A Computer Simulation Model for Investigating the Effect of Land Application

of Sludge on Runoff Water Quality

by

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(ABSTRACT)

CREAMS-NT, a modified version of the field-scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model, was developed to simulate the nitrogen (N) transformations and subsequent nutrient transport processes which occur in the soil following organic waste applications. CREAMS-NT accounts for nutrient addition through fertilization and rainfall and losses of N by volatilization, denitrification, plant uptake, leaching, and overland flow. Data required by CREAMS-NT includes runoff volume, sediment yield, percolation, and soil environmental conditions which is generated by the hydrologic and erosion components of the original CREAMS model. The mineralization, nitrification, denitrification, and volatilization processes are simulated using first-order kinetic equations adjusted for the effects of soil environmental conditions including temperature, moisture, pH, soil/sludge contact, and soil cation exchange capacity. Prior to a runoff event, soil ammonium-N ($NH_4^+ - N$) is partitioned between adsorbed and desorbed phases. CREAMS-NT predicts the transport of organic-N, $NH_4^+ - N$, and sediment-bound phosphorus (P_{sb}) in runoff using enrichment ratios. The transport of soluble nutrients, nitrate-N ($NO_3^- - N$), $NH_4^+ - N$, and soluble P (P_{TF}), is estimated using extraction coefficients.

A rainfall simulator was used to study the effect of tillage system and sludge application method and rate on runoff, sediment, P, and N losses from agricultural lands. CREAMS-NT was verified using the data obtained from these field plot studies. The predicted yields were very close to the observed values for all nutrient forms. The effects of tillage practice, sludge application method, and loading rate were also well represented by the model for most N and P forms. CREAMS-NT

shows great potential for use as a planning tool since it is able to predict nutrient losses under various field conditions.

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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. 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 water 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. The

N and P concentrations of water leaving land application sites are of great concern. High levels of these nutrients in surface and ground waters are unacceptable due to the adverse impact that high nutrient concentrations have on aquatic life and the health risks imposed on the human population resulting from contaminated drinking water supplies. 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 have been reported that compare the effects of different tillage practices on runoff quality. Field data is required for the development of Best Management Practices (BMP's) for nonpoint source pollution control and development and verification of water quality models for assessing the impact of BMP's.

The fate of N in the soil is complex due to the many processes that affect its form and availability. The key N transformation processes include immobilization, mineralization, nitrification, volatilization, ammonium adsorption/desorption, and denitrification. Unlike P reactions, the N transformation processes are significantly affected by the application of organic wastes to the soil

system. Of the factors introduced through waste addition, those having the greatest impact on the N transformation processes include the form of the applied N, the carbon (C) to N (C:N) ratio and the pH of the waste, and the loading rate and method of application. The applied N form determines the amount of N available to each of the transformation processes. The C:N ratio of the soil/waste system is inversely related to the amount of N mineralized. The addition of proteinaceous wastes (low C:N ratio) such as sewage sludge tends to stimulate mineralization. The denitrification process is also strongly influenced by the addition of organic wastes as the denitrifying bacteria are heterotrophic and require organic matter as a source of energy. Sludge application increases the pH of the soil system which, in turn, increases mineralization, nitrification, volatilization, and denitrification rates in most soils.

Many of the existing water quality models do not adequately describe one or more of the N transformation processes, particularly those processes altered by, or unique to, waste application systems. In addition, these models often rely on input parameters which are poorly defined or difficult to obtain. The need for developing a nutrient transport model which simulates the impact of organic waste applications on the N transformation processes is therefore established.

Objectives

The overall goal of this project was to develop a computer simulation model for predicting the runoff losses of N from sludge-amended agricultural lands. The specific objective were:

1. To measure nutrient losses in runoff and sediment from field plots as affected by sludge application method, sludge loading rate, and tillage practice.

2. To develop a model which simulates the N transformations that occur in waste-treated soils. This model was incorporated into an existing model to generate the required hydrologic and erosion data.

3. To evaluate the model by comparing model predictions of N losses with observed data from rainfall simulator plot experiments.

LITERATURE REVIEW

Land Application of Sludge

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 (Typic Fragiudult). 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 indicated that although sludge addition increased the saturated hydraulic conductivity initially,

after 50-80 days it decreased to that of the original soil. The percent 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 reported 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 (Aquic Hapludalf, fine, mixed mesic), Blount (Aeric Ochraqualf, fine, illitic mesic), and Tracy (Ultic Hapludalf, coarse-loamy, mixed mesic) soils. Liquid anaerobically digested sludge was applied at rates of 0, 22.4, 56, and 89.6 Mg/ha of dry solids to the Celina silt loam soil and at rates of 0 and 56 Mg/ha to the Blount silt loam and Tracy sandy loam soils. After the sludge dewatered, it was allowed to remain on the soil surface or was incorporated into the soil by rototilling or disking. Soil samples were collected from the 0-5 and 5-15 cm depths of each plot 2, 4, 6, and 12 months following sludge application. 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 the control soils, although these differences were not statistically significant. Disking was the most effective in improving the soil physical condition of three application methods studied. The authors suggested that this result was due to the greater concentration of sludge in the top 5 cm of soil and better soil/sludge interaction resulting from the slicing action of disking.

Chang et al. (1983) and Hall and Coker (1983) observed 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.

Changes in Soil Nutrient Level and Crop Yield

Nitrogen and P 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 were 3.3 and 2.3 percent, respectively, of the total dry sludge solids. He stated that the chemical composition of sludge varied considerably with waste source and treatment process and that the amount required for crop fertilization would depend on the composition of the sludge and the nutrient requirements of the crop grown.

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 with a total solids concentration of 7.3 percent to a loam soil at rates of 9.1, 18.2, and 36.4 dry Mg/ha. On a dry weight basis, the sludge consisted of 3.2% N. Of the N supplied by the sludge, 3-12 percent was recovered by the corn (Zea mays) crop and 6-10 percent remained in the soil. Application rates in excess of 9.1 Mg/ha did not produce significant crop yield increases. Pomares-Garcia and Pratt (1978) conducted a greenhouse pot experiment in a Hanford sandy loam soil (Typic Xerorthent) to determine the N fertilization value of feedlot manure and anaerobically digested sewage sludge. Yields of barley (Hordeum vulgare) 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. The authors observed that the mineralization rates obtained from the manure treatment were lower, and from the sludge treatment were higher, than those reported in the literature. They suggested that these discrepancies may be due to the stability, N content, and quality of the wastes applied.

Magdoff and Amadon (1980) used corn (<u>Zea</u> <u>mays</u>) and hay growing on Hadley sandy loam (Fluventic Dystrochrept) and Nellis loam (Typic Eutrochrept) soils to study the N availability from sewage sludge. The experiments were conducted 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, particularly in the second year of the study. 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 the residual N effect from the previous year's sludge application. 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 the sludge. Sims and Boswell (1980) evaluated the effect of nutrient source on soil N, crop yield, and elemental composition of corn. Soil levels of $NH_4^+ - N$, $NO_3^- - N$, 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 tall fescue (<u>Festuca</u> <u>arundinacea</u>) grown in Evesboro loamy sand (Typic Quartzipsamment) and Fauquier silt loam (Ultic Hapludalf) 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 (<u>Sus</u> <u>scrofa</u> <u>domesticus</u>) manure on timothy (<u>Phyleum</u> <u>pratense</u>) 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 treat-

ment 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.

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 of these investigations, 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 (1979) also reported that $NO_3^- - N$ concentrations in groundwater under a forested area that received sludge at rates applicable to a sludge disposal system exceeded the 10 mg/L limit established by the Public Health Service (1962) for drinking water.

Inman et al. (1982) investigated the effect of applying high rates of composted sewage sludge on $NO_3^- - N$ and $PO_4^- - P$ levels in soil water collected at various soil depths under forested plots. Sludge was incorporated into a Chester silt loam soil (Typic Hapludult). During the following year, $NO_3^- - N$ concentrations of 70 - 80 mg/L were measured at the 100 cm depth. These concentrations, however, decreased to less than 10 mg/L, 30 months after the sludge application. The $PO_4^- - P$ 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 $PO_4^- - P$ values in sludge treated soils to chemical insolubility, microbial activity, and soil fixation of the $PO_4^- - P$ in the sludge.

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 overapplication 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 applications rates, particularly because of the limited mobility of P through the soil profile.

The Metropolitan Sanitary District of Greater Chicago purchased land in Fulton County, Illinois to assess the environmental impacts of land application of digested sludge. Nitrite ($NO_2^- - N$) + $NO_3^- - N$, $NH_4^+ - N$, and P_T concentrations of the stream draining the area were measured upstream and downstream of the application site. The size of the treatment area and sludge loading rate varied considerably over the three year study. In 1972, four fields with a total 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. The results indicated that surface runoff did not affect the water quality of the stream (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 served as a control site. The mean concentrations of total Kjeldahl nitrogen (TKN), $NH_4^+ - N$, $NO_2^- - N$ + $NO_3^- - N$, and P_T increased significantly in the runoff water following sludge application relative to the concentrations in runoff from the same site prior to sludge addition. Due to changes in the runoff water quality from the control watershed, however, the increases in TKN and P_T, however, may not have been a result of sludge application as the concentrations of these constituents also increased in the runoff from the control watershed. 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 4 winter months from 1976-78. When ground conditions permitted, the sludge was spread on the test site and incorporated immediately. A total of 31 runoff events were sampled for $NO_3^- - N$ and $PO_4^- - P$. Nutrient concentrations were found to be 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 soluble 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 losses were found in runoff from the sludge-amended grass areas. The authors suggested that the high nutrient losses from the grass areas were 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 on snow, dewatered sewage sludge applied on thawing soil, and dewatered lime stabilized sludge applied on thawing soil. The $NH_4^+ - N$, N_T, and P_T concentrations in runoff increased significantly immediately after the sludge application on snow. Application of lime-stabilized sludge on thawing soil also resulted in an increase in P_T concentration. Elevated P concentrations in runoff were detected two years following sludge application. The 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 sludge 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 nu-

trient losses. The coincidence of a runoff event with the fall sludge application on November 20, 1974 resulted in elevated losses of N and P (University of Guelph, 1976).

McLeod and Hegg (1984) evaluated the effects of fertilizer source on the surface runoff quality from a fescue pasture. Test plots received surface applications of dairy manure, poultry manure, municipal sludge, and ammonium nitrate fertilizer. Due to 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 when compared to the dairy and poultry manure or to the commercial fertilizer.

Rate and Method of Application

Kelling et al. (1977a) used field applications of a liquid digested wastewater sludge containing approximately 3% solids 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. Following sludge application, the plots were tilled using a field cultivator. 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 $PO_4^- - P$, 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 with increasing application rate.

A rainfall simulator was used by Kladivko and Nelson (1979b) to determine the effects of sludge application rate and incorporation method 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 (Aquic Hapludalf). Studies were also conducted on

a Blount silt loam (Aeric Ochraqualf) and a Tracy sandy loam (Ultic Hapludalf) involving a control soil and the 56 Mg/ha sludge application. After the sludge dewatered, it was either allowed to remain on the soil surface or was incorporated into the soil by rototilling or disking. Core samples were collected 2.5 months after sludge incorporation. There were significant decreases in sediment yield as a result of sludge addition. Nutrient concentrations in runoff and sediment from sludge-treated soils were generally higher than those from untreated soils. These effects were more pronounced for higher application rates. The method of sludge application and incorporation had a significant effect on sediment and nutrient losses. Sludge remaining 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 particles protected the soil from erosion. The total amount of nutrients lost from sludge incorporated areas were greater than those from the control areas. The amount of N and P lost from the surface applied sludge areas, however, was less than that from control areas due to the reduction in sediment loss and runoff with the surface applied treatments.

Dunigan and Dick (1980) reported 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 essentially no 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 Kentucky bluegrass (Poa pratense) sod and a bare tilled soil at a rate 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 (COD), N, or TSS in the runoff.

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 total loss of soluble N and P. 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 small losses of soluble N and P.

Barisas et al. (1978) evaluated the effects of different 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 did 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 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.

Nitrogen Transformations in Waste-Treated Soils

Of the N applied with sludge, approximately 50 to 90 percent is in the organic form (Sommers, 1977), and greater than 90 percent of the inorganic N is present as $NH_4^+ - N$ (Sommers et al., 1976). The fate of nitrogen in the soil is complex due to the many processes that affect its form and availability. The key N transformations include immobilization, mineralization, nitrification, volatilization, ammonium adsorption/desorption and denitrification. A diagram of these processes is shown in Figure 1. The chemical and biological reactions involving N which take place in the soil are changed after the addition of waste (Reddy, 1980). The following section summarizes some of the available literature pertaining to the N transformations in waste-treated soils.

Immobilization and Mineralization

The proportion of the total N present in a soil/waste system that is in organic or inorganic forms is determined by the relative magnitude of the two opposing processes-- immobilization and mineralization. Nitrogen immobilization is defined as the conversion of inorganic N to organic N forms. This is accomplished as microorganisms use inorganic N in the synthesis of cell tissue. Nitrogen mineralization, the reverse of immobilization, is defined as the conversion of organically combined N to inorganic N as a result of microbial decomposition. Ammonification, the conversion of organic N to $NH_4^+ - N$, is performed by microbial enzymes that utilize organic compounds as energy sources (Bartholomew, 1965). Mineralization and immobilization processes occur continuously and simultaneously in the soil and are very difficult to separate in the laboratory. Therefore, in research studies it is net mineralization, the amount of inorganic N released in excess of that immobilized, that is measured (Keeney, 1981). In most agricultural systems, $NH_4^+ - N$ is rapidly oxidized to $NO_3^- - N$ such that little $NH_4^+ - N$ is present in the soil at any given time. For
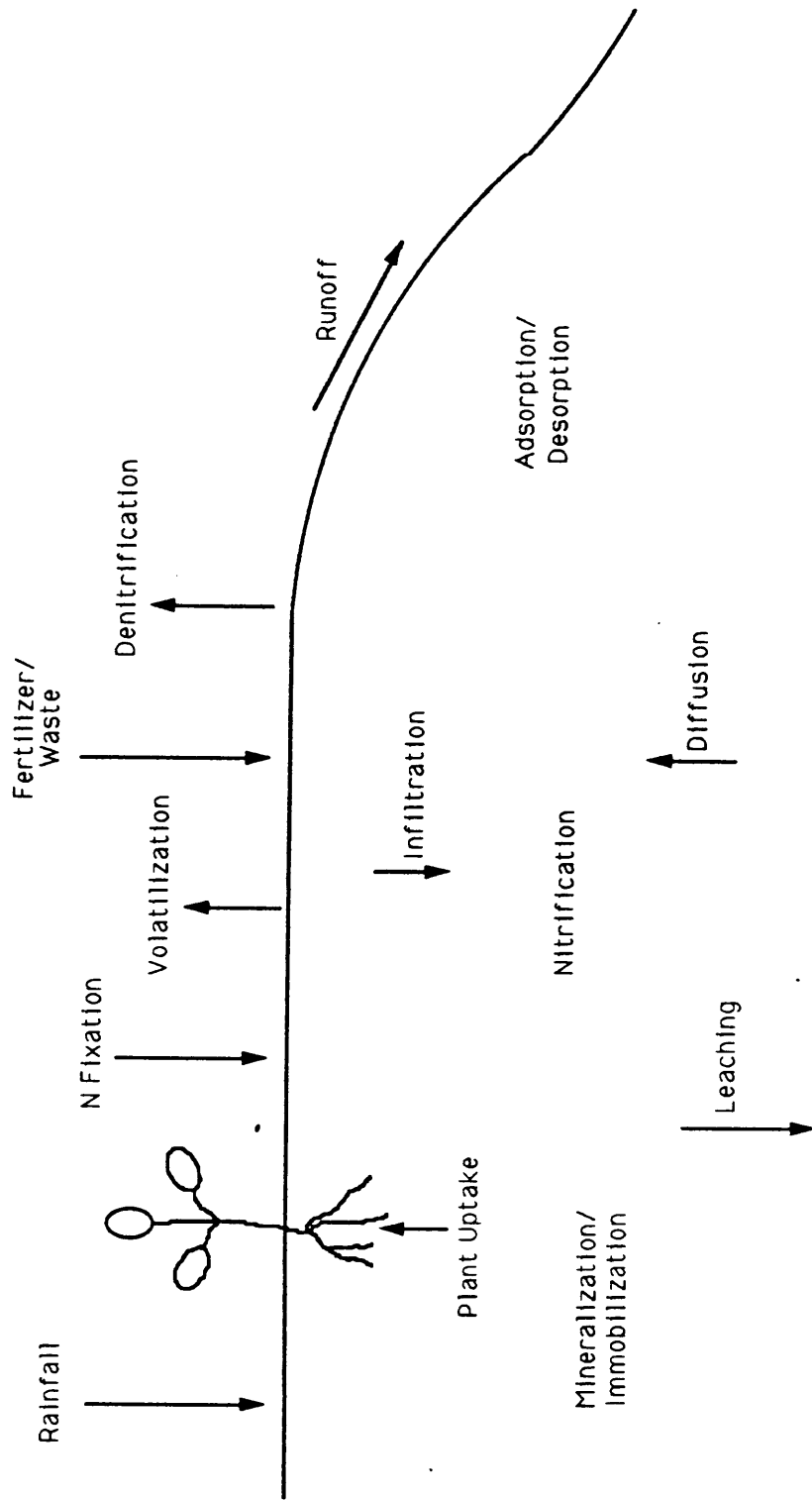
Figure 1. Soil nitrogen transformation and transport processes.

this reason, the measured accumulation of $NO_3^- - N$ is often used to indicate net mineralization (Reddy, 1980).

The application of waste to the soil introduces several factors which affect net mineralization rates. These factors include the C:N ratio, lignin content, and chemical composition of the waste and the loading rate, time, and method of application (Reddy, 1980). The C:N ratio of the soil-waste mixture is inversely related to the amount of N mineralized. If the added waste is carbonaceous (high C:N ratio), more energy is available for growth than N for synthesis, resulting in net immobilization. The addition of proteinaceous wastes (low C:N ratio) tends to stimulate N mineralization (Keeney, 1981). The critical C:N ratio at which mineralization equals immobilization is approximately 23 which corresponds to a nitrogen content of 1.3 to 1.7 percent (Bartholomew, 1965; Reddy et al., 1979a). The quality of the organic materials must also be considered. The lignin components of plant residues, for example, are somewhat resistant to decomposition (Bartholomew, 1965).

Enwezor (1976) conducted a 12 week laboratory study to determine the effect of C:N ratio on N mineralization trends in a soil/waste system. Varying proportions of powdered straw and peas were mixed into soil samples to obtain C:N ratios ranging from 9.8 to 44.4. Nitrogen mineralization increased as C:N ratios decreased. Net immobilization occurred in the soil sample treated with straw alone (C:N ratio of 44.4). Some N was mineralized in the sample treated with three parts straw and one part peas (C:N ratio of 23.8), but this was less than the amount of N released in the control soil sample. All other treatments resulted in N mineralization in excess of the control treatment.

Sabey et al. (1975) applied mixtures of anaerobically digested sewage sludge, wood, and bark residues to a Nunn clay loam (Aridic Argiustoll). Nitrate accumulations in the soil decreased as the percentage of wood and bark in the waste increased. Mixtures which contained greater than 50 percent wood waste resulted in net N immobilization. Bark was more effective in immobilizing N than was wood. Yoneyama and Yoshida (1978) indicated that the accumulation of inorganic N

forms in the soil could be reduced by the addition of sludge plus wastes low in N content such as straw, glucose, or cellulose, relative to the application of sludge alone.

The patterns of N mineralization are also a function of sludge treatment process and source. In a laboratory experiment, Magdoff and Chromec (1977) compared the rates of N mineralization from two sludges. The sludges were mixed with a fine sandy loam soil at rates of 150, 300, and 600 ppm organic-N. Soil/sludge mixtures were then incubated for 13 weeks. In soils treated with aerobically digested sewage sludge, 36.1 to 60.8 percent of the organic-N applied had been mineralized. While only 13.7 to 25.2 percent had mineralized in soils treated with anaerobically digested sludge. Similar results were obtained by King (1984). Epstein et al. (1978) reported that net N mineralization in soils increased in the order of sludge compost, control, digested sludge, and raw sludge treatments. Parker and Sommers (1983) concluded that the amount of mineralizable N in sewage sludge was proportional to the total organic N content. The anaerobic digestion or composting of sludges reduced organic N levels and thus decreased amounts of potentially mineralizable N. The percentages of organic N mineralized were 8, 15, 25, and 40 percent for composted, anaerobically digested, raw and primary, and waste-activated sludges, respectively. Parker and Sommers (1983) and Wright (1978) observed a significant decrease in mineralization rates with time after sludge application.

Ryan et al. (1973) and Premi and Cornfield (1971) reported that the amount of N mineralized increased as sludge loading rate increased. The percent mineralization of the applied organic N, however, decreased with increasing sludge rate. Ryan et al. (1973) indicated that from 4 to 48 percent of the organic N in the anaerobically digested sewage sludge was mineralized in 16 weeks. Premi and Cornfield (1971) recovered 4.2, 3.3, and 2.3 percent of the added organic N as mineral N where sludge had been applied at rates of 5, 10, and 20 g sludge/kg soil, respectively.

The method of waste application may affect N mineralization processes (Bartholomew, 1965). Reddy et al. (1980) evaluated N transformations in a coastal plain soil treated with beef, poultry, and swine manures. The method of manure application did not produce any difference in nitrate accumulation in soils receiving poultry or swine waste. They suggested that the N in these wastes

is easily mineralizable even when manure is surface applied. The surface application of beef manure resulted in lower soil $NO_3^- - N$ accumulations than did incorporation, indicating that incorporation of beef manure stimulated N mineralization. King (1973) reported $NO_3^- - N$ accumulation was 22 percent of the applied N when digested sewage sludge was surface-applied and 38 percent when sludge was incorporated. Similar results were obtained in a later study conducted by King and Vick (1978). They explained that these differences were caused by differences in the amount of gaseous N losses rather than differences in mineralization rates.

Environmental factors such as soil type, temperature, moisture, and pH also influence mineralization and immobilization rates (Bartholomew, 1965). The results from studies conducted to determine the effects of soil type on N mineralization are somewhat contradictory. Lindemann and Cardenas (1984) compared $NO_3^- - N$ accumulations in a clayey soil and a sandy soil amended with anaerobically digested sewage sludge. Cumulative $NO_3^- - N$ at the end of 32 weeks was dependent on sludge rate, but not on soil type. Kelling et al. (1977b) indicated that mineralization was more rapid on a well-aerated sandy loam soil than on a silt loam soil. Tester et al. (1977) mixed freeze-dried compost made from undigested sewage sludge with a loamy sand, a silt loam, and a silty clay soil. More N was mineralized in the Evesboro loamy sand (Typic Quartzipsamment) than in the other two soils. The Fauquier silt loam (Ultic Hapludalf) was able to fix a significant quantity of $NH_4^+ - N$ resulting in decreased nitrification and $NO_3^- - N$ accumulation. Net immobilization occurred in the Christiana silty clay (Typic Paleudult) due to its higher fraction of clay and lower pH. Garau et al. (1986) reported that net mineralization was higher in a sandy clay loam with a pH of 7.8 than from a sandy loam with a pH of 5.5.

Katayama et al. (1986) indicated that the mineralization process was retarded at lower temperatures due to decreased microbial activity in the soil. Hsieh et al. (1981) concluded that varying the soil moisture tension between of 0.06 and 0.33 atm had no significant impact on the N mineralization rate. Terry et al. (1981) studied the effects of pH, moisture, and temperature on N transformations in sludge-amended soils. Temperature was the only factor which markedly affected mineralization

processes. The rate of N mineralization increased with increasing temperature from 15° C to 30° C.

Nitrification

Nitrification, the enzymatic oxidation of $NH_4^+ - N$ to $NO_3^- - N$ is accomplished in two steps. First, $NH_4^+ - N$ is oxidized to $NO_2^- - N$ by the autotrophic bacterium, Nitrosomonas. The bacterium, Nitrobacter, then converts $NO_2^- - N$ to $NO_3^- - N$ The second oxidation is much more rapid than the first, such that very little $NO_2^- - N$ accumulates in the soil.

Beauchamp et al. (1979) monitored $NO_3^- - N$ production in soils treated with six anaerobically digested sewage sludges. In 16 weeks, 17 to 30 percent of the sludge N was nitrified. Different chemical treatments during sewage processing did not appear to influence $NO_3^- - N$ production. Incubation of soils treated with reconstituted sludges, from which soluble and exchangeable $NH_4^+ - N$ and soluble organic N were removed, resulted in 29 to 32 percent nitrification of the organic N during the first 16 weeks. Nitrification was rapid in the early part of the 49 week incubation study but slowed substantially later.

Several studies have been conducted to determine the effect of sludge loading rate on the nitrification process (Premi and Cornfield, 1969b; Rothwell and Hortenstine, 1969; Premi and Cornfield, 1971; Ryan et al., 1973; Yoneyama and Yoshida, 1978). In all instances, nitrification decreased with increasing sludge rate. The decrease in nitrification was attributed to the higher concentrations of toxic organic materials and the higher pH levels associated with increasing sludge rates, both of which may have an inhibitory effect on nitrification. Wilson (1977) incorporated domestic and industrial sewage sludges into soil at rates of 0, 1, 4, and 16 mg/g. At the highest loading rate, the domestic sludge reduced nitrification only slightly. At the two highest rates, industrial sludge significantly reduced nitrification. He concluded that the presence of metals in the

industrial sludge was responsible for the reductions in nitrification. Several researches have indicated that the presence of trace metals inhibits nitrification (Premi and Cornfield, 1969a; Liang and Tabatabai, 1978; Chang and Broadbent, 1982).

Soil environmental conditions such as temperature, pH, and moisture content markedly affect nitrification processes. Because microbial activities are stimulated by increasing temperature, nitrification rates increase with increasing temperature (Terry et al., 1981; Katayama et al., 1986). The optimum temperature for maximum nitrification rates falls somewhere between 30° and 35° C (Alexander, 1965). Nitrification will essentially cease at temperatures below freezing or above 45° C (Brady, 1974). Nitrification kinetics are also influenced by pH. The optimum condition for the $NH_4^+ - N$ oxidizers is a slightly alkaline medium, while that for the $NO_2^- - N$ oxidizers is a neutral environment (Alexander, 1965). Terry et al. (1981) reported that nitrification rates were faster in sludge-amended soils as compared to acidic soils treated with $NH_4^+ - N$, as the addition of calcareous sewage sludge produced a more favorable soil pH. Nitrification was faster in sludge-amended soil having an initial pH of 7.5 than in samples at pH 6.0 or 5.3. A significant quantity of $NO_2^- - N$, however, had accumulated in the treatment with an initial pH of 7.5. The nitrification rates in sludge-amended soils adjusted to 0.25 and 0.5 atm moisture tension were faster than those in samples at 1 atm (Terry et al., 1981).

Ammonium Adsorption/Desorption and Fixation

Nommik (1965) suggested that there exists a dynamic equilibrium among the soluble, exchangeable, and fixed forms of $NH_4^+ - N$ in the soil. Both inorganic and organic fractions of the soil have the ability to fix $NH_4^+ - N$ such that it is relatively unavailable to microorganisms (Brady, 1974). Some clay minerals with a 2:1-type structure can fix $NH_4^+ - N$ and potassium (K^+). Vermiculites have the greatest capacity to fix these ions. These minerals have internal negative charges that attract cations to the internal surfaces between crystal units. Ammonium and K^+, unlike most other

cations, prevent the normal expansion of the crystal and are, therefore, held in a relatively nonexchangeable form, being released very slowly to plants and microorganisms. Soil organic matter can fix ammonia ($NH_3 - N$), although the exact mechanism by which this reaction occurs is not well understood (Brady, 1974). Keeney (1981) concluded that $NH_4^+ - N$ fixation could not be considered a major N sink as few soils can fix appreciable amounts of $NH_4^+ - N$ and because the fixation capacity of a soil is finite.

The exchangeable $NH_4^+ - N$ is that which is adsorbed onto the exchange sites of the soil particles. The majority of the $NH_4^+ - N$ in soil is in the exchangeable form (Mehran and Tanji, 1974). Soils which have a higher cation exchange capacity (CEC), clay content, and organic matter content have a greater capacity to adsorb $NH_4^+ - N$ (Jenny et al., 1945; Goring and Martin, 1959). Several other factors can influence the equilibrium between the adsorbed (exchangeable) and desorbed (soluble) phases. Increasing the amount of $NH_4^+ - N$ added, tends to increase the amount of $NH_4^+ - N$ adsorbed (James and Harward, 1964; Parr and Papendick, 1966). A certain point is reached, however, where increasing the amount applied results in little additional adsorption due to the competition for the remaining unoccupied exchange sites (Parr and Papendick, 1966). The rate of adsorption is highest immediately following $NH_4^+ - N$ addition and decreases with time until an equilibrium condition is attained (Parr and Papendick, 1966.) The adsorption rate increases with decreasing soil pH (Jackson and Chang, 1947). The addition of other cations present in fertilizers and wastes may reduce $NH_4^+ - N$ adsorption through competition for the available exchange sites (Pasricha, 1976). Little quantitative information is available on the adsorption/desorption process for two primary reasons. Both the soluble and exchangeable forms of $NH_4^+ - N$ are available to plants and microorganisms. The partitioning between these two phases has, therefore, received little attention in the past. Because both forms of $NH_4^+ - N$ are available to microorganisms, the $NH_4^+ - N$ is continually oxidized to $NO_3^- - N$ making field measurements of adsorption/desorption kinetics difficult (Pasricha, 1976).

Volatilization

A significant portion of the applied sludge N may be lost by ammonia ($NH_3 - N$) volatilization. The rate and extent of volatilization losses are influenced by pH, temperature, moisture, air movement, soil physical and chemical properties, waste application rate, and application method.

The $NH_4^+ - N$ and $NH_3 - N$ forms of N exist in the soil in a dynamic equilibrium. The pH of the soil/sludge system directly controls the ratio of $NH_4^+ - N$ to $NH_3 - N$ present and thus the $NH_3 - N$ volatilization losses (Terry et al., 1978). Several researchers have demonstrated that $NH_3 - N$ losses increase with increasing pH (Tester et al., 1977; Terry et al., 1978; Tester et al., 1979; Hoff et al., 1981; Donovan and Logan, 1983). Terry et al. (1978) reported that $NH_3 - N$ volatilization was 61 percent greater from sludge applied to soil having an initial pH of 7.5 than from samples having a pH of 6.0 and 5.3. Hoff et al. (1981) measured $NH_3 - N$ volatilization from cropland receiving swine manure. In a 3.5-day period, approximately 65 percent of the applied $NH_4^+ - N$ was volatilized from the high pH soil (7.0) and manure (7.8) treatment, whereas only 14 percent was volatilized from the low pH soil (6.4) and manure (6.4) treatment. Donovan and Logan (1983) reported that 20, 21, and 24 percent of the applied sludge $NH_4^+ - N$ was volatilized from soils with a pH of 5.1, 6.7, and 7.5, respectively, over a 24 hour period.

Volatilization losses increase with increasing temperature (Beauchamp et al., 1978; Steenhuis et al., 1979; Hoff et al., 1981; Donovan and Logan, 1983). Beauchamp et al. (1978) and Hoff et al. (1981) stated that $NH_3 - N$ volatilization rates followed a diurnal pattern, paralleling air temperatures, with maximums occurring at midday. Donovan and Logan (1983) reported that over the 24-hour study period, $NH_3 - N$ losses accounted for 2.3, 9.8, and 13.6 percent of the applied $NH_4^+ - N$ when samples were incubated at 12.8°, 18.3°, and 26.7° C, respectively.

The effects of soil moisture on $NH_3 - N$ volatilization are not clearly defined. Terry et al. (1978) indicated that $NH_3 - N$ losses were greater from the initially drier soils. Donovan and Logan

(1983), however, reported greater NH_3-N losses from wetter soils. They suggested that NH_3-N volatilization was related to the amount of moisture lost via evaporation. Terry et al. (1978) tested the hypothesis that volatilization rates were proportional to rates of moisture loss by studying the effects of relative humidity and air movement on water evaporation and NH_3-N volatilization. The rate of moisture loss increased with decreasing relative humidity and increasing air flow rate. Increasing the air flow rate had a significant impact on NH_3-N volatilization, while the effects of relative humidity were not as pronounced. Similar results were obtained by Steenhuis et al. (1979) and Hoff et al. (1981). Terry et al. (1978) reported that after 49 days of incubation, 9, 26, and 35 percent of the added sludge NH_4^+-N was lost from the 20, 200, and 500 ml/m air flow treatments, respectively. They concluded that rapid drying of the soil effectively increased the concentration of NH_4^+-N in the solution phase of the soil/sludge system and prevented nitrification, both of which resulted in increased NH_3-N losses. King and Morris (1974) established that sludge NH_4^+-N was less susceptible to volatilization on sod than on bare soil, as the grass stubble restricted air movement over the sludge. The average NH_3-N loss was 36 percent of the applied NH_4^+-N on bare soil and 24 percent under grass cover.

Soil properties such as cation exchange capacity and clay content also affect volatilization losses (Ryan and Keeney, 1975; Terry et al., 1978). Terry et al. (1978) reported that 75 percent of the sludge NH_4^+-N added to quartz sand was lost as NH_3-N, while only 13 to 25 percent of the added NH_4^+-N was volatilized from the three soils studied. The authors offered several explanations accounting for the differences in NH_3-N losses. The sand/sludge system was characterized by a higher pH, faster drying rate, and lower nitrification potential as compared to the soil/sludge systems. All of these factors have been shown to increase NH_3-N volatilization. They also observed that there was an inverse linear relationship between the clay content of the soil and the percent of added NH_4^+-N volatilized. Ammonium can be fixed by soil clays or adsorbed onto the exchange sites of the clay particles. These reactions reduce the amount of NH_4^+-N in solution and thus reduces the potential for volatilization. Ryan and Keeney (1975) also determined that there is an inverse linear relationship between clay content and NH_3-N volatilization. They reported

losses of 11 to 60 percent of the applied $NH_4^+ - N$, depending on the soil used and the rate of sludge application.

Increasing the rate of sludge application results in an increase in the amount and percentage of N lost by volatilization (Premi and Cornfield, 1969b; Ryan and Keeney, 1975; Terry et al., 1978; Steenhuis et al., 1979). Premi and Cornfield (1969b) reported that 4 and 13 percent of the added $NH_4^+ - N$ was lost by volatilization from treatments receiving 57 and 457 kg $NH_4^+ - N$/ha, respectively. The thicker layer of sludge on the soil may increase the amount of $NH_4^+ - N$ retained in the sludge layer, and thus available for loss, because of the competition of $NH_4^+ - N$ for exchange sites. The increase in sludge rate may also effectively increase the system pH, as the sludge usually has a higher pH than does the soil to which it is added (Ryan and Keeney, 1975; Terry et al., 1978).

The method of sludge application has a significant impact on $NH_3 - N$ volatilization (Terry et al., 1978; Sommers et al., 1979; Hoff et al., 1981; Donovan and Logan, 1983). Incorporated sludge $NH_4^+ - N$ would not be directly exposed to air movement, higher air temperatures, or evaporation. The incorporation of sludge would also tend to decrease surface pH as opposed to surface application or broadcasting. When surface applied, much of the waste $NH_4^+ - N$ is not in contact with soil adsorption sites. When incorporated, however, contact of $NH_4^+ - N$ with these sites increases, and volatilization losses decrease (Reddy et al., 1979b). Ammonia volatilization over a study period of 54 days was decreased by 73 percent as a result of incorporation as compared to the surface application of sludge (Terry et al., 1978). Sommers et al. (1979) reported that less than 1 percent of the $NH_4^+ - N$ incorporated was lost through volatilization. Similar results were presented by Hoff et al. (1981).

Denitrification

Denitrification is the biological reduction of $NO_3^- - N$ and $NO_2^- - N$ to volatile gases, usually nitrous oxide (N_2O) and molecular nitrogen (N_2). This process is carried out by facultatively anaerobic bacteria capable of using $NO_3^- - N$ or $NO_2^- - N$ as a terminal electron acceptor in the absence of oxygen (Broadbent and Clark, 1965). Denitrifying bacteria are abundant in most soils. The bacteria are heterotrophic and require organic matter as a source of energy (Keeney, 1981). Anaerobic conditions, at least in the immediate cell environment, are required for denitrification to occur. Under certain conditions, the microenvironment of the bacteria may become anaerobic even when the soil is well aerated (Broadbent and Clark, 1965).

Because denitrification is a microbial process, it is strongly influenced by environmental factors such as soil temperature, moisture, and pH (Broadbent and Clark, 1965). Denitrification rates increase with increasing temperature, although there appears to be some disagreement over what the optimum temperature is for this process (Keeney, 1981). Denitrification also increases with increasing moisture content. A higher moisture content not only decreases oxygen levels, but also creates a more favorable environment for denitrifying bacteria (Broadbent and Clark, 1965). Neutral to alkaline soils are required for any extensive denitrification (Keeney, 1981).

Considerable N may be lost by denitrification in waste-treated soils. The effect of waste application on denitrification is twofold. Sludge can supply the energy needed for the growth of denitrifying bacteria and serve as a hydrogen donor for the denitrification process. The decomposition of sludge can also exert a significant biological oxygen demand and thus create anaerobic zones within the soil. Biswas and Warnock (1985) applied wastes with C : N ratios ranging from 2 to 6 to soil columns. They reported that denitrification increased sharply with the increase in carbon content of the applied waste. The optimum C : N ratio was 4, at which N removal was in excess of 90 percent of the applied N. In their experiment, the aerobic condition of the soil columns apparently did not substantially limit denitrification processes. The rate of waste application did not affect N removal

percentages. Reddy et al. (1980) stated that the denitrification potential of the soil was increased by manure application. Epstein et al. (1978) concluded that amendments high in available C (raw sludge) are biologically very active and may lose significant quantities of N as result of denitrification processes. Digested and composted sludges contain lower levels of readily oxidizable C and are therefore not as active as raw sludges.

Volz and Heichel (1979) suggested that from 48 to 70 percent of the applied N in fermentation residue was lost as N_2O or N_2. They attributed this to the elevated soil $NO_3^- - N$ levels, denitrifier populations, and organic C levels in the treated soils. Ryan et al. (1973), Kelling et al. (1977b), Sommers et al. (1979), Feigin et al. (1981), Hsieh et al. (1981), and Lindemann and Cardenas (1984) concluded that the unrecovered N in their experiments was lost by denitrification. Hsieh et al. (1981) reported that the amount of unrecovered N was greater at a higher soil moisture content.

Aulakh et al. (1984) measured gaseous losses of N from conventional-till and no-till crop fields treated with commercial fertilizer. Denitrification losses were greater under no-till than under conventional tillage. The authors suggested that this was the result of the more dense surface soil and higher moisture content of the no-till plots. Soil moisture and air temperature were the only two of several factors studied by Aulakh et al. (1984) that affected gaseous N fluxes under field conditions.

Phosphorus Reactions in Waste-Treated Soils

Organic waste application rates are usually determined based on the available N content of the waste and the crop N requirements. The majority of the research conducted to determine the im-

pact of an organic waste application has, therefore, focused on soil N transformations. Very little information is available describing the P reactions in waste treated soils.

The P in the soil is subject to adsorption/desorption, precipitation, and mineralization/immobilization. Of these processes, the adsorption/desorption and precipitation of inorganic P are by far the most significant in determining the quantity and form of P present. Phosphorus, like N, is mineralized or immobilized depending on the P content of the soil/waste system. In systems where the P content exceeds 0.2%, net mineralization occurs (Reddy, 1980). Most organic wastes contain P in excess of this critical level. Of the P applied in sludge, only 10-30 percent is organic P (Sommers et al., 1976). Due to the low percentage of organic P applied, the application of sludge does not significantly alter P transformation and transport processes, particularly over an extended period of time (Reddy, 1980).

Modeling Nitrogen Transformations

Modeling N transformations has received the attention of many investigators in recent years. Mathematical models have been used for both quantitative and qualitative understanding of the fate of N in soil systems. Some models concentrate on a particular process while others consider several processes. Modeling approaches vary considerably between the different models. A review of the available models which simulate the N transformation processes is presented in the following section.

Mineralization - Immobilization

Mineralization-immobilization modeling approaches can be divided into three categories:

1. Models which do not consider the relationship between carbon (C) and nitrogen (N) decomposition,

2. Models which consider C and N and use the C : N ratio to determine net mineralization or immobilization rates, and

3. Models which consider C and N as substrates for the microbial biomass and determine net mineralization or immobilization from gross mineralization and immobilization (Bosatta et al., 1981).

Within the first category, models have been developed which utilize empirical equations or first order kinetics. Duffy et al. (1975) proposed an empirical relationship to describe the net rate of mineralization of organic-N to inorganic-N in tile-drained corn belt soils:

$$r_m = 0.0060; \quad 15 \text{ April} - 2 \text{ June} \tag{1a}$$

$$r_m = 0.0023; \quad 1 \text{ March} - 14 \text{ April and } 3 \text{ June} - 30 \text{ Oct.} \tag{1b}$$

$$r_m = 0.0; \quad \text{remainder of the year} \tag{1c}$$

where: r_m = net mineralization rate (mg-N/day/cm^2).

These different rates were intended to reflect the effects of moisture and temperature on the mineralization process. Several investigators have utilized a first-order kinetic equation to model the mineralization and immobilization processes (Stanford and Smith, 1972; Frere et al., 1975; Mehran and Tanji, 1974; Cameron and Kowalenko, 1976; Donigian and Crawford, 1976; Sinha et

al., 1977; Watts and Hanks, 1978; Frere et al., 1980; Hsieh et al., 1981; Tanji et al., 1981; Johanson et al., 1984). The first-order kinetic equation can be expressed in differential form as:

$$-\frac{d[N]}{dt} = k[N] \qquad (2)$$

where: $[N]$ = concentration of organic-N (or $NH_4^+ - N$)

t = time

k = first order rate constant for mineralization (or immobilization)

Sinha et al. (1977), Hsieh et al. (1981), and Lindemann and Cardenas (1984) experimentally determined mineralization rate constants for several soil-waste systems.

Attempts have been made to incorporate the effects of environmental factors on these processes. Donigian and Crawford (1976) and Johanson et al. (1984) considered temperature effects using a simplified Arrhenius equation of the form:

$$k = k^{35} \times \theta^{(T-35)} \qquad (3)$$

where: k = first order rate constant corrected for temperature

k^{35} = rate constant at 35° C

θ = temperature correction coefficient

T = soil temperature (° C)

Johanson et al. (1984) assumed a temperature correction coefficient of 1.07 for mineralization. Stanford et al. (1973) calculated a regression equation to predict values of k for temperatures below 35° C:

$$\log k = 7.71 - 2758\left(\frac{1}{T_a}\right) \qquad (4)$$

where: T_a = absolute temperature (°K)

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k = first-order rate constant for mineralization (1/week)

If the soil temperature exceeded 35° C, the rate constant was set equal to 0.057 week^{-1}. This relationship was used in models developed by Frere et al. (1975), Watts and Hanks (1978) and Frere et al. (1980).

Stanford and Epstein (1974) concluded that there was a direct relationship between soil N mineralization and water content. Based on the data presented by Stanford and Epstein (1974), Watts and Hanks (1978) expressed the effect of soil moisture on N mineralization as:

$$N_t = R_m N_{to} \tag{5}$$

where: N_t = N mineralized under existing moisture conditions

N_{to} = N mineralized at optimum soil moisture content

$$R_m = \begin{cases} 1.111 \, FPS; & 0 \le FPS < 0.9 \\ 10.0 - 10.0 \, FPS; & 0.9 \le FPS \le 1.0 \end{cases}$$

FPS = fraction of fillable pore space containing water

Cameron and Kowalenko (1976) incorporated a term into Equation 2 to account for microbial population activity, P(t), and derived standardized P(t) curves for various soil temperatures and moisture contents using experimental data.

Molina et al. (1980) suggested that N mineralization should be modeled as the sum of two or more exponentials, thus accounting for the varying decay rates of different nitrogenous compounds. Assuming that only two decomposable compounds were present, the model describing N mineralization was:

$$N_t = N_o S(1 - e^{-ht}) + N_o(1 - S)(1 - e^{-kt}) \tag{6}$$

where: N_t = amount of N mineralized (kg/ha)

N_o = amount of potentially mineralizable N in the soil (kg/ha)

S = fraction of potentially mineralizable N in one compound

h, k = specific mineralization rate constants for the two different nitrogenous compounds (week^{-1})

t = time (weeks)

Lindemann and Cardenas (1984) concluded that this model adequately predicted N mineralization in sludge-amended soils over a period of 32 weeks.

Several existing models consider the relationship between the soil N and C cycles. One of the earliest models of soil N transformations was reported by Dutt et al. (1972). Empirical rate equations were determined using multiple regression analyses of literature data. The equation describing the net rate of $NH_4^+ - N$ immobilization or the net rate of organic-N mineralization was:

$$R_{M/I} = 0.892 + 0.00216\,T + 0.027\,[Org\text{-}N] + 0.392\,\log_{10}[NH_4^+ - N] \qquad (7)$$

where: $R_{M/I}$ = Net mineralization or immobilization rate ($\mu g/g/day$)

T = Temperature (°C)

Org-N = Soil organic N ($\mu g/g$ soil)

$NH_4^+ - N$ = Ammonium N ($\mu g/g$ soil)

The output of Equation 7 was then multiplied by the factor, M, where:

$$M = -2.51 + 1.85 \times \log_{10}(C{:}N) \qquad (8)$$

Equation 8 was used to determine if net mineralization or immobilization occurred. A positive rate, corresponding to a C:N ratio greater than 23, indicated net immobilization while a negative rate, corresponding to a C:N ratio less than 23, indicated net mineralization. Dutt et al. (1972) also presented an equation for $NO_3^- - N$ immobilization:

$$R_I = (1.52T)/[Org\text{-}N]^2 \qquad (9)$$

$$+ (3.23 \times 10^{-15})e^{T} - 0.0049 \left(T[\text{Org-N}] - [\text{NO}_3^- - \text{N}] \right)/[\text{Org-N}]$$

where: R_I = Immobilization rate (μg/g/day)

$\text{NO}_3^- - \text{N}$ = Nitrate N (μg/g soil)

This process was assumed to take place only at C:N ratios greater than 23.

Hagin and Amberger (1974) determined if net mineralization or immobilization occurred using the equation:

$$N_x = N_{OM} - (N_S + N_{AM})\left(\frac{C_{OM}}{2.3 \, C_S} \right) \tag{10}$$

where: N_x = amount of N producing disequilibrium

N_{OM} = N in added organic materials

N_S = soil N

N_{AM} = mineral N added

C_{OM} = carbon in added organic materials

C_S = soil carbon

A negative value of N_x indicated net immobilization, while a positive N_x indicated net mineralization. The organic matter present in the soil/waste system was divided into five components: soil organic matter, lignin, cellulose, hemicellulose, and sugar. The decomposition of each fraction was treated separately, using first-order kinetics to model the mineralization or immobilization process. Rate constants were obtained from the literature. The effects of soil temperature, pH, and moisture were also considered.

Because most experiments which have been performed determine only total inorganic N formation, Reddy et al. (1979a) proposed that a composite k value be used:

$$NO_3^- - N(t) = (N_x + N_S)(1 - e^{-kt}) \qquad (11)$$

where: N_x = potentially mineralizable N in the added waste (kg/ha)

N_s = potentially mineralizable N for the soil (kg/ha)

k = composite mineralization rate constant (day^{-1})

t = time (days)

The value for N_x was calculated using an equation similar to Equation 10. Based on the data presented by Stanford and Smith (1972), Reddy et al. (1979a) developed a regression equation for predicting the potentially mineralizable N present in the soil (N_s) as a function of TKN. First order rate constants (k) were presented for each of the soil/waste systems considered including soils amended with beef, swine, and poultry wastes. To adjust for environmental conditions, Reddy et al. (1979a) used the equation:

$$\bar{k}_{T1} = k_{T2} \, F_M \, F_{pH} \, F_{mA} \, \theta^{(T_1 - T_2)} \qquad (12)$$

where: $\bar{k}_{T1}$ = first order rate constant corrected for environmental conditions

k_{T2} = first order rate constant for a given temperature

F_M = moisture factor

F_{pH} = pH factor

F_{mA} = method of application factor

θ = temperature correction coefficient

Empirical relationships were developed from literature data to predict values for moisture, pH, temperature, and method of application factors. For wastes with a C:N ratio greater than 23, a lag period was calculated using:

$$t_D = [\ln(C/N)_0 - \ln 23] / A_{T1} \, \theta^{(T_1 - T_2)} F_M \, F_{pH} \, F_{mA} \qquad (13)$$

where: t_D = lag period (days)

$(C/N)_0$ = initial C:N ratio of added waste

A = first order immobilization rate constant (days^{-1})

This lag period accounted for the initial immobilization period which resulted from the addition of low N wastes.

O'Brien and Mitsch (1980) divided the N and C pools into stable and unstable fractions. Nitrogen mineralization was modeled for each fraction using first order kinetics (Equation 2) and corrected for the effects of varying C:N ratio of the soil/waste system.

The models which consider C and N as substrates for the microbial biomass use various approaches for modeling microbial activity. Beek and Frissel (1973) considered six components of soil organic matter including humus, protein, sugars, cellulose, lignin, and microbial biomass. Humus was assumed to be the end product of decomposition. All fractions, with the exception of humus, underwent similar decomposition processes. These processes were simulated independently for each fraction, but were described using generalized equations. The rate of decomposition was expressed as:

$$RDECX = CMPX \times SPRCFX \times SPERA \times TDEC \times WDEC \times SX \times KX \qquad (14)$$

where: RDECX = rate of decomposition of 'X' organic matter fraction
(mg C/day/soil layer)

CMPX = amount available (mg C/soil layer)

SPRCFX = specific rate coefficient

SPERA = specific rate of decomposition (1/day)

TDEC = temperature reduction factor

WDEC = water content reduction factor

SX, KX = boundary conditions

SPERA represents the fraction by which the quantity of protein, the most easily decomposing component, decreases per day at optimum conditions. SPRCFX represents the ratio of the specific rate of each of the other four components to that of protein. The boundary conditions SX and KX, are set equal to one if there is organic matter and inorganic nitrogen available for decomposition, and equal to zero if the soil conditions are not suitable for decomposition. The growth rate of biomass was assumed to be proportional to the rate of decomposition:

$$GRBIMX = EFX \times RDECX \qquad (15)$$

where: GRBIMX = growth rate of biomass (mg C/day/layer)

EFX = efficiency factor which represents the fraction of decomposed C in biomass

Beek and Frissel (1973) introduced the factor, PX, to indicate if net mineralization or immobilization occurred such that:

$$PX = \frac{1}{CNCMX} - \frac{EFX}{CNBIMA} \qquad (16)$$

where: CNCMX = C:N ratio of the decomposing substrate (mg C/mg N)

CNBIMA = C:N ratio of the biomass (mg C/mg N)

If PX was positive, mineralization (RPRN3X) occurred at a rate of:

$$RPRN3X = RDECX \times PX \qquad (17)$$

If PX was negative, the rate of immobilization (RCON3X) was calculated using a similar equation.

In a subsequent model, van Veen and Frissel (1976) defined the amount of N mineralized as the summation of the amount mineralized from dead biomass, fresh organic matter, and soil organic matter. The N mineralization from soil organic matter and dead biomass was assumed to follow first-order kinetics. The amount of N in the dead biomass (m_D), needed to calculate the mineralization of this fraction, was determined using the first-order equation:

$$\frac{dm_D}{dt} = k_D \times m \qquad (18)$$

where: k_D = death rate constant for biomass (1/day)

   m = amount of N in the biomass (mg N/g soil).

The parameter, m, was defined as the product of the concentration of N per cell, C, and the number of cells per gram of soil, n. The growth-rate of biomass was assumed to occur according to Michaelis-Menten or Monod-type kinetics:

$$\frac{dn}{dt} = \mu_{max} \frac{[C]}{K_s + [C]} \, n \qquad (19)$$

where: μ_{max} = maximum growth rate constant (1/day)

   K_s = Michaelis-Menten half-saturation constant (or Monod constant)

   n = number of cells/g soil

The mineralization of N from fresh organic matter was expressed as:

$$\frac{dN_0}{dt} = k_0 \times F \times O \times f \qquad (20)$$

where: N_0 = N mineralized from fresh organic matter (mg N/g soil)

   k_0 = rate constant (1/day)

   F = activity factor

   O = amount of N in the fresh organic matter (mg N/g soil)

   f = availability factor

The activity factor, F, accounts for the increase in decomposition rate due to the increase in biomass activity and is calculated as a function of the growth rate. The availability factor, f, is a function of the type of added organic material and the fraction of the organic material which had previously mineralized.

Frissel and van Veen (1981) revised the mineralization-immobilization component of their earlier model. In this version, the soil organic matter was divided into six C pools, three of which contained N. The active, resistant N (pool 5) and old organic N (pool 6) fractions were assumed to decompose according to first-order kinetics, while the decomposition of the easily decomposable N (pool 3) fraction was assumed to follow Michaelis-Menten kinetics. Only a fraction of the total biomass, proportional to the fraction of total C within each pool, was involved in the decomposition of the different organic substrates. The equations used to simulate these processes were similar to those previously described.

McGill et al. (1981) divided the microbial biomass into bacteria and fungi components. These components had different C:N ratios, which were allowed to vary within certain limits. Biomass growth was modeled using Michaelis-Menten kinetics. Bosatta (1981) assumed that the total biomass, having a fixed C:N ratio, was involved in the decomposition of organic matter. Juma and Paul (1981) simulated the dynamics of microbial growth and N immobilization using first-order kinetics. Therefore in most cases, the decomposition of C was limited by substrate concentration and not by the biomass concentration. In this model, C and N substrates were divided into active, stabilized, and old pools.

Nitrification

Several different methods have also been employed to simulate the nitrification processes. Among those reported include empirical relationships, sigmoid and logarithmic functions, and zero order, first order, and Michaelis-Menten kinetic equations. Dutt et al. (1972) proposed the following empirical equation:

$$R_N = 4.64 + 0.00162\, T[NH_4^+ - N] \qquad (21)$$

$$+ 0.238\, \log_{10}[NH_4^+ - N] - 2.51\, \log_{10}[NO_3^- N]$$

where: R_N = Nitrification rate (μg/g/day)

  T = Temperature (°C)

  $NH_4^+ - N$ = Soil ammonium N (μg/g soil)

  $NO_3^- - N$ = Soil nitrate N (μg/g soil)

Duffy et al. (1975) also used an empirical relationship:

$$r_n = (\frac{4}{5})(\frac{F}{20}), \qquad\qquad tf \leq t \leq tf + 20 \tag{22a}$$

$$r_n = 0.005, \qquad\qquad t > tf + 20, \quad \text{until all fertilizer converted} \tag{22b}$$

where: r_n = nitrification rate (mg N/day/cm²)

  F = amount of applied N fertilizer (mg N/cm²)

  tf = day of fertilizer application

  t = days since application

Hagin and Amberger (1974) used the nitrification rate equation formulated by Lees and Quastel (1946) who suggested that $NO_3^- - N$ production followed a sigmoid curve:

$$\log \frac{y}{A - y} = K(t - t_{1/2}) \tag{23}$$

where: y = $NO_3^- - N$ produced (μg/g soil)

  A = asymptotic value of y (= 80 % of original $NH_4^+ - N$ concentration)

  K = experimentally determined constant

  t = time (days)

  $t_{1/2}$ = time when $y = \dfrac{A}{2}$

Hagin and Amberger (1974) modified Equation 23 to include the effects of microbial population dynamics.

A zero-order kinetic model assumes that the rate is not dependent on substrate concentration and can be expressed in general form as:

$$-\frac{d[S]}{dt} = k_0 \qquad (24)$$

where: [S] = substrate ($NH_4^+ - N$ or $NO_2^- - N$) concentration

t = time

k_0 = zero-order rate constant

Sabey et al. (1969) presented a zero-order nitrification model:

$$N = k_F R_K (t - t_F r_t) \qquad (25)$$

where: N = amount of $NO_3^- - N$ produced ($\mu g/g$)

t = time (days)

k_F = characteristic nitrifying capacity (μg $NO_3^- - N/g/day$)

R_K = composite factor

t_F = characteristic delay period under optimum conditions

r_t = composite factor

The parameter k_F was defined as the maximum $NO_3^- - N$ accumulation rate for a particular soil under optimum conditions. The composite factors, R_K and r_t, were based on the relative accumulation rate and delay period, respectively, under less favorable conditions. The model developed by Beek and Frissel (1973) to describe nitrification was based on microbial kinetics and did not consider substrate concentration:

$$RNH3N = AMOXL \times RAMOX \times TCOF \times WCCOF \qquad (26)$$

where: RNH3N = rate of nitrification of $NH_4^+ - N$ (mg N/day/layer)

AMOXL = number of ammonium oxidizers (number/layer)

RAMOX = specific rate of oxidation (mg N/day/number)

TCOF   = temperature coefficient

WCCOF   = water content coefficient

The growth of ammonium oxidizers was assumed to be exponential, while the death rate was proportional to the number of microorganisms present.

Several investigators (Cameron and Kowalenko, 1976; Donigian et al., 1977; Selim and Iskandar, 1978; Watts and Hanks, 1978; O'Brien and Mitsch, 1980; Nakano et al., 1981; Rao et al., 1981; Selim and Iskandar, 1981; Tanji et al., 1981; Wagenet, 1981; Wagenet and Rao, 1983) have modeled the nitrification process using a single first-order equation of the form:

$$\frac{-d[NH_4^+ - N]}{dt} = k_1[NH_4^+ - N] \qquad (27)$$

Watts and Hanks (1978) calculated the rate coefficient (k_1) using:

$$k_1 = (0.0105\,T_C + 0.00095\,T_C^2)k_{35}, \quad 0°C \leq T_C \leq 10°C \qquad (28a)$$

$$k_1 = (0.032\,T_C - 0.12)k_{35}, \quad 10°C \leq T_C \leq 35°C \qquad (28b)$$

$$k_1 = (-0.1\,T_C + 4.5)k_{35}, \quad 35°C \leq T_C \leq 45°C \qquad (28c)$$

where: T_C = soil temperature (°C)

k_{35} = first-order rate constant at 35°C

Watts and Hanks (1978) simulated the effect of soil water content on nitrification using Equation 5. Rao et al. (1981) multiplied the right side of Equation 27 by the volumetric soil water content to account for moisture effects. Selim and Iskandar (1981) used empirical functions to describe the influence of environmental factors such as soil suction, aeration, temperature, and pH on the nitrification rate constant. Cameron and Kowalenko (1976) represented the nitrification process as a microbially mediated first-order kinetic function. This was accomplished by including a microbial population activity function in Equation 27.

Because nitrification is a two step process, several others (McLaren, 1969a; Mehran and Tanji, 1974; Donigian and Crawford, 1976; Hsieh et al., 1981) have used two first order equations:

$$\frac{-d(NH_4^+ - N)}{dt} = k_1(NH_4^+ - N) \tag{29}$$

$$\frac{d(NO_2^- - N)}{dt} = k_1(NH_4^+ - N) - k_2(NO_2^- - N) \tag{30}$$

Donigian and Crawford (1976) simulated temperature effects using a simplified Arrhenius equation similar to Equation 3. For non-steady state conditions, McLaren (1969b) developed a model which considers the growth of the nitrifiers, Nitrosomonas (m_1) and Nitrobacter (m_2), using Michaelis-Menten kinetics. The N substrate was related to biomass by the equations:

$$\frac{-d(NH_4^+ - N)}{dt} = A\frac{dm_1}{dt} \tag{31}$$

and

$$\frac{-d(NO_2^- - N)}{dt} = B\frac{dm_2}{dt} \tag{32}$$

where A and B are proportionality constants for growth and equal the reciprocal of growth yield (N oxidized per unit weight of biomass synthesized). Biomass growth was determined using:

$$\frac{dm}{dt} = \gamma m(1 - \frac{m}{m_{max}}) \tag{33}$$

where: γ = growth rate constant

m_{max} = maximum attainable biomass of a species

The growth rate is dependent upon substrate concentration:

$$\gamma = \gamma_{max}\frac{(S)}{K_m + S} \tag{34}$$

where: γ_{max}= maximum specific growth rate constant at "infinite" substrate concentration

S   = substrate, $NH_4^+ - N$ or $NO_2^- - N$, concentration

K_m = Michaelis-Menten half-saturation constant.

This approach was adopted by Ardakani et al. (1975), Frissel and van Veen (1981), Leggett and Iskandar (1981), and McGill et al. (1981).

In the case where $S < < K_m$, Equations 31-34 reduce to first order kinetics, while if $S > > K_m$, then these approach zero order kinetics. For intermediate concentrations of S the reaction order is between zero and one. Leggett and Iskandar (1981) presented empirical equations relating growth rate constants to temperature and pH.

In a later investigation, McLaren (1970) suggested that the change in substrate concentration could be described by:

$$-\frac{dS}{dt} = A\frac{dm}{dt} + \alpha m + \frac{k''\beta m(S)}{km + S} \qquad (35)$$

where: α = N oxidized per unit weight per unit time for maintenance.

β = amount of enzyme per unit biomass involved in waste metabolism

k'' = proportionality constant

The first term ($A\frac{dm}{dt}$) accounts for microbial growth, the second term (αm) provides for maintenance, and the third term ($\frac{k''\beta m(S)}{km + S}$) represents the substrate oxidized in excess of that needed for growth and maintenance.

Iskandar and Selim (1978) reviewed the literature on the simulation of the nitrification process. They concluded that the Michaelis-Menton type model is the most reasonable, providing a better representation of the actual soil processes. Little quantitative information, however, is available for models of this type.

Ammonium Adsorption/Desorption

Three types of mathematical models have been used to describe the adsorption/desorption processes in the soil. Mehran and Tanji (1974), Donigian and Crawford (1976), Donigian et al. (1977), van Veen and Frissel (1976), Frissel and van Veen (1981), Hsieh et al. (1981), and Tanji et al. (1981) modeled the adsorption/desorption process using a reversible first-order kinetic equation, very similar in form to Equation 27. In most cases, the fixation rate constant was assumed to be much greater than the release rate constant. Donigian and Crawford (1976) and Donigian et al. (1977) adjusted the rate constant for temperature effects using Equation 3.

Another method employed to simulate the ion exchange process was the application of chemical equilibrium equations (Dutt et al., 1972; Shaffer et al., 1977; Parton et al., 1981; Selim and Iskandar, 1981; Wagenet, 1981). It has often been assumed that the soluble $(NH_4^+ - N)_S$ and exchangeable $(NH_4^+ - N)_E$ forms of $NH_4^+ - N$ exist in equilibrium in the soil (Terry et al., 1978) such that:

$$(NH_4^+ - N)_S \overset{K}{\leftrightharpoons} (NH_4^+ - N)_E \tag{36}$$

The equilibrium constant (K) can then be expressed as a ratio of concentrations:

$$K = \frac{[NH_4^+ - N]_E}{[NH_4^+ - N]_S} \tag{37}$$

Dutt et al. (1972) and Shaffer et al. (1977) considered the competition between sodium (Na^+) and $NH_4^+ - N$ ions for exchange sites using:

$$\frac{[NH_4^+ - N]_S}{[Na^+]_S} = K \frac{[NH_4^+ - N]_E}{[Na^+]_E} \tag{38}$$

Models of this type are based on the assumption that chemical equilibrium is reached instantaneously.

Adsorption isotherms have also been used to predict the concentrations of $NH_4^+ - N$ in solution and adsorbed to soil particles (Cameron and Kowalenko, 1976; Bosatta, 1981; Johanson et al., 1984). Two of the more common equations used to describe the adsorption phenomenon have been the Langmuir and Freundlich isotherms (Sawyer and McCarty, 1978). The Langmuir equation:

$$\frac{C}{Y} = \frac{a}{Y_m} + \frac{C}{Y_m}$$
(39)

where: C   = concentration of solute

          Y   = amount of material adsorbed per unit weight of adsorbent

          Y_m = maximum adsorption

          a   = constant

was utilized by Cameron and Kowalenko (1976) to show the relationship between exchangeable and clay-fixed $NH_4^+ - N$. Cameron and Kowalenko (1976) and Johanson et al. (1984) applied the Freundlich equation to describe the relationship between soluble and exchangeable $NH_4^+ - N$, such that:

$$Y = KC^{1/n}$$
(40)

The constants K and n must be evaluated for each solute and temperature. It should be noted that a linear Freundlich isotherm (n = 1) is equivalent to Equation 37.

Hunt and Adamsen (1985) fit $NH_4^+ - N$ adsorption data from two different soils to the Langmuir and Freundlich models. For low $NH_4^+ - N$ levels both models predicted the $NH_4^+ - N$ concentration in the soil solution with varying levels of $NH_4^+ - N$ in the soil. They concluded that the Langmuir model gave a slightly better fit over the range of $NH_4^+ - N$ levels tested.

Ammonia Volatilization

A significant quantity of the applied $NH_4^+ - N$ in organic fertilizers can be lost to the atmosphere through $NH_3 - N$ volatilization. Interest in modeling this process has increased in recent years due to the growing dependence on fertilizer use within the agronomic industry.

Fenn and Kissel (1974, 1975, 1976) developed several polynomial equations, based on laboratory studies, to predict cumulative $NH_3 - N$ loss. Ammonia loss, given as a percentage of $NH_4^+ - N$ applied, was calculated as a function of time, temperature, application rate, $CaCO_3$ content of the soil, pH, and CEC. Correlation coefficients as high as 0.80 were reported when all of these variables were included in the model.

Several investigators have assumed that $NH_3 - N$ volatilization follows a first-order kinetic equation (Reddy et al., 1979b; Steenhuis et al., 1979; O'Brien and Mitsch, 1980; Wagenet, 1981). Reddy et al. (1979b) presented correction factors which were used to adjust the volatilization rate constant for differences in temperature, CEC, and wind velocity. The adjusted rate constant was obtained using:

$$k_{T_2} = k_{T_1} \theta^{(T_2 - T_1)} \left(\frac{F_{CEC2}}{F_{CEC1}} \right) F_{AFR} \tag{41}$$

where: k_{T_2} = first-order rate constant corrected for environmental conditions

k_{T_1} = first-order rate constant for a given temperature

θ = temperature correction coefficient

F_{CEC1} = CEC factor for the soils corresponding to K_{T_1}

F_{CEC2} = CEC factor the soil to be simulated

F_{AFR} = air flow rate factor

The CEC factor was calculated using:

$$F_{CEC} = \begin{cases} 1.00 - 0.038 \, CEC_s & ; \text{waste incorporated} \\ 1.00 & ; \text{waste surface} - \text{applied} \end{cases} \tag{42}$$

where: CEC_s = CEC of the receiving soil (meq/100 g soil)

This equation was considered valid for soils with a CEC $\leq$ 30 meq/100 g soil. The air flow rate factor was expressed as:

$$F_{AFR} = 1.44 + 0.16 \, \ln(AFR) \tag{43}$$

where: AFR = air flow rate (km/h)

According to this relationship, a maximum loss of $NH_3 - N$ corresponded to an air flow rate of 0.06 km/h.

Frissel and van Veen (1981) and Parton et al. (1981) first determined the concentrations of $NH_3 - N$ in solution and in the gas phase using a chemical equilibrium equation similar in concept to Equations 36 and 37. Parton et al. (1981) then calculated the diffusion of $NH_3 - N$ gas (NH_3^g) within the soil according to Fick's law of diffusion:

$$F_i = [(NH_3^g)_{i-1} - (NH_3^g)_i] \, \frac{D}{\Delta x} \tag{44}$$

where: F_i = flux of NH_3^g from the ith layer to the i-1 soil layer (g/cm²/sec)

D = diffusion rate of NH_3^g in the soil (cm²/sec)

Δx = distance between soil layers (cm)

The diffusion rate (D) was expressed as a function of soil porosity:

$$\frac{D}{D_0} = S^{1.33} \tag{45}$$

where: D_0 = diffusion coefficient of NH_3^g in free air (0.185 cm²/sec)

S = fraction of a soil layer occupied by air

The transfer of NH_3^g from the top soil layer to the atmosphere was described using the equation:

$$F_a = [(NH_3^g)_{air} - (NH_3^g)_1] / \gamma \qquad (46)$$

where: F_a = flux of $NH_3 - N$ from the top soil layer into the atmosphere

γ = the resistance to flow of NH_3^g into the atmosphere (function of wind speed)

Frissel and van Veen (1981) applied Fick's law of diffusion (Equation 44) to the diffusion of NH_3^g from the surface soil into the atmosphere. Additional research is required to provide quantitative estimates of the parameters used in these equations (Equations 41 - 46) and to define the effects of soil type and environmental conditions on the $NH_3 - N$ volatilization process.

Denitrification

The modeling approaches utilized to describe the denitrification process have been similar to those used to simulate nitrification, including empirical equations, chemical kinetics, and biomass based kinetics. Duffy et al. (1975) assumed that denitrification occurred in the top soil layer when $NO_3^- - N$ quantities were in excess of 0.005 mg/cm² and when water content was at field capacity or above. When these conditions were met, the rate of denitrification was set equal to 0.005 mg N/day/cm².

Shaffer et al. (1977) and Hsieh et al. (1981) modeled denitrification using a zero-order kinetic model (Equation 24) with $NO_3^- - N$ being the substrate concentration simulated. Several investigators have applied a first-order kinetic equation to this process (Hagin and Amberger, 1974; Mehran and Tanji, 1974; Stanford et al., 1975a; Stanford et al., 1975b; Donigian and Crawford, 1976; Donigian et al., 1977; Frere et al., 1980; O'Brien and Mitsch, 1980; Rao et al., 1981; Selim and Iskandar, 1981;

Tanji et al., 1981; Wagenet, 1981; Wagenet and Rao, 1983; Johanson et al., 1984). Donigian and Crawford (1976), Donigian et al. (1977), and Johanson et al. (1984) corrected the first-order rate constant for temperature effects using Equation 3. Frere et al. (1980) computed the temperature adjusted rate constant using the following equation:

$$DKT = e^{(0.0693\ ATP+DB)}$$ (47)

where: DKT = temperature adjusted rate constant (1/day)

ATP = average temperature (°C)

DB = ln(DK) - 2.4255

DK = unadjusted rate constant (1/day)

Stanford et al. (1975a) developed regression equations to predict denitrification rate constants from soil extractable glucose-C or total organic-C contents. Frere et al. (1980), utilized the equations presented by Stanford et al. (1975a) to calculate the rate constant, DK, in Equation 47 as a function of total soil organic carbon (SC) content:

$$DK = 24\ (0.0011\ SC + 0.0025)$$ (48)

where: SC = OM/0.1724 (mg C/g soil)

OM = percent organic matter

Frere et al. (1980) simulated denitrification only when the moisture content of the soil exceeded field capacity. Hagin and Amberger (1974), Rao et al. (1981), and Selim and Iskandar (1981) used empirical relationships to incorporate the effects of environmental conditions including temperature, pH, moisture content, and availability of organic matter.

Because denitrification is an enzymatic process, Frissel and van Veen (1981), McGill et al. (1981), and Nakano et al. (1981) applied a Michaelis-Menten type equation:

$$\frac{d(NO_3^-)}{dt} = K_d \frac{(NO_3^-)}{(K_{NO_3} + (NO_3^-))} \qquad (49)$$

where: K_d = maximum denitrification rate

K_{NO_3} = half-saturation constant for $NO_3^- - N$

Bosatta et al. (1981) suggested that a double Michaelis-Menten equation may provide a more accurate estimate of the denitrification process due to the dependence of this process on C availability. This was expressed as:

$$\frac{d(NO_3^-)}{dt} = K_d \left(\frac{(NO_3^-)}{K_{NO_3} + (NO_3^-)} \right) \left(\frac{(C_{sol})}{K_{solC} + (C_{sol})} \right) \qquad (50)$$

where: C_{sol} = soluble or biodegradable organic C

K_{solC} = half-saturation constant for soluble C

K_{NO_3} and K_d are as defined in Equation 49.

Frissel and van Veen (1981) simulated the presence of anaerobic zones in the soil. The diffusion of oxygen (O_2) and $NO_3^- - N$ through the soil was calculated using concentration gradients. For O_2 diffusion, this equation was given as:

$$R_d = D_{O_2} f_t \theta \frac{[(O_2)_n - (O_2)_{n+1}]}{dx_d} \qquad (51)$$

where: R_d = rate of O_2 diffusion (mg O_2/day)

D_{O_2} = diffusion coefficient of O_2 in solution (cm²/day)

f_t = tortuosity factor

θ = water content of the soil around the air-filled pores (cm³/cm³)

$(O_2)_n$ = O_2 concentration in layer n (mgO_2/cm³)

dx_d = diffusion distance (cm)

Denitrification was assumed to occur in the absence of O_2

The kinetics of denitrification are very complex and are not well understood. Focht and Chang (1975) concluded that the denitrification process would appear to follow zero or first order kinetics, with respect to $NO_3^- - N$, depending on whether the system was C or N limited, respectively. Models which involve a dual substrate enzyme complex provide a more accurate description of the denitrification process. Models of this type, such as Equation 50, were however, developed for idealized systems and are not able at this time to reflect the complex conditions existing in the soil system (Iskandar and Selim, 1978).

Review of Selected Water Quality Models

Many of the existing N models simulate only one or two of the processes described in the previous section. These models were developed for use as a research tool, to provide a better understanding of the mechanisms involved. Due to the recent increase in concern over nonpoint source pollution, efforts have been made to integrate the information available on N transformation and transport processes into models describing the complete system. Some of the available comprehensive models are discussed in the following section.

ACTMO

Frere et al. (1975) developed the Agricultural Chemical Transport Model (ACTMO). The primary objective of ACTMO was to trace a single application of a chemical over an agricultural watershed. The model was developed for continuous simulation using an hourly time step. The hydrologic component of the model is based on the USDA Hydrograph Lab model and simulates surface flow,

snow accumulation and melt, infiltration, interflow, and evapotranspiration. A modified version of the USLE is used to describe rill and interrill erosion. The chemical component includes pesticides and nitrate options. Nitrogen mineralization, plant uptake, and leaching and runoff losses of N are the only transformation and transport processes included in the nitrate option. The mineralization of organic N to $NO_3^- -N$ is estimated using first-order kinetics. The reaction rate is adjusted for the effects of temperature and moisture on the mineralization process. Plant uptake is modeled as a function of water use. The input data required by the model is well documented, however, application of ACTMO is difficult as the user's manual does not provide complete instructions. The $NO_3^- -N$ option of ACTMO has not been field tested (Tanji and Gupta, 1978).

NDS

The Nitrogen Dynamics in Soil (NDS) model was developed by Hagin and Amberger (1974) to simulate the contribution of fertilizers and manures to the N and P load of ground and surface waters. NDS is the only model in existence which specifically describes the effect of an organic waste application on the N transformations of the soil system. The model includes the processes of N mineralization and immobilization, nitrification, denitrification, and plant uptake and leaching losses of $NO_3^- -N$ (Hagin and Amberger, 1974; Kruh and Segall, 1981). Applied P is assumed to remain fixed in the upper soil layer. The model assumes that the runoff losses of N and P are only associated with the sediment load. The contribution of N and P to surface waters is estimated using enrichment ratios. The erosion component of the model is comprised of four submodels which calculate the detachment by rainfall and runoff and the transport capacity of rainfall and runoff water. The equation describing these mechanisms were taken from Meyer and Wischmeier (1969).

The model documentation provides a very detailed explanation of the relationships used in the model to simulate the N transformations. Input parameters to the N component, however, are not

readily available. The model was presented to simulate Mediterranean and Central European conditions, but has not been tested.

ARM

The Agricultural Runoff Management (ARM) model simulates runoff, sediment, pesticide, and nutrient loadings to stream channels from small agricultural watersheds (Donigian and Crawford, 1976; Donigian et al., 1977; Donigian and Davis, 1978). The hydrologic component of the model is based on the Stanford Watershed Model and estimates overland flow, interflow, and groundwater flow resulting from rainfall and snowmelt. The detachment and transport of soil particles in overland flow are simulated using equations developed by Negev (1967). Application of the ARM model is limited to small watersheds as it contains no channel routing processes and assumes uniform land use and slope over the entire watershed. The model requires calibration for a particular watershed with a minimum of three years of historical data. The application of the model for use in evaluating alternative management practices may, therefore, be limited to management practices of the calibration period.

The nutrient component of ARM assumes that all transformation processes follow first order kinetics. Rate constants are corrected for temperature effects using a simplified Arrhenius equation. Nitrogen transformations include immobilization, mineralization, nitrification, denitrification, ammonium adsorption, desorption, and plant uptake. Phosphorus immobilization, mineralization, adsorption, desorption, and plant uptake processes are also described. Nutrient transport is modeled using potency factors. Information is not given relating input parameter values to measurable field characteristics, particularly those parameters required for the simulation of nutrient transformations. While the hydrologic and erosion components of ARM have been tested extensively, the chemical component requires additional testing (Tanji, 1982). Donigian et al. (1977) applied ARM to small watersheds in Georgia and Michigan and reported that the transport of sediment-

bound nutrients was adequately represented with the model, while the simulation of soluble nutrient transport was not accurately described.

ANSWERS

The Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS) Model was developed to simulate the hydrologic and erosion responses of ungaged agricultural watersheds during and immediately following a rainfall event to evaluate alternative management practices. ANSWERS is a distributed parameter, deterministic, process model. The parameters required by the model are relatively well defined. The original hydrologic model (Huggins and Monke, 1966) describes the processes of interception, infiltration, surface storage, interflow, and overland flow. Beasley (1977) expanded the model to include erosion, sediment transport, tile drainage, and channel flow. The continuity equation was used to describe surface runoff and tile flow. The infiltration element is a modified version of the Holtan and Overton equation. The erosion component was based on the work of Meyer and Wischmeier (1969). Parallel tile outlet terraces, sediment basins, grassed waterways, and field borders can also be simulated (Beasley and Huggins, 1981). The erosion component was expanded to include the transport of individual particle classes of sediment in surface runoff (Dillaha and Beasley, 1983).

Storm et al. (1986) recently incorporated a phosphorus submodel into ANSWERS to simulate the transport of soluble and sediment-bound P in runoff. A nitrogen submodel is currently being developed which will simulate mineralization, nitrification, ammonium adsorption/desorption, and runoff losses of soluble and sediment-bound N (Dillaha et al., 1988).

ANSWERS requires that the watershed be divided into a grid of small square elements. Watershed characteristics are assumed constant within each element. The greatest advantage of using ANSWERS is the spatial variability allowed by the grid representation. Critical erosion areas within

a watershed can be identified. The effectiveness of BMPs on small areas can also be evaluated. The major disadvantage of using distributed parameter models, like ANSWERS, is the large amount of input data and computational time required for simulation.

AGNPS

Young et al. (1986) introduced the Agricultural Nonpoint Source Pollution Model (AGNPS). AGNPS is a distributed parameter, event-based model which predicts runoff volumes and sediment, N, and P losses. The model is physically-based and as a result, requires little or no calibration. Input parameters are well defined and readily available through soil surveys, topographic maps, and the model documentation. AGNPS utilizes a grid system to represent the spatial variability of an agricultural watershed. Similar to ANSWERS, the greatest advantage of using AGNPS is the ability of the model to simulate the nonpoint source pollution potential of small elements within the watershed. The disadvantages include the large quantity of input data and computational time required. The model has been tested and applied principally to watersheds of less than 10,000 ha within the state of Minnesota (Young et al., 1986).

Runoff volume is calculated using the SCS curve number method. Total detached sediment is predicted for single storm events using the USLE. Empirical extraction coefficients are utilized to predict soluble N and P transport in runoff. Sediment-bound nutrient loadings are calculated using enrichment ratios. The equations used to estimate N and P losses were developed by Frere et al. (1980) in CREAMS. AGNPS, however, sets values for the extraction coefficient, enrichment ratio, and initial soil nutrient concentrations. Although setting these values aids the user in input data determination, variability in these parameters due to soil conditions and management practice is not allowed. Nitrogen transformations are not simulated.

CREAMS

Knisel (1980) presented a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS). CREAMS is a continuous, lumped parameter model which was developed to evaluate nonpoint source pollution from field-sized agricultural areas. Although CREAMS is a lumped parameter model, spatial variability is allowed along the flow profile. Lateral variability cannot be analyzed. This model simulates infiltration, soil water movement, surface runoff, and erosion during rainfall events, and evapotranspiration between rainfall events. The hydrologic component consists of two options. The first option estimates runoff using the SCS curve number method when daily rainfall data is available. When hourly or breakpoint rainfall data is available, the second option uses an infiltration-based model to simulate runoff. The erosion component uses the modified USLE to estimate detachment and includes a sediment transport capacity model for overland flow to determine if and when deposition occurs. Channel erosion and deposition and impoundment deposition are also simulated. The parameters required by the hydrologic and erosion components are well defined.

The transport of sediment-bound N and P is simulated using enrichment ratios. The amount of soluble N and P transported by surface runoff is calculated using an empirical extraction coefficient. Within the root zone, the nutrient submodel considers mineralization, denitrification, and plant uptake and leaching losses of N. Surface layer N transformations are not simulated.

Summary

Unlike P reactions, the N transformation processes are significantly affected by the application of organic wastes to the soil system. Many of the existing nutrient transport models do not adequately

describe one or more of the N transformation processes, particularly those processes altered by, or unique to, waste treatment. Many of the existing models also use input parameters which are poorly defined or hard to obtain.

The need for a nutrient transport model which simulates the impact of an organic waste application is therefore established. This model should describe the N transformation processes which occur in soil/waste systems using sound relationships. These reactions proceed continuously in the soil and should be modeled as such. Because N is transported in runoff in both soluble and sediment-bound forms, the proposed model should be incorporated into an existing comprehensive model capable of simulating the hydrologic and erosion response of an agricultural field-sized area. The model should also rely on easily obtainable input parameters. The development and verification of a model to be used as a planning tool in describing the effects of alternative management practices and fertilization methods on runoff water quality is described in the following chapters.

MODEL DEVELOPMENT

The development of CREAMS-NT, a modified version of the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Knisel, 1980), is described in this chapter. The CREAMS model was chosen for this application for several reasons. CREAMS was developed for use as a planning tool for simulating the hydrologic and erosion response of an agricultural field-sized area. It also contains a chemical component which describes the soluble and sediment-bound transport of nutrients and pesticides. CREAMS represents the physical system relatively well using easily obtained input parameters. Data from many regions of the country were used in the development and verification of CREAMS. The model is physically-based and, therefore, does not require calibration to represent the relative differences in the hydrologic and erosion response of a field as affected by the implementation of various BMP's. Because CREAMS is a continuous model, it is well suited for simulating the nitrogen transformation processes. A review of the original CREAMS model components, as well as a description of all modifications made to the original model, is presented in this chapter.

A block diagram of CREAMS-NT is shown in Figure 2. This model simulates the nitrogen transformation processes which occur in the soil following an organic waste application. The specific processes considered include mineralization, ammonium adsorption/desorption, ammonia volatilization, nitrification, denitrification, and leaching and runoff losses of $NO_3^- - N$, $NH_4^+ - N$,
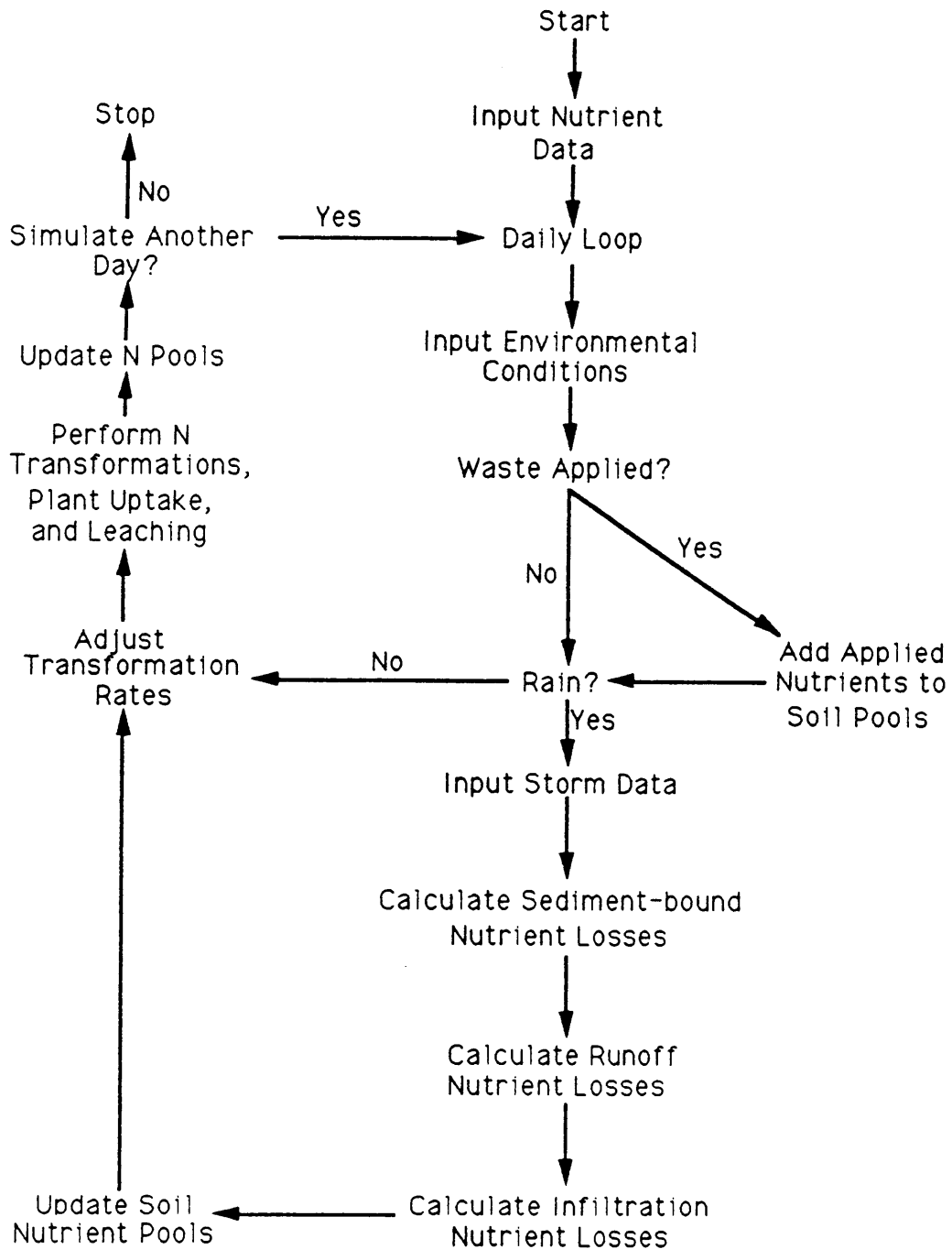
Figure 2. Block diagram of CREAMS-NT nitrogen component.

and organic N. The model is written in FORTRAN 77 and incorporated into the Washington Computer Center (WCC) version of CREAMS. To aid in cross referencing, the units of the parameters used in the equations shown in the following sections are identical to those used in the original CREAMS model.

Hydrologic Component

The hydrologic component of CREAMS consists of two options. The first option predicts runoff from daily rainfall amounts using the SCS curve number method:

$$Q = \frac{(P - 0.2\,S)^2}{P + 0.8\,S} \qquad (52)$$

where: Q = daily runoff (in)

   P = daily rainfall (in)

   S = retention parameter (in)

The retention parameter, S, is related to soil water content with the equation:

$$S = S_{mx}(\frac{UL - SM}{UL}) \qquad (53)$$

where: S_{mx} = maximum value of S (in)

   UL = upper limit of soil water storage in the root zone (in)

   SM = root zone soil water content (in)

The maximum value of S is estimated as:

$$S_{mx} = \frac{1000}{CN_I} - 10 \qquad (54)$$

where: CN_I = moisture condition I curve number

Condition I corresponds to soils having a low antecedent moisture condition and thus, low runoff potential. The root zone is divided into seven layers and weighting factors are applied which account for the soil water distribution within the root zone.

The second hydrologic option simulates runoff using an infiltration-based model. The initial saturation of the soil is defined as:

$$S_i = \frac{\Theta_i}{\Phi}$$ (55)

where: S_i = initial saturation

Θ_i = initial water content by volume (in/in)

Φ = soil porosity (in/in)

In the initial phase of infiltration, the surface saturation increases as a function of rainfall from S_i to a maximum value, S_0 (theoretically equal to 1.0), when the time of ponding, t_p, is reached. CREAMS determines the time of ponding and the shape of the subsequent infiltration curve using the Green and Ampt infiltration model (Green and Ampt, 1911):

$$K_s t = F - \Phi H_c (S_0 - S_i) \ln \left[1 + \frac{F}{\Phi H_c (S_0 - S_i)} \right]$$ (56)

where: K_s = effective saturated hydraulic conductivity

t = time from start of ponding

F = cumulative depth of infiltration

H_c = effective capillary tension, a soil parameter

Φ, S_0, and S_i are as defined previously.

The mean infiltration rate, $\bar{f}$, over a time interval, i, is calculated as:

MODEL DEVELOPMENT   61

$$\bar{f}_i = \frac{\Delta F_i}{\Delta t_i} \tag{57}$$

Runoff rate over interval i is defined as the difference between the rainfall rate and the mean infiltration rate. Total runoff for a storm is given as:

$$Q = \sum_{i=1}^{n} q_i \Delta t_i \tag{58}$$

where: Q = storm runoff (in)

q_i = runoff rate over interval i

n = number of time intervals in the storm

The CREAMS model maintains a continuous water balance in the soil, such that on any day, i:

$$SM_i = SM_{i-1} + F_i - ET_i - O_i + M_i \tag{59}$$

where: SM = Soil water storage

SM_{i-1} = Soil water storage on previous day

F = infiltration

ET = plant and soil evapotransporation

O = seepage below the root zone

M = snowmelt amount

Soil environmental conditions, such as soil moisture and temperature, have a significant impact on the nitrogen transformation processes. The original CREAMS model adjusts the root zone N transformation processes for environmental conditions using the average air temperature and soil moisture content between storms as input to the N component. Soil temperatures, however, do not directly correspond to air temperatures. Several complex physically-based soil temperature models are available in the literature (Wierenga and deWit, 1970; Hanks et al., 1971; Cruse et al.,

1980; Gupta et al., 1981; Gupta et al., 1982). These models, however, require numerous parameters which are not readily available. CREAMS-NT predicts mean monthly soil temperatures from mean monthly air temperatures using the equations presented by Toy et al. (1978):

$$T_s = 15.322 + 0.656 T_a \text{ (December − February) } r^2 = 0.919 \tag{60a}$$

$$T_s = 0.179 + 1.052 T_a \text{ (March − May) } \qquad r^2 = 0.964 \tag{60b}$$

$$T_s = 16.115 + 0.856 T_a \text{ (June − August) } \qquad r^2 = 0.863 \tag{60c}$$

$$T_s = 1.578 + 1.023 T_a \text{ (September − November) } r^2 = 0.971 \tag{60d}$$

where: T_s = mean monthly soil temperature (°F)

T_a = mean monthly air temperature (°F)

These equations were developed using data obtained over 10 years of record from several locations distributed throughout the United States. Soil, cover, and slope characteristics varied somewhat among the sites. Soil temperatures recorded at a depth of two inches were used in the regression analyses. Average daily soil temperatures are calculated using the subroutines in the original CREAMS model which determine average daily air temperatures from average monthly air temperatures using sine and cosine functions. CREAMS-NT assumes that soil temperature does not vary with depth. The error introduced with this assumption is relatively small over long term simulation. Information provided by Smith et al. (1964) and the U.S. Department of Agriculture (1975) indicate that mean annual soil temperatures do not vary significantly with depth from two inches through the root zone. A daily pass file is created by the hydrologic component and is used as input for the nitrogen component. This file contains information on soil environmental conditions including average daily soil temperature and soil moisture content, actual and potential plant transpiration, and actual and potential soil evaporation.

Additional details on the hydrologic component of CREAMS may be obtained in Smith and Williams (1980). The second hydrologic option of CREAMS, which requires breakpoint rainfall data, was utilized in this study due to the nature of the field investigations used in the verification of CREAMS-NT. All modifications of the hydrologic component, including the addition of soil temperature estimations and the creation of a file containing daily soil environmental conditions for use in the N component, were applied to both options.

Erosion Component

The CREAMS model represents a field-sized area as a combination of overland flow, channel flow, and impoundment elements. The sediment load is assumed to be limited by detachment or by transport capacity. Detachment on interrill and rill areas is described by a modified USLE:

$$D_{Li} = 0.210 \text{ EI } (s + 0.014) \text{ KCP } (\sigma_p/V_u) \tag{61}$$

and

$$D_{Fr} = 37983 m V_u \sigma_p^{\frac{1}{3}} (x/72.6)^{m-1} \text{ s}^2 \text{ KCP}(\sigma_p/V_u) \tag{62}$$

where: D_{Li} = interrill detachment rate (lb/ft²/s)

D_{Fr} = rill detachment rate (lb/ft²/s)

EI = Wischmeier's rainfall erosivity [100 (ft-ton/acre)(in/hr)]

s = sine of slope angle

K = USLE soil erodibility factor [(tons/acre)(acre/100 ft-tons)(hr/in)]

C = soil loss ratio of the USLE cover-management factor

P = USLE contouring factor

σ_p = peak runoff rate (ft/sec)

V_u = runoff volume (ft)

m = slope length exponent

x = distance downslope (ft)

Detachment for a channel element is predicted by:

$$D = K_{ch}(1.35\overline{\tau} - \tau_{cr})^{1.05} \qquad (63)$$

where: K_{ch} = Channel erodibility factor $[(lb/ft^2/s)(ft^2/lb)^{1.05}]$

$\overline{\tau}$ = average shear of the flow in the channel (lb/ft^2)

τ_{cr} = critical shear stress below which erosion is negligible (lb/ft^2)

The sediment transport capacity for each particle type, i, in a mixture is determined using Yalin's equation:

$$W_{si} = (P_e)_i (S_g)_i \rho_w g d_i V_* \qquad (64)$$

where: W_{si} = transport capacity

$(P_e)_i$ = the effective nondimensional transport

$(S_g)_i$ = particle specific gravity

ρ_w = mass density of the fluid

g = acceleration due to gravity

d_i = particle diameter

V_* = shear velocity

For each segment, the potential sediment load is determined as the sum of the sediment load from the upslope segment and that added by lateral inflow. If this load is less than the transport capacity of the flow, detachment occurs at a rate equal to the lesser of the calculated detachment or transport capacity. If the potential sediment load is greater than the transport capacity, deposition is assumed to occur and a new distribution of particle types is calculated. The transport capacity of an

impoundment is considered negligible such that only deposition is allowed to occur. The erosion component of CREAMS was not changed in this study and is described in further detail in Foster et al. (1980c).

Nitrogen Transformations in the Root Zone

This portion of CREAMS-NT is based on the nitrogen component of the original CREAMS model and maintains a continuous balance of the organic- N and $NO_3^- -N$ pools in the root zone. The processes considered are shown in Figure 3. Organic-N and $NO_3^- -N$ are added to the root zone through the incorporation of organic wastes. Soluble N is also carried to the root zone with infiltrating water and added to the N pools. The equation used to describe the transport of N from the surface layer to the root zone will be presented in the "Nitrogen Transformations in the Surface Layer" section. Diffusion, plant uptake, and leaching losses of $NO_3^- -N$ are simulated. The equations used in CREAMS-NT to simulate these processes were taken from the original CREAMS model with only three modifications. The soil temperature estimates described in Equations 60a-d were incorporated into the transformation equations in place of air temperature values. The time step used in all calculations was decreased to one day to allow for a daily accounting of the root zone N pools. The original CREAMS model only simulates the root zone processes prior to each rainfall event. In addition, the original CREAMS model requires that the root zone potentially mineralizable N content be input to the model. CREAMS-NT calculates this value as a function of soil TKN content. To aid in cross referencing between the text and program listing, the variable names and units of the equations presented in the following sections are identical to those used in the program.
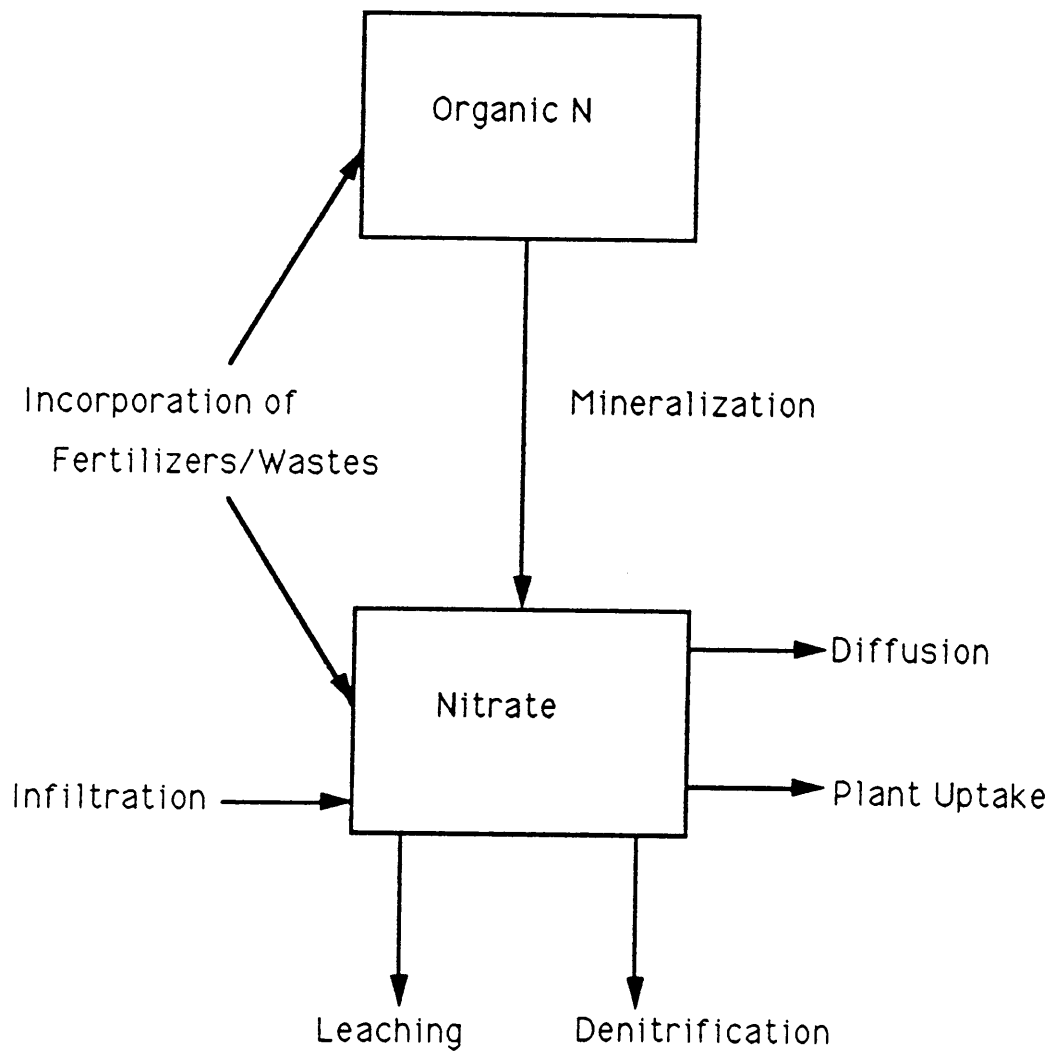
Figure 3.   Simulated nitrogen transformations in the root zone.

Mineralization

The mineralization process is simulated using a first-order rate equation (Equation 2). Equation 2 can be rearranged and integrated to yield:

$$MN = RPMN * WK * (1 - e^{(-TK * \Delta t)}) \qquad (65)$$

where: MN   = Mineralized N in the root zone (kg/ha)

RPMN = potentially mineralizable N in the root zone (kg/ha)

WK   = water content coefficient

TK   = first-order rate constant (1/day)

Δt = time interval (= 1 day)

The model calculates the water content coefficient using:

$$WK = ARSW/FC \qquad (66)$$

where: ARSW = average root zone volumetric water content (mm^3/mm^3)

FC = field capacity (mm^3/mm^3)

The first-order rate constant is calculated as a function of soil temperature (Stanford et al., 1973) such that:

$$TK = e^{(15.807 - 6350/TA)} \qquad (67)$$

where: TA = soil temperature (°K)

Denitrification

The denitrification component also utilizes a first-order rate equation:

$$DNI = RNO_3*(1 - e^{(-DKT*\Delta t)}) \tag{68}$$

where: DNI = amount of denitrification in the root zone (kg/ha)

   RNO_3 = nitrate in the root zone (kg/ha)

   DKT = first-order rate constant (1/day)

   Δt = time interval ($= 0.5$ or 1 day)

Denitrification is assumed to occur when the moisture content of the root zone exceeds field capacity. The time interval used is dependent on the length of the drainage period. The first-order rate constant, DKT, is a function of the total organic soil carbon content and temperature and is determined from equations (47) and (48).

Diffusion

A fraction of the $NO_3^- - N$ in the root zone is transported to the surface layer with evaporating water. CREAMS simulates the diffusion of $NO_3^- - N$ using:

$$EVAPN = (RNO_3*DASEV)/(ARSW*RZMAX) \tag{69}$$

where: EVAPN = $NO_3^- - N$ diffusion (kg/ha)

   DASEV = Amount of soil evaporation (mm)

   RZMAX = Root zone depth (mm)

   RNO_3 and ARSW are as defined in equations (68) and (66), respectively.

Leaching

Nitrate can be leached below the root zone with percolating water. CREAMS estimates the fraction of water leached, assuming complete mixing, with:

$$FL = DPERC/(DPERC + RZC) \qquad (70)$$

where: FL = fraction leached

$DPERC$ = daily percolation (mm)

RZC = water remaining in the root zone (mm)

The amount of daily percolation ($DPERC$) is obtained from the hydrologic component of the model. The amount of water remaining in the root zone after percolation (RZC) is calculated as the product of the field capacity and the root zone depth. The amount of $NO_3^- - N$ leached (NL) in kg/ha is calculated as:

$$NL = FL * RNO_3 \qquad (71)$$

Plant Uptake

Crop growth removes a significant quantity of $NO_3^- - N$ from the root zone. CREAMS provides two options for estimating plant uptake of N. The first option simulates plant growth as a function of water use and N uptake as a function of plant N content. Accumulated dry matter production is calculated using the equation:

$$DM_i = \frac{\Sigma WU_i}{PWU} (YP)(K) \qquad (72)$$

where: DM_i = accumulated dry matter production on day i

WU_i = daily plant water use for the growing season

PWU = total plant water use for the growing season

YP = crop yield potential

K = ratio of dry matter to crop yield at maturity.

The N concentration in plants is determined as:

$$c_i = \text{minimum}[b_i(\frac{DM_i}{TDM})^{b_2}, b_3(\frac{DM_i}{TDM})^{b_4}] \tag{73}$$

where: c_i = N concentration in the plant on day i

TDM = total dry matter production for the growing season

b_1, b_2, b_3, b_4 = crop parameters

The accumulated N uptake in any day, i, is estimated as the product of the N concentration (c_i) and the dry matter production (DM_i) .

When the concentration parameters required by Equation 73 are not available, the second option can be used. This option assumes that the potential N uptake follows a normal probability curve. The actual N uptake is then determined as:

$$UN = (PUN - PPUN)(PU)(TR) \tag{74}$$

where: UN = amount of N taken up on day i

PUN = fraction of the potential annual plant N taken up by day i

PPUN = fraction of the potential N taken up through the previous day

PU = potential annual N uptake for the crop (kg/ha)

TR = ratio of actual to potential transpiration for day i

Nitrogen Transformation in the Surface Layer

The surface layer N transformation and transport processes simulated in CREAMS-NT are shown in Figure 4. The original CREAMS model does not consider any N transformation processes in the surface soil layer. These transformation processes dictate the amount of the various N forms carried in surface runoff. Three N pools, organic-N, $NH_4^+ - N$, and $NO_3^- - N$ are maintained in CREAMS-NT. Nitrogen is added to these pools through the application of fertilizers and organic wastes. Nitrogen is lost from the soil/waste system through volatilization and denitrification and carried in runoff and infiltrating water.

Mineralization

Only a fraction of the organic N in the soil is susceptible to mineralization. Stanford and Smith (1972) determined the mineralization potential of several soil series. Based on the data presented by Stanford and Smith (1972), Reddy et al. (1979a) developed a regression equation for predicting the potentially mineralizable N present in the soil as a function of TKN (equivalent to the sum of organic-N and $NH_4^+ - N$):

$$SPMN = -591 + 112 \ \ln(ORGN + NH4T) \tag{75}$$

where: SPMN = soil potentially mineralizable N (mg/kg soil)

   ORGN = soil organic N (mg/kg soil)

   NH4T = soil $NH_4^+ - N$ (mg/kg soil)

This relationship is used in CREAMS-NT to determine the potentially mineralizable N in both the surface layer and the root zone.
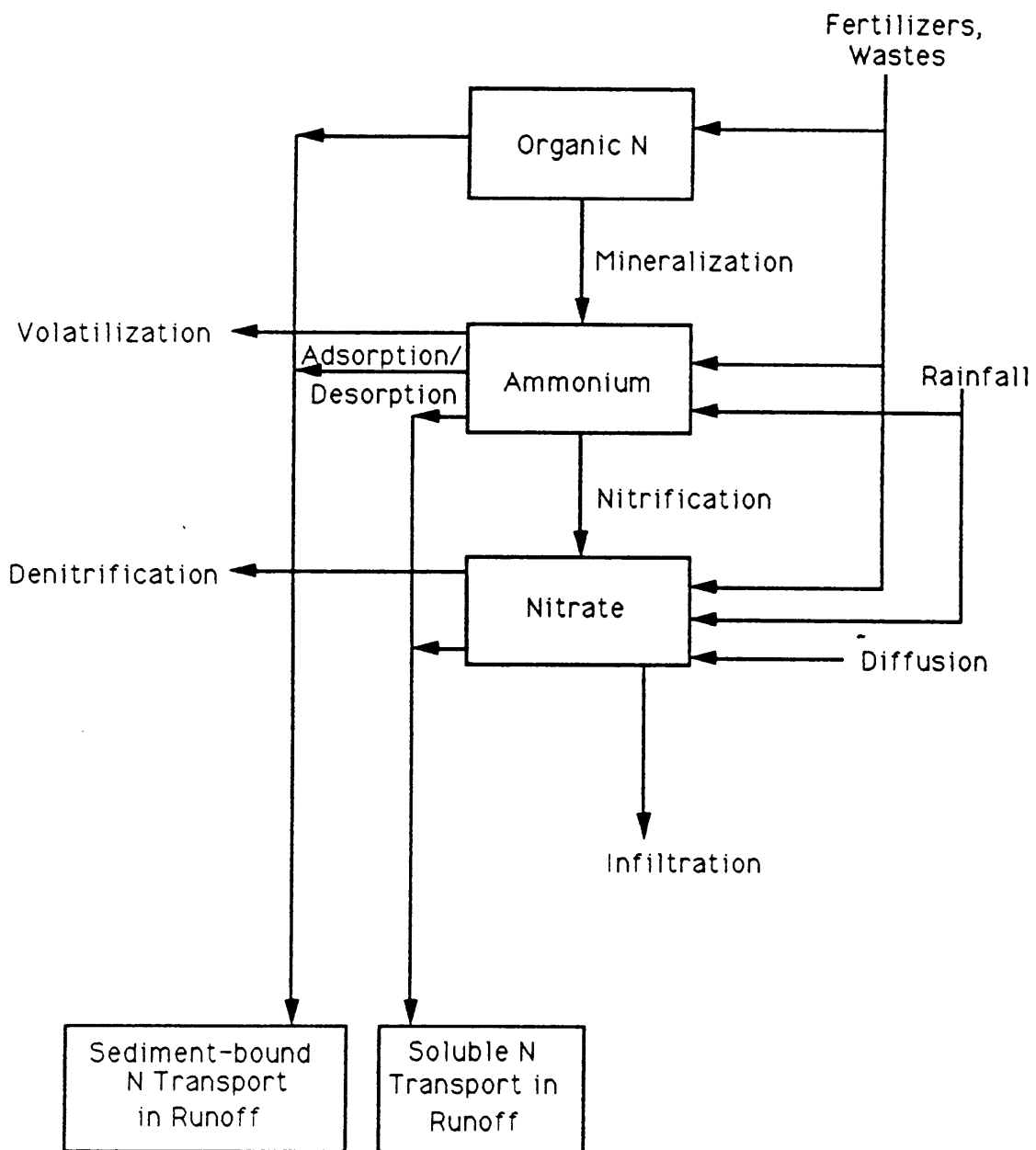
Figure 4. Simulated nitrogen transformations in the surface layer by CREAMS-NT.

The mineralization potential of the soil system is altered by the application of an organic waste. The amount of waste N available to mineralization is dependent on the C:N ratio of the waste (Reddy et al., 1979a), such that:

$$FPMN = FN - \frac{FN*FCNR}{23} \qquad (76)$$

where: FPMN = organic waste potentially mineralizable N (kg/ha)

FN = N content of the applied waste (kg/ha)

FCNR = C : N ratio of the waste

The waste organic N not available to mineralization (as well as the $NH_4^+ - N$ added with the waste) is added to the soil N pools and a new value of SPMN is calculated using Equation 75. The total potentially mineralizable N of the soil/waste system is then the sum of the waste potentially mineralizable N (FPMN) and the soil potentially mineralizable N (SPMN). The model assumes that no immobilization of organic N occurs. This assumption is valid if the applied waste has a C:N ratio of less than 23. The C:N ratio of sewage sludges and animal wastes typically range from 3 to 20 (Sommers, 1977; Reddy et al., 1979a; Parker and Sommers, 1983).

A first-order rate equation (Equation 2) is used to describe the mineralization process. The mineralization rate constant for the native soil is calculated using Equation 67. A composite mineralization rate constant, which applies to the soil/waste system, is used following each organic waste application. The model allows for up to 20 fertilizer or waste applications per simulation. Reddy et al. (1979a) presented composite rate constants for soils treated with beef, swine, and poultry wastes. The reported data for the various sludge types are given in Table 1.

The mineralization rate constant is adjusted for environmental conditions in CREAMS-NT, using Equation 12. Values for the moisture, pH, and method of application factors are determined using the empirical relationships developed by Reddy et al. (1979a). The soil moisture factor is calculated as a function of moisture tension such that:

Table 1. First-order mineralization rate constants for soils treated with sewage sludges.

Sludge	$K(day^{-1})$	Temp(°C)	Source	Reference [*]
Aerobically Digested	.0208	30	Domestic-Source L'Estartit,Costa Brava, Spain	1
	.0590	23	Medina, OH	4
Anaerobically Digested	.0197	30	Domestic-Industrial Source Palencia, Spain	1
	.0245	21		2
	.0220	35	Albuquerque,NM	3
	.0300	23	Average from 8 locations	4
Anaerobically digested + CaCO$_3$	.0126	23	Marion, IN	4
Anaerobically digested + FeCl$_3$	.0491	23	Average from Baltimore, MD and Chicago, IL	4
Anaerobically digested Imhoff Tank	.0306	23	Chicago, IL	4
Composed Raw Sludge + CaO + FeCl$_3$	.0231	23	Blue Plains, D.C.	4
Composted Anaerobically digested + FeCl$_3$	.0166	23	Baltimore, MD	4
Composted Anaerobically digested + Polymer	.0204	23	Los Angeles, CA	4
Primary	.0146	23	Grand Haven, MI	4
Primary + Waste Activated	.0541	23	Seattle, WA	4
Raw + CaO + FeCl$_3$	.0151	23	Blue Plain, D.C.	4
Raw, Wet-air oxidized	.0207	23	Grand Rapid, MI	4
Waste Activated	.0265	21		2
	.0979	23	Seattle, WA	4
Waste Activated + FeCl$_3$	.0609	23	Chicago, IL	4

*   (1) Garau et al., 1986
      (2) Hsieh et al., 1981
      (3) Lindemann and Cardenas, 1984
      (4) Parker and Sommers, 1983

$$F_m = 1.51 + 0.453 \; \ln MT; \quad 0.07 \leq MT \leq 0.33 \qquad (77a)$$

$$F_m = 1.00 \qquad\qquad ; \quad 0.33 \leq MT \leq 0.85 \qquad (77b)$$

$$F_m = 0.97 - 0.118 \; \ln MT; \quad 0.85 \leq MT \leq 10.0 \qquad (77c)$$

where: $\quad F_m =$ moisture factor

$\qquad\qquad$ MT $=$ moisture tension (bars)

The hydrologic component of CREAMS-NT predicts the volumetric moisture content of the soil for each day of simulation. For use in Equation 77, the moisture tension can be calculated as a function of volumetric moisture content (Brady, 1974; Kenimer, 1987) using the equation:

$$\log MT = MTSL*ASSW + MTINT \qquad (78)$$

where: $\quad$ ASSW $=$ daily average surface layer volumetric water content

$\qquad$ MTSL, MTINT $=$ regression coefficients

The regression coefficients (MTSL and MTINT) are determined by the model from input data describing the soil moisture content at field capacity and wilting point moisture conditions. The equations used to quantify the effect of pH on mineralization is:

$$F_{pH} = 0.19 \; pH - 0.173 \; ; 4.0 \leq pH \leq 6.2 \qquad (79a)$$

$$F_{pH} = 1.00 \qquad\qquad ; \quad 6.2 \leq pH \leq 9.0 \qquad (79b)$$

$$F_{pH} = 3.25 - 0.25 \; pH \; ; 9.0 \leq pH \leq 10.0 \qquad (79c)$$

where: $\quad F_{pH} =$ soil system pH factor

$\qquad\qquad$ pH $=$ pH of the soil/waste system

Based on the work of King (1973) the method of application factor, f_{mA}, used in Equation 12 is set equal to 1.0 if the sludge is incorporated or 0.53 if the sludge is surface applied. Stanford et al. (1973) reported a temperature correction coefficient, Θ, of 1.07 for the mineralization process.

Nitrification

The nitrification process is simulated using a single first-order rate equation (Equation 27). Rate constants can be calculated using:

$$K = \frac{0.693}{t_{1/2}} \qquad (80)$$

where: $t_{1/2}=$ half-life of $NH_4^+ - N$ (days)

Nitrification rates vary with soil type and waste source. Much literature is available which provides information concerning nitrification rates for the various soil types. Rate constants were calculated using Equation 80 for some representative soil and soil/sludge systems and are shown in Table 2.

The effects of soil moisture, pH, and temperature are simulated using:

$$K_{NIT} = K_{NITI}*FM_{NIT}*FPH_{NIT}*FMA_{NIT}*\Theta_{NIT}^{(ADST-TNIT)} \qquad (81)$$

where: $K_{NIT}=$ first-order rate constant corrected for environmental conditions

         $K_{NITI}=$ first-order rate constant for a given temperature

       $FM_{NIT}=$ moisture factor

       $FPH_{NIT}=$ pH factor

       $FMA_{NIT}=$ method of application factor

Table 2. First-order nitrification rate constants for some soil and soil/sludge systems.

Soil	K(day^{-1})	Temp (°C)	Remarks	Reference*
Milville loam	0.143	22	150 ppm N as $(NH_4)_2 SO_4$ Added	2
Salinas clay	0.220	24	50 ppm N as $(NH_4)_2SO_4$ Added	1
Maury silt loam	0.058	23	84 kg/ha NH_4NO_3 added Conventional tillage	6
	0.108	23	84 kg/ha NH_4NO_3 added No-till	6
Plano silt loam	0.112	23	100 ppm N as $(NH_4)_2SO_4$ added	3
Chalmers silty clay loam	0.162	21	Control Soil	5
	0.402	21	22.4 MT/ha of Anaerobically digested sewage sludge added	5
Fincastle silt loam	0.088	21	Control soil	5
	0.561	21	22.4 MT/ha of Anaerobically digested sewage sludge added	5
Freehold sandy loam	0.472	21	Activated sludge added (Average of 4 rates)	4
	0.571	21	Anaerobically digested sludge added (Average of 4 rates)	4

*   (1) Broadbent et al.,1957

       (2) Justice and Smith, 1962

       (3) Dancer et al., 1973

       (4) Hsieh et al., 1981

       (5) Terry et al., 1981

       (6) Rice and Smith, 1983

Θ_{NIT} = temperature correction coefficient

ADST = average daily soil temperature (°C)

TNIT = temperature corresponding to K_{NITI}

The moisture factor is calculated using the empirical relationship proposed by Reddy et al. (1979a) from literature data, such that:

$$FM_{NIT} = 0.599 - 0.173 \ln MT ; \quad 0.1 \leq MT \leq 15.0 \tag{82}$$

where: MT = moisture tension (bars)

Similarly, the influence of soil pH on nitrification (Reddy et al., 1979a) is estimated using:

$$FPH_{NIT} = 0.307 \text{ pH} - 1.269 ; \quad 4.5 \leq \text{pH} \leq 7.0 \tag{83a}$$

$$FPH_{NIT} = 1.00 \qquad\qquad ; \quad 7.0 \leq \text{pH} \leq 7.4 \tag{83b}$$

$$FPH_{NIT} = 5.367 - 0.599 \text{ pH} ; \quad 7.4 \leq \text{pH} \leq 9.0 \tag{83c}$$

The method of application factor, FMA_{NIT}, is set equal to 1.0 if the waste is incorporated or 0.53 if it is surface-applied (King, 1973). A temperature correction coefficient, Θ_{NIT}, of 1.06 is used for the nitrification process. This value is an average of those reported by Gerretsen (1942), Frederick (1956), Sabey et al. (1969), and Endelman et al. (1974).

Ammonia Volatilization

A first order rate equation, similar to (Equation 2), is used to simulate the $NH_3 - N$ volatilization process. The rate constant is initially set equal to zero, as this process is assumed negligible when no wastes are applied (King and Morris, 1974; Hoff et al., 1981). Rate constants for several animal

waste/soil systems are presented by Reddy et al. (1979b). Table 3 summarizes the available data describing volatilization rates for sludge/soil systems. These rates are assumed applicable for a period of seven days following a waste application (King and Morris, 1974; Ryan and Keeney, 1975; Beauchamp et al., 1978; Terry et al., 1978; Reddy et al., 1979b). Volatilization rate constants are adjusted for temperature, soil CEC, and wind velocity using equations (41), (42), and (43), respectively. Equation 43 essentially only alters the volatilization rate constant at wind velocities below detection limits. Although the equation used to quantify the effects of wind velocity should be applicable to a wider range of velocities, the data currently available which describes this phenomenon was obtained from experiments designed to test only extremely low velocities (Fritschen et al., 1970; Terry et al., 1978). A temperature correction coefficient of 1.05 is used in Equation 44 (Fenn and Kissel, 1974; Srinath and Loehr, 1974).

Denitrification

The denitrification process is also assumed to follow a first-order kinetic equation (Equation 2). The denitrification rate constant is determined from Equation 48. The impact of organic waste applications is taken into account since this equation calculates the rate constant as a function of soil carbon content. The rate constant is adjusted for effects of soil temperature and pH:

$$K_{DNI} = K_{DNII} * FPH_{DNI} * \Theta_{DNI}^{(ADST-TDNI)} \tag{84}$$

where: K_{DNI} = first-order rate constant corrected for environmental conditions.

K_{DNII} = first-order rate constant for a given temperature

FPH_{DNI} = pH factor

Θ_{DNI} = temperature correction coefficient

$ADST$ = average daily soil temperature (°C)

$TDNI$ = temperature corresponding to K_{DNII} (= 35°C)

Table 3. First-order volatilization rate constants for some soil/sludge systems.

Sludge	K(day^{-1})	Temp(°C)	Source	Reference [*]
Anaerobically digested from Janesville, WI	0.20	21	Lab study. Sludge surface-applied to quartz sand.	1
Anaerobically digested from Kitchener, Ontario	0.193	7-20	Field study. Sludge surface-applied to soil in May. 150 kg NH_4^+-N/ha.	2
Anaerobically digested from Guelph, Ontario	0.117	4-20	Field study. Sludge surface-applied to soil in October. 89 kg NH_4^+-N/ha.	2
Anaerobically digested from Lafayette and Muncie, IN	0.29	21	Lab study. Sludge surface-applied to Tracy sandy loam. 22.4 MT/ha sludge.	3
Liquid Anaerobically digested	0.58	29-44	Lab study. Sludge surface-applied to Cecil sandy clay loam.	4

[*] (1) Ryan and Keeney, 1975
(2) Beauchamp et al., 1978
(3) Terry et al., 1978
(4) King and Morris, 1974

From the figures presented by Hagin and Amberger (1974), the following relationship was used to quantify the effect of pH on the denitrification rate:

$$FPH_{DNI} = -0.527 + 0.129 \, (pH) \quad ; 4.1 \leq pH \leq 4.8 \tag{85a}$$

$$FPH_{DNI} = -3.942 + 0.84 \; (pH) \quad ; 4.8 \leq pH \leq 5.8 \tag{85b}$$

$$FPH_{DNI} = \;\; 0.745 + 0.032 \, (pH) \quad ; 5.8 \leq pH \leq 8.0 \tag{85c}$$

$$FPH_{DNI} = \quad\; 7.0 - 0.75 \; (pH) \quad ; 8.0 \leq pH \leq 9.2 \tag{85d}$$

$$FPH_{DNI} = \quad 1.414 - 0.143 \, (pH) \quad ; 9.2 \leq pH \leq 9.9 \tag{85e}$$

where: pH = pH of the soil/waste system

A value of 1.08 was used for the temperature correction coefficient (Stanford et al., 1975b). The denitrification process is assumed to occur only on days when the soil moisture content exceeds field capacity. If this condition is not met, the rate constant is set equal to zero.

The equations describing the mineralization, nitrification, ammonia volatilization, and denitrification processes were coupled to provide the rate of change in concentration of the various N species. The coupled differential equations are presented in Table 4. The exact solution of this system was obtained and is shown in Appendix A. The use of these equations allows for simultaneous computation of the N transformation processes. In CREAMS-NT, all calculations are made using a daily time step such that Δt is equal to one day in the transformation equations (Appendix A).

Table 4. Coupled differential equations governing the nitrogen transformation processes

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Organic N:

$$\frac{d(Org - N)}{dt} = -K_{min}(Org - N)$$

Ammonium N:

$$\frac{d(NH_4)}{dt} = K_{min}(Org - N) - K_{NIT}(NH_4) - K_{VOL}(NH_4)$$

Nitrate N:

$$\frac{d(NO_3)}{dt} = K_{NIT}(NH_4) - K_{DNI}(NO_3)$$

Ammonia N:

$$\frac{d(NH_3)}{dt} = K_{VOL}(NH_4)$$

Nitrous Oxide:

$$\frac{d(N_2O, N_2)}{dt} = K_{DNI}(NO_3)$$

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*For detailed information on the exact solution of these equations, refer to Appendix A.

Ammonium Adsorption/Desorption

When a runoff event occurs, the $NH_4^+ - N$ is partitioned between the adsorbed and desorbed phases allowing for the simulation of subsequent transport processes. This phenomenon is not calculated on a daily basis as both $NH_4^+ - N$ forms are available to the various transformation processes. This process is often modeled as a reversible first-order kinetic equation such that:

$$\frac{d(NH_4)_{ads}}{dt} = K_{ads}(NH_4)_{des} \tag{86}$$

and

$$\frac{d(NH_4)_{des}}{dt} = K_{des}(NH_4)_{ads} \tag{87}$$

where: K_{ads} = first-order adsorption rate constant

K_{des} = first-order desorption rate constant

CREAMS-NT assumes that chemical equilibrium has been reached instantaneously in the soil system. This equilibrium condition is represented by Equation 36. The equilibrium constant (K), or the ratio of concentrations, is equal to the ratio of the rate constants of the forward and reverse reactions:

$$K = \frac{K_{ads}}{K_{des}} \tag{88}$$

Relatively little information is available which provides adsorption and desorption rate constants for various soil types. The model allows the user to select these values, if known. The rate constants, however, can be approximated using a value of 1.0 for the adsorption process and 0.2 for the desorption process (Mehran and Tanji, 1974; Donigian et al., 1977; Hsieh et al., 1981; Dillaha et al., 1988). The effect of temperature on the adsorption/desorption processes is not simulated in

CREAMS-NT as previous investigators have concluded that changes in temperature affect the opposing rate constants by the same magnitude (Donigian and Crawford, 1976; Donigian et al., 1977).

Sediment-bound Nitrogen Transport

The equations used in the original CREAMS model to simulate the sediment-bound and soluble transport of N were incorporated into this version. In CREAMS-NT, however, separate equations are provided for each N species such that the quantity of each N form transported can be estimated. The form of N entering surface waters is very important due to the differences in availability of the different forms. The sediment-bound transport of organic N and adsorbed $NH_4^+ -N$ in runoff is estimated using enrichment ratios:

$$SEDN = SOILN*SED*ERN \qquad (89)$$

where: $SEDN$ = N load (Org-N or $NH_4^+ -N$) associated with the sediment (kg/ha)

$SOILN$ = N concentration (Org-N or $NH_4^+ -N$) in the soil/waste system (kg N/kg soil)

SED = Sediment yield (kg/ha) from the erosion component

ERN = Enrichment ratio for N (Org-N or $NH_4^+ -N$)

The enrichment ratio is calculated as:

$$ERN = A*SED^B \qquad (90)$$

The relationship was determined from an analysis of the available data (Frere et al., 1980). Although the coefficients A and B are dependent on soil type, crop, and management practice, Frere et al. (1980) suggested a value of 7.4 for A and -0.2 for B. Using these values, the enrichment ratio for both N and P can be predicted within a factor of two for an average annual and a factor of five for individual storm events (Frere et al., 1980). These constants, however, are more accurately determined for a specific soil and management practice using experimental data (Menzel, 1980).

Menzel (1980) presented enrichment ratio data from several different soil types, cropping conditions and climatic areas, but concluded that not enough information was available to quantify the effects of these conditions on enrichment ratios. Much research is currently underway which may assist in defining these relationships (Menzel, 1980).

Soluble N Transport

CREAMS-NT considers the transport of $NO_3^- - N$ and desorbed $NH_4^+ - N$ in runoff and in infiltrating water. The amount of $NO_3^- - N$ in runoff is calculated as:

$$RONO_3 = \frac{[(CZRNO_3 - CHKNO_3) * e^{(-XKFN1*EFI)}]}{COEFF}$$

$$- \frac{[(CZRNO_3 - CHKNO_3) * e^{(-XKFN1*EFI - XKFNO_3*RUNOFF)}]}{COEFF} \quad (91)$$

$$+ (0.3 * RN * \frac{RUNOFF}{EFRAIN})$$

where: $RONO_3$ = $NO_3^- - N$ load in runoff (kg/ha)

$CZRNO_3$ = Available $NO_3^- - N$ content in the soil surface (kg/ha)

$CHKNO_3$ = Available $NO_3^- - N$ due to rainfall (kg/ha)

$XKFN1$ = Rate constant for downward movement of NO_3 into the soil

$XKFNO_3$ = Rate constant for $NO_3^- - N$ movement into runoff

$COEFF$ = Porosity factor = 0.00001/Porosity

$EFRAIN$ = Rainfall available for movement (mm) = Rainfall - Porosity

EFI = Rainfall available for downward movement (mm)

$RUNOFF$ = Total runoff (mm)

RN = N content of rainfall (kg/ha)

0.3 = $NO_3^- - N$ fraction of the total N content of rainfall

The downward movement of $NO_3^- - N$ ($DWNO_3$) is estimated by:

$$DWNO_3 = \frac{[(CZRNO_3 - CHKNO_3) * (1 - e^{(-XKFN1*EFI)})]}{COEFF}$$

$$+ (0.3 * RN * \frac{EFI}{EFRAIN}) \tag{92}$$

The amount of NO_3^--N remaining in the soil surface (SNO_3) following a rainfall event is then:

$$SNO_3 = \frac{[CHKNO_3 + (CZRNO_3 - CHKNO_3) * e^{(-XKFN1*EFI - XKFNO_3*RUNOFF)}]}{COEFF} \tag{93}$$

The available soil $NO_3^- - N$ content ($CZRNO_3$) used in Equations (91-93) is determined from the relationship:

$$CZRNO_3 = SNO_3 * COEFF \tag{94}$$

In this equation, SNO_3 represents the $NO_3^- - N$ content in the surface one centimeter of soil prior to the rainfall event and is determined previously in this subroutine as a function of fertilizer application and transformation processes. The available NO_3^--N in the rainfall is estimated by:

$$CHKNO_3 = RCN * 0.30 * 0.000001 \tag{95}$$

where: RCN = N concentration in rainfall (mg/l)

0.000001 = Conversion factor

and CHKNO3 and 0.30 as defined in Equation 91

CREAMS suggests a value of 1.0 mg/l for the N concentration in rainfall. Although the concentration varies with rainfall event and location, this estimate is reasonable (Frere et al., 1980). It should also be noted that in most agronomic applications, this N contribution can be considered

negligible. Nitrate and NH_4^+-N are the principle N forms contributed by rainfall. CREAMS-NT assumes that 30 percent of the rainfall N is in the $NO_3^- -N$ form, while the remaining 70 percent is soluble $NH_4^+ -N$ (Brady, 1974).

The rate constant for the movement of $NO_3^- -N$ into runoff ($XKFNO_3$) is calculated using the relationship:

$$XKFNO_3 = \frac{EXKNO_3}{TOTPOR} \tag{96}$$

where: $EXKNO_3$ = Extraction coefficient for movement of NO_3^--N into runoff

TOTPOR = soil porosity

A similar equation is used to determine the value of the rate constant for the downward movement of $NO_3^- -N$ ($XKFN1$). The extraction coefficient for downward movement is assumed to equal 0.25 (Frere et al., 1980). The extraction coefficient for movement into runoff is user specified. The only constraint on this parameter is that it should be set at some value less than or equal to 0.25. This coefficient is best determined using experimental data. When data is not available, Frere et al. (1980) suggested using a value in the range of 0.05 to 0.10. A similar set of equations (Equations 91-96) is used to describe the transport of desorbed $NH_4^+ -N$. Additional details on the derivation of these equations may be obtained in Frere et al. (1980).

A complete list of the variables used and the program listing of the N component are given in Appendices B and C, respectively. Model output includes the yield of the various N components in runoff and the amount of $NO_3^- -N$ leached below the root zone. The user can select the desired level of detail for the output. The options include an annual summary for each year of simulation, monthly and annual summaries, and individual storm summaries describing the quantity of each nutrient form carried in runoff. A daily accounting of the organic-N, $NH_4^+ -N$, and $NO_3^- -N$ soil pools is also available.

FIELD INVESTIGATIONS OF NUTRIENT MOVEMENT

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 in surface runoff 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.

Plot Design and Location

Sixteen experimental field plots, located at Virginia Tech's Price's Fork Agricultural Research Farm, 10 km west of Blacksburg, Virginia, 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 5.

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 are 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 a FW-1 stage recorder for flow measurements.

Plot Preparation

All plots were planted in winter rye in the fall of 1986. In the 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

Table 5. 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

Surface 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

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 also shown in Table 5.

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 6. 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.

Rainfall Simulator

The Department of Agricultural Engineering's rainfall simulator (Shanholtz et al., 1981; and Dillaha et al., 1987b) 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

Table 6. Analysis of the anaerobically digested, polymer conditioned sludge applied to the experimental plots.

solids (%)	16.0
pH	7.3
$NH_4^+ - N$(%)	0.96
TKN (%)	3.02
phosphorus (%)	2.0
potassium (%)	0.07
sulfur (%)	2.80
calcium (%)	3.20
magnesium (%)	0.32
sodium (%)	0.04
chloride (%)	0.46
copper ($mgkg^{-1}$)	660
zinc ($mgkg^{-1}$)	1800
cadmium ($mgkg^{-1}$)	7.0
chromium ($mgkg^{-1}$)	65
nickel ($mgkg^{-1}$)	35
lead ($mgkg^{-1}$)	60
molybdenum ($mgkg^{-1}$)	20
boron ($mgkg^{-1}$)	30

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 rain gages within each plot. The rain gages 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 7. 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.

Sampling Procedure

Runoff water samples for nutrients analyses were collected manually from the plots discharge at 3-minute intervals throughout the runoff process, using plastic bottles. 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.

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 , $PO_4^- - P$, $NH_4^+ - N$, $NO_3^- - N$, TKN, filtered total phosphorus (P_{TF}) and filtered total Kjeldahl nitrogen (TKN_F). Total N (N_T) was calculated as the sum of TKN and NO_3^- -N concentrations or yields. Sediment-bound P (P_{sb}) was calculated as the difference between P_T and

Table 7. Rainfall simulator data.

PLOT

Run	QF 1 Rainfall (mm)	U.C. %*	QF 2 Rainfall (mm)	U.C. %	QF 3 Rainfall (mm)	U.C. %	Mean QF1-QF3 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

Run	QF 4 Rainfall (mm)	U.C. %	QF 5 Rainfall (mm)	U.C. %	QF 6 Rainfall (mm)	U.C. %	Mean QF4-QF6 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

Run	QF A Rainfall (mm)	U.C. %	QF B Rainfall (mm)	U.C. %	QF C Rainfall (mm)	U.C. %	Mean QFA-QFC 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

Run	QF D Rainfall (mm)	U.C. %	QF E Rainfall (mm)	U.C. %	QF F Rainfall (mm)	U.C. %	Mean QFD-QFF 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

Run	QF K Rainfall (mm)	U.C. %	QF L Rainfall (mm)	U.C. %	QF M Rainfall (mm)	U.C. %	QF N Rainfall (mm)	U.C. %	Mean QFK-QFN 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

P_{TF}. Nitrogen, P, and sediment yields were determined from the concentrations of each sample and 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. The collected water quality data is presented in Appendix F.

Analytical Techniques

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 pre-weighed 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 re-weighed on an analytical balance. The change in dry weight divided by the sample volume was then determined and expressed in mg/L.

Total Kjeldahl 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 two and one-half hours in the presence of sulfuric acid (H_2SO_4), potassium sulfate (K_2SO_4), and mercuric sulfate ($HgSO_4$). 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.

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.

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 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).

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 two and one-half hours in the presence of H_2SO_4, K_2SO_4 and $HgSO_4$. The resulting residue was cooled and diluted to 50 ml. Concentrations of P_T were measured with an autoanalyzer.

Orthophosphorus

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

Statistical Analyses

The experimental set-up can be described as an incomplete randomized block design. Due to the nature of the experiment, interactions between tillage practice, application method, and sludge loading rate were not analyzed. Statistical analyses were performed on the least square means obtained using SAS (SAS Inst., Inc., 1985). The least square means are unbiased estimates of the mean for each treatment effect, taking into account the impact of the remaining treatment variables. In other words, the use of the least square means accounts for the incomplete nature of the design, or the fact that all treatments were not paralleled. The effects of tillage system and sludge application method were analyzed using the two-sided t-test (Neter et al., 1985). The results of these analyses at the 0.05 and 0.10 significance level are presented in the following tables. The Bonferroni multiple comparison test (Neter et al., 1985) was applied at the 0.05 significance level to analyze the effects of sludge application rate. It should be noted that for a two-way comparison the results of the Bonferroni multiple comparison test are identical to those of the two-sided t-test. For the comparison of three or more means, however, the Bonferroni multiple comparison test is more conservative than the t-test. The results of these analyses are described in the results and discussion section of this chapter.

Results and Discussion

Runoff and Sediment Losses

Effects of Tillage System

Sediment and runoff losses, sediment concentrations, and peak runoff rates, averaged across the tillage treatments, for runs R1, R2, and R3 are given in Table 8. Total sediment and runoff losses from conventional tillage plots averaged 1891 kg/ha and 3.32 cm, respectively. Sediment and runoff from the no-till plots were 73 and 54 percent less, respectively, than those of the conventional tillage plots. Compared to the no-till treatments, the conventional tillage produced an average sediment concentration 2.5 times greater and an average peak runoff rate 2.1 times greater. The conventional-tillage plots produced significantly higher sediment losses, sediment concentrations, and runoff rates than did the no-till plots (Table 8).

The lower runoff rate and volume from the no-till treatments may be attributed to increased surface detention, 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 reduced surface sealing by protecting the soil surface from raindrop impact and slowed 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 large soil loss from these plots is the result of high runoff volumes and sediment detachment rates.

Table 8. 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. Conc. * (mg/L)	Peak Runoff * (cm/hr)
No-till	R1	155.7	0.32	1877.5*	0.8*
	R2	114.6	0.35	1840.3†	1.4†
	R3	234.5	0.85	2137.9#	2.2#
	TOTAL	504.8*	1.52	---	---
Conv.	R1	379.4	0.72	4255.3*	2.2*
	R2	458.4	0.93	4183.1†	3.2†
	R3	1053.7	1.67	6018.3#	3.9#
	TOTAL	1891.5*	3.32	---	---

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.

Effects of Sludge Application Method

The rate and volume of runoff from the sludge amended conventional tillage plots were relatively unaffected by sludge application method (Table 9). Surface application of sludge, however, decreased sediment concentration and soil loss, relative to incorporation. Sediment concentrations and soil loss were on the average 1.7 and 2.0 times greater for incorporated plots than for surface-applied plots, respectively. The differences due to application method were more pronounced at the higher application rate (Table 10). Similar results were obtained by Kladivko and Nelson (1979b) who suggested that the surface-applied sludge particles protected the soil surface from eroding by forming a crust. Higher application rates afforded more protection by providing a more continuous and thicker crust.

Effects of Sludge Application Rate

The effects of application rate on runoff and sediment losses are shown in Table 10. Runoff amounts and peak runoff rates generally decreased with increasing application rates, with the effects being more pronounced on the conventional tillage plots. The highest application rate on the conventional tillage plots reduced runoff volume and peak rate by 41.2 and 27.8 percent, respectively, compared to the control treatments. These results may indicate an increase in water retention and infiltration capacity due to sludge treatment as was reported by Epstein et al. (1976) and Kladivko and Nelson (1979a). These differences, however, were not significant.

Sediment yields and concentrations also decreased with increasing application rates. 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. The corresponding reductions in sediment load were 95.5, 89.6, and 72.4 percent. While the effects of sludge addition were sig-

Table 9. Effects of sludge incorporation on soil loss, runoff, sediment concentration, and peak runoff rate from conventional tillage system.

Sludge Application Method	Run	Soil Loss (kg/ha)	Runoff (cm)	Avg. Sed. Conc. (mg/L)	Peak Runoff Rate (cm/hr)
Incorporated	R1	356.65*	0.89	3975.10*	2.70
	R2	425.16†	0.97	4318.20†	3.19
	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††	3.84
	Total	800.91#	2.80	---	---

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 10. Effects of tillage and sludge application method and rate on soil loss, runoff, sediment concentration and peak runoff rate.

Tillage	Application Rate Kg-N/ha*	Run	Soil Loss (kg/ha)			Runoff (cm)			Avg. Sed. Conc. (mg/L)			Peak Runoff (cm/hr)		
			I**	C	S	I	C	S	I	C	S	I	C	S
No-till	0	R1		459.74			0.68			4885.30			1.25	
		R2		329.86			0.56			4671.20			1.98	
		R3		610.83			1.17			4843.60			2.78	
		Total		1400.43			2.41			---			---	
	75	R1			2.90			0.12			449.90			0.26
		R2			3.35			0.13			408.50			0.71
		R3			44.63			0.49			1096.20			1.40
		Total			50.88			0.74			---			---
	150	R1			4.42			0.18			297.40			0.75
		R2			10.66			0.36			441.30			1.62
		R3			48.10			0.88			473.90			2.48
		Total			63.18			1.42			---			---
Conv.	0	R1		924.00			0.89			7272.60			2.28	
		R2		1143.11			1.18			8487.30			3.80	
		R3		2519.39			1.96			12793.40			4.46	
		Total		4586.50			4.03			---			---	
	75	R1	546.12			1.36			3929.50			3.42		
		R2	607.63			1.29			4843.80			3.54		
		R3	849.89			1.85			4608.90			4.01		
		Total	2003.64			4.50			---			---		
	150	R1	167.18			0.42			4020.80			1.98		
		R2	242.69			0.65			3792.50			2.83		
		R3	855.62			1.42			6046.50			3.39		
		Total	1265.49			2.49			---			---		

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

nificant, doubling the application rate did not cause a reduction 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 layer of mulch or crust over the plots.

Nutrient Concentrations

The nutrient concentrations in runoff material from all of the treatments studied are shown in Tables 11 and 12. The form of P and N entering surface waters is very important. Soluble inorganic P, $PO_4^- - P$, is the key form of P which stimulates excessive 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 aquatic vegetation. To prevent the development of algal nuisances, the generally accepted upper concentration limit in lakes and reservoirs is 0.01 mg/L for $PO_4^- - P$. Effluent discharge permits for municipal and industrial discharges to lakes or streams commonly limit the concentration to 1.0 mg/L of $PO_4^- - P$ (Viessman and Hammer, 1985). The $PO_4^- - P$ concentrations in runoff exceeded the 0.01 mg/L level for all treatments and in some instances exceeded the 1.0 mg/L limit (Table 11).

Nitrate and $NH_4^+ - N$ are also 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 about 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 all sludge-treated plots exceeded the 3 mg/L limit (Table 12).

Table 11. Effects of sludge incorporation and application rate on P concentrations in runoff.

Tillage system	Application Rate Kg-N/ha*	Run	PO$_4$-P			P$_{sb}$			P$_{TF}$			P$_T$		
			I**	C	S	I	C	S	I	C	S	I	C	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
Conv.	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 12. Effects of sludge incorporation and application rate on N concentrations in runoff.

Tillage system	Application Rate Kg-N/ha*	Run	$NH_4^+ - N$			$NO_3^- - N$			TKN			N_T		
			I**	C	S	I	C	S	I	C	S	I	C	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	.70		.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

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 13). 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. The soluble forms of P, $PO_4^- - P$ and P_{TF}, are primarily transported via runoff. Orthophosphorus and P_{TF} concentrations appeared to be inversely related to runoff volumes (Table 8). Thus, concentrations were generally higher from no-till plots with the exception of R2 where runoff volumes were lower and soluble P concentrations were higher from conventional tillage plots (Table 13). The increase in soluble P concentrations with no-till may be the result of reduced dilution effects associated with the lower runoff volumes from these plots (Mostaghimi et al., 1987).

The average $NH_4^+ - N$ concentrations in runoff from the conventional tillage plots were greater than those from the no-till plots (Table 14). Ammonium N concentrations from surface-applied 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 greater sediment concentrations and yields from these plots (Table 8). 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 present in runoff from the conventional tillage and no-till plots, respectively. Nitrate concentrations from surface-applied treatments 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 indicate that nitrogen mineralization rates are higher with conventional tillage. The increased soil/sludge contact area on conventional tillage plots, resulting from the absence of residue on these plots, may increase the potential for soil/sludge interaction and thus increase mineralization rates. This hypothesis is further supported by the relatively low proportion

Table 13. Effects of tillage system on the average P concentrations in runoff.

Tillage system	Run	PO_4-P	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
Conv. (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 14. Effects of tillage system on the average N concentrations in runoff.

Tillage system	Run	$NH_4^+ - N$	$NO_3^- - N$	TKN	N_T
		-----------	-----------	mg/L -----------	-----------
No-till	R1	6.84	.55	20.15	20.69
	R2	6.18	.51	20.25	20.77
	R3	8.50	.86	26.17	27.03
	Average	7.17*	.64	22.19	22.83
Conv. (Surface)	R1	26.40	4.02	35.94	39.96
	R2	26.16	2.10	40.36	42.46
	R3	12.11	.83	21.73	22.57
	Average	21.56*	2.32	32.68	35.00

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.

of organic N found in runoff from the conventional tillage plots. Only 32 percent of the N_T concentration from the conventional tillage treatments was organic N, versus 65 percent for no-till treatments.

Effects of Sludge Application Method

The average P and N concentrations in runoff from incorporated and surface-applied conventional tillage plots are presented in Tables 15 and 16, respectively. In general, surface application of sludge resulted in higher nutrient concentrations in runoff than did incorporation. The surface-applied sludge was directly exposed to rainfall and runoff which may have led to the increased N and P concentrations in runoff and sediment. Orthophosphorus and P_{TF} concentrations were an average of 2.3 and 1.4 times greater for the surface-applied plots than for the incorporated plots, respectively (Table 15).

During R1, concentrations of P_{sb} and P_T were higher from incorporated plots than from surface-applied plots. This may be a result of the increased sediment concentrations from incorporated plots since these constituents are transported mainly by sediment. Dunigan and Dick (1980) explained that the incorporation of P may cause rapid sorption, resulting in decreased $PO_4^- - P$ and increased P_{sb} initially available for transport. Surface-applied sludge may have been mineralized slowly but continually throughout the study period, causing P_{sb} concentrations to increase and $PO_4^- - P$ concentrations to decrease with succeeding rainfall events (Dunigan and Dick, 1980).

Surface application increased $NH_4^+ - N$, TKN, and N_T concentrations relative to sludge incorporation (Table 16). Ammonium-N, 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. Throughout the initial storm, concentrations of $NO_3^- - N$ and TKN_F were higher from the

Table 15. Effects of sludge incorporation on average P concentration in runoff from conventional tillage system.

Application method	Run	PO_4-P	P_{sb}	P_{TF}	P_T
				—mg/L—	
Incorporated	R1	.34	3.92	.75	4.67
	R2	.26	1.70	.58	2.29
	R3	.18	1.80	.47	2.27
	Average	.26*	2.47	.60	3.08
Surface-applied	R1	.66	1.65	.87	2.52
	R2	.75	1.81	1.03	2.84
	R3	.34	2.96	.57	3.53
	Average	.58*	2.14	.82	2.96

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 16. Effects of sludge incorporation on N concentration in runoff from conventional tillage system.

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	.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	.83	21.73	22.57
	Average	21.56*	2.32	32.68*	35.00*

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.

incorporated plots. 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).

Effects of Sludge Application Rate

The effects of application rate on nutrient concentrations in runoff are shown in Table 11. 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 10) and therefore reduced dilution ratios. The application of sludge at the 150 kg-N/ha rate significantly increased P_{TF} concentrations as compared to both 75 kg-N/ha and 0 kg-N/ha treatments. In most instances, concentrations of P_{sb} and P_T increased in the following treatment order: 75 kg-N/ha < 0 kg-N/ha < 150 kg-N/ha. Apparently, increasing the rate of sludge application resulted in two opposing effects -- increasing the amount of P_{sb} available for transport and decreasing the sediment concentration in runoff. At the lower application rate the decrease in sediment concentration (Table 10) 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 11). 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 $NH_4^+ - N$ concentrations in runoff increased significantly as a result of sludge application (Table 12). For the no-till and conventional tillage surface-applied plots, both application rates increased the average $NH_4^+ - N$ concentration by over 1000 percent relative to the control treatments. $NO_3^- - N$ 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_F concentrations significantly increased with increasing application rate, and

TKN and T_N concentrations significantly increased at the higher loading rate, relative to both 75 kg-N/ha and 0 kg-N/ha treatments.

Nutrient Yields

The greatest losses of $PO_4^- - P$ recorded for no-till and conventional tillage plots were 0.17 and 0.19 kg/ha, respectively, as a result of surface application of sludge at the 150 kg-N/ha rate (Table 17). The greatest loss of P_T recorded was 1.50 kg/ha from surface-applied sludge at the rate of 75 kg-N/ha on conventional tillage. This loss 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, or 3.3 percent of the total N applied was lost (Table 18). 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.

Effects of Tillage System

Orthophosphorus and P_{TF} losses were slightly higher from the conventional tillage plots than from the no-till plots (Table 19). 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 and produced similar 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 less than those for conventional tillage, respectively. No-till reduced TKN, N_T, and $NH_4^+ - N$ losses, relative to conventional tillage (Table 20). The reductions in $NH_4^+ - N$, TKN, and N_T losses due to no-till were 85, 60, and 61 percent,

Table 17. Effects of sludge incorporation and application rate on P yields.

Tillage system	Application Rate Kg-N/ha*	Run	PO₄-P			P_sb			P_TF			P_T		
			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
Conv.	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 18. Effects of sludge incorporation and application rate on N yields.

Tillage system	Application Rate Kg-N/ha*	Run	NH₄–N (kg/ha)			NO₃–N (kg/ha)			TKN (kg/ha)			Nᴛ (kg/ha)		
			I**	C	S	I	C	S	I	C	S	I	C	S
No-till	0	R1		.06			.09			.34			.43	
		R2		.05			.09			.39			.48	
		R3		.06			.16			.60			.76	
		Total		.17			.34			1.33			1.67	
	75	R1	—		.12	—		.01	—		.16	—		.17
		R2	—		.06	—		.03	—		.18	—		.20
		R3	—		.53	—		.08	—		1.05	—		1.13
		Total	—		.71	—		.12	—		1.39	—		1.50
	150	R1	—		.14	—		.01	—		.71	—		.72
		R2	—		.36	—		.02	—		1.86	—		1.88
		R3	—		.65	—		.04	—		4.09	—		4.13
		Total	—		1.15	—		.07	—		6.66	—		6.73
Conv.	0	R1		.15			.13			2.46			2.60	
		R2		.17			.14			3.14			3.27	
		R3		.27			.27			1.41			1.68	
		Total		.59			.54			7.01			7.55	
	75	R1	1.57		1.25	1.71		.28	3.03		1.69	4.74		1.96
		R2	.75		1.82	.13		.12	2.14		2.68	2.27		2.80
		R3	.87		2.64	.17		.31	3.47		4.61	3.64		4.92
		TOTAL	3.19		5.71	2.01		.71	8.64		8.98	10.65		9.68
	150	R1	.30		2.27	.15		.19	1.10		2.99	1.25		3.18
		R2	.34		1.99	.16		.14	1.32		3.19	1.48		3.33
		R3	.47		2.85	.15		.10	2.90		4.92	3.04		5.02
		TOTAL	1.11		7.11	.46		.43	5.32		11.10	5.77		11.53

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

Table 19. Effects of tillage system on P yields (surface applied for conventional tillage).

Tillage System	Run	PO_4^--P	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*
Conv.	R1	0.04	0.12	0.05	0.17
(Surface)	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*

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 tillage system on N yields (surface applied for conventional tillage).

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**
Conv.	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**

* Means, in a column, followed by the same symbol are different from each other at the 0.05 significance level according

** Means, in a column, followed by the same symbol are different from each other at the 0.10 significance level according to the two sided t-test.

respectively. Nitrate-N and TKN_F yields were also lower from no-till plots, although these reductions were not significant. Sediment-bound N losses represented 26.3 and 40.4 percent of the N_T losses from surface-applied, no-till and conventional tillage plots, respectively.

Effects of Sludge Application Method

In general, surface application of sludge resulted in higher nutrient losses than did incorporation (Tables 21 and 22). The surface-applied plots produced $PO_4^- - P$ yields 2.0 times greater than the incorporated plots (Table 21). 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 15) and the higher sediment losses (Table 9) associated with sludge incorporation. Ammonium-N, TKN, and N_T yields were 3.0, 1.4, and 1.3 times greater, respectively, from surface application as compared to incorporation (Table 22). The effects of application method on $NO_3^- - N$ and TKN_F yields varied with runoff event. Similar trends were seen in nutrient concentrations (Table 16).

Effects of Sludge Application Rate

Soluble P losses generally increased with increasing application rate (Table 17). The application of sludge at the rate of 150 kg-N/ha significantly increased $PO_4^- - P$ losses relative to the control treatments. The total amount of P_{sb} lost was greatest from the control plots, regardless of tillage system. Apparently, the decrease in sediment yield associated with sludge addition (Table 10) outweighed the increase in P availability and reduced P losses by sediment. Ammonium-N, TKN_F , TKN, and N_T yields generally increased with increasing sludge application rate (Table 18). The effects of sludge application on $NH_4^+ - N$ and TKN_F losses were significant, with the highest loading rate producing $NH_4^+ - N$ and TKN_F losses of 6.9 and 2.5 times greater than the control

Table 21. Effects of sludge incorporation on P yields from conventional tillage system.

Application method	Run	PO_4^--P	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

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 22. Effects of sludge incorporation on N yields from conventional tillage system.

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*

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.

treatments, averaged over all tillage and sludge application treatments. As with the $NO_3^- - N$ concentrations (Table 12), $NO_3^- - N$ yields were not affected by application rate.

MODEL VERIFICATION

The performance of the CREAMS-NT model was evaluated by comparing model predictions with observed N runoff losses from the rainfall simulator plot studies. Eight of the sixteen field plots, QF1, QF4, QF6, QFB, QFE, QFF, QFK, and QFN, were used in model verification. These plots represent all of the treatments studied and were selected randomly. Treatments and plot characteristics are given in Table 5. The preparation of input data files, calibration of the hydrologic and erosion components of the model, and verification of the nutrient component of CREAMS-NT are described in this chapter.

Calibration

The runoff and sediment yield predictions generated by CREAMS were calibrated to closely approximate the observed field data. This calibration allows for a more accurate evaluation of the N transformation and transport component by minimizing the effects of inadequate runoff and erosion predictions. Because N is transported in runoff and attached to the sediment, these parameters directly effect nutrient yield predictions. Calibration was accomplished by adjusting the input pa-

rameters of the hydrologic and erosion components of the model to approximate the observed daily runoff volumes and sediment loads.

The input parameters required by the hydrologic and erosion components of CREAMS were determined as follows. Estimates of soil saturated conductivity and capillary tension, or effective suction at the wetting front, were obtained from Williams et al. (1980). Average monthly solar radiation values of 172, 274, 338, 414, 508, 525, 510, 430, 375, 281, 202, and 168 cal/cm²/day were taken from historical data obtained at the Mt. Weather, Virginia weather station (Williams et al., 1980). The Manning's n values for overland flow conditions were determined from the table presented by Foster et al. (1980b). It should be noted that the Manning's n values suggested by Foster et al. (1980b) are relatively low as compared to others reported in the literature for overland flow conditions. For consistency, the values suggested by Foster et al. (1980b) should be used as input to CREAMS. Soil parameters such as wilting point and field capacity moisture conditions were obtained from England (1970). The soil evaporation parameter was estimated from data presented by Ritchie (1972). Average monthly temperatures for 1987 were taken from the climatological data summary for Blacksburg, Virginia. The average surface soil particle size distribution of the field plots was experimentally determined for a previous study and was input as 20.0 percent sand, 51.1 percent silt, and 28.9 percent clay (Deizman et al., 1987). The surface area of the sand, silt, clay, and organic matter particles was represented using values of 0.04, 2.3, 40.0, and 1000.0 m²/g , respectively (Dillaha et al., 1987a). The organic matter content of the surface soil was obtained from Kool et al. (1986). The USLE soil erodibility (K) factor was estimated from the Soil Survey of Montgomery County, Virginia (USDA, 1985). The USLE C and P factors were estimated from the information given by Wischmeier and Smith (1978). The P factor used represents contoured conditions and varies with plot slope (Wischmeier and Smith, 1978). Data for the plot area, plot slope, slope length, bulk density, and initial soil moisture content parameters was collected in the field prior to the start of rainfall simulations. The soil porosity was calculated as a function of bulk density (Peck et al., 1974). Breakpoint rainfall data was recorded for input to the hydrologic component of CREAMS. For the rainfall simulator used, a rainfall energy ratio of 0.4 was used for all

plots (Neff, 1979; Kenimer, 1987). This ratio is defined as the ratio of rainfall simulator drop impact energy to natural raindrop impact energy and was used to adjust the predicted sediment losses for the difference between the energy of natural and simulated rainfall. The rainfall energy ratio is a function of the rainfall simulator used. A summary of the input values used for simulating the runoff volumes and sediment yields from the experimental field plots is presented in Table 23.

The hydrologic component of CREAMS was first calibrated such that the predicted values of daily runoff volume approximated the observed values. This was achieved by varying the effective saturated conductivity and the wilting point moisture content of the soil. The calibrated input parameters along with the corresponding suggested input parameters for each of the field plots are listed in Table 24. It should be noted that the suggested input parameters do not reflect the effects of sludge addition because little quantitative data is available. The calibrated saturated conductivity values generally increased as sludge application rates increased. Williams et al. (1980) indicated that this parameter is dependent on soil conditions and should reflect the management practices employed. Practices which improve soil aggregation and increase the mulch or canopy cover would result in greater values of saturated conductivity (Brady, 1974; Williams et al., 1980). Calibrated values for the soil moisture content at wilting point were greater for no-till plots than for conventional tillage plots, probably due to the improved soil aggregation associated with no-till. Moisture content values also increased slightly with sludge application. The application of sludge has been shown to increase the saturated conductivity of the soil as well as the water content at wilting point and field capacity (Epstein, 1975; Gupta et al., 1977; Chang et al., 1983; Hall and Coker, 1983). These phenomena can be attributed to the increase in soil organic matter content and the formation of a protective mulch-type cover resulting from sludge application.

After runoff losses were calibrated, input parameters to the erosion component were adjusted to calibrate sediment yield predictions. Foster et al. (1980b) suggested varying the USLE soil erodibility (K) factor and the Manning's n parameters when calibrating the model for areas of overland flow. The authors further indicated that in some situations, the USLE management practice (C) factor may also require adjustment. As compared to the suggested parameter values,

Table 23. CREAMS Hydrologic and Erosion Component input parameters.

Parameter	QFN	QFK	QFB	QF1	QF4	QF6	QFE	QFF
Drainage Area (ha)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Fraction of pore space filled at field capacity	0.381	0.356	0.424	0.419	0.423	0.636	0.611	0.664
Fraction of available water content filled when simulation begins	0.611	0.600	0.562	0.567	0.722	0.380	0.027	0.026
Soil evaporation parameter	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Soil porosity (cm/cm)	0.5956	0.6415	0.5616	0.5572	0.5623	0.4845	0.5075	0.4811
Surface layer depth (cm)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Capillary tension (cm)	38.1	38.1	38.1	38.1	38.1	38.1	38.1	38.1
Slope (m/m)	0.114	0.117	0.089	0.092	0.141	0.140	0.086	0.083
Slope length (m)	18.3	18.3	18.3	18.3	18.3	18.3	18.3	18.3
Organic matter fraction	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037
USLE P (contouring) factor	0.60	0.60	0.60	0.60	0.70	0.70	0.50	0.50
Average monthly air temperature (°C) for Jan. - Dec. 1987	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4
	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6
	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7
	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4
	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9
	23.2	23.2	23.2	23.2	23.2	23.2	23.2	23.2
	22.8	22.8	22.8	22.8	22.8	22.8	22.8	22.8
	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8
	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7

Table 24. Suggested and Calibrated Input Parameters

PLOT	RC *	BR15	NFACT	KSOIL	CFACT
QFN: CT, 0 kg/ha					
Suggested	0.28	0.12	0.023	0.28	0.74
Calibrated	0.30	0.07	0.024	0.28	0.65
QFK: CT, 75 kg/ha, Incorporated					
Suggested	0.28	0.12	0.023	0.28	0.74
Calibrated	0.28	0.08	0.033	0.25	0.52
QFB: CT, 75 kg/ha, Surface-Applied					
Suggested	0.28	0.12	0.023	0.28	0.74
Calibrated	0.38	0.09	0.048	0.21	0.50
QF1: CT, 150 kg/ha, Incorporated					
Suggested	0.28	0.12	0.023	0.28	0.74
Calibrated	0.53	0.08	0.033	0.25	0.52
QF4: CT, 150 kg/ha, Surface-Applied					
Suggested	0.28	0.12	0.023	0.28	0.74
Calibrated	0.61	0.09	0.053	0.18	0.31
QF6: NT, 0 kg/ha					
Suggested	0.58	0.12	0.047	0.28	0.11
Calibrated	0.71	0.17	0.049	0.28	0.12
QFE: NT, 75 kg/ha, Surface-Applied					
Suggested	0.58	0.12	0.064	0.28	0.07
Calibrated	0.81	0.18	0.064	0.21	0.08
QFF: NT, 150 kg/ha, Surface-Applied					
Suggested	0.58	0.12	0.058	0.28	0.07
Calibrated	0.91	0.18	0.066	0.18	0.06
Range of Published Data	(0.13-1.27)	(0.03-0.30)	(0.01-0.40)	(0.0-1.0)	(0.0-1.0)

* RC = Effective Saturated Conductivity (cm/hr)
BR15 = Wilting Point Soil Moisture (cm/cm)
NFACT = Manning's n for Overland Flow
KSOIL = USLE Soil Erodibility (K) Factor
CFACT = USLE Management Practice (C) Factor

the application of sludge resulted in an increase in Manning's n and a decrease in soil erodibility and management factors (Table 24). The Manning's n values increased due to the additional roughness resulting from surface application of the sludge. The additional tillage operations also increased the surface roughness, to a lesser extent, on the incorporated sludge plots. The stability of the sludge particles effectively decreased the soil erodibility factor. The decrease in the management practice (C) factor can be attributed to the protective mulch-type cover formed on the plots treated with sludge. All of the calibrated input parameter values listed in Table 24 are realistic and are within the published ranges for the specific variables.

The predicted and observed runoff and sediment losses are given in Table 25. The relative error of the predictions, with respect to the observed data, was calculated and is presented in Table 25. As indicated in this table, the calibrated model provided reasonable predictions of runoff and sediment losses for use in the nutrient component of CREAMS-NT.

Plot Simulations

CREAMS-NT Parameter Estimation

Input parameters describing the soil physical and chemical properties, crop growth, and the organic waste characteristics are required by CREAMS-NT. A list of the required CREAMS-NT input parameters along with the corresponding parameter values used for the field plot simulations is given in Tables 26 and 27. Soil properties including surface layer and root zone organic matter content, pH, and surface layer cation exchange capacity were estimated from data presented by Kool et al. (1986). The soil moisture contents at wilting point and field capacity were set equal to the values used as input to the calibrated hydrologic component. Samples were collected in the field

Table 25. Predicted and Observed Runoff and Sediment Losses.

Plot : Treatment	R1	R2 + R3	R1	R2 + R3
	Runoff (cm)		Sediment (kg/ha)	
QFN: CT, 0 kg/ha				
Predicted	1.5	3.1	1839.1	6934.2
Observed	1.3	3.4	1801.8	6511.3
Relative Error (%)*	15.4	-8.8	2.1	6.5
QFK: CT, 75 kg/ha, Incorporated				
Predicted	1.5	2.6	974.5	1794.0
Observed	1.1	3.0	377.6	1798.9
Relative Error (%)	36.4	-13.3	158.1	-0.3
QFB: CT, 75 kg/ha, Surface-Applied				
Predicted	0.8	2.3	144.6	581.9
Observed	0.6	2.9	73.7	725.3
Relative Error (%)	33.3	-20.7	96.2	-19.8
QF1: CT, 150 kg/ha, Incorporated				
Predicted	0.4	2.0	194.8	822.9
Observed	0.4	2.0	198.7	1098.2
Relative Error (%)	0.0	0.0	-2.0	-25.1
QF4: CT, 150 kg/ha, Surface-Applied				
Predicted	0.3	1.7	59.6	578.1
Observed	0.2	1.6	58.5	565.2
Relative Error (%)	50.0	6.2	1.9	2.3
QF6: NT, 0 kg/ha				
Predicted	0.2	1.2	61.4	342.8
Observed	0.2	1.1	46.1	359.1
Relative Error (%)	0.0	9.1	33.2	-4.5
QFE: NT, 75 kg/ha, Surface-Applied				
Predicted	0.2	1.1	4.9	55.8
Observed	0.2	0.9	1.8	55.1
Relative Error (%)	0.0	22.2	172.2	1.3
QFF: NT, 150 kg/ha, Surface-Applied				
Predicted	0.1	0.9	2.7	33.2
Observed	0.1	0.8	2.9	24.2
Relative Error (%)	0.0	12.5	-6.9	37.2

$$*\text{Relative Error (\%)} = \left(\frac{\text{Predicted} - \text{Observed}}{\text{Observed}}\right) * 100$$

Table 26. CREAMS-NT input parameters used for all field plots.

Parameter	Value	Parameter	Value
Surface organic matter (%)	3.7	Soluble P extraction coefficient	0.07
Root zone organic matter (%)	1.8	NH_4^+-N enrichment ratio coefficient	7.4
Soil pH	5.85	NH_4^+-N enrichment ratio exponent	-0.2
Soil CEC (meq/100g)	8.31	Rainfall N concentration (mg/l)	1.0
Surface NO_3^--N (kg/ha)	0.482	Organic waste C: N	10.0
Surface NH_4^+-N (kg/ha)	0.397	Organic waste pH	7.3
Surface organic-N (kg/ha)	262.4	Mineralization rate constant (day^{-1})*	0.022
Surface soluble P (kg/ha)	0.2	Temperature associated with mineralization rate constant (°C)*	35.0
Surface adsorbed P (kg/ha)	55.3	Volatilization rate constant (day^{-1})*	0.21
Root zone inorganic N (kg/ha)	20.23	Temperature associated with volatilization rate constant (°C)*	21.0
Root zone organic N (kg/ha)	6299.7		
Root zone depth (mm)	1220.0		
NO_3^--N extraction coefficient	0.05		
NH_4^+-N extraction coefficient	0.25		

*CREAMS-NT calculates these values for control plots

Table 27. CREAMS-NT input parameters for individual plots.

Parameter	QFN	QFK	QFB	QF1	QF4	QF6	QFE	QFF
Soil porosity (cm/cm)	0.5956	0.6415	0.5616	0.5572	0.5623	0.4845	0.5075	0.4811
Bulk density (g/cm^3)	1.072	0.95	1.162	1.173	1.160	1.366	1.305	1.375
Organic-N enrichment ratio coefficient	2.363	2.363	15.226	2.363	15.226	2.363	15.226	15.226
Organic-N enrichment ratio exponent	-0.188	-0.188	-0.423	-0.188	-0.423	-0.188	-0.423	-0.423
P enrichment ratio coefficient	9.984	9.984	3.267	9.984	3.267	9.984	3.267	3.267
P enrichment ratio exponent	-0.377	-0.377	-0.206	-0.377	-0.206	-0.377	-0.206	-0.206
Organic waste NO_3^--N (kg/ha)	---	0.0	0.0	0.0	0.0	---	0.0	0.0
Organic waste NH_4^+-N (kg/ha)	---	55.8	55.8	111.7	111.7	---	55.8	111.7
Organic waste organic-N (kg/ha)	---	119.2	119.2	238.5	238.5	---	119.2	238.5
Organic waste P (kg/ha)	---	116.1	116.1	232.2	232.2	---	116.1	232.2
Fraction of waste in surface layer	---	0.067	1.0	0.067	1.0	---	1.0	1.0
Waste applied (kg/ha)	---	36287	36287	72575	72575	---	36287	72575
NH_4^+-N adsorption rate constant (day^{-1})	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
NH_4^+-N desorption rate constant (day^{-1})	0.2	1.0	1.0	1.0	1.0	0.2	1.0	1.0
Nitrification rate constant (day^{-1})	0.08	0.40	0.40	0.40	0.40	0.08	0.40	0.40
Temperature associated with nitrification rate constant (°C)	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0
Average daily wind velocity for week following waste application (km/hr)	--- --- --- --- --- ---	7.11 5.27 6.06 5.93 6.33 7.74	6.75 5.52 7.11 5.27 6.06 5.93	6.75 5.52 7.11 5.27 6.06 5.93	6.75 5.52 7.11 5.27 6.06 5.93	--- --- --- --- --- ---	7.11 5.27 6.06 5.93 6.33 7.74	7.11 5.27 6.06 5.93 6.33 7.74
		5.15	6.33	6.33	6.33		5.15	5.15

prior to the start of rainfall simulation for the determination of soil bulk density and nutrient content (Page et al., 1982). Initial soil nutrient concentrations, however, were not available for the sludge-treated plots. The N and P concentrations of the initial soil for all plots were estimated as the average of the concentrations determined for the four control plots. The required concentrations include surface layer $NO_3^- -N$, $NH_4^+ -N$, organic-N, adsorbed and desorbed P, and root zone inorganic and organic N (Table 26). The initial soil $NH_4^+ -N$ adsorption and desorption rates were set at 1.0 and 0.2, respectively (Mehran and Tanji, 1974; Hsieh et al., 1981). The soil nitrification rate was estimated from data presented by Terry et al. (1981).

Sludge properties such as pH, $NO_3^- -N$, $NH_4^+ -N$, organic-N, and total P contents were determined in the laboratory using the methods described in Page et al. (1982). The C:N ratio of the sludge was estimated from the data given by Parker and Sommers (1983) for various sludge types. The fraction of the applied waste in the surface one centimeter of soil is required as input to CREAMS-NT. This parameter was calculated as the inverse of the depth of application for the incorporated plots. The surface fraction of the applied waste was set equal to 1.0 for surface-applied plots. The first-order rate constants describing the mineralization, nitrification, and volatilization processes in soil/waste systems were approximated from the data presented by Lindemann and Cardenas (1984), Terry et al. (1981), and Ryan and Keeney (1975), respectively (Table 27). The $NH_4^+ -N$ adsorption and desorption rate constants were both set equal to 1.0 following sludge application. The use of these rate constants implies that 50 percent of the applied $NH_4^+ -N$ remains in soluble form (Hunt and Adamsen, 1985). Wind velocities for one week following sludge application were obtained from the Turf Grass Center at VPI&SU (Elmore and Wolfe, 1987).

The input parameters describing the enrichment ratio relationships and extraction coefficients were calibrated using field plot data. Calibration aids in model evaluation by identifying problems within the model as opposed to those resulting from inaccurate input data. Frere et al. (1980) indicated that the enrichment ratio parameters were dependent on management practices and soil characteristics and suggested using field data, if available, to determine these parameters. Frere et al. (1980) also reported that accurate estimation of these parameters was more critical for event-based simu-

lations than for long-term simulations. The enrichment ratio for each nutrient constituent is determined in CREAMS-NT as a function of sediment yield (Equation 90). Equation 90 can be expressed in logarithmic form as:

$$\ln(ER) = c_0 + c_1 \ln(Sed) \tag{97}$$

where: ER = Enrichment ratio

Sed = Sediment yield (kg/ha)

c_0, c_1 = regression coefficients

The regression coefficients in Equation 97, c_0 and c_1, can be related to CREAMS-NT input parameters using:

$$A = e^{c_0} \tag{98}$$

$$B = c_1 \tag{99}$$

where: A = Enrichment ratio coefficient input parameter

B = Enrichment ratio exponent input parameter

A plot of $\ln(ER)$ versus $\ln(Sed)$ for organic-N and P_{sb} is given in Figures 5 and 6 for surface-applied treatments and Figures 7 and 8 for incorporated and control treatments, respectively. The results of these regression analyses (Figures 5 - 8) suggest that the enrichment ratio parameters vary with waste application method. The surface application of sludge resulted in higher organic-N enrichment ratios than did the incorporation of sludge (Figures 5 and 7). This increase is probably due to the greater amount of organic-N available to runoff transport on the surface-applied plots. The effect of sludge application method on the P_{sb} enrichment ratios varied with sediment yield (Figures 6 and 8). Due to the limited data available for quantifying these effects, however, CREAMS-NT does not allow the user to reinitialize the enrichment ratio parameters following an organic waste application. This option can be included in future versions of the model.

MODEL VERIFICATION   133
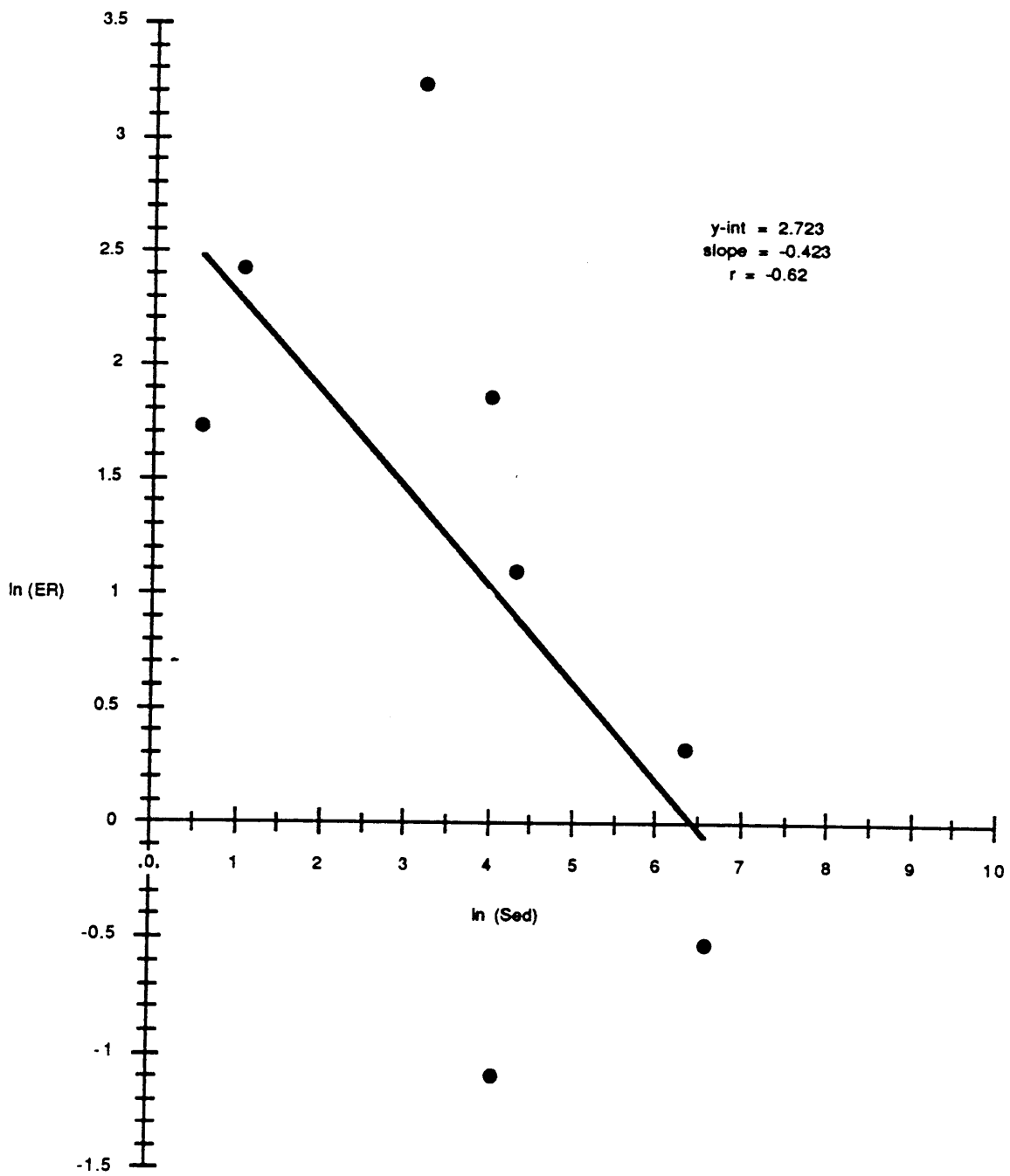
Figure 5.   Organic nitrogen enrichment ratio relationships on surface-applied plots.
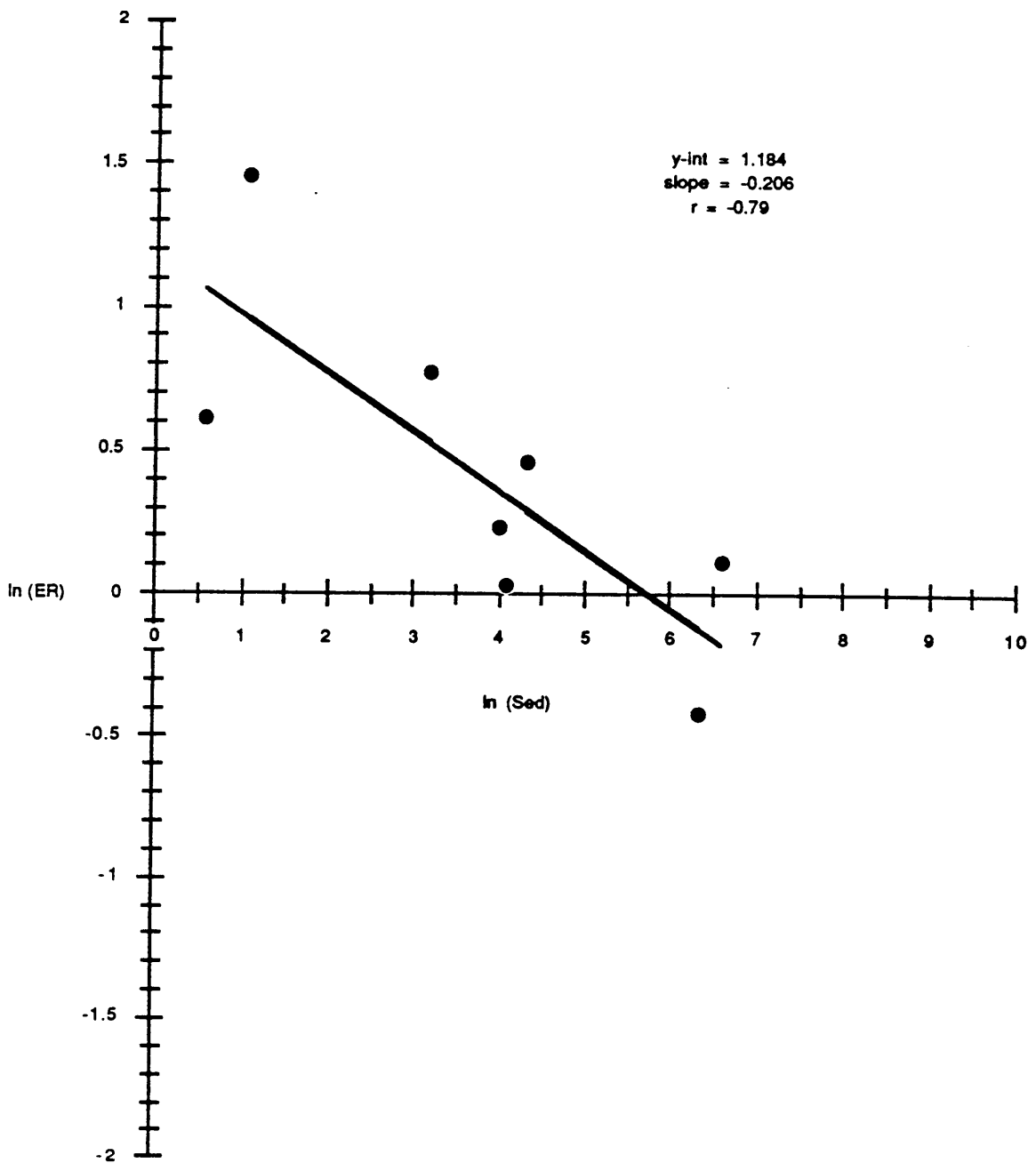
Figure 6. Sediment-bound phosphorus enrichment ratio relationships on surface-applied plots.
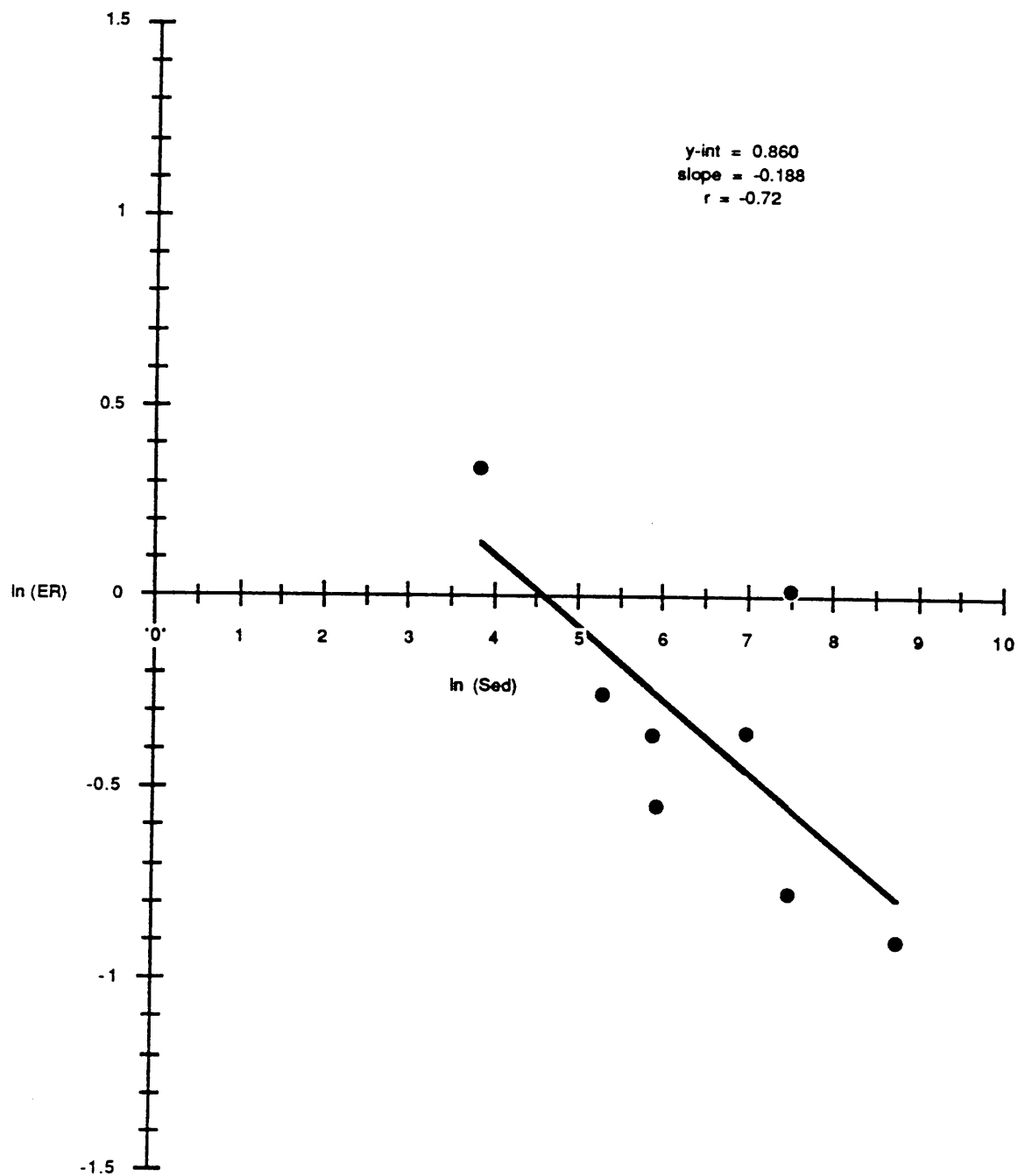
Figure 7. Organic nitrogen enrichment ratio relationships on incorporated and control plots.
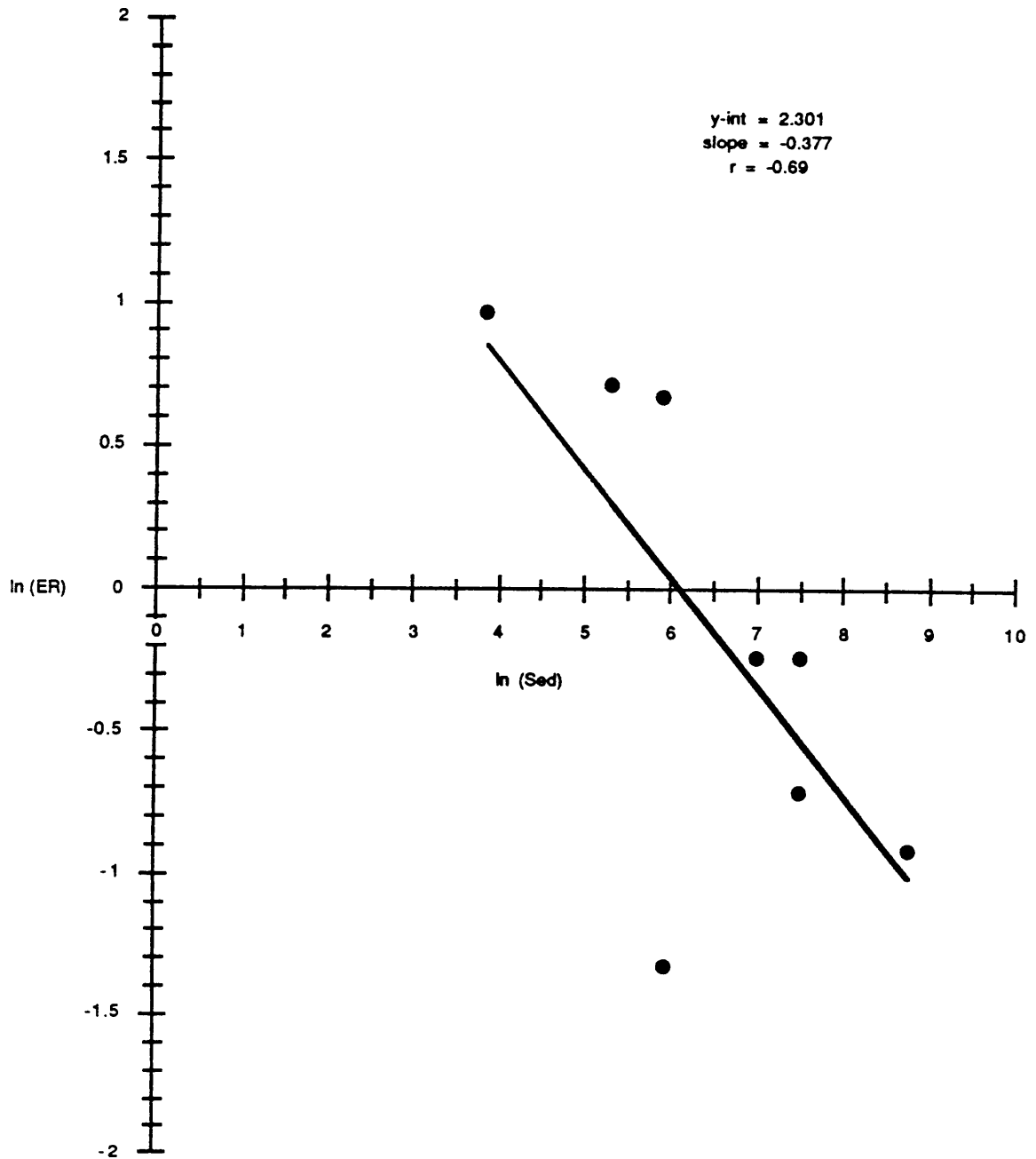
Figure 8. Sediment-bound phosphorus enrichment ratio relationships on incorporated and control plots.

The $NO_3^- - N$ and P_{TF} extraction coefficients were determined for all of the experimental plots by trial-and-error. Due to the limited data available, it was assumed for these simulations that the extraction coefficients were unaffected by sludge loading rate, application method, and tillage practice. The values which provided the best overall representation of the observed yields were used. The resulting values were 0.05 for $NO_3^- - N$ and 0.07 for P_{TF}. These values are within the range suggested by Frere et al. (1980). Ammonium-N is transported in both soluble and sediment-bound forms, with the majority in soluble form. The analyses performed on the field collected samples, however, did not distinguish between the two forms. Calibration of the enrichment ratio parameters for $NH_4^+ - N$ was, therefore, considered impractical. These parameters were approximated using values of 7.4 for the enrichment ratio coefficient and -0.2 for the enrichment ratio exponent as suggested by Frere et al. (1980). The extraction coefficient for $NH_4^+ - N$ was then varied to obtain agreement between the predicted and observed $NH_4^+ - N$ losses. A value of 0.25 was used for all simulations to represent the $NH_4^+ - N$ extraction coefficient. While calibration was used in this study to refine model predictions for verification purposes, calibration is not necessary to obtain adequate predictions of nutrient losses in surface runoff. If data is available, however, calibration should be performed to minimize the differences between observed and predicted losses.

Results and Discussion

A summary of the predicted and observed nutrient yields is presented in Table 28. As compared to the observed values, the predicted yields were very good for the sediment-bound nutrients and satisfactory for the soluble nutrients. The observed nutrient yields were lower from no-till treatments than from conventional tillage treatments. As stated previously, this result is most likely due to the decrease in sediment yield and runoff volume attributed to the reduced tillage and increased residue cover of no-till. The effects of tillage treatment were also reflected in model predictions (Table 28). Averaged over the control and surface-applied treatments, the observed reductions due

Table 28. Predicted and observed nutrient yields.

	$NO_3^- $-N	NH_4^+-N	Org-N	P_{sb}	P_{tf}
			-(kg/ha)-		
QFN: CT, 0 kgN/ha					
Predicted	0.432	0.420	10.117	1.817	0.108
Observed	0.485	0.765	10.975	2.072	0.155
QFK: CT, 75 kgN/ha, Incorporated					
Predicted	0.846	0.934	4.724	1.168	0.159
Observed	0.907	2.320	2.978	0.647	0.183
QFB: CT, 75 kgN/ha, Surface-Applied					
Predicted	0.572	5.780	2.843	0.936	0.794
Observed	0.136	6.621	2.126	1.283	0.375
QF1: CT, 150 kgN/ha, Incorporated					
Predicted	0.724	0.763	1.709	0.543	0.116
Observed	0.219	1.895	2.196	0.754	0.217
QF4: CT, 150 kgN/ha, Surface Applied					
Predicted	0.523	5.918	3.267	1.351	0.606
Observed	0.522	3.847	3.456	0.989	0.161
QF6: NT, 0 kgN/ha					
Predicted	0.063	0.118	0.647	0.206	0.041
Observed	0.223	0.132	0.606	0.334	0.067
QFE: NT, 75 kgN/ha, Surface Applied					
Predicted	0.121	1.377	0.564	0.112	0.140
Observed	0.181	0.973	1.061	0.089	0.088
QFF: NT, 150 kgN/ha, Surface Applied					
Predicted	0.136	1.840	0.516	0.115	0.154
Observed	0.092	1.721	2.354	0.125	0.121

to no-till in $NO_3^- - N$, $NH_4^+ - N$, organic-N, P_{sb}, and P_{TF} yields were 56.7, 74.8, 75.7, 87.4, and 60.0 percent, respectively, as compared to conventional tillage. The corresponding reductions in predicted yields due to no-till were 79.0, 72.5, 91.2, 89.5, and 78.0 percent.

On the conventional tillage plots, organic-N and P_{sb} yields decreased with sludge application while $NH_4^+ - N$, $NO_3^- - N$ and P_{TF} yields increased with sludge application. These same trends were observed in the predicted values (Table 28). The effects of sludge application on predicted yields of $NH_4^+ - N$, P_{sb}, and P_{TF} from no-till treatments also represented the trends seen in observed data, while the predicted yields of organic-N and $NO_3^- - N$ did not. For the three no-till plots used in model verification, $NO_3^- - N$ yields appeared to increase slightly with increasing sludge application rate. As indicated in the "Field Investigations of Nutrient Movement" chapter, however, the effects of sludge application on the observed $NO_3^- - N$ yields were not significant. The variations in predicted yields did not appear to be substantial. The discrepancy between predicted and observed $NO_3^- - N$ yields on the no-till plots may, however, indicate that the extraction coefficient for $NO_3^- - N$ may be a function of management practice. CREAMS-NT underpredicted the sediment-bound organic-N yields on the no-till surface-applied plots. There are two possible explanations for the discrepancy between the observed and predicted organic-N yields. First, the enrichment ratio parameters used may not adequately represent the system for the extremely low sediment yields produced from these treatments (Table 25). Second, CREAMS-NT assumes that organic-N is transported only in sediment-bound form. Over a long term simulation, this assumption is valid since organic-N is found in the soil primarily in adsorbed and particulate forms. For short-term simulations, however, this assumption may not be accurate due to the decreased time available for soil/sludge interaction. Model verification was performed using a short-term simulation with very little time elapsing between sludge application and the first runoff event. Underprediction of organic-N yields would probably be most evident on the no-till surface-applied plots due to the decrease in sediment yield and soil/sludge interaction area associated with this treatment. The runoff water quality data from the field plot studies presented in Appendix F further

indicates that some of the organic-N was transported in soluble form. The observed TKN_F concentrations were greater than $NH_4^+ - N$ concentrations for many of the experimental plots.

Model results represented the effects of sludge application method relatively well (Table 28). The observed $NO_3^- - N$ yields decreased, while the yields of the remaining nutrients increased, as a result of surface application on the conventional tillage plots. With the exception of organic-N yields (for the reasons stated above), model predictions followed these same trends.

For individual plots, CREAMS-NT results were fairly consistent with the observed data for most nutrient forms. Nitrate-N yields were greatest from the conventional tillage treatments where the lower sludge application rate was incorporated into the soil. The observed and predicted $NO_3^- - N$ yields from this plot were 0.907 and 0.846 kg/ha, respectively. The simulated $NH_4^+ - N$ yields were underpredicted for the conventional tillage control and incorporated plots and slightly overpredicted for all surface-applied treatments. The relationship between the $NH_4^+ - N$ predictions and observed sediment yields may suggest that the enrichment ratio parameters used for $NH_4^+ - N$ did not adequately reflect the actual field conditions. The sediment-bound $NH_4^+ - N$ losses from the incorporated and control plots may have represented a relatively large proportion of the total $NH_4^+ - N$ losses due to the high sediment yields observed from these treatments (Table 25). Model predictions of $NH_4^+ - N$ losses may, therefore, improve with more accurate estimates of the enrichment ratio parameters. The greatest loss of organic-N seen in the field was approximately 11 kg/ha from the conventional tillage control plot, while the lowest yield was observed from the no-till control plot. Model predictions of the organic-N yield from these treatments were within 8 percent of the observed yields. Sediment-bound P yields were also well represented by the model. For the nutrients transported with sediment, the greatest discrepancy between the observed and predicted yields was found on incorporated plots. On these plots, the underprediction or overprediction of sediment-bound nutrient yields was directly related to the accuracy of CREAMS sediment yield estimates (Table 25). Soluble P losses were consistently overpredicted for surface-applied treatments (Table 28). Inaccurate estimates of the soluble P extraction coefficient may have contributed to the differences between observed and predicted yields. Although the modeling efforts

of this study did not concentrate on P reactions in the soil/waste system, these results may indicate the need for future research in this area.

To aid in model verification, CREAMS-NT was then applied, without calibration, to three of the remaining eight field plots. Since the previous verification runs were performed on the plots used to quantify the effects of sludge application on input parameter values, the results of these additional simulations are more representative of the results expected in future model applications. The three field plots used represent the conventional tillage surface-applied treatments at both sludge loading rates (QFL and QFD) and the no-till surface-applied treatment at the lower sludge loading rate (QF3). The required input parameters which reflect the characteristics of the individual plots including initial soil moisture content, soil porosity, bulk density, plot slope, and the residue cover on the no-till plot were determined from field data and are shown in Table 29. The remaining input parameters were set equal to the calibrated input values determined for the corresponding treatments from model calibration simulations (Tables 23, 24, 26, and 27).

The results of the hydrologic, erosion, and nutrient components of CREAMS-NT for plots QFL, QFD, and QF3 are presented in Table 30. As indicated in Table 30, CREAMS-NT provided reasonable predictions of runoff, sediment, and nutrient losses. The predicted runoff volumes and sediment yields were very similar to the observed yields for each of these three plots. The effects of tillage treatment on nutrient yields were very well represented by the model. For the surface-applied treatments at the lower sludge application rate, the observed reductions due to no-till in $NO_3^- -N$, $NH_4^+ -N$, organic-N, P_{sb}, and P_{TF} yields were 96.1, 90.6, 93.5, 96.9, and 91.5 percent, respectively, as compared to conventional tillage. The corresponding reductions in predicted yields due to no-till were 83.0, 82.1, 89.6, 94.6, and 87.9. The effects of sludge application rate on the predicted yields of $NO_3^- -N$ and P_{sb} reflected the trends seen in the observed data. As suggested above, the discrepancy between the predicted and observed $NH_4^+ -N$ and organic-N yields may be the result of inaccurate estimates of the enrichment ratio parameters and the validity of model assumptions for short-term simulations.

Table 29.   Input parameters for additional plot simulations.

Parameter	QFL	QFD	QF3
Fraction of pore space filled at field capacity	0.386	0.386	0.636
Fraction of available water content filled when simulation begins	0.455	0.564	0.053
Soil porosity (cm/cm)	0.6075	0.6088	0.4943
Bulk density (g/cm³)	1.040	1.037	1.340
Slope (m/m)	0.114	0.094	0.099
USLE P (contouring) factor	0.60	0.60	0.60
USLE C (management) factor	0.50	0.31	0.05
Manning's n	0.048	0.053	0.074

Table 30. Predicted and observed runoff, sediment, and nutrient losses.

	Runoff (cm)	Sediment	$NO_3^- - N$	$NH_4^+ - N$	Organic-N	P_{sb}	P_{TF}
				(kg/ha)			
QFL: CT, 75 kgN/ha, Surface-Applied							
Predicted	3.4	1257.5	0.605	6.293	4.432	1.626	0.874
Observed	3.2	1453.5	1.272	4.791	4.427	1.071	0.260
QFD: CT, 150 kgN/ha, Surface Applied							
Predicted	2.1	314.4	0.543	5.988	2.442	0.877	0.651
Observed	2.7	327.5	0.329	10.374	4.520	0.354	0.267
QF3: NT, 75 kgN/ha, Surface-Applied							
Predicted	1.1	44.9	0.103	1.124	0.463	0.088	0.106
Observed	0.3	44.9	0.049	0.451	0.289	0.033	0.022

CREAMS-NT was designed for use over long-term simulations and uses a daily time step for all N transformation calculations. For shorter simulations, a smaller time step may be required. The model assumes that the N transformation processes are a function of time and soil N levels. For the model verification runs, the error introduced using a daily time step may be significant since field investigations were performed over a 48 hour period with sludge applied only 24 hours prior to the first runoff event. The $NO_3^- -N$ and $NH_4^+ -N$ yield estimates would be affected by this error to the greatest degree as the amount of these N forms in the soil available to runoff is dictated by the N transformation processes. In addition, the discrepancy between observed and predicted nutrient yields may be more pronounced for short duration simulations. Input parameter values usually represent an average of the long range expected field conditions which may not necessarily reflect field conditions for a single storm event.

The results of the model evaluation indicate that the predictive capability of CREAMS-NT may improve with more accurate estimates of the enrichment ratio parameters and extraction coefficients for each N and P form. More research is required to better define these parameters as a function of management practice and field conditions. Additional verification of CREAMS-NT, over a long-term simulation, would assist in identifying deficiencies of the model in simulating the nutrient transformation and transport processes. Because input parameter estimates generally represent an average of the expected field conditions, these values tend to be more representative of the system over a long-term simulation.

Although some discrepancies exist between the observed and predicted nutrient yields, model verification results imply that CREAMS-NT can predict $NO_3^- -N$, $NH_4^+ -N$, organic-N, P_{sb}, and P_{TF} yields with reasonable accuracy. The effects of tillage practice, sludge application method, and sludge loading rate were also adequately reflected in model predictions. Based on the above discussion, it can be concluded that CREAMS-NT shows great potential for use as a planning tool in evaluating the impact of organic waste applications and BMP implementation on runoff water quality.

SENSITIVITY ANALYSIS

An analysis was performed to determine the sensitivity of CREAMS-NT to variations in input parameters. The sensitivity analysis aids in identifying the individual processes and input parameters which have the greatest impact on the model predictions of nutrient losses in surface runoff. The input data for plot QFK was used in this analysis. The relative deviations of model predictions resulting from variations in input parameters are given in Table 31. Relative deviations were calculated using:

$$RD = \frac{P_v - P_i}{P_i} \times 100 \qquad (100)$$

where: RD = Relative deviation (%)

P_v = Model prediction generated using varied input data

P_i = Model prediction generated using original input data

As indicated in Table 31, predicted runoff losses of $NO_3^- - N$ were moderately sensitive to the $NO_3^- - N$ extraction coefficient and the organic waste $NO_3^- - N$ and $NH_4^+ - N$ contents. Nitrate runoff loss predictions were mildly sensitive to the soil porosity, pH, initial soil surface layer organic matter and $NO_3^- - N$ content, rainfall N concentration, fraction of applied waste in the surface layer, and the nitrification rate constant. The categories of mildly, moderately, and extremely sensitive

Table 31. Relative deviation of CREAMS-NT predictions due to changes in input parameters.

	$NO_3^- - N$	$NH_4^+ - N$	Org-N	P_{sb}	P_{TF}	P_T
			---------(%)---------			
Soil porosity						
-50%	-19.86	-30.30	0.00	0.00	21.38	2.56
-25%	-4.37	-10.81	0.00	0.00	5.03	0.60
-10%	-0.95	-3.53	0.00	0.00	1.89	0.23
+10%	0.24	2.57	0.00	0.00	-1.26	-0.15
+25%	-0.35	5.46	0.00	0.00	-3.14	-0.38
+50%	-2.60	8.03	0.00	0.00	-6.92	-0.83
Soil moisture content at field capacity						
-50%	0.83	0.00	0.00	0.00	0.00	0.00
-25%	0.24	0.00	0.00	0.00	0.00	0.00
-10%	0.12	0.00	0.00	0.00	0.00	0.00
+10%	-0.12	0.00	0.00	0.00	0.00	0.00
+25%	-0.24	0.00	0.00	0.00	0.00	0.00
+50%	-0.35	0.00	0.00	0.00	0.00	0.00
Soil moisture content at wilting point						
-50%	0.83	-1.50	0.00	0.00	0.00	0.00
-25%	0.47	-0.86	0.00	0.00	0.00	0.00
-10%	0.24	-0.43	0.00	0.00	0.00	0.00
+10%	-0.24	0.43	0.00	0.00	0.00	0.00
+25%	-0.59	0.96	0.00	0.00	0.00	0.00
+50%	-1.30	2.25	0.00	0.00	0.00	0.00
Soil surface layer organic matter content						
-50%	1.30	0.00	0.00	0.00	0.00	0.00
-25%	0.59	0.00	0.00	0.00	0.00	0.00
-10%	0.24	0.00	0.00	0.00	0.00	0.00
+10%	-0.24	0.00	0.00	0.00	0.00	0.00
+25%	-0.71	0.00	0.00	0.00	0.00	0.00
+50%	-1.30	0.00	0.00	0.00	0.00	0.00
Soil bulk density						
-50%	-0.47	4.60	97.16	97.09	0.00	85.46
-25%	-0.12	1.50	33.64	33.65	0.00	29.62
-10%	-0.12	0.43	10.44	10.45	0.00	9.19
+10%	0.00	-0.43	-8.62	-8.56	0.00	-7.54
+25%	0.00	-0.86	-20.11	-20.12	0.00	-17.71
+50%	0.00	-1.28	-33.00	-32.96	0.00	-29.01
Soil pH						
-50%	-1.77	7.07	0.04	0.00	0.00	0.00
-25%	-1.89	7.39	0.02	0.00	0.00	0.00
-10%	-0.47	3.00	0.02	0.00	0.00	0.00
+10%	1.65	-3.10	0.00	0.00	0.00	0.00
+25%	4.02	-7.82	0.00	0.00	0.00	0.00
+50%	-1.89	5.67	0.00	0.00	0.00	0.00

	$NO_3^- - N$	$NH_4^+ - N$	Org-N	P_{sb}	P_{TF}	P_T
			(%)			

Soil cation exchange capacity

	$NO_3^- - N$	$NH_4^+ - N$	Org-N	P_{sb}	P_{TF}	P_T
-50%	-0.35	-3.32	0.00	0.00	0.00	0.00
-25%	-0.12	-1.71	0.00	0.00	0.00	0.00
-10%	-0.12	-0.75	0.00	0.00	0.00	0.00
+10%	0.00	0.64	0.00	0.00	0.00	0.00
+25%	0.12	1.71	0.00	0.00	0.00	0.00
+50%	0.24	3.43	0.00	0.00	0.00	0.00

Initial soil surface layer NO_3^- -N content

-50%	-2.01	0.00	0.00	0.00	0.00	0.00
-25%	-1.06	0.00	0.00	0.00	0.00	0.00
-10%	-0.47	0.00	0.00	0.00	0.00	0.00
+10%	0.35	0.00	0.00	0.00	0.00	0.00
+25%	0.95	0.00	0.00	0.00	0.00	0.00
+50%	2.01	0.00	0.00	0.00	0.00	0.00

Initial soil surface layer NH_4^+-N content

-50%	-0.35	-3.21	0.00	0.00	0.00	0.00
-25%	-0.24	-1.61	0.00	0.00	0.00	0.00
-10%	-0.12	-0.64	0.00	0.00	0.00	0.00
+10%	0.00	0.64	0.00	0.00	0.00	0.00
+25%	0.12	1.50	0.00	0.00	0.00	0.00
+50%	0.24	3.10	0.00	0.00	0.00	0.00

Initial soil surface layer organic-N content

-50%	-0.12	-0.64	-48.54	0.00	0.00	0.00
-25%	0.00	-0.21	-24.26	0.00	0.00	0.00
-10%	0.00	-0.11	-9.70	0.00	0.00	0.00
+10%	0.00	0.00	9.70	0.00	0.00	0.00
+25%	0.00	0.21	24.28	0.00	0.00	0.00
+50%	0.00	0.32	48.56	0.00	0.00	0.00

Initial soil surface layer soluble P content

-50%	0.00	0.00	0.00	0.00	-25.79	-3.09
-25%	0.00	0.00	0.00	0.00	-12.58	-1.51
-10%	0.00	0.00	0.00	0.00	-5.03	-0.60
+10%	0.00	0.00	0.00	0.00	5.03	0.60
+25%	0.00	0.00	0.00	0.00	13.21	1.58
+50%	0.00	0.00	0.00	0.00	25.79	3.09

Initial soil surface layer adsorbed P content

-50%	0.00	0.00	0.00	-44.43	0.00	-39.11
-25%	0.00	0.00	0.00	-22.17	0.00	-19.52
-10%	0.00	0.00	0.00	-8.82	0.00	-7.76
+10%	0.00	0.00	0.00	8.82	0.00	7.76
+25%	0.00	0.00	0.00	22.17	0.00	19.52
+50%	0.00	0.00	0.00	44.52	0.00	39.19

NO_3^--N extraction coefficient

-50%	-39.95	0.00	0.00	0.00	0.00	0.00
-25%	-18.68	0.00	0.00	0.00	0.00	0.00

	$NO_3^- - N$	$NH_4^+ - N$	Org-N	P_{sb}	P_{TF}	P_T
			(%)			
-10%	-7.68	0.00	0.00	0.00	0.00	0.00
+10%	7.45	0.00	0.00	0.00	0.00	0.00
+25%	17.61	0.00	0.00	0.00	0.00	0.00
+50%	35.82	0.00	0.00	0.00	0.00	0.00

NH_4^+-N extraction coefficient

-50%	0.24	-23.34	0.00	0.00	0.00	0.00
-25%	0.12	-10.28	0.00	0.00	0.00	0.00
-10%	0.00	-3.96	0.00	0.00	0.00	0.00
+10%	-0.12	3.53	0.00	0.00	0.00	0.00
+25%	-0.12	8.24	0.00	0.00	0.00	0.00
+50%	-0.24	15.20	0.00	0.00	0.00	0.00

Soluble P extraction coefficient

-50%	0.00	0.00	0.00	0.00	-47.80	-5.73
-25%	0.00	0.00	0.00	0.00	-23.90	-2.86
-10%	0.00	0.00	0.00	0.00	-9.43	-1.13
+10%	0.00	0.00	0.00	0.00	9.43	1.13
+25%	0.00	0.00	0.00	0.00	23.27	2.79
+50%	0.00	0.00	0.00	0.00	44.03	5.28

NH_4^+-N enrichment ratio coefficient

-50%	0.00	-3.00	0.00	0.00	0.00	0.00
-25%	0.00	-1.50	0.00	0.00	0.00	0.00
-10%	0.00	-0.64	0.00	0.00	0.00	0.00
+10%	0.00	0.54	0.00	0.00	0.00	0.00
+25%	0.00	1.39	0.00	0.00	0.00	0.00
+50%	0.00	2.89	0.00	0.00	0.00	0.00

NH_4^+-N enrichment ratio exponent

-50%	0.00	6.10	0.00	0.00	0.00	0.00
-25%	0.00	2.46	0.00	0.00	0.00	0.00
-10%	0.00	0.86	0.00	0.00	0.00	0.00
+10%	0.00	-0.86	0.00	0.00	0.00	0.00
+25%	0.00	-1.82	0.00	0.00	0.00	0.00
+50%	0.00	-3.10	0.00	0.00	0.00	0.00

Organic-N enrichment ratio coefficient

-50%	0.00	0.00	-49.87	0.00	0.00	0.00
-25%	0.00	0.00	-24.94	0.00	0.00	0.00
-10%	0.00	0.00	-9.95	0.00	0.00	0.00
+10%	0.00	0.00	9.95	0.00	0.00	0.00
+25%	0.00	0.00	24.89	0.00	0.00	0.00
+50%	0.00	0.00	49.68	0.00	0.00	0.00

Organic-N enrichment ratio exponent

-50%	0.00	0.00	97.21	0.00	0.00	0.00
-25%	0.00	0.00	40.47	0.00	0.00	0.00
-10%	0.00	0.00	14.73	0.00	0.00	0.00
+10%	0.00	0.00	-12.83	0.00	0.00	0.00
+25%	0.00	0.00	-28.81	0.00	0.00	0.00
+50%	0.00	0.00	-49.34	0.00	0.00	0.00

	NO$_3^-$–N	NH$_4^+$–N	Org-N	P$_{sb}$	P$_{TF}$	P$_T$
			(%)			
P enrichment ratio coefficient						
-50%	0.00	0.00	0.00	-49.91	0.00	-43.93
-25%	0.00	0.00	0.00	-24.91	0.00	-21.93
-10%	0.00	0.00	0.00	-9.93	0.00	-8.74
+10%	0.00	0.00	0.00	9.93	0.00	8.74
+25%	0.00	0.00	0.00	24.83	0.00	21.85
+50%	0.00	0.00	0.00	49.66	0.00	43.71
P enrichment ratio exponent						
-50%	0.00	0.00	0.00	288.78	0.00	254.18
-25%	0.00	0.00	0.00	96.83	0.00	85.23
-10%	0.00	0.00	0.00	31.51	0.00	27.73
+10%	0.00	0.00	0.00	-24.66	0.00	-21.70
+25%	0.00	0.00	0.00	-49.23	0.00	-43.33
+50%	0.00	0.00	0.00	-74.40	0.00	-65.49
Rainfall N concentration						
-50%	-7.92	-15.52	0.00	0.00	0.00	0.00
-25%	-4.02	-7.82	0.00	0.00	0.00	0.00
-10%	-1.65	-3.10	0.00	0.00	0.00	0.00
+10%	1.54	3.00	0.00	0.00	0.00	0.00
+25%	3.90	7.71	0.00	0.00	0.00	0.00
+50%	7.80	15.42	0.00	0.00	0.00	0.00
Organic waste NO$_3^-$ -N content						
5 kg/ha	7.45	0.00	0.00	0.00	0.00	0.00
10 hg/ha	14.89	0.00	0.00	0.00	0.00	0.00
25 kg/ha	37.35	0.00	0.00	0.00	0.00	0.00
Organic waste NH$_4^+$-N content						
-50%	-29.08	-29.98	0.00	0.00	0.00	0.00
-25%	-14.54	-14.99	0.00	0.00	0.00	0.00
-10%	-5.79	-6.00	0.00	0.00	0.00	0.00
+10%	5.79	5.89	0.00	0.00	0.00	0.00
+25%	14.54	14.88	0.00	0.00	0.00	0.00
+50%	29.08	29.87	0.00	0.00	0.00	0.00
Organic waste Organic-N content						
-50%	0.00	-0.32	-1.46	0.00	0.00	0.00
-25%	0.00	-0.11	-0.72	0.00	0.00	0.00
-10%	0.00	-0.11	-0.28	0.00	0.00	0.00
+10%	0.00	0.00	0.30	0.00	0.00	0.00
+25%	0.00	0.11	0.74	0.00	0.00	0.00
+50%	0.00	0.11	1.48	0.00	0.00	0.00
Organic waste P content						
-50%	0.00	0.00	0.00	-5.65	-23.90	-7.84
-25%	0.00	0.00	0.00	-2.83	-11.95	-3.92
-10%	0.00	0.00	0.00	-1.11	-5.03	-1.58
+10%	0.00	0.00	0.00	1.11	5.03	1.58
+25%	0.00	0.00	0.00	2.83	11.95	3.92
+50%	0.00	0.00	0.00	5.65	24.53	7.91

	NO$_3^-$ -N	NH$_4^+$ -N	Org-N	P$_{sb}$	P$_{TF}$	P$_T$
			----(%)----			

Fraction of applied waste in surface one centimeter of soil

-50%	-1.06	-29.66	-1.44	-5.48	-23.90	-7.69
-25%	-0.59	-15.31	-0.74	-2.83	-11.95	-3.92
-10%	-0.24	-6.32	-0.30	-1.20	-5.03	-1.66
+10%	0.24	6.21	0.32	1.20	5.03	1.66
+25%	0.47	15.20	0.76	2.83	12.58	3.99
+50%	0.95	29.55	1.46	5.57	23.90	7.76

Mineralization rate constant

-50%	-0.12	-1.50	0.04	0.00	0.00	0.00
-25%	-0.12	-0.86	0.02	0.00	0.00	0.00
-10%	0.00	-0.32	0.02	0.00	0.00	0.00
+10%	0.00	0.21	0.00	0.00	0.00	0.00
+25%	0.00	0.75	0.00	0.00	0.00	0.00
+50%	0.12	1.50	-0.02	0.00	0.00	0.00

Temperature associated with mineralization rate constant

-50%	0.59	6.75	-0.13	0.00	0.00	0.00
-25%	0.24	2.36	-0.04	0.00	0.00	0.00
-10%	0.00	0.75	0.00	0.00	0.00	0.00
+10%	-0.12	-0.64	0.02	0.00	0.00	0.00
+25%	-0.12	-1.39	0.04	0.00	0.00	0.00
+50%	-0.24	-2.14	0.06	0.00	0.00	0.00

Nitrification rate constant

-50%	-2.84	5.14	0.00	0.00	0.00	0.00
-25%	-1.42	2.46	0.00	0.00	0.00	0.00
-10%	-0.59	0.96	0.00	0.00	0.00	0.00
+10%	0.47	-0.96	0.00	0.00	0.00	0.00
+25%	1.30	-2.46	0.00	0.00	0.00	0.00
+50%	2.48	-4.71	0.00	0.00	0.00	0.00

Temperature associated with nitrification rate constant

-50%	4.02	-7.60	0.00	0.00	0.00	0.00
-25%	1.77	-3.43	0.00	0.00	0.00	0.00
-10%	0.71	-1.28	0.00	0.00	0.00	0.00
+10%	-0.71	1.07	0.00	0.00	0.00	0.00
+25%	-1.42	2.57	0.00	0.00	0.00	0.00
+50%	-2.60	4.71	0.00	0.00	0.00	0.00

Volatilization rate constant

-50%	0.59	8.14	0.00	0.00	0.00	0.00
-25%	0.24	3.53	0.00	0.00	0.00	0.00
-10%	0.12	1.39	0.00	0.00	0.00	0.00
+10%	-0.12	-1.39	0.00	0.00	0.00	0.00
+25%	-0.35	-3.43	0.00	0.00	0.00	0.00
+50%	-0.59	-7.28	0.00	0.00	0.00	0.00

Temperature associated with volatilization rate constant

-50%	-0.83	-9.10	0.00	0.00	0.00	0.00
-25%	-0.35	-4.18	0.00	0.00	0.00	0.00

	$NO_3^- - N$	$NH_4^+ - N$	Org-N	P_{sb}	P_{TF}	P_T
			(%)			
-10%	-0.12	-1.61	0.00	0.00	0.00	0.00
+10%	0.12	1.39	0.00	0.00	0.00	0.00
+25%	0.24	3.32	0.00	0.00	0.00	0.00
+50%	0.47	6.10	0.00	0.00	0.00	0.00

NH_4^+-N adsorption rate constant

-50%	-0.71	8.89	0.00	0.00	0.00	0.00
-25%	-0.35	4.28	0.00	0.00	0.00	0.00
-10%	-0.12	1.71	0.00	0.00	0.00	0.00
+10%	0.12	-1.71	0.00	0.00	0.00	0.00
+25%	0.24	-4.07	0.00	0.00	0.00	0.00
+50%	0.35	-7.49	0.00	0.00	0.00	0.00

NH_4^+-N desorption rate constant

-50%	0.71	-13.38	0.00	0.00	0.00	0.00
-25%	0.24	-5.25	0.00	0.00	0.00	0.00
-10%	0.12	-1.82	0.00	0.00	0.00	0.00
+10%	-0.12	1.50	0.00	0.00	0.00	0.00
+25%	-0.24	3.43	0.00	0.00	0.00	0.00
+50%	-0.47	5.89	0.00	0.00	0.00	0.00

correspond to relative deviations of model output ranging from 0 to 5, 5 to 25, and greater than 25 percent, respectively, with a 25 percent change in input parameter values. Model predictions of NH_4^+-N losses were moderately sensitive to the soil porosity, NH_4^+-N extraction coefficient, NH_4^+-N content of the organic waste, fraction of the applied waste in the surface one centimeter of soil, and the rainfall N concentration. Ammonium-N losses were mildly sensitive to the soil bulk density, pH, cation exchange capacity, initial soil surface layer NH_4^+-N content, enrichment ratio parameters, and the nitrification, volatilization, and NH_4^+-N adsorption/desorption rate constants. Model predictions of the sediment-bound nutrients, including organic-N and P_{sb}, were extremely sensitive to the enrichment ratio exponents and the soil bulk density, moderately sensitive to the enrichment ratio coefficients and initial soil surface layer organic N and adsorbed P content, and slightly sensitive to the fraction of applied waste in the surface layer and the nutrient content of the organic waste. Soluble P losses were moderately sensitive to the soil porosity, soluble P content of the initial soil, P extraction coefficient, organic waste P content, and depth of application. Although not shown, CREAM-NT was not sensitive to variations in the amount of organic waste applied, the C:N ratio and pH of the waste, and wind velocities immediately following waste application. The sensitivity of the model to changes in the remaining input parameters is shown in Table 31. On surface-applied plots, the model was approximately twice as sensitive to the input parameters describing volatilization rates and organic waste characteristics and roughly half as sensitive to the parameters defining initial soil nutrient contents, as compared to the results for incorporated plots.

Since the runoff volume and sediment yield predictions generated by CREAMS were calibrated to match observed losses as closely as possible, the impact of these parameters on CREAMS-NT predictions was not evaluated. Variations in the output from the hydrologic and erosion components, however, would directly affect nutrient loss predictions. Based on the results of the sensitivity analysis, the parameters describing the soil bulk density, initial soil nutrient content, extraction coefficients, enrichment ratio relationships, and organic waste nutrient contents are the most critical in terms of model accuracy. Efforts in determining input parameter values and additional research

should, therefore, concentrate on these parameters. Of these parameters, the extraction coefficients and enrichment ratio parameters are the most difficult to determine. As suggested by Frere et al. (1980), values in the range of 0.05 to 0.10 for the extraction coefficients will provide reasonable estimates of soluble nutrient losses. For a short-term simulation as described in the preceding chapter, the use of a value in this range for $NO_3^- -N$, $NH_4^+ -N$, and P_{TF} would result in a maximum relative error of prediction of soluble nutrient losses of approximately $\pm$ 50%. The input values used to describe the enrichment ratio relationships, however, can have a much greater impact on the accuracy of model predictions. For the simulations described above, the use of an enrichment ratio coefficient of 7.4 and an exponent of -0.2 (Frere et al., 1980) for organic-N and P_{sb} would have resulted in a relative error of prediction ranging from $\pm$ 40 to $\pm$ 400%. Frere et al. (1980) indicated that the accuracy of model inputs is more critical for individual runoff events than for long-term simulations. Field characteristics are transient in nature. Estimates of input parameters usually describe an average of the range expected in the field and are, therefore, more representative of the system over a long-term simulation. Based on this information, extreme care should be taken in determining input parameter values and in interpreting model results for short-term simulations.

POTENTIAL MODEL APPLICATIONS

Due to the numerous management options available to landowners for reducing nonpoint source pollution, it is impractical to monitor the runoff water quality resulting from each of the various management schemes. For this reason, computer models are often employed to select the BMP's to be implemented. The selection of BMP's on a field-sized area is dependent on many factors including the soil and nutrient loss reduction goal, potential problems associated with the presence of sediment and nutrients in surface and groundwaters, effects on crop production, and costs. In addition to weighing the importance of these factors, the planner must also consider the uncertainty of model predictions. As indicated in the preceding chapter, the degree of uncertainty in model results is dependent on the accuracy of the values used for input parameters. While the absolute value of model predictions may be in question, relative differences in sediment and nutrient losses under various BMP's can be evaluated with reasonable confidence.

An example of how CREAMS-NT may be used is to compare the relative differences in sediment and nutrient losses under different management schemes and fertilizer sources. In this chapter, an example of the model's application is presented. In addition, the predictive capability of CREAMS-NT in relation to the N content in the surface and root zone soil layers is illustrated.

Scenario Descriptions and Parameter Estimation

The field used to demonstrate the use of CREAMS-NT is located in the Georgia Piedmont region. This field was used by Foster et al. (1980a) to demonstrate the use of the original CREAMS model. The field consists of approximately 1.3 ha (3.2 acres). The gently rolling topography of the field is typical of Piedmont cropland. Drainage from the field is restricted at the fence line which causes some temporary ponding of runoff. The soil is a sandy loam. It was assumed that continuous corn is grown on the field. The period of simulation was one year. The scenarios simulated include conventional tillage with no fertilizer applied (1), commerical fertilizer incorporated to a depth of 15 cm at a rate of 150 kg-N/ha (2), anaerobically digested sewage sludge incorporated into the soil at rates supplying 75 and 150 kg/ha of plant available N (3 and 4), sludge surface-applied at a rate of 150 kg/ha of plant available N (5), and no-till with sludge surface-applied at a rate of 150 kg/ha of plant available N (6).

For this example, the first hydrologic option of CREAMS was utilized. This option estimates runoff volumes from daily rainfall amounts using the SCS curve number method (Equation 52). The daily rainfall amounts were taken from Foster et al. (1980a) for the 1975 calendar year. The input to the hydrologic and erosion components of CREAMS was also obtained from Foster et al. (1980a) to represent the scenarios with no sludge applied. Based on the results of the plot studies, the SCS curve number and USLE C-factor parameters given in Foster et al. (1980a) were decreased and the saturated hydraulic conductivity and Manning's n values were increased (Table 32) to reflect the impacts of sludge application on the hydrologic and erosion response of this field. For the purposes of these simulations, it was assumed that the applied sludge acted as a mulch-type cover. The input parameters were then adjusted accordingly. A detailed description of parameter estimation procedures is available in Foster et al. (1980a).

Table 32. CREAMS - NT input parameters for individual scenarios.

Parameter	Scenario* 1	2	3	4	5	6
SCS Curve Number	80.0	80.0	79.0	77.0	77.0	73.0
Saturated Conductivity (cm/hr)	0.48	0.48	0.56	0.71	0.71	0.76
USLE C-factor:						
01/01 - 04/04	0.26	0.26	0.26	0.26	0.26	0.15
04/15 - 04/30	0.40	0.40	0.40	0.40	0.40	0.15
05/01 - 05/29	0.62	0.62	0.61	0.60	0.59	0.06
05/30 - 06/13	0.54	0.54	0.52	0.50	0.48	0.05
06/14 - 06/28	0.42	0.42	0.41	0.40	0.38	0.05
06/29 - 07/18	0.20	0.20	0.20	0.20	0.19	0.05
07/19 - 09/30	0.20	0.20	0.20	0.20	0.20	0.05
10/01 - 12/31	0.20	0.20	0.20	0.20	0.20	0.07
Manning's n:						
01/01 - 04/14	0.03	0.03	0.03	0.03	0.03	0.03
04/15 - 14/30	0.03	0.03	0.03	0.03	0.03	0.03
05/10 - 05/29	0.01	0.01	0.01	0.01	0.01	0.03
05/30 - 06/13	0.01	0.01	0.01	0.01	0.02	0.03
06/14 - 16/28	0.01	0.01	0.01	0.01	0.01	0.03
06/29 - 07/18	0.01	0.01	0.01	0.01	0.01	0.03
07/19 - 09/30	0.01	0.01	0.01	0.01	0.01	0.03
10/01 - 12/31	0.04	0.04	0.04	0.04	0.04	0.04
Fertilizer $NO_3^- - N$ (kg/ha)	---	116.0	0.0	0.0	0.0	0.0
Fertilizer $NH_4^+ - N$ (kg/ha)	---	34.0	55.8	111.7	111.7	111.7
Fertilizer Organic-N (kg/ha)	---	0.0	119.2	238.5	238.5	238.5
Fertilizer P (kg/ha)	---	50.0	116.1	232.2	232.2	232.2
Fraction of Fertilizer in Surface Layer	---	0.067	0.067	0.067	1.000	1.000
Fertilizer Applied (kg/ha)	---	375	36287	72575	72575	72575
Fertilizer C:N	---	0.0	10.0	10.0	10.0	10.0
Fertilizer pH	---	5.5	7.3	7.3	7.3	7.3
$NH_4^+ - N$ Adsorption Rate Constant (day^{-1})	---	1.0	1.0	1.0	1.0	1.0
NH_4^+ Desorption Rate Constant (day^{-1})	---	1.0	1.0	1.0	1.0	1.0

Table 32 (Cont.).	1	2	3	4	5	6
Mineralization Rate Constant (day⁻¹)	---	0.008	0.022	0.022	0.022	0.022
Temperature Associated with Mineralization Rate Constant (°C)	---	35.0	35.0	35.0	35.0	35.0
Nitrification Rate Constant (day⁻¹)	---	0.080	0.400	0.400	0.400	0.400
Temperature Associated with Nitrification Rate Constant (°C)	---	21.0	21.0	21.0	21.0	21.0
Volatilization Rate Constant (day⁻¹)	---	0.210	0.210	0.210	0.210	0.210
Temperature Associated with Volatilization Rate Constant (°C)	---	21.0	21.0	21.0	21.0	21.0

* 1 = CT - No Ferilizer
2 = CT - 150 kg/ha NH_4NO_3, Incorporated
3 = CT - 75 kgN/ha Sludge, Incorporated
4 = CT - 150 kgN/ha Sludge, Incorporated
5 = CT - 150 kgN/ha Sludge, Surface-applied
6 = NT - 150 kgN/ha Sludge, Surface-applied

The input parameters needed for the nutrient component of CREAMS-NT describing soil physical properties, nutrient transport characteristics, and plant N uptake parameters were obtained from Foster et al. (1980a) and are shown in Table 33. Soil pH and CEC values for a sandy loam soil in the Georgia Piedmont region were estimated from figures presented by Brady (1974). The N transformation rate constants were estimated using the methods described in the "Model Development" and "Model Verification" chapters (Tables 32 and 33). For this application, it was assumed that 1975 was the first year that sludge was applied. The initial soil nutrient contents given in Foster et al. (1980a) were converted to the appropriate units and input to the model (Table 33). It was assumed that the applied commerical fertilizer has a N:P ratio of 3:1 and that the N was applied as NH_4NO_3. The applied sludge was assumed to be identical to that used in plot simulations (Table 32).

Runoff, Sediment, and Nutrient Losses

The simulated runoff, sediment, and nutrient losses for these management scenarios are shown in Table 34. As indicated in Table 34, the application of sludge to conventional tillage treatments reduced runoff and sediment yields by as much as 20 and 35 percent, respectively, as compared to the control and commerical fertilizer scenarios. The corresponding reductions resulting from the no-till sludge treatment were 40 and 72 percent. The greatest $NO_3^- - N$ yield resulted from the commerical fertilizer treatment. Nitrate-N yields were lower from all of the sludge treatments. The differences in $NO_3^- - N$ yields between treatments may be attributed to the original N form of these two fertilizer sources (Table 32). Ammonium-N, organic-N, P_{sb}, and P_{TF} yields were greatest from the conventional tillage, surface-applied sludge treatment (Table 34). Approximately two-thirds of the N applied with sludge was assumed to be in the organic-N form. Only 25% of the sludge organic-N was assumed to be plant-available within the first growing season (Simpson et al. 1985). Because the fertilizer loading rates were based on plant-available N, the total amount of N and P

Table 33. CREAMS-NT input parameters used for all scenarios.

Parameter	Value	Parameter	Value
Surface organic matter (%)	1.0	Organic-N and NH_4^+ −N enrichment ratio coefficient	16.8
Root zone organic matter (%)	0.5	Organic-N and NH_4^+ −N enrichment ratio exponent	-0.16
Soil pH	5.5	P enrichment ratio coefficient	11.2
Soil CEC (meq/100g)	5.5	P enrichment ratio exponent	-0.146
Surface NO_3^- -N (kg/ha)	0.2	Rainfall N concentration (mg/l)	0.8
Surface NH_4^+-N (kg/ha)	0.2	Soil NH_4^+ −N adsorption rate constant (day^{-1})	1.0
Surface organic-N (kg/ha)	52.3	Soil NH_4^+ −N desorption rate constant (day^{-1})	0.2
Surface soluble P (kg/ha)	0.2	Soil nitrification rate constant (day^{-1})	0.08
Surface adsorbed P (kg/ha)	27.0	Temperature associated with nitrification rate constant (°C)	21.0
Root zone inorganic N (kg/ha)	20.0	Crop yield potential (kg/ha)	5700.0
Root zone organic N (kg/ha)	1376.7	Dry matter to crop yield ratio	2.5
Root zone depth (mm)	450.0	Growth required for 50% N uptake (days)	73.0
NO_3^--N extraction coefficient	0.0576	Standard deviation of N uptake	30.0
NH_4^+-N extraction coefficient	0.0576	Potential N uptake (kg/ha)	250.0
Soluble P extraction coefficient	0.07		

Table 34. Simulated runoff, sediment, and nutrient losses from a Georgia Piedmont field-sized area.

Scenario	Runoff (cm)	Sediment (Mg/ha)	$NO_3^- - N$	$NH_4^+ - N$	Organic-N (kg/ha)	P_{sb}	P_{TF}
CT - No Fertilizer	18.9	18.0	0.934	1.283	12.570	5.047	0.645
CT - 150 kgN/ha NH_4NO_3, Incorporated	18.9	18.0	1.472	1.256	12.563	5.328	0.649
CT - 75 kgN/ha Sludge, Incorporated	17.6	16.6	1.014	1.176	12.359	5.305	0.607
CT - 150 kgN/ha Sludge, Incorporated	15.2	14.1	1.015	1.029	10.818	4.820	0.531
CT - 150 kgN/ha Sludge, Surface-Applied	15.2	11.8	0.892	1.467	28.642	17.629	0.665
NT - 150 kgN/ha Sludge, Surface-Applied	11.4	5.0	0.554	0.992	16.148	9.741	0.452

applied with the sludge treatment was approximately 2.3 and 4.6 times greater, respectively, than that of the commercial fertilizer treatment. Apparently the increase in nutrient availability due to the higher total nutrient loadings with sludge and the greater nutrient content in the surface layer resulting from surface application outweighed the decreases in runoff and sediment yield associated with this treatment. The lowest $NO_3^- -N$, $NH_4^+ -N$, and P_{TF} yields resulted from the no-till sludge treatment, while the lowest organic-N and P_{sb} yields resulted from the conventional tillage treatment where sludge was incorporated at a rate of 150 kg/ha of plant available N. With respect to sediment yields, the no-till scenario resulted in the least overall pollution potential for this field. For reducing total nutrient losses, however, the conventional tillage, sludge incorporated scenarios exhibited the least overall pollution potential. Based on the results of these simulations, it can be concluded that injecting sludge with no-till is the most effective method, followed by incorporating sludge with conventional tillage, for reducing N losses in surface runoff while still providing the required crop nutrients.

Soil N Levels

For scenario 4 (CT - 150 kg N/ha sludge, incorporated), a daily accounting of the soil N levels in the surface and root zone soil layers is plotted in Figures 9 and 10, respectively. These figures are provided to illustrate some of the additional capabilities of CREAMS-NT. The organic-N levels in both the surface layer and the root zone decrease slowly but continually throughout the growing season as a result of mineralization. This process is accelerated as a result of sludge application (Figures 9 and 10). Surface soil $NH_4^+ -N$ levels are affected by mineralization, nitrification, volatilization, runoff, and infiltration. Immediately following fertilizer application, the volatilization process has a significant impact on soil $NH_4^+ -N$ content (Figure 9). For the remainder of the year, however, soil $NH_4^+ -N$ levels remain low and relatively constant. Because nitrification rates are
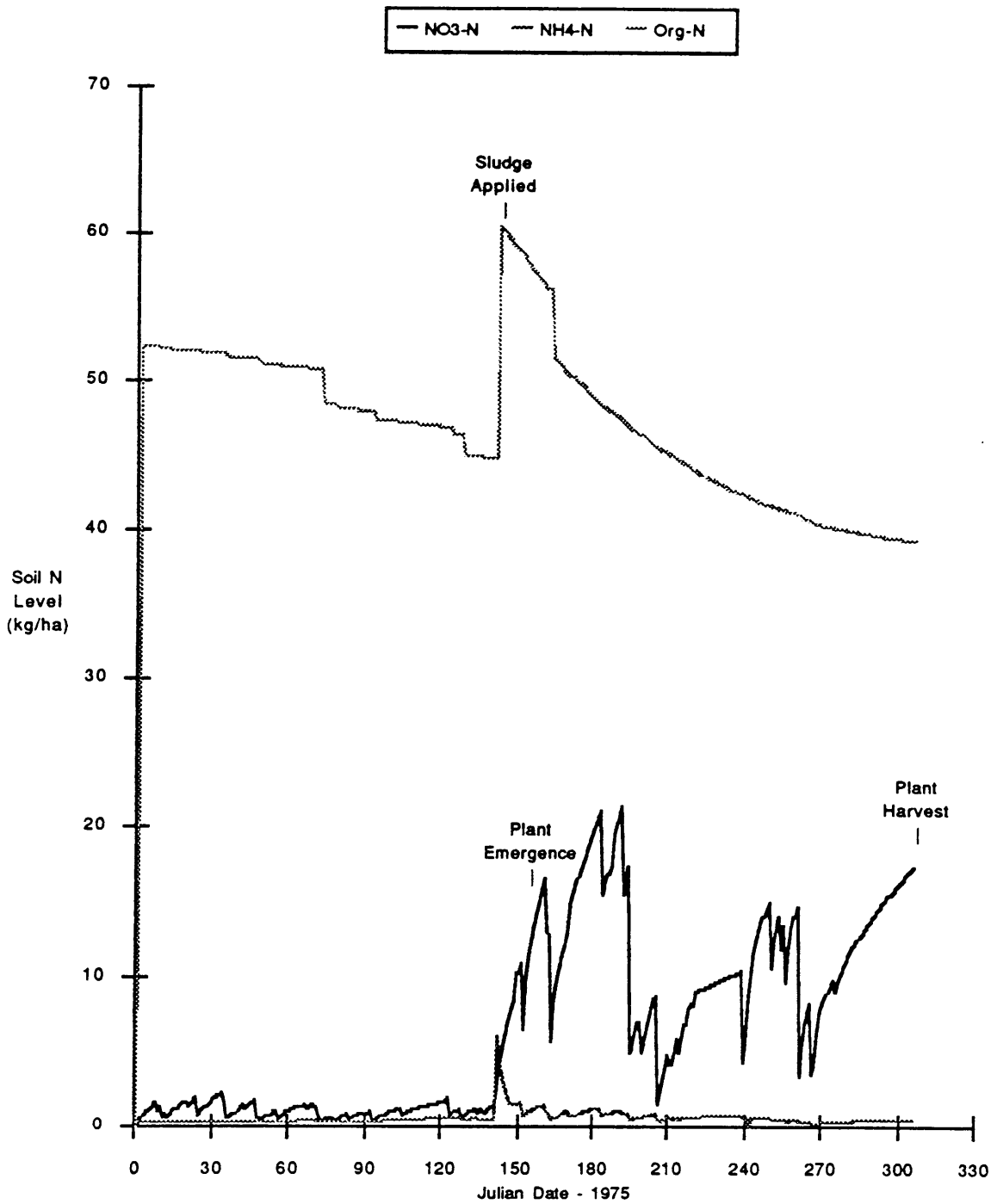
Figure 9. Surface layer soil N levels.
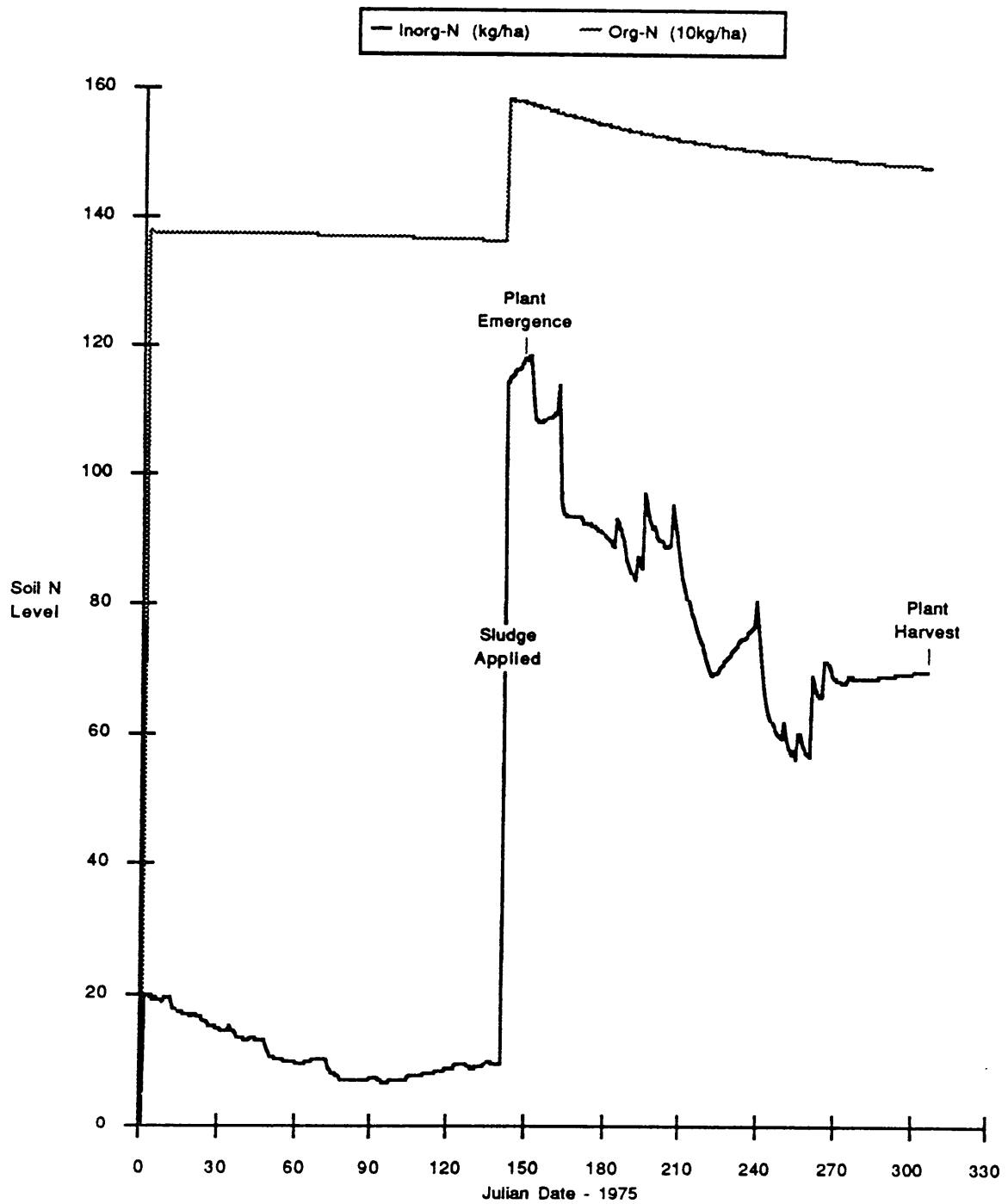
Figure 10. Root zone soil N levels.

generally much greater than mineralization rates, $NH_4^+ - N$ does not accumulate in the soil. Surface soil $NO_3^- - N$ levels vary considerably over time due to the many processes which affect this N pool (Figure 9). Since $NO_3^- - N$ is the end product of mineralization, $NO_3^- - N$ levels tend to accumulate in the soil. Between storm events, $NO_3^- - N$ is also transported from the root zone to the surface layer with evaporating water. Under moist field conditions, however, significant quantities of $NO_3^- - N$ can be lost from the surface layer through denitrification and the infiltration and runoff transport processes. Inorganic-N levels in the root zone are most affected by plant N uptake during the growing season and the mineralization of organic-N throughout the remainder of the year (Figure 10). A daily accounting of the soil N levels provides a quantitative representation of the N transformation and transport processes. Information describing the soil N content at various times throughout the year can also be utilized by the land planner to determine the required fertilizer application rates and the optimum dates for performing tillage operations. In addition, the potential for groundwater contamination under various management schemes can be assessed.

SUMMARY AND CONCLUSIONS

A summary of the three major components of this study, model development, field investigations of nutrient movement, and model verification, is presented in this section. The corresponding conclusions of this research are also given.

Model Development

CREAMS-NT, a modified version of the CREAMS model, was developed to simulate the N transformations and subsequent nutrient transport processes which occur in the soil following organic waste applications. The runoff volume and sediment yield predictions required by CREAMS-NT are provided by the original CREAMS model. The hydrologic component of CREAMS also supplies the necessary information on daily soil environmental conditions including soil temperatures and moisture contents. CREAMS-NT maintains a continuous balance of the organic-N and inorganic-N pools in the root zone. The root zone processes considered include fertilization, mineralization, infiltration, denitrification, leaching, diffusion, and plant uptake. Three N pools, organic-N, NH_4^+-N and NO_3^--N, are maintained in the surface soil layer.

CREAMS-NT utilizes first-order rate equations to describe the mineralization, nitrification, denitrification, and volatilization processes. The rate constants used in these equations are adjusted for environmental conditions using empirical relationships. Preceding a runoff event, $NH_4^+ - N$ is partitioned between the adsorbed and desorbed phases using a partition coefficient equivalent to the ratio of the adsorption to desorption rate constants. Sediment-bound nutrient transport is simulated using enrichment ratios. The transport of soluble nutrients in runoff and infiltrating water is estimated with empirical extraction coefficients.

The basic assumptions of CREAMS-NT include:

1. The original CREAMS model provides an adequate representation of the hydrologic and erosion response of a field-size area.

2. Applied nutrients are completely mixed within the soil to the maximum depth of application.

3. Only the nutrients in the surface one centimeter of soil are available to runoff processes.

4. The mineralization, nitrification, denitrification, and volatilization of the various N forms are a function of soil N content, time, and environmental conditions.

5. Net immobilization of organic N does not occur.

6. The $NH_4^+ - N$ adsorption/desorption equilibrium in instantaneous and independent of pH, temperature, and soil moisture content.

7. The transport of nutrients is adequately described using enrichment ratios and extraction coefficients. In addition, organic-N is transported only in sediment-bound form.

Field Plot Studies

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 and 150 kg/ha of 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:

1. No-till reduced soil loss and runoff by 73 and 54 percent, respectively, relative to conventional tillage. Sludge application significantly reduced runoff, peak runoff rates, and sediment concentrations and yields. Surface application of sludge reduced runoff volume by 25 percent relative to the incorporated treatments. Runoff volumes and peak runoff rates 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.

2. Orthophosphorus concentrations in runoff from all treatments exceeded the 0.01 mg/L level considered to prevent excessive algal growth in surface waters. Orthophosphorus concentrations were generally higher from no-till than conventional tillage plots, but $PO_4^- - P$ yields were slightly lower.

3. Ammonium-N, $NO_3^- - N$, TKN, and N_T concentrations and yields were greater with conventional tillage than with no-till, regardless of the sludge application method or rate.

4. 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.

5. 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.

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

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 concentrations and yields 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.

Model Verification

CREAMS-NT was verified using nutrient yield data obtained from eleven of the sixteen rainfall simulator study plots. The predicted yields were good for all nutrients when compared to the ob-

served data. The effects of tillage practice, sludge application method, and loading rate were also well represented by the model for $NO_3^- - N$, $NH_4^+ - N$, organic-N, and P_{sb} runoff losses. Values for the majority of the model input parameters can be estimated from available literature. Model predictions, particularly for short-term simulations, will improve through the use of experimentally determined input data. The parameters describing the soil porosity, bulk density, initial soil nutrient contents, extraction coefficients, enrichment ratio relationships, and organic waste nutrient loads are the most critical in terms of model accuracy.

CREAMS-NT shows great potential for use as a planning tool, evaluating the impact of BMPs on runoff water quality from agricultural lands. Although the model was developed specifically for use on agricultural fields treated with organic wastes, the equations used are applicable for the simulation of untreated fields as well as fields amended with commercial inorganic fertilizers.

RECOMMENDATIONS

For the purpose of model development, several assumptions and simplifications were made due to the limited information available on nutrient transformations and transport processes in soil/waste systems. Recommendations to guide future research are presented as follows:

1. The impact of waste application on the runoff and erosion response of agricultural lands needs to be quantified and related to model input parameters.

2. First-order rate constants used to simulate the N transformation processes need to be determined for a greater variety of soil/waste systems.

3. The effects of environmental conditions including soil temperatures, moisture contents, pH, and wind velocities on the N transformation processes need to be further investigated for the range of conditions experienced in the field. Research should be conducted to better define the combined effects of these conditions.

4. Research concentrating on the $NH_4^+ - N$ adsorption/ desorption process is needed to allow for more accurate simulation of the soluble and sediment-bound transport of $NH_4^+ - N$. This processes should be related to measurable field characteristics.

5. Procedures for estimating the extraction coefficient and enrichment ratio relationships as a function of management practice, soil characteristics, and cropping conditions must be developed. Once this information is available, CREAMS-NT should be modified to allow for variability in these parameters over the duration of simulation.

6. The N immobilization process should be incorporated into the model such that the water quality impact of carbonaceous waste applications may be simulated.

7. The P transformations and reactions in soils treated with organic wastes need to be investigated. The model should be expanded to provide a more complete representation of the P reactions which occur within the soil system.

8. Additional model verification over a wide range of conditions is required. These conditions should include the application of a variety of fertilizer sources, including both organic and inorganic fertilizers, and the implementation of various BMPs other than no-till.

9. Due to the nature of the processes considered, the model should be tested for long-term simulations.

10. The models ability to accurately predict the daily soil $NO_3^- -N$, $NH_4^+ -N$ and organic-N levels should be verified.

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APPENDICES

Appendix A: N Transformation Equations

Organic N:

$$(Org - N)_t = Org - N_{t-1}(e^{-K_{min}*\Delta t})$$

Ammonium N:

$$(NH_4)_t = \frac{K_{min}}{(K_{NIT} + K_{VOL} - K_{min})}(Org - N)_{t-1}(e^{-K_{min}*\Delta t} - e^{-(K_{NIT} + K_{VOL})*\Delta t})$$

$$+ (NH_4)_{t-1}(e^{-(K_{NIT} + K_{VOL})*\Delta t})$$

Nitrate N:

$$(NO_3)_t = \frac{K_{NIT}{}^*K_{min}}{(K_{NIT} + K_{VOL} - K_{min}){}^*(K_{DNI} - K_{min}(Org - N)_{t-1}(e^{-K_{min}{}^*\Delta t} - e^{-K_{DNI}{}^*\Delta t}))}$$

$$+ \frac{K_{NIT}{}^*K_{min}}{(K_{NIT} + K_{VOL} - K_{min}){}^*(K_{DNI} - K_{NIT} - K_{VOL})}(Org - N)_{t-1}(e^{-K_{DNI}{}^*\Delta t} - e^{-(K_{NIT} + K_{VOL}){}^*\Delta t})$$

$$+ \frac{K_{NIT}}{(K_{DNI} - K_{NIT} - K_{VOL})}(NH_4)_{t-1}(e^{-(K_{NIT} + K_{VOL}){}^*\Delta t} - e^{-K_{DNI}{}^*\Delta t})$$

$$+ (NO_3)_{t-1}(e^{-K_{DNI}{}^*\Delta t})$$

Ammonia N:

$$(NH_3)_t = \frac{K_{VOL}{}^*K_{min}}{(K_{NIT} + K_{VOL} - K_{min}){}^*(K_{NIT} + K_{VOL})}(Org - N)_{t-1}(e^{-(K_{NIT} + K_{VOL}){}^*\Delta t} - 1)$$

$$+ \frac{K_{VOL}}{(K_{NIT} + K_{VOL} - K_{min})}(Org - N)_{t-1}(1 - e^{-K_{min}{}^*\Delta t})$$

$$+ \frac{K_{VOL}}{(K_{NIT} + K_{VOL})}(NH_4)_{t-1}(1 - e^{-(K_{NIT} + K_{VOL}){}^*\Delta t})$$

Nitrous Oxide and Molecular N:

$$N_2O, N_2 = \frac{K_{DNI}{}^*K_{NIT}}{(K_{NIT} + K_{VOL} - K_{min}){}^*(K_{DNI} - K_{min})} (Org - N)_{t-1}(1 - e^{-K_{min}{}^*\Delta t})$$

$$+ \frac{K_{NIT}{}^*K_{min}}{(K_{NIT} + K_{VOL} - K_{min}){}^* (K_{DNI} - K_{min})} (Org - N)_{t-1}(e^{-K_{DNI}{}^*\Delta t} -1)$$

$$+ \frac{K_{NIT}{}^*K_{min}}{(K_{NIT} + K_{VOL} - K_{min}){}^*(K_{DNI} - K_{NIT} - K_{VOL})} (Org - N)_{t-1}(1 - e^{-K_{DNI}{}^*\Delta t})$$

$$+ \frac{K_{DNI}{}^*K_{NIT}{}^*K_{min}}{(K_{NIT} + K_{VOL} - K_{min}){}^*(K_{DNI} - K_{NIT} - K_{VOL}){}^*(K_{NIT} + K_{VOL})}$$

$$^*(Org - N)_{t-1}(e^{- (K_{NIT} + K_{VOL}){}^*\Delta t} -1)$$

$$+ \frac{K_{NIT}}{(K_{DNI} - K_{NIT} - K_{VOL})} (NH_4)_{t-1}(e^{-K_{DNI}{}^*\Delta t} -1)$$

$$+ \frac{K_{NIT}{}^*K_{DNI}}{(K_{DNI} - K_{NIT} - K_{VOL}){}^*(K_{NIT} + K_{VOL})} (NH_4)_{t-1}(1 - e^{- (K_{NIT} + K_{VOL}){}^*\Delta t})$$

$$+ (NO_3)_{t-1}(1 - e^{-K_{DNI}{}^*\Delta t})$$

Appendix B: CREAMS-NT Variable Listing

Variable	Unit	Type *	Description
ACCPEV	(mm)	RV	Actual transpiration from plants for period between storms
ACCSEV	(mm)	RV	Actual evaporation from soil for period between storms
ACEC	(meq/100g soil)	RA	Cation exchange capacity of the soil corresponding to the input volatilization rate constant.
ADST	(°C)	RV	Average daily soil temperature
AKADS	(day⁻¹)	RA	NH_4^+-N adsorption rate constant for soil/waste system
AKDES	(day⁻¹)	RA	NH_4^+-N desorption rate constant for soil/waste system
AKMIN	(day⁻¹)	RA	Mineralization rate constant for soil/waste system
AKNIT	(day⁻¹)	RA	Nitrification rate constant for soil/waste system
AKVOL	(day⁻¹)	RA	Volatilization rate constant for soil/waste system
AMN	(kg/ha)	RV	Cummulative amount of N mineralized in the root zone
ANH4		RV	Enrichment ratio coefficient for NH_4^+-N
AORN		RV	Enrichment ratio coefficient for organic -N
AP		RV	Enrichment ratio coefficient for P
ARN	(kg/ha)	RV	Cummulative amount of N added with rainfall
ARSW	(mm³/mm³)	RV	Average daily root zone volumetric water content
ASSW	(mm³/mm³)	RV	Average daily surface layer volumetric water content
ATMIN	(°C)	RA	Soil temperature corresponding to the input mineralization rate constant
ATNIT	(°C)	RA	Soil temperature corresponding to the input nitrification rate constant
ATVOL	(°C)	RA	Soil temperature corresponding to the input volatilization rate constant
AVGSWC	(mm³/mm³)	RV	Average root zone volumetric water content for period between storms
AVGTMP	(°C)	RV	Average air temperature for period between storms

AWU	(mm)	RV	Actual plant water use
BASPUN	(mm)	RV	Fraction of the potential annual plant N taken up between storms
BD	(g/cm³)	RV	Soil bulk density
BDATE		IV	Starting date for simulation
BNH4		RV	Enrichment ratio exponent for NH_4^+-N
BORN		RV	Enrichment ratio exponent for organic -N
BP		RV	Enrichment ratio exponent for P
BR15	(mm³/mm³)	RV	Volumetric soil moisture content at wilting point
CDATE		IV	Last date on which updateable nutrient parameters are valid
CEC	(meq/100g soil)	RV	Soil cation exchange capacity
CHECKP	(kg/ha)	RV	Available soluble P in initial soil
CHKNH4	(kg/ha)	RV	Available NH_4^+-N due to rainfall
CHKNO3	(kg/ha)	RV	Available NO_3^--N due to rainfall
CNP	(g/g)	RV	N concentration in plant
COEFF		RV	Soil porosity factor
COLP	(kg/ha)	RV	Soluble P in soil surface prior to runoff event
CZEROP	(kg/ha)	RV	Available soluble P in soil surface
CZRNH4	(kg/ha)	RV	Available NH_4^+-N in soil surface
CZRNO3	(kg/ha)	RV	Available NO_3^--N in soil surface
C1,C2,C3,C4		RV	Crop parameters
DAPEV	(mm)	RV	Actual daily plant transpiration
DASEV	(mm)	RV	Actual daily soil evaporation
DATEF		IV	Date of waste application
DAYS		IV	Number of days between storms
DB		RV	Parameter for denitrification in root zone
DELT	(days)	RV	Time step for N transformation processes
DEMERG		IV	Date of plant emergence

DF		IA	Number of fertilizer (waste) applications
DHRVST		IV	Date of plant harvest
DIFF	(kg/ha)	RV	Daily root zone NO_3^--N loss
DK	(day^{-1})	RV	Root zone denitrification rate constant
DKT	(day^{-1})	RV	Temperature corrected root zone denitrification rate constant
DM	(kg/ha)	RV	Crop dry matter production
DMY		RV	Ratio of dry matter to crop yield at maturity
DNI	(kg/ha)	RV	Daily root zone denitrification
DOM	(days)	RV	Days of growth required for plant to take up 50% of annual N uptake
DP	(days)	IV	Days of drainage between storms
DPERC	(mm)	RV	Daily percolation below the root zone
DPPEV	(mm)	RV	Potential daily plant transpiration
DPSEV	(mm)	RV	Potential daily soil evaporation
DRAIN	(mm)	RV	Annual depth of percolation
DTDNI	(°C)	RV	Average daily soil temperature for denitrification
DTMIN	(°C)	RV	Average daily soil temperature for mineralization
DTNIT	(°C)	RV	Average daily soil temperature for nitrification
DTVOL	(°C)	RV	Average daily soil temperature for volatilization
DWNH4	(kg/ha)	RV	NH_4^+-N moving downward from surface layer to root zone
DWNO3	(kg/ha)	RV	NO_3^--N moving downward from surface layer to root zone
EFI	(mm)	RV	Effective infiltration
EFRAIN	(mm)	RV	Effective rainfall
ENRICH		RV	Sediment enrichment ratio
ERNH4		RV	NH_4^+-N enrichment ratio
ERORN		RV	Organic-N enrichment ratio
ERP		RV	P enrichment ratio
EVAPN	(kg/ha)	RV	NO_3^--N diffused from root zone to surface layer
EX		RV	Drainage parameter

EXKNH4		RV	Runoff NH_4^+-N extraction coefficient
EXKNO3		RV	Runoff NO_3^--N extraction coefficient
EXKN1		RV	Downward N extraction coefficient
EXKP		RV	Runoff P extraction coefficient
EXKP1		RV	Downward P extraction coefficient
FA		RA	Surface fraction of applied fertilizer
FAFVOL		RV	Airflow rate factor for volatilization
FAPP	(kg/ha)	RA	Application rate of waste
FC	(mm^3/mm^3)	RV	Volumetric soil moisture content at field capacity
FCEC		RV	Cation exchange capacity factor for volatilization
FCECI		RV	Cation exchange capacity factor for incorporated wastes
FCECS		RV	Cation exchange capacity factor for surface-applied wastes
FCECRF		RV	Cation exchange capacity factor for soil corresponding to the input volatilization rate constant
FCNR		RA	Carbon to N ratio of waste
FDAOUT		IV	Option for daily output of N pools
FDATE		IA	Waste application dates
FDM	(kg/ha)	RV	Dry matter production of crop
FL		RV	Fraction of water leached
FLB		RV	Fraction of water leached (estimate B)
FLGIN		IV	Option describing units of input
FLGNUT		IV	Option for simulation of nutrients
FLGOUT		IV	Option describing detail of output
FLGPAS		IV	Option describing format of pass file
FLGPST		IV	Option for simulation of pesticides
FMAMIN		RV	Method of application factor for mineralization
FMANIT		RV	Method of application factor for nitrification
FMMIN		RV	Soil moisture factor for mineralization

FMNIT		RV	Soil moisture factor for nitrification
FN	(kg/ha)	RA	Waste N applied
FNH4T	(kg/ha)	RA	Waste NH_4^+-N applied
FNO3	(kg/ha)	RA	Waste NO_3^--N applied
FORGN	(kg/ha)	RA	Waste organic -N applied
FP	(kg/ha)	RA	Waste P applied
FPH		RA	Waste pH
FPHDNI		RV	pH factor for denitrification
FPHMIN		RV	pH factor for mineralization
FPHNIT		RV	pH factor for nitrification
FPMN	(kg/ha)	RV	Potentially mineralizable N of added waste
FRESN	(kg/ha)	RV	Residual N of added waste
FU		RV	Fraction of potential annual plant uptake of N
IBEG		IV	Flag to mark beginning of simulation
ID		IV	Waste application reference
IDATE		IV	Date following the last date updateable nutrient parameters are valid
IDPF		IV	Flag to signify if drainage below root zone occurred on current day
IDP1		IV	Number of days of drainage between storms
IDS		IV	Flag to signify if seepage below surface layer of soil occurred on current day
IFAP		IV	Flag for nutrient pass file
IGROW	(days)	IV	Days of crop growth between storms
INSUM		IV	Flag to determine if waste application or crop growth to be simulated
IN1,IN2,IN3		IV	Flags to signify waste applied and crops grown
IROT		IV	Flag to signify irrigation
ITEST		IV	Flag to terminate execution if nutrient or pesticide simulations not desired
IWD	(days)	IV	Days following waste application

JDATE		IV	Date simulating
KADS	(day^{-1})	RV	Adjusted NH_4^+-N adsorption rate constant
KADSI	(day^{-1})	RV	NH_4^+-N adsorption rate constant
KDES	(day^{-1})	RV	Adjusted NH_4^+-N desorption rate constant
KDESI	(day^{-1})	RV	NH_4^+-N desorption rate constant
KDNI	(day^{-1})	RV	Denitrification rate constant adjusted for environmental conditions
KDNII	(day^{-1})	RV	Denitrification rate constant
KMIN	(day^{-1})	RV	Mineralization rate constant adjusted for environmental conditions
KMINI	(day^{-1})	RV	Mineralization rate constant
KNIT	(day^{-1})	RV	Nitrification rate constant adjusted for environmental conditions
KNITI	(day^{-1})	RV	Nitrification rate constant
KVOL	(day^{-1})	RV	Volatilization rate constant adjusted for environmental conditions
KVOLI	(day^{-1})	RV	Volatilization rate constant
LDP		IV	Flag to signify the last day of drainage between rainfall events
LMONTH		IV	Month of previous rainfall event
LSTORM		IV	Date of previous rainfall event
LYEAR		IV	Year of previous rainfall event
MAMN	(kg/ha)	RV	Amount of root zone N mineralized in month
MARN	(kg/ha)	RV	Monthly accumulated rainfall N
MDATE	(kg/ha)	IV	Date of next rainfall event
MN	(kg/ha)	RV	Daily root zone N mineralized
MONTH		IV	Current month
MONTHS		CA	Name of month
MOTDNI	(kg/ha)	RV	Monthly accumulated root zone denitrification
MOTDRN	(mm)	RV	Monthly accumulated drainage
MOTNL	(kg/ha)	RV	Monthly accumulated NO_3^--N leached

MOTP	(kg/ha)	RV	Monthly accumulated total P lost via runoff
MOTRON	(kg/ha)	RV	Monthly accumulated soluble N in runoff
MOTROP	(kg/ha)	RV	Monthly accumulated soluble P in runoff
MOTSDN	(kg/ha)	RV	Monthly accumulated sediment-bound N
MOTSDP	(kg/ha)	RV	Monthly accumulated sediment-bound P
MPRECP	(cm)	RV	Monthly accumulated precipitation
MPUN	(kg/ha)	RV	Monthly accumulated plant N uptake
MRUNFF	(cm)	RV	Monthly accumulated runoff
MT	(bars)	RV	Soil moisture tension
MTINT,MTSL		RV	Moisture tension coefficients
MTRNH4	(kg/ha)	RV	Monthly accumulated soluble runoff NH_4^+ -N
MTRNO3	(kg/ha)	RV	Monthly accumulated soluble runoff NO_3^- -N
MTSNH4	(kg/ha)	RV	Monthly accumulated sediment-bound NH_4^+ -N
MTSORN	(kg/ha)	RV	Monthly accumulated sediment-bound organic -N
NEWNT		IV	Flag to initialize updateable nutrient parameters
NF		IV	Number of waste (fertilizer) applications
NL	(kg/ha)	RV	NO_3^--N leached below root zone
NMONTH		IV	Month of next storm
NRNFFM		IV	Number of runoff events in month
NRNFFS		IV	Accumulated number of runoff events
NRNFFY		IV	Number of runoff events in year
NSTRMM		IV	Number of rainfall events in month
NSTRMS		IV	Accumulated number of rainfall events
NSTRMS		IV	Number of rainfall events in year
NYEAR		IV	Year of next rainfall event
OM	(%)	RV	Root zone organic matter content
OPT		IV	Flag to signify which plant N uptake option to simulate
P	(cm)	RV	Rainfall amount

PERC	(mm)	RV	Percolating water
PERCOL	(cm)	RV	Percolating water
PFU		RV	Fraction of potential annual plant N uptake taken up through previous day
PH		RV	Soil pH
POR	(mm^3/mm^3)	RV	Soil porosity
POTPEV	(mm)	RV	Potential plant transpiration for period between storms
POTSEV	(mm)	RV	Potential soil evaporation for period between storms
PPMN	(mg/l)	RV	Concentration of N in runoff
PPMNH4	(mg/l)	RV	Concentration of NH_4^+-N in runoff
PPMNO3	(mg/l)	RV	Concentration of NO_3^--N in runoff
PPMP	(mg/l)	RV	Concentration of P in runoff
PPUN		RV	Fraction of potential annual plant N uptake taken up through previous day
PRED		IV	Date of last storm
PSG	(mm)	RV	Daily plant water use
PU	(kg/ha)	RV	Potential plant N uptake
PUN		RV	Fraction of potential annual plant N uptake taken up through current day
PWU	(mm)	RV	Potential plant water use
Q	(cm)	RV	Runoff amount
RCN	(mg/l)	RV	Concentration of N in rainfall
RFPMN	(kg/ha)	RV	Root zone organic waste potentially mineralizable N
RFRACT		RV	Fraction of root zone organic N that is potentially mineralizable
RFRESN	(kg/ha)	RV	Root zone waste residual N
RN	(kg/ha)	RV	Amount of N in rainfall
RNFALL	(mm)	RV	Rainfall amount
RNO3	(kg/ha)	RV	Root zone NO_3^--N
RON	(kg/ha)	RV	Soluble N in runoff water

RONH4	(kg/ha)	RV	Soluble NH_4^+-N in runoff water
RONO3	(kg/ha)	RV	NO_3^--N in runoff water
ROP	(kg/ha)	RV	Soluble P in runoff water
RORGN	(kg/ha)	RV	Root zone organic N
RPMN	(kg/ha)	RV	Root zone potentially mineralizable N
RSPMN	(kg/ha)	RV	Initial root zone soil potentially mineralizable N
RUNOFF	(mm)	RV	Runoff amount
RZC	(mm)	RV	Water remaining in root zone
RZDEP	(mm)	RV	Effective root zone depth
RZMAX	(mm)	RV	Maximum depth of root zone
S		RV	Plant N uptake probability parameter
SC	(mg/gsoil)	RV	Carbon content of root zone
SD		RV	One standard deviation of plant N uptake cycle
SDATE		IV	Storm date
SDB		RV	Initial value of DB for soil
SED	(kg/ha)	RV	Sediment yield
SEDN	(kg/ha)	RV	Sediment-bound N in runoff
SEDNH4	(kg/ha)	RV	Sediment-bound NH_4^+-N in runoff
SEDORN	(kg/ha)	RV	Sediment-bound organic-N in runoff
SEDP	(kg/ha)	RV	Sediment-bound P in runoff
SFPMN	(kg/ha)	RV	Surface layer organic waste potentially mineralizable N
SFRACT		RV	Fraction of surface layer organic-N that is potentially mineralizable
SFRESN	(kg/ha)	RV	Surface layer waste residual N
SG	(mm)	RV	Actual plant water use for growing season
SGRT	(mm)	RV	Potential plant water use for growing season
SKADSI	(day^{-1})	RV	Initial soil NH_4^+-N adsorption rate
SKDESI	(day^{-1})	RV	Initial soil NH_4^+-N desorption rate

SKDNII	(day^{-1})	RV	Initial soil denitrification rate
SKMINI	(day^{-1})	RV	Initial soil mineralization rate
SKNITI	(day^{-1})	RV	Initial soil nitrification rate
SNH3	(kg/ha)	RV	Surface layer NH_3-N volatilization
SNH4A	(kg/ha)	RV	Surface layer adsorbed NH_4^+-N
SNH4S	(kg/ha)	RV	Surface layer desorbed NH_4^+-N
SNH4T	(kg/ha)	RV	Surface layer total NH_4^+-N
SNH4TI	(kg/ha)	RV	Surface layer total NH_4^+-N on previous day
SNO3	(kg/ha)	RV	Surface layer NO_3^--N
SNO3I	(kg/ha)	RV	Surface layer NO_3^--N on previous day
SN2O	(kg/ha)	RV	Surface layer denitrification
SOILP	(kg/ha)	RV	Surface layer soil P
SOLOSS	(kg/ha)	RV	Sediment yield
SOLP	(kg/ha)	RV	Surface layer soluble P
SOLPOR	(mm^3/mm^3)	RV	Soil porosity
SOM	(%)	RV	Surface layer organic matter content
SORGN	(kg/ha)	RV	Surface layer organic -N
SPH		RV	Surface layer soil pH
SPHDNI		RV	Initial soil pH factor for denitrification
SPHMIN		RV	Initial soil pH factor for mineralization
SPHNIT		RV	Initial soil pH factor for nitrification
SPMN	(kg/ha)	RV	Surface layer potentially mineralizable N
SPMNI	(kg/ha)	RV	Surface layer potentially mineralizable N on previous day
SSC	(mg/gsoil)	RV	Surface layer soil carbon content
SSEPM	(mm)	RV	Amount of water moving downward from surface layer to root zone
SSPMN	(kg/ha)	RV	Surface layer soil potentially mineralizable N
STMIN	(°C)	RV	Soil temperature corresponding to initial soil mineralization rate

STNIT	(°C)	RV	Soil temperature corresponding to initial soil nitrification rate
T	(days)	RV	Days of crop growth between storms
TA	(°K)	RV	Average daily soil temperature
TDATE		IV	Date currently simulating
TDNI	(°C)	RV	Temperature corresponding to denitrification rate constant
THDNI		RV	Temperature correction coefficient for denitrification
THMIN		RV	Temperature correction coefficient for mineralization
THNIT		RV	Temperature correction coefficient for nitrification
THVOL		RV	Temperature correction coefficient for volatilization
TK	(day^{-1})	RV	Root zone mineralization rate constant
TMIN	(°C)	RV	Temperature corresponding to mineralization rate constant
TNIT	(°C)	RV	Temperature corresponding to nitrification rate constant
TOTDNI	(kg/ha)	RV	Total accumulated root zone denitrification
TOTDRN	(mm)	RV	Total accumulated drainage
TOTNL	(kg/ha)	RV	Total accumulated NO_3^--N leached
TOTP	(kg/ha)	RV	Total P in runoff water
TOTPOR	(mm^3/mm^3)	RV	Total soil porosity
TOTRON	(kg/ha)	RV	Total accumulated soluble runoff N
TOTROP	(kg/ha)	RV	Total accumulated soluble runoff P
TOTSDN	(kg/ha)	RV	Total accumulated sediment-bound N
TOTSDP	(kg/ha)	RV	Total accumulated sediment-bound P
TPRECP	(cm)	RV	Total accumulated precipitation
TR		RV	Ratio of daily actual to potential plant transpiration
TRONH4	(kg/ha)	RV	Total accumulated soluble runoff NH_4^+-N
TRONO3	(kg/ha)	RV	Total accumulated soluble runoff NO_3^--N
TRUNFF	(cm)	RV	Total accumulated runoff amount

TSDNH4	(kg/ha)	RV	Total accumulated sediment-bound NH_4^+-N
TSDORN	(kg/ha)	RV	Total accumulated sediment-bound organic-N
TTOTP	(kg/ha)	RV	Total accumulated total P lost via runoff
TVOL	(°C)	RV	Temperature corresponding to volatilization rate constant
UP	(kg/ha)	RV	Plant N uptake
WDATE		IV	Last day following waste application that volatilization simulated
WIND	(mi/hr)	RA	Average daily wind velocity
WK		RV	Water content factor for root zone mineralization
WND		IV	Day following waste application
X,XX		RV	Plant N uptake cycle parameter
XKFNH4		RV	Extraction coefficient factor for movement of NH_4^+-N into runoff
XKFNO3		RV	Extraction coefficient factor for movement of NO_3^--N into runoff
XKFN1		RV	Extraction coefficient factor for movement of N into infiltrating water
XKFP1		RV	Extraction coefficient factor for movement of P into infiltrating water
XKFP2		RV	Extraction coefficient factor for movement of P into runoff
XRON	(kg/ha)	RV	Non-potentially mineralizable N in root zone
XSON	(kg/ha)	RV	Non-potentially mineralizable N in surface layer
YAMN	(kg/ha)	RV	Annual accumulated root zone N mineralization
YARN	(kg/ha)	RV	Annual accumulated rainfall N
YEAR		IV	Current year
YOTDNI	(kg/ha)	RV	Annual accumulated root zone denitrification
YOTDRN	(mm)	RV	Annual accumulated drainage
YOTNL	(kg/ha)	RV	Annual accumulated NO_3^--N leached
YOTP	(kg/ha)	RV	Annual accumulated total P lost via runoff
YOTRON	(kg/ha)	RV	Annual accumulated soluble N in runoff

YOTROP	(kg/ha)	RV	Annual accumulated soluble P in runoff
YOTSDN	(kg/ha)	RV	Annual accumulated sediment-bound N
YOTSDP	(kg/ha)	RV	Annual accumulated sediment-bound P
YP	(kg/ha)	RV	Crop yield potential
YPRECP	(cm)	RV	Annual accumulated precipitation
YPUN	(kg/ha)	RV	Annual accumulated plant N uptake
YRUNFF	(cm)	RV	Annual accumulated runoff
YTRNH4	(kg/ha)	RV	Annual accumulated soluble NH_4^+-N in runoff
YTRNO3	(kg/ha)	RV	Annual accumulated soluble NO_3^--N in runoff
YTSNH4	(kg/ha)	RV	Annual accumulated sediment-bound NH_4^+-N
YTSORN	(kg/ha)	RV	Annual accumulated sediment-bound organic-N

* IA = Integer Array
IV = Integer Variable
CA = Character Array
CV = Character Variable
RA = Real Array
RV = Real Variable

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C**********************************************************************C
C                   C R E A M S - N T                                 C
C                                                                     C
C          MODIFIED VERSION OF CREAMS 1.8                             C
C         TO SIMULATE SOIL N TRANSFORMATIONS                          C
C                                                                     C
C     A COMPUTER SIMULATION MODEL FOR INVESTIGATING                   C
C      THE EFFECT OF LAND APPLICATION OF SLUDGE ON                    C
C               RUNOFF WATER QUALITY                                  C
C                                                                     C
C              AUTHOR                                                 C
C              ------                                                 C
C         MARCIA MCCUTCHAN DEIZMAN                                    C
C         DEPARTMENT OF AGRICULTURAL ENGINEERING                      C
C         VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY         C
C         BLACKSBURG, VA 24061                                        C
C**********************************************************************C
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CIO                                                                IOC
CIO          SYSTEM DEPENDENT I/O UNIT AND FILE SELECTION          IOC
CIO                                                                IOC
CIO             EROSION PASS FILE      -  READ FROM   UNIT 1       IOC
CIO             INPUT PARAMETERS FILE  -  READ FROM   UNIT 2       IOC
CIO             OUTPUT REPORT FILE     -  WRITE TO    UNIT 3       IOC
CIO             OUTPUT PASS FILE       -  WRITE TO    UNIT 4       IOC
CIO             DUMMY DATA FILE        -  WRITE/READ  UNIT 5       IOC
CIO             OUTPUT PASS FILE       -  WRITE TO    UNIT 7       IOC
CIO             HYD DAILY PASS FILE    -  READ FROM   UNIT 8       IOC
CIO             DAILY OUTPUT PASS FILE -  WRITE TO    UNIT 9       IOC
CIO             OUTPUT PASS FILE       -  WRITE TO    UNIT 10      IOC
CIO                                                                IOC
CIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOIOC
      REAL APRATE(10),H2OSOL(10),KD(10),DECAY(10),
     1      HAFLIF(10),FOLFRC(10),SOLFRC(10),FOLRES(10),
     1      SOLRES(10),WSHFRC(10),THRWSH(10),TOTPST(10),
     1      FOLRSV(10),DEPINC(10),EFFINC(10),
     1      NL,MN
      INTEGER LDATE(10),NEWPST(10),              APDATE(10),
     1        FLGOUT,FLGIN,PBDATE,PEDATE,PDATE,CDATE,SDATE,
     1        FLGPST,FLGNUT,DP,WCHMON,FLGPAS,FDAOUT
      CHARACTER *16 PSTNAM (10)
      CHARACTER*14 EROPAS,INFIL,OUTFIL,CHPAS1,CHPAS2,DUMMY,HDPAS2,
     1             DNTOUT,SNFORM
      CHARACTER*4 IHEAD(2),IDASH(2)
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          COMMON/PASS/PAS(40),IFAP(10)
          COMMON /PRCP/ SDATE,RNFALL,RUNOFF,SOLOSS,ENRICH,DP,IDP1,PERCOL,
       1              AVGTMP,AVGSWC,ACCPEV,POTPEV,ACCSEV,POTSEV
          COMMON /PPST/ ACCLOS(10)
          COMMON /FILE/ EROPAS,INFIL,OUTFIL,CHPAS1,CHPAS2,DUMMY,HDPAS2,
       1              DNTOUT,SNFORM
         DATA NSTRMS,NRNFFS,TPRECP,TRUNFF/0,0,0.0,0.0/
         DATA PUN/0.0/
         DATA DRAIN,TRONO3,TRONH4,TOTROP,TSDNH4,TSDORN,TOTSDP,
       1       TOTDRN,TOTNL,TOTDNI/10*0.0/
         IHEAD(1)='G/HA'
         IHEAD(2)='PPM '
         IDASH(1)='----'
         IDASH(2)='----'
            CALL INTRO
            CALL FILES
            WRITE(*,5)
C
         DO 10 I=1,10
            ACCLOS(I) =0.0
            TOTPST(I) =0.0
            FOLRSV(I) =0.0
            APDATE(I) =0
            IFAP(I)   =0
   10    CONTINUE
C
C  INPUT SIMULATION INFORMATION
C
         CALL INITCH(CDATE,FLGOUT,FLGIN,FLGPST,FLGNUT,FLGPAS,FDAOUT,
       1            SOLPOR,FC,BR15,SOM,OM,BD,PH,CEC,IROT)
         IBEG     =1
         IF(FLGPST.EQ.0) GO TO 16
         CALL INITPS(NPEST,PBDATE,PEDATE)
         DO 15 I=1,NPEST
            CALL ALLPST(I,PSTNAM,H2OSOL(I),HAFLIF(I),DECAY(I),
       1                 KD(I),FOLRES(I),SOLRES(I),WSHFRC(I))
   15    CONTINUE
         CALL PESTIN(CDATE,PBDATE,PEDATE,IROT,NNYR)
   16    CONTINUE
C
C   INPUT SOIL NUTRIENT PARAMETERS
C
         IF(FLGNUT .EQ. 1) CALL INITNT(RNO3,FC,BR15,SOM,OM,BD,PH,CEC,
       1                              AMN,ARN,CDATE)
         IF(FLGNUT .EQ. 1) GO TO 17
C
C PESTS
         IF (NPEST .GT. 5) THEN
                MPEST = 5
         ELSE
```

```
                  MPEST = NPEST
          ENDIF
C
       IF (FLGPAS .EQ. 1 .OR. FLGPAS .EQ. 3) THEN
         WRITE(4,4004) NNYR,NPEST
         WRITE(4,4000)   (PSTNAM(M1),M1=1,NPEST)
         WRITE(4,4001) ( (IDASH(M2),M2=1,2) ,M1=1,MPEST)
         WRITE(4,4002) ( (IHEAD(M2),M2=1,1) ,M1=1,MPEST)
       ENDIF
C
       IF (FLGPAS .EQ. 2 .OR. FLGPAS .EQ. 3) THEN
           WRITE(7,4004) NNYR,NPEST
           WRITE(7,4000)   (PSTNAM(M1),M1=1,NPEST)
           WRITE(7,4001) ( (IDASH(M2),M2=1,2) ,M1=1,MPEST)
           WRITE(7,4002) ( (IHEAD(M2),M2=2,2) ,M1=1,MPEST)
       ENDIF
       GO TO 18
C NUTRIENTS
  17     IF (FLGPAS .EQ. 1 .OR. FLGPAS .EQ. 3) THEN
             WRITE (4,4005)
             WRITE (10,5002)
         ENDIF
         IF (FLGPAS .EQ. 2 .OR. FLGPAS .EQ. 3) THEN
             WRITE (7,7003)
         ENDIF
         IF (FDAOUT .EQ. 1) THEN
             WRITE (9,5001)
         ENDIF
C
C   INPUT RAINFALL AND RUNOFF PARAMETERS
C
  18     CALL STRMIN(FLGIN)
         IF(SDATE.LE.0) GO TO 130
         LMONTH    =WCHMON(SDATE)
         LYEAR     =SDATE/1000
  20     CONTINUE
         IF(CDATE.GE.SDATE) GO TO 60
         IF(IBEG.EQ.1)THEN
           IDATE=0
         ELSE
           IDATE     =(MOD(CDATE,1000))+1
         ENDIF
         IBEG=0
         CALL DATEIN(PDATE,CDATE,IPST,FLGPST,FLGNUT)
         IF(CDATE.LE.0) GO TO 100
         IF(FLGPST.LE.0) GO TO 40
         CALL UPPEST(IPST,APDATE,APRATE,DEPINC,EFFINC,
      1              FOLFRC,SOLFRC,THRWSH,
      1              TOTPST,NEWPST,NPEST,PDATE)
  40     CONTINUE
```

```
        IF(FLGNUT.LE.0) GO TO 50
C
C    INPUT CROP AND FERTILIZATION PARAMETERS
C
        CALL NUTRIN
        NEWNT     =1
   50   CONTINUE
        GO TO 20
   60   CONTINUE
C
C   WRITE PERTINENT STORM AND ENVIRONMENTAL DATA
C
        CALL STROUT(SDATE,RNFALL,RUNOFF,SOLOSS,ENRICH,
     1              PERCOL,AVGTMP,AVGSWC,ACCPEV,POTPEV,ACCSEV,POTSEV,
     1              NSTRMS,NRNFFS,TPRECP,TRUNFF,FLGOUT)
        IF(FLGPST.LE.0) GO TO 80
        IF(SDATE.LT.PBDATE.OR.SDATE.GT.PEDATE) GO TO 80
        THRDWN    =0.32
        IF(AVGSWC.GT.0.0) THRDWN=SOLPOR*AVGSWC
        DO 70 I=1,NPEST
        IF(APDATE(I) .LE. 0) GO TO 70
            CALL PST208(I,FLGOUT,APDATE(I),APRATE(I),H2OSOL(I),KD(I),
     1                DECAY(I),HAFLIF(I),ENRICH,FOLRES(I),
     1                SOLRES(I),FOLFRC(I),SOLFRC(I),WSHFRC(I),
     1                THRWSH(I),THRDWN,FOLRSV(I),DEPINC(I),
     1                EFFINC(I),SOLPOR,NEWPST(I),LDATE(I))
   70   CONTINUE
        IF(FLGPAS.GE.1.AND.RUNOFF.GT.0.0) CALL PSTPAS( NPEST,FLGPAS)
   80   CONTINUE
        IF(FLGNUT.LE.0) GO TO 90
C
C   CONVERT STORM AND SOIL WATER PARAMETERS TO MM
C
        RNFALL    =RNFALL*10.0
        RUNOFF    =RUNOFF*10.0
        PERCOL    =PERCOL*10.0
        ACCPEV    =ACCPEV*10.0
        POTPEV    =POTPEV*10.0
        ACCSEV    =ACCSEV*10.0
        POTSEV    =POTSEV*10.0
C
C   CALL SUBROUTINE WHICH PERFORMS ALL N TRANSFORMATIONS, PLANT UPTAKE,
C        LEACHING AND RUNOFF LOSSES OF NUTRIENTS
C
        CALL NUT208(NEWNT,FC,RONO3,RONH4,ROP,SEDNH4,SEDORN,
     1              SEDP,DRAIN,PUN,NL,TRONO3,TRONH4,
     1              TOTROP,TSDNH4,TSDORN,TOTSDP,TOTDRN,TOTNL,
     1              RN,TOTDNI,UP,MN,AMN,ARN,RNO3,SOLPOR,DNI,PH,BD,FDAOUT,
     1              IDATE)
        IF(FLGOUT.GT.1) CALL NUTRES(SDATE,RUNOFF,RONO3,RONH4,
```

```
       1                                         ROP,SEDNH4,SEDORN,SEDP,
       1                                         PERCOL,DRAIN,NL,UP,MN,RNO3,DNI)
             IF(FLGPAS.LE.0) GO TO 90
             CALL NUTPAS(NL,RONO3,RONH4,ROP,SEDNH4,SEDORN,SEDP,
       1                 UP,MN,RNO3,DNI,RN,FLGPAS)
    90   CONTINUE
             LSTORM   =SDATE
C
C    INPUT STORM DATA FOR NEXT STORM
C
             CALL STRMIN(FLGIN)
   100   CONTINUE
             IF(CDATE.LE.0) SDATE=0
             NMONTH    =WCHMON(SDATE)
             NYEAR     =SDATE/1000
             IF(LMONTH.EQ.NMONTH.AND.LYEAR.EQ.NYEAR) GO TO 120
             IF(FLGOUT.LE.0) GO TO 110
             CALL MONPCP(LMONTH,LSTORM,NSTRMS,NRNFFS,TPRECP,TRUNFF)
             IF(FLGPST.GT.0) CALL MONPST(ACCLOS,TOTPST,APDATE,PSTNAM,NPEST,
       1                                 LSTORM)
C
C    CALL MONTHLY SUMMARY SUBROUTINE
C
             IF(FLGNUT.GT.0) CALL MONNUT(TRONO3,TRONH4,TOTROP,TSDNH4,
       1                                 TSDORN,TOTSDP,TOTNL,
       1                                 TOTDRN,TOTDNI,AMN,PUN,RNO3,ARN)
   110   CONTINUE
             LMONTH    =NMONTH
             IF(LYEAR.EQ.NYEAR) GO TO 120
             CALL ANNPCP(LSTORM,NSTRMS,NRNFFS,TPRECP,TRUNFF)
             IF(FLGPST.GT.0) CALL ANNPST(ACCLOS,TOTPST,APDATE,PSTNAM,NPEST,
       1                                 LSTORM)
C
C    CALL ANNUAL SUMMARY SUBROUTINE
C
             IF(FLGNUT.GT.0) CALL ANNNUT(TRONO3,TRONH4,TOTROP,TSDNH4,
       1                                 TSDORN,TOTSDP,TOTNL,
       1                                 TOTDRN,TOTDNI,AMN,PUN,RNO3,ARN)
             LYEAR     =NYEAR
   120   CONTINUE
             IF(SDATE.GT.0) GO TO 20
   130   CONTINUE
             CALL PCPEND(NSTRMS,NRNFFS,TPRECP,TRUNFF)
             IF(FLGPST.GT.0) CALL PSTEND(ACCLOS,TOTPST,PSTNAM,NPEST)
C
C    CALL SIMULATION SUMMARY SUBROUTINE
C
             IF(FLGNUT.GT.0) CALL NUTEND(TRONO3,TRONH4,TOTROP,TSDNH4,
       1                                 TSDORN,TOTSDP,TOTNL,
       1                                 TOTDRN,TOTDNI,AMN,PUN,RNO3,ARN)
```

```
   5   FORMAT (////,10X, 'DATA FILES OPENED, PROGRAM IS RUNNING')
4000 FORMAT(1H ,/,6X,52H LINE 1 = WATER FRACTION; LINE 2 = SEDIMENT FRA
    1CTION/,30H   DATE RAIN RUNOFF   SDMNT , 5(1X,A8 ,1X) /)
4001 FORMAT(30H                              , 5(1X,2A4,1X) )
4002 FORMAT(30H             CM     CM    KG/HA , 5(4X,A4,2X) )
4004 FORMAT(1H /38HNO. YRS. SIMULATION    NO. PESTICIDES / 2I16)
4005 FORMAT(1H ,/46H  DATE  RAIN RUNOFF  PERC   SDMNT       RUNOFF N,3X,
    1      30H  RUNOFF P    SDMNT N  SDMNT P,/,20H--------------------,
    1 60H------------------------------------------------------------,
    1 /,8X,47H CM    CM    CM   KG/HA   KG/HA    PPM    KG/HA   ,
    1 25H    PPM    KG/HA    KG/HA,/)
7003 FORMAT(1H ,/32H   DATE   RAIN RUNOFF PERC   SDMNT,2X,
    1 46H(L-1)RUNOFF N  RUNOFF P     SDMNT N    SDMNT P ,/,38X,
    1 42H//////////////////////////////////////////,/,6X,9H (LINE 2),
    1 23X,42HMINRLZ  UPTAKE   LEACH   DENIT  SOILN  RAINN/11H----------,
    1 61H------------------------------------------------------------,
    1 8H--------/8X,12H  CM     CM  ,
    1 60H CM      ------------------------KG/HA--------------------,
    1 /)
5001  FORMAT(1H ,/,5X,7HSURFACE,1X,7HSURFACE,2X,7HSURFACE,
    1            1X,7HSURFACE,1X,7HSURFACE,2X,4HROOT,4X,4HROOT,/,4HDATE,
    1            1X,7HNITRATE,1X,8HAMMONIUM,2X,
    1            5HORG-N,2X,6HDENITR,4X,3HVOL,3X,7HNITRATE,2X,5HORG-N,/,
    1            4H----,
    1            1X,7H-------,1X,8H--------,1X,
    1   -        7H-------,1X,7H-------,1X,7H-------,1X,7H-------,2X,
    1            5H-----,/)
5002  FORMAT(1H ,/,1X,5HSTORM,2X,7HSURFACE,2X,7HSURFACE,2X,7HSURFACE,
    1            3X,4HROOT,6X,4HROOT,/,2X,4HDATE,2X,7HNITRATE,1X,
    1            8HAMMONIUM,3X,5HORG-N,3X,7HNITRATE,3X,5HORG-N,/,
    1            1X,5H-----,1X,8H--------,1X,8H--------,1X,8H--------,
    1            1X,8H--------,1X,8H--------,/)
      STOP
      END
C
C*********************************************************************C
C
      SUBROUTINE INTRO
C     INTRODUCTION PAGE
      CHARACTER YN
      DO 10 I=1,1
      WRITE (*,100)
 100  FORMAT (' ')
  10  CONTINUE
      WRITE (*,102)
 102  FORMAT (' *********************************************')
      WRITE (*,100)
      WRITE (*,104)
 104  FORMAT (' CREAMS-NT NUTRIENT/PESTICIDE PROGRAM ')
      WRITE (*,106)
```

```
  106 FORMAT (' AUTHOR - MARCIA M. DEIZMAN')
      WRITE (*,108)
  108 FORMAT (' DEPARTMENT OF AGRICULTURAL ENGINEERING,  VPI&SU ')
      WRITE (*,109)
  109 FORMAT ('                      BLACKSBURG, VA')
      WRITE (*,100)
      WRITE (*,110)
  110 FORMAT (' *********************************************')
      WRITE (*,100) ·
      WRITE (*,112)
  112 FORMAT (' ORIGINAL PC PROGRAM (VERSION 1.7) IMPLEMENTED BY')
      WRITE (*,113)
  113 FORMAT ('            D.J. COOK - JUNE, 1984')
      WRITE (*,116)
  116 FORMAT (' MODIFIED VERSION OF CREAMS 1.8,')
      WRITE (*,118)
  118 FORMAT ('               DR. W. G. KNISEL.')
      WRITE (*,110)
      WRITE (*,120)
  120 FORMAT (' VERSION 1.8 IMPLEMENTED BY D.A. STILL,')
      WRITE (*,122)
  122 FORMAT (' USDA-ARS-SEWRL, TIFTON, GA. - MAY 1, 1985')
      WRITE (*,110)
      WRITE (*,110)
      WRITE (*,132)
  132 FORMAT (' PRESS RETURN TO CONTINUE :>')
      READ (*,134) YN
  134 FORMAT (A1)
      DO 20 I=1,25
      WRITE (*,100)
   20 CONTINUE
      RETURN
      END
C
C***********************************************************************C
C
      SUBROUTINE FILES
C
C     OPEN INPUT AND OUTPUT FILES
C
      COMMON /FILE/ EROPAS,INFIL,OUTFIL,CHPAS1,CHPAS2,DUMMY,HDPAS2,
     1             DNTOUT,SNFORM
      INTEGER BDATE,FLGOUT,FLGIN, FLGPST, FLGNUT, FLGPAS,FDAOUT
      CHARACTER*14 EROPAS,INFIL,OUTFIL,CHPAS1,CHPAS2,DUMMY,HDPAS2,
     1             DNTOUT,SNFORM
      CHARACTER*80 TITLE(3)
C     I/O FILE SELECTION
C
C     EROSION TO CHEMISTRY PASS  FILE  - READ FROM UNIT 1
C     CHEMISTRY INPUT PARAMETER  FILE  - READ FROM UNIT 2
```

```
C       CHEMISTRY OUTPUT REPORT    FILE  - WRITE TO   UNIT 3
C       CHEMISTRY NUMBER 1    PASS FILE  - WRITE TO   UNIT 4
C       WRITE/READ INPUT PARAMETER FILE  - WRITE TO   UNIT 5
C       CHEMISTRY NUMBER 2    PASS FILE  - WRITE TO   UNIT 7
C       HYDRO TO CHEM DAILY   PASS FILE  - READ FROM UNIT 8
C       DAILY CHEM OUTPUT     PASS FILE  - WRITE TO   UNIT 9
C       PART 2 OF CHEM NO 1   PASS FILE  - WRITE TO   UNIT 10
C
        WRITE (*,100)
  100 FORMAT (' INSERT INPUT/OUTPUT DATA DISK INTO DEFAULT DRIVE :'/)
        WRITE (*,102)
  102 FORMAT (/1X,'EROSION TO CHEMISTRY PASS FILE :')
        READ (*,104) EROPAS
        OPEN (1,FILE=EROPAS)
  104 FORMAT (A14)
        WRITE (*,114)
  114 FORMAT (/1X,'DAILY HYDROLOGY TO CHEMISTRY PASS FILE :')
        READ (*,104) HDPAS2
        OPEN (8,FILE=HDPAS2)
        WRITE (*,106)
  106 FORMAT (/1X,'CHEMISTRY INPUT PARAMETER FILENAME :')
        READ (*,104) INFIL
        OPEN (2,FILE=INFIL)
           DO 10 I = 1, 3
             READ (2,2000) TITLE(I)
   10      CONTINUE
             READ (2,2010) BDATE,FLGOUT,FLGIN,FLGPST,FLGNUT,FLGPAS,FDAOUT
        WRITE (*,108)
  108 FORMAT (/1X,'CHEMISTRY OUTPUT REPORT FILENAME   :')
        READ (*,104) OUTFIL
        OPEN (3,FILE=OUTFIL,STATUS='NEW')
C
C * * DECIDE WHICH PAS FILES TO OPEN
        IF (FLGPAS .EQ. 1 .OR. FLGPAS .EQ. 3) THEN
           WRITE (*,110)
  110      FORMAT (/1X,'CHEMISTRY 1 PASS FILENAME :')
           READ (*,104) CHPAS1
           OPEN  (4,FILE=CHPAS1,STATUS='NEW')
           WRITE (*,118)
  118      FORMAT (/1X,'PART 2 OF CHEM 1 PASS FILENAME :')
           READ (*,104) SNFORM
           OPEN  (10,FILE=SNFORM,STATUS='NEW')
        ENDIF
C
        IF (FLGPAS .EQ. 2 .OR. FLGPAS .EQ. 3) THEN
           WRITE (*,112)
  112      FORMAT (/1X,'CHEMISTRY 2 PASS FILENAME :')
           READ (*,104) CHPAS2
           OPEN (7,FILE=CHPAS2,STATUS='NEW')
        ENDIF
```

```
            IF (FDAOUT .EQ. 1) THEN
                WRITE (*,116)
    116         FORMAT (/1X,'DAILY CHEMISTRY PASS FILENAME :')
                READ (*,104) DNTOUT
                OPEN (9,FILE=DNTOUT,STATUS='NEW')
            ENDIF
C
C * * DOES THE USER NEED A PEST FILE?
            IF (FLGPST .NE. 1) GO TO 300
C       WRITE (*,111)
C 111   FORMAT ( /1X,'DUMMY WRITE/READ FILENAME :')
C       READ (*,104)DUMMY
            OPEN (5,FILE='DUMMY.DAT',STATUS='NEW')
    300 CONTINUE
    2000    FORMAT(A80)
    2010    FORMAT(10I8)
        REWIND (2)
        RETURN
        END
C
C*********************************************************************C
C
        SUBROUTINE INITCH(BDATE,FLGOUT,FLGIN,FLGPST,FLGNUT,FLGPAS,FDAOUT,
    1                    SOLPOR,FC,BR15,SOM,OM,BD,PH,CEC,IROT)
C
C   THIS SUBROUTINE READS SIMULATION INFORMATION
C
        INTEGER BDATE,FLGPST,FLGNUT,FLGOUT,FLGIN,FLGPAS,FDAOUT
        COMMON /HEAD/ TITLE
        CHARACTER*80 TITLE(3)
        WRITE(3,3001)
        DO 10 J=1,3
            READ (2,2002) TITLE(J)
            WRITE(3,3002) TITLE(J)
    10    CONTINUE
        READ (2,2000) BDATE,FLGOUT,FLGIN,FLGPST,FLGNUT,FLGPAS,FDAOUT,IROT
        ITEST       = FLGPST + FLGNUT
        IF(ITEST.LE.1) GO TO 11
        WRITE(3,300)
        IF(FLGPAS.GT.0) WRITE(4,300)
        IF(FLGPAS.GT.0) WRITE(10,300)
        IF(FLGPAS.GT.1) WRITE(7,300)
        STOP
    11    CONTINUE
        IF(FDAOUT.LT.1) GO TO 13
        DO 14 II=1,3
        WRITE(9,2002)TITLE(II)
    14    CONTINUE
    13    IF(FLGPAS.LT.1) GO TO 15
        DO 12 JJ=1,3
```

```
        IF(FLGPAS.EQ.2) GO TO 115
        WRITE(4,2002)TITLE(JJ)
        WRITE(10,2002)TITLE(JJ)
   115  IF(FLGPAS.GT.1) WRITE(7,2002)TITLE(JJ)
    12  CONTINUE
    15  READ (2,2001) SOLPOR,FC,BR15,SOM,OM,BD,PH,CEC
        WRITE(3,3000) BDATE,SOLPOR,FC,BR15,SOM,OM,BD,PH,CEC
        RETURN
   300  FORMAT(///,48H ***********************************************,/,
      1            48H PESTICIDES AND NUTRIENTS MUST BE RUN SEPARATELY,/,
      2            48H *********************************************** )
  2000  FORMAT(10I8)
  2001  FORMAT(10F8.0)
  2002  FORMAT(A80)
  3000  FORMAT(1H ,/,18X,28HSTARTING DATE FOR SIMULATION,1X,I5,1X,
      1               11HJULIAN DATE,//,
      1            22X,24HPOROSITY OF SOIL        ,F6.2,/,
      1            22X,24HFIELD CAPACITY          ,F6.2,/,
      1            22X,24HWILTING POINT           ,F6.2,/,
      1            22X,24HSURFACE ORGANIC MATTER  ,F6.2,/,
      1            22X,22H(PERCENT OF SOIL MASS)/,
      1            22X,24HROOT ZONE ORGANIC MATTER,F6.2,/,
      1            22X,22H(PERCENT OF SOIL MASS)/,
      1            22X,24HBULK DENSITY (G/CU.CM.) ,F6.2,/,
      1            22X,24HSOIL PH                 ,F6.2,/,
      1            22X,24HSOIL CEC (MEQ/100 G)    ,F6.2,//)
  3001  FORMAT(1H1,//,12X,34HC R E A M S - N T  NONPOINT SOURCE,
      1               28H POLLUTION MODEL (CHEMICALS),/,
      1            23X,41HMOD. VERSION 1.8  MARCH 31, 1989  VPI&SU ,//)
  3002  FORMAT(A80)
        END
C
C*********************************************************************C
C
        SUBROUTINE STRMIN(FLGIN)
C
C   THIS SUBROUTINE READS RAINFALL, RUNOFF, AND SOIL ENVIRONMENTAL
C   PARAMETERS FROM EROSION PASS FILE AND CONVERT TO METRIC
C
        INTEGER FLGIN,SDATE,DP
        COMMON /PRCP/ SDATE,RNFALL,RUNOFF,SOLOSS,ENRICH,DP,IDP1,PERCOL,
      1               AVGTMP,AVGSWC,ACCPEV,POTPEV,ACCSEV,POTSEV
        READ (1,1000) SDATE,RNFALL,RUNOFF,SOLOSS,ENRICH,DP,IDP1,PERCOL,
      1               AVGTMP,AVGSWC,ACCPEV,POTPEV,ACCSEV,POTSEV
        IF(SDATE.LE.0) RETURN
        IF(FLGIN.EQ.1) GO TO 10
        RNFALL   =RNFALL*2.54
        RUNOFF   =RUNOFF*2.54
        SOLOSS   =SOLOSS*2241.6
        PERCOL   =PERCOL*2.54
```

```
          AVGTMP     =(AVGTMP-32.0)*5.0/9.0
          ACCPEV -   =ACCPEV*2.54
          POTPEV     =POTPEV*2.54
          ACCSEV     =ACCSEV*2.54
          POTSEV     =POTSEV*2.54
    10    CONTINUE
          RETURN
 1000     FORMAT(I6,2F6.0,F8.0,F6.0,I2,I2,7F6.0)
          END
C
C*****************************************************************C
C
          SUBROUTINE STROUT(SDATE,RNFALL,RUNOFF,SOLOSS,ENRICH,PERCOL,
     1                      AVGTMP,AVGSWC,ACCPEV,POTPEV,ACCSEV,POTSEV,
     1                      NSTRMS,NRNFFS,TPRECP,TRUNFF,FLGOUT)
C
C   SUBROUTINE WRITES STORM INFORMATION TO OUTPUT FILE
C
          INTEGER SDATE,FLGOUT
          IF(FLGOUT.LE.1) GO TO 10
          WRITE(3,3001)
          WRITE(3,3000) SDATE,RNFALL,RUNOFF,SOLOSS,ENRICH,PERCOL,AVGTMP,
     1                  AVGSWC,ACCPEV,POTPEV,ACCSEV,POTSEV
    10    CONTINUE
C                                                              -
C   MAINTAIN RUNNING TOTAL OF RAINFALL PARAMETERS
C
          NSTRMS     =NSTRMS+1
          TPRECP     =TPRECP+RNFALL
          IF(RUNOFF.LE.0.0) GO TO 20
          NRNFFS     =NRNFFS+1
          TRUNFF     =TRUNFF+RUNOFF
          RETURN
    20    CONTINUE
          IF(FLGOUT.GT.1) WRITE(3,3002)
          RETURN
 3000     FORMAT(1H ,/,23X,4HDATE,10X,I7,3X,11HJULIAN DATE,/,
     1             23X,8HRAINFALL,7X,F6.2,3X,3HCM.,/,
     1             23X,13HRUNOFF VOLUME,2X,F6.2,3X,3HCM.,/,
     1             23X,9HSOIL LOSS,4X,F8.2,3X,5HKG/HA,/,
     1             23X,13HENRICH. RATIO,F8.2,3X,/,
     1             23X,11HPERCOLATION,4X,F6.2,3X,3HCM.,/,
     1             23X,10HAVG. TEMP.,5X,F6.2,3X,10HDEGREES C.,/,
     1             23X,15HAVG. SOIL WATER,F6.2,3X,7HVOL/VOL,/,
     1             23X,14HACCUMULATED EP,1X,F6.2,3X,3HCM.,/,
     1             23X,14HPOTENTIAL   EP,1X,F6.2,3X,3HCM.,/,
     1             23X,14HACCUMULATED ES,1X,F6.2,3X,3HCM.,/,
     1             23X,14HPOTENTIAL   ES,1X,F6.2,3X,3HCM., /)
 3001     FORMAT(1H ,   /,35X,12HSTORM INPUTS,/,
```

```
      1                   35X,12H-----------)
3002   FORMAT(1H ,23X,33H***   NO RUNOFF - NO LOSSES   ***)
       END
C
C**********************************************************************C
C
       SUBROUTINE DATEIN(PDATE,CDATE,IPST,FLGPST,FLGNUT)
C
C    SUBROUTINE READS IN CRITICAL DATES AND DETERMINES APPROPRIATE MONTH
C      AND YEAR
C
       INTEGER CDATE,PDATE,FLGPST,FLGNUT
       IF(FLGNUT .GT. 0) GO TO 10
       READ (5,2000) PDATE,CDATE,IPST
       RETURN
   10  READ(2,2000) PDATE,CDATE,IPST
       RETURN
2000   FORMAT(3I8)
       END
C
C**********************************************************************C
C
       INTEGER FUNCTION WCHMON(DATE)
C
C    FUNCTION TO DETERMINE MONTH OF A GIVEN JULIAN DATE
C
       INTEGER CAL(12),DATE,DAY,YEAR
       DATA CAL /31,60,91,121,152,182,213,244,274,305,335,366/
       IF(DATE.LE.0) GO TO 30
       DAY           =MOD(DATE,1000)
       YEAR          =DATE/1000
       IF(DAY.GT.CAL(1).AND.MOD(YEAR,4).GT.0) DAY=DAY+1
       DO 10 WCHMON=1,12
           IF(DAY.LE.CAL(WCHMON)) GO TO 20
   10  CONTINUE
       WCHMON        =1
   20  CONTINUE
       RETURN
   30  CONTINUE
       WCHMON        =13
       RETURN
       END
C
C**********************************************************************C
C
       SUBROUTINE MONPCP(MONTH,DATE,NSTRMS,NRNFFS,TPRECP,TRUNFF)
C
C    SUBROUTINE TO WRITE MONTHLY PRECIPITATION SUMMARY TO OUTPUT FILE
C
       INTEGER DATE,YEAR
```

```
          REAL MPRECP,MRUNFF
          CHARACTER*3 MONTHS(12)
          DATA MPRECP,MRUNFF,NSTRMM,NRNFFM/2*0.0,0,0/
          MONTHS(1)='JAN'
          MONTHS(2)='FEB'
          MONTHS(3)='MAR'
          MONTHS(4)='APR'
          MONTHS(5)='MAY'
          MONTHS(6)='JUN'
          MONTHS(7)='JUL'
          MONTHS(8)='AUG'
          MONTHS(9)='SEP'
          MONTHS(10)='OCT'
          MONTHS(11)='NOV'
          MONTHS(12)='DEC'
          YEAR      =DATE/1000
          NSTRMM    =NSTRMS-NSTRMM
          NRNFFM    =NRNFFS-NRNFFM
          MPRECP    =TPRECP-MPRECP
          MRUNFF    =TRUNFF-MRUNFF
          WRITE(3,3000) MONTHS(MONTH),YEAR,NSTRMM,MPRECP,NRNFFM,MRUNFF
          NSTRMM    =NSTRMS
          NRNFFM    =NRNFFS
          MPRECP    =TPRECP
          MRUNFF    =TRUNFF
          RETURN
3000      FORMAT(1H ,////,26X,20HMONTHLY SUMMARY FOR ,A3,3H 19,I2,/,
     1              26X,29H-----------------------------,//,
     1              18X,I4,17H STORMS PRODUCED ,F8.2,16H CM. OF RAINFALL,
     1              /,18X,I4,17H STORMS PRODUCED ,F8.2,14H CM. OF RUNOFF,/)
          END
C
C*******************************************************************************
C
          SUBROUTINE ANNPCP(DATE,NSTRMS,NRNFFS,TPRECP,TRUNFF)
C
C    SUBROUTINE TO WRITE ANNUAL PRECIPITATION SUMMARY TO OUTPUT FILE
C
          INTEGER DATE,YEAR
          DATA YPRECP,YRUNFF,NSTRMY,NRNFFY/2*0.0,0,0/
          YEAR      =DATE/1000
          NSTRMY    =NSTRMS-NSTRMY
          NRNFFY    =NRNFFS-NRNFFY
          YPRECP    =TPRECP-YPRECP
          YRUNFF    =TRUNFF-YRUNFF
          WRITE(3,3000) YEAR,NSTRMY,YPRECP,NRNFFY,YRUNFF
          NSTRMY    =NSTRMS
          NRNFFY    =NRNFFS
          YPRECP    =TPRECP
          YRUNFF    =TRUNFF
```

```
          RETURN
3000      FORMAT(1H ,     /,29X,21HANNUAL SUMMARY FOR 19,I2,/,
     1              29X,23H----------------------,//,
     1              18X,I4,17H STORMS PRODUCED ,F8.2,16H CM. OF RAINFALL,
     1            /,18X,I4,17H STORMS PRODUCED ,F8.2,14H CM. OF RUNOFF,/)
          END
C
C**********************************************************************
C
          SUBROUTINE PCPEND(NSTRMS,NRNFFS,TPRECP,TRUNFF)
C
C   SUBROUTINE TO WRITE SIMULATION PRECIPITATION SUMMARY TO OUTPUT FILE
C
          COMMON /HEAD/ TITLE
          CHARACTER*80  TITLE(3)
          WRITE(3,3000) (TITLE(J),J=1,3),NSTRMS,TPRECP,NRNFFS,
     1              TRUNFF
          RETURN
3000      FORMAT(1H1,//,12X,34HC R E A M S - N T  NONPOINT SOURCE,
     1              28H POLLUTION MODEL (CHEMICALS),/,
     1              23X,41HMOD. VERSION 1.8  MARCH 31,1989  VPI&SU ,//,
     1              3(A80,/),//,
     1              34X,13HSTORM SUMMARY,/,
     1              34X,13H-------------,//,
     1              18X,I4,17H STORMS PRODUCED ,F8.2,16H CM. OF RAINFALL,
     1            /,18X,I4,17H STORMS PRODUCED ,F8.2,14H CM. OF RUNOFF,//)
          END
C
C**********************************************************************
C
          SUBROUTINE INITNT(RNO3,FC,BR15,SOM,OM,BD,PH,CEC,AMN,ARN,CDATE)
C
C   SUBROUTINE TO READ SOIL PARAMETERS FROM INPUT FILE AND CALCULATE
C   N TRANSFORMATION PARAMETERS FOR THE INITIAL SOIL
C
          INTEGER DF,OPT,DEMERG,DHRVST,PRED,CDATE
          REAL NL,KMINI,KMIN,KADSI,KADS,KDESI,KDES,KNITI,KNIT,KVOLI
          REAL KVOL,KDNII,KDNI,MTSL,MTINT
          COMMON /ORIG/ SNO3,SNH4T,SNH4S,SNH4A,SORGN,SOLP,SOILP,RORGN,
     1          EXKNO3,EXKNH4,EXKP,ANH4,BNH4,AORN,BORN,AP,BP,
     1          RCN,ANO3,COLP,SPMN,RPMN,XSON,XRON,PRED
          COMMON /TRANS/ KMINI,KMIN,TMIN,THMIN,FMMIN,FPHMIN,FMAMIN,
     1          KNITI,KNIT,TNIT,THNIT,FMNIT,FPHNIT,FMANIT,KDNII,KDNI,
     1          TDNI,THDNI,FPHDNI,KVOLI,KVOL,TVOL,THVOL,FAFVOL,FCECI,
     1          FCECS,FCEC,FCECRF,KADSI,KADS,
     1          KDESI,KDES,DK,DB,MTSL,MTINT,MT,WDATE,RZDEP,SC,SSC,SDB,
     1          SKDNII,SKMINI,STMIN,SKNITI,STNIT,SPHMIN,SPHNIT,SPHDNI,
     1          SKADSI,SKDESI
          COMMON /ALLN/ OPT,RZMAX
          READ (2,2000) OPT
```

```
        IF(OPT.LE.0) RETURN
C
C     READ IN VALUES FOR INITIAL SOIL NUTRIENT CONTENTS, SOLUBLE NUTRIENT
C     EXTRACTION COEFFICIENTS, AND ENRICHMENT RATIO PARAMETERS
C
        READ (2,2001) SNO3,SNH4T,SORGN,SOLP,SOILP,RNO3,RORGN
        READ (2,2001) EXKNO3,EXKNH4,EXKP
        READ (2,2001) ANH4,BNH4,AORN,BORN,AP,BP,RCN
        WRITE(3,3000) EXKNO3,EXKNH4,EXKP,ANH4,AORN,AP,BNH4,BORN,
     1                BP,RCN
        WRITE(3,3001) SNO3,SNH4T,SORGN,SOLP,SOILP
        ANO3      =RNO3
        COLP      =SOLP
C
C     READ IN RATE CONSTANTS FOR AMMONIUM ADSORPTION, DESORPTION, AND
C     NITRIFICATION
C
        READ(2,2001) KADSI,KDESI,KNITI,TNIT
C
C     CALCULATE ROOT ZONE DENITRIFICATION RATE
C
        SSC       =SOM/0.1724
        SC        =OM/0.1724
        DK        =24.0*(0.0011*SC+0.0025)
        DB        =ALOG(DK)-2.4255
C
C     CALCULATE SURFACE LAYER N TRANSFORMATION RATES
C
        KDNII     =24.0*(0.0011*SSC+0.0025)
        TDNI      =35.0
        KVOLI     =0.0
        TVOL      =20.0
        KMINI     =EXP(15.807-6350.0/308.0)
        TMIN      =35.0
        THMIN     =1.07
        THNIT     =1.06
        THVOL     =1.05
        THDNI     =1.08
        WDATE     =0
C
C     SET METHOD OF APPLICATION, CATION EXCHANGE CAPACITY, PH AND
C     TEMPERATURE FACTORS FOR THE INITIAL SOIL
C
        FMAMIN    =1.0
        FMANIT    =1.0
        IF(CEC.GT.26.0)CEC=26.0
        FCECI     =1.00-0.038*CEC
        FCECS     =1.00
        FCECRF    =1.00
        SPH       =PH
```

```
      IF(PH.LT.4.0)SPH=4.0
      IF(PH.GT.10.0)SPH=10.0
      IF(SPH.LT.6.2)FPHMIN=0.19*SPH-0.173
      IF(SPH.GE.6.2.AND.SPH.LE.9.0)FPHMIN=1.00
      IF(SPH.GT.9.0)FPHMIN=3.25-0.25*SPH
      SPH       =PH
      IF(PH.LT.4.5)SPH=4.5
      IF(PH.GT.8.95)SPH=8.95
      IF(SPH.LT.7.0)FPHNIT=0.307*SPH-1.269
      IF(SPH.GE.7.0.AND.SPH.LE.7.4)FPHNIT=1.00
      IF(SPH.GT.7.4)FPHNIT=5.367-0.599*SPH
      SPH       =PH
      IF(PH.LT.4.1)SPH=4.1
      IF(PH.GT.9.9)SPH=9.9
      IF(SPH.LT.4.8)FPHDNI=0.129*SPH-0.527
      IF(SPH.GE.4.8.AND.SPH.LT.5.8)FPHDNI=0.84*SPH-3.942
      IF(SPH.GE.5.8.AND.SPH.LT.8.0)FPHDNI=0.745+0.032*SPH
      IF(SPH.GE.8.0.AND.SPH.LE.9.2)FPHDNI=7.0-0.75*SPH
      IF(SPH.GT.9.2)FPHDNI=1.414-0.1428*SPH
      SDB       =DB
      SKDNII    =KDNII
      SKMINI    =KMINI
      STMIN     =TMIN
      SKNITI    =KNITI
      STNIT     =TNIT
      SKADSI    =KADSI
      SKDESI    =KDESI
      SPHMIN    =FPHMIN
      SPHNIT    =FPHNIT
      SPHDNI    =FPHDNI
      KADS      =KADSI
      KDES      =KDESI
      READ(2,2001)RZMAX
      RZDEP     =RZMAX/10.0-1.0
C
C   CALCULATE POTENTIALLY MINERALIZABLE N IN SURFACE AND ROOT ZONE
C
      SPMN      =-591.0+112.0*ALOG((SORGN+SNH4T)*10.0/BD)
      RPMN      =-591.0+112.0*ALOG(RORGN*10.0/(RZDEP*BD))
      SPMN      =SPMN*BD/10.0
      RPMN      =RPMN*BD*RZDEP/10.0
      IF(SPMN.GT.SORGN)SPMN=SORGN
      IF(SPMN.LT.0.0)SPMN=0.0
      IF(RPMN.LT.0.0)RPMN=0.0
      XSON      =SORGN-SPMN
      XRON      =RORGN-RPMN
C
C   DETERMINE RELATIONSHIP BETWEEN MOISTURE CONTENT AND TENSION FOR SOIL
C
      MTSL      =(ALOG10(0.1)-ALOG10(15.0))/(FC-BR15)
```

```
            MTINT      =ALOG10(15.0)-MTSL*BR15
C
C    WRITE INITIAL SOIL N TRANSFORMATION PARAMETERS TO OUTPUT FILE
C
            WRITE(3,3003)SPMN
            WRITE(3,3002)KMINI,KADSI,KDESI,KNITI,KVOLI,KDNII
            WRITE(3,3004)RNO3,RORGN,RPMN
            AMN       =0.0
            ARN       =0.0
            PRED      =MOD(CDATE,1000)
            RETURN
2000    FORMAT(10I8)
2001    FORMAT(10F8.0)
3000    FORMAT(1H ,/ 30X,21HPLANT NUTRIENT INPUTS,/,
       1              30X,21H--------------------,//,
       1              29X,24HEXTRACTION COEFFICIENTS:,/,
       1              20X,5HNO3 =,F6.3,8H,   NH4 =,F6.3,
       1                  6H,   P =,F6.3,//,
       1              26X,30HENRICHMENT RATIO COEFFICIENTS:,/,
       1              22X,5HNH4 =,F6.3,10H,   ORG-N =,F6.3,6H,   P =,F6.3,//,
       1              28X,26HENRICHMENT RATIO EXPONENT:,/,
       1              22X,5HNH4 =,F6.3,10H,   ORG-N =,F6.3,6H,   P =,F6.3,//,
       1              24X,21HNITROGEN IN RAINFALL ,F8.2,4H PPM)
3001     FORMAT(1H ,/,24X,35HINITIAL CONDITIONS (SURFACE LAYER):,/,
       1              13X,7HNITRATE,7X,8HAMMONIUM,4X,9HORGANIC N,2X,
       1                  9HSOLUBLE P,4X,6HSOIL P,/,
       1              13X,F7.4,7X,F7.4,5X,F8.2,2(4X,F7.4))
3003    FORMAT(1H ,/,27X,29HPOTENTIALLY MINERALIZABLE N =,F8.2)
3002    FORMAT(1H ,/,24X,35HFIRST ORDER RATE CONSTANTS (1/DAY):,/,
       1              30X,17HMINERALIZATION   =,F7.4,/,
       1              30X,17HADSORPTION       =,F7.4,/,
       1              30X,17HDESORPTION       =,F7.4,/,
       1              30X,17HNITRIFICATION    =,F7.4,/,
       1              30X,17HVOLATILIZATION   =,F7.4,/,
       1              30X,17HDENITRIFICATION =,F7.4)
3004    FORMAT(1H ,/,26X,31HINITIAL CONDITIONS (ROOT ZONE):,/,
       1              22X,7HNITRATE,5X,9HORGANIC N,3X,15HMINERALIZABLE N,/,
       1              22X,F7.4,5X,F8.2,7X,F8.2)
            END
C
C*********************************************************************
C
            SUBROUTINE NUTRIN
C
C    SUBROUTINE TO READ IN CROP AND FERTILIZATION PARAMETERS
C
            INTEGER DF,OPT,DEMERG,DHRVST
            REAL NL
            COMMON /CROP/ DM,YP,AWU,PWU,DMY,DEMERG,DHRVST,DOM,SD,
       1          PU,C1,C2,C3,C4
```

```
      COMMON /FERT/ NF,DF(20),FNO3(20),FNH4T(20),FORGN(20),FP(20),
     1        FA(20),FAPP(20),FCNR(20),FPH(20),AKMIN(20),AKNIT(20),
     1        AKVOL(20),ATMIN(20),ATNIT(20),ATVOL(20),ACEC(20),
     1        WIND(7,20),AKADS(20),AKDES(20)
      COMMON /ALLN/ OPT,RZMAX
C
C   READ IN CROP INFORMATION
C
      READ (2,2000) IN1,IN2,IN3
      INSUM     =IN1+IN2+IN3
      IF(INSUM.LE.0) RETURN
      NF        =IN1
      DEMERG    =IN2
      DHRVST    =IN3
      IF(OPT.EQ.1) GO TO 10
      READ (2,2001) YP,DMY,DOM,SD,PU
      GO TO 20
  10  CONTINUE
      READ (2,2001) YP,DMY,AWU,PWU
      READ (2,2001) C1,C2,C3,C4
  20  CONTINUE
      IF(NF.LE.0) GO TO 40
C
C   READ IN FERTILIZATION INFORMATION INCLUDING NUTRIENT CONTENT OF
C   FERTILIZER AND N TRANSFORMATION PARAMETERS FOR TREATED SOIL
C
C   MODEL ALLOWS FOR UP TO 20 APPLICATIONS PER YEAR
C
      DO 30 I=1,NF
          READ (2,2000) DF(I)
          READ (2,2001) FNO3(I),FNH4T(I),FORGN(I),FP(I),FA(I)
          READ (2,2001) FAPP(I),FCNR(I),FPH(I)
          READ (2,2001) AKMIN(I),ATMIN(I),AKNIT(I),ATNIT(I),AKVOL(I),
     1                  ATVOL(I),ACEC(I)
          READ (2,2001) AKADS(I),AKDES(I)
          READ (2,2001) WIND(1,I),WIND(2,I),WIND(3,I),WIND(4,I),
     1                  WIND(5,I),WIND(6,I),WIND(7,I)
  30  CONTINUE
  40  CONTINUE
      WRITE(3,3000) OPT
      WRITE(3,3001) RZMAX,YP,DMY
      IF(OPT.EQ.1) GO TO 50
      WRITE(3,3004) DOM,SD,PU
      GO TO 60
  50  CONTINUE
      WRITE(3,3005) AWU,PWU
      WRITE(3,3002) C1,C2,C3,C4
  60  CONTINUE
      WRITE(3,3006) DEMERG,DHRVST
      IF(NF.GT.0) WRITE(3,3003) (DF(I),FNO3(I),FNH4T(I),FORGN(I),
```

```
      1                          FP(I),FA(I),I=1,NF)
            IF(NF.GT.0) WRITE(3,3007) (DF(I),AKMIN(I),AKNIT(I),AKVOL(I),
      1                          AKADS(I),AKDES(I),I=1,NF)
            RETURN
 2000    FORMAT(10I8)
 2001    FORMAT(10F8.0)
 3000    FORMAT(1H ,//,25X,32HUPDATEABLE PLANT NUTRIENT INPUTS,/,
      1             25X,32H-----------------------------,//,
      1             29X,23HNITROGEN UPTAKE OPTION ,I1)
 3001    FORMAT(1H ,/,21X,24HMAXIMUM ROOT ZONE        ,F8.2,3H MM,/,
      1             21X,24HPOTENTIAL YIELD          ,F8.2,6H KG/HA,/,
      1             21X,24HDRY MATTER YIELD RATIO   ,F8.2)
 3002    FORMAT(1H ,/,24X,36HCOEFFICIENTS FOR N CONTENT OF PLANTS ,//,
      1             15X,4F12.6)
 3003    FORMAT(1H ,/,34X,13HFERTILIZATION,//,
      1             7X,6HJULIAN,7X,3HNO3,9X,3HNH4,8X,5HORG-N,9X,1HP,10X,
      1              7HSURFACE,/,
      1             8X,4HDATE,7X,5HKG/HA,7X,5HKG/HA,7X,5HKG/HA,7X,5HKG/HA,
      1             7X,8HFRACTION,/,
      1             7X,6H------,5X,6H------,6X,6H------,6X,6H------,6X,
      1             6H------,7X,8H--------,/,
      1             20(8X,I5,4X,F7.2,3(5X,F7.2),7X,F7.2,/))
 3004    FORMAT(1H ,20X,24HMIDPOINT FOR N UPTAKE    ,F8.2,5H DAYS,/,
      1             21X,24HSTD. DEV. FOR MIDPOINT   ,F8.2,5H DAYS,/,
      1             21X,24HPOTENTIAL N UPTAKE       ,F8.2,6H KG/HA)
 3005    FORMAT(1H ,20X,24HACTUAL WATER USE         ,F8.2,3H MM,/,
      1             21X,24HPOTENTIAL WATER USE      ,F8.2,3H MM)
 3006    FORMAT(1H ,/,20X,23HDATE OF PLANT EMERGENCE,I7,12H JULIAN DATE,/,
      1             20X,23HDATE OF HARVESTING      ,I7,12H JULIAN DATE,/)
 3007    FORMAT(1H ,/,18X,44HTREATED SOIL: N TRANSFORMATION RATES (1/DAY),
      1             //,7X,6HJULIAN,7X,3HMIN,9X,3HNIT,9X,3HVOL,9X,3HADS,
      1              11X,3HDES,/,
      1             7X,6H------,5X,6H------,6X,6H------,6X,6H------,6X,
      1             6H------,8X,6H------,/,
      1             20(8X,I5,4X,F7.3,3(5X,F7.3),7X,F7.3,/))
            END
C
C********************************************************************
C
         SUBROUTINE NUT208(NEWNT,FC,RONO3,RONH4,ROP,SEDNH4,SEDORN,
      1                 SEDP,DRAIN,PUN,NL,TRONO3,TRONH4,
      1                 TOTROP,TSDNH4,TSDORN,TOTSDP,TOTDRN,TOTNL,
      1                 RN,TOTDNI,UP,MN,AMN,ARN,RNO3,POR,DNI,PH,BD,
      1                 FDAOUT,IDATE)
C
C   SUBROUTINE TO PERFORM ALL N TRANSFORMATIONS, CROP N UPTAKE, N
C   LEACHING, AND NUTRIENT RUNOFF LOSSES
C
         INTEGER SDATE,DAYS,PRED,DF,DATEF,OPT,DEMERG,DHRVST,DP
         INTEGER FDATE,TDATE,WDATE,FDAOUT
```

```
      REAL NL,MN,WND(7),FN(20)
      REAL KMIN,KNIT,KDNI,KVOL,KADS,KDES
      REAL KMINI,KNITI,KDNII,KVOLI,KADSI,KDESI,MT,MTSL,MTINT
      COMMON /ORIG/ SNO3,SNH4T,SNH4S,SNH4A,SORGN,SOLP,SOILP,RORGN,
     1        EXKNO3,EXKNH4,EXKP,ANH4,BNH4,AORN,BORN,AP,BP,
     1        RCN,ANO3,COLP,SPMN,RPMN,XSON,XRON,PRED
      COMMON /TRANS/ KMINI,KMIN,TMIN,THMIN,FMMIN,FPHMIN,FMAMIN,
     1        KNITI,KNIT,TNIT,THNIT,FMNIT,FPHNIT,FMANIT,KDNII,KDNI,
     1        TDNI,THDNI,FPHDNI,KVOLI,KVOL,TVOL,THVOL,FAFVOL,
     1        FCECI,FCECS,FCEC,FCECRF,KADSI,KADS,
     1        KDESI,KDES,DK,DB,MTSL,MTINT,MT,WDATE,RZDEP,SC,SSC,SDB,
     1        SKDNII,SKMINI,STMIN,SKNITI,STNIT,SPHMIN,SPHNIT,SPHDNI,
     1        SKADSI,SKDESI
      COMMON /CROP/ DM,YP,AWU,PWU,DMY,DEMERG,DHRVST,DOM,SD,
     1        PU,C1,C2,C3,C4
      COMMON /FERT/ NF,DF(20),FNO3(20),FNH4T(20),FORGN(20),FP(20),
     1        FA(20),FAPP(20),FCNR(20),FPH(20),AKMIN(20),AKNIT(20),
     1        AKVOL(20),ATMIN(20),ATNIT(20),ATVOL(20),ACEC(20),
     1        WIND(7,20),AKADS(20),AKDES(20)
      COMMON /ALLN/ OPT,RZMAX
      COMMON/PASS/PAS(40),IFAP(10)
      COMMON /PRCP/ SDATE,RNFALL,RUNOFF,SED,ENRICH,DP,IDP1,PERC,ATP,
     1              AWC,ACCPEV,POTPEV,ACCSEV,POTSEV
      DATA PFU,PPUN,SG,PSG,BASPUN/5*0.0/
C
C   INITIALIZE PARAMETERS
C
      LYEAR     =365
      IF(MOD((SDATE/1000),4).EQ.0) LYEAR=366
      MDATE     =MOD(SDATE,1000)
      IF(NEWNT.EQ.0) GO TO 10
      NEWNT     =0
      ID        =1
      IF(NF.GT.0) DATEF=DF(ID)
      IF(NF.LE.0) DATEF=1000000
      RZC       =RZMAX*FC
      EX        =(RZMAX-300.)/10.
   10 CONTINUE
      RN        =RCN*RNFALL*0.01
      ARN       =ARN+RN
      RONO3     =0.0
      RONH4     =0.0
      ROP       =0.0
      SEDNH4    =0.0
      SEDORN    =0.0
      SEDP      =0.0
      DAYS      =MDATE-PRED
      IF(DAYS.LT.0) DAYS=DAYS+LYEAR
      FDATE     =MOD(DATEF,1000)
      TDATE     =PRED
```

```
             PRED      =MDATE
             DELT      =1.0
C
C  BEGIN DAILY LOOP - TO DETERMINE AMOUNTS OF EACH N FORM IN SOIL
C    FOR EACH DAY BETWEEN STORMS
C
             DO 50 I=1,DAYS
C
C  READ IN DAILY VALUES OF PERCOLATING WATER, TEMPERATURE, SOIL WATER
C  CONTENT, ACTUAL AND POTENTIAL PLANT EVAP, AND ACTUAL AND
C  POTENTIAL SOIL EVAPORATION FROM DAILY HYDROLOGIC PASS FILE
C
             READ(8,1000)JDATE,IDPF,IDS,DPERC,SSEPM,ADST,ASSW,ARSW,DAPEV,
          1 DPPEV,DASEV,DPSEV
C
C  INITIALIZE SOME OF THE PLANT UPTAKE AND SOIL N POOL PARAMETERS
C
             NL        =0.0
             DNI       =0.0
             UP        =0.0
             EVAPN     =0.0
             IGROW     =0
             IF(DEMERG.LT.DHRVST) GO TO 20
             IF(TDATE.GT.DHRVST.AND.TDATE.LT.DEMERG) GO TO 30
             IF(DPPEV.LE.0.0) GO TO 30
             SG        =SG+DAPEV
             PSG       =PSG+DPPEV
             IF(TDATE.GT.DEMERG) IGROW=TDATE-DEMERG
             IF(TDATE.LT.DEMERG) IGROW=LYEAR-DEMERG+TDATE
             GO TO 40
   20    CONTINUE
             IF(TDATE.GT.DHRVST.OR.TDATE.LT.DEMERG) GO TO 30
             IF(DPPEV.LE.0.0) GO TO 30
             SG        =SG+DAPEV
             PSG       =PSG+DPPEV
             IGROW     =TDATE-DEMERG
             GO TO 40
   30    CONTINUE
             SG        =0.0
             PSG       =0.0
             IF(OPT.EQ.2) GO TO 40
             BASPUN    =PUN
   40    CONTINUE
             IF(DPPEV.GT.0.0) TR=DAPEV/DPPEV
C
C  IF DATE CURRENTLY SIMULATING IS AFTER THE LAST DATE THAT UPDATEABLE
C  NUTRIENT PARAMETERS ARE VALID,
C  RESET TRANSFORMATION PARAMETERS TO VALUES FOR SOIL ALONE
C
             IF(TDATE.NE.FDATE.AND.TDATE.EQ.IDATE)THEN
```

```
            DB=SDB
            KDNII=SKDNII
            KMINI=SKMINI
            TMIN =STMIN
            KNITI=SKNITI
            TNIT =STNIT
            KADSI=SKADSI
            KDESI=SKDESI
            FPHMIN=SPHMIN
            FPHNIT=SPHNIT
            FPHDNI=SPHDNI
            KVOLI =0.0
            WDATE=0
            FMAMIN=1.0
            FMANIT=1.0
            RORGN      =RPMN+XRON
            SORGN      =SPMN+XSON
            SPMN       =-591.0+112.0*ALOG((SORGN+SNH4T)*10.0/BD)
            RPMN       =-591.0+112.0*ALOG(RORGN*10.0/(RZDEP*BD))
            SPMN       =SPMN*BD/10.0
            RPMN       =RPMN*BD*RZDEP/10.0
            IF(SPMN.GT.SORGN)SPMN=SORGN
            IF(SPMN.LT.0.0)SPMN=0.0
            IF(RPMN.LT.0.0)RPMN=0.0
            XSON       =SORGN-SPMN
            XRON       =RORGN-RPMN
         ENDIF
C
C  IF SLUDGE IS APPLIED ON THIS DAY - ADD SLUDGE N & P TO SOIL POOLS
C  AND UPDATE TRANSFORMATION PARAMETERS
C
         IF(TDATE.EQ.FDATE) CALL ADFERT(RNO3,BD,DATEF,FDATE,ID,PH,WND)
C
C  ADJUST TRANSFORMATION RATE CONSTANTS FOR ENVIRONMENTAL CONDITIONS
C  INCLUDING TEMPERATURE ....
C
         DTVOL=ADST
         IF(ADST.GT.35.0)THEN
            DTMIN=35.0
            DTNIT=35.0
            DTDNI=35.0
         ELSE IF(ADST.LT.0.0)THEN
            DTMIN=0.0
            DTNIT=0.0
            DTDNI=0.0
         ELSE
            DTMIN=ADST
            DTNIT=ADST
            DTDNI=ADST
```

```
      ENDIF
C
C   MOISTURE CONTENT ....
C
      MT=10.0**(MTSL*ASSW+MTINT)
      IF(MT.LT.0.0357)MT=0.0357
      IF(MT.LT.0.33)FMMIN=1.51+0.453*ALOG(MT)
      IF(MT.GE.0.33.AND.MT.LE.0.85)FMMIN=1.0
      IF(MT.GT.0.85)FMMIN=0.97-0.118*ALOG(MT)
      IF(MT.LT.0.0985)THEN
          FMNIT=1.0
      ELSE
          FMNIT=0.599-0.173*ALOG(MT)
      ENDIF
C
C   WIND VELOCITY ....
C
      IF(TDATE.GT.WDATE)THEN
          KVOL=0.0
      ELSE
          IWD=7-(WDATE-TDATE)
          IF(WND(IWD).GT.0.06)WND(IWD)=0.06
          IF(WND(IWD).LE.0.00013)THEN
            KVOL=0.0
          ELSE
            FAFVOL=1.44+0.16*ALOG(WND(IWD))
            KVOL=KVOLI*FAFVOL*FCEC/FCECRF*THVOL**(DTVOL-TVOL)
          ENDIF
          IF(IWD.EQ.7)WDATE=0
      ENDIF
C
C   CALCULATE ADJUSTED FIRST ORDER RATE CONSTANTS
C
      IF(IDS.LE.0)THEN
          KDNI=0.0
      ELSE
          KDNI=KDNII*FPHDNI*THDNI**(DTDNI-TDNI)
      ENDIF
      KADS=KADSI
      KDES=KDESI
      KMIN=KMINI*FMMIN*FPHMIN*FMAMIN*THMIN**(DTMIN-TMIN)
      KNIT=KNITI*FMNIT*FPHNIT*FMANIT*THNIT**(DTNIT-TNIT)
C
C PERFORM N TRANSFORMATIONS IN ROOT ZONE (USING EQUATIONS
C FROM THE ORIGINAL CREAMS MODEL)
C
C DENITRIFICATION
C
      IF(IDPF.LE.0) GO TO 70
      DKT       =EXP(0.0693*ADST+DB)
```

```fortran
      IF(I.EQ.LDP)THEN
      DNI       =RNO3*(1.0-EXP(-DKT*(FLOAT(IDPF)-0.5)))
      ELSE
      DNI       =RNO3*(1.0-EXP(-DKT*(FLOAT(IDPF))))
      ENDIF
  70  CONTINUE
C
C  MINERALIZATION
C
      TA        =273.+ADST
      TK        =EXP(15.807-6350./TA)
      WK        =ARSW/FC
      IF(WK.GT.1.0) WK=1.0
      MN        =RPMN*WK*(1.-EXP(-TK*DELT))
C
C  PERFORM N TRANSFORMATIONS IN SURFACE SOIL LAYER
C
C  INITIALIZE N POOLS TO BEGINNING OF TIME STEP
C
      SNH4TI=SNH4T
      SNO3I=SNO3
      SPMNI=SPMN
C
C  CALCULATE CONTENT OF EACH N POOL AT END OF TIME STEP
C  USING EXACT SOLUTION OF COUPLED DIFFERENTIAL EQUATIONS
C
      SPMN=SPMNI*EXP((-KMIN)*DELT)
      SNH4T=KMIN/(KNIT+KVOL-KMIN)*SPMNI*(EXP(-KMIN*DELT)-EXP(-(KNIT+
     1       KVOL)*DELT))+SNH4TI*EXP(-(KNIT+KVOL)*DELT)
      SNH3=KVOL*KMIN/((KNIT+KVOL-KMIN)*(KNIT+KVOL))*SPMNI*
     1     (EXP(-(KNIT+KVOL)*DELT)-1.0)+KVOL/(KNIT+KVOL-KMIN)*SPMNI*
     1     (1.0-EXP(-KMIN*DELT))+KVOL/(KNIT+KVOL)*SNH4TI*(1.0-
     1     EXP(-(KNIT+KVOL)*DELT))
      SNO3=KNIT*KMIN/((KNIT+KVOL-KMIN)*(KDNI-KMIN))*SPMNI*
     1     (EXP(-KMIN*DELT)-EXP(-KDNI*DELT))+KNIT*KMIN/
     1     ((KNIT+KVOL-KMIN)*(KDNI-KNIT-KVOL))*
     1     SPMNI*(EXP(-KDNI*DELT)-EXP(-(KNIT+KVOL)*DELT))+KNIT/
     1     (KDNI-KNIT-KVOL)*SNH4TI*(EXP(-(KNIT+KVOL)*DELT)-EXP(-KDNI*
     1     DELT))+SNO3I*EXP(-KDNI*DELT)
      SN2O=KDNI*KNIT/((KNIT+KVOL-KMIN)*(KDNI-KMIN))*SPMNI*(1.0-
     1     EXP(-KMIN*DELT))+KNIT*KMIN/((KNIT+KVOL-KMIN)*(KDNI-KMIN))*
     1     SPMNI*(EXP(-KDNI*DELT)-1.0)+KNIT*KMIN/((KNIT+KVOL-KMIN)*
     1     (KDNI-KNIT-KVOL))*SPMNI*(1.0-EXP(-KDNI*DELT))+KDNI*KNIT*
     1     KMIN/((KNIT+KVOL-KMIN)*(KDNI-KNIT-KVOL)*(KNIT+KVOL))*
     1     SPMNI*(EXP(-(KNIT+KVOL)*DELT)-1.0)+KNIT/
     1     (KDNI-KNIT-KVOL)*SNH4TI*(EXP(-KDNI*DELT)-1.0)+KNIT*KDNI/
     1     ((KDNI-KNIT-KVOL)*(KNIT+KVOL))*SNH4TI*(1.0-EXP(-(KNIT+
     1     KVOL)*DELT))+SNO3I*(1.0-EXP(-KDNI*DELT))
C
C  DETERMINE THE AMOUNT OF NO3 MOVING FROM ROOT ZONE TO SURFACE LAYER
```

```
C  WITH EVAPORATING WATER
C
        EVAPN     =RNO3*DASEV/(ARSW*RZMAX)
C
C  DETERMINE THE AMOUNT OF NO3 LEACHING DOWNWARD FROM ROOT ZONE
C
        IF(DPERC.LE.0.0) GO TO 80
        FL        =DPERC/(DPERC+RZC)
        NL        =FL*RNO3
        DRAIN     =DRAIN+DPERC
        FLB       =(DRAIN/(DRAIN+10.0*FC))**EX
   80   CONTINUE
C
C  DETERMINE THE AMOUNT OF NO3 IN ROOT ZONE THAT IS TAKEN UP BY PLANTS...
C
        UP        =0.0
        IF(IGROW.LE.0) GO TO 170
C
C  USING OPTION 1 (CREAMS) OR.......................................
C
        IF(OPT.EQ.2) GO TO 140
        SGRT      =SG/PWU
        FDM       =SG/AWU
        A         =C1*FDM**C2
        B         =C3*FDM**C4
        CNP       =AMIN1(A,B)
        DM        =YP*SGRT*DMY
        PUN       =CNP*DM
        PUN       =PUN+BASPUN
        IF(PPUN.GT.PUN) PUN=PPUN
        UP        =PUN-PPUN
        GO TO 170
  140   CONTINUE
C
C  OR OPTION 2 (CREAMS)
C
        T         =FLOAT(IGROW)
        X         =(T-DOM)/SD
        XX        =X
        IF(X.GE.0.0) GO TO 150
        X         =-X
  150   CONTINUE
        S         =1.0+0.196854*X+0.115194*X**2+0.000344*X**3+0.01957*X**4
        FU        =1.0-S**(-4)/2.0
        IF(XX.LT.0.0) FU=1.0-FU
        UP        =PU*TR*(FU-PFU)
        IF(UP.GE.0.0) GO TO 160
        UP        =0.0
  160   CONTINUE
        PFU       =FU
```

```
          DM         =DMY*YP*SG/PSG
   170    CONTINUE
C
C   UPDATE ROOT ZONE POTENTIALLY MINERALIZABLE N AND NO3 POOLS
C
          RPMN       =RPMN-MN
          AMN        =AMN+MN
          RORGN      =RPMN+XRON
          SORGN      =SPMN+XSON
          RNO3       =RNO3+MN
          ANO3       =ANO3+MN
          DIFF       =NL+DNI+UP+EVAPN
          IF(DIFF.LE.RNO3) GO TO 180
          NL         =NL*RNO3/DIFF
          DNI        =DNI*RNO3/DIFF
          UP         =UP*RNO3/DIFF
          EVAPN      =EVAPN*RNO3/DIFF
   180    CONTINUE
          IF(OPT.EQ.2) GO TO 190
          PUN        =PPUN+UP
          PPUN       =PUN
          GO TO 200
   190    CONTINUE
          PUN        =PUN+UP
   200    CONTINUE
          RNO3       =RNO3-NL-DNI-UP-EVAPN
          IF(RNO3.LT.0.0) RNO3=0.0
          ANO3       =ANO3-DNI-UP
          SNO3       =SNO3+EVAPN
C
C   IF DESIRED, WRITE DAILY VALUES FOR EACH OF THE N POOLS
C
          IF(FDAOUT.EQ.1)THEN
            WRITE(9,2000)TDATE,SNO3,SNH4T,SORGN,SN2O,SNH3,RNO3,RORGN
          ENDIF
C
C   ADD UP ACCUMULATED ROOT ZONE N LEACHED AND DENITRIFICATION
C
          TOTNL      =TOTNL+NL
          TOTDRN     =TOTDRN+DPERC
          TOTDNI     =TOTDNI+DNI
          TDATE      =TDATE+1
          IF(TDATE.GT.LYEAR)THEN
            TDATE=TDATE-LYEAR
            IF(WDATE.GT.LYEAR)WDATE=WDATE-LYEAR
          ENDIF
    50    CONTINUE
          LDP        =DP
C
```

```
C  IF SLUDGE IS APPLIED ON THIS DAY - ADD SLUDGE N TO SOIL N POOLS
C
        IF(TDATE.EQ.FDATE) CALL ADFERT(RNO3,BD,DATEF,FDATE,ID,PH,WND)
        RORGN      =RPMN+XRON
        SORGN      =SPMN+XSON
        SFRACT     =SPMN/SORGN
        RFRACT     =RPMN/RORGN
        KADS       =KADSI
        KDES       =KDESI
C
C   PARTITION AMMONIUM BETWEEN ADSORBED AND DESORBED PHASES PRIOR TO
C   RUNOFF
C
        SNH4S      =SNH4T/(1.0+KADS/KDES)
        SNH4A      =SNH4T-SNH4S
C
C  IF SEDIMENT IS LOST WITH RUNOFF, CALCULATE THE QUANTITY OF N AND P
C  LOST FROM SURFACE LAYER OF SOIL IN SEDIMENT-BOUND FORM
C
        IF(SED.LE.0.0) GO TO 100
        ERNH4      =ANH4*SED**BNH4
        ERORN      =AORN*SED**BORN
        SEDNH4     =SNH4A*SED*ERNH4/(BD*100000.0)
        SEDORN     =SORGN*SED*ERORN/(BD*100000.0)
        ERP        =AP*SED**BP
        SEDP       =SOILP*SED*ERP/(BD*100000.0)
        IF(SEDP.GT.SOILP)SEDP=SOILP
        IF(SEDNH4.GT.SNH4A)SEDNH4=SNH4A
        IF(SEDORN.GT.SORGN)SEDORN=SORGN
C
C  UPDATE SOIL NUTRIENT LEVELS ASSOCIATED WITH SOIL PARTICLES
C
        SNH4A      =SNH4A-SEDNH4
        SORGN      =SORGN-SEDORN
        SOILP      =SOILP-SEDP
        IF(SNH4A.LT.0.0)SNH4A=0.0
        IF(SORGN.LT.0.0)SORGN=0.0
        IF(SOILP.LT.0.0)SOILP=0.0
  100   CONTINUE
C
C  CALCULATE THE QUANTITY OF N AND P LOST FROM SURFACE LAYER OF SOIL
C  IN SOLUBLE FORMS VIA RUNOFF AND INFILTRATING WATER
C
        TOTPOR     =10.0*POR
        EFRAIN     =RNFALL-TOTPOR
        IF(EFRAIN.LT.0.0) EFRAIN=0.0
        EFI        =EFRAIN-RUNOFF
        COEFF      =0.00001/POR
        CZRNO3     =SNO3*COEFF
        CZRNH4     =SNH4S*COEFF
```

```
        CZEROP    =SOLP*COEFF
        CHKNO3    =RCN*0.30*1.0E-06
        CHKNH4    =RCN*0.70*1.0E-06
        CHECKP    =COLP*COEFF
        EXKN1     =0.25
        EXKP1     =0.25
        XKFN1     =EXKN1/TOTPOR
        XKFP1     =EXKP1/TOTPOR
        XKFNO3    =EXKNO3/TOTPOR
        XKFNH4    =EXKNH4/TOTPOR
        XKFP2     =EXKP/TOTPOR
        CFINO3    =CHKNO3+(CZRNO3-CHKNO3)*EXP(-XKFN1*EFI-XKFNO3*RUNOFF)
        CFINH4    =CHKNH4+(CZRNH4-CHKNH4)*EXP(-XKFN1*EFI-XKFNH4*RUNOFF)
        CFINP     =CHECKP+(CZEROP-CHECKP)*EXP(-XKFP1*EFI-XKFP2*RUNOFF)
        SNO3      =CFINO3/COEFF
        SNH4S     =CFINH4/COEFF
        SOLP      =CFINP/COEFF
        IF(EFRAIN.LE.0.0) GO TO 110
        RONO3     =((CZRNO3-CHKNO3)*EXP(-XKFN1*EFI)-(CZRNO3-CHKNO3)*
     1             EXP(-XKFN1*EFI-XKFNO3*RUNOFF))/COEFF+
     1             0.30*RN*RUNOFF/EFRAIN
        RONH4     =((CZRNH4-CHKNH4)*EXP(-XKFN1*EFI)-(CZRNH4-CHKNH4)*
     1             EXP(-XKFN1*EFI-XKFNH4*RUNOFF))/COEFF+
     1             0.70*RN*RUNOFF/EFRAIN
        ROP       =((CZEROP-CHECKP)*EXP(-XKFP1*EFI)-(CZEROP-CHECKP)*
     1             EXP(-XKFP1*EFI-XKFP2*RUNOFF))/COEFF+
     1             CHECKP*XKFP2*RUNOFF/COEFF
        DWNO3     =((CZRNO3-CHKNO3)*(1.0-EXP(-XKFN1*EFI))/COEFF)+
     1             0.30*RN*EFI/EFRAIN
        DWNH4     =((CZRNH4-CHKNH4)*(1.0-EXP(-XKFN1*EFI))/COEFF)+
     1             0.70*RN*EFI/EFRAIN
        GO TO 120
 110    CONTINUE
        RONO3     =0.0
        RONH4     =0.0
        ROP       =0.0
        DWNO3     =0.0
        DWNH4     =0.0
        SNO3      =SNO3+RN*0.30
        SNH4S     =SNH4S+RN*0.70
 120    CONTINUE
C
C   UPDATE SOIL N LEVELS
C
        RNO3      =RNO3+DWNO3+DWNH4
        RPMN      =RORGN*RFRACT
        XRON      =RORGN-RPMN
        SPMN      =SORGN*SFRACT
        XSON=SORGN-SPMN
```

```
              SNH4T      =SNH4S+SNH4A
C
C   UPDATE RUNOFF AND SEDIMENT NUTRIENT LOSSES
C
              TRONO3     =TRONO3+RONO3
              TRONH4     =TRONH4+RONH4
              TOTROP     =TOTROP+ROP
              TSDNH4     =TSDNH4+SEDNH4
              TSDORN     =TSDORN+SEDORN
              TOTSDP     =TOTSDP+SEDP
  1000   FORMAT(I6,2I2,3F7.2,6F7.3)
  2000   FORMAT(1H ,/,1X,I3,1X,F7.3,1X,F7.3,2X,F7.3,3(1X,F7.3),
      1                1X,F8.2)
          RETURN
          END
C
C***********************************************************************
C
          SUBROUTINE ADFERT(RNO3,BD,DATEF,FDATE,ID,PH,WND)
C
C   SUBROUTINE TO ADD FERTILIZER N & P TO SOIL NUTRIENT POOLS
C   AND TO CALCULATE N TRANSFORMATION PARAMETERS AFFECTED BY TREATMENT
C
          INTEGER DF,DATEF,FDATE,WDATE
          REAL WND(7),FN(20)
          REAL KMIN,KNIT,KDNI,KVOL,KADS,KDES
          REAL KMINI,KNITI,KDNII,KVOLI,KADSI,KDESI
          COMMON /ORIG/ SNO3,SNH4T,SNH4S,SNH4A,SORGN,SOLP,SOILP,RORGN,
      1           EXKNO3,EXKNH4,EXKP,ANH4,BNH4,AORN,BORN,AP,BP,
      1           RCN,ANO3,COLP,SPMN,RPMN,XSON,XRON,PRED
          COMMON /TRANS/ KMINI,KMIN,TMIN,THMIN,FMMIN,FPHMIN,FMAMIN,
      1           KNITI,KNIT,TNIT,THNIT,FMNIT,FPHNIT,FMANIT,KDNII,KDNI,
      1           TDNI,THDNI,FPHDNI,KVOLI,KVOL,TVOL,THVOL,FAFVOL,
      1           FCECI,FCECS,FCEC,FCECRF,KADSI,KADS,
      1           KDESI,KDES,DK,DB,MTSL,MTINT,MT,WDATE,RZDEP,SC,SSC,SDB,
      1           SKDNII,SKMINI,STMIN,SKNITI,STNIT,SPHMIN,SPHNIT,SPHDNI,
      1           SKADSI,SKDESI
          COMMON /FERT/ NF,DF(20),FNO3(20),FNH4T(20),FORGN(20),FP(20),
      1           FA(20),FAPP(20),FCNR(20),FPH(20),AKMIN(20),AKNIT(20),
      1           AKVOL(20),ATMIN(20),ATNIT(20),ATVOL(20),ACEC(20),
      1           WIND(7,20),AKADS(20),AKDES(20)
          COMMON/PASS/PAS(40),IFAP(10)
C
C   INITIALIZE PARAMETERS
C
              RORGN      =RPMN+XRON
              SORGN      =SPMN+XSON
              WDATE      =FDATE+6
              DO 60 IW=1,7
              WND(IW)    =WIND(IW,ID)
```

```
      60   CONTINUE
C
C    ADD FERTILIZER N TO SOIL N POOLS
C
         SNO3       =SNO3+(FNO3(ID)*FA(ID))
         SNH4T      =SNH4T+(FNH4T(ID)*FA(ID))
        FN(ID)      =FNO3(ID)+FNH4T(ID)+FORGN(ID)
C
C    CALCULATE ADDED WASTE POTENTIALLY MINERALIZABLE N
C
         FPMN       =FN(ID)-FN(ID)*FCNR(ID)/23.0
         IF(FPMN.GT.FORGN(ID))FPMN=FORGN(ID)
C
C    RECALCULATE SOIL POTENTIALLY MINERALIZABLE N
C
         FRESN      =FORGN(ID)-FPMN
         SFPMN      =FPMN*FA(ID)
         RFPMN      =FPMN*(1.0-FA(ID))
         SFRESN     =FRESN*FA(ID)
         RFRESN     =FRESN*(1.0-FA(ID))
         SORGN      =SORGN+SFRESN
         RORGN      =RORGN+RFRESN
         SSPMN      =-591.0+112.0*ALOG((SORGN+SNH4T)*10.0/BD)
         RSPMN      =-591.0+112.0*ALOG(RORGN*10.0/(RZDEP*BD))
         SSPMN      =SSPMN*BD/10.0
         RSPMN      =RSPMN*BD*RZDEP/10.0
         IF(SSPMN.GT.SORGN)SSPMN=SORGN
         IF(SSPMN.LT.0.0)SSPMN=0.0
         IF(RSPMN.LT.0.0)RSPMN=0.0
         XSON       =SORGN-SSPMN
         XRON       =RORGN-RSPMN
         SPMN       =SFPMN+SSPMN
         RPMN       =RFPMN+RSPMN
C
C    ADD FERTILIZER P TO SOIL P POOLS
C
         SOILP      =SOILP+(0.9*FP(ID)*FA(ID))
         SOLP       =SOLP+(0.1*FP(ID)*FA(ID))
C
C    ADD FERTILIZER NITRATE TO ROOT ZONE NITRATE POOL
C
         RNO3       =RNO3+(FNO3(ID)+FNH4T(ID))*(1.0-FA(ID))
C
C    SET ENVIRONMENTAL CORRECTION FACTORS TO VALUES APPROPRIATE TO
C    TREATED SOIL
C
         IF(FA(ID).EQ.1.0)THEN
            FMAMIN=0.53
            FMANIT=0.53
            FCEC  =FCECS
```

```
          ELSE
             FMAMIN=1.0
             FMANIT=1.0
             FCEC   =FCECI
          ENDIF
          IF(ACEC(ID).GT.26.0)ACEC(ID)=26.0
          FCECRF   =1.00-0.038*ACEC(ID)
          PH=-ALOG10((10.0**(-PH)*BD*100000.0+10.0**(-FPH(ID))*FAPP(ID)*
     1      FA(ID))/(BD*100000.0+FAPP(ID)*FA(ID)))
          SPH       =PH
          IF(PH.LT.4.0)SPH=4.0
          IF(PH.GT.10.0)SPH=10.0
          IF(SPH.LT.6.2)FPHMIN=0.19*SPH-0.173
          IF(SPH.GE.6.2.AND.SPH.LE.9.0)FPHMIN=1.00
          IF(SPH.GT.9.0)FPHMIN=3.25-0.25*SPH
          SPH       =PH
          IF(PH.LT.4.5)SPH=4.5
          IF(PH.GT.8.95)SPH=8.95
          IF(SPH.LT.7.0)FPHNIT=0.307*SPH-1.269
          IF(SPH.GE.7.0.AND.SPH.LE.7.4)FPHNIT=1.00
          IF(SPH.GT.7.4)FPHNIT=5.367-0.599*SPH
          SPH       =PH
          IF(PH.LT.4.1)SPH=4.1
          IF(PH.GT.9.9)SPH=9.9
          IF(SPH.LT.4.8)FPHDNI=0.129*SPH-0.527
          IF(SPH.GE.4.8.AND.SPH.LT.5.8)FPHDNI=0.84*SPH-3.942
          IF(SPH.GE.5.8.AND.SPH.LT.8.0)FPHDNI=0.745+0.032*SPH
          IF(SPH.GE.8.0.AND.SPH.LE.9.2)FPHDNI=7.0-0.75*SPH
          IF(SPH.GT.9.2)FPHDNI=1.414-0.1428*SPH
          SC=SC+(FCNR(ID)*FN(ID)*(1.0-FA(ID))/(BD*RZDEP*100.0))
          SSC=SSC+(FCNR(ID)*FN(ID)*FA(ID)/(BD*100.0))
C
C     SET TRANSFORMATION RATES TO VALUES APPROPRIATE FOR TREATED SOIL
C
          DK        =24.0*(0.0011*SC+0.0025)
          DB        =ALOG(DK)-2.4255
          KDNII     =24.0*(0.0011*SSC+0.0025)
          KMINI     =AKMIN(ID)
          TMIN      =ATMIN(ID)
          KNITI     =AKNIT(ID)
          TNIT      =ATNIT(ID)
          KVOLI     =AKVOL(ID)
          TVOL      =ATVOL(ID)
          KADSI     =AKADS(ID)
          KDESI     =AKDES(ID)
          ID        =ID+1
          IF(ID.GT.NF) DATEF=1000000
          IF(ID.LE.NF) DATEF=DF(ID)
          IFAP(1)  = 1
          RETURN
```

```
      END
C
C*****************************************************************
C
      SUBROUTINE NUTRES(SDATE,RUNOFF,RONO3,RONH4,ROP,SEDNH4,
     1                  SEDORN,SEDP,PERC,DRAIN,NL,UP,MN,RNO3,DNI)
C
C  SUBROUTINE TO WRITE INDIVIDUAL STORM NUTRIENT LOSS SUMMARY TO OUTPUT
C
      INTEGER SDATE
      REAL NL,MN
      COMMON /ORIG/ SNO3,SNH4T,SNH4S,SNH4A,SORGN,SOLP,SOILP,RORGN,
     1        EXKNO3,EXKNH4,EXKP,ANH4,BNH4,AORN,BORN,AP,BP,
     1        RCN,ANO3,COLP,SPMN,RPMN,XSON,XRON,PRED
      IF(RUNOFF.LE.0.0) GO TO 10
C
C   CALCULATE AVERAGE NUTRIENT CONCENTRATION IN RUNOFF FOR STORM
C
      PPMNO3    =100.0*RONO3/RUNOFF
      PPMNH4    =100.0*RONH4/RUNOFF
      RON       =RONO3+RONH4
      PPMN      =100.0*RON/RUNOFF
      PPMP      =100.0*ROP/RUNOFF
      SEDN      =SEDNH4+SEDORN
      TOTP      =ROP+SEDP
      WRITE(3,3000) SDATE,RONO3,PPMNO3,RONH4,PPMNH4,RON,
     1              PPMN,ROP,PPMP,SEDNH4,SEDORN,SEDN,SEDP,TOTP
   10 CONTINUE
      WRITE(3,3001) PERC,DRAIN,MN,UP,NL,RNO3,RORGN,SNO3,SNH4T,SORGN,
     1              SOLP,SOILP,DNI
      RETURN
 3000 FORMAT(1H ,///,14X,42HTHE QUANTITY OF PLANT NUTRIENTS IN RUNOFF ,
     1                  11HAND LEACHED,/,
     1               30X,16HVALUES FOR STORM,I6,//,
     1               19X,27HNITRATE IN RUNOFF          ,F10.4,6H KG/HA,/,
     1               19X,27HNITRATE IN RUNOFF          ,F10.4,4H PPM,/,
     1               19X,27HAMMONIUM IN RUNOFF         ,F10.4,6H KG/HA,/,
     1               19X,27HAMMONIUM IN RUNOFF         ,F10.4,4H PPM,/,
     1               19X,27HTOTAL N IN RUNOFF          ,F10.4,6H KG/HA,/,
     1               19X,27HTOTAL N IN RUNOFF          ,F10.4,4H PPM,/,
     1               19X,27HPHOSPHORUS IN RUNOFF       ,F10.4,6H KG/HA,/,
     1               19X,27HPHOSPHORUS IN RUNOFF       ,F10.4,4H PPM,/,
     1               19X,27HAMMONIUM N WITH SEDIMENT   ,F10.4,6H KG/HA,/,
     1               19X,27HORGANIC N WITH SEDIMENT    ,F10.4,6H KG/HA,/,
     1               19X,27HTOTAL N WITH SEDIMENT      ,F10.4,6H KG/HA,/,
     1               19X,27HPHOSPHORUS WITH SEDIMENT   ,F10.4,6H KG/HA,/,
     1               19X,27HTOTAL PHOSPHORUS LOST      ,F10.4,6H KG/HA)
 3001 FORMAT(1H ,18X,27HDRAINAGE THIS STORM        ,F8.2,5H   MM,/,
     1               19X,27HACCUMULATED DRAINAGE       ,F8.2,5H   MM,/,
     1               19X,27HROOT ZONE MINERALIZED N    ,F10.4,6H KG/HA,/,
```

```
      1             19X,27HN UPTAKE                   ,F10.4,6H KG/HA,/,
      1             19X,27HNITRATE LEACHED THIS STORM ,F10.4,6H KG/HA,/,
      1             19X,27HROOT ZONE SOIL NITRATE      ,F10.4,6H KG/HA,/,
      1             19X,27HROOT ZONE ORGANIC N         ,F10.4,6H KG/HA,/,
      1             19X,27HSURFACE NITRATE             ,F10.4,6H KG/HA,/,
      1             19X,27HSURFACE AMMONIUM N          ,F10.4,6H KG/HA,/,
      1             19X,27HSURFACE ORGANIC N           ,F10.4,6H KG/HA,/,
      1             19X,27HSURFACE SOLUBLE P           ,F10.4,6H KG/HA,/,
      1             19X,27HSURFACE SOIL P              ,F10.4,6H KG/HA,/,
      1             19X,27HROOT ZONE DENITRIFICATION   ,F10.4,6H KG/HA)
      END
C
C*************************************************************************
C
      SUBROUTINE MONNUT(TRONO3,TRONH4,TOTROP,TSDNH4,TSDORN,
     1                  TOTSDP,TOTNL,TOTDRN,TOTDNI,AMN,PUN,RNO3,ARN)
C
C  SUBROUTINE TO DETERMINE AND WRITE MONTHLY NUTRIENT LOSS
C    SUMMARY TO OUTPUT FILE
C
      REAL MOTRON,MOTROP,MOTSDN,MOTSDP,MOTDRN,MOTNL,MOTDNI,
     1     MAMN,MPUN,MARN,MTRNO3,MTRNH4,MTSNH4,MTSORN,MOTP
      DATA MOTRON,MOTROP,MOTSDN,MOTSDP,MOTDRN,MOTNL,MOTDNI,MAMN,
     1     MPUN,MARN,MTRNO3,MTRNH4,MTSNH4,MTSORN/14*0.0/
      MTRNO3    =TRONO3-MTRNO3
      MTRNH4    =TRONH4-MTRNH4
      MOTRON    =MTRNO3+MTRNH4
      MOTROP    =TOTROP-MOTROP
      MTSNH4    =TSDNH4-MTSNH4
      MTSORN    =TSDORN-MTSORN
      MOTSDN    =MTSNH4+MTSORN
      MOTSDP    =TOTSDP-MOTSDP
      MOTP      =MOTROP+MOTSDP
      MOTDRN    =TOTDRN-MOTDRN
      MOTNL     =TOTNL-MOTNL
      MOTDNI    =TOTDNI-MOTDNI
      MAMN      =AMN-MAMN
      MPUN      =PUN-MPUN
      MARN      =ARN-MARN
      WRITE(3,3000) MTRNO3,MTRNH4,MOTRON,MOTROP,MTSNH4,MTSORN,
     1              MOTSDN,MOTSDP,MOTP,MOTDRN
      WRITE(3,3001) MAMN,MPUN,RNO3,MARN,MOTNL,MOTDNI
      MTRNO3    =TRONO3
      MTRNH4    =TRONH4
      MOTROP    =TOTROP
      MTSNH4    =TSDNH4
      MTSORN    =TSDORN
      MOTSDP    =TOTSDP
      MOTDRN    =TOTDRN
      MOTNL     =TOTNL
```

```
              MOTDNI    =TOTDNI
              MAMN      =AMN
              MPUN      =PUN
              MARN      =ARN
              RETURN
3000     FORMAT(1H ,//,28X,25HTHE PLANT NUTRIENT LOSSES,/,
        1            28X,25H------------------------,//,
        1            19X,27HNITRATE IN RUNOFF         ,F10.4,6H KG/HA,/,
        1            19X,27HAMMONIUM IN RUNOFF        ,F10.4,6H KG/HA,/,
        1            19X,27HORGANIC N IN RUNOFF       ,F10.4,6H KG/HA,/,
        1            19X,27HTOTAL NITROGEN IN RUNOFF  ,F10.4,6H KG/HA,/,
        1            19X,27HPHOSPHORUS IN RUNOFF      ,F10.4,6H KG/HA,/,
        1            19X,27HAMMONIUM WITH SEDIMENT    ,F10.4,6H KG/HA,/,
        1            19X,27HTOTAL N WITH SEDIMENT     ,F10.4,6H KG/HA,/,
        1            19X,27HPHOSPHORUS WITH SEDIMENT  ,F10.4,6H KG/HA,/,
        1            19X,27HTOTAL PHOSPHORUS LOST     ,F10.4,6H KG/HA,/,
        1            19X,27HACCUMULATED DRAINAGE      ,F8.2,5H   MM)
3001     FORMAT(1H ,18X,27HMINERALIZED N             ,F10.4,6H KG/HA,/,
        1            19X,27HN UPTAKE                  ,F10.4,6H KG/HA,/,
        1            19X,27HSOIL NITRATE              ,F10.4,6H KG/HA,/,
        1            19X,27HRAINFALL NITROGEN         ,F10.4,6H KG/HA,/,
        1            19X,27HESTIMATE 1 NITRATE LEACHED ,F10.4,6H KG/HA,/,
        1            19X,27HACCUMULATED DENITRIFICATION,F10.4,6H KG/HA)
         END
C
C*****************************************************************
C
         SUBROUTINE ANNNUT(TRONO3,TRONH4,TOTROP,TSDNH4,
        1                 TSDORN,TOTSDP,TOTNL,
        1                 TOTDRN,TOTDNI,AMN,PUN,RNO3,ARN)
C
C  SUBROUTINE TO DETERMINE AND WRITE ANNUAL NUTRIENT LOSS
C   SUMMARY TO OUTPUT FILE
C
         DATA YOTRON,YOTROP,YOTSDN,YOTSDP,YOTDRN,YOTNL,YOTDNI,YAMN,
        1     YPUN,YARN,YTRNO3,YTRNH4,YTSNH4,YTSORN/14*0.0/
            YTRNO3    =TRONO3-YTRNO3
            YTRNH4    =TRONH4-YTRNH4
            YOTRON    =YTRNO3+YTRNH4
            YOTROP    =TOTROP-YOTROP
            YTSNH4    =TSDNH4-YTSNH4
            YTSORN    =TSDORN-YTSORN
            YOTSDN    =YTSNH4+YTSORN
            YOTSDP    =TOTSDP-YOTSDP
            YOTP      =YOTROP+YOTSDP
            YOTDRN    =TOTDRN-YOTDRN
            YOTNL     =TOTNL-YOTNL
            YOTDNI    =TOTDNI-YOTDNI
            YAMN      =AMN-YAMN
            YPUN      =PUN-YPUN
```

```
      YARN       =ARN-YARN
      WRITE(3,3000) YTRNO3,YTRNH4,YOTRON,YOTROP,YTSNH4,YTSORN,
     1              YOTSDN,YOTSDP,YOTP,YOTDRN
      WRITE(3,3001) YAMN,YPUN,RNO3,YARN,YOTNL,YOTDNI
      YTRNO3     =TRONO3
      YTRNH4     =TRONH4
      YOTROP     =TOTROP
      YTSNH4     =TSDNH4
      YTSORN     =TSDORN
      YOTSDP     =TOTSDP
      YOTDRN     =TOTDRN
      YOTNL      =TOTNL
      YOTDNI     =TOTDNI
      YAMN       =AMN
      YPUN       =PUN
      YARN       =ARN
      RETURN
3000  FORMAT(1H ,//,28X,25HTHE PLANT NUTRIENT LOSSES,/,
     1              28X,25H------------------------,//,
     1              19X,27HNITRATE IN RUNOFF          ,F10.4,6H KG/HA,/,
     1              19X,27HAMMONIUM IN RUNOFF         ,F10.4,6H KG/HA,/,
     1              19X,27HTOTAL NITROGEN IN RUNOFF   ,F10.4,6H KG/HA,/,
     1              19X,27HPHOSPHORUS IN RUNOFF       ,F10.4,6H KG/HA,/,
     1              19X,27HAMMONIUM WITH SEDIMENT     ,F10.4,6H KG/HA,/,
     1              19X,27HORGANIC N WITH SEDIMENT    ,F10.4,6H KG/HA,/,
     1              19X,27HTOTAL N WITH SEDIMENT      ,F10.4,6H KG/HA,/,
     1              19X,27HPHOSPHORUS WITH SEDIMENT   ,F10.4,6H KG/HA,/,
     1              19X,27HTOTAL PHOSPHORUS LOST      ,F10.4,6H KG/HA,/,
     1              19X,27HACCUMULATED DRAINAGE       ,F8.2,4H  MM)
3001  FORMAT(1H ,18X,27HMINERALIZED N              ,F10.4,6H KG/HA,/,
     1              19X,27HN UPTAKE                   ,F10.4,6H KG/HA,/,
     1              19X,27HSOIL NITRATE               ,F10.4,6H KG/HA,/,
     1              19X,27HRAINFALL NITROGEN          ,F10.4,6H KG/HA,/,
     1              19X,27HESTIMATE 1 NITRATE LEACHED ,F10.4,6H KG/HA,/,
     1              19X,27HACCUMULATED DENITRIFICATION,F10.4,6H KG/HA)
      END
C
C***************************************************************************
C
      SUBROUTINE NUTEND(TRONO3,TRONH4,TOTROP,TSDNH4,
     1                  TSDORN,TOTSDP,TOTNL,
     1                  TOTDRN,TOTDNI,AMN,PUN,RNO3,ARN)
C
C  SUBROUTINE TO WRITE NUTRIENT LOSS SUMMARY FOR PERIOD OF SIMULATION
C   TO OUTPUT FILE
C
      TOTRON =TRONO3+TRONH4
      TOTSDN =TSDNH4+TSDORN
      TTOTP  =TOTROP+TOTSDP
      WRITE(3,3000) TRONO3,TRONH4,TOTRON,TOTROP,TSDNH4,TSDORN,
```

```
      1                     TOTSDN,TOTSDP,TTOTP,TOTDRN
            WRITE(3,3001) AMN,PUN,RNO3,ARN,TOTNL,TOTDNI
            RETURN
3000  FORMAT(1H ,///,14X,42HTHE QUANTITY OF PLANT NUTRIENTS IN RUNOFF ,
      1                11HAND LEACHED,/,
      1                30X,21HVALUES FOR ALL STORMS,//,
      1                19X,27HNITRATE IN RUNOFF         ,F10.4,6H KG/HA,/,
      1                19X,27HAMMONIUM IN RUNOFF        ,F10.4,6H KG/HA,/,
      1                19X,27HTOTAL NITROGEN IN RUNOFF  ,F10.4,6H KG/HA,/,
      1                19X,27HPHOSPHORUS IN RUNOFF      ,F10.4,6H KG/HA,/,
      1                19X,27HAMMONIUM WITH SEDIMENT    ,F10.4,6H KG/HA,/,
      1                19X,27HORGANIC N WITH SEDIMENT   ,F10.4,6H KG/HA,/,
      1                19X,27HTOTAL N WITH SEDIMENT     ,F10.4,6H KG/HA,/,
      1                19X,27HPHOSPHORUS WITH SEDIMENT  ,F10.4,6H KG/HA,/,
      1                19X,27HTOTAL PHOSPHORUS LOST     ,F10.4,6H KG/HA,/,
      1                19X,27HACCUMULATED DRAINAGE      ,F8.2,5H   MM)
3001  FORMAT(1H ,18X,27HMINERALIZED N             ,F10.4,6H KG/HA,/,
      1                19X,27HN UPTAKE                  ,F10.4,6H KG/HA,/,
      1                19X,27HSOIL NITRATE              ,F10.4,6H KG/HA,/,
      1                19X,27HRAINFALL NITROGEN         ,F10.4,6H KG/HA,/,
      1                19X,27HESTIMATE 1 NITRATE LEACHED ,F10.4,6H KG/HA,/,
      1                19X,27HACCUMULATED DENITRIFICATION,F10.4,6H KG/HA)
            END
C
C************************************************************************
C
            SUBROUTINE NUTPAS (NL,RONO3,RONH4,ROP,SEDNH4,SEDORN,SEDP,
      1                        UP,MN,RNO3,DNI,RN,FLGPAS)
C
C  SUBROUTINE TO WRITE SOIL NUTRIENT POOL AND NUTRIENT LOSS INFORMATION
C   TO PASS FILES
C
            COMMON /ORIG/ SNO3,SNH4T,SNH4S,SNH4A,SORGN,SOLP,SOILP,RORGN,
      1           EXKNO3,EXKNH4,EXKP,ANH4,BNH4,AORN,BORN,AP,BP,
      1           RCN,ANO3,COLP,SPMN,RPMN,XSON,XRON,PRED
            COMMON/PASS/PAS(40),IFAP(10)
            COMMON /PRCP/ SDATE,RNFALL,RUNOFF,SOLOSS,ENRICH,DP,IDP1,PERCOL,
      1                AVGTMP,AVGSWC,ACCPEV,POTPEV,ACCSEV,POTSEV
            INTEGER SDATE,DP,FLGPAS
            REAL NL,MN
            CHARACTER*1 J,ISTAR,IBLANK
            ISTAR='*'
            IBLANK=' '
            J    = IBLANK
            IF(RUNOFF.GT.0.)  GO TO 10
            PPMN = 0.
            PPMNO3 = 0.
            PPMNH4 = 0.
            PPMP = 0.
            GO TO 20
```

```
  10    PPMNO3 = 100. * RONO3/ RUNOFF
        PPMNH4 = 100. * RONH4/ RUNOFF
        RON = RONO3+RONH4
        PPMN = 100. * RON/ RUNOFF
        PPMP = 100. * ROP/ RUNOFF
        IF(IFAP(1).GT.0) J=ISTAR
        IFAP(1) = 0
  20    P    = RNFALL/10.
        Q    = RUNOFF/10.
        PERC = PERCOL/10.
        SEDN = SEDNH4+SEDORN
        IF(FLGPAS - 2) 30,40,30
  30    IF(Q .LE. 0.0) GO TO 40
        WRITE(4,400)SDATE,J,P,Q,PERC,SOLOSS,RON,PPMN,ROP,PPMP,SEDN,SEDP
        WRITE(10,500)SDATE,SNO3,SNH4T,SORGN,RNO3,RORGN
  40    IF(FLGPAS .LT. 2) GO TO 50
        WRITE(7,700)SDATE,J,P,Q,PERC,SOLOSS,RON,ROP,SEDN,SEDP,MN,UP,NL,
     1              DNI,RNO3,RN
  50    CONTINUE
        RETURN
 400    FORMAT(I6,A1,3F6.2,F8.1,2F7.2,F8.2,F7.2,2F9.2)
 500    FORMAT(I6,4F8.3,F8.2)
 700    FORMAT(I6,A1,3F6.2,F8.1,F12.2,F11.2,F12.2,F11.2,1X/
     1          38X,F6.2,F8.2,4F7.2)
        END
```

Appendix D: CREAMS-NT Sample Input

```
             PLOT QFB 1987 - NUTRIENT PARAMETERS
                 CONVENTIONAL TILLAGE PLOT
              SLUDGE SURFACE APPLIED AT RATE 75 KG N/HA
   87128       2       0       0       1       3       1
   0.5616    0.29    0.09    3.70    1.80    1.162    5.85    8.31
        2
   0.482    0.397  262.40     0.2    55.30   20.230  6299.7
   0.050    0.250   0.070
     7.4   -0.200  15.226  -0.423   3.267   -0.206     1.0
     1.0     0.20    0.08    21.0
  1220.0
   87128    87305
       1      150     305
  9400.0      2.5    60.0    27.0   200.0
   87128
     0.0     55.8   119.2   116.1     1.0
 36287.0     10.0     7.3
   0.022     35.0   0.400    21.0    0.21    21.0     0.0
     1.0      1.0
    6.75     5.52    7.11    5.27    6.06    5.93    6.33
              0
```

Appendix E: CREAMS-NT Sample Output

1

CREAMS-NT NONPOINT SOURCE POLLUTION MODEL (CHEMICALS)
MOD. VERSION 1.8 MARCH 31, 1989 VPI&SU

PLOT QFB 1987 - NUTRIENT PARAMETERS
CONVENTIONAL TILLAGE PLOT
SLUDGE SURFACE APPLIED AT RATE 75 KG N/HA

STARTING DATE FOR SIMULATION 87128 JULIAN DATE

POROSITY OF SOIL	0.56
FIELD CAPACITY	0.29
WILTING POINT	0.09
SURFACE ORGANIC MATTER	3.70
(PERCENT OF SOIL MASS)	
ROOT ZONE ORGANIC MATTER	1.80
(PERCENT OF SOIL MASS)	
BULK DENSITY (G/CU.CM.)	1.16
SOIL PH	5.85
SOIL CEC (MEQ/100 G)	8.31

PLANT NUTRIENT INPUTS

EXTRACTION COEFFICIENTS:
NO3 = 0.050, NH4 = 0.250, P = 0.070

ENRICHMENT RATIO COEFFICIENTS:
NH4 = 7.400, ORG-N =15.226, P = 3.267

ENRICHMENT RATIO EXPONENT:
NH4 =-0.200, ORG-N =-0.423, P =-0.206

NITROGEN IN RAINFALL   1.00 PPM

INITIAL CONDITIONS (SURFACE LAYER):

NITRATE	AMMONIUM	ORGANIC N	SOLUBLE P	SOIL P
0.4820	0.3970	262.40	0.2000	55.3000

POTENTIALLY MINERALIZABLE N =   31.85

               FIRST ORDER RATE CONSTANTS (1/DAY):
                        MINERALIZATION = 0.0081
                        ADSORPTION   = 1.0000
                        DESORPTION   = 0.2000
                        NITRIFICATION   = 0.0800
                        VOLATILIZATION = 0.0000
                        DENITRIFICATION = 0.6266

                    INITIAL CONDITIONS (ROOT ZONE):
                 NITRATE   ORGANIC N   MINERALIZABLE N
                 20.2300   6299.70   1304.08

                  UPDATEABLE PLANT NUTRIENT INPUTS

                      NITROGEN UPTAKE OPTION 2

               MAXIMUM ROOT ZONE   1220.00 MM
               POTENTIAL YIELD   9400.00 KG/HA
               DRY MATTER YIELD RATIO   2.50
               MIDPOINT FOR N UPTAKE   60.00 DAYS
               STD. DEV. FOR MIDPOINT   27.00 DAYS
               POTENTIAL N UPTAKE   200.00 KG/HA

               DATE OF PLANT EMERGENCE   150 JULIAN DATE
               DATE OF HARVESTING   305 JULIAN DATE

                           FERTILIZATION

JULIAN DATE	NO3 KG/HA	NH4 KG/HA	ORG-N KG/HA	P KG/HA	SURFACE FRACTION
87128	0.00	55.80	119.20	116.10	1.00

         TREATED SOIL: N TRANSFORMATION RATES (1/DAY)

JULIAN	MIN	NIT	VOL	ADS	DES
87128	0.022	0.400	0.210	1.000	1.000

                          STORM INPUTS

                DATE   87129   JULIAN DATE

```
                 RAINFALL           4.09   CM.
                 RUNOFF VOLUME      0.76   CM.
                 SOIL LOSS        144.58   KG/HA
                 ENRICH. RATIO      1.75
                 PERCOLATION        0.00   CM.
                 AVG. TEMP.        14.84   DEGREES C.
                 AVG. SOIL WATER    0.22   VOL/VOL
                 ACCUMULATED EP     0.00   CM.
                 POTENTIAL    EP    0.00   CM.
                 ACCUMULATED ES     0.50   CM.
                 POTENTIAL    ES    0.50   CM.
```

THE QUANTITY OF PLANT NUTRIENTS IN RUNOFF AND LEACHED
VALUES FOR STORM 87129

```
        NITRATE IN RUNOFF               0.0590 KG/HA
        NITRATE IN RUNOFF               0.7745 PPM
        AMMONIUM IN RUNOFF              1.9796 KG/HA
        AMMONIUM IN RUNOFF             25.9794 PPM
        TOTAL N IN RUNOFF               2.0386 KG/HA
        TOTAL N IN RUNOFF              26.7538 PPM
        PHOSPHORUS IN RUNOFF            0.3261 KG/HA
        PHOSPHORUS IN RUNOFF            4.2795 PPM
        AMMONIUM N WITH SEDIMENT        0.0779 KG/HA
        ORGANIC N WITH SEDIMENT         0.8810 KG/HA
        TOTAL N WITH SEDIMENT           0.9589 KG/HA
        PHOSPHORUS WITH SEDIMENT        0.2331 KG/HA
        TOTAL PHOSPHORUS LOST           0.5592 KG/HA
        DRAINAGE THIS STORM             0.00   MM
        ACCUMULATED DRAINAGE            0.00   MM
        ROOT ZONE MINERALIZED N         1.1461 KG/HA
        N UPTAKE                        0.0000 KG/HA
        NITRATE LEACHED THIS STORM      0.0000 KG/HA
        ROOT ZONE SOIL NITRATE         38.5802 KG/HA
        ROOT ZONE ORGANIC N          6298.5469 KG/HA
        SURFACE NITRATE                 0.4801 KG/HA
        SURFACE AMMONIUM N             27.5858 KG/HA
        SURFACE ORGANIC N             380.3652 KG/HA
        SURFACE SOLUBLE P               3.2823 KG/HA
        SURFACE SOIL P                159.5568 KG/HA
        ROOT ZONE DENITRIFICATION       0.0000 KG/HA
```

STORM INPUTS

```
        DATE               87130   JULIAN DATE
        RAINFALL            4.29   CM.
```

```
RUNOFF VOLUME      2.31    CM.
SOIL LOSS        581.47    KG/HA
ENRICH. RATIO      1.23
PERCOLATION        0.00    CM.
AVG. TEMP.        15.03    DEGREES C.
AVG. SOIL WATER    0.24    VOL/VOL
ACCUMULATED EP     0.00    CM.
POTENTIAL   EP     0.00    CM.
ACCUMULATED ES     0.50    CM.
POTENTIAL   ES     0.50    CM.
```

THE QUANTITY OF PLANT NUTRIENTS IN RUNOFF AND LEACHED VALUES FOR STORM 87130

```
NITRATE IN RUNOFF                0.5132 KG/HA
NITRATE IN RUNOFF                2.2205 PPM
AMMONIUM IN RUNOFF               3.6183 KG/HA
AMMONIUM IN RUNOFF              15.6541 PPM
TOTAL N IN RUNOFF                4.1315 KG/HA
TOTAL N IN RUNOFF               17.8745 PPM
PHOSPHORUS IN RUNOFF             0.4677 KG/HA
PHOSPHORUS IN RUNOFF             2.0236 PPM
AMMONIUM N WITH SEDIMENT         0.1046 KG/HA
ORGANIC N WITH SEDIMENT          1.9621 KG/HA
TOTAL N WITH SEDIMENT            2.0666 KG/HA
PHOSPHORUS WITH SEDIMENT         0.7029 KG/HA
TOTAL PHOSPHORUS LOST            1.1706 KG/HA
DRAINAGE THIS STORM              0.00   MM
ACCUMULATED DRAINAGE             0.00   MM
ROOT ZONE MINERALIZED N          1.1588 KG/HA
N UPTAKE                         0.0000 KG/HA
NITRATE LEACHED THIS STORM       0.0000 KG/HA
ROOT ZONE SOIL NITRATE          44.9108 KG/HA
ROOT ZONE ORGANIC N           6297.3867 KG/HA
SURFACE NITRATE                  1.9139 KG/HA
SURFACE AMMONIUM N              11.9305 KG/HA
SURFACE ORGANIC N              378.4028 KG/HA
SURFACE SOLUBLE P                1.4283 KG/HA
SURFACE SOIL P                 158.8539 KG/HA
ROOT ZONE DENITRIFICATION        0.0000 KG/HA
```

MONTHLY SUMMARY FOR MAY 1987

```
       2 STORMS PRODUCED        8.38 CM. OF RAINFALL
       2 STORMS PRODUCED        3.07 CM. OF RUNOFF


                    THE PLANT NUTRIENT LOSSES
                    -------------------------

        NITRATE IN RUNOFF               0.5723 KG/HA
        AMMONIUM IN RUNOFF              5.5979 KG/HA
        ORGANIC N IN RUNOFF            6.1702 KG/HA
        TOTAL NITROGEN IN RUNOFF       0.7938 KG/HA
        PHOSPHORUS IN RUNOFF           0.1825 KG/HA
        AMMONIUM WITH SEDIMENT         2.8431 KG/HA
        TOTAL N WITH SEDIMENT          3.0255 KG/HA
        PHOSPHORUS WITH SEDIMENT       0.9360 KG/HA
        TOTAL PHOSPHORUS LOST          1.7299 KG/HA
        ACCUMULATED DRAINAGE           0.00   MM
        MINERALIZED N                  2.3049 KG/HA
        N UPTAKE                       0.0000 KG/HA
        SOIL NITRATE                  44.9108 KG/HA
        RAINFALL NITROGEN              0.8382 KG/HA
        ESTIMATE 1 NITRATE LEACHED     0.0000 KG/HA
        ACCUMULATED DENITRIFICATION    0.0000 KG/HA


                    ANNUAL SUMMARY FOR 1987
                    -----------------------


       2 STORMS PRODUCED        8.38 CM. OF RAINFALL
       2 STORMS PRODUCED        3.07 CM. OF RUNOFF


                    THE PLANT NUTRIENT LOSSES
                    -------------------------

        NITRATE IN RUNOFF               0.5723 KG/HA
        AMMONIUM IN RUNOFF              5.5979 KG/HA
        TOTAL NITROGEN IN RUNOFF       6.1702 KG/HA
        PHOSPHORUS IN RUNOFF           0.7938 KG/HA
        AMMONIUM WITH SEDIMENT         0.1825 KG/HA
        ORGANIC N WITH SEDIMENT        2.8431 KG/HA
        TOTAL N WITH SEDIMENT          3.0255 KG/HA
        PHOSPHORUS WITH SEDIMENT       0.9360 KG/HA
        TOTAL PHOSPHORUS LOST          1.7299 KG/HA
        ACCUMULATED DRAINAGE           0.00   MM
        MINERALIZED N                  2.3049 KG/HA
        N UPTAKE                       0.0000 KG/HA
        SOIL NITRATE                  44.9108 KG/HA
        RAINFALL NITROGEN              0.8382 KG/HA
```

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            ESTIMATE 1 NITRATE LEACHED      0.0000 KG/HA
            ACCUMULATED DENITRIFICATION     0.0000 KG/HA
1


     C R E A M S - N T  NONPOINT SOURCE POLLUTION MODEL (CHEMICALS)
            MOD. VERSION 1.8  MARCH 31,1989  VPI&SU ,

          PLOT QFB 1987 - NUTRIENT PARAMETERS
                CONVENTIONAL TILLAGE PLOT
          SLUDGE SURFACE APPLIED AT RATE 75 KG N/HA



                        STORM SUMMARY
                        -------------

          2 STORMS PRODUCED      8.38 CM. OF RAINFALL
          2 STORMS PRODUCED      3.07 CM. OF RUNOFF




        THE QUANTITY OF PLANT NUTRIENTS IN RUNOFF AND LEACHED
                        VALUES FOR ALL STORMS

            NITRATE IN RUNOFF               0.5723 KG/HA
            AMMONIUM IN RUNOFF              5.5979 KG/HA
            TOTAL NITROGEN IN RUNOFF        6.1702 KG/HA
            PHOSPHORUS IN RUNOFF            0.7938 KG/HA
            AMMONIUM WITH SEDIMENT          0.1825 KG/HA
            ORGANIC N WITH SEDIMENT         2.8431 KG/HA
            TOTAL N WITH SEDIMENT           3.0255 KG/HA
            PHOSPHORUS WITH SEDIMENT        0.9360 KG/HA
            TOTAL PHOSPHORUS LOST           1.7299 KG/HA
            ACCUMULATED DRAINAGE            0.00   MM
            MINERALIZED N                   2.3049 KG/HA
            N UPTAKE                        0.0000 KG/HA
            SOIL NITRATE                   44.9108 KG/HA
            RAINFALL NITROGEN               0.8382 KG/HA
            ESTIMATE 1 NITRATE LEACHED      0.0000 KG/HA
            ACCUMULATED DENITRIFICATION     0.0000 KG/HA
```

Appendix F: Field Plot Water Quality Data

Plot/Test/Run	Time* (min)	TSS (g/L)	NH₄⁺-N	NO₃⁻-N	TKN-N	P_T	PO₄⁻-P	TKN_F-N	P_TF	ΔT (min)	Flow (cm/hr)
						ppm					
QFIT7R1	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	6	0.03526
	21	5.474	6.616	0.186	11.194	0.916	0.257	8.529	0.513	3	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
QFIT7R2	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
QFIT7R3	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

Plot/Test/Run	Time* (min)	TSS (g/L)	NH$_4$–N	NO$_3^-$–N	TKN–N	P$_T$	PO$_4$–P	TKN$_F$–N	P$_{TF}$	ΔT (min)	Flow (cm/hr)
						ppm					
QF2T7R3	29	0.832	1.381	0.661	4.012	1.227	0.517	3.352	0.573	2	3.79987
	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
	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	0.230	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

Plot/Test/Run	Time* (min)	TSS (g/L)	NH₄⁺ – N	NO₃⁻ – N	TKN – N	P_T	PO₄⁼ – P	TKN$_F$ – N	P_{TF}	ΔT (min)	Flow (cm/hr)
					ppm						
QF4T7R3	25	1.220	18.900	5.435	29.505	2.432	0.748	4.464	1.126	2	1.78468
	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	6	2.89606
QF5T7R3	6	7.332	1.614	1.179	24.535	4.732	0.321	17.087	0.767	3	1.93589
	9	7.544	1.028	0.680	21.898	5.979	0.859	15.754	1.020	6	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	6	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

Plot/Test/Run	Time* (min)	TSS (g/L)	NH_4^+-N	NO_3^--N	$TKN-N$	P_T	$PO_4^=-P$	TKN_F-N	P_{TF}	ΔT (min)	Flow (cm/hr)
					———— ppm ————						
	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	4.998	1.482	2.115	6.289	4.175	0.661	1.763	0.661	3	0.02667
	9	3.702	1.496	1.808	6.795	4.554	0.605	1.937	0.605	3	0.18524
	12	2.848	1.602	2.263	6.592	4.303	0.854	0.795	0.605	3	0.50526
	18	2.648	1.486	2.023	5.864	4.150	0.605	0.921	0.605	6	0.77193
	21	1.330	1.556	1.716	6.107	3.237	0.474	0.969	0.474	3	1.08910
	23	0.806	1.783	2.504	7.280	2.261	0.429	0.871	0.429	2	1.19014
	25		1.810	2.751	6.006	2.389	0.448	1.000	0.448	2	0.27506
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

Plot/Test/Run	Time* (min)	TSS (g/L)	NH_4^+-N	NO_3^--N	TKN-N	P_T	PO_4^--P	TKN_F-N	P_{TF}	ΔT (min)	Flow (cm/hr)
					ppm						
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
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

Plot/Test/Run	Time* (min)	TSS (g/L)	NH$_4^+$–N	NO$_3^-$–N	TKN–N	P$_T$	PO$_4^-$–P	TKN$_F$–N	P$_{TF}$	ΔT (min)	Flow (cm/hr)
						— ppm —					
	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	2	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

Plot/Test/Run	Time* (min)	TSS (g/L)	$NH_4^+ - N$	$NO_3^- - N$	$TKN - N$	P_T	$PO_4^- - P$	$TKN_F - N$	P_{TF}	ΔT (min)	Flow (cm/hr)
						ppm					
	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
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	2	0.24925
	23	0.068	26.590	2.146	40.177	5.600	1.056	29.585	1.399	3	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

Plot/Test/Run	Time* (min)	TSS (g/L)	NH$_4^+$ – N	NO$_3^-$ – N	TKN – N	P$_T$	PO$_4^-$ – P	TKN$_F$ – N	P$_{TF}$	ΔT (min)	Flow (cm/hr)
						───── ppm ─────					
	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	4	0.39502
QFKT7R3	6	7.624	3.475	0.990	7.194	2.854	0.259	6.366	0.577	2	2.85905
	9	4.224	3.041	1.037	9.534	2.736	0.263	6.894	0.587	6	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	3	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

	Plot/Test/Run	Time* (min)	TSS (g/L)	NH₄⁺–N	NO₃⁻–N	TKN–N	P_T	PO₄⁻–P	TKN_F–N	P_TF	ΔT (min)	Flow (cm/hr)
				NH_4^+-N	NO_3^--N	$TKN-N$ (ppm)	P_T	PO_4^--P	TKN_F-N	P_{TF}		
		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
		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	6	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	3	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	0.176	6	1.42918
		36	10.004	0.696	1.584	3.109	0.322	0.041	2.820	0.319	6	1.51724
		42	8.620	0.626	1.296	4.235	0.400	0.028	3.101	0.255	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	0.303	6	1.16502
		56	11.076	0.690	2.574	3.691	0.430	0.046	1.067	0.335	2	0.96690
		58	1.196	0.678	1.588	7.126	0.609	0.106	3.933	0.239	2	0.83058
	QFMT7R2	3	6.548	1.181	2.345	6.358	2.586	0.045	5.925	0.255	3	0.00000
		9	6.838	0.922	1.489	2.327	3.217	0.070	4.270	0.239	6	0.85344
		12	8.896	0.712	1.321	7.283	3.374	0.047	3.090	0.255	6	1.36314
		15	8.410	0.667	1.174	6.821	3.217	0.04	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

Plot/Test/Run	Time* (min)	TSS (g/L)	NH$_4^+$-N	NO$_3^-$-N	TKN-N	P$_T$	PO$_4^-$-P	TKN$_F$-N	P$_{TF}$	ΔT (min)	Flow (cm/hr)
					ppm						
QFMT7R3	34	8.210	0.493	1.979	4.567	2.517	0.049	3.333	0.224	2	0.55626
	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	3	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	6	3.68811
	35	1.442	4.893	1.952	6.119	0.989	0.382	2.913	0.640	2	0.67960
QFNT7R3	6	20.816	1.916	0.967	8.299	2.151	0.017	5.388	0.242	3	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