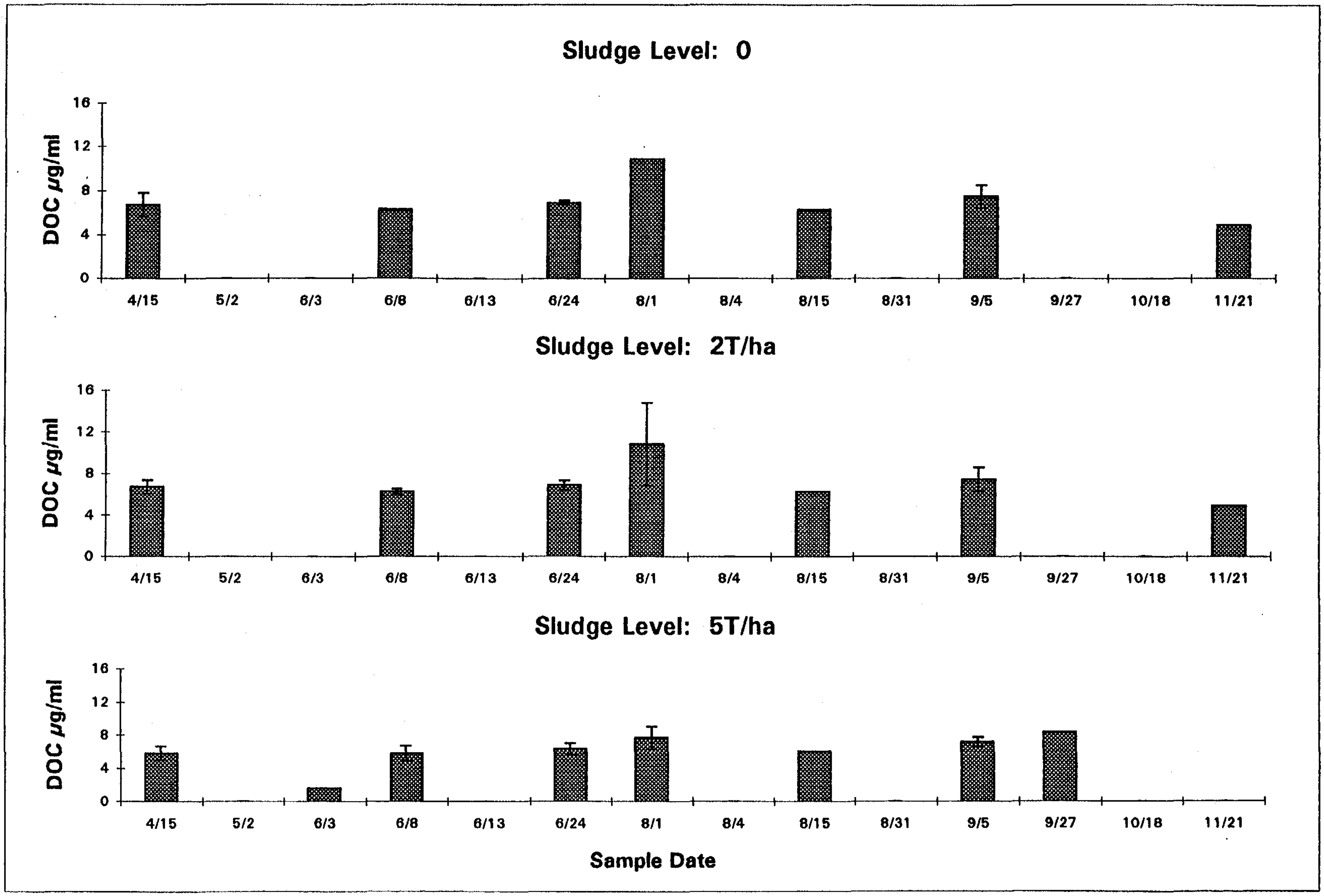

Fig. 10. Mean DOC Leaching under Tree Plots 1994

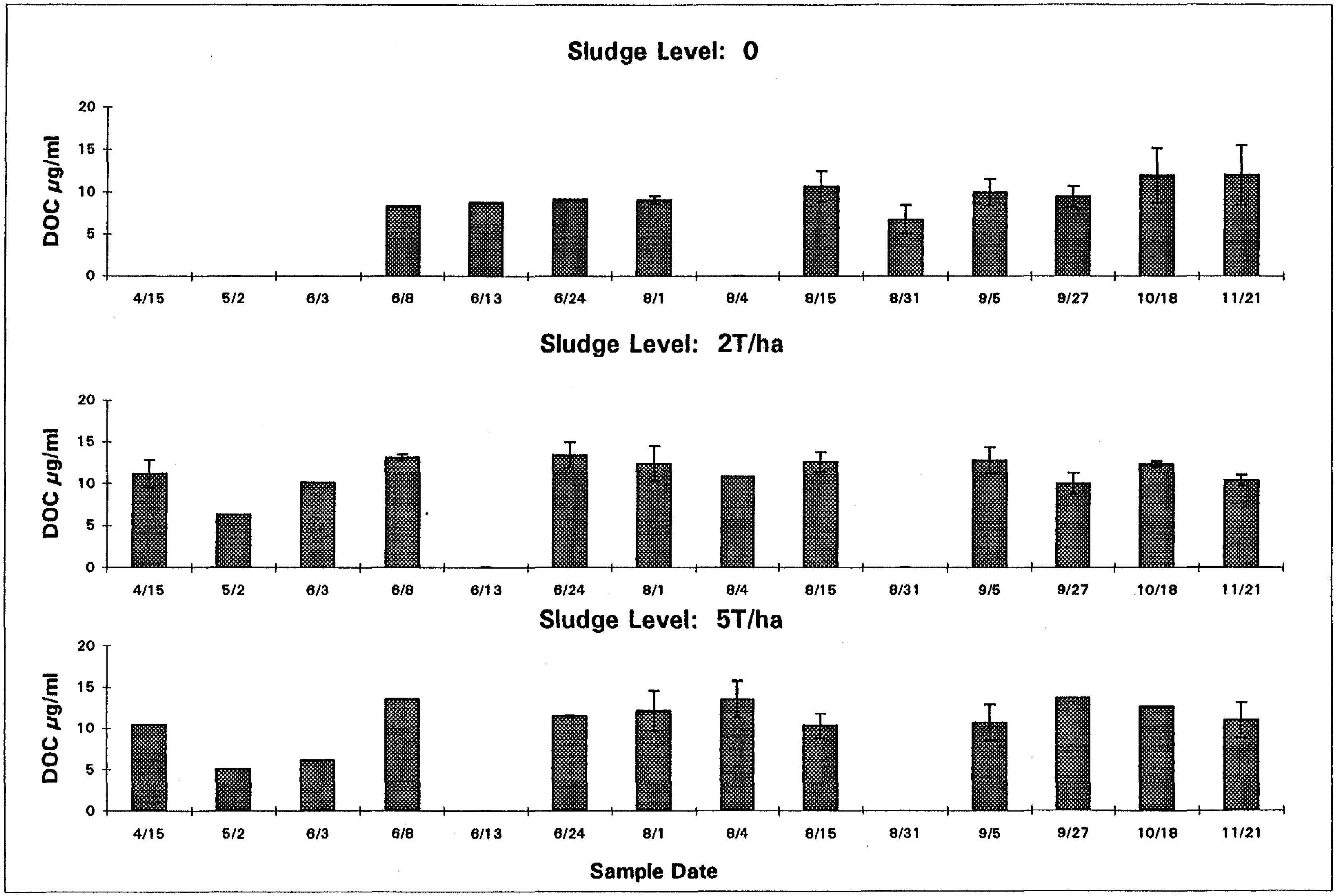

Fig. 11. Mean DOC Leaching under Grass Plots 1994

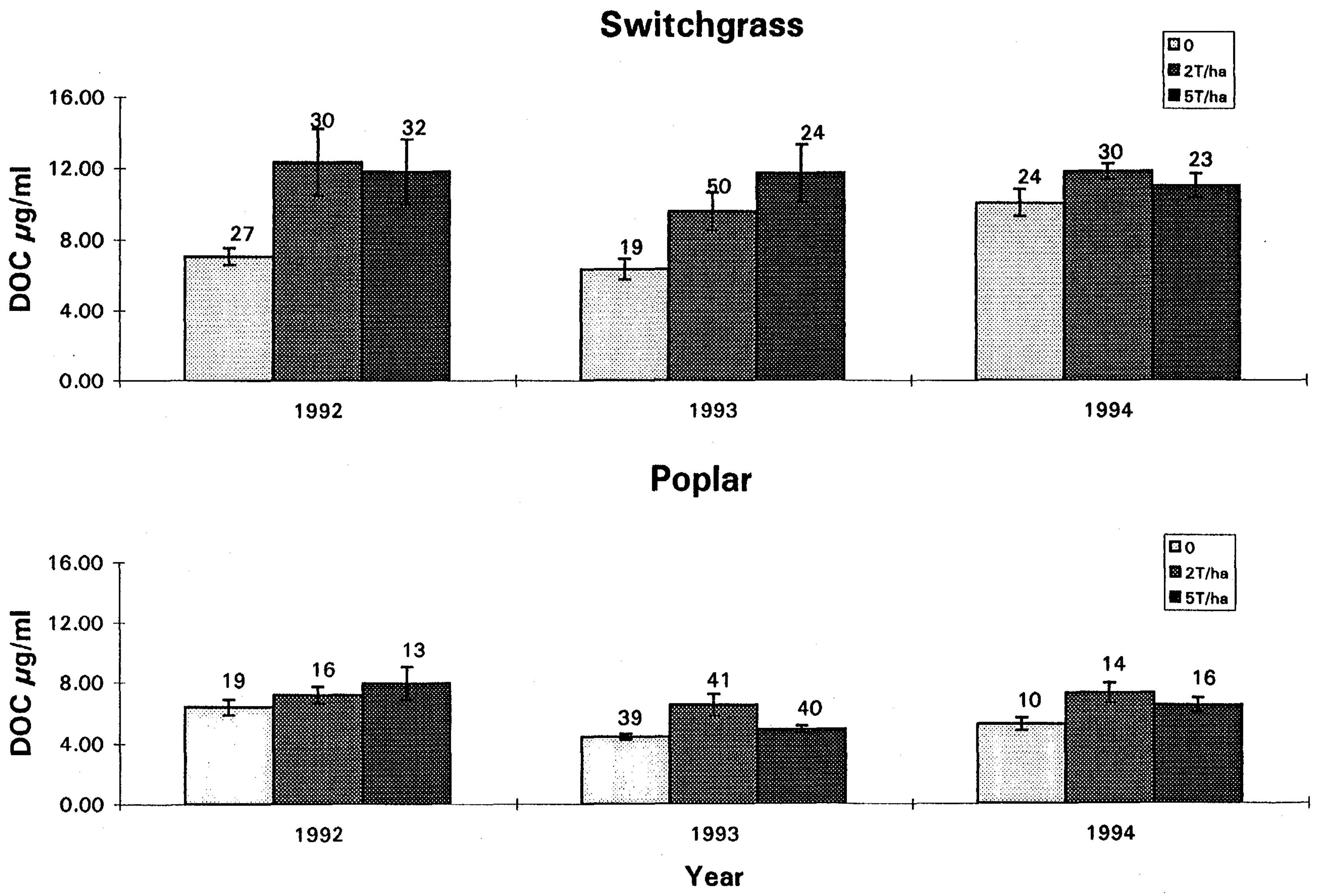

Fig. 12. Mean Dissolved Organic Carbon Concentrations in Mobile Soil Water

$$\begin{gathered}\text{turbidity} = 15.9 - 5.8\,(\text{EC}) + 12.8\,(\text{Fe}) \\ r^2 = 0.41 \\ \text{probability} > F\,(\text{EC}) = 0.0423 \\ \text{probability} > F\,(\text{Fe}) = 0.0001\end{gathered}$$

The very strong correlation of turbidity and Fe raises some doubt about whether turbidity is the best index of mobile colloids for these soils. Although Fe oxides do occur in colloidal size, they are not expected to be very mobile in this form at the pHs of the soil and water in this study. It is possible that Fe^{2+} may have moved into the lysimeters in solution phase, then oxidized and precipitated as colloidal Fe oxides before there was opportunity to measure turbidity in the collected sample. Such oxidation could have occurred very rapidly upon sample collection, but it could also have occurred in the lysimeter before sample collection. If such is the case, turbidity measurements would provide an inaccurate index of colloidal particles that are truly mobile in the soil and correlations of contaminant mobility with turbidity would be invalid.

Levels of heavy metals in the soil water were always very low. In fact, it was rarely possible to detect Cd in the water by the ICP technique that we employed. Levels of Zn and Ni were typically in the ranges of 5 - 20 mg L^{-1}, and these concentrations were not clearly correlated with any of the other parameters that we measured. Cu occurred in concentrations that were low (also typically 5 - 20 mg L^{-1}), but Cu levels could be correlated both to treatment effects and to other soil water parameters. For example, significantly more Cu leached into the ZTLs installed in plots receiving biosolids treatment than in control plots. In addition, significantly more Cu leached into the ZTLs under switchgrass than into ZTLs under trees. There are a number of possible reasons for the variation in Cu leaching with vegetation, but the most likely is that the trees are more effective at taking up Cu and storing it in the biomass than are switchgrass plants.

For 1993, multiple linear regression analyses indicated a correlation of mobile Cu with DOC, turbidity, and phosphorus (below). These statistics suggest that Cu moved through the soil in an organically complexed form, consistent with laboratory studies that have demonstrated strong complexation of Cu by soil organic matter.

$$\begin{array}{lccccc}\text{ug / mL Cu} = & -0.45 & +0.44\,(\text{DOC}) & +\ 0.03\,(\text{turbidity}) & +\ 3.2\,(\text{P}), & r^2 = 0.66 \\ & (0.33) & (0.0001) & (0.0034) & (0.0001) & \end{array}$$

We conclude that movement of both dissolved organic carbon and Cu was affected significantly by the type of vegetation growing in the soil, that Cu probably moved as an organometallic complex, and that turbidity could be related to inorganic colloids suspended in the soil solution collected by the ZTLs. Cd was not significantly mobile in the soil (at detectable levels). Ni and Zn appeared to be mobile at low concentrations, but those concentrations were not clearly related to other measured parameters. The validity of these conclusions is statistically more certain because of the number of ZTLs we were able to install and monitor at the site.

Rainfall Simulation Experiments at WPCF

We conducted a snow melt simulation test at the Ames site on April 20, 1994. This was accomplished with the rainfall simulator using distilled water as simulated, low-ionic strength snow. At a simulated intensity of 6.4 cm / hr, preferential flow to the ZTL started within 15 minutes of the application of water to the soil surface. The suspensions were observed to be very cloudy and turbid in the field. The simulation experiment re-confirmed that the ZTL was sampling preferential flow of water through the soil, as it was designed to do. In addition, the cloudy leachates obtained during the experiment supported the hypothesis that low-ionic-strength water can mobilize colloidal materials as it travels preferentially through the soil.

During November, 1994, we completed three rainfall simulation experiments at the City of Ames Water Pollution Control Facility to test how the zero-tension lysimeters would function at different depths in the soil. ZTLs were installed at 10-, 35-, and 57-cm depths, and simulated rainfall (10^{-3} M $CaCl_2$) was applied at an intensity that averaged about 3.0 cm / hr. Analysis of the leachates recovered indicated that:

- Relatively large volumes of rainwater could move down macropores and into the lysimeters very quickly. For example, as much as 250 mL of water could be collected in the deepest ZTL within about 30 minutes of the start of rain simulation. The electrical conductivity of the leachates indicated that there had been very little dilution of the water by pre-existing soil water. This is important because it validates the assumption that ZTLs are needed to monitor *preferential* flow of water through contaminated soil.
- Water collected by the lysimeters picked up some organic matter and possibly Fe as it passed through the soil. This conclusion was reached by analysis of the water for dissolved organic carbon (DOC) and turbidity. We are still uncertain whether turbidity values primarily reflect mobilized colloids (e.g., organic matter or phyllosilicate clay minerals) or Fe oxides that precipitate from Fe^{2+} dissolved in the leachate.
- The amount of organic matter dissolved in the water decreased with travel distance through the soil. In other words, leachate collected in the deepest lysimeters had the lowest DOC values. This observation implies that organic matter mobilized from the surface of the soil may be sorbed by the soil along macropore walls during transport.

In all, these experiments confirm that ZTLs installed at fairly shallow depths could be used to monitor colloid and dissolved solute transport effectively where contaminants occur near the soil surface.

AUTOMATION OF ZTL SAMPLING

Need

One of the problems with the ZTL as currently designed is that it requires both manual determination of whether leachate has been collected and manual pumping of the sample. At many contaminated sites, safety rules require technicians to work only in pairs as well as to dress out in personal protective equipment before entering contaminated sites. An automated sampling system for the ZTLs could result in significant savings of both worker time and operating expenses. While there would be added expense for each ZTL, the savings in human time and personal protection equipment required for every entry into a radiological control (RCA) area would likely offset the cost. Moreover, installation at remote locations would be more feasible.

Design

During July through September 1994, design work for automation of the zero-tension lysimeters was conducted in conjunction with engineers in the Technology Integration Program of Ames Laboratory. The design work has been completed, and portions of prototype units have been fabricated.

In the current design, sensing probes are to be placed through the side of the ZTL to determine the presence of a chosen level of leachate (e.g., 20 mL). The probes are to be connected to a monitor box in which a light, buzzer, and microprocessor are located. When water is present to the level of an indicator sensor, the light will flash and the buzzer will sound. When a predetermined amount of water is present (i.e., to the level of a pump sensor), a pump will be automatically activated to empty the lysimeter into an above-ground container that can be retrieved by personnel later. The microprocessor has been programmed to check the status of the sensors every 500 seconds. If the pump sensor detects water and the indicator sensor is also detecting water, the pump will turn on and run for 500 seconds. If, after this time, the water level has dropped below the level of the pump sensor, a no-detect signal will stop the pump and the light / buzzer display. We are currently trying to determine the best kind of pump to use in remote locations where power must come from batteries.

ALTERNATIVE APPROACHES TO SAMPLING ZERO-TENSION SOIL WATER

Alternative sampling devices include zero-tension lysimeters of conventional design (i.e., lateral installation) and piezometers. The disadvantages of conventional-design zero-tension lysimeters are related to the possibility of site disturbance during installation and the cost of opening a large pit so that the device may be installed laterally. An advantage of the improved design described herein is that more devices can be installed in a given amount of time, making feasible more reliable assessments of the spatial variability of colloid-facilitated transport of contaminants.

Piezometers have been used to sample groundwater for mobilized colloids, but serious questions have been raised about disturbance of fine-grained aquifer material during purging and sampling of wells (Puls and Powell, 1992). To prevent disturbance may require extremely slow pumping rates that are not cost-effective in routine monitoring situations. In addition, the soil volume through which water has moved before reaching a piezometer is difficult to define, making localization of contaminant sources difficult.

Another zero-tension lysimeter design requiring installation with an hydraulic probe at a 45-degree angle was recently described by Simmons and Baker (1993). They identified the main limitation of their sampler as the inability to calculate an accurate cross-sectional area of soil through which the sampled water had moved. In contrast, the volume of soil sampled by the ZTL of the present report is much more easily estimated. A second advantage of our design is that the soil immediately above the lysimeter is not smeared during installation and the integrity of natural pores at that position is maintained. A final advantage of the present design is the ability to maintain hydraulic contact with the overlying soil by an increment of appropriately sized sand at the top of the ZTL. Therefore, soil water that moves through the overlying soil has a greater chance of entering the lysimeter.

LIMITATIONS OF THE DESIGN

Water collected in the zero-tension lysimeter described here is expected to have moved primarily vertically through the overlying column. Thus the approach may not be appropriate for sites where significant lateral flux is expected due to surface topography, landscape position, or vertical anisotropy of permeability.

Where clay content of the soil exceeds about 350 g kg^{-1}, the sampled core may remain separated from the undisturbed soil that surrounds it through more than one wetting cycle. Thus pore discontinuities at the lateral boundaries of the core can persist. There are two alternatives to address the problem. First, the discontinuities may be encouraged in order to know more accurately the volume of soil through which water has moved. Lateral movement of water and roots into and out of the core may be prevented by coating the circumference of the core with a thin layer of rubberized asphalt before returning the core to its position in the soil (Kluitenberg et al., 1991). This procedure is most appropriate for lysimeters used in precipitation simulation studies where mass balances are required. Alternatively, after the soil core is replaced in the ground, air-dry soil material, ground to pass a 2-mm sieve, may be used to fill in around the core wall. The soil material should be similar to (if not identical with) the soil horizon(s) contained in the core. Such a procedure encourages normal root growth and water movement across the core boundary, eventually leading to disappearance of the core boundary.

If the lysimeter is to be used for quantitative measurements of solute flux through saturated soil, ideally it should be installed at sufficient depth that the exit boundary does not affect flow processes in the column (van Genuchten and Parker, 1984). An estimation of that depth usually involves applying a model based on the advection-dispersion equation to miscible displacement experiments on undisturbed soil columns in the laboratory (van Genuchten and Wierenga, 1986). To estimate the dispersion coefficient, a nonreactive solute such as chloride is typically used as a tracer in such experiments. Unfortunately, dispersion coefficients for nonreactive solutes are unlikely to represent dispersion coefficients for suspended soil colloids. An important area for future research is to investigate the effects of the exit boundary on colloid transport in zero-tension lysimeters of all types.

BENEFITS OF THE IMPROVED ZERO-TENSION LYSIMETER

Zero-tension lysimeters are intended to capture samples of suspended colloids as they move in the vadose zone. The specific benefits of the proposed design are related to the simplicity of installation and the concomitant reduction of cost of monitoring. Because more ZTLs of the proposed design than of the conventional design can be installed to assess site variability, more accurate monitoring of the temporal heterogeneity of contaminant transport before, during, and after remediation will be achieved. In addition, because of the improved spatial resolution in sampling and monitoring, if contaminants *are* mobilized, their source can be more easily identified than with piezometer-based monitoring methods.

ACKNOWLEDGEMENTS

We sincerely thank Iggy Litaor, Gil Barth, Phil Molzer, and other co-workers of EG&G / Rocky Flats for enormous amounts of assistance, both in the field and conceptually, in demonstrating this technology at Rocky Flats. The project also benefited greatly from the technical assistance of Robert Lahn and co-workers of Woodward-Clyde Federal Services in 1993 and of Steve Aldridge and co-workers of S.M. Stoller Associates in 1994. In 1994, Site Safety Officer John Gregg of ITT, facilitated our work immeasurably.

We also thank our colleagues at Iowa State University and Ames Laboratory for significant support in the laboratory and field throughout the period of the project. These persons include: Aaron Steinwand, Faruque Khan, Nizhou Han, Hua Ren, Linda Schultz, Yaobing Sui, and Monday Mbila. The advice and general support of the Ames Laboratory Environmental Technology Development Program Director, Jim Corones, is also great appreciated. Marvin Anderson of Ames Laboratory was especially helpful in the design of the automated-sampling version of the ZTL.

This work was funded by the Characterization, Monitoring, & Sensor Technology Crosscutting Program of the U.S. Department of Energy's Office of Technology Development (ADS Number CH131002). Steve Webster was the Technical Program Officer at the Chicago Operations Office.

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APPENDIX A

General Description and Classification of Soils at the Rocky Flats Environmental Technology Site (RFETS)

Most of the soils at the RFETS are Argiustolls, i.e., soils formed in a semi-arid climate under the influence of prairie vegetation and containing subsurface accumulations of clay. They typically have mollic epipedons that are relatively thick surficial horizons with abundant organic matter. Mollic epipedons reflect annual below-ground additions of organic matter to the soil by decomposition of the roots of prairie grasses and forbs.

Few of the soils at RFETS have no evidence of lithologic discontinuities. This fact suggests the importance of alluvial and colluvial parent materials to soil development (Shroba and Carrara, 1994). Similarly, even though the fine-earth fraction (i.e., < 2-mm material) is dominated by clay particles in most of the soils, there are often abundant coarse fragments that result in classification of the soils into clayey-skeletal particle-size groups Some soils have horizons near the soil surface that have high clay contents, making them susceptible to cracking in summer months.

Most of the soils at RFETS are classified as having argillic horizons, reflecting apparent accumulations of clay in the subsurface. Argillic horizons generally have at least 20 percent more clay than the soil horizons overlying them. The common occurrence of lithologic discontinuities (see below), however, suggests that not all the clay in the subsurface horizons is illuvial. Most of the soils have a surficial cap of silt loam (loess?) that is 10-15 cm thick. Most of the soils have subsurface accumulations of calcium carbonate as well. In several soils that accumulation is great enough to formally identify calcic horizons.

The majority of soil horizons have clay fractions consisting of a mixture of smectite, clay mica, and kaolinite. But in most horizons, smectite is the dominant clay mineral, typically accounting for as much as 60% of the clay fraction. The abundance of smectite in the soils probably reflects the many potential sources of smectite as well as its characteristic particle size. Smectite in these soils was probably derived partly from Cretaceous-age shale. The shale formed the parent material for many of the soils investigated, either directly or as a source of the colluvium or alluvium in which the soils developed. Smectite may also have formed by neoformation as primary minerals weathered and released Si, Al, Fe, Mg, and Ca. Finally, smectite commonly occurs in fine clay fractions, a size that makes smectite particles susceptible both to transport by wind and water erosion and to accumulation in low-lying landscape positions.

With a few exceptions, clay mica contents are greatest near the soil surface and decrease with depth. This is the opposite trend from what one would expect in moderately to highly weathered soils, and it confirms the hypothesis that the soils have not significantly weathered since deposition of the parent materials.

APPENDIX B

Soil Characterization at the Sites of ZTL Installations at the Rocky Flats Environmental Technology Site

Table 1A presents chemical, physical, and mineralogical data for **Pit 1** of the five intensively monitored trenches east of the 903 Storage Pad that was the source of Am and Pu contamination. The presence of a calcic horizon at about 27 cm is indicated by the calcium carbonate data. In addition, micromorphological observations (Table 2A) suggest that faunal activity in the soil surface horizons has been great. Pu added at the surface by aerial deposition may have been carried into and mixed with the soil A horizon by fauna such as ants and earthworms. Because of its irregular decrease in organic carbon with depth, the soil was classified as a fine-loamy, mixed (calcareous), mesic Fluvaquentic Haplustoll. The series most closely matched and mapped in the area is Halverson (a fine-loamy, mixed (calcareous), mesic Ustic Torrifluvent).

Pit 2 occurs in a colluvial footslope position to the east of the storage pad that was the source of Pu and Am contamination. Table 3A presents the chemical, physical, and mineralogical data for the soil at Pit 2. This soil has a weakly developed argillic horizon that begins at 19 cm depth. In addition, there is a paralithic contact with weathered shale at 50 cm depth. The higher clay contents and bulk densities of materials at these depths (relative to overlying horizons) are likely to limit deep vertical migration of contaminants. But lateral translocation along these horizons may still occur. The Am and Pu survey indicated very little radioactivity at depths greater than 19 cm. The soil at this site would probably be classified as a fine, montmorillonitic, mesic Torrertic Argiustoll (Kutch series).

Table 4A summarizes the micromorphological descriptions of the soil at Pit 2. As at Pit 1, micromorphological observations suggest that faunal activity in the soil surface horizons has been great. Pu and Am added at the surface by aerial deposition may have been carried into and mixed with the soil A and Bw horizons by fauna such as ants and earthworms.

Pit 3 occurs in a colluvial footslope position. Table 5A presents the chemical, physical, and mineralogical data for the soil at Pit 3. This soil has an argillic horizon (a zone of clay accumulation) with about 40 per cent clay that begins at a depth of 51 cm. Inset into the argillic horizon is a pocket of very sandy material, probably the filling of an erosional channel. Whereas the high clay content of the argillic horizon would be predicted to limit deep vertical migration of contaminants, lateral translocation through the sandy channel fill could still occur. The Am and Pu survey indicated activities of Am and Pu of 40 and 250-300 pCi/g between 6 and 14 cm depth, but very little radioactivity occurred at depths greater than 18 cm. Therefore, at this point, there is little evidence of significant actinide migration below the organic-matter-rich A horizon of the soil. The soil at this site is classified as a fine-loamy, mixed, mesic Aridic Argiustoll.

Table 6A summarizes micromorphological descriptions of thin sections of the soil at Pit 3. As at Pits 1 and 2, micromorphological observations suggest that faunal activity in the soil surface horizons has been great. In fact, there was evidence (in the form of fecal pellets) of faunal activity in the argillic horizon. Although a lithologic discontinuity is suggested by the abrupt change in sand and clay content at 18 cm depth, the B horizons of this soil (to a depth of 108 cm) did exhibit microlaminated clay coatings in channels as well as embedded in the soil matrix. Therefore, identification of an argillic horizon is well justified. The soil was classified as a fine, montmorillonitic, mesic Aridic Argiustoll and correlates well with the Standley series.

Pit 4. Also in a colluvial footstep position on the intensively monitored slope, the soil at Pit 4 exhibits a well-developed mollic epipedon that overlapped with the uppermost portion of the argillic horizon (i.e., 18-41 cm). Although a lithologic discontinuity is suggested by the abrupt change in sand and clay content at 18 cm depth, the B horizons of this soil (to a depth of 108 cm) do exhibit microlaminated clay coatings in channels as well as embedded in the soil matrix. Therefore, identification of an argillic horizon is well justified. The soil is classified as a fine, montmorillonitic, mesic Aridic Argiustoll and correlates well with the Standley series.

Pit 5 occurs in a backslope position to the east of the 903 Storage Pad. The soil at this location is the most contaminated of the monitored soils. In the upper 10 cm of the soil, Pu 239/240 was measured at levels of 200-700 pCi g^{-1}, and Am 241 occurred at levels of 20-70 pCi g^{-1}.

Table 9A presents the chemical, physical, and mineralogical data for the soil at Pit 5, and Table 10A summarizes micromorphological descriptions of thin sections of the soil. Mollic colors extended to a depth of 48 cm, and an argillic horizon could be clearly identified to start at 48 cm depth. Thin section studies corroborated the argillic classification because microlaminated infillings and embedded coatings were observed in a sample from the 48-120-cm zone. Evidence of biological activity included tissue fragments and roots in the A horizon, tissue fragments and fecal pellets in the Bw horizon, and roots in the Bt horizon. The large content of coarse fragments in the Bw horizon placed this soil into the loamy-skeletal, mixed, mesic family of Aridic Argiustolls (Nederland soil series).

PIT 1

PARTICLE SIZE DISTRIBUTION

HORIZON	DEPTH	SAND	SILT			CLAY
		50µ-2mm	20-50µm	5-20µm	2-5µm	<2µm
	cm			%		
A	0-16	46.9	7.1	8.0	3.9	34.1
AB	16-27	27.5	8.9	8.8	4.1	40.7
Bkl	27-58	35.3	11.2	12.5	5.6	35.3
Bkg	58-76	35.6	11.2	13.7	6.4	33.1
Bg	76-103	41.3	11.8	12.2	5.4	29.2
2BCg	103-123+	34.2	14.3	13.5	5.8	31.7

CLAY MINERALOGY

Smectite	Vermiculite	Clay mica	Kaolinite	Hydroxy-interlayered	Goethite	Quartz	Feldspar	Other (specify)
**	a	***	**	a	a	*	*	m*
***	a	**	**	a	a	*	*	m*
***	*	*	**	a	a	*	*	
***	*	*	**	*	a	*	*	
****	*	**	**	*	a	*	*	
****	*	**	**	*	a	*	*	

a = absent, * = trace (<5%), ** = present (5-30%), *** = abundant (30-60%),
**** = dominant (>60%), ND = not determined, m = mica

HORIZON	DEPTH	SPECIFIC SURFACE AREA	BULK DENSITY
	cm	m2/g	g/cm3
A	0-16	182	1.22
AB	16-27	237	1.53
Bkl	27-58	184	1.43
Bkg	58-76	172	1.42
Bg	76-103	152	1.56
2BCg	103-123+	180	1.61

CHEMICAL ANALYSIS

PASTE pH	PASTE E.C.	O.M.	CaCO3 EQUIV	EXCHANGEABLE CATIONS					FREE SESQUIOXIDES (DITHIONITE EXTRACTABLE)			
				Ca	Mg	Na	K	CEC	Fe	Mn	Al	Si
	mmhos/cm	%			meq/100					µg /g		
7.4	0.8	4.1	2.0	21.8	2.9	0.1	1.7	28.6	2029	30	607	1568
7.7	1.1	2.8	5.6	26.9	3.5	0.1	1.5	30.3	3281	28	965	925
8.0	0.4	1.3	12.2	26.7	3.9	0.2	0.5	29.9	2150	10	742	611
7.9	0.5	1.6	10.7	26.7	3.8	0.2	0.3	25.8	2112	4	558	513
7.9	0.5	0.4	9.0	23.8	2.8	0.2	0.2	22.5	1822	8	526	662
8.0	0.6	0.2	5.6	24.7	3.0	0.3	0.3	24.4	1497	7	471	760

Table 1A

Micromorphological Features at Study Sites Pit 1

Horizon	Depth (cm)	Microstructure/ Dominant porosity	Related Distribution Pattern (c/f-50, unless otherwise noted)	Birefringence Fabric	Mineral Components	Organic Components	Pedological Features
A	0-16	spongy with complex packing pores	single-spaced porphyric (embedded grain)	grano-striated and mosaic speckled	quartz, microcline and plagioclase; chlorite, some highly weathered	common root fragments; occasional tissue fragments	common elipsoidal fecal pellets, about 80 μm diam
AB	16-27	weak subangular blocky / channel	single-spaced porphyric	crystallitic	polycrystalline and monocrystalline quartz	few tissue fragments	few sand grains coated with calcite
Bkl	27-58	weak subangular blocky / channel	single-spaced porphyric	crystallitic	polycrystalline and monocrystalline quartz ; weathered orthoclase(?); few feldspars		few micritic nodules, 2-3 μm diam
Bkg	58-76	channel, 100-250 μm diam	single-spaced and double-spaced porphyric	crystallitic	monocrystalline quartz, some polycrystalline quartz; very few weathered feldspars; one large chlorite flake		zones of dense micrite common; abundant grain coatings of calcite and possibly clay
Bg	76-103	weak subangular blocky / channel	single-spaced and double-spaced porphyric	weakly crystallitic and stipple-speckled	quartz; plagioclase feldspars; microcline		abundant calcite nodules and pore fillings
2BCg	103-123+	weak subangular blocky / channel	double-spaced porphyric	crystallitic and stipple-speckled	gravelly: gravels are coated with micritic calcite; gravel is chert or polycrystalline quartz; sand grains are quartz, plagioclase, microcline		common micritic nodules, coatings, hypocoatings

Table 2A

PIT 2

		PARTICLE SIZE DISTRIBUTION				
		SAND	SILT			CLAY
HORIZON	DEPTH	50μ-2mm	20-50μm	5-20μm	2-5μm	<2μm
	cm			%		
A	0-7	64.4	8.0	7.2	3.9	16.5
Bw	7-19	69.8	6.6	5.5	3.2	14.9
Bt	19-50	49.1	5.7	6.9	4.1	34.2
2Bt	50-105	36.1	7.6	12.8	7.0	36.5
3BC1	50-105	84.6	2.0	2.4	1.2	9.8
3BC2	50-105	70.2	5.2	5.0	2.2	16.9
4BCgk1	105+	14.1	12.3	18.7	9.9	45.0

CLAY MINERALOGY								
Smectite	Vermiculite	Clay mica	Kaolinite	Hydroxy-interlayered	Geothite	Quartz	Feldspar	Other (specify)
**	a	**	**	a	a	*	*	m*
**	a	**	**	a	a	*	*	m*
***	*	**	**	a	*	*	a	m*
***	a	**	**	a	*	*	*	m*
**	a	*	**	*	*	*	*	
****	*	**	**	*	*	*	*	
****	*	**	**	*	a	*	*	m*

a = absent, * = trace (<5%), ** = present (5-30%), *** = abundant (30-60%),
**** = dominant (>60%), ND = not determined, m = mica

				CHEMICAL ANALYSIS												
								EXCHANGEABLE CATIONS					FREE SESQUIOXIDES (DITHIONITE EXTRACTABLE)			
HORIZON	DEPTH	SPECIFIC SURFACE AREA	BULK DENSITY	PASTE pH	PASTE E.C.	O.M.	CaCO3 EQUIV	Ca	Mg	Na	K	CEC	Fe	Mn	Al	Si
	cm	m2/g	g/cm3		mmhos/cm	%				meq/100				μg/g		
A	0-7	62	1.01	7.2	1.0	10.4	0.4	16.4	2.0	0.2	0.9	27.4	4411	137	435	1649
Bw	7-19	70	1.39	7.0	1.4	5.4	0.3	15.0	2.0	0.1	0.9	19.8	4120	90	451	1180
Bt	19-50	169	1.46	7.0	0.5	1.3	0.2	17.4	2.8	0.2	0.7	22.8	10604	150	1370	1101
2Bt	50-105	166	1.40	7.0	0.6	0.6	0.5	15.1	2.1	0.1	0.2	19.8	29474	1340	1680	971
3BC1	50-105	31		7.4	0.3	0.4	0.5	4.3	0.4	0.1	0.1	6.0	40731	8288	729	1493
3BC2	50-105	114		6.1	2.9	0.2	0.3	9.0	1.3	0.1	0.1	9.8	6146	48	547	777
4BCgk1	105+	228	1.59	7.5	0.9	0.2	2.7	29.7	3.5	0.1	0.3	26.5	2207	113	288	1169

Table 3A

Micromorphological Features at Study Sites Pit 2

Horizon	Depth (cm)	Microstructure/ Dominant porosity	Related Distribution Pattern (c/f-50, unless otherwise noted)	Birefringence Fabric	Mineral Components	Organic Components	Pedological Features
A	0-7	weak crumb, with complex packing pores	enaulic (intergrain microaggregate)	undifferentiated (too much organic matter)	quartz, microcline, plagioclase	common roots and tissue fragments; occasional worm fragments; abundant finely comminuted debris	
Bw	7-19	weak, medium, subangular blocky; channels	single-spaced porphyric (embedded grain)	zones of high organic matter (50%) are undifferentiated; other zones are randomly striated	monocrystalline, polycrystalline, metamorphosed quartz	decomposing leaves, roots	decomposing roots with fecal pellets inside; some sections are like Bt, some are like A with lots of organic matter; earthworm body filled with soil material; striated b-fabric suggests B horizon
Bt	19-50	weak, medium, subangular blocky; channels	double-spaced porphyric	randomly and grano-striated	quartz, chert, plagioclase, microcline	occasional pore with loose filling of fecal pellets; common root fragments and traces	most grains are surrounded by clay coatings 25-50 μm thick; little evidence of illuviation (undisturbed pore clay coatings)
2Bt	50-105	channels, dominantly 200-400 μm diameter	double-spaced porphyric	grano- and randomly striated; weakly poro-striated	dominantly quartz; apparently rare feldspars		shale fragment? Fe oxides in irregular zones 1-5 μm in diameter, approx. 30 % of surface; little evidence of illuviation
3BC1	50-105	channels	coarser zones (c/f - 200): close porphyric	grano- and randomly striated	dominantly 250-500 μm quartz, moderately sorted and spherical; chert		
3BC2	50-105	channels	finer zone (c/f - 50): double-spaced porphyric	grano- and randomly striated			Fe oxide mottles covering zones 1-5 μm in diameter; little to no evidence of illuviation
4BCgk1	105+	massive	open porphyric	dominantly randomly striated	quartz dominant; rare chert and plagioclase; occasional hornblende		common CaCO3 nodules, spherical, 200-600 μm diam, micritic; few Fe oxide mottles and nodules 1-500 μm diameter

Table 4A

PIT 3

		PARTICLE SIZE DISTRIBUTION				
		SAND	SILT			CLAY
HORIZON	DEPTH	50μ-2mm	20-50μm	5-20μm	2-5μm	<2μm
	cm			%		
A	0-18	67.3	6.5	6.8	3.8	15.6
AB	18-35	58.1	6.2	6.0	3.5	26.3
Bw	35-51	60.4	4.9	5.6	3.5	25.7
BCg (clay)	51-120	16.0	14.9	19.1	10.0	39.9
BC1 (sand)	51-120	75.0	4.3	3.8	2.5	14.5
BC2	51-120	51.2	5.0	5.4	3.6	34.8
BCk1	120 +	22.4	17.1	18.7	7.8	34.0

CLAY MINERALOGY								
Smectite	Vermiculite	Clay mica	Kaolinite	Hydroxy-Interlayered	Geothite	Quartz	Feldspar	Other (specify)
**	a	**	**	a	a	*	*	m*
***	a	**	**	a	a	*	a	l&m*
***	a	**	**	*	*	*	*	m*
****	a	**	**	*	*	*	*	m*
**	a	*	**	*	*	*	*	m*
**	a	**	**	a	a	*	*	a
****	a	**	**	*	a	*	*	a

a = absent, * = trace (<5%), ** = present (5-30%), *** = abundant (30-60%), **** = dominant (>60%), ND = not determined, m = mica, l = lepidocrocite

CHEMICAL ANALYSIS

HORIZON	DEPTH	SPECIFIC SURFACE AREA	BULK DENSITY	PASTE pH	PASTE E.C.	O.M.	CaCO3 EQUIV	EXCHANGEABLE CATIONS					FREE SESQUIOXIDES (DITHIONITE EXTRACTABLE)			
								Ca	Mg	Na	K	CEC	Fe	Mn	Al	Si
	cm	m2/g	g/cm3		mmhos/cm	%			meq/100						μg /g	
A	0-18	60	1.63	7.0	1.1	10.0	1.0	16.7	1.9	0.1	1.3	27.9	4080	162	479	
AB	18-35	130	1.36	7.1	0.5	2.0	0.4	16.2	2.5	0.1	0.6	23.3	6379	84	1051	865
Bw	35-51	120	1.48	7.0	0.4	0.9	0.2	14.4	2.6	0.2	0.4	20.8	7755	126	1004	817
BCg (clay)	51-120	168	1.53	7.7	0.6	0.3	2.3	25.4	4.4	0.3	0.3	29.6	10243	188	799	873
BC1 (sand)	51-120	94	1.43	7.2	0.4	0.4	0.2	8.5	1.2	0.1	0.2	8.4	9663	48	792	678
BC2	51-120	179	1.39	6.7	0.4	1.5	0.1	17.4	2.7	0.1	0.6	28.0	7676	131	1662	971
BCk1	120 +	171	1.53	7.8	0.9	0.2	3.5	26.3	4.7	0.4	0.3	26.0	2853	178.5	265	1009

Table 5A

Micromorphological Features at Study Sites Pit 3

Horizon	Depth (cm)	Microstructure/ Dominant porosity	Related Distribution Pattern (c/f-50, unless otherwise noted)	Birefringence Fabric	Mineral Components	Organic Components	Pedological Features
A	0-18	strong granular (2-5 mm), with compound packing pores	single-spaced porphyric (embedded grain)	undifferentiated (too much organic matter)	monocrystalline and polycrystalline quartz, plagioclase, microcline, chert	abundant tissue fragments (coarse and fine); abundant roots; common worms; humified organic matter	
AB	18-35	dominantly channel porosity	chitonic-gefuric (bridged and coated grain)	grano-striated	200-600 μm diam well sorted spherical-oblate quartz; occasional chert, microcline, plagioclase		clay coatings around most sand grains, 25-50 μm; Fe oxides associated with clay
Bw	35-51	channels, dominantly 200-500 μm diameter	fine-aggregate portion(c/f - 50): open porphyric; coarse aggregate portion(c/f - 100): single-spaced porphyric	fine aggregate portion: poro- and randomly striated; coarse aggregate portion: grano- and randomly striated	quartz > > chert > microcline > plagioclase	few strongly - moderately decomposed roots	
BCg (clay)	51-120	channels (200-500 μm diameter)	open porphyric	mono- and randomly striated; randomly striated	Fe oxide - cemented sandstone fragment 1-2 cm diameter, quartz; dominantly quartz; one microcline grain	rare, moderately decomposed root	occasional micritic nodules and infillings 500-1000 μm diameter; common cryptocrystalline Fe oxide diffuse mottles and discrete nodules, 500-2000 μm diameter; clay coatings on pores not present
BC1 (sand)	51-120	channels and vughs (200-500 μm)	chitonic-gefuric	grano- and randomly striated	quartz > chert > > microcline		clay coatings on sand grains (25-50 μm thick or 250-500 μm diameter)
BC2	51-120	weak channel: 200-400 μm diameter	poorly sorted; open porphyric, with 250-300 μm diam. sand grains most common	grano- and randomly striated	quartz > chert (which is common) > microcline and plagioclase	one large tissue fragment with fecal pellets throughout	microlaminated clay coatings around pores are not apparent, but oriented grain coatings, 50-100 μm thick, are abundant
BCk1	120+	mainly planar pores, 50-200 μm diameter; low porosity	open and single-spaced porphyric	randomly striated	quartz grains dominantly 50 μm; dominantly clayey --- weathered shale?		

Table 6A

PIT 4

		PARTICLE SIZE DISTRIBUTION				
		SAND	SILT			CLAY
HORIZON	DEPTH	50μ-2mm	20-50μm	5-20μm	2-5μm	<2μm
	cm		%			
A	0-18	64.1	7.3	7.5	3.9	17.3
Bt1	18-41	38.4	7.6	9.2	4.8	40.0
Bt2	41-77	37.9	9.4	9.5	4.6	38.5
Bt3	41-77	38.6	8.9	10.0	5.1	37.5
BCg	77-108	39.6	12.7	10.5	5.6	31.5
2BCg	108+	24.4	13.5	15.7	8.0	38.4

CLAY MINERALOGY								
Smectite	Vermiculite	Clay mica	Kaolinite	Hydroxy-interlayered	Goethite	Quartz	Feldspar	Other (specify)
••	a	••	•		a	•	•	m•
••	a	••	••	a	a	•	•	m•
•••	a	••	••	•	•	•	•	m•
•••	a	••	••	a	•	•	•	m•
••••	•	••	••	•	•	•	•	m•
••••	•	••	••	•	a	•	•	m•

a = absent, * = trace (<5%), ** = present (5-30%), *** = abundant (30-60%),
**** = dominant (>60%), ND = not determined, m = mica

CHEMICAL ANALYSIS

HORIZON	DEPTH	SPECIFIC SURFACE AREA	BULK DENSITY
	cm	m2/g	g/cm3
A	0-18	59	1.09
Bt1	18-41	149	1.20
Bt2	41-77	114	1.50
Bt3	41-77	178	
BCg	77-108	159	1.50
2BCg	108+	205	1.41

				EXCHANGEABLE CATIONS					FREE SESQUIOXIDES (DITHIONITE EXTRACTABLE)			
PASTE pH	PASTE E.C.	O.M.	CaCO3 EQUIV	Ca	Mg	Na	K	CEC	Fe	Mn	Al	Si
	mmhos/cm	%			meq/100					μg /g		
6.7	2.5	16.0	0.6	16.2	1.8	0.0	1.7	24.1	4057	245	480	1499
6.5	0.9	1.8	0.4	17.5	3.8	0.1	1.8	27.9	6982	238	1112	1132
7.5	0.6	0.6	<.1	14.6	3.6	0.2	0.7	19.7	6158	93	829	908
6.9	0.6	0.9	0.9	16.0	3.8	0.1	1.2	26.4	9476	70	1585	1014
7.3	1.1	0.4	0.3	16.8	4.5	0.2	0.5	22.6	11387	268	982	825
7.8	0.5	0.4	0.4	18.1	5.2	0.2	0.4	26.4	3236	9	465	1202

Table 7A

Micromorphological Features at Study Sites Pit 4

Horizon	Depth (cm)	Microstructure/ Dominant porosity	Related Distribution Pattern (c/f-50, unless otherwise noted)	Birefringence Fabric	Mineral Components	Organic Components	Pedological Features
A	0-18		double-spaced porphyric (embedded grain)	undifferentiated	monocrystalline and polycrystalline quartz; occasional calcite grains and chert; common microcline and plagioclase; aragonite(?) precipitate on some quartz grains	abundant tissue fragments, common worms and roots	one disorthic subangular blocky ped from the underlying Bt horizon, 2.5-3.0 mm
Bt1	18-41	vughy porosity 100-500 µm diameter; wk - f - sbk	open porphyric	grano- and randomly striated	monocrystalline and polycrystalline quartz/ microcline, plagioclase; granitic rock fragments?	rare, strongly decomposed tissue fragments	abundant clay coatings, 25-50 µm thick, on grain > 100 µm diameter; few cryptocrystalline Fe oxide coatings; clay abundance in matrix common weakly laminated to nonlaminated clay coatings on pores
Bt2	41-77	vugh and channel, 250-500 µm diameter	single-spaced porphyric	grano- and randomly striated	quartz > > chert; microcline and plagioclase; Fe oxide-coated mica fragments? ; approx. 20 µm x 100 µm laths	none observed	
Bt3	41-77	channel 125-250 µm diameter	single-spaced porphyric	randomly striated	lack of grains coarser than about 150 µm; well sorted with respect to 100 µm diameter grains; quartz with few other sand minerals present	few, fine, highly decomposed root fragments; occasional channels with loose incomplete filling of fecal pellets	occasional moderately oriented clay coatings are associated with pores; occasional channels coated with microlaminated clay, 25 - 50 µm thick; cryptocrystalline Fe oxide mottles, 1-6 mm; irregular nodules, 2-5 mm diam; and hypocoatings 100-200 µm across
BCg	77-108	channel 200-500 µm	single-spaced porphyric	stipple-speckled and randomly striated	very few grains >150 µm; well-sorted 100 µm grains; mostly quartz, with occasional chert; rare microcline		illuvial clay, moderately oriented and associated with channels; occasional Fe oxide nodules 1-2 mm ; common Fe oxide mottles 2-8 mm (irregular)
2BCg	108+	channel 200-500 µm	single-spaced porphyric	stipple-speckled and weakly randomly striated	moderately well sorted with grain > µm; quartz; occasional decomposed shale fragments	rare decomposed root fragment	pore coatings of clay not present; few calcite, micritic nodules 500 µm diameter; infilling

Table 8A

PIT 5

		PARTICLE SIZE DISTRIBUTION				
		SAND	SILT			CLAY
HORIZON	DEPTH	50µ-2mm	20-50µm	5-20µm	2-5µm	<2µm
	cm			%		
A	0-15	62.3	11.3	6.3	2.8	15.4
Bt	15-48	57.7	7.5	8.2	3.8	21.8
BCg	48-120+	43.8	13.9	7.7	4.3	30.3

CLAY MINERALOGY								
Smectite	Vermiculite	Clay mica	Kaolinite	Hydroxy-interlayered	Geothite	Quartz	Feldspar	Other (specify)
**	a	**	**		a	*	*	
**	a	**	**	a	*	*	*	m*
***	*	**	**	*	*	*	*	m*

a = absent, * = trace (<5%), ** = present (5-30%), *** = abundant (30-60%), **** = dominant (>60%), ND = not determined, m = mica

HORIZON	DEPTH	SPECIFIC SURFACE AREA	BULK DENSITY
	cm	m2/g	g/cm3
A	0-15	57	1.15
Bt	15-48	102	1.27
BCg	48-120+	208	1.82

CHEMICAL ANALYSIS												
				EXCHANGEABLE CATIONS					FREE SESQUIOXIDES (DITHIONITE EXTRACTABLE)			
PASTE pH	PASTE E.C.	O.M.	CaCO3 EQUIV	Ca	Mg	Na	K	CEC	Fe	Mn	Al	Si
	mmhos/cm	%			meq/100					µg /g		
7.6	0.5	6.9	0.9	15.1	1.3	<0.1	1.6	20.5				
7.6	0.4	4.4	0.9	14.4	1.1	0.1	1.2	21.6	6790	223	1187	951
6.0	0.3	0.7	0.6	19.1	3.6	<0.1	0.4	25.9	15076	295	1578	1016

Table 9A

Micromorphological Features at Study Sites
Pit 5

Horizon	Depth (cm)	Microstructure/ Dominant porosity	Related Distribution Pattern (c/f-50, unless otherwise noted)	Birefringence Fabric	Mineral Components	Organic Components	Pedological Features
A	0-15	granular and subangular blocky (1-5 mm)	c/f-50: single-spaced porphyric	undifferentiated	monocrystalline and polycrystalline quartz; common microcline, chert; occasional plagioclase	mainly fine, humified organic matter; occasional tissue fragments and roots	
Bt	15-48	granular	many coarse c/f-50: bridged and coated grain; chitonic-gefuric	grains undifferentiated	monocrystalline and polycrystalline quartz; abundant plagioclase and microcline; occasional chert	highly birefringent organic tissue fragment; abundant fecal pellets, 75-250 µm in diameter	
BCg	48-120+	channel and vughy	sand content much less; clay content more; c/f-50:single-spaced porphyric (embedded grain)	randomly striated	shale fragment decomposing?	roots common	infillings of clayey material; embedded clay coatings; embedded cryptocrystalline Fe oxides laminated near edge of sample; also mottles and nodules (500 µm-3 mm diam); heterogeneous material suggests colluvium

Table 10A

APPENDIX C

Chemical and Physical Characteristics of Soil at the Ames Water Pollution Control Facility Research Site

		Particle size distribution				Exchangeable cations					
Depth	pH	sand	coarse silt	fine silt	clay	Ca	Mg	K	Organic carbon	Free Fe oxides	Free Mn oxides
cm		$g\ kg^{-1}$				$cmol\ kg^{-1}$			$g\ kg^{-1}$		
0-14	6.2	240	140	240	380	22.5	5.8	0.7	22.8	5.8	0.78
14-28	6.0	260	120	230	390	22.1	4.8	0.4	20.3	5.8	0.87
28-58	6.0	310	120	200	370	21.0	5.8	0.4	13.7	4.8	0.89
58-142	6.2	430	100	180	300	14.4	4.7	0.2	4.9	2.9	0.63
142-182	6.2	640	90	100	170	9.0	3.1	0.3	2.3	3.4	0.69
182-215	6.4	840	140	20	0	4.7	1.1	0.2	0.8	1.7	0.01
215-224	6.5	890	30	20	60	2.7	0.3	0.2	8.7	7.5	0.03
224-271	6.3	880	20	30	80	3.8	0.9	0.2	1.1	3.9	0.04
271-286	6.3	900	20	20	60	2.7	0.7	0.2	0.3	1.4	0.01

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