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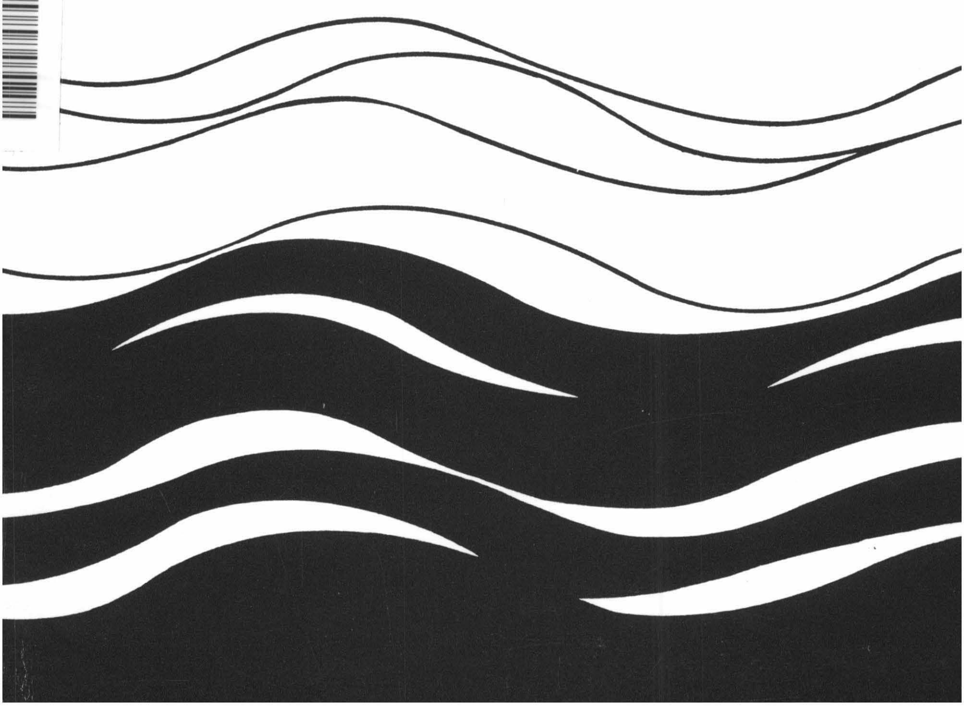
S. Mostaghimi, M.M. Deizman, T.A. Dillaha
C.D. Heatwole, and J.V. Perumpral



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S. Mostaghimi
M.M. Deizman
T.A. Dillaha
C.D. Heatwole
J.V. Perumpral

Department of Agricultural Engineering
Virginia Polytechnic Institute and State University

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ABSTRACT

A rainfall simulator was used to study the effects of tillage system and sludge application method and rate on runoff, sediment, phosphorus (P), and nitrogen (N) losses from agricultural lands. Surface application and incorporation of sludge were studied. Anaerobically digested sewage sludge was applied at rates supplying 0, 75, and 150 kg/ha of plant-available N. These rates resulted in applications of 0, 115, and 230 kgP/ha, respectively. A total of 90 mm of rainfall, with an intensity of 40-45 mm/hr, was applied to sixteen 0.01 ha plots, on a silt loam soil. Runoff water samples were collected from plot discharge and later analyzed for sediment and nutrient contents.

No-till was found to be effective in reducing runoff and sediment losses. Runoff and sediment losses decreased as sludge application rates increased, regardless of the tillage system. The surface application of sludge was more effective in reducing sediment losses than sludge incorporation. Nutrient concentrations and yields were greater from conventional tillage plots than from no-till plots. Surface application of sludge to conventional tillage plots resulted in higher concentrations and yields of most forms of P and N, relative to incorporated sludge treatments. Sediment-bound and total-P yields were less from sludge-treated plots than from the control treatments due to decreased erosion and runoff as a result of sludge application. With respect to sediment and nutrient yields in surface runoff, no-till appears to be a safer alternative for disposal of sewage sludge than conventional tillage. The structural characteristics of the soil under the two tillage systems are also discussed.

Keywords: No-till, Conventional Tillage, Sludge, Nitrogen, Phosphorus, Application Method, Application Rate, Rainfall Simulator, Land Application

INTRODUCTION

Nearly 6.2 million dry metric tons (Mg) of wastewater sludge are produced by municipal wastewater treatment facilities in the United States each year (U.S. Environmental Protection Agency [EPA] 1984). The annual sludge production in the U.S. is expected to reach 12 million Mg by the year 2000 (U.S. EPA 1984). Methods of sludge disposal include landfilling, ocean dumping, incineration, and land application. The escalating costs of most sludge disposal procedures and chemical fertilizers have promoted increased interest in application of sludge to agricultural lands as an economical disposal system. Currently, Virginia farmers apply approximately 4,500 Mg of nitrogen (N) annually to agricultural land in the form of sewage sludge. The main objective of land application of sludge is to use the biologically active upper layers of the soil profile to reduce pathogenic microorganisms and assimilate high levels of organics, metals, and nutrients in the sludge. Land application of sludge has many beneficial effects including: supplying nutrients to crops, improving soil physical properties, and increasing soil organic matter content. However, these benefits can be offset by N and phosphorus (P) movement to surface and ground waters and contamination of soil, water, and crops by heavy metals and pathogenic microorganisms if sludge is applied improperly.

Agricultural practices have been increasingly criticized for contributing to the deterioration of the nation's water resources. Nonpoint sources of nutrients, primarily in runoff from agricultural lands, are thought to be a major factor promoting accelerated eutrophication of lakes and streams. Nitrogen and P concentrations of water leaving the land application sites are of great concern since high levels of these nutrients in surface and ground water are unacceptable. The Chesapeake Bay study indicated that agricultural nonpoint sources contribute nearly 67 percent of the N and 39 percent of the P entering the Bay each year (U.S. EPA 1983). The concern over the transport of nutrients from land application systems must be addressed to ensure a safe, economical, and environmentally sound approach to land application of sludge.

Conservation tillage practices, which leave all or part of the previous year's crop residue on the soil surface, are known to be effective in controlling soil erosion; however, some studies indicate that these practices may increase nutrient concentrations in surface runoff. Concentrations may increase, despite significant reductions in soil loss, because fertilizers and sludges are usually surface-applied with conservation tillage and tend to concentrate on the soil surface where they are most susceptible to transport by surface runoff. The widespread use of conservation tillage has been presumed to improve downstream water quality by reducing runoff and sediment losses, but the anticipated improvements in water quality may not be realized unless conservation tillage farming systems also reduce nutrient losses. The exact effects of conservation tillage systems on nutrient losses from sludge-amended soils are impossible to determine at the present time. Little research has been conducted on the transport of sludge constituents in runoff from land application sites, and none has been reported that compare the effects of different tillage practices on runoff quality. The intent of this study was to determine the effects of various sludge application methods, application rates, and tillage practices on nutrient losses from agricultural lands. Specific objectives were to:

1. Determine the effects of sludge application method and loading rate on N and P losses from no-till and conventional tillage systems;

2. Compare the N and P losses of sludge-amended soils with N and P losses from conventionally fertilized no-till and conventional tillage systems; and

3. Investigate the structural characteristics of soils under different tillage systems

This information is required for the development of Best Management Practices (BMPs) for nonpoint source pollution control and the development and verification of water quality models for assessing the impact of BMPs.

LITERATURE REVIEW

I. Changes in Soil Nutrient Level and Crop Yield

Nitrogen and phosphorus are essential elements for plant growth and production. Sommers (1977) analyzed the chemical composition and potential fertilizer value of several sewage sludges. Median concentrations of N and P, on a dry weight basis, were 3.3 and 2.3 percent, respectively. He found that the chemical composition of sludge varied considerably with waste source and treatment process and that the amount of sludge required for crop fertilization depended on the composition of the sludge and the nutrient needs of the crop.

Several researchers have studied the effects of sludge application on soil chemical properties, crop composition, and yield. Stewart et al. (1975) applied anaerobically digested sewage sludge to a loam soil at rates of 1.25, 2.5, and 5.0 cm/ha. Of the N supplied by the sludge, 3-12 percent was recovered by the corn crop and 6-10 percent remained in the soil. Application rates in excess of 1.25 Mg/ha did not produce significant yield increases. Pomares-Garcia and Pratt (1978) conducted a greenhouse pot experiment in a Hanford soil to determine the N fertilization value of feedlot manure and sewage sludge. Yields of barley forage were increased by additions of organic materials and inorganic fertilizer. In a 2.5-month period after application, 4.2 percent of the N in the manure and 17.0 percent of the N in the sludge were mineralized. After 10 months, 17.2 and 40.9 percent of the N had mineralized from the manure and sludge, respectively.

Magdoff and Amadon (1980) used corn and hay growing on Hadley sandy loam and Nellis loam soils to study the N availability from sewage sludge over a two-year period. On the Hadley soil, yields of corn and hay were greater on sludge-amended plots than on either check plots or plots treated with ammonium nitrate. Nitrate recovery to 1.2 m, however, indicated that the available N supplied by the sludge was slightly less than that supplied by ammonium nitrate. The authors attributed the increased crop yields on sludge-amended plots to the higher potassium supply and residual N effect from sludge. Corn yields on the Nellis loam soil did not improve with either fertilizer source, while the hay responded more to the inorganic N source than to the sludge. Sims and Boswell (1980) evaluated the effect of nutrient source on soil N, yield, and elemental composition of corn. Soil levels of ammonium (NH_4^+ — N), nitrate (NO_3^- — N), and total-N (N_t) indicated that the organic wastes provided sufficient amounts of available-N for crop growth. Sewage sludge produced corn yields exceeding those from ammonium-nitrate or urea-treated plots. The N and P content of corn tissue from plots receiving organic wastes was similar to the tissue levels obtained using inorganic fertilizer.

Sikora et al. (1982) measured P uptake by fescue grown in Evesboro loamy sand and Fauquier silt loam soils amended with combinations of sludge compost and

N and P fertilizers. Inorganic fertilizer additions to both compost-amended soils resulted in greater P uptake by fescue. Fescue grown in soils amended only with compost contained sufficient P levels to satisfy the nutritional requirements of feed for ruminants. Fescue on these soils absorbed about 4.5 percent of the total P (P_t) added at the 44.8 Mg/ha compost amendment rate. Warman (1986) compared the effects of commercial fertilizer, sewage sludge, and pig manure on timothy yield, tissue composition, and soil fertility. Dry matter yields from the waste-treated plots equalled or exceeded yields from the plots receiving commercial fertilizer additions. The N and P tissue content of the timothy was increased by all treatments over the control. The average recovery of applied N and P from sewage sludge amendments was 21 and 6.5 percent, respectively. The sewage sludge treatment significantly increased the NO_3^- — N content of the sandy loam soil and the extractable P content of both the sandy loam and clay loam soils.

II. Leaching Losses of Nitrogen and Phosphorus

Numerous investigators have studied the movement of N and P from sludge into the soil profile and the resulting effects on groundwater quality (Urie 1973; Trout et al. 1976; Clapp et al. 1977; Furrer 1980; Duncomb et al. 1982; Inman et al. 1982; Higgins 1984). Groundwater contamination by NO_3^- — N was evident in all cases, but there was little or no indication of P enrichment. Kotreba et al. (1979) investigated the effect of sludge application on soil water solutions in a forested area and reported that NH_4^+ — N and P_t concentrations in the soil remained virtually unchanged; however, NO_3^- — N concentrations increased two to three times that of control soils. Sidle and Kardos (1970) also found that NO_3^- — N concentrations in groundwater below a forested area that received application of sludge exceeded the 10 mg/L limit established by the Public Health Service (1967) for drinking water.

Inman et al. (1982) investigated the effect of composted sewage sludge on NO_3^- — N and PO_4^- levels in soil water collected at various soil depths. Sludge was incorporated into a Chester silt loam soil. During the following year, NO_3^- — N concentrations of 70-80 mg/L were measured at 100 cm depth. These concentrations, however, decreased to less than 10 mg/L 30 months after the sludge application. The orthophosphorus (PO_4^-) concentrations of water samples were generally below 0.08 mg/L and never exceeded concentrations measured in the untreated soil. The authors attributed the low PO_4^- values in sludge-treated soils to chemical insolubility, microbial activity, and soil fixation of the PO_4^- in the sludge.

III. Runoff Losses of Nitrogen and Phosphorus

Sludge application rates are generally based on crop N requirements. Due to the chemical composition of sludges, this usually results in over application of P.

Kelley et al. (1984) suggested that the potential for high P concentrations in surface runoff is greater with the elevated P levels associated with these application rates, particularly because of the limited mobility of P through the soil profile. The Metropolitan Sanitary District of Greater Chicago developed an extensive monitoring system to assess the environmental impacts of land application of digested sludge in Fulton County, Illinois. Nitrite (NO_2^- —N), NO_3^-— N, NH_4^+ — N, and P_t content were measured upstream and downstream of the application site. The size of the treatment area and sludge-loading rate varied considerably over the 3-year study. In 1972, four fields with a total area of 108 ha received 6 Mg/ha of sludge solids. In 1974, 39.8 Mg/ha of sludge was applied to a 695 ha area. Monitoring indicated that sludge application did not affect the water quality of the stream draining the site (Zenz et al. 1976). Matthews et al. (1981) investigated the feasibility of applying aerobically digested sewage sludge to agricultural land. The test site was divided into two subwatersheds, one receiving surface applications of sludge, the other serving as a control site. The mean concentration of total Kjeldahl nitrogen (TKN), NH_4^+ — N, NO_2^- —N + NO_3^- — N, and P_t increased significantly in the runoff water from the sludge application site. Overman and Shanze (1985) irrigated coastal bermudagrass with effluent from a municipal wastewater treatment plant. Surface runoff did not significantly degrade stream quality with regard to N content. Runoff contribution to stream P, however, was significant.

Municipal sewage sludge was applied to a 3.6 ha cultivated watershed in Milan, Tennessee, during the winter from 1976-78. When ground conditions permitted, sludge was spread and incorporated immediately. A total of 31 runoff events were sampled for NO_3^- — N and PO_4. Nutrient concentrations were fairly low and constant throughout the sampling period (Shelton et al. 1981). Clapp et al. (1977) studied the effects of digested sludge application on corn yield and water quality. Sludge was surface-applied in the spring and fall of 1974 and the spring of 1975, and was injected into the soil in the fall of 1975. Soluble N (NO_3^- — N and NH_4^+ — N) and P in runoff averaged 2.8 and 0.05 kg/ha for the control area (receiving commercial fertilizer) and 29 and 0.23 kg/ha for the sludge-treated areas, respectively. An extension of this study was reported by Duncomb et al. (1982). Sludge was applied to corn areas with a subsurface injector once per year. Grass treatment areas received four surface applications of the sludge per year. While nutrient losses from all areas were considered minimal, the highest nutrient loss was in runoff from the sludge-amended grass areas. The authors suggested this was a result of the method and frequency of application.

Ahtiainen (1984) conducted field experiments to determine the movement of nutrients following sludge application when the existing guidelines of Finland were observed. Three sludge treatments were studied: dewatered sewage sludge applied to snow, thawing soil, and dewatered lime-stabilized sludge applied to thawing soil. The NH_4^+ — N, N_t, and P_t concentrations in runoff increased significantly immediately after sludge application to snow. Application of lime-stabilized sludge to thawing soil increased P_t concentrations. Elevated P concentrations in runoff were detected for two years following sludge application. University of Guelph (1976) and Bates et al. (1977) studied the effects of sludge application rate, time of application, and field slope on runoff water quality. In general, the greatest losses of N and P were during the winter months from plots treated with sludge at the beginning of the winter period. Higher application rates and increased field slopes produced slightly greater nutrient losses. The coincidence of a runoff event with the fall sludge application in 1974 resulted in elevated losses of N and P (University of Guelph 1976).

McLeod and Hegg (1984) evaluated the effects of fertilizer source on surface runoff quality from a fescue pasture. Test plots received surface applications of dairy and poultry manure, municipal sludge, and ammonium nitrate fertilizer. Because of an extremely dry year, surface runoff was produced by irrigation. Runoff samples were analyzed for P_t, TKN, NH_4^+ — N, and NO_3^- — N. Runoff from plots receiving municipal sludge exhibited the least overall potential for pollution compared to the dairy and poultry manure or commercial fertilizer.

IV. Rate and Method of Application

Kelling et al. (1977) used liquid-digested wastewater sludge to study the influence of application rate on the N, P, and sediment content of surface runoff. Sludge was applied at rates of 3.75, 7.5, 15, 30, and 60 Mg/ha of dry solids. For all simulated storms, sludge treatment significantly reduced the quantity of sediment and runoff, relative to the control areas. The authors attributed the reduction in runoff and sediment losses to increased infiltration and improved soil aggregation on the sludge-treated areas. Runoff from sludge-treated areas contained increased amounts of PO_4^-, P_t, and $NO_2 + NO_3^-$, whereas organic -N in the runoff was somewhat reduced. The effects of sludge application on nutrient losses were enhanced (increased) with increasing application rate.

A laboratory rainfall simulator was used by Kladivko and Nelson (1979b) to determine the effects of sludge application rates and incorporation methods on the amount of sediment and nutrients lost in surface runoff. Liquid anaerobically digested wastewater sludge was applied at rates of 0, 22.4, 56, and 89.6 Mg/ha of dry solids to a Celina silt loam soil and 0 and 56 Mg/ha on a Blount silt loam and a Tracy sandy loam soil. After the sludge dewatered, it was left on the soil surface or incorporated into the soil by rototilling or disking. Core samples were collected 2.5 months after sludge incorporation and subjected to rainfall. There were significant decreases in sediment yield as a result of sludge treatment. Nutrient concentrations in runoff and sediment from the sludge-treated soils were generally higher than those from the untreated soils. These effects were more pronounced at the higher application rates. The method of sludge application and incorporation had a significant effect on sediment and nutrient losses. Sludge on the soil surface was much more effective in decreasing sediment and nutrient losses than was the incorporated sludge. The authors indicated that the surface-applied sludge formed a mulch which protected the soil from erosion. Nutrient losses from the sludge-incorporated areas were greater than those from the control areas. Nitrogen and P losses from the surface-applied sludge areas, however, were less than that from control areas due to the reduction in sediment loss and runoff

Dunigan and Dick (1980) found that incorporating approximately equal amounts of N and P from commercial fertilizer and sewage sludge did not result in significant differences in N and P losses in runoff from forage plots. Surface application of sewage sludge resulted in higher N and P losses relative to those from incorporated sludge. Increasing the rates of surface-applied sludge from 16.2 to 28.9 Mg/ha increased P losses by 28 percent and had no significant effect on N losses. Ross et al. (1978) injected liquid dairy manure into the soil at depths of 15 and 30 cm and also applied it to the surface of a Bluegrass sod and a bare-tilled soil at rates of 87 Mg/ha. Injection of the manure essentially eliminated any pollutant yield in surface runoff relative to surface application. Runoff quality from the injected plots was very similar to that from the control plots. The depth of injection had no effect on levels of chemical oxygen demand, N, or sediment in the runoff.

Baker and Laflen (1982) used simulated rainfall to study the effects of rate and placement of commercial fertilizer on soluble nutrient losses from a fallow soil. Surface application significantly increased nutrient concentrations in runoff as compared to point-injection. However, injection of fertilizer also increased nutrient concentrations and losses in runoff compared with unfertilized plots.

V. Tillage Practice

Although no literature was available relating tillage practice to the runoff quality from sludge-amended soils, past studies conducted using commercial fertilizers have shown significant tillage effects. Romkens et al. (1973) used a rainfall simulator to compare the N and P composition in runoff water and sediment from five tillage systems. The coulter and chisel systems reduced soil losses, but the surface application of fertilizer on these plots resulted in high concentrations of soluble and sediment-bound N and P and the greatest soluble N and P yields. Disk and till systems were less effective in controlling soil erosion, but had lower concentrations of N and P in runoff. Conventional tillage, in which the fertilizers were plowed under, had the highest losses of soil, runoff, and sediment-bound nutrients but lower losses of soluble N and P.

Barisas et al. (1978) evaluated the effects of tillage practices on nutrient losses from experimental plots using simulated rainfall. Soluble nutrient content increased significantly with percent residue cover, indicating that conservation tillage practices may not reduce the losses of soluble nutrients in runoff. The authors suggested that this was due to reduced fertilizer incorporation and increased leaching of nutrients from residues. Conservation tillage, however, effectively reduced N_t losses by reducing soil erosion and was somewhat effective in reducing P_t losses.

McIsaac et al. (1987) used simulated rainfall to investigate the effects of tillage practices on nutrient losses in runoff. Concentrations of Bray P-1 and TKN in the eroded sediment were greatest from no-till plots; however, the greatest N_t and P_t losses were from the conventional tillage plots. Nitrate and NH_4^+ — N losses were strongly correlated with runoff volume. Soluble P losses were not correlated with either runoff or soil loss.

VI. Changes in Soil Physical Properties

The application of wastewater sludge to agricultural land has been shown to have a significant impact on soil physical properties and hydraulic characteristics. The beneficial effects of sludge addition may include improved soil environment for plant growth, increased infiltration capacity and reduced runoff (Khaleel et al. 1981). These changes are generally attributed to the organic matter content of the sludge and its assimilation into the soil.

Epstein (1975) incorporated 5 percent by weight of raw and digested sewage sludges into a Beltsville silt loam soil. He observed that the addition of sludge shifted the water retention curve so that the water content at specific water potential values was higher, but that the difference between field capacity and wilting point was essentially the same as that of the original soil. He also found that although sludge addition increased the saturated hydraulic conductivity initially, after 50-80 days it decreased to that of the original soil. The percent of water-stable aggregates increased from 17 percent for the original soil to 18-35 percent for the sludge-amended soil. Epstein et al. (1976) also studied the effects of sewage sludge and sludge compost addition on soil physical properties. They found that both sludge and compost increased the water-holding capacity, water retention, and cation exchange capacity of a silt loam soil.

Gupta et al. (1977) applied anaerobically digested sewage sludge at rates of 0, 112, 225, and 450 Mg/ha to a sandy soil. Soil-water retention was increased by the incorporation of sludge due to water adsorption by organic matter. As the rate of sludge increased, unsaturated hydraulic conductivity and soil-water diffusivity decreased and saturated hydraulic conductivity increased. Kladivko and Nelson (1979a) reported that the application of sludge improved the physical condition of Celina, Blount, and Tracy soils. Significant increases were observed in the mean weight diameter of water-stable aggregates, large pore space, water content, organic carbon, and cation exchange capacity as a result of sludge addition. Bulk density was significantly decreased by sludge application. The infiltration rates and water-holding capacities of sludge-amended soils were generally higher than those of control soils, although differences were not statistically significant. Disking was the most effective of three application methods studied. The authors suggested that this was because of the greater concentration of sludge in the top 5 cm of soil and better soil/sludge interaction with disking.

Chang et al. (1983) and Hall and Coker (1983) found that the sewage sludge reduced bulk density and cohesion and increased water-holding capacity and hydraulic conductivity. Chang et al. (1983) indicated, however, that the amount of sludge required to cause significant changes in soil properties was much greater than the amount normally used to satisfy crop nutrient requirements. Guidi et al. (1983) applied sludge at rates equivalent to 50 and 150 Mg/ha of manure. Soil porosity and water stability index of soil aggregates increased at both application rates indicating the higher application rate was unnecessary.

Under some circumstances, however, sludge application may result in adverse effects such as decreased hydraulic conductivity and infiltration capacity due to soil pore clogging. Clogging may be caused by physical, chemical, and biological reactions between the sludge and soil-water media (DeVries 1972).

VII. Summary

Several researchers have reported on the interaction of sludge and soil in relation to soil physical properties and hydraulic characteristics. Relatively little information is available relating sludge application to runoff water quality from different tillage systems. The application of sludge has been shown to reduce runoff and sediment losses. However, nutrient concentrations in runoff from sludge-treated soils are reported to be generally higher than those from control areas. The surface application of sludge, as opposed to incorporation, tends to increase N and P concentrations in runoff. The effects of sludge addition, application technique, and loading rate on nutrient yields, however, are not as clear. Results from past studies appear to be somewhat contradictory. In addition, the effects of conservation practices such as no-till on losses of nutrients from sludge-amended soils are poorly defined. The present study investigated the effects of tillage system, sludge application method, and loading rate on N and P losses from agricultural lands.

EXPERIMENTAL PROCEDURES

Field experiments were conducted in the spring of 1987 to study the effects of sludge application method and loading rates on N and P losses from no-till and conventional tillage systems. Because of the unreliability of natural precipitation for short-term field investigations, a rainfall simulator was used to produce runoff from the field plots.

I. Plot Design and Location

Sixteen experimental field plots, located at Virginia Tech's Price's Fork Agricultural Research Farm, 10 km west of Blacksburg, were used for this study. Plots are located on a Groseclose silt loam soil (clayey, mixed, mesic Typic Hapludult). Groseclose soils occur on nearly level to very steep convex ridges and sideslopes in the Appalachian Valley, and are formed from materials weathered from interbedded limestone, shale and sandstone. The soil is deep and well drained with a slowly permeable subsoil. The Ap horizon is typically 0.25 m thick and has a loam texture with moderate fine granular structure. Some general characteristics of Groseclose silt loam soil are presented in Table 1.

Plots were prepared by installing metal borders to a depth of 15 cm along the boundaries and a concrete gutter with a pipe outlet at the base of each plot. Each plot had a surface area of 0.01 ha (5.5 m by 18.3 m). All border and gutter joints were sealed with caulking compounds to prevent leakage into or out of the plots. The gutters were installed so that their upper edge was level with the upslope soil surface. The interface between the soil surface and the gutter was sealed with a cement grout and caulking to minimize leakage. The gutter was designed to collect and transport surface runoff to a 15-cm H-flume equipped with an FW-1 stage recorder for flow measurements.

II. Plot Preparation

All plots were planted in winter rye in the fall of 1986. In early spring of 1987, they were sprayed with paraquat about a week before the rainfall simulation runs. The no-till treatments were established on the killed rye stand. The crop residue amounts on the no-till plots were measured by randomly locating a 0.6- by 0.6-m square in each plot and removing all residue in the square for laboratory analysis. Conventional tillage was represented by removing crop residue from the plots, tilling to a depth of 15-20 cm with a PTO-driven rototiller, and disking.

Within each tillage treatment, two sludge application rates, designed to supply 75 kg/ha and 150 kg/ha of plant-available N were applied to each plot. Loading rates were determined using the procedure described by Simpson et al. (1985), assuming that 25 percent of the organic N present would be mineralized within the first growing season and 20 percent of the NH_4^+ — N present would be lost due to volatilization. There also were two control plots for each tillage system to which no sludge was applied. Sludge was surface-applied to the no-till plots. For the conventional tillage plots, sludge was both surface-applied and incorporated. Two replications of each of these treatments required a total of sixteen plots. All treatments were randomly assigned to the experimental plots. Plot assignments and treatments are shown in Table 1.

Anaerobically digested, polymer-conditioned sewage sludge was obtained from the James River plant in Hampton Roads, Virginia. The chemical analysis of the sewage sludge is shown in Table 2. The sludge contained 16 percent solids and 0.96 percent NH_4^+ — N, 3.02 percent TKN, and 2.0 percent P_t, on a dry-weight basis.

Sludge was distributed uniformly over the plots by subdividing each plot into 4 equal-sized subareas and manually applying 1/4 of the total sludge required for each plot to each subarea. Sludge was then spread manually within each subarea with rakes, as uniformly as possible. The conventional tillage plots with the sludge-incorporated treatments were tilled again to incorporate the sludge into the upper 15-20 cm of the soil profile.

III. Rainfall Simulator

The Department of Agricultural Engineering's rainfall simulator (Shanholtz et al. 1981; and Dillaha et al. 1987) was used to apply approximately 90 mm of rainfall to each set of plots over a 2-day period. A 1-hr initial run (R1) was followed 24 hours later by a 30-minute run (R2) and followed 30 minutes later by another 30-minute run (R3). A rainfall intensity of 40-45 mm/hr was used for all simulations. The three-run sequence is a common artificial rainfall sequence used to simulate different initial soil moisture conditions for erosion research in the United States. A 40-45 mm/hr rainfall intensity with 1-hour duration has a 2-5 year return period in Virginia (Hershfield 1961) and should create worst case conditions for nutrient losses in surface runoff, since sludge had been applied during the previous 24 hours. The plots were protected from natural precipitation during the study period by covering them with plastic sheets when rain appeared imminent. The plots were left uncovered at all other times so that the soil would dry normally.

Rainfall simulator application rates and uniformity were measured for each event by locating 12 volumetric raingages within each plot. The raingages were read after each event to determine the total amount of rain and the coefficient of uniformity for each run. The total simulated rainfall amounts along with the uniformity coefficients for simulation runs are presented in Table 3. The rainfall simulator performed remarkably well for all simulations. The mean application rate during all simulations was 43.9 mm/hr and ranged from 41.0 mm/hr to 48.6 mm/hr. Uniformity coefficients, a measure of the uniformity of rainfall application, were excellent, averaging 92.8 percent.

IV. Sampling Procedure

Runoff water samples for nutrients analyses were collected manually from the plots' discharges at 3-minute intervals throughout the runoff process. A mark was made on the stage recorder charts whenever a sample was collected to precisely record the time and flow rate at which the sample was taken. This procedure greatly simplified mass flow calculations and minimized timing errors. All water quality samples were frozen immediately after collection and stored for subsequent analysis. Runoff rates were checked gravimetrically by making time-volume measurements frequently during the simulations. Other data collected from the plots included soil moisture before and after each simulation, residue cover, and soil bulk density. Nutrient and sediment losses from each simulated event were calculated using the corresponding concentrations of each sample by assuming that the average flow rate for the sample interval was equal to the average of flow rates at the beginning and end of the interval. Statistical analyses were performed on the least square means obtained using SAS (SAS Inst., Inc. 1985.). The least square means is an unbiased estimate of the mean.

Water samples collected from runoff events were analyzed at the Agricultural Engineering Water Quality Laboratory within 8-12 weeks of collection. Analyses were conducted to determine TSS, P_t, PO_4^-, NH_4^+ — N, NO_3^- — N, TKN, filtered total phosphorus (P_{tf}) and filtered total Kjeldahl nitrogen (TKN_f).

V. Analytical Techniques

A. Suspended Solids

Suspended solids concentrations were determined in accordance with Method 160.2 contained in Methods for Chemical Analysis of Water and Wastes (U.S. EPA 1979). Sample volumes of 100 mL were filtered through preweighed 0.45-micron glass fiber filters. Filters and residue were then dried for approximately 24 hours at 105° C, transferred to a desiccator until cool and then reweighed on an analytical balance. The change in dry weight divided by the sample volume was then determined and expressed in mg/L.

B. Total Kjeldah1 Nitrogen

Total Kjeldahl nitrogen was determined on both filtered and unfiltered samples in accordance with Method 351.2 in Methods for Chemical Analysis of Water and Wastes (U.S. EPA 1979). Samples were heated for 2.5 hours in the presence of sulfuric acid, K_2SO_4, and $HgSO_4$. Next, the residue was diluted to 50 mL and a portion placed in an autoanalyzer for ammonia determination. A 99 percent recovery for this analysis has been reported.

C. Ammonium-Nitrogen

Method 350.1 described in Methods for Chemical Analysis of Water and Wastes (U.S. EPA 1979) was used for ammonium (NH_4^+ — N) determinations. Samples filtered through 0.45-micron glass fiber filters were analyzed colorimetrically at 660 nm in a 50-mm tubular flow cell. Ammonium concentrations were determined by comparing sample readings with a standard curve.

D. Nitrate-Nitrite Nitrogen

The cadmium reduction method was used to determine combined nitrate-nitrite nitrogen (designated as NO_3^- — N) concentrations. A filtered sample was passed through a column containing granulated copper-cadmium to reduce nitrate to nitrite. The nitrite (that originally present plus reduced nitrate) was determined by diazotizing with sulfanilamide and then coupling with N-(1-napthyl)-ethylenediamine dihydrochloride to form a colored azo dye that was measured colormetrically at 520 nm. This procedure is defined in Method 353.2 contained in Methods for Chemical Analysis of Water and Wastes (U.S. EPA 1979).

E. Total Phosphorus

Total P for both filtered and unfiltered samples was determined following the procedures outlined in Method 365.4 in Methods for Chemical Analysis of Water and Wastes (U.S. EPA 1979). Samples were digested for 2.5 hours in the presence of sulfuric acid, K_2SO_4, and $HgSO_4$. The resulting residue was cooled and diluted to 50 mL. Concentration of P_t was measured with an autoanalyzer.

F. Orthophosphorus

Orthophosphorus was determined in a manner similar to the procedure used to obtain P_t with the exception that acid digestion was not utilized and therefore organic P was not mineralized.

VI. Penetrometer Tests

A hydraulically operated, tractor-mounted cone penetrometer was used (Jayatissa 1986) to collect penetration resistance data. The penetrometer assembly was mounted on a tractor which was backed 3 m into each plot. The penetrometer setup was positioned at approximately the same relative location in each plot, 60 cm away from the side. The data acquisition system was activated and the penetrometer was pushed into the soil. During the downward stroke of the hydraulic cylinder, the data acquisition system collected penetration resistance and depth data to a depth of 45 cm at 1 - to 2-cm intervals. At the end of the stroke, the cylinder was retracted and the data was transferred to a cassette tape. The penetrometer was moved 30 cm laterally (perpendicular to the longer dimension of the test plot) using the hand crank mechanism available with the penetrometer assembly and similar data was collected at a second location. This procedure was repeated 6 more times to obtain data at 8 locations within each plot. The penetrometer assembly was then shifted to the left and 7 additional sets of readings were taken at 30-cm intervals. Thus, at each location 15 sets of data were collected across the plot. Similar sets of readings were taken at two other locations (9 and 15 m into the plots) within each plot.

Using calibration equations, the field data were translated into depth (cm) and penetration resistance (kPa). For each penetration test, resistance data was averaged within 7.5-cm depth intervals. This average of penetration resistance together with two other corresponding values from the other two sections in the same plot were used in calculating the average penetration resistance for a particular depth range. Thus, a matrix (7 x 15) of penetration resistance values was created for each plot. Then, the data matrices from similar treatments were averaged again and the representative contours of penetration resistance were plotted for each treatment. Interpolation technique was used to draw the contour lines.

RESULTS AND DISCUSSION

I. Runoff and Sediment Losses

A. Effects of Tillage System

Tillage system and sludge application effects on runoff and sediment yields, sediment concentrations, and peak runoff rates are shown in Table 4. Total sediment and runoff losses from conventional tillage plots averaged 1,891 kg/ha and 3.3 cm, respectively. Sediment and runoff from the no-till plots were 73 and 54 percent less, respectively, than those from the conventional tillage plots. Average sediment concentrations and peak runoff rates were 2.5 and 1.9 times greater, respectively, with conventional tillage than with no-till. These differences were statistically significant (Table 4).

The lower runoff rate and volume with no-till may be attributed to increased surface detention and retention, and infiltration caused by reduced tillage and crop residue on the soil surface. Mannering et al. (1987) reported that the crop residue on no-till plots reduces surface sealing by protecting the soil surface from rainfall impact and slows runoff. The loose, exposed soil of conventional tillage plots is easily detached and transported by raindrop impact and overland flow. This is apparent in the higher sediment concentrations in runoff from the conventional plots. The greater soil loss from these plots is the result of high runoff volumes and sediment detachment rates.

B. Effects of Sludge Application Method

The peak runoff rate from the sludge-amended conventional tillage plots was relatively unaffected by sludge application method (Table 5). Surface application of sludge, however, significantly decreased runoff, sediment concentration, and soil loss relative to incorporation. Sediment concentrations and soil loss were 1.7 and 2.0 times greater for incorporated plots than for surface-applied plots, respectively. Surface application of sludge reduced runoff volume by 2.5 percent compared to the incorporated treatments. The differences due to application method were more pronounced at the higher application rate (Table 6). Similar results were obtained by Kladivko and Nelson (1979b) who suggested that the surface-applied sludge particles protected the soil surface from erosion by forming a protective crust. Higher application rates afforded more protection by providing a more continuous and thicker crust.

C. Effects of Sludge Application Rate

Runoff amounts and peak runoff rates generally decreased with increasing application rates, with the effects being more pronounced on the conventional tillage plots(Table 6). The highest application rate on the conventional tillage plots reduced runoff volume and peak runoff rate by 38.2 and 32.0 percent, respectively, compared to the control treatments. These results may indicate an increase in water retention and infiltration capacity of the soil due to sludge application as reported by Epstein et al. (1976) and Kladivko and Nelson (1979a).

Sediment yields and concentrations also decreased with increasing application rate. Relative to the control treatments, the highest application rate reduced the average sediment concentration by 91.6 percent for the no-till surface-applied plots, 80.0 percent for conventional tillage surface-applied plots. and 51.5 percent for conventional tillage incorporated plots (Table 6). The corresponding reductions in sediment load were 93.0, 83.8, and 53.4 percent. While the effects of sludge addition were significant at the 0.05 level, doubling the application rate did not cause significant reductions in sediment concentration or load. The reduced sediment concentrations and loads from sludge-treated plots were probably the result of the stability of the sludge which formed a protective mulch or crust over the plots.

D. Comparison with Commercial Fertilizers

In 1985, field studies were conducted on these same plots to assess the effects of commercial fertilizer application techniques and tillage treatments on runoff water quality (Mostaghimi et al. 1987). The application rate of ammonium nitrate fertilizer was designed to supply 150 kg of plant available N ha^{-1}, equivalent to the highest plant-available N rate with the sludge. The average sediment and runoff losses, sediment concentrations, and peak runoff rates for runs R1, R2, and R3 from the 1985 experiments are presented in Table 7. Data from these two studies were compared to determine the effects of fertilizer source on runoff and sediment losses. Sludge application significantly reduced peak runoff rates, sediment concentrations, and soil losses at the 0.05 level. These effects were more pronounced for the conventional tillage treatments than for the no-till treatments. These results indicate that sludge provided a protective mulch layer on the soil surface, causing a reduction in runoff and sediment losses.

II. Nutrient Concentrations

The P concentrations in runoff from the plots are shown in Table 8. The form of P entering surface waters is very important. Orthophosphorus is readily available to aquatic vegetation and may stimulate excessive euthrophic plant growth in lakes, estuaries, and slow-moving rivers. In contrast, sediment-bound P (P_{sb}) and soluble organic P are not readily available. To prevent the development of algal nuisances, the generally accepted upper concentration limit in lakes and reservoirs is 0.01 mg-P/L of PO_4^-. Effluent discharge permits for municipal and industrial discharges to lakes or streams commonly limit PO_4^- concentration to 1.0 mg-P/L (Viessman and Hammer 1985). In this study, the PO_4^- concentrations in runoff exceeded the 0.01 mg-P/L level for all treatments and in some instances exceeded the 1.0 mg-P/L limit (Table 8).

Nitrogen concentrations in runoff from the treatments studied are shown in Table 9. Nitrate and NH_4^+ — N are readily available to aquatic vegetation. Thus, high N concentrations can contribute to accelerated eutrophication of surface waters. Ammonium N is toxic to fish in relatively low concentrations and can exert a significant biochemical oxygen demand. At a pH of 8.0, the maximum allowable NH_4^+ — N concentration in municipal and industrial effluents is 3 mg/L to protect warm-water fish and 1 mg/L to protect cold-water fish (Viessman and Hammer 1985). The NH_4^+ — N concentrations in runoff from the sludge-treated plots exceeded the 3 mg/L limit (Table 9).

A. Effects of Tillage System

When averaged over the surface-applied plots, concentrations of P_{sb} and P_t were generally greater with conventional tillage than with no-till (Table 10). Concentrations of P_{sb} and P_t for no-till averaged 40 and 25 percent less, respectively, than those for conventional tillage. Because P_{sb} is transported with eroded soil, the higher concentrations from conventional plots may be attributed to the greater sediment concentrations in runoff from these plots. Soluble forms of P, PO_4^-, and P_{tf} are primarily transported via runoff. Orthophosphorus and P_{tf} concentrations appear to be inversely related to runoff volumes (Tables 4 and 8). Thus, concentrations were generally higher with no-till except during R2 where runoff volumes were lower and soluble P concentrations were higher from the conventional tillage plots (Table 10). The increase in soluble P concentrations with no-till is the result of increased P concentrations on surface soil due to lack of incorporation, leaching from plant residue, and reduced dilution effects associated with the lower runoff volumes from these plots (Mostaghimi et al. 1988).

The average NH_4^+ — N concentrations in runoff from the conventional tillage plots were significantly greater than those from the no-till plots (Table 11). Ammonium N concentrations from conventional tillage treatments were an average of 3.0 times greater than those for no-till, and TKN and N_t concentrations each averaged 1.5 times greater than those from no-till. The greater concentrations of NH_4^+ — N, TKN, and N_t from the conventional tillage plots could be partially explained by the significantly greater sediment concentrations and yields from these plots (Table 4). This is evident in that sediment-bound N (N_t —NO_3^- — TKN_f) accounted for 48 and 22 percent of the N_t concentration found in runoff from the conventional tillage and no-till plots, respectively. Nitrate concentrations were an average of 3.6 times greater with conventional tillage than with no-till. The higher concentrations of NO_3^- — N and NH_4^+ — N in runoff from the conventional tillage plots may be partially due to increased mineralization of organic N caused by increased soil/sludge interaction. The increased soil/sludge interaction is due to the absence of protective crop residue on the soil surface of conventional tillage plots. This hypothesis is further supported by the relatively low proportion of organic N found in runoff from the conventional tillage plots. Only 32 percent of the N_t yield from the conventional tillage treatments was organic N, versus 65 percent for no-till treatments.

B. Effects of Sludge Application Method

Average P concentrations in runoff from incorporated and surface-applied conventional tillage plots are presented in Table 12. In general, surface application of sludge resulted in higher P concentrations in runoff than sludge incorporation. Surface-applied sludge was directly exposed to rainfall and runoff which contributed to increased P concentrations in runoff and sediment. The difference in PO_4^- concentrations due to application method was significant at the 0.05 level (Table 12). Orthophosphorus and P_{tf} concentrations were 2.3 and 1.4 times greater for the surface-applied plots than for the incorporated plots.

During R1, concentrations of P_t were higher from the incorporated plots than from the surface-applied plots. This may be a result of the higher concentrations of sediment in runoff from the incorporated plots. Since P_t is predominantly associated with sediment, an increase in sediment concentrations will cause corresponding increases in P_t. Dunigan and Dick (1980) reported that the incorporation of P may cause rapid sorption, resulting in decreased PO_4^- and increased P_{sb} available for transport. In our study, surface-applied sludge may have been mineralized slowly but continually throughout the study period, causing P_{sb} concentrations to increase and PO_4^- concentrations to decrease with succeeding rainfall events.

Surface application of sludge significantly increased NH_4^+ — N, TKN, and N_t concentrations at the 0.05 significance level relative to sludge incorporation (Table 13). Ammonium, TKN, and N_t concentrations averaged 4.1, 1.9, and 1.7 times greater for surface-applied plots than for incorporated plots, respectively. Kladivko and Nelson (1979b) indicated that sediment from surface-applied plots consisted mostly of eroded sludge particles and therefore contained higher concentrations of the constituents initially present in the sludge. In our experiment, concentrations of NO_3^- — N were higher from the incorporated plots throughout the initial storm. Incorporation of sludge may have increased the rate of sludge decomposition and stimulated nitrification rates, thus releasing greater quantities of soluble NH_4^+ — N and NO_3^- — N to runoff water (Kladivko and Nelson 1979b).

C. Effects of Sludge Application Rate

The effects of sludge application rate on P concentrations in runoff and sediment are shown in Table 8. Orthophosphorus and P_{tf} concentrations in runoff generally increased with increasing application rate. Increasing application rates not only increased the availability of these constituents, but also reduced runoff volumes (Table 6) and therefore reduced dilution. The application of sludge at the 150 kg-N/ha rate significantly increased P_{tf} concentrations compared to both the 75 and 0 kg-N/ha treatments at the 0.05 significance level. In most instances, concentrations of P_{sb} and P_t in runoff increased in the following treatment order: 75 kg-N/ha $<$ 0 kg-N/ha $<$ 150 kg-N/ha. Apparently, sludge application resulted in two opposing effects. One increased the amount of P_{sb} available for transport while the other decreased runoff, soil loss, and consequently sediment concentrations in runoff. At the lower application rate the significant decrease in sediment concentration appears to have a greater impact on P_{sb} concentrations. This is indicated by the low P_{sb} concentrations found in runoff from plots treated with the lower sludge rate (Table 8). At the higher application rate, however, the increase in P_{sb} availability seemed to outweigh the decrease in sediment concentration, since this treatment produced the highest P_{sb} concentrations.

The effects of application rate on nutrient concentrations in runoff are shown in Table 9. The NH_4^+ — N concentrations in runoff increased significantly as a result of sludge application. For the no-till and conventional tillage surface-applied plots, both application rates increased the average NH_4^+ — N concentration by over 1,000 percent relative to the control treatments. Nitrate concentrations, however, were not affected by sludge addition. The original N composition of the sludge applied may partially account for these results. A significant proportion of the total N in anaerobically digested sludge is NH_4^+ — N and very little is present as NO_3^- — N. (Sommers 1977). TKN and N_t concentration increased significantly at the highest loading rate, relative to both 75 kg-N/ha and 0 kg-N/ha treatments.

D. Comparison with Commercial Fertilizer

The average N concentrations in runoff from plots fertilized with commercial ammonium nitrate fertilizer are shown in Table 14. Sludge application significantly increased TKN and N_t concentrations at the 0.10 level and NH_4^+ — N and TKN_f concentrations at the 0.05 level over commercial fertilizer application. NO_3^- — N concentrations in runoff from plots treated with ammonium nitrate were usually higher than those from sludge-treated plots; however, these differences were not statistically significant. The differences in N concentrations due to fertilizer source were probably due to the higher N application with sludge and the varying N composition of the two sources. The predominant forms of N in the anaerobically digested sludge were organic N and NH_4^+ and in the commercial fertilizer were NO_3^- — N and NH_4^+ — N. Because application loading rates were based on plant-available N, the amount of N applied with the sludge treatment was approximately 2.6 times greater than that of commercial fertilizer treatment. Approximately two-thirds of the N applied with sludge was organic N, and only 25 percent of the total was assumed to be plant-available within the first growing season (Simpson et al. 1985).

III. Nutrient Yields

The greatest yields of PO_4^- recorded for no-till and conventional tillage plots were 0.17 and 0.19 kg-P/ha, respectively, as a result of surface application of sludge at the 150 kg-N/ha rate (Table 15). The greatest yield of P_t recorded was 1/50 kg/ha from surface-applied sludge at the rate of 75 kg-N/ha with conventional tillage. This yield represents 1.3 percent of the applied P at this loading rate. For all treatments, the majority of the P lost was in the sediment-bound form. Sediment-bound P yields as a percent of P_t yield ranged from 53 percent for the no-till surface-applied, 150 kg-N/ha treatment, to 85 percent for the conventional tillage, control treatment. The treatment yielding the greatest N_t losses was the surface application of sludge at the 150 kg-N/ha rate on the conventional tillage plots, where 11.53 kg/ha was lost (Table 16). This loss represents 3.0 percent of the total N applied at this loading rate. The greatest losses of NH_4^+ — N recorded for no-till and conventional tillage plots were 1.15 and 7.11 kg/ha, respectively, as a result of surface application of sludge at the 150 kg-N/ha rate.

A. Effects of Tillage System

Orthophosphorus and P_{tf} yields were slightly higher from the conventional tillage plots than from the no-till plots (Table 17). Although the concentrations of soluble P were slightly higher from the no-till plots, the reductions in runoff due to no-till compensated for the higher concentrations resulting in lower P yields. Tillage system had a greater impact on P_{sb} yields. The P_{sb} and P_t losses from no-till treatments averaged 75.3 and 63.0 percent, respectively, less than those for conventional tillage. No-till significantly reduced TKN and N_t losses at the 0.10 level and NH_4^+ — N losses at the 0.05 level, relative to the conventional tillage treatments (Table 18). The reductions in NH_4^+ — N, TKN, and N_t losses due to no-till were 86 percent, 60 percent, and 61 percent, respectively. Nitrate yields were also lower from no-till plots, although these reductions were not statistically significant. Sediment-bound N losses represented 26.5 and 40.4 percent of the N_t losses from surface-applied no-till and conventional tillage plots, respectively. The corresponding yields from incorporated, conventional tillage plots, were 30 percent.

B. Effects of Sludge Application Method

In general, surface application of sludge resulted in higher P yields than did incorporation (Table 19). The effects of sludge application method on PO_4^- yields were significant at the 0.05 level, with surface-applied plots producing PO_4^- yields 2.0 times greater than the incorporated plots (Table 19). Sediment-bound P and P_t yields were greater from the incorporated plots during R1 and R2 events, but lower during R3. This is probably due to the initial increase in P_{sb} availability (Table 12) and the higher sediment losses associated with sludge incorporation. Surface application of sludge resulted in higher N yields than sludge incorporation (Table 18). Ammonium, TKN, and N_t yields were 3.0, 1.4, and 1.3 times greater, respectively, with surface application than incorporation (Table 20). These differences were statistically significant. The effects of application method on NO_3^- — N yields varied with runoff event. Similar trends were seen in concentrations of all N forms measured in this study (Table 13).

C. Effects of Sludge Application Rate

Soluble P yields generally increased with increasing application rate (Table 15). The application of sludge at the rate of 150 kg-N/ha significantly increased PO_4^- yields relative to the control treatments. The total amount of P_{sb} lost was greatest from the control plots, regardless of the tillage system. Apparently, the significant decrease in sediment yield associated with sludge addition (Table 6) outweighed the increase in P availability and reduced P losses by sediment. Ammonium, TKN, and N_t yields generally increased with increasing application rates (Table 16). The effects of sludge application on NH_4^+ — N and TKN yields were significant, with the highest loading rate producing NH_4^+ — N yields of 6.9 times greater than the control treatments, averaged over all tillage and application treatments. As with NO_3^- — N concentrations (Table 9), NO_3^- — N yields were not affected by application rate.

D. Comparison with Commercial Fertilizer

Nitrogen losses from the 1985 commercial fertilizer experiments are presented in Table 21. Sludge application significantly increased TKN_f yields at the 0.05 level, relative to commercial fertilizer application. NH_4^+ — N and TKN losses also were greater from the sludge-treated plots, although these differences were not statistically significant. Nitrate losses were generally higher from plots treated with ammonium nitrate fertilizer. On the conventional tillage plots, N_t losses were not affected by fertilizer source. No-till plots, however, had greater N_t losses with the sludge treatments. Although concentrations of most N forms were greater with sludge-treated plots, reductions in runoff and sediment due to sludge application seemed to offset the higher concentrations to some degree. Differences in N yields due to fertilizer source were considerably less than those in N concentrations (Table 14). Total N losses from the conventional tillage plots treated with commercial fertilizer were equivalent to 8.4 and 3.4 percent of the total N applied to the surface-applied and incorporated plots, respectively. The corresponding losses from plots treated with sludge were 3.0 and 1.5 percent, respectively. Total N losses from the surface-applied no-till plots represented 1.7 percent of the total N applied with sludge and 1.5 percent of the total N applied with commercial fertilizer. Since most standards are based on pollutant concentrations and not yields, application of sludge as a fertilizer source appears to increase the potential for nonpoint source pollution problems as compared to the application of commercial fertilizers. As more research on sludge decomposition rates is conducted and more accurate methods for determining sludge loading rates are developed, this may be subject to reevaluation.

IV. Penetrometer Tests

Contour plots developed using penetration resistance data are shown in Figures 1-7. Comparison of these plots show essentially similar penetration resistance within conventional and no-till plots. Normally, one would expect higher penetration resistance values within no-till plots because of higher bulk density and soil strength (Bauder et al. 1988; and Lindstrom and Onstad 1984). The bulk density data taken from each plot at various depths, however, indicates comparable densities up to a depth of 20 cm for the two tillage systems and higher density for greater than 20 cm depth within no-till plots. This increase in soil density, however, did not cause an increase in penetration resistance probably due to the differences in moisture content. Previous studies have shown that the cone penetration resistance, or cone index is dependent on both soil bulk density and moisture content. A study by Ayers and Perumpral (1982) showed a reduction in penetration resistance with an increase in soil moisture level. Thus, a low penetration resistance reading, even at higher soil density, is possible depending on soil moisture level. Our results indicate that soil moisture levels in no-till plots are generally higher than those of conventional tillage plots. Therefore, it is logical to conclude that the penetration resistance was similar in both tillage systems, mainly because of higher soil moisture levels in no-till plots. Comparable penetration resistances may also mean that even though an increase in soil density and strength are expected with no-till practice, plant root development may not be severely affected because of the potential for increased soil moisture content.

Penetration resistance data from all test plots except QF1 and QF2 were taken after a heavy rain. Therefore, the penetration resistance data matrices from surface-applied sludge and sludge-incorporated sludge treatments under conventionally tilled plots were not averaged. If contours from these two plots (QF1 and QF2) are compared against those with similar treatments (Figures 1 versus 3 and 2 versus 4) the influence of moisture level on penetration resistance is substantiated.

Comparison of penetration resistance data from conventional and no-till plots show that surface application of sludge had minimal influence on the penetration resistance. However, within no-till treatments, when plots with and without sludge were compared (Figures 6 and 7), plots with sludge showed reduced penetration resistance.

Similar comparison of conventionally tilled plots (Figure 4 versus 3 and 5) reveals that the no-sludge treatments had higher penetration resistance values at every depth. However, a small reduction in resistance within surface layers is indicated when the sludge is surface-applied. Again, this difference could be attributed to the soil moisture content. Even though sludge application increased the soil moisture level, the surface layer may have dried out by the time the readings were taken because the soil in those plots had no residue cover.

Comparing Figures 3 and 5 reveals that sludge incorporation in conventionally tilled plots reduced soil resistance in the deeper layers, relative to surface application treatments. This reduction could be due to increased soil moisture capacity of the soil as a result of sludge incorporation.

SUMMARY AND CONCLUSIONS

A rainfall simulator was used to study the effects of tillage system and sludge application method and rate on runoff, sediment and nutrient yields from agricultural lands. Surface application and incorporation of sludge were studied. Anaerobically digested sewage sludge was applied at rates supplying 75 kg and 150 kg-N/ha plant-available N. A total of 90 mm of rainfall with an intensity of 40-45 mm/hr was applied to 16 field plots. Runoff water samples were collected from H-flumes at the base of each plot and analyzed for sediment and nutrient content. The following conclusions were drawn from this study:

- No-till reduced soil loss and runoff by 73 and 54 percent, respectively, relative to conventional tillage. Surface application of sludge reduced runoff volume by 25 percent relative to the incorporated treatments. Sludge application, however, significantly reduced runoff, peak runoff rates, and sediment concentrations and yields. Runoff volume and peak runoff rate from the 150 kg N/ha surface sludge application on conventionally tilled plots were reduced by 38 and 32 percent, respectively compared to the control treatments.

- Orthophosphorus concentrations in runoff from all treatments exceeded the 0.01 mg/L level required for algae growth in surface water. Orthophosphorus concentrations were generally higher from no-till than conventional tillage plots, but PO_4^- yields were slightly lower.

- NH_4^+ — N, NO_3^- — N, TKN, and N_t concentrations and yields were greater with conventional tillage than with no-till, regardless of the application method or rate.

- Sediment-bound P and P_t concentrations from the no-till plots averaged 40 and 25 percent less, respectively, than those from conventional tillage plots. Corresponding P_{sb} and P_t yields were reduced by 75 and 64 percent. Phosphorus concentrations and yields were generally greater with surface application than with incorporation. For both tillage systems, P_{sb} losses were greatest from the control plots to which no sludge was applied. Substantial reductions in sediment yield as a result of sludge addition partially explains this result.

- On conventional tillage plots, N concentrations and yields were generally higher when sludge was surface-applied than when incorporated. Incorporation of sludge reduced the amount of nutrients on the soil surface available for loss in surface runoff. Incorporation of sludge, however, increased NO_3^- — N concentrations in runoff during the initial run, which can be attributed to the increased mineralization due to greater soil/sludge interaction.

- Nitrate concentrations and yields were unaffected by sludge application rate. Ammonium, TKN, and N_t concentrations and yields generally increased with increasing sludge application rate.

- Sludge application significantly increased NH_4^+ — N, TKN_f, TKN, and N_t concentrations over commercial fertilizer application. Nitrate concentrations in runoff from plots treated with commercial fertilizer were generally higher than those from sludge-treated plots. The effects of fertilizer source on NO_3^- yields were less evident.

- Conventionally tilled plots had comparable soil resistance values to no-till plots. Soil moisture content may have been the influencing factor. Surface application of sludge in no-till plots resulted in reduced penetration resistance within all layers. Surface application of sludge in conventionally tilled plots, however, resulted in reduced penetration resistance compared to no-sludge treatment. Incorporation of sludge reduced the penetration resistance at all depths in conventionally tilled plots over no-sludge treatment which could be due to soil disturbance and high moisture content. Sludge incorporation reduced penetration resistance in deeper layers compared to surface sludge application. The no-till plots were established on first-year no-till treatments; therefore, these results on the effects of no-till soil structure are not conclusive. A longer term research is needed for this analysis.

The tillage system and method of sludge application employed can have a significant impact on sediment and nutrient losses. In this study, no-till was effective in reducing sediment, runoff, and nutrient yields, thereby reducing potential nonpoint source pollution problems from cropland. The incorporation of sludge, in contrast to surface application, seems to reduce both concentration and yield of nutrients in runoff from conventional tillage systems. Application of sludge to no-till fields (as opposed to conventional tillage) appears to be environmentally safer from the surface water quality standpoint. Efforts should be made to investigate the groundwater quality impacts of land application of sludge on no-till agricultural lands.

FIGURES

FIGURE 1
Soil Penetration Resistance Contour Line for Plot QF1

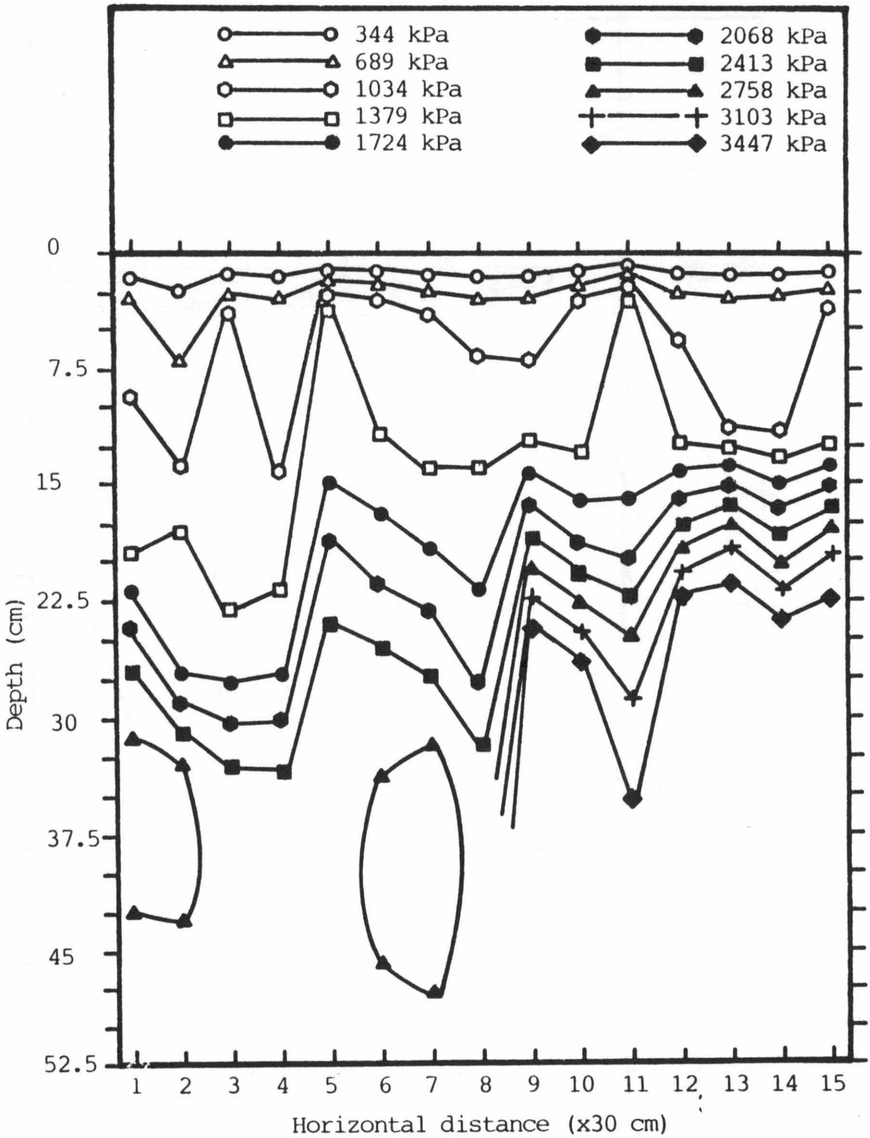


FIGURE 2
Soil Penetration Resistance Contour Line for Plot QF2

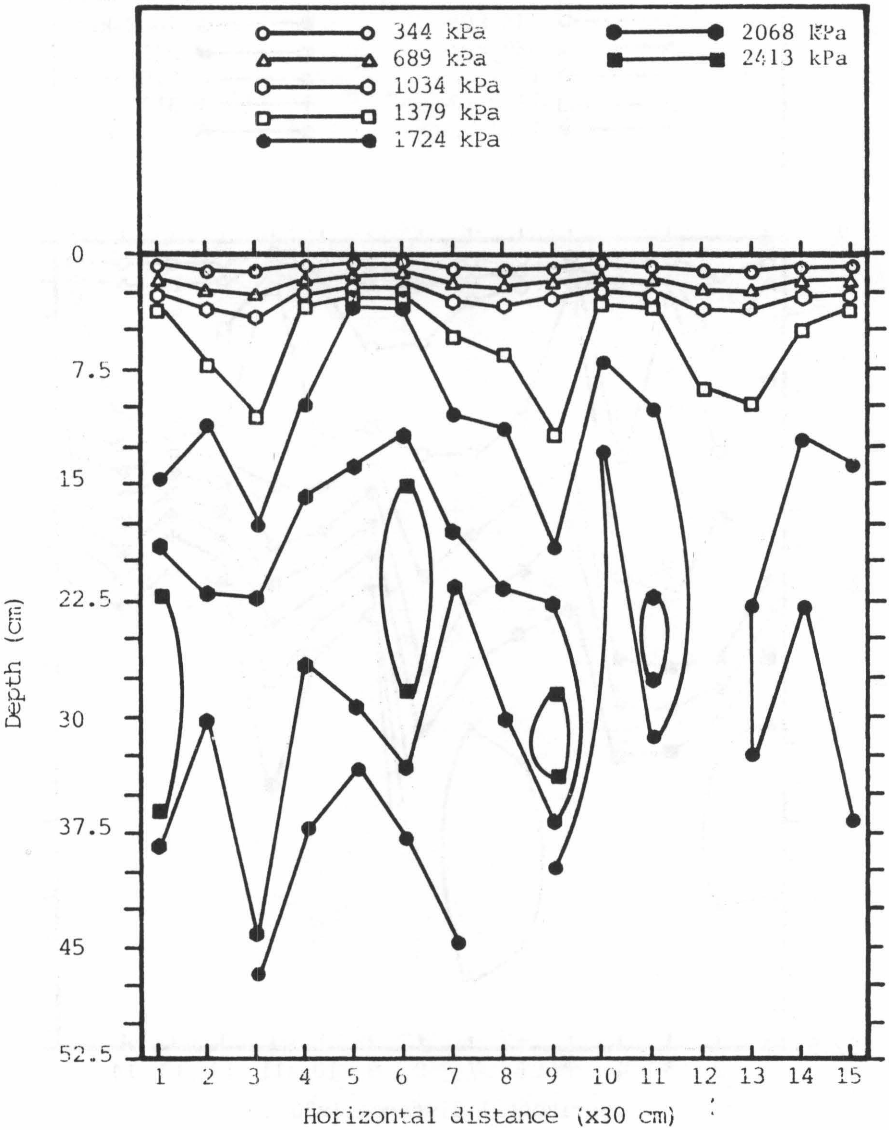


FIGURE 3
Soil Penetration Resistance Contour Line for Plot QF3

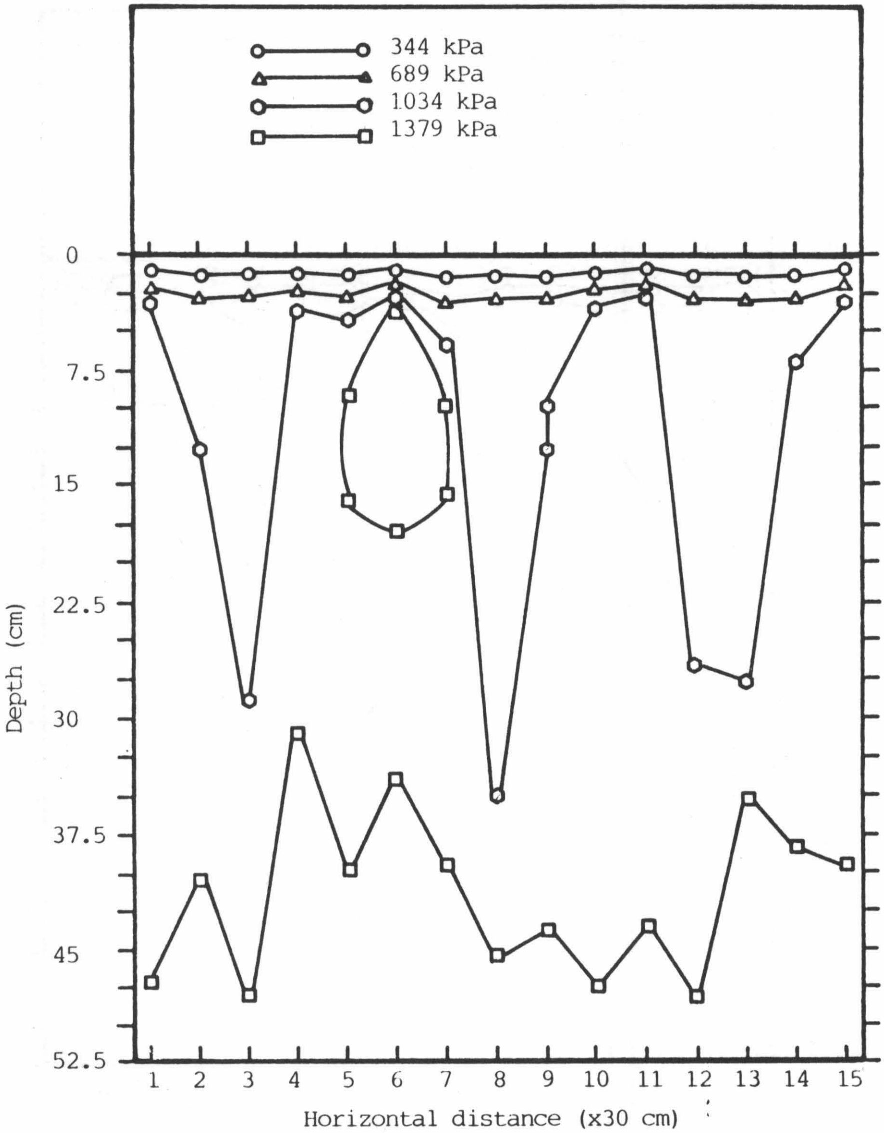


FIGURE 4
Soil Penetration Resistance Contour Line for Plot QF4

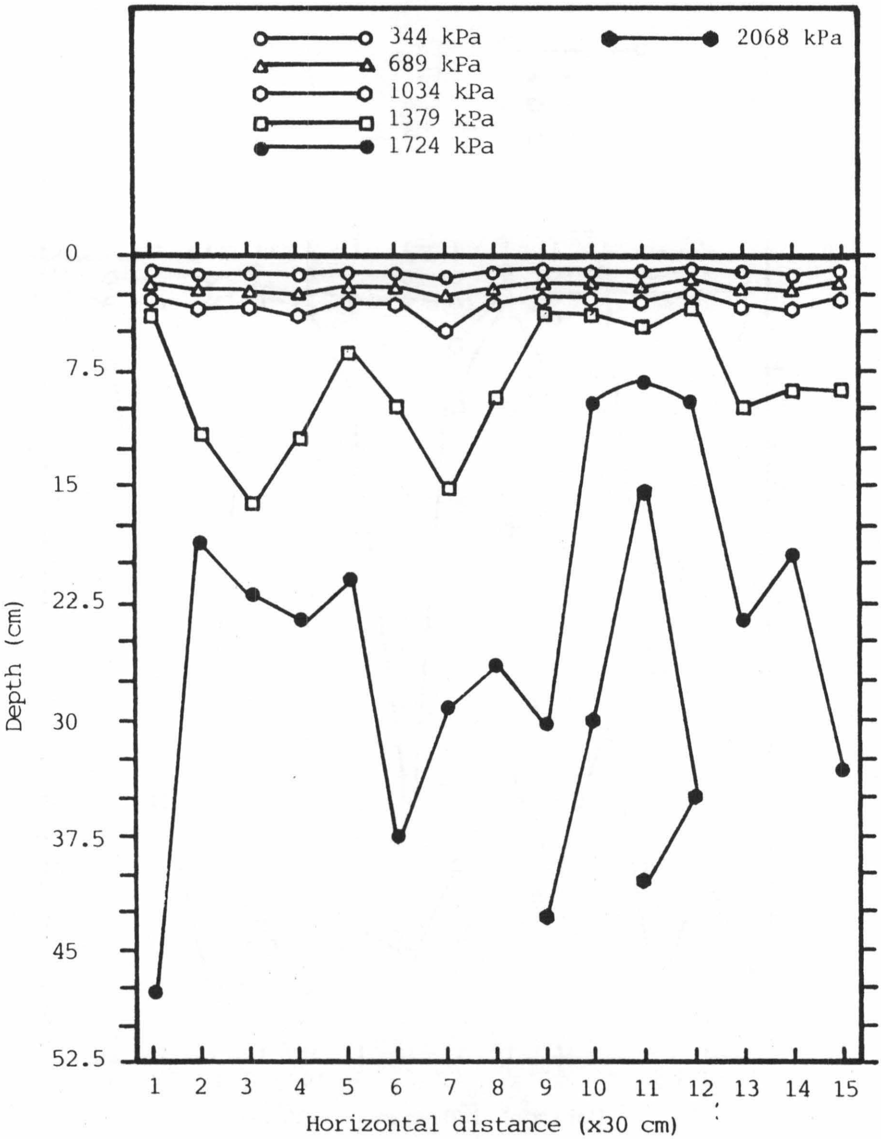


FIGURE 5
Average Soil Penetration Resistance Contour Line for Plots QF4 and QFD

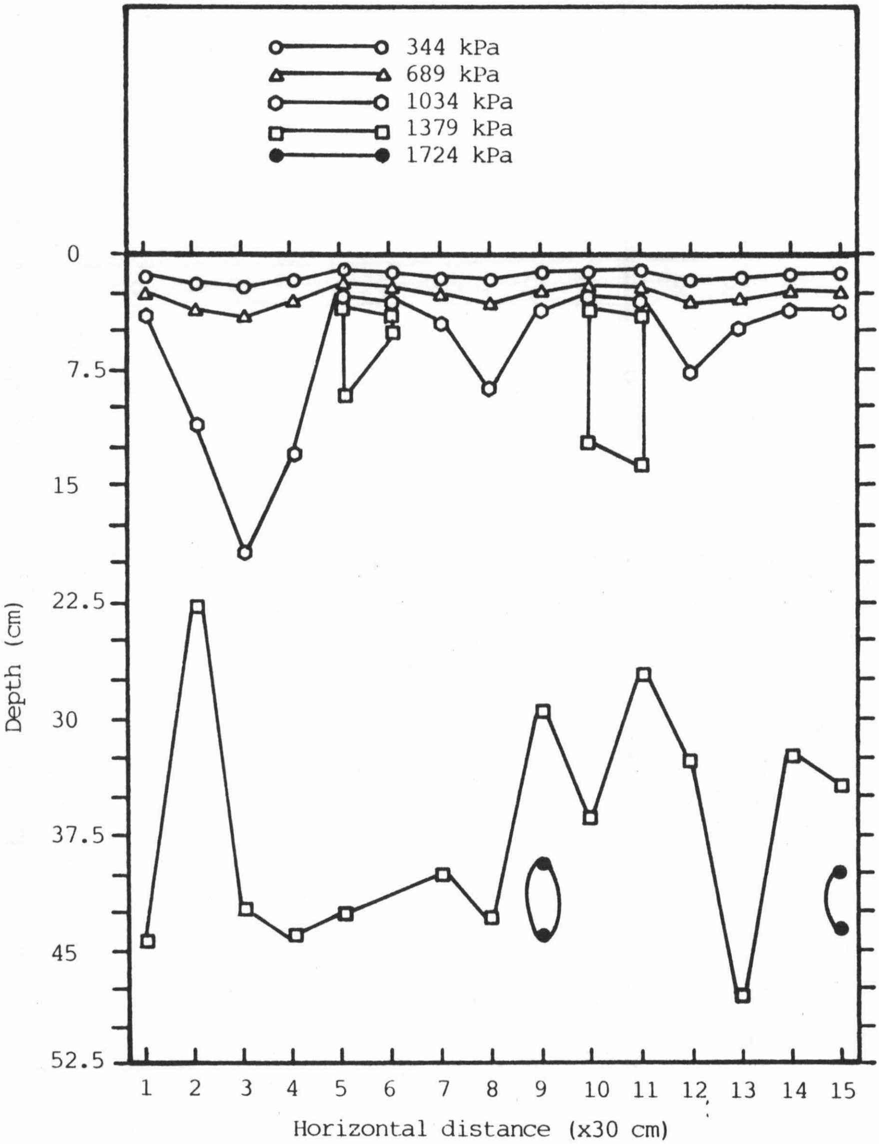


FIGURE 6
Average Soil Penetration Resistance Contour Line for Plots QF6 and QFM

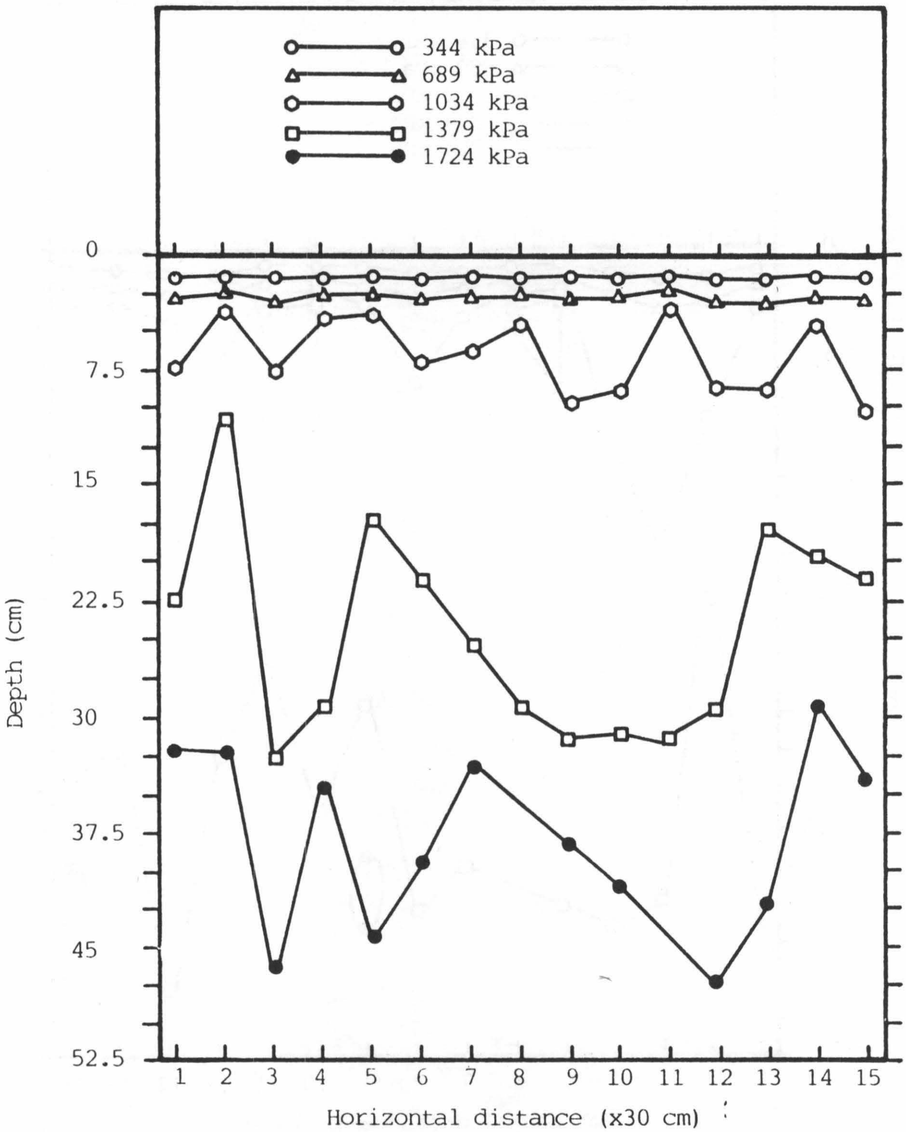
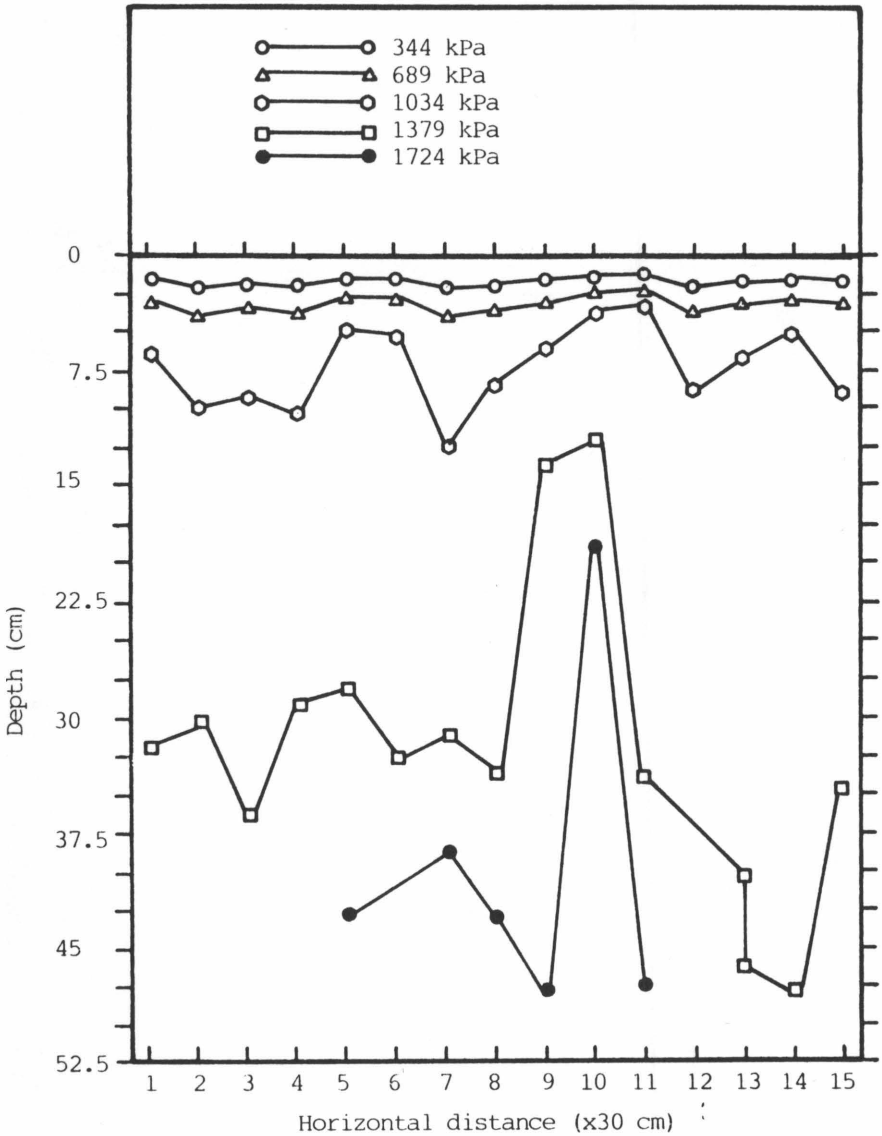


FIGURE 7
Average Soil Penetration Resistance Contour Line for Plots QFC and QFF



TABLES

TABLE 1
Plot Characteristics and Treatments

Plot	Tillage	Application Rate (Kg-N/ha)*	Application Method	Slope (%)
QF1	Conv.	150	Incorporated	9.2
QF2	Conv.	0	None	9.0
QF3	No-till	75	Surface	9.9
QF4	Conv.	150	Surface	14.1
QF5	Conv.	150	Incorporated	15.1
QF6	No-till	0	None	14.0
QFA	Conv.	75	Incorporated	9.7
QFB	Conv.	75	Surface	8.9
QFC	No-till	150	Surface	9.1
QFD	Conv.	150	Surface	9.4
QFE	No-till	75	Surface	8.6
QFF	No-till	150	Surface	8.3
QFK	Conv.	75	Incorporated	11.7
QFL	Conv.	75	Surface	11.4
QFM	No-till	0	None	11.3
QFN	Conv.	0	None	11.4

Soil Characteristics:

Soil type - Groseclose silt loam
Bulk density: - 1.39 g/cm^3
% sand: - 17.9
% silt: - 58.9
% clay: - 23.2
% organic matter: - 3.7

Rainfall Simulator:

Simulated rainfall intensity: - 45 mm/hr
Simulated rainfall duration: - Run 1(R1), 60 min
- Run 2(R2), 30 min
- Run 3(R3), 30 min

*Plant available nitrogen

TABLE 2
Analysis of the Anaerobically Digested, Polymer-Conditioned Sludge Applied to the Experimental Plots

solids (%)	16.00
pH	7.30
NH_4 - M (%)	0.96
TKN (%)	3.02
phosphorus (%)	2.00
potassium (%)	0.07
sulfur (%)	2.80
calcium (%)	3.20
magnesium (%)	0.32
sodium (%)	0.04
chloride (%)	0.46
copper ($mgkg^{-1}$)	660.00
zinc ($mgkg^{-1}$)	1800.00
cadmium ($mgkg^{-1}$)	7.00
chromium ($mgkg^{-1}$)	65.00
nickel ($mgkg^{-1}$)	35.00
lead ($mgkg^{-1}$)	60.00
molybdenum ($mgkg^{-1}$)	20.00
boron ($mgkg^{-1}$)	30.00

TABLE 3
Rainfall Simulator Data

	QF 1		QF 2		QF 3		Mean QF 1-QF 3			
Run	Rainfall (mm)	U.C. %*	Rainfall (mm)	U.C. %	Rainfall(mm)	U.C. %	Rainfall (mm)	U.C. %		
R1	42.5	92.0	42.5	91.9	42.2	88.2	42.4	90.7		
R2	21.9	92.3	22.9	89.4	22.0	90.0	22.3	90.6		
R3	21.5	89.7	22.1	88.7	22.1	90.8	21.9	89.7		
	QF 4		QF 5		QF 6		Mean QF 4-QF 6			
Run	Rainfall (mm)	U.C. %	Rainfall (mm)	U.C. %	Rainfall(mm)	U.C. %	Rainfall (mm)	U.C. %		
R1	42.3	95.2	42.4	95.8	42.3	90.4	42.3	93.8		
R2	20.6	92.7	21.0	92.5	21.3	93.3	21.0	92.8		
R3	21.7	91.9	20.8	94.4	21.3	95.4	21.3	93.9		
	QF A		QF B		QF C		Mean QF A-QF C			
Run	Rainfall (mm)	U.C. %	Rainfall (mm)	U.C. %	Rainfall(mm)	U.C. %	Rainfall (mm)	U.C. %		
R1	41.6	94.0	40.8	96.7	44.2	96.9	42.2	95.9		
R2	20.5	91.7	21.5	94.0	23.0	95.5	21.7	93.7		
R3	22.0	92.6	21.5	96.0	23.1	96.5	22.2	95.0		
	QF D		QF E		QF F		Mean QF D-QF F			
Run	Rainfall (mm)	U.C. %	Rainfall (mm)	U.C. %	Rainfall(mm)	U.C. %	Rainfall (mm)	U.C. %		
R1	43.5	92.4	44.6	92.3	44.3	94.5	44.1	93.1		
R2	21.8	90.6	22.5	98.3	22.8	96.1	22.4	95.0		
R3	22.4	95.6	22.8	93.9	22.0	97.7	22.4	95.7		
	QF K		QF L		QF M		QF N		Mean QF K-QF N	
Run	Rainfall (mm)	U.C. %	Rainfall (mm)	U.C. %	Rainfall(mm)	U.C. %	Rainfall (mm)	U.C. %	Rainfall (mm)	U.C. %
R1	42.7	92.1	44.0	87.7	45.1	92.3	46.8	92.6	44.6	91.2
R2	22.0	93.7	22.7	92.0	23.5	93.8	24.3	93.1	23.1	93.2
R3	21.5	90.1	23.2	91.1	24.0	75.5	23.7	92.2	23.1	87.2

*U.C. = Uniformity Coefficient

TABLE 4

Effects of Tillage System on Soil Loss, Runoff, Sediment Concentration, and Peak Runoff Rate

Tillage System	Run	Soil Loss (kg/ha)	Runoff (cm)	Avg. Sed. Concentration[1] (mg/L)	Peak Runoff[1] (cm/hr)
No-till	R1	155.7	0.32	1877.5*	0.9*
	R2	114.6	0.35	1840.3†	1.7†
	R3	234.5	0.85	2137.9‡	2.2‡
	Total	504.8*	1.52	—	—
Conventional	R1	379.4	0.72	4255.3*	2.2*
	R2	458.4	0.93	4183.1†	3.0†
	R3	1053.7	1.67	6018.3‡	3.9‡
	Total	1891.5*	3.32	—	—

[1] Means, in a column, followed by the same symbol are different from each other at the 0.05 significance level according to the two sided t-test.

TABLE 5
Effects of Sludge Incorporation on Soil Loss, Runoff, Sediment Concentration, and Peak Runoff Rate from Conventional Tillage System

Sludge Application Method	Run	Soil Loss[1] (kg/ha)	Runoff (cm)	Avg. Sed. Concentration[1] (mg/L)	Peak Runoff Rate[1] (cm/hr)
Incorporated	R1	356.65*	0.89	3975.10*	2.70
	R2	425.16†	0.97	4318.20†	2.64
	R3	852.75‡	1.63	5327.70‡	3.69
	Total	1634.56††	3.49	—	—
Surface applied	R1	129.76*	0.48	3026.90*	1.66
	R2	149.29†	0.76	1895.90†	3.01
	R3	521.86‡	1.56	3321.40‡	3.77
	Total	800.91††	2.80	—	—

[1] Means, in a column, followed by the same symbol are different from each other at the 0.05 significance level according to the two sided t-test.

TABLE 6
Effects of Tillage and Sludge Application Method and Rate on Soil Loss, Runoff, Sediment Concentration and Peak Runoff Rate

Tillage	Applic. Rate		Soil Loss (kg/ha)			Runoff (cm)			Av. Sed. Conc. (mg/L)			Peak Runoff (cm/hr)		
System	Kg-N/ha*	Run	I**	C	S	I	C	S	I	C	S	I	C	S
No-till	0	R1		459.74			1.68			4885.30			1.25	
		R2		329.86			0.56			4671.20			1.93	
		R3		610.83			1.17			4843.60			2.78	
		Total		1400.43			2.41			—			—	
	75	R1			2.90			0.12			449.90			0.67
		R2			3.35			0.13			408.50			1.65
		R3			44.63			0.49			1096.20			1.40
		Total			50.88			0.74						
	150	R1			4.42			0.18			297.40			0.69
		R2			10.66			0.36			441.30			1.57
		R3			48.10			0.88			473.90			2.41
		Total			63.18			1.42			—			—
Conventional	0	R1		924.00			0.89			7272.60			2.28	
		R2		1143.11			1.18			8487.40			3.65	
		R3		2519.39			1.96			12793.40			4.43	
		Total		4586.50			4.03			—			—	
	75	R1	546.12		206.31	1.36		0.52	3929.50		4479.20	3.42		1.76
		R2	607.63		236.59	1.29		0.95	4843.80		2620.40	3.49		3.72
		R3	849.89		683.36	1.85		1.86	4608.90		3677.90	3.10		4.49
		Total	2003.64		1126.26	4.50		3.33	—		—	—		—
	150	R1	167.18		53.21	0.42		0.43	4020.80		1574.60	1.98		1.56
		R2	242.69		62.00	0.65		0.57	3792.50		1171.40	1.79		2.29
		R3	855.62		360.36	1.42		1.25	6046.50		2965.00	3.39		3.06
		Total	1265.49		475.57	2.49		2.25	—		—	—		—

* = Plant available N
**I = Incorporated
C = Control
S = Surface-applied

TABLE 7
Effects of Commercial Fertilizer Application on the Average Soil Loss, Runoff, Sediment Concentration, and Peak Runoff Rate

Tillage System	Application Method	Run	Soil Loss (kg/ha)	Runoff (cm)	Ave. Sed. Conc. (mg/L)	Peak Runoff Rate (cm/hr)
No-till	Surface	R1	204.77	0.83	2677.95	1.351
		R2	80.22	0.51	1754.36	1.651
		R3	131.47	1.07	1379.91	1.633
		Total	416.45	2.41	—	—
Conventional	Surface	R1	2981.11	2.15	13693.28	3.218
		R2	2618.68	1.47	17145.43	3.418
		R3	2339.76	1.65	13928.00	2.679
		Total	7939.55	5.27	—	—
Conventional	Incorporated	R1	1451.94	1.67	8059.15	2.841
		R2	1521.55	1.36	10358.90	3.269
		R3	1685.74	1.63	9575.65	3.480
		Total	4659.23	4.67	—	—

TABLE 8
Effects of Sludge Incorporation and Application Rate on P Concentration in Runoff

Tillage system	Applic. Rate Kg-N/ha*	Run	PO_4^- I**	PO_4^- C	PO_4^- S	P_{sb} I	P_{sb} C	P_{sb} S	P_{tf} I	P_{tf} C	P_{tf} S	P_t I	P_t C	P_t S
			mg/L											
No-till	0	R1		0.05			0.19			0.15			0.34	
		R2		0.05			1.52			0.18			1.69	
		R3		0.21			1.51			0.26			1.77	
		Average		0.10			1.07			0.20			1.27	
	75	R1			0.04			0.03			0.08			0.11
		R2			0.44			0.57			0.45			1.02
		R3			0.49			0.87			0.55			1.42
		Average			0.32			0.49			0.36			0.85
	150	R1			1.47			3.66			1.61			5.27
		R2			0.71			0.50			1.13			1.63
		R3			0.64			2.02			1.80			3.82
		Average			0.94			2.06			1.51			3.57
Conventional	0	R1		0.23			3.05			0.75			3.80	
		R2		0.25			3.59			0.51			4.09	
		R3		0.12			1.16			0.35			1.51	
		Average		0.20			2.60			0.54			3.13	
	75	R1	0.20		0.48	1.04		2.62	0.59		1.03	1.64		3.64
		R2	0.22		0.39	0.79		1.61	0.44		0.95	1.23		3.55
		R3	0.08		0.34	0.93		3.15	0.26		0.61	1.19		3.76
		Average	0.17		0.40	0.92		2.46	0.43		0.86	1.35		3.65
	150	R1	0.47		0.84	6.80		0.69	0.90		0.71	7.70		1.40
		R2	0.31		1.12	2.62		2.01	0.73		1.11	3.34		3.12
		R3	0.28		0.35	2.67		2.77	0.69		0.53	3.36		3.30
		Average	0.35		0.77	4.03		1.82	0.77		0.78	4.80		2.61

* = Plant available N
** I = Incorporated
C = Control
S = Surface-applied

TABLE 9
Effects of Sludge Incorporation and Application Rate on N Concentrations

Tillage system	Applic. Rate Kg-N/ha*	Run	NH_4^+ I**	NH_4^+ C	NH_4^+ S	NO_3^- I	NO_3^- C	NO_3^- S	TKN I	TKN C	TKN S	N_t I	N_t C	N_t S
			mg/L											
No-till	0	R1		0.42			0.69			2.62			3.32	
		R2		0.38			0.85			3.89			4.37	
		R3		0.38			1.00			3.57			4.57	
		Average		0.39			0.85			3.36			4.09	
	75	R1			0.94			0.07			1.49			1.56
		R2			8.93			0.80			12.25			13.05
		R3			9.58			1.33			17.55			18.88
		Average			6.48			0.73			10.43			11.16
	150	R1			12.74			1.03			38.80			39.83
		R2			3.43			0.22			28.26			28.48
		R3			7.42			0.40			34.78			35.18
		Average			7.86			0.55			33.95			34.50
Conv.	0	R1		1.54			1.61			19.89			21.50	
		R2		1.41			1.22			22.94			24.17	
		R3		0.86			0.88			4.58			5.46	
		Average		1.27			1.24			15.80			17.04	
	75	R1	11.59		23.52	11.50		6.28	21.61		31.27	33.11		37.55
		R2	5.71		18.91	1.02		1.34	16.25		28.65	17.27		29.99
		R3	2.76		9.38	0.54		1.12	10.96		16.50	11.49		17.62
		Average	6.69		17.27	4.35		2.91	16.27		25.47	20.62		28.39
	150	R1	7.22		29.29	3.44		1.76	26.42		40.61	29.86		42.37
		R2	1.82		33.40	2.06		2.86	14.89		52.06	16.95		54.94
		R3	2.28		14.84	0.70		0.54	14.00		26.98	14.70		27.51
		Average	3.77		25.84	2.07		1.72	18.44		39.88	20.50		41.61

* = Plant available N
**I = Incorporated
C = Control
S = Surface-applied

TABLE 10
Effects of Tillage System on the Average P Concentrations

Tillage system	Run	PO_4^-	P_{sb}	P_{tf}	P_t
		mg/L			
No-till	R1	0.76	1.84	0.85	2.69
	R2	0.58	0.54	0.79	1.32
	R3	0.56	1.45	1.18	2.62
	Average	0.63	1.28	0.94	2.21
Conventional (Surface)	R1	0.66	1.65	0.87	2.52
	R2	0.75	1.81	1.03	2.84
	R3	0.34	2.96	0.57	3.53
	Average	0.58	2.14	0.82	2.96

TABLE 11

Effects of Tillage System on the Average N Concentrations[1]

Tillage system	Run	NH_4^+ — N	NO_3^- — N	TKN	N_t
		mg/L			
No-till	R1	6.84	0.55	20.15	20.69
	R2	6.18	0.51	20.25	20.77
	R3	8.50	0.86	26.17	27.03
	Average	7.17*	0.64	22.19	22.83
Conventional (Surface)	R1	26.40	4.02	35.94	39.96
	R2	26.16	2.10	40.36	42.46
	R3	12.11	0.83	21.73	22.57
	Average	21.56*	2.32	32.68	35.00

[1] Means, in a column, followed by the same symbol are different from each other at the 0.05 significance level according to the two-sided t-test.

TABLE 12

Effects of Sludge Incorporation on Average P Concentration in Runoff from Conventional Tillage System[1]

Application method	Run	PO_4^-	P_{sb}	P_{tf}	P_t
		mg/L			
Incorporated	R1	0.34	3.92	0.75	4.67
	R2	0.26	1.70	0.58	2.29
	R3	0.18	1.80	0.47	2.27
	Average	0.26*	2.47	0.60	3.08
Surface-applied	R1	0.66	1.65	0.87	2.52
	R2	0.75	1.81	1.03	2.84
	R3	0.34	2.96	0.57	3.53
	Average	0.58*	2.14	0.82	2.96

[1] Means, in a column, followed by the same symbol are different from each other at the 0.05 significance level according to the two sided t-test.

TABLE 13

Effects of Sludge Incorporation on N Concentration in Runoff from Conventional Tillage System[1]

Application method	Run	NH_4^+ — N	NO_3^- — N	TKN	N_t
		mg/L			
Incorporated	R1	9.40	7.47	24.01	31.48
	R2	3.76	1.54	15.57	17.11
	R3	2.52	0.62	12.48	13.10
	Average	5.23*	3.21	17.35*	20.56*
Surface-applied	R1	26.40	4.02	35.94	39.96
	R2	26.16	2.10	40.36	42.46
	R3	12.11	0.83	21.73	22.57
	Average	21.56*	2.32	32.68*	35.00*

[1] Means, in a column, followed by the same symbol are different from each other at the 0.05 significance level according to the two-sided t-test.

TABLE 14
Effects of Commercial Fertilizer Application on the Average N Concentrations

Tillage System	Applic. Method	Run	NH_4^+ — N	NO_3^- — N	TKN	N_t
			mg/L			
No-till	Surface	R1	4.20	3.39	8.27	11.66
		R2	2.28	2.96	5.56	8.52
		R3	2.52	2.55	4.58	7.13
		Average	3.00	2.97	6.14	9.10
Conventional	Surface	R1	6.04	4.87	17.53	22.41
		R2	6.90	1.75	27.31	29.06
		R3	2.63	1.15	18.89	20.04
		Average	5.19	2.59	21.24	23.84
Conventional	Incorporated	R1	0.20	1.46	7.58	9.03
		R2	0.78	0.68	9.48	10.16
		R3	0.25	0.68	11.95	12.63
		Average	0.41	0.94	9.67	10.61

TABLE 15
Effects of Sludge Incorporation and Application Rate on P Yields

Tillage	Applic. Rate		PO_4^-			P_{sb}			P_{tf}			P_t		
system	Kg-N/ha*	Run	I**	C	S	I	C	S	I	C	S	I	C	S
			kg/ha											
No-till	0	R1		0.01			0.03			0.02			0.05	
		R2		0.01			0.16			0.02			0.18	
		R3		0.03			0.23			0.04			0.27	
		Total		0.05			0.42			0.08			0.50	
	75	R1			0.01			0.01			0.01			0.01
		R2			0.01			0.01			0.01			0.02
		R3			0.02			0.05			0.04			0.09
		Total			0.04			0.07			0.06			0.12
	150	R1			0.03			0.07			0.03			0.10
		R2			0.04			0.03			0.07			0.10
		R3			0.09			0.29			0.25			0.54
		Total			0.16			0.39			0.35			0.74
Conventional	0	R1		0.01			0.38			0.05			0.43	
		R2		0.03			0.48			0.06			0.54	
		R3		0.03			0.37			0.11			0.48	
		Total		0.07			1.23			0.22			1.45	
	75	R1	0.03		0.03	0.15		0.14	0.08		0.06	0.23		0.19
		R2	0.03		0.04	0.10		0.16	0.06		0.09	0.16		0.24
		R3	0.02		0.10	0.28		0.89	0.08		0.17	0.36		1.06
		Total	0.08		0.17	0.53		1.19	0.22		0.32	0.75		1.49
	150	R1	0.02		0.06	0.28		0.09	0.04		0.05	0.32		0.15
		R2	0.03		0.07	0.24		0.12	0.07		0.06	0.31		0.18
		R3	0.06		0.06	0.55		0.46	0.14		0.10	0.70		0.56
		Total	0.11		0.19	1.07		0.67	0.25		0.21	1.33		0.89

* = Plant available N
**I = Incorporated
C = Control
S = Surface-applied

TABLE 16
Effects of Sludge Incorporation and Application Rate on N Yields

Tillage system	Applic. Rate Kg-N/ha*	Run	NH_4^+ I**	NH_4^+ C	NH_4^+ S	NO_3^- I	NO_3^- C	NO_3^- S	TKN I	TKN C	TKN S	N_t I	N_t C	N_t S
			kg/ha											
No-till	0	R1		0.06			0.09			0.34			0.43	
		R2		0.05			0.09			0.39			0.48	
		R3		0.06			0.16			0.60			0.76	
		Total		0.17			0.34			1.33			1.67	
	75	R1			0.12			0.01			0.16			0.17
		R2			0.06			0.03			0.18			0.20
		R3			0.53			0.08			1.05			1.13
		Total			0.71			0.12			1.39			1.50
	150	R1			0.14			0.01			0.71			0.72
		R2			0.36			0.02			1.86			1.88
		R3			0.65			0.04			4.09			4.13
		Total			1.15			0.07			6.66			6.73
Conventional	0	R1		0.15			0.13			2.46			2.60	
		R2		0.17			0.14			3.14			3.27	
		R3		0.27			0.27			1.41			1.68	
		Total		0.59			0.54			7.01			7.55	
	75	R1	1.57		1.25	1.71		0.28	3.03		1.69	4.74		1.96
		R2	0.75		1.82	0.13		0.12	2.14		2.68	2.27		2.80
		R3	0.87		2.64	0.17		0.31	3.47		4.61	3.64		4.92
		Total	3.19		5.71	2.01		0.71	8.64		8.98	10.65		9.68
	150	R1	0.30		2.27	0.15		0.19	1.10		2.99	1.25		3.18
		R2	0.34		1.99	0.16		0.14	1.32		3.19	1.48		3.33
		R3	0.47		2.85	0.15		0.10	2.90		4.92	3.04		5.02
		Total	1.11		7.11	0.46		0.43	5.32		11.10	5.77		11.53

* = Plant available N
**I = Incorporated
C = Control
S = Surface-applied

TABLE 17
Effects of Tillage System on P Yields[1]

Tillage system	Run	PO_4^-	P_{sb}	P_{tf}	P_t
		kg/ha			
No-till	R1	0.02	0.04	0.02	0.06
	R2	0.03	0.02	0.04	0.06
	R3	0.06	0.17	0.14	0.32
	Total	0.11	0.23*	0.20	0.44*
Conventional (Surface)	R1	0.04	0.12	0.05	0.17
	R2	0.06	0.14	0.08	0.21
	R3	0.08	0.67	0.14	0.81
	Total	0.18	0.93*	0.27	1.19*

[1] Means, in a column, followed by the same symbol are different from each other at the 0.05 significance level according to the two-sided t-test.

TABLE 18
Effects of Tillage System on N Yields[1]

Tillage System	Run	NH_4^+ — N	NO_3^- — N	TKN	N_t
		kg/ha			
No-till	R1	0.13	0.01	0.44	0.44
	R2	0.21	0.02	1.02	1.04
	R3	0.59	0.06	2.57	2.63
	Total	0.93*	0.09	4.03*	4.11*
Conventional (Surface)	R1	1.76	0.23	2.34	2.57
	R2	1.91	0.13	2.94	3.07
	R3	2.75	0.20	4.77	4.97
	Total	6.42*	0.56	10.05*	10.61*

[1] Means, in a column, followed by the same symbol are different from each other at the 0.05 significance level according to the two sided t-test.

TABLE 19
Effects of Sludge Incorporation on P Yields from Conventional Tillage System[1]

Application method	Run	PO_4^-	P_{sb}	P_{tf}	P_t
		kg/ha			
Incorporated	R1	0.02	0.22	0.06	0.28
	R2	0.03	0.17	0.06	0.23
	R3	0.04	0.42	0.11	0.53
	Total	0.09*	0.81	0.23	1.04
Surface-applied	R1	0.04	0.12	0.05	0.17
	R2	0.06	0.14	0.08	0.21
	R3	0.08	0.67	0.14	0.81
	Total	0.18*	0.93	0.27	1.19

[1] Means, in a column, followed by the same symbol are different from each other at the 0.05 significance level according to the two-sided t-test.

TABLE 20
Effects of Sludge Incorporation on N Yields from Conventional Tillage System[1]

Application method	Run	NH_4^+ — N	NO_3^- — N	TKN	N_t
		kg/ha			
Incorporated	R1	0.93	0.93	2.07	2.99
	R2	0.55	0.15	1.73	1.87
	R3	0.67	0.16	3.19	3.34
	Total	2.15*	1.24	6.99*	8.20*
Surface-applied	R1	1.76	0.23	2.34	2.57
	R2	1.91	0.13	2.94	3.07
	R3	2.75	0.20	4.77	4.97
	Total	6.42*	0.56	10.05*	10.61*

[1] Means, in a column, followed by the same symbol are different from each other at the 0.05 significance level according to the two-sided t-test.

TABLE 21
Effects of Commercial Fertilizer Application on N Yields

Tillage System	Applic. Method	Run	NH_4^+ — N	NO_3^- — N	TKN	N_t
			kg/ha			
No-till	Surface	R1	0.38	0.24	0.68	0.92
		R2	0.12	0.17	0.30	0.46
		R3	0.32	0.33	0.53	0.86
		Total	0.82	0.74	1.51	2.24
Conventional	Surface	R1	1.32	1.03	3.84	4.88
		R2	1.08	0.25	4.12	4.37
		R3	0.44	0.19	3.17	3.36
		Total	2.84	1.47	11.13	12.61
Conventional	Incorporated	R1	0.04	0.25	1.29	1.54
		R2	0.12	0.10	1.34	1.44
		R3	0.04	0.12	2.02	2.14
		Total	0.20	0.47	4.65	5.12

APPENDIX

TABLE A-1
Water Quality Concentration Data and Plot Discharges

Plot/ Test/ Run	Time* (min)	TSS (g/L)	NH_4^+ — N	NO_3^- — N	TKN-N	P_t	PO_4^-	TKN_f	P_{tf}	Δ t (min)	Flow (cm/hr)
			ppm								
QF1T7R1	3	0.808	1.722	0.373	5.000	0.973	0.177	3.649	0.434	3	0.00000
	6	2.906	2.349	0.713	7.484	2.838	0.189	6.618	0.529	3	0.00848
	9	4.102	2.663	1.629	8.323	0.899	0.244	7.647	0.529	3	0.01834
	12	4.614	2.887	0.259	9.161	1.391	0.187	7.157	0.434	3	0.02258
	15	1.790	3.952	0.157	10.850	0.930	0.129	7.108	0.370	3	0.03526
	21	5.474	6.616	0.186	11.194	0.916	0.257	8.529	0.513	6	0.03526
	24	5.816	10.345	0.321	15.613	1.633	0.135	13.529	0.513	3	0.03526
	27	6.042	14.554	0.315	19.915	2.751	0.103	17.120	0.529	3	0.03526
	30	4.796	15.673	0.315	19.258	2.635	0.153	18.231	0.625	3	0.09164
	33	5.622	18.443	0.572	20.500	7.140	0.128	19.893	0.529	3	0.11984
	36	4.890	8.280	0.475	17.250	4.085	0.311	10.846	0.537	3	0.13678
	39	4.344	16.525	0.625	23.182	9.152	0.234	21.741	0.545	3	0.17628
	41	4.800	12.402	0.564	21.550	6.619	0.355	18.590	0.673	2	0.22565
QF1T7R2	3	0.640	2.226	1.421	7.612	0.988	0.278	1.994	1.000	3	0.00000
	8	2.688	8.170	1.827	9.881	1.467	0.429	2.913	2.648	5	0.01130
	11	3.095	2.031	0.813	19.870	2.576	0.510	8.685	1.731	3	0.11280
	14	3.502	7.013	0.922	17.196	2.455	0.376	8.102	0.940	3	0.20589
	20	3.784	9.004	0.764	12.966	4.147	0.327	9.268	0.871	6	0.81801
	26	3.626	8.139	1.129	14.782	6.157	0.402	11.478	0.700	6	1.93368
	29	2.326	9.507	1.450	15.772	1.845	0.504	11.999	0.790	3	2.61203
	31	1.900	9.265	1.463	16.436	2.840	0.492	13.399	1.240	2	2.72628
QF1T7R3	6	4.756	4.579	0.642	11.925	3.513	0.355	4.852	0.890	6	0.83917
	9	3.588	6.087	0.740	17.960	3.072	0.390	6.757	0.970	3	2.38356
	12	3.766	6.208	0.786	15.171	3.581	0.379	7.141	0.640	3	3.00977
	18	3.786	5.987	0.786	17.150	3.022	0.410	7.374	0.820	6	3.09159
	24	16.482	5.585	0.872	13.627	3.497	0.430	6.853	1.000	6	3.26083
	30	3.424	5.323	0.798	16.341	2.030	0.491	7.237	1.130	6	3.21711
	33	1.244	6.108	1.044	18.912	6.605	0.415	7.113	0.930	3	1.67698

QF2T7R1	3	1.166	1.160	0.760	2.208	2.154	0.353	0.483	0.450	3	0.00000
	6	1.132	1.220	0.704	2.208	1.356	0.391	0.408	0.860	3	0.06299
	12	4.058	1.160	1.473	3.069	2.800	0.430	0.566	0.940	6	0.09449
	15	4.296	1.059	1.865	4.713	2.246	0.427	0.918	0.810	3	0.12598
	26	0.946	1.260	1.827	4.356	1.812	0.439	0.733	1.210	11	0.12598
QF2T7R2	3	1.148	1.099	1.184	2.168	1.785	1.137	0.724	1.000	3	0.00000
	6	2.528	1.180	1.462	2.753	1.529	0.416	0.334	0.930	3	0.22047
	9	3.952	1.260	1.260	1.881	2.344	0.429	0.455	1.540	3	0.28346
	12	4.148	1.200	1.557	2.455	2.012	0.361	0.696	0.940	3	0.36723
	15	3.880	1.160	2.286	2.356	1.453	0.404	0.992	0.573	3	0.77318
	21	3.806	1.260	1.836	3.000	2.328	0.446	0.977	0.604	6	1.22225
	24	3.444	1.260	1.780	6.199	1.936	0.418	2.472	0.542	3	3.00231
	27	2.242	1.361	2.915	4.713	1.710	0.470	2.912	0.557	3	3.51742
	29	0.832	1.381	0.661	4.012	1.227	0.517	3.352	0.573	2	3.79987
QF2T7R3	6	5.084	1.119	0.664	5.208	2.030	0.301	1.674	0.587	6	0.59078
	9	4.456	1.160	2.350	13.046	1.876	0.388	3.846	0.603	3	2.16411
	12	3.816	1.220	1.369	12.373	1.664	0.341	4.074	0.498	3	3.69827
	18	3.348	1.260	1.802	11.988	3.023	0.304	3.501	0.468	6	4.32412
	24	3.200	1.140	2.066	9.713	2.147	0.336	2.939	0.602	6	4.48871
	30	3.154	1.099	1.767	6.721	1.936	0.325	2.473	1.122	6	4.48871
	33	0.996	1.361	2.231	2.832	1.483	0.351	1.946	1.166	3	3.85067
QF3T7R1	3	1.608	8.907	0.598	16.158	0.854	0.380	11.029	0.641	3	0.00000
	6	1.436	11.038	0.556	14.178	0.848	0.421	11.961	0.657	3	0.00823
	9	1.674	7.841	0.493	18.574	0.714	0.385	11.667	0.533	3	0.01372
	12	1.590	8.534	0.440	16.168	0.714	0.420	11.372	0.529	3	0.02195
	15	2.178	1.341	0.374	13.980	0.689	0.369	9.119	0.348	3	0.02195
	18	1.594	8.161	0.401	12.990	0.718	0.359	17.195	0.747	3	0.03018
	24	0.702	7.841	0.440	17.584	0.783	0.332	5.362	1.175	3	0.03429
QF3T7R2	3	1.194	6.776	1.563	19.307	1.732	0.281	13.992	0.281	3	0.00000
	5	1.530	8.427	1.518	17.555	1.618	0.334	17.580	0.513	2	0.00823
	8	1.008	10.780	1.518	16.584	1.260	0.340	14.531	0.398	3	0.01783
	11	0.834	13.980	0.584	20.149	1.244	0.680	15.174	0.568	3	0.03429
	14	1.150	15.580	1.749	21.931	1.738	0.782	15.623	0.565	3	0.05075
	16	0.556	18.080	1.377	23.515	1.971	0.866	17.946	0.843	2	0.05486
QF3T7R3	6	0.860	8.560	1.448	11.163	0.862	0.608	8.418	0.459	6	0.05486
	9	1.510	10.630	1.227	14.188	1.248	0.663	10.392	0.525	3	0.14275
	12	1.848	15.290	1.232	18.941	2.057	0.901	13.826	0.586	3	0.24425
	18	1.900	15.110	2.214	19.951	1.866	0.839	14.074	0.788	6	0.56535

TABLE A-1 continued

Plot/ Test/ Run	Time* (min)	TSS (g/L)	NH_4^+ — N	NO_3^- — N	TKN-N	P_t	PO_4^-	TKN_f	P_{tf}	Δ t (min)	Flow (cm/hr)
			ppm								
	24	1.044	12.380	1.215	18.149	1.680	0.767	13.368	0.521	6	0.73414
	30	1.080	11.490	1.474	27.736	1.454	0.744	16.216	0.474	6	0.79591
	32	3.636	16.710	1.990	19.555	0.969	0.804	14.521	0.550	2	0.44869
QF4T7R1	3	1.022	27.766	6.975	16.500	11.730	0.420	11.607	1.295	3	0.00000
	6	3.516	37.889	6.956	42.000	3.020	0.559	35.445	2.105	3	0.00269
	9	3.028	17.644	6.994	38.750	2.770	0.280	29.395	0.621	3	0.00810
	12	3.130	44.868	9.681	47.000	5.620	0.916	33.020	1.158	3	0.00945
	25	2.356	51.101	8.870	54.500	6.666	0.499	38.351	1.150	13	0.01217
QF4T7R2	3	2.260	16.792	2.406	30.650	3.780	0.478	24.520	0.842	3	0.00000
	6	3.036	32.828	2.266	48.650	1.580	0.452	36.352	0.984	3	0.00406
	9	0.096	39.807	1.620	48.650	3.360	0.481	36.283	0.968	3	0.01082
	12	4.976	6.125	6.056	46.450	4.620	0.567	33.095	0.953	3	0.02560
	18	4.930	38.262	3.394	47.150	2.350	0.408	36.103	0.812	6	0.16835
	21	0.000	37.037	3.952	43.100	5.320	0.482	37.384	0.937	3	1.37521
	23	1.254	43.047	4.256	47.500	3.330	0.644	34.275	1.079	2	1.69174
	25	1.220	18.900	5.435	29.505	2.432	0.748	4.464	1.126	2	1.78468
QF4T7R3	6	4.578	12.886	0.427	17.469	9.022	0.324	27.829	0.676	6	1.21895
	9	5.764	11.659	1.024	54.162	13.282	0.209	22.331	0.244	3	2.10792
	12	3.408	12.323	0.773	36.568	8.563	0.328	29.591	0.716	3	2.60363
	18	5.464	12.162	1.225	40.801	6.505	0.314	30.249	0.700	6	2.60363
	24	3.340	11.840	0.328	37.061	6.505	0.758	27.135	1.047	6	2.83527
	30	4.302	10.030	0.769	30.762	5.582	0.316	23.203	0.676	6	2.75717
	32	1.406	24.484	1.330	39.137	6.752	0.477	29.520	0.811	2	0.90777
	34	2.086	32.072	1.297	42.300	6.783	0.384	36.868	0.937	2	0.17777
QF5T7R1	3	5.652	1.241	7.932	26.446	6.225	0.512	18.342	1.760	3	0.00000
	6	6.908	2.132	12.058	37.560	5.184	0.430	32.121	1.720	3	0.00462
	9	7.824	2.164	10.058	36.988	4.009	0.431	34.331	1.620	3	0.00462
	12	7.786	2.319	10.128	37.681	3.306	0.482	33.226	1.540	3	0.00310
	15	7.846	1.924	8.631	32.741	4.321	0.458	27.877	1.000	3	0.00462
	18	8.436	1.758	6.868	30.602	5.680	0.478	26.222	1.480	3	0.00462

	21	7.970	1.673	5.437	31.084	3.902	0.509	23.039	1.240	3	0.00927
	23	3.198	1.924	6.302	31.416	8.886	0.605	19.064	1.130	2	0.01544
QF5T7R2	3	3.620	0.537	3.641	24.429	5.577	0.557	21.912	0.970	3	0.00000
	6	7.506	0.772	1.977	23.314	3.365	0.517	21.447	0.726	3	0.00772
	9	7.226	1.294	3.009	19.772	9.840	0.428	13.881	0.848	3	0.02469
	12	5.932	1.545	3.441	19.731	5.930	0.496	15.050	0.889	3	0.32984
	18	6.108	1.508	3.341	27.664	4.786	0.501	23.458	0.930	6	1.14366
	21	6.576	1.390	3.375	27.639	5.346	0.452	19.693	1.099	3	2.68798
	23	4.566	1.620	3.674	28.187	5.961	0.531	25.377	1.480	2	2.77119
	25	2.006	1.337	4.672	23.115	6.592	0.563	19.238	1.510	2	2.89606
QF5T7R3	6	7.332	1.614	1.179	24.535	4.732	0.321	17.087	0.767	6	1.93589
	9	7.544	1.028	0.680	21.898	5.979	0.859	15.754	1.020	3	3.15501
	12	7.208	1.028	1.212	28.776	5.336	0.339	15.597	0.711	3	3.37853
	18	5.976	0.932	0.879	22.530	5.430	0.328	12.439	0.573	6	3.24442
	24	6.124	0.985	1.312	22.651	7.980	0.359	15.039	1.033	6	3.42323
	30	2.680	0.964	1.478	27.343	7.834	0.290	17.877	1.840	6	3.37853
	32	6.284	0.734	1.146	29.458	4.735	0.293	14.197	0.818	2	0.61496
	34	1.616	1.150	1.74	23.102	4.940	0.438	21.075	1.760	2	0.26045
QF6T7R1	3	5.112	1.555	1.417	6.020	5.042	0.994	1.128	1.079	3	0.00000
	8	3.832	2.065	1.316	6.431	3.675	0.916	1.095	0.462	5	0.01824
	10	4.254	1.522	0.862	5.500	3.890	0.823	1.295	0.705	2	0.03932
	13	4.210	1.502	1.024	6.269	4.118	0.804	1.095	0.607	3	0.03932
	16	3.944	1.622	1.215	5.905	4.300	1.011	1.095	0.570	3	0.08423
	19	4.526	1.381	1.294	6.026	3.552	0.524	0.984	0.524	3	0.09825
	22	0.842	1.160	1.317	6.046	2.140	0.552	1.032	0.552	3	0.11227
	25	3.982	2.122	1.291	5.925	3.660	0.786	1.016	0.786	3	0.20488
	28	4.056	3.854	1.238	6.000	4.411	0.811	1.190	0.811	3	0.24978
	30	1.632	1.662	2.339	7.583	2.435	0.484	1.032	0.484	2	0.39715
QF6T7R2	3	4.370	1.502	2.359	6.188	4.132	0.520	0.771	0.520	3	0.00000
	6	4.370	1.482	2.115	6.289	4.175	0.661	1.763	0.661	3	0.02667
	9	4.998	1.496	1.808	6.795	4.554	0.605	1.937	0.605	3	0.18524
	12	3.702	1.602	2.263	6.592	4.303	0.854	0.795	0.854	3	0.50526
	18	2.848	1.486	2.023	5.864	4.150	0.605	0.921	0.605	6	0.77193
	21	2.648	1.556	1.716	6.107	3.237	0.474	0.969	0.474	3	1.08910
	23	1.330	1.783	2.504	7.280	2.261	0.429	0.871	0.429	2	1.19014
	25	0.806	1.810	2.751	6.006	2.389	0.448	1.000	0.448	2	0.27506

TABLE A-1 continued

Plot/ Test/ Run	Time* (min)	TSS (g/L)	NH_4^+ — N	NO_3^- — N	TKN-N	P_t	PO_4^-	TKN_f	P_{tf}	Δ t (min)	Flow (cm/hr)
			ppm								
QF6T7R3	6	5.466	0.504	1.396	6.208	4.119	0.653	0.953	0.653	6	0.68773
	9	4.424	1.183	1.519	6.431	3.149	0.459	2.158	0.459	3	1.60983
	12	5.976	0.890	1.730	6.208	3.563	0.484	2.000	0.484	3	1.98877
	18	2.928	0.734	1.455	5.602	2.537	0.473	1.842	0.473	6	2.16141
	24	2.964	0.504	1.448	5.177	3.256	0.562	1.447	0.500	6	2.26670
	30	2.756	0.413	1.351	3.208	2.823	0.460	1.495	0.468	6	2.23159
	32	1.128	0.313	1.589	4.732	1.394	0.568	2.010	0.244	2	0.39715
	34	1.272	0.969	1.750	4.317	1.675	0.689	3.168	0.329	2	0.01824
QFAT7R1	3	1.798	4.142	0.986	16.455	4.844	0.178	9.655	0.954	3	0.00000
	6	5.172	14.403	0.348	31.536	2.658	0.186	30.621	0.827	3	0.13188
	9	7.410	15.210	0.845	30.665	4.507	0.212	25.932	1.447	3	0.13188
	12	5.700	14.726	1.073	32.290	2.178	0.224	27.640	1.177	3	0.14506
	15	6.082	13.417	2.857	33.226	1.323	0.093	25.217	1.177	3	0.15824
	31	2.068	9.967	16.940	21.721	2.803	0.160	18.889	0.843	6	0.14506
	33	4.546	11.401	18.547	25.968	2.148	0.134	20.901	0.667	2	0.17145
QFAT7R2	3	5.606	10.953	5.147	24.906	1.230	0.137	22.888	0.922	3	0.00000
	6	5.042	9.967	1.166	24.194	0.718	0.211	20.357	0.513	3	0.94772
	9	4.648	10.953	1.292	29.950	2.840	0.166	17.989	0.497	3	2.70340
	12	4.244	8.040	1.761	28.400	3.050	0.204	14.559	0.502	3	3.04416
	18	5.020	7.278	0.403	22.296	1.357	0.159	12.990	0.574	6	3.17523
	24	4.016	7.547	1.266	20.645	1.259	0.115	11.520	0.467	6	3.22765
	27	2.366	7.368	0.567	20.742	0.441	0.115	11.716	0.383	3	3.28008
	30	0.516	5.889	0.197	17.807	0.674	0.091	10.196	0.383	3	3.28008
	32	1.156	7.592	1.066	15.000	0.972	0.143	13.284	0.645	2	1.11097
QFAT7R3	6	5.404	7.368	0.227	38.524	0.982	0.115	16.325	0.513	6	3.09659
	9	4.114	6.516	0.288	25.161	1.508	0.104	10.735	0.521	3	3.41114
	12	5.224	5.844	0.444	21.774	1.073	0.134	10.098	0.529	3	3.70528
	24	4.178	5.172	0.439	23.226	0.638	0.069	10.245	0.418	12	3.70528
	33	1.910	7.682	0.605	27.950	0.780	0.090	10.098	0.386	9	3.85234
	35	1.172	6.472	0.523	22.903	0.682	0.114	12.255	0.386	2	0.86860

QFBT7R1	3	3.411	26.731	0.338	37.313	2.731	0.804	30.275	0.975	3	0.00000
	6	4.736	25.015	0.317	35.377	3.438	0.677	26.221	1.220	3	0.11176
	9	4.410	25.905	0.195	35.000	3.341	0.767	24.937	0.997	3	0.11176
	12	2.544	25.876	0.283	35.943	3.373	2.295	27.433	1.020	3	0.11176
	15	3.402	25.164	0.262	35.642	3.616	0.828	27.275	1.287	3	0.12192
	18	3.320	24.304	0.104	32.812	3.454	1.408	23.362	1.045	3	0.12192
	21	1.764	22.584	0.122	32.812	4.599	1.007	23.673	1.389	3	0.14224
	24	1.066	25.253	0.106	37.264	3.778	0.788	27.620	1.143	3	0.15240
QFBT7R2	3	2.590	21.012	0.478	36.509	2.131	0.667	27.957	0.673	3	0.00000
	6	4.700	20.330	0.363	30.446	2.179	0.458	22.027	0.710	3	0.04064
	9	0.938	20.923	0.162	28.267	2.260	0.526	21.058	0.827	3	0.11176
	12	1.894	22.524	1.106	28.663	2.050	0.572	20.996	0.620	3	0.54356
	18	1.938	22.168	0.162	26.089	2.179	0.839	19.872	0.664	6	1.28186
	24	1.916	19.618	0.162	24.109	2.503	0.547	18.399	0.815	6	2.99926
	27	0.672	16.237	0.363	28.267	2.292	0.448	22.319	0.818	3	3.37416
	29	0.286	24.897	1.066	17.650	3.260	0.623	13.865	0.815	2	3.46255
QFBT7R3	6	3.694	20.804	0.302	21.400	8.651	0.905	14.915	1.117	6	0.70358
	9	3.602	20.686	0.182	28.342	4.476	2.134	17.926	0.848	3	2.41404
	12	2.610	20.567	0.122	24.100	6.019	0.973	15.186	1.117	3	3.90451
	18	3.474	18.847	0.101	20.097	7.562	0.986	13.223	1.243	6	3.99291
	24	3.865	12.003	0.573	20.314	5.931	0.397	13.888	1.230	6	4.25808
	29	3.966	11.864	0.556	25.776	4.304	0.359	11.984	1.200	5	4.34647
	33	0.998	13.117	0.784	14.455	9.934	0.160	15.787	1.440	4	4.43487
	35	0.668	14.823	0.985	16.771	1.255	0.363	17.205	1.260	2	0.88562
QFCT7R1	3	2.154	22.656	0.304	30.450	4.038	0.858	23.869	2.820	3	0.00000
	6	2.278	25.754	0.891	37.882	6.286	1.011	28.411	3.120	3	0.06401
	9	1.718	28.330	0.099	40.950	6.726	1.061	29.174	4.560	3	0.08534
	10	2.456	39.904	0.246	46.550	6.446	1.531	35.261	3.400	1	0.12802
	14	0.148	3.792	0.143	41.215	6.165	1.951	42.043	1.939	4	0.12802
QFCT7R2	3	1.122	15.624	0.803	27.701	8.980	0.922	19.134	0.956	3	0.00000
	6	1.652	23.596	0.773	34.373	4.492	0.922	25.478	1.109	3	0.07468
	9	1.122	3.206	0.064	40.137	6.474	1.176	35.304	3.660	3	0.11735
	12	1.138	3.633	0.143	40.375	7.056	1.176	30.304	3.160	3	0.17069
	15	1.168	3.260	0.427	43.750	6.355	1.176	36.609	3.470	3	0.28956
	18	0.746	3.260	0.078	41.568	5.493	1.366	34.043	2.430	3	0.33528
	20	0.162	2.772	0.680	48.861	3.848	1.404	45.924	2.030	2	0.78232
	22	0.100	3.087	0.247	52.985	2.678	1.379	47.703	2.061	2	1.63916

TABLE A-1 continued

Plot/ Test/ Run	Time* (min)	TSS (g/L)	NH_4^+ — N	NO_3^- — N	TKN-N	P_t	PO_4^-	TKN_f	P_{tf}	Δ t (min)	Flow (cm/hr)
			ppm								
QFCT7R3	6	0.834	1.097	1.013	28.976	3.334	0.642	20.401	1.186	6	0.14935
	9	1.204	1.636	0.214	36.145	3.693	1.214	26.217	1.738	3	0.32004
	12	1.068	2.233	0.148	42.946	5.722	1.430	40.808	2.153	3	0.83820
	18	0.718	2.825	0.148	43.243	7.896	1.519	33.087	3.920	6	2.31379
	24	1.014	2.281	0.148	49.703	6.538	1.658	30.913	4.280	6	2.76896
	29	0.886	2.116	0.148	44.271	13.389	1.201	28.000	3.440	5	3.03449
	31	0.138	2.164	0.514	42.223	2.850	1.430	40.668	3.370	2	2.99654
	34	0.098	2.324	0.314	42.295	7.419	1.315	32.294	3.190	3	2.10518
QFDT7R1	3	1.674	11.362	1.411	41.024	33.750	0.103	23.652	0.661	3	0.00000
	6	1.716	15.573	1.113	48.428	3.180	0.141	31.347	0.849	3	0.08534
	9	1.854	20.718	1.521	58.956	3.441	0.172	36.608	1.003	3	0.09754
	12	1.842	42.486	1.653	67.368	4.647	2.707	5.994	0.840	3	0.10973
	15	2.324	40.251	1.587	73.900	3.995	1.107	5.692	0.993	3	0.12192
	18	1.988	41.369	1.568	78.521	4.049	1.981	5.571	0.774	3	0.13411
	21	2.286	44.723	1.910	81.598	5.135	2.303	5.390	0.840	3	0.14630
	24	1.978	49.810	1.739	76.502	4.245	2.941	5.390	0.854	3	0.14630
	27	2.190	35.781	1.765	78.521	5.765	3.417	6.776	0.920	3	0.19507
	32	0.654	40.251	2.477	72.656	2.224	1.920	5.418	1.208	5	0.25570
	34	0.678	55.340	2.719	76.118	1.899	1.577	6.378	1.334	2	0.35052
QFDT7R2	3	1.552	15.123	1.031	95.347	2.615	1.251	26.954	1.238	3	0.00000
	6	2.422	40.531	0.280	75.066	4.136	1.473	5.087	1.020	3	0.04877
	9	1.680	41.369	0.260	78.906	4.245	1.997	5.450	1.008	3	0.12192
	12	1.780	43.604	0.258	72.753	4.353	1.997	5.329	0.933	3	0.19507
	15	1.578	41.928	0.224	66.984	4.158	1.835	4.966	0.958	3	0.55202
	18	1.794	38.575	0.710	63.619	3.680	1.803	5.198	0.983	3	1.41732
	21	1.694	34.383	0.490	61.311	3.875	1.803	4.966	1.185	3	2.13769
	23	0.848	34.383	0.156	55.927	3.463	2.287	4.906	1.412	2	2.32565
	25	0.462	37.178	0.160	66.407	2.789	1.319	5.692	1.015	2	2.40083
	28	0.230	42.766	1.621	73.522	2.789	1.291	5.786	1.214	3	2.52783

QFDT7R3	6	2.552	28.796	0.405	49.663	2.255	1.028	4.423	0.981	6	0.31496
	9	2.698	37.178	0.222	50.112	2.975	1.289	4.725	1.077	3	2.50548
	12	1.848	37.483	0.238	45.618	2.271	0.511	4.785	1.125	3	2.79606
	18	1.734	33.668	0.766	41.236	1.833	0.539	37.420	1.053	6	2.90782
	24	1.926	31.875	0.901	36.477	1.927	0.530	35.771	0.551	6	3.04193
	30	1.574	29.025	1.000	39.312	2.146	0.514	32.146	0.527	6	3.01958
	32	0.362	31.370	0.982	38.977	0.942	0.600	27.787	0.587	2	2.43843
	34	0.272	29.865	1.167	35.000	0.926	0.776	31.272	0.707	2	1.21989
	36	0.060	34.273	0.987	35.455	1.286	0.852	30.532	0.756	2	0.50462
	38	0.040	4.038	0.364	44.944	1.020	0.862	36.378	0.949	2	0.29126
QFET7R1	3	0.714	3.387	1.026	11.596	0.698	0.281	9.007	0.295	3	0.00000
	6	0.638	4.617	0.926	12.208	0.787	0.430	9.486	0.621	3	0.04572
	9	0.230	5.730	0.805	10.282	0.787	0.290	6.164	0.684	3	0.06401
	12	0.202	6.609	0.825	9.139	0.847	0.379	6.350	0.732	3	0.07315
	18	1.020	7.487	0.882	9.094	0.921	0.351	7.884	0.732	6	0.10058
	21	0.374	8.014	1.603	11.122	1.025	0.447	8.461	0.795	3	0.11887
	24	0.668	8.893	0.697	10.727	1.174	0.279	8.157	0.684	3	0.10973
	26	0.024	11.587	0.885	12.861	1.084	0.499	10.411	0.843	2	0.12802
QFET7R2	3	0.306	1.118	1.387	4.563	0.609	0.108	3.204	0.351	3	0.00000
	6	0.404	4.031	1.118	6.649	0.490	0.248	4.814	0.494	3	0.05486
	9	0.432	7.546	1.215	10.612	0.936	0.408	7.904	0.780	3	0.10973
	12	0.890	2.567	2.005	11.886	0.936	0.217	9.420	0.764	3	0.15545
	15	0.548	9.654	1.468	11.453	1.174	0.343	9.780	0.795	3	0.26416
	18	0.380	3.153	0.857	11.506	1.025	0.255	8.668	0.613	3	0.35560
	21	0.316	1.337	1.458	12.065	1.055	0.361	8.041	0.613	3	0.44704
	23	0.262	1.980	1.864	14.865	1.174	0.615	11.430	0.954	2	0.72542
	25	0.032	0.427	2.521	12.514	1.114	0.393	11.565	0.811	2	0.76505
QFET7R3	6	0.820	0.210	1.669	7.004	0.668	0.134	3.591	0.303	6	0.27432
	9	0.952	8.689	1.606	6.805	11.450	0.217	3.405	0.303	3	0.84430
	12	0.788	11.193	0.146	25.449	1.230	0.221	12.938	0.954	3	1.36484
	18	1.426	11.143	1.425	25.160	1.382	0.387	12.378	0.954	6	1.56804
	24	0.512	10.151	2.871	26.242	1.626	0.422	11.457	0.796	6	1.68656
	30	0.530	9.765	1.247	16.875	0.783	0.422	8.776	0.684	6	1.83695
	32	0.316	10.975	0.942	19.466	1.289	0.495	10.554	0.716	2	0.88392
	34	0.000	11.950	0.988	20.879	1.015	0.574	12.229	0.930	2	0.43688
	36	0.100	12.135	1.772	19.272	1.243	0.785	12.253	0.954	2	0.20320
	38	0.000	12.370	1.842	21.692	0.962	0.515	12.866	0.827	2	0.13716

TABLE A-1 continued

Plot/ Test/ Run	Time* (min)	TSS (g/L)	$NH_4^+ — N$	$NO_3^- — N$	TKN-N	P_t	PO_4^-	TKN_f	P_{tf}	Δ t (min)	Flow (cm/hr)
			ppm								
QFFT7R1	3	0.000	12.509	2.431	45.376	4.100	0.049	38.416	0.779	3	0.00000
	6	4.672	18.735	2.185	33.961	3.526	0.953	22.552	1.097	3	0.06096
	9	0.384	18.380	2.054	37.896	2.894	1.166	25.145	1.177	3	0.11176
	12	0.876	19.480	1.890	37.269	4.524	0.881	24.481	1.097	3	0.16256
	15	0.212	18.600	0.972	39.285	4.778	0.920	27.178	1.240	3	0.20320
	18	0.416	18.600	1.838	33.174	3.478	0.973	25.311	1.113	3	0.22624
	21	0.426	17.060	1.864	30.340	3.863	1.020	24.170	1.089	3	0.24925
	23	0.068	26.590	2.146	40.177	5.600	1.056	29.585	1.399	2	0.29533
QFFT7R2	3	0.142	15.740	3.159	32.647	2.436	0.532	21.410	0.771	3	0.00000
	6	0.848	27.480	1.867	39.294	1.914	0.577	26.183	0.779	3	0.13208
	9	1.472	26.810	1.963	43.961	1.806	0.689	27.676	1.034	3	0.28379
	12	0.752	26.566	1.465	46.705	1.840	0.278	29.834	1.954	3	0.39896
	15	1.050	17.912	1.787	45.604	1.760	0.442	23.367	1.056	3	0.46805
	18	0.522	49.722	1.181	46.105	2.293	0.514	26.229	1.230	3	0.64008
	20	0.320	46.681	2.215	52.528	2.027	0.700	30.637	1.632	2	0.82296
	22	0.190	46.617	2.360	57.428	2.027	0.623	27.944	0.461	2	0.29533
QFFT7R3	6	0.436	5.182	1.583	19.102	1.095	0.111	12.140	0.752	6	0.47955
	9	0.572	14.414	0.819	41.967	2.213	0.325	17.696	1.821	3	0.77724
	12	0.462	16.285	0.238	53.619	3.570	0.341	32.434	1.286	3	1.21448
	18	0.000	17.912	0.873	55.734	2.833	0.342	36.565	1.370	6	1.42309
	24	0.264	16.500	0.745	49.677	3.169	0.605	36.217	1.815	6	1.73601
	30	0.248	16.040	0.835	46.504	3.169	0.330	32.391	1.386	6	1.78819
	32	0.000	19.315	0.737	45.735	2.268	0.553	31.043	1.285	2	0.37592
	34	0.282	32.881	0.446	48.379	2.224	0.480	17.263	1.301	2	0.15240
	36	0.040	20.251	1.877	50.543	2.268	0.452	33.304	1.432	2	0.04064
QFKT7R1	3	8.834	5.168	1.753	10.834	0.962	0.074	4.434	0.256	3	0.00000
	9	8.398	7.394	1.656	13.315	1.955	0.081	8.180	0.398	6	0.02997
	12	5.962	8.420	2.089	13.623	1.128	0.072	7.224	0.295	3	0.04496
	18	8.478	9.093	2.731	15.161	0.678	0.139	8.315	0.367	6	0.07493

	23	8.448	8.908	2.333	15.546	0.655	0.099	8.315	0.351	5	0.10490
	27	8.092	8.824	2.151	14.873	0.744	0.094	12.528	0.298	4	0.11989
	29	4.678	9.546	3.168	13.570	1.269	0.116	12.914	0.290	2	0.10490
	31	3.200	11.815	4.872	17.273	1.095	0.260	15.762	0.511	2	0.10490
QFKT7R2	4	0.860	4.619	2.310	9.805	0.995	0.275	6.727	0.525	4	0.00000
	6	4.080	5.621	1.045	5.088	0.834	0.278	4.118	0.711	2	0.47671
	9	4.794	3.847	1.336	9.347	0.624	0.271	8.478	0.494	3	0.95976
	12	6.590	4.910	1.025	9.717	0.400	0.286	8.633	0.494	3	2.05463
	15	6.064	3.070	0.897	12.042	0.503	0.297	8.447	0.335	3	2.52580
	18	5.920	4.851	0.858	10.745	0.400	0.288	8.106	0.398	3	2.77574
	24	6.676	2.927	0.861	9.196	0.419	0.293	7.329	0.366	6	3.10899
	30	7.484	2.654	1.116	10.281	2.220	0.286	6.584	0.366	6	3.46255
	32	3.410	3.031	1.307	11.953	2.440	0.325	8.074	0.287	2	1.13817
	34	1.308	3.880	1.571	11.553	3.780	0.355	9.658	0.398	2	0.39502
QFKT7R3	6	7.624	3.475	0.990	7.194	2.854	0.259	6.366	0.577	6	2.85905
	9	4.224	3.041	1.037	9.534	2.736	0.263	6.894	0.587	3	3.58041
	12	4.778	2.993	1.220	13.882	2.306	0.136	7.081	0.485	3	3.87505
	18	7.300	3.135	1.306	12.806	2.636	0.211	6.801	0.516	6	3.81612
	24	6.084	3.003	1.341	11.177	3.611	0.199	8.571	0.374	6	3.87505
	30	5.978	3.012	1.406	12.640	3.319	0.060	7.329	0.303	6	3.99291
	32	1.248	4.059	1.731	12.648	4.700	0.041	9.534	0.335	2	2.83129
	34	0.266	4.371	2.119	13.083	4.676	0.045	9.783	0.351	2	0.65827
QFLT7R1	3	7.370	2.185	1.055	9.984	17.660	0.041	7.174	0.398	3	0.00000
	6	9.140	6.703	1.496	13.455	2.871	0.040	11.257	0.398	3	0.02997
	12	4.842	13.056	2.519	20.824	3.602	0.056	17.887	0.398	6	0.02997
	15	7.000	624.000	13.879	17.861	0.319	3.117	2.599	21.802	3	0.04496
	21	7.054	17.268	2.801	21.139	2.722	0.723	18.119	0.339	6	0.05994
	25	5.196	16.303	2.850	23.267	2.712	0.109	21.268	0.368	4	0.08992
	27	4.624	16.974	2.791	25.663	2.539	0.218	24.408	0.644	2	0.07493
	29	3.142	20.809	12.679	27.775	3.326	0.049	25.446	0.606	2	0.08992
	31	7.854	18.600	12.837	25.562	3.548	0.121	20.559	0.811	2	0.08992
QFLT7R2	3	2.466	1.311	1.880	16.069	1.326	0.072	13.956	0.366	3	0.00000
	6	2.992	2.588	1.368	6.474	0.956	0.043	4.192	0.732	3	0.25476
	9	7.176	3.569	0.944	12.023	1.433	0.043	10.564	0.875	3	0.33104
	12	6.374	4.314	0.938	12.567	2.208	0.041	10.150	1.288	3	0.44381
	15	3.550	6.531	0.941	15.289	2.744	0.089	12.293	0.843	3	0.64313
	18	4.738	12.279	1.362	28.262	2.901	0.052	20.683	1.002	3	1.03632

TABLE A-1 continued

Plot/ Test/ Run	Time* (min)	TSS (g/L)	NH_4^+ — N	NO_3^- — N	TKN-N	P_t	PO_4^-	TKN_f	P_{tf}	Δ t (min)	Flow (cm/hr)
			ppm								
	24	5.412	17.644	2.069	36.348	1.420	0.105	28.696	0.987	6	1.35636
	30	4.220	17.350	2.419	36.508	2.429	0.174	29.286	1.177	6	3.68201
	32	1.960	25.300	2.829	35.775	2.334	0.321	32.329	1.177	2	2.26774
	34	0.084	20.810	2.624	39.941	6.853	0.510	36.863	1.462	2	1.02108
QFLT7R3	6	7.438	10.161	1.440	16.640	5.590	0.170	6.276	0.700	6	0.87630
	9	5.748	12.805	1.843	28.083	3.182	0.219	18.854	0.621	3	1.50774
	12	4.552	14.666	1.627	27.490	5.622	0.294	22.640	1.097	3	4.06707
	18	5.102	13.587	3.117	28.739	6.719	0.218	23.540	0.851	6	4.33631
	24	6.328	11.483	3.271	29.901	4.361	0.165	24.876	0.478	6	4.36324
	30	0.278	11.779	2.887	28.083	4.565	0.417	20.373	0.533	6	4.36324
	32	4.524	14.231	3.500	23.795	4.910	0.768	20.714	0.430	2	3.79242
	34	0.560	18.944	4.559	28.415	5.958	1.071	23.789	0.716	2	1.09728
QFMT7R1	3	10.978	0.984	1.374	9.480	2.901	0.069	3.559	0.478	3	0.00000
	6	8.808	0.733	1.130	7.110	0.481	0.023	2.901	0.478	3	0.14173
	9	9.146	0.648	1.037	3.429	0.460	0.088	3.242	0.414	3	0.41283
	12	8.770	0.632	2.105	3.760	0.314	0.067	3.438	0.271	3	0.78486
	18	8.948	0.749	0.921	2.986	0.243	0.033	2.708	0.160	6	0.96690
	24	9.750	0.643	0.162	4.454	0.295	0.033	3.888	0.160	6	1.09898
	30	7.828	0.796	0.503	3.364	0.295	0.030	2.989	0.160	6	1.42918
	36	10.004	0.696	1.584	3.109	0.322	0.041	2.820	0.176	6	1.51724
	42	8.620	0.626	1.296	4.235	0.400	0.028	3.101	0.319	6	1.56126
	48	7.438	0.591	1.474	5.876	0.430	0.045	5.514	0.255	6	1.27508
	54	7.270	0.462	1.389	5.081	0.638	0.059	1.112	0.255	6	1.16502
	56	11.076	0.690	2.574	3.691	0.430	0.046	1.067	0.303	2	0.96690
	58	1.196	0.678	1.588	7.126	0.609	0.106	3.933	0.335	2	0.83058
QFMT7R2	3	6.548	1.181	2.345	6.358	2.586	0.045	5.925	0.239	3	0.00000
	9	6.838	0.922	1.489	2.327	3.217	0.070	4.270	0.255	6	0.85344
	12	8.896	0.712	1.321	7.283	3.374	0.047	3.090	0.239	3	1.36314
	15	8.410	0.667	1.174	6.821	3.217	0.040	2.528	0.208	3	1.47320
	18	7.920	0.652	1.222	6.763	3.138	0.045	2.879	0.255	3	1.53924

	24	6.390	0.518	1.437	7.746	2.744	0.045	2.475	0.216	6	2.06352
	30	5.632	0.530	1.523	9.191	3.126	0.034	2.475	0.414	6	2.56847
	32	5.728	0.421	1.747	5.549	2.768	0.040	2.727	0.271	2	1.29710
	34	8.210	0.493	1.979	4.567	2.517	0.049	3.333	0.224	2	0.55626
QFMT7R3	6	9.208	0.756	1.157	7.630	3.358	0.052	3.539	0.225	6	1.29710
	9	7.098	0.688	1.217	6.705	2.649	0.045	2.640	0.224	3	1.85524
	12	6.976	0.535	1.396	6.590	2.681	0.041	2.191	0.216	3	2.82857
	18	6.192	0.369	1.439	5.549	0.916	0.072	1.854	0.239	6	3.18620
	24	6.796	0.347	1.436	4.278	2.192	0.049	0.000	0.224	6	3.25123
	30	6.168	0.348	1.181	4.798	2.133	0.040	1.742	0.208	6	3.21871
	32	3.224	0.325	1.538	3.370	1.254	0.040	2.022	0.176	2	2.95862
	34	2.792	0.346	1.724	3.561	0.916	0.040	2.135	0.239	2	0.60198
QFNT7R1	3	13.500	4.019	0.835	34.318	5.086	0.027	3.278	0.103	3	0.00000
	6	15.482	0.618	0.801	37.614	5.649	0.040	3.561	0.527	3	0.07493
	9	17.870	0.618	0.792	43.034	7.195	0.023	3.101	0.526	3	0.14986
	13	26.124	0.342	0.646	52.472	9.199	0.018	0.972	0.795	4	0.20980
	18	28.916	1.078	0.606	58.090	10.590	0.018	0.923	0.362	5	0.36779
	24	28.510	0.526	0.777	70.450	11.873	0.018	2.036	0.271	6	0.46990
	30	24.162	1.307	1.455	52.360	9.136	0.021	2.109	0.189	6	0.48351
	36	16.358	3.468	1.547	47.303	7.541	0.027	2.036	0.249	6	0.72979
	42	18.142	2.595	1.242	48.539	8.042	0.075	1.794	0.201	6	1.98021
	45	17.724	1.629	1.100	41.685	6.556	0.030	1.649	0.298	3	2.68430
	47	7.884	1.582	1.600	23.083	3.647	0.015	1.698	0.347	2	2.79606
QFNT7R2	3	8.018	1.743	1.250	22.331	3.272	0.015	3.489	0.359	3	0.00000
	6	12.382	1.703	0.858	34.660	4.804	0.015	3.440	0.383	3	0.55413
	9	6.960	1.904	0.761	38.300	5.696	0.016	3.561	0.359	3	1.48539
	12	15.752	1.307	0.669	41.798	6.400	0.012	3.101	0.347	3	2.61724
	15	12.632	1.537	0.688	38.182	6.051	0.012	3.005	0.347	3	2.88547
	18	13.330	1.307	0.751	46.292	6.876	0.012	2.835	0.323	3	2.97487
	24	18.400	0.986	0.832	46.292	7.260	0.012	3.053	0.347	6	3.16690
	30	17.584	1.307	0.874	45.843	7.213	0.021	2.908	0.443	6	3.45646
	32	13.042	1.662	1.299	36.477	6.243	0.017	2.087	0.720	2	3.68811
	35	1.442	4.893	1.952	6.119	0.989	0.382	2.913	0.640	3	0.67960

TABLE A-1 continued

Plot/ Test/ Run	Time* (min)	TSS (g/L)	NH_4^+ — N	NO_3^- — N	TKN-N	P_t	PO_4^-	TKN_f	P_{tf}	Δ t (min)	Flow (cm/hr)
			ppm								
QFNT7R3	6	20.816	1.916	0.967	8.299	2.151	0.017	5.388	0.242	6	3.06428
	9	22.796	1.419	0.643	6.075	2.909	0.017	4.196	0.179	3	3.68811
	12	5.970	1.390	0.875	11.045	2.815	0.017	3.393	0.266	3	4.03558
	18	28.550	1.565	0.840	6.299	1.885	0.017	1.698	0.400	6	3.80393
	24	25.540	1.507	0.793	3.045	2.506	0.016	1.488	0.242	6	3.97767
	30	27.548	1.565	0.806	3.515	3.065	0.016	1.458	0.211	6	4.31465
	32	13.018	1.244	1.180	6.784	4.910	0.016	4.394	0.371	2	3.51437
	34	2.798	2.500	1.837	7.665	3.920	0.017	4.444	0.478	2	0.60432

*** Time after the start of runoff event.**

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NOTES

The Virginia Water Resources Research Center is a federal-state partnership agency attempting to find solutions to the state's water resources problems through careful research and analysis. Established at Virginia Polytechnic Institute and State University under provisions of the Water Research and Development Act of 1978 (P.L. 95-467), the Center serves six primary functions.

- It studies the state's water and related land use problems, including their ecological, political, economic, institutional, legal, and social implications.
- It sponsors, coordinates, and administers research investigations of these problems.
- It collects and disseminates information about water resources and water resources research.
- It provides training opportunities in research for future water scientists enrolled at the state's colleges and universities.
- It provides other public services to the state in a wide variety of forms.
- It facilitates coordinated actions among universities, state agencies, and other institutions.

More information on programs and activities may be obtained by writing or telephoning the Water Center.

Virginia Water Resources Research Center
Virginia Polytechnic Institute and State University
617 North Main Street
Blacksburg, Virginia 24060-3397
Phone (703) 961-5624