

GLEAMS

VERSION 2.10

PART I: NUTRIENT COMPONENT DOCUMENTATION

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THE GLEAMS MODEL PLANT NUTRIENT COMPONENT

ABSTRACT

A component to simulate the plant nutrients nitrogen and phosphorus was developed and incorporated into the **GLEAMS** model. The component includes the major processes and transformations of nitrogen and phosphorus, and considers surface and subsurface pathways to estimate edge-of-field and bottom-of-root zone loadings to assess management alternatives. It includes land application of animal waste as well as inorganic fertilizers, and nitrogen fixation by legumes.

INTRODUCTION

Nitrogen and phosphorus in surface water bodies and ground water aquifers are recognized as significant water quality problems in many areas of the world. The two elements, when in surface waters in conjunction with optimum water pH, turbidity, and temperature, may result in eutrophic conditions that severely impair water quality (Middlebrooks, et al., 1974). Recreational uses may be limited, and drinking water use may be impaired due to odor and taste during some parts of the year. Waterwork inlets may become clogged or reduced in efficiency with massive growth of algae and aquatic weeds. Groundwater aquifers may become polluted due to recharge of high loadings of nitrogen. Drinking water with nitrate-nitrogen concentrations in excess of 10 mg/L may lead to methemoglobinemia in infants. Although most aquifer systems in the U.S. do not exceed drinking water standards for nitrogen and phosphorus, concentrations have steadily increased over the last several years in many areas (U.S. Geological Survey, 1985). There are a significant number of shallow domestic water wells with nitrogen concentrations in excess of drinking water standards. Municipal wells in some countries have been abandoned due to sustained concentrations in excess of 60 mg NO₃/L (Bjelm et al., 1980). de Mare (1982) reported some concentrations as high as 1,000 mg NO₃/L in private wells in the Skåne region of Sweden.

Agricultural management practices contribute to water quality problems associated with surface and groundwater. A combination of high fertilization and/or animal waste disposal practices on certain soils in some climatic regions can result in excess nitrogen and phosphorus in runoff or in groundwater recharge during certain periods of the year. Most water quality problems related to phosphorus result from transport with sediment in surface runoff into receiving waters. However, continuous high loadings from animal waste on very sandy soils with little buffering capacity may contribute significant quantities of labile phosphorus to subsurface drainage. Such is the case in south Florida where intensive dairy operations result in high loadings of phosphorus through the sandy soil above spodic horizons into lateral flow to channels and streams (Knisel, et al., 1985). Fertilization for maximum crop production oftentimes result in relatively high soil nitrate levels at the time of crop harvest. Reduced evapotranspiration without further crop uptake of nitrate may lead to excess leaching and/or lateral movement to streams during the non-crop period. Mathematical models that represent the major physical processes, such as **CREAMS** (Knisel, 1980) or EPIC (Williams et al., 1990), are needed to assess the impact of management practices on edge-of-field and bottom-of-root zone losses of plant nutrients.

Few presently available models adequately represent important management systems. For example, **CREAMS** (Knisel, 1980) did not include nitrogen fixation by legumes. Thus, crop rotations that included legumes required some special consideration in model application. Land application of animal waste also required special attention with representation of the organic-N content as potentially mineralizable nitrogen, and the nitrate and ammonia content represented as fertilization. Fertigation (Hubbard, et al., 1985) could

not be represented satisfactorily with models. These are only a few examples of how existing models fall short of management representation.

The **GLEAMS** model (Leonard, et al., 1987) was developed to consider the vertical flux of pesticides into, within, and through the root zone. Pesticides are routed through computational layers of the root zone using the water storage routing technique in **CREAMS** (Knisel, 1980) and pesticide adsorptivity on soil organic carbon. The model contains the option for pesticide application by chemigation (Leonard, et al., 1989). The **GLEAMS** model structure with soil layering was considered advantageous for incorporation of a plant nutrient component. Major processes in nutrient cycling and transformations were formulated and incorporated into **GLEAMS**. The purpose of this paper is to describe the concepts and relationships used in the plant nutrient component. Results of validation with readily available field data and results of sensitivity analysis will be given in Part II of this paper and the model user manual is given in Part III.

MODEL DESCRIPTION

The hydrology, erosion, and pesticide components of the **GLEAMS** model have been described in detail elsewhere (Knisel et al., 1989; Leonard et al., 1987; Leonard et al., 1989; Leonard et al., 1990), and will not be repeated here. However, sufficient detail is given so the reader will not need these publications in order to understand the interactions and applications of plant nutrients. There have been a number of changes in the hydrology component to aid in the development of the nutrient component, and these modifications will be described here.

Hydrology Component

A modification of the SCS curve number method (U.S. Soil Conservation Service, 1972) is used in **GLEAMS** hydrology to simulate runoff from daily rainfall. The daily time step was deemed satisfactory for hydrologic computations, and thus all processes in pesticide and nutrient transformations and fate use the same time increment.

Two options are provided in **GLEAMS** to estimate potential evapotranspiration. The Priestly-Taylor method (1972) using daily temperature and radiation data interpolated from fitting mean monthly data (Kothandraman and Evans, 1972), contained in earlier versions, is one option. The second option for estimating potential ET is the Penman-Monteith method (Jensen et al., 1990). Additional input data include monthly wind movement and monthly dew point temperature which are also fitted by the method of Kothandraman and Evans (1972). Actual soil evaporation and plant transpiration are simulated separately by the method developed by Ritchie (1972) for incomplete cover. Separate components of evapotranspiration are needed to partition chemical movement upward in the soil and into the transpiration stream for plant uptake.

The plant root zone effective for water uptake by crops is divided into a minimum of 3 and a maximum of 12 computational layers in **GLEAMS** depending on depth and thickness of genetic soil horizons (Knisel, et al., 1989). Water retention and transmission characteristics of the root zone are entered into the model by soil horizon. All computational layers in a horizon are assumed to have the same characteristics. The surface layer, fixed at 1 cm thickness, is assumed to be active in the entrainment of chemicals into the runoff stream. The surface active layer is known to vary in time as a function of management, e. g. tillage type and depth, soil crusting, reconsolidation with rainfall or irrigation since last tillage, and surface residue among others. The fixed thickness is used for simplification since data are not available to quantitatively define effective relationships. Redistribution of water with infiltration and percolation, and daily soil water accounting are simulated for each computational layer.

Soil physical properties needed for calculation of hydrologic, erosion, and pesticide processes in **GLEAMS** were included in the hydrology parameters (Leonard et al., 1987). Some additional properties needed in the plant nutrient component were added to the hydrology parameter file to keep them all together. They are input by soil genetic horizon and assigned into the soil computational layers in the hydrology component. They are described where referenced in that component.

Water Routing: In earlier versions of the **GLEAMS** model, a single value of effective saturated conductivity was user defined to represent the most restrictive soil layer within or at the bottom of the root zone. It was assumed that conductivity generally decreased with depth, and oftentimes the effective root zone depth was estimated as some restrictive layer such as a spodic layer (Knisel, et al., 1985) or an aquiclude-like clay layer (Knisel, et al., 1991). Use of a single value to represent such confining layers did not give adequate consideration to water and solute movement in the less restricted soil horizons such as the plow layer (Ap horizon). This is more critical when considering major nitrogen transformations that can occur in the root zone where a high water table exists at times following high rainfall, i. e. ammonification and nitrification in the upper horizons and denitrification in the saturated layers of the lower horizons containing the water table. Saturated conductivity is entered in the present version of **GLEAMS** hydrology (version 2.0) by soil horizon, and each computational layer within a horizon is assigned the same conductivity value. The same storage-routing technique is used (Knisel, 1980), but travel time through the layers may change. The routing equation to calculate outflow, OF, cm, from soil computational layer 1 is

$$OF_1 = \sigma_1 (F + ST_1) \quad \text{for } (F + ST_1) > FC_1 \quad [1]$$

and for layers $i=2, ncl$ (number of computational layers)

$$OF_i = \sigma_i (OF_{i-1} + ST_i) \quad \text{for } (OF_{i-1} + ST_i) > FC_i \quad [2]$$

where F is the storage coefficient, ST is storage volume, cm, F is infiltration, cm, and FC is field capacity, cm. The storage coefficient for each layer i is

$$\sigma_i = \frac{2 \Delta t}{(2 tt_i + \Delta t)} \quad [3]$$

where tt is travel time in hours and) t is time interval in hours. Travel time in each layer i is calculated as

$$tt_i = \frac{SM_i - FC_i}{(K_s)_i} \quad [4]$$

where SM is soil moisture, cm, and K_s is saturated conductivity, cm/h. Since the time step in **GLEAMS** is 1 day, the numerator of eqn. [3] becomes 48 and the last term of the denominator is 24, and tt is converted to days in the model.

Some restrictive soil layers, or horizons, may impede root growth and water movement, and thus may have characteristics that determine effective root depth. For example, a clay pan, a plow pan, or a genetic layer such as plinthic or caliche material, generally impede water movement. Saturated conductivity of such layers is generally considerably less than that in the active root zone. In fact, the restriction of water movement may result in water tables perched within the root zone during prolonged wet periods. In the present model version, the saturated conductivity for the horizon immediately below the effective root depth is used with a 30 cm thickness to calculate travel time. If the conductivity is the same as or greater than that for the bottom horizon, the same values of porosity and field capacity as that of the bottom horizon are used.

If the conductivity is less than that of the bottom horizon, characteristics of clay are assumed for porosity and field capacity. Percolation is assumed to occur through the layer, but it is not allowed to move back up into the root zone since depth to water table is not known.

Another improvement in **GLEAMS** version 2.10 is the capability to update root depth for each crop. If a rotation contains a shallow rooting vegetable crop with a full rooting field crop, for example snap beans or peas with corn for grain, the root depth specified for each crop is used in their respective years of the rotation. Transpiration is limited to depth of the shallow rooted crop only during that year of the rotation. Other processes, i. e. evaporation, percolation, solute transport, and chemical transformations, continue to the full "effective root depth".

In previous versions of **GLEAMS**, rooting of each crop was assumed to begin at zero depth at planting. In this version, perennial crops are coded, and in subsequent years roots remain at the full depth, i. e. effective root depth (RD) or current crop root depth (CCRD) if they are different. After initial planting of trees, RD is maintained each year. The same is true for such agricultural crops as alfalfa, bermuda grass, timothy grass, and sugarcane, for example.

Penman-Monteith Option for Potential Evapotranspiration: Jensen et al. (1990) gave excellent treatment of the concepts and methods for estimating evapotranspiration and irrigation requirements. The Priestly-Taylor method (1972) was recognized as an effective method for estimating potential evapotranspiration in humid areas, and also under a nearly complete canopy in an arid or semiarid environment. However, with little or no crop canopy, vapor diffusion from crop leaves and bare soil require more intense treatment for adequate estimation. Thus, methods incorporating wind movement and vapor pressure deficit are generally more effective estimators of potential ET for these conditions.

Methods of calculating ET for the short term to determine timing and amount of irrigation admittedly require hourly measurements of estimators (Jensen et al., 1990). This is not feasible for extended periods of simulation such as that desired for **GLEAMS** applications. Simplifications and averaging are required for computational feasibility. Since methods cannot be changed periodically during a long-term simulation, the most appropriate method must be selected by the model user to give the best representation for the duration of the simulation.

The Penman-Monteith method (Monteith, 1965) of estimating ET was shown to accurately represent ET measured in lysimeters at 11 locations around the world (Jensen et al., 1990). Therefore, the Penman-Monteith method is included in **GLEAMS** as an alternative option to the Priestly-Taylor method.

Potential ET is described by Jensen et al. (1990) as the evapotranspiration for a "well watered reference crop such as grass or alfalfa" and is designated by E_{tr} . Actual ET is estimated by a crop coefficient which is a ratio of the reference crop ET. In **GLEAMS**, the method developed by Ritchie (1972) for an incomplete cover is used to estimate the actual ET for a specific crop.

The Penman-Monteith (1965) expression for daily ET, mm/day, is

$$\lambda E_{tr} = \frac{\Delta}{\Delta + \gamma^*} (R_n - G_h) + \frac{\gamma}{\Delta + \gamma^*} K_1 \frac{0.622 \lambda \rho}{P} \frac{1}{r_a} (e_z^o - e_z) \quad [5]$$

where Δ is the slope of the saturation vapor pressure-temperature curve, kPa/EC, γ is the psychrometric constant, kPa/EC, γ^* is the psychrometric constant modified by the ratio of canopy resistance to atmospheric resistance, kPa/EC, R_n is net radiation, MJ/m²/day, G_h is the heat flux density to the ground, MJ/m²/day, λ is latent heat of vaporization, MJ/kg, D is density of air, kg/m³, P is atmospheric pressure, kPa, r_a is diffusion resistance of the air layer (aerodynamic resistance), sec/m, e_z^o is saturation vapor pressure of air at height z ,

kPa, e_s is saturation vapor pressure of air, kPa, and K_1 is a dimension coefficient to assure correct units. Since E_{tr} is defined as potential ET (Jensen et al., 1990), it is equivalent to E_o for the Priestley-Taylor method (Priestley and Taylor, 1972).

The slope of the saturation vapor pressure-temperature curve, Δ in eqn. [5] is defined as

$$\Delta = 0.20 (0.00738 T_c + 0.8072)^7 - 0.000116 \quad [6]$$

where T_c is the mean daily air temperature in EC. The psychrometric constant, γ in eqn. [5] is defined as

$$\gamma = \frac{c_p P}{0.622 \lambda} = \frac{1.013 P}{0.622 \lambda} = \frac{1.629 P}{\lambda} \quad [7]$$

where c_p is the specific heat of moist air at constant pressure and is equal to 1.013 kJ °C/kg. P in eqns. [5] and [7] is

$$P = P_o \left(\frac{T_o - \alpha ELEV}{T_o} \right)^{g/\alpha R} = 101.3 \left(\frac{288 - 0.0065 ELEV}{288} \right)^{5.257} \quad [8]$$

where P_o is atmospheric pressure at mean sea level, T_o is absolute temperature of a standard atmosphere, α is the adiabatic lapse rate, and ELEV is the mean sea level elevation, m, of the location of interest. The latent heat of vaporization, λ , in eqn. [7] is estimated from the mean daily temperature as

$$\lambda = 2.501 - 0.002361 T_c \quad [9]$$

The density of air, D , in eqn. [5] is a function of elevation (Jensen et al., 1990), expressed as

$$\rho = 1.23 - 0.000112 ELEV \quad [10]$$

The procedure for estimating net solar radiation from total incoming radiation for the Priestley-Taylor method is not satisfactory for R_n in eqn. [5]. Jensen et al. (1990) cited the works of several researchers for simplified methods of estimating R_n . It is not the purpose of this paper to review the literature, individual citations will not be given. It will suffice to say that Jensen et al. (1990) made an exhaustive survey of all the methods and literature, and provided accurate representation of the different authors.

Net solar radiation, R_n , MJ/m₂, is estimated from incoming solar radiation, R_s , MJ/m², as

$$R_n = (1.0 - ALB) R_s - R_b \quad [11]$$

where ALB is albedo (used as a constant in **GLEAMS**, ALB = 0.23), and R_b is the net outgoing long-wave radiation, MJ/m². R_b can be estimated as

$$R_b = \left[0.9 \frac{R_s}{R_{so}} - 0.1 \right] R_{bo} \quad [12]$$

where R_{so} is radiation, MJ/m², that is expected on a day without clouds, and R_{bo} is the net outgoing long-wave radiation, MJ/m₂, on a clear day. R_{so} in eqn. [12] can be estimated as a function of latitude and elevation as

$$R_{so} = AP + BP \cos \left[\left(2 \pi \frac{d}{365} \right) - CP \right] \quad [13]$$

where AP, BP, and CP are coefficients, and d is the Julian day of the year. Coefficient AP is estimated as

$$AP = 31.54 - 0.73 \text{ LAT} + 0.00078 \text{ELEV} \quad [14]$$

where LAT is latitude in degrees, and ELEV is mean sea level elevation, m. Coefficient BP is

$$BP = -0.30 + 0.268 \text{ LAT} + 0.00041 \text{ ELEV} \quad [15]$$

Coefficient CP is the longest day of the year, day 172 in the northern hemisphere, and day 355 in the southern hemisphere.

R_{bo} in eqn. [12] is given by Jensen et al. (1990) as

$$R_{bo} = \epsilon \sigma' T_k^4 \quad [16]$$

where ϵ is emittance, σ' is a constant, $4.903 \times 10^{-9} \text{ MJ/m}^2\text{/day/EK}^4$, and T_k is mean daily temperature, EK. ϵ is estimated from mean daily temperature as

$$\epsilon = -0.02 + 0.261 \exp [-7.77 \times 10^{-4} (273 - T_k)^2] \quad [17]$$

In their comparison of evapotranspiration methods, Jensen et al. (1990) calculated daily ET from monthly variables rather than estimating daily ET on a daily basis as is done in **GLEAMS**. The heat flux density to the ground, G_h in eqn. [5], is estimated as

$$G_h = 4.2 \left(\frac{T_{i+1} - T_{i-1}}{\Delta t} \right) \quad [18]$$

In their example, Jensen et al. (1990) estimated ET for a month, and T_{i+1} and T_{i-1} were the mean monthly temperatures after and before the month of concern, respectively. Also, the corresponding Δt in eqn. [18] was given as 60, the number of days between occurrence of T_{i+1} and T_{i-1} . Since ET calculations are made daily in **GLEAMS**, eqn. [18] becomes

$$G_h = 4.2 \left(\frac{(T_c)_{i+1} - (T_c)_{i-1}}{2} \right) = 2.1 [(T_c)_{i+1} - (T_c)_{i-1}] \quad [19]$$

where T_c is the mean daily temperature, EC.

When wind movement is input in km/day,

$$K_1 \frac{0.622 \lambda \rho}{P} = 19.8 - 0.08 T_c \quad [20]$$

in eqn. [5]. When wind speed is input in m/sec,

$$K_1 \frac{0.622 \lambda \rho}{P} = 1710 - 6.85 T_c \quad [21]$$

in eqn. [5].

(^{*} in eqn. [5] is defined as

$$\gamma^* = \gamma \left(1 + \frac{r_{cc}}{r_a} \right) \quad [22]$$

where r_{cc} is crop canopy resistance, sec/m, determined as

$$r_{cc} = \frac{100}{0.5 LAI} = \frac{200}{LAI} \quad [23]$$

where LAI is leaf area index. When no crop is growing, r_{cc} is 0, and (^{*} = (in eqn. [22].

The variable r_a in eqns. [5] and [22] is the diffusion resistance of the air layer, i. e. aerodynamic resistance, estimated as

$$r_a = \frac{\ln [(Z_w - d_c) / Z_{om}] \ln [(Z_p - d_c) / Z_{ov}]}{(0.41)^2 U_z} \quad [24]$$

where Z_w is height of the anemometer, cm, Z_p is the height of the psychrometer and thermometer, cm, Z_{om} is a momentum roughness length, cm, Z_{ov} is a roughness length for heat and water vapor, cm, d_c is a crop height parameter in cm, and U_z is wind speed at height z , m/sec. The crop height parameter, d_c , in eqn. [24] is estimated as

$$d_c = 0.667 h_c \quad [25]$$

where h_c is estimated from the leaf area index (Jensen et al., 1990) by

$$h_c = \exp (0.667 LAI) \quad [26]$$

Calculations by Jensen et al. (1990) are given for a grass or alfalfa "reference" crop for which the relation in eqn. [26] is undoubtedly very valid. Their procedure of estimating a crop coefficient to extrapolate evapotranspiration for a reference crop to that for a specific crop, for example a vegetable crop such as radishes, obviously must consider different functional relations. Sharpley and Williams (1990) include maximum height in their EPIC model crop parameters, and height during the growing season is scaled from zero to the maximum height as a function of simulated crop growth.

The roughness length variables in eqn. [24], z_{om} and z_{ov} , are functions of crop height as

$$z_{om} = 0.123 h_c \quad [27]$$

and

$$z_{ov} = 0.1 z_{om} \quad [28]$$

Since both terms appear in the denominator of the logarithmic functions of eqn. [24], the Penman-Monteith method of estimating ET was not conceptualized to simulate potential soil evaporation alone. Sharpley and Williams (1990) reported a slight adjustment by always adding 0.01 cm to h_c , resulting in a negligible value preventing division by zero.

Wind movement in eqn. [24] is needed for a height 2 m above the crop height. Thus, during the growing season, daily wind movement is needed for varying heights, and can be estimated from the relation

$$U_z = U_{rh} \left(\frac{z}{rh} \right)^{0.2} \quad [29]$$

where z is the desired height, cm ($h_c + 200$), and rh is the reference height, cm (height of the anemometer cup).

Jensen et al. (1990) gave five methods for estimating vapor pressure deficit used in eqn. [5]. In the absence of hourly data, the method that appeared to give the best results entails averaging vapor pressure at the daily maximum and minimum temperatures and subtracting the vapor pressure at the dew point temperature as

$$(e^{\circ}_z - e_z) = \frac{e^{\circ}(T_x) + e^{\circ}(T_n)}{2} - e^{\circ}(T_d) \quad [30]$$

where T_x , T_n , and T_d are daily maximum, minimum, and dew point temperatures, EC, respectively. Vapor pressure at a specific Centigrade temperature, T_c , is estimated as

$$e^{\circ}(T_c) = \exp \left[\frac{16.78 T_c - 116.9}{T_c + 237.3} \right] \quad [31]$$

The Penman-Monteith method of estimating potential ET is recommended for semi-arid and arid areas if wind movement and dew-point temperature data are available, or can be used from the tabulated locations in **GLEAMS**. The Priestly-Taylor method should be used for forested areas of semi-arid and arid regions because of the relatively low evaporative flux under forest canopy.

Crop Rotation: Another feature in the revised hydrology component allows the use of crop rotation data similar to that in the other model components. In earlier versions, leaf area index (LAI) data for each year with different crops had to be input for the entire period of simulation. For example, a 2-year rotation of winter wheat-soybeans simulated for 20 years required user input of LAI for each of the 20 years. The erosion and pesticide components contained simplifications that allowed input only for the 2-year period with data storage internally and re-used in the subsequent nine 2-year periods. The hydrology component of the current version contains a similar feature with LAI data for the major crops stored internally in the model as a data statement. Only code indices representing the crops, planting and harvesting dates, and crop rooting depth are input for the rotation period. The model creates a dummy file by reusing the initial data for subsequent rotation periods for the duration of simulation. The dummy file contains the full data for the entire simulation.

Root depth is specified for each crop in the rotation so that shallow-rooted crops, such as most vegetables, can be better represented in a rotation with field crops. Plant transpiration and chemical uptake occurs only in those computational soil layers in the specified root depth, but chemical transformations and movement are calculated for the entire effective root depth. When a deep rooted crop follows a shallow

rooted crop, root growth continues to the effective rooting depth. During fallow no-crop periods of the rotation, the entire effective root depth is active, but there is no transpiration during these periods.

Irrigation: Two significant changes were made in the irrigation routing in **GLEAMS**. In earlier versions, only surface irrigation was considered, and automatic (model applied) irrigation was conditioned on soil water content for the entire effective root depth. This assumption was unrealistic during the early crop growth stages when roots might only be in the plow layer.

Need for irrigation and depth of irrigation to be applied are now based upon the threshold water content in the computational soil layers in which the roots have grown. Each day, the depth of root growth is calculated, and if growth extends into a given computational layer, the entire layer thickness is assumed to supply water to the crop. For some soils, this computation can result in a fictitiously low irrigation volume, e. g. less than 0.1 cm. A minimum volume of 6.4 cm is assumed to be realistic, and if the computed irrigation requirement is less than 6.4, the depth of application is set as 6.4 cm.

This modification is more representative of actual management. The upper level of plant available water after irrigation remains as a user input for water deficit management or excess for leaching salts.

Also in earlier versions, only surface or sprinkler irrigation was considered, and it was assumed that application was always at rates and depths not to cause runoff. These assumptions have been eliminated in the current version. Any time that the upper level of plant available water is specified, runoff calculations are made to estimate any potential runoff, e. g. tailwater in flood or furrow irrigation.

Erosion Component

The erosion component of **GLEAMS** version 2.10 remains unchanged from that described by Leonard et al. (1987). The basic component is the same as given by Foster et al. (1980) with some simplification of input, and an improved subroutine for particle size (Foster et al., 1985). The reader is referred to those publications, and details are not given here.

Nutrient Component

Controlled laboratory and plot experiments have been conducted by numerous researchers for many years to document changes in the nitrogen and phosphorus content of soils as a function of time, temperature, and soil water content. Following these measurements, attempts have been made to conceptualize the processes describing the complex interactions of the physical system and the associated transformations. Formulations of the concepts have resulted in various levels of models to simplify the complexities and simulate the system. The systems necessarily treat each hypothesized process or transformation as a discrete entity, some of which may operate simultaneously in the formulations. At best these are modelers' efforts to develop a procedure for representing their perspective of the physical system. For example, McGill et al. (1981) documented their conceptualized fundamental carbon, bacteria, and fungi dynamics. It is an excellent description of the several processes, defining structural and metabolic components of humads based upon carbon:nitrogen (C:N) ratios. Likewise, soil organic carbon pools were delineated by similar C:N descriptors. Yet, if one takes a soil sample for laboratory analyses, digestion procedures result in a single value of C:N ratio and total organic carbon. This is not intended as a criticism of McGill et al. (1981) work, but merely points out that the complex system must be characterized by simplifications to formulate processes that must occur in nature. Their work is very fundamental to understanding the complex system.

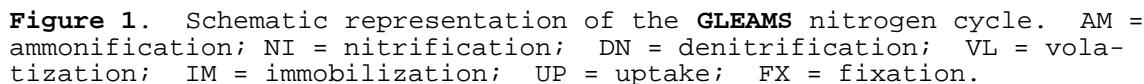
The surface runoff and sediment losses of nutrients and leaching losses are considered in the model. In order to represent the daily nutrient state of the system, relatively complete nitrogen and phosphorus cycling are included. The two nutrient elements are treated as nearly alike as possible, that is mineralization from crop residue, from soil organic matter, and from animal waste, immobilization to crop residue, solution and adsorbed phases for transport and routing, and crop uptake. There are some obvious differences considered such as nitrogen fixation by legumes, denitrification, nitrogen in rainfall, ammonia volatilization from animal waste, and two-stage mineralization of nitrate--ammonification and nitrification.

Most models consider nitrogen mineralization as a one-step first-order process from mineralizable N (crop residue, animal waste, or active soil organic carbon) to nitrate (Knisel, 1980; Reddy et al., 1979; Seligman and van Keulen, 1981; Sharpley and Williams, 1990.) This is adequate for all practical purposes of nitrogen transformation. McGill et al. (1981) thought the ammonification and nitrification processes should be formulated separately for long-term simulation of carbon, bacteria, and fungi dynamics in a cool prairie grassland ecosystem. Iskandar and Selim (1981) found that routing of ammonia-nitrogen ($\text{NH}_4\text{-N}$) with an adsorptivity coefficient based upon clay content of the soil was essential to explain some of the differences in nitrogen content in the layered soil. Bhat et al., (1981) also considered the separate processes necessary in mineralization of animal slurry. Since ammonia volatilization may be an important pathway of nitrogen loss in surface application of animal waste in **GLEAMS**, the two-stage processes are differentiated here.

Similarly, phosphorus transformations have been glossed over in the past largely because its translocation into, within, and through the root zone is not generally a problem. An exception is the low buffering capacity sandy soils that are generally subjected to high loadings of animal waste. Models such as **CREAMS** (Knisel, 1980) only considered the surface losses of phosphorus in runoff and adsorbed onto sediment. These process formulations were adequate for most surface water quality problems, but were not sufficient for the dairy cattle waste problem on the spodosols of south Florida (Knisel et al., 1985.) The recent work of Jones et al. (1984) is an excellent description of the simplified phosphorus cycle processes. That work (Jones et al., 1984) was incorporated into the successful EPIC model (Sharpley and Williams, 1990).

Some of the basic concepts mentioned above have been incorporated and extended with additional processes into the **GLEAMS** model. The following sections describe the nutrient component of **GLEAMS**.

Nitrogen Component: A schematic representation of the nitrogen component is shown in Fig. 1 with the processes and flow directions. Some of the compartments delineated in Fig. 1 are for surface only (grain, stover, atmospheric N, and assimilated N), some are for both surface and subsurface computational soil layers (fresh organic N in crop residue and roots, fertilizer, nitrate, ammonia, and organic N in animal waste), and the active and stable soil N occurs only in the soil.



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Sharpley and Williams (1990), following the work Seligman and van Keulan (1978), defined an active mineralizable pool with a C:N ratio less than 25, and a stable pool from which mineralization did not occur without denoting a C:N ratio. Sharpley and Williams (1990) further indicated a nitrogen flux between the two pools governed by the relative pool sizes.

The procedure of Sharpley and Williams (1990) for nitrogen flux is included in **GLEAMS** and is expressed as

$$RTN_i = \frac{POTMN_i}{(POTMN_i + SOILN_i)} \quad [32]$$

where RTN is the ratio of readily mineralizable N to total soil N, POTMN is the active N pool (potentially mineralizable), kg/ha, SOILN is the stable soil N pool, kg/ha, and the subscript i is computational soil layer. This definition of RTN is used rather than the length of time the field has been in cultivation as given in the EPIC model (Sharpley and Williams, 1990). A flux of organic N between the active and stable pools, RON for layer i, kg/ha/d, is defined as

$$RON_i = BKN \left[POTMN_i \left(\frac{1}{RTN_i} \right) - SOILN_i \right] \quad [33]$$

where BKN is a rate constant, 1×10^{-5} kg/ha/d. The daily flow of RON is added to SOILN and subtracted from POTMN. If POTMN becomes small compared with SOILN, then the resultant RON in eqn. [33] becomes negative and the daily flow is from SOILN to POTMN.

Mineralization of nitrogen, MN, kg/ha/d, occurring in layer i from the active N pool is estimated as

$$MN_i = (CMN) (POTMN_i) [(SWFA_i) (TFA_i)]^{0.5} \quad [34]$$

where CMN is mineralization constant (0.0003 kg/ha/d), TFA is the temperature factor for ammonification, and SWFA is the soil water factor for ammonification. The daily MN is added to the NH_4-N (AMON) and subtracted from POTMN. The soil water factor for ammonification, SWFA, is defined as

$$SWFA_i = \frac{(SW_i - WP_i)}{(FC_i - WP_i)} \quad \text{for } SW \leq FC \quad [35]$$

where SW is the volumetric soil water content in layer i, cm/cm, WP is the volumetric water content of layer i at 1500 kPa, cm/cm, and FC is the volumetric water content in layer i at 33 kPa, cm/cm. If $SW > FC$, the $SWFA = 0$, and ammonification does not occur. The temperature factor for ammonification, TFA, is calculated from the relation

$$TFA_i = \frac{T_i}{T_i + \exp(9.93 - 0.312 T_i)} \quad \text{for } T_i > 0 \quad [36]$$

where T is soil temperature, EC. For $T \neq 0$, $TFA = 0$.

The second stage of mineralization, nitrification, is represented as a zero-order process, i. e. the rate of nitrification is not a function of the amount of ammonia in the soil layer. Nitrification, NIT, kg/ha/d, is expressed as

$$NIT_i = \frac{(TFN_i) (SWFN_i)}{SOILMS_i} \quad [37]$$

where TFN is the temperature function for nitrification, SWFN is the soil water factor for nitrification, and SOILMS is the soil mass, Mg/ha. The maximum rate of nitrification given by Bhat et al. (1981) is 100 mg NO₃-N/kg soil/wk. NIT is added to the mass of nitrate-nitrogen, SNO₃, kg/ha, and subtracted from the ammonia-nitrogen, AMON, daily. The temperature factor, TFN, is defined as

$$\begin{aligned} TFN_i &= 0 & T_i &\leq 0 \text{ } ^\circ C \\ TFN_i &= 0.496 T_i & 0 < T_i &\leq 10 \text{ } ^\circ C \\ TFN_i &= \exp \left(22.64 - \frac{5956.4}{(T_i + 273)} \right) & T_i &> 10 \text{ } ^\circ C \end{aligned} \quad [38]$$

Nitrification occurs when the soil water content is above immobile water content and below saturation with an optimum at field capacity. The soil water factor for nitrification, SWFN, ranges from 0 to 1, and is determined as

$$\begin{aligned} SWFN_i &= 0 & SW_i &\leq WP_i \\ SWFN_i &= \frac{SW_i - WP_i}{FC_i - WP_i} & WP_i < SW_i &\leq FC_i \\ SWFN_i &= 1 - \left(\frac{SW_i - FC_i}{SAT_i - FC_i} \right) & FC_i < SW_i &< SAT_i \\ SWFN_i &= 0 & SW_i &\geq SAT_i \end{aligned} \quad [39]$$

where SW is volumetric water content, cm/cm, WP is volumetric water content at 1500 kPa, cm/cm, FC is volumetric water content, cm/cm, at 33 kPa, SAT is volumetric water content at saturation, cm/cm, and subscript i is computational soil layer index.

Mineralization of nitrogen also occurs from crop residue on the soil surface and root residue in the soil. It occurs also from organic nitrogen in animal waste on the soil surface and in the root zone.

Ammonification of crop residue in the soil is simulated in **GLEAMS** the same as that in the EPIC model (Sharpley and Williams, 1990). Fresh organic nitrogen in the root zone from crop residue, FON, kg/ha, acted upon by soil microbes results in ammonification expressed as

$$RMN_i = (DCR_i) (FON_i) \quad [40]$$

where RMN is residue mineralization rate, kg/ha/d, and DCR is a residue decay rate constant, kg/ha/d, which is a function of C:N and C:P ratios, crop residue composition, temperature, and soil water content. DCR is estimated from

$$DCR_i = (CNP_i) (RC_i) [(SWFA_i) (TFA_i)]^{0.5} \quad [41]$$

where CNP is a C:N and C:P ratio factor, RC is a residue composition factor, SWFA is a soil water factor for ammonification defined in eqn. [35], and TFA is a temperature factor for ammonification given by eqn. [36]. The value of CNP is calculated from

$$CNP_i = \min \left(\frac{\exp[-0.693 (CNR - 25) / 25]}{\exp[-0.693 (CPR_i - 200) / 200]}, 1.0 \right) \quad [42]$$

where CNR is C:N ratio and CPR is C:P ratio. CNR is defined as

$$CNR_i = \frac{0.58 (FRES_i + OMAW_i)}{FON_i + ORGNW_i + SNO3_i + AMON_i} \quad [43]$$

where FRES is fresh residue, kg/ha, OMAW is organic matter in animal waste, kg/ha, FON is fresh organic nitrogen, kg/ha, ORGNW is the organic nitrogen in animal waste, kg/ha, SNO3 is NO₃-N, kg/ha, and AMON is NH₄-N, kg/ha. The CPR is determined as

$$CPR_i = \frac{0.58 (FRES_i + OMAW_i)}{FOP_i + ORGPW_i + PLAB_i} \quad [44]$$

where FOP is fresh organic phosphorus, kg/ha, ORGPW is the organic phosphorus in animal waste, kg/ha, and PLAB is labile phosphorus, kg/ha.

The value of residue composition factor, RC, in eqn. [41] is determined by the stage of residue decomposition. The rate for the first 20% is for carbo-hydrate-like material, for 20-90% is for cellulose-like material, and the final 10% is for lignin (Sharpley and Williams, 1990). Values of RC are

$$\begin{aligned} RC &= 0.8 & DECOMP &\leq 20\% \\ RC &= 0.05 & 20\% < DECOMP &\leq 90\% \\ RC &= 0.0095 & DECOMP &> 90\% \end{aligned} \quad [45]$$

where DECOMP is the decomposition of fresh residue as a percentage of the initial residue amount.

Sharpley and Williams (1990) assumed in the EPIC model that 20% of the mineralized fresh organic nitrogen in crop residue (FON) went to mineralizable soil N and 80% went to nitrate-nitrogen. The same assumptions are made in **GLEAMS**: 20% of ammonification from FON goes to POTMN and 80% goes to AMON even though mineralization here is assumed to be a two-step process.

Bhat et al. (1981) developed a model for nitrogen cycling in land-applied animal waste. Their data indicated a mineralization rate for dairy slurry twice that for active mineralizable soil nitrogen (POTMN). They further hypothesized that 80% of the mineralization from ORGNW is added to the ammonia pool (AMON) and 20% is added to POTMN. This is consistent with the assumptions in EPIC and here in **GLEAMS** about the division of mineralization from fresh organic nitrogen in crop residue.

Since crop residue and animal waste are both organic materials, their micro-bial decomposition should differ mainly by their relative composition. In fact, depending upon the types of animal facilities, methods of handling, etc., animal waste may include crop residue, e. g. straw for animal bedding, hay residue in holding pens, sorghum fodder or sawdust in poultry housing for moisture control. All these materials alter the carbon:nitrogen and carbon:phosphorus ratios that affect the mineralization rates. There cannot be a

physical separation of the relative amounts of nitrate, ammonia, and labile phosphorus onto which C:N and C:P ratios are calculated for crop residue (FON and FOP) and animal waste (ORGNW and ORGPW). Therefore, the total residue, nitrate, ammonia, and phosphorus masses were used for calculation of CNR, CPR, and CNP in eqns. [42] to [44].

In order to be consistent for the organic mineralization processes, the same type of relationship is used in the present model for animal waste mineralization (AWMN, kg/ha/d) as was used for crop residue in eqn. [15], that is,

$$AWMN_i = (AWDCR_i) (ORGNW_i) \quad [46]$$

where AWDCR is the animal waste decomposition rate, kg/ha/d, defined as

$$AWDCR_i = (CNP_i) (AWRC_i) [(SWFA_i) (TFA_i)]^{0.5} \quad [47]$$

The animal waste residue composition, AWRC, has the same relative decomposition structure as that for crop residue

$$\begin{aligned} AWRC &= 0.8 & DECOMP &\leq 20\% \\ AWRC &= 0.05 & 20\% < DECOMP &\leq 90\% \\ AWRC &= 0.0095 & DECOMP &> 90\% \end{aligned} \quad [48]$$

The only difference between eqns. [45] and [48] is the relative masses of crop residue and animal waste. Just as with ammonification of FON in EPIC (Sharpley and Williams, 1990), ammonification from ORGNW here is partitioned 80% to AMON and 20% to POTMN as hypothesized by Bhat et al. (1981).

Ammonification of organic nitrogen in animal waste and crop residue on the soil surface is calculated the same as for the soil. The only difference is that the soil water factor for the surface 1 cm of soil is used ($SWFA_1$), and the TFA is calculated by eqn. [38] using mean daily air temperature. Ammonification of organic N in animal waste on the surface is added to a soluble ammonia pool on the surface, SOLNH, instead of adding to AMON in the surface computational soil layer (top 1 cm).

Nitrification of SOLNH is assumed to occur on the soil surface, but the soil water factor of soil layer 1 (the top 1 cm of soil), $SWFN_1$, is used. The same maximum 100 mg NO_3 -N/kg of soil/wk is assumed on the surface as in the soil. Nitrification from SOLNH is added to a soluble nitrate pool, SOLN. Both SOLNH and SOLN are accumulated, and immobilized onto residue as will be given later, until rain or tillage occurs. On a day of rain or tillage, SOLNH is added to $AMON_1$ for routing with infiltration or mixing with tillage, and SOLNH is initialized. SOLN is manipulated similarly except that it is added to $SNO3_1$.

Immobilization--The C:N ratio of residue must be less than about 25:1 in order to have an optimum population of microorganisms for mineralization. For a C:N ratio greater than 25, microbes assimilate nitrogen onto the residue from readily-available sources such as soil nitrate and ammonia. Immobilization continues until the C:N ratio is decreased to approximately 25. This process, or transformation, is important in the complete nitrogen cycling since it may affect the state of some species relative to other processes, e. g. ammonia and nitrate available in the shallow soil layers for newly-emerged plants or available for movement deeper into the root zone.

Immobilization in **GLEAMS** is patterned after that in the PAPRAN model (Seligman and van Keulen, 1981) except that **GLEAMS** considers two sources of nitrogen: ammonia and nitrate. It is calculated as

$$WIMN_i = (DCR_i) (FRES_i) (0.016 - c_{nfr}) \quad [49]$$

where WIMN is the nitrogen immobilization rate, kg/ha/d, and c_{nfr} is the concentration of nitrogen in the fresh residue, kg/ha, estimated as

$$(c_{nfr})_i = \frac{FON_i}{FRES_i} \quad [50]$$

where FON is the nitrogen in fresh residue, kg/ha. The value 0.016 in eqn. [49] results from the assumptions: C = 0.4 FRES, that 0.4 of the C is assimilated, and the C:N ratio of 10 for the microbial biomass and their labile products. If the amount of available nitrate and ammonia is less than the immobilization es-timated by eqn. [24], the decay rate is adjusted as

$$DCRPR_i = \frac{0.95 (SNO3_i + AMON_i)}{FRES_i (0.016 - c_{nfr})} \quad [51]$$

which allows only 95% of the available NO_3 -N and NH_4 -N in layer i to be immobilized. The fresh residue in each layer is reduced by DCR from eqn. [41] or by DCRPR from eqn. [51], whichever is appropriate, as

$$FRES_i = (FRES_i)_o - (DCRPR_i) (FRES_i)_o \quad [52]$$

where the subscript o denotes the value of $FRES_i$ at the beginning of the day.

The amount of immobilization, $WIMN_i$, or the amount adjusted to 95% avail- ability is added to FON_i on the day of occurrence. If immobilization is not limited, WIMN is partitioned between SNO3 and AMON by the relative amounts of each. That is, the fraction of nitrogen immobilization as nitrate from SNO3 is

$$FRACNO_i = \frac{SNO3_i}{SNO3_i + AMON_i} \quad [53]$$

and the fraction of $AMON_i$ is

$$FRACNH_i = 1 - FRACNO \quad [54]$$

The amount of NO_3 -N and NH_4 -N immobilized is subtracted from $SNO3_i$ and $AMON_i$, respectively.

Immobilization of nitrate and ammonia onto surface residue is simulated in the same manner as that given above. The only difference is that SOLN and SOLNH on the surface, described under mineralization above, is included in the sum of availability as well as the nitrate and ammonia in soil computational layer 1 for estimating DCRPR as

$$DCRPR_s = \frac{0.95 (SNO3_1 + AMON_1) + SOLN + SOLNH}{RESDW (0.016 - c_{nres})} \quad [55]$$

where RESDW is surface residue weight, kg/ha, and the concentration of nitrogen in the residue is

$$C_{nres} = \frac{RESDN}{RESDW} \quad [56]$$

where RESDN is the nitrogen in surface residue, kg/ha. Nitrogen immobilized on the surface residue is added to RESDN. Soluble nitrate and ammonia on the surface is totally immobilized before the 95% in the surface soil layer.

Denitrification--Soil nitrate can be reduced to nitrogen gases, denitrification, by anaerobic bacteria when soil water content exceeds field capacity. The process is important in humid climate where percolation occurs frequently or a high water table occurs within the root zone. Denitrification is a first-order process with a rate constant a function of organic carbon and modified by soil water content and temperature.

Frere et al. (1980) used total organic carbon in estimating denitrification in the **CREAMS** model. However, only the readily reactive organic carbon is expected to be effective in denitrification. In the present model, fresh organic residue, organic carbon in animal waste, and organic carbon in potentially mineralizable nitrogen is used. The active energy source is defined as

$$SC_i = \frac{18 \text{ POTMN}_i + 0.58 (FRES_i + OMAW_i)}{SOILMS_i} \quad [57]$$

where SC is the active soil carbon, mg/g, and the other terms are as defined above. The daily decay rate, DK, was given by Smith et al. (1980) for total soil carbon as

$$DK_i = 24 [(0.0011 SC_i) + 0.0025] \quad [58]$$

where the 24 is hourly conversion to day. Stanford et al. (1975) gave the relation for DK from glucose as

$$DK_i = 24 [(0.0188 SC_i) + 0.0093] \quad [59]$$

In the present model it is assumed that something between total soil carbon and glucose would be more appropriate considering only mineralizable soil N (POTMN) and the carbon in crop residue and animal waste as given in eqn. [57]. Coefficients were interpolated between those of Stanford et al. (1975) to give

$$DK_i = 24 [(0.0022 SC_i) + 0.0042] \quad [60]$$

The soil temperature adjustment for denitrification rate for soil layer i, TFDN_i, is (Sharpley and Williams, 1990)

$$TFDN_i = \frac{T_i}{T_i + \exp(9.93 - 0.321 T_i)} \quad [61]$$

where T_i is the soil temperature in layer i, EC.

In **CREAMS** (Frere et al., 1980), denitrification was calculated for the number of days of percolation between rainfall events, and it was thought that 0.5 day was necessary for the population of bacteria to become effective. Also, Frere et al. (1980) considered the soil water factor for denitrification to be a single

value of unity beginning at field capacity. Smith et al. (1980) stated that denitrification really begins when soil water content is 5 to 10% above field capacity. With daily calculation of all processes in the present **GLEAMS** model, it is thought that the half-day criteria should be eliminated, and that denitrification should begin at 10% above field capacity and increase to a maximum of unity at saturation as given by

$$SWFD_i = \frac{SW_i - [FC_i + 0.10 (SAT_i - FC_i)]}{SAT_i - [FC_i + 0.10 (SAT_i - FC_i)]} \quad [62]$$

where SW, FC, and SAT are volumetric water content for the day, at 33 kPa, and at saturation, respectively, cm/cm. Denitrification, DNI, kg/ha, is

$$DNI_i = SNO3_i \{ 1 - \exp [- (DK_i) (TFDN_i) (SWFD_i)] \} \quad [63]$$

DNI is subtracted from SNO3 for each layer on the day of occurrence. The model structure allows: (a) denitrification in the upper soil layers on days of rainfall and irrigation that may not produce percolation out of the root zone, and (b) denitrification in the lower soil layers when percolation may occur over an extended period due to perched water table.

Nitrogen in runoff, sediment, and percolation--Rainfall infiltrates into the soil surface, and the water moves some of the chemicals in an assumed 1-cm surface-active layer deeper into the soil. At some time when the infiltration rate decreases below the rainfall rate, water ponds on the soil surface and may initiate runoff. The mass of chemicals that are moved out of the surface active layer is dependent upon the chemical and soil characteristics. When runoff begins, the surface active layer interacts with the runoff stream, imparting some of the soil chemicals to the runoff water. Since the entire soil mass in the 0-1 cm layer is not completely mixed, (dispersed) in runoff and since the solute concentration in runoff is less than the solute concentration in the soil pore water, the extraction process is incomplete. This incomplete extraction is assumed to be reflected by an extraction coefficient ranging from about 0.05 to 0.5. The extraction of pesticides was related to the organic carbon content of the soil which determines the mobility of the particular compound (Leonard et al., 1987). Without repeating their entire development here, it will suffice to say that the partitioning coefficient, K_d , between the solid (soil) phase and the solution (water) phase is

$$K_d = \frac{C_s}{C_w} \quad [64]$$

where C_s is concentration in the soil and C_w is the concentration in the water. The concentration of a chemical in the water phase is

$$C_w = \frac{C_{av} \beta}{1 + \beta K_d} \quad [65]$$

where C_{av} is the available chemical concentration in the surface soil layer, $\mu\text{g/g}$, and β is the extraction coefficient. Likewise, the concentration in the solid phase is

$$C_s = \frac{C_{av} K_d \beta}{1 + K_d \beta} \quad [66]$$

From eqn. [65], when $K_d = 0$, $C_w = C_{av} \beta$, while $K_d = 0$ in eqn. [66] gives $C_s = 0$.

In order to be consistent among the components of **GLEAMS** as possible, similar relationships are used here for the extraction coefficient as that in pesticides (Leonard et al., 1987) except the magnitudes of K_d . The relations of β_{nh} to K_d , are

$$\begin{aligned}\beta_{nh} &= 0.5 && \text{for } K_d \leq 1.0 \\ \beta_{nh} &= 0.598 \exp(-0.179 K_d) && \text{for } 1.0 < K_d < 10.0 \\ \beta_{nh} &= 0.1 && \text{for } K_d \geq 10.0\end{aligned}\quad [67]$$

The chemical concentration in layer 1 available for runoff and infiltration, C_{av} , in eqns. [65] and [66] is defined as

$$C_{av} = C_1 \exp \left[\frac{-(F - ABST)}{(K_d)_1 \left(\frac{1 - POR_1}{2.65} \right) + POR_1} \right] \quad [68]$$

where C is the chemical concentration or chemical mass/soil mass, $\mu\text{g/g}$, F is total storm infiltration or rainfall minus runoff, cm, POR_1 is the porosity of the surface soil layer, and $ABST$ is the initial abstraction from rainfall, cm, as estimated by

$$ABST = 0.2 (SAT_1 - SW_1) \quad [69]$$

Equations [62] to [66] are given in generic form since they are applicable for nitrate, ammonia, and phosphorus, as well as pesticides.

Nitrate is not adsorbed and moves entirely in solution with a $K_d = 0$. Then from eqn. [65], the concentration of nitrate in the water, $CNO3W$, mg/L is

$$CNO3W_1 = 0.5 \frac{(SNO3_1) 10^3}{SOILMS_1} \quad [70]$$

and the runoff nitrate, $RONO3$, kg/ha, is

$$RONO3 = 0.1 (CNO3W_1) (Q) \quad [71]$$

where Q is runoff in cm.

Iskandar and Selim (1981) found that ammonia is partially adsorbed to the clay fraction of soil, and that use of the partitioning coefficient was necessary to account for the proper movement within the root zone (Selim and Iskandar, 1981). In order to account for a range of clay content, an empirical relation was developed between K_d for ammonia ($CNHKD$) and clay content as

$$CNHKD_i = 1.34 + 0.083 CL_i \quad [72]$$

where CL is clay content in percent and i is the soil layer.

The concentration of ammonia in the water in layer 1, $CNH4W_1$, mg/L, for interaction with the runoff stream and percolation into layer 2, from eqns. [65] and [68], is

$$CNH4W_1 = \left[\frac{AMON_1 \cdot 10^3}{SOILMS_1} \right] \exp \left[\frac{-(F - ABST)}{CNHKD_1 \left(\frac{1 - POR_1}{2.65} \right) + POR_1} \right] \left[\frac{\beta_{nh}}{(1 + \beta_{nh} CNHKD_1)} \right] \quad [73]$$

where $AMON_1$ is the ammonia in soil layer 1, kg/ha. Then from eqn. [64], the concentration of ammonia in the solid phase, $\mu\text{g/g}$, is

$$CNH4S_1 = (CNH4W_1) (CNHKD_1) \quad [74]$$

and the runoff ammonia, $RONH4$, kg/ha, is

$$RONH4 = 0.1 (CNH4W_1) (Q) \quad [75]$$

The total runoff loss of nitrogen, $TRON$, kg/ha, is

$$TRON = RONO3 + RONH4 \quad [76]$$

Since ammonia is partially adsorbed, then the adsorbed portion is subject to erosion/sediment transport losses. The concentration in the solid phase is calculated from eqn. [66], or more simply from eqn. [74], and applied to the product of sediment yield, SY , kg/ha, and enrichment ratio, ER , to give $SEDNH$, kg/ha, as

$$SEDNH = 0.1 (SY) (ER) (CNH4S_1) \quad [77]$$

The enrichment ratio, ER , in eqn. [77] is defined as the ratio of specific surface area of sediment to the specific surface area of the residual soil, $SS_{\text{sed}}/SS_{\text{soil}}$ (Leonard et al., 1987).

Runoff losses of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ decrease the mass of nitrogen that remains in the top layer of soil available for movement with infiltrating water into the second and/or lower layers. The $\text{NO}_3\text{-N}$ remaining in the surface layer after the runoff event is

$$SNO3_1 = (SNO3_1)_0 - RONO3 \quad [78]$$

where $(SNO3_1)_0$ is the $\text{NO}_3\text{-N}$ in soil layer 1 at the beginning of the runoff event. Likewise, the $\text{NH}_4\text{-N}$ remaining in layer 1 following runoff is

$$AMON_1 = (AMON_1)_0 - RONH4 - SEDNH \quad [79]$$

Percolation of nitrate and ammonia out of the surface 1-cm of soil cannot be calculated using $CNO3W_1$ and $CNH4W_1$ from eqns. [70] and [73], respectively. The initial mass of nitrate available for runoff and leaching is the product of C_{av} and soil mass in the layer 1, kg/ha, is

$$AVNOMS = (CNO3_1) (SOILMS_1) \quad [80]$$

where $CNO3$ is the $\text{NO}_3\text{-N}$ concentration based upon the dry weight of soil. The available mass of ammonia, kg/ha, is

$$AVNHMS = (CNH_4)_1 (SOILMS_1) \quad [81]$$

where CNH4 is the concentration of NH₄-N based upon the dry weight of soil.

The percolation component of the available mass for nitrate is

$$PRNOMS = AVNOMS - [(C_{av})_{no} (SOILMS_1)] \quad [82]$$

and for ammonia is

$$PRNHMS = AVNHMS - [(C_{av})_{nh} (SOILMS_1)] \quad [83]$$

Average percolate concentration of nitrate from layer 1, PERCNO₁, mg/L, is simply the mass divided by the percolate (water) mass,

$$PERCNO_1 = \frac{0.1 PRNOMS}{PERC_1} \quad [84]$$

where PERC₁ is the depth of percolation, cm. Likewise, the percolate concentration of ammonia from layer 1, PERCNH₁, mg/L, is

$$PERCNH_1 = \frac{0.1 PRNHMS}{PERC_1} \quad [85]$$

The percolation mass determined in eqns. [82] and [83] are added to the respective masses in layer 2 as well as the mass of water percolated. Computations are the same for layers 2 through ncl (number of computational layers). For ammonia,

$$AMON_i = AMON_i + [(PERCNH_{i-1}) (PERC_{i-1})] \quad [86]$$

and for nitrate,

$$SNO3_i = SNO3_i + [(PERCNO_{i-1}) (PERC_{i-1})] \quad [87]$$

The water mass, WM, cm, for equilibration of nitrogen is

$$WM_i = SWC_i + PERC_{i-1} \quad [88]$$

where SWC is the absolute soil water content of the layer before rainfall, snowmelt, or irrigation. Percolation out of the layer, calculated in the hydrology component, is the difference between WM and the absolute water content of the layer at field capacity.

Since nitrate is not adsorbed there is no extraction into the layer above, and thus the concentration is

$$CNO3W_i = \frac{SNO3_i \cdot 10}{WM_i} \quad [89]$$

The concentration of the partially-adsorbed ammonia in water is

$$CNH4W_i = \frac{AMON_i \cdot 10}{[(CNHKD_i) (SOILMS_i)] + WM_i} \quad [90]$$

The percolate and associated concentrations out of the last computational layer, $PERC_{ncl}$, $PERCNO_{ncl}$, and $PERCNH_{ncl}$, represent potential loadings to the vadose zone from the root zone.

Edge-of-field sediment yield also carries potentially mineralizable nitrogen (POTMN), stable soil nitrogen (SOILN), and organic nitrogen in animal waste (ORGNW), that are in the surface 1-cm of soil. Each erosion-associated component, kg/ha, is respectively,

$$SEDMN = \frac{(SY) (ER) (POTMN_1)}{SOILMS_1} \quad [91]$$

$$SEDSN = \frac{(SY) (ER) (SOILN_1)}{SOILMS_1} \quad [92]$$

$$SEDON = \frac{(SY) (ER) (ORGNW_1)}{SOILMS_1} \quad [93]$$

Then the total sediment-associated nitrogen, SEDN, kg/ha, is

$$SEDN = SEDNH + SEDMN + SEDSN + SEDON \quad [94]$$

Nitrogen uptake, evaporation, and fixation--Nitrogen uptake in the **CREAMS** model (Frere et al., 1980) was calculated by one of two options: (a) a normal-shaped supply curve with potential uptake, date of mid-uptake, and a standard deviation of days from mid-uptake specified by the user, and (b) concentration on nitrogen in the biomass expressed as a power function of total dry matter. Smith et al. (1980) gave the relationships for only a few crops to be used in **GLEAMS**. The procedure provided an estimate of nitrogen demand based upon an optimum content of the total dry matter.

Seligman and van Keulen (1981) and Sharpley and Williams (1990) used a supply and demand similar to that in **CREAMS**, but added many additional crops. An additional feature of the procedure by Sharpley and Williams (1990) was inclusion of a nitrogen stress factor. The stress factor, applied daily, was based on the ratio of nitrogen availability to optimal nitrogen demand, and it constrained the biomass production. The nitrogen stress was not in addition to moisture stress resulting from soil water deficiency, but the greater (most restrictive) of the two.

Nitrogen uptake in **GLEAMS** is patterned after that in the EPIC model (Sharpley and Williams, 1990) for estimation of nitrogen demand. The uptake by transpiration differs in that **GLEAMS** contains both nitrate

and ammonia uptake. All crops differ in their affinity for nitrate or ammonia, but it is assumed for model representation that nitrate and ammonia uptake is equal to the relative mass of each specie in the soil layer from which transpiration occurs.

The concentration of nitrogen, CN, percent of the crop biomass, is calculated daily from the relation

$$CN = (C1) (GRT)^{C2} \quad [95]$$

where C1 and C2 are empirical coefficients and GRT is a growth ratio defined as

$$GRT = \frac{SUMLAI}{POTLAI} \quad [96]$$

where SUMLAI is the accumulated leaf area index, m²/m², and POTLAI is the potential leaf area index, m²/m², on the day of harvest (or date of truncation for hay crops, corn silage, and etc.). POTLAI is the sum of idealized daily LAI over the growing period without water or nitrogen stress. The growth ratio is used to calculate total dry matter, TDM, kg/ha, as

$$TDM = (GRT) (PY) (DMY) \quad [97]$$

where PY is potential yield, kg/ha, of the harvestable portion of the crop, and DMY is the dry matter ratio, i. e. ratio of total dry matter to harvestable yield. Then the total dry matter nitrogen, TDMN, kg/ha, is

$$TDMN = 0.01 (CN) (TDM) \quad [98]$$

The daily nitrogen demand, DEMN, kg/ha, is the difference in TDMN on successive days

$$DEMN_d = TDMN_d - TDMN_{d-1} \quad [99]$$

The supply of nitrogen is based upon availability and transpiration from the respective layers. If either ammonia or nitrate is exceptionally low compared with the other, the partitioning procedure of eqns. [98] and [99] will take care of it automatically. Then the uptake of ammonia, UPNH, kg/ha, is

$$UPNH_i = 0.1 (CNH4W_i) (TR_i) \quad [100]$$

and the uptake of nitrate, UPNO, kg/ha, is

$$UPNO_i = 0.1 (CNO3W_i) (TR_i) \quad [101]$$

where CNH4W and CNO3W are determined from eqns. [89] and [90], and TR is the transpiration calculated for each computational layer of root growth in the hydrology component. The uptake of nitrogen, UPN, kg/ha, is summed for each specie over the number of transpiration layers, ntl,

$$UPN = \sum (UPNH_i + UPNO_i)_{i=1, ntl} \quad [102]$$

It is assumed that an over abundance of nitrate and ammonia does not result in a flush of uptake greater than the demand calculated from eqns. [95] through [99]. Such a flush occurs in nature as evidenced by dark green, almost black, color of growing crops. However, it is not known how to simulate the flush. Thus, a demand factor, DMNFAC, is calculated as

$$DMNFAC = \frac{DEM N}{UPN} \quad [103]$$

The adjusted uptake is calculated as

$$AJUPNH_i = (DMNFAC) (UPNH_i) \quad [104]$$

and

$$AJUPNO_i = (DMNFAC) (UPNO_i) \quad [105]$$

The adjusted total uptake, TUPN, kg/ha, is

$$TUPN = \sum (AJUPNH_i + AJUPNO_i)_{i=1, nt1} \quad [106]$$

The adjusted values from eqns. [104] and [105] are subtracted from the respective pools in each layer, AMON_i and SNO_{3i}.

If nitrate and ammonia availability are limited, and UPN is less than DEMN, a nitrogen stress factor, SFN, is calculated to reduce SUMLAI (eqn. [96]). SFN is calculated in two stages: the first is an uptake factor, UPFAC,

$$UPFAC = 2 \left[1 - \left(\frac{UPN}{DEM N} \right) \right] \quad [107]$$

and the second stage is

$$SFN = 1 - \left[\frac{UPFAC}{UPFAC + \exp(3.39 - 10.93 UPFAC)} \right] \quad [108]$$

The minimum of the moisture and nitrogen stress factors is used to reduce the daily leaf area index increment for accumulation in the SUMLAI of eqn. [96].

Leguminous plants take nitrogen from the soil if the concentration exceeds some threshold value, and assimilate (fix) nitrogen from the atmosphere if soil nitrogen is below the threshold value. The threshold varies with crop, soil pH, and other factors, but a single value of 5 mg/L is assumed here. It is also assumed that the 5 mg/L is the combined ammonia and nitrate content.

The nitrogen demand for a legume is calculated as in eqns. [95] through [99]. Then the concentrations of nitrate and ammonia in the solution phase, eqns. [89] and [90], are summed in the layers where transpiration occurs. If the sum exceeds 5 mg/L, uptake is calculated as for other crops in equations [100] through [106]. If the combined concentrations are less than 5 mg/L, the mass fixed (FIXN) is equal to the DEMN. The calculations are made daily, and legumes may use nitrogen from the soil during early crop development and fix nitrogen in the later crop stages when the demand is higher and/or when fertilizer nitrogen is depleted by uptake, denitrification, and leaching.

Nitrogen fixation is not assumed to add nitrogen to the soil until harvest and/or tillage. At harvest or tillage, the appropriate amounts of the crop residue and roots are added to surface residue nitrogen, RESDN, and fresh organic nitrogen, FON, as a part of the nitrogen cycle.

Analogous to the pesticide component of **GLEAMS** (Leonard et al., 1987), $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ are moved upward in the soil one computational layer above that from which evaporation occurs except the surface 1 cm layer. To repeat the assumptions here, movement upward one layer is considered by water flux, and further upward movement would be considered vapor flux. Ammonia is not considered evaporated (volatilized) from the surface layer even though a volatilization component is included for ammonia in animal waste as will be shown later.

The nitrate evaporated from a layer, EVNO_i , kg/ha, is

$$\text{EVNO}_i = 0.1 (\text{EVAP}_i) (\text{CNO3W}_i) \quad [109]$$

and ammonia evaporated from a layer, EVNH_i , kg/ha, is

$$\text{EVNH}_i = 0.1 (\text{EVAP}_i) (\text{CNH4W}_i) \quad [110]$$

where EVAP_i is the evaporation, cm, from layer i . EVNH_i and EVNO_i are subtracted from AMON_i and SNO3_i , respectively, and added to AMON_{i-1} and SNO3_{i-1} . If $i=1$, the evaporation masses are not subtracted from the respective components. This procedure results in an "enrichment" of ammonia and nitrate in the surface 1 cm of soil for subsequent interaction between runoff and percolation.

Rainfall and fertilizer nitrogen--Nitrogen input, other than fixation by legumes, in the form of instantaneously available nitrogen include that in rainfall and in fertilizer. Rainfall contains both ammonia and nitrate. Their relative concentrations vary throughout the year, and their total concentration changes as well. For simplification of model input, it is assumed that all of the rainfall nitrogen is in the form of nitrate. Also, it is assumed that the concentration in rainfall remains the same throughout the model simulation period. The concentration of nitrate in rainfall is user supplied from local data or from a national map of the United States (Frere et al., 1980). It is used to calculate the nitrate addition as

$$\text{RN} = 0.01 (\text{RCN}) (\text{PCP}) \quad [111]$$

where RN is rainfall nitrate, kg/ha, RCN is the concentration of nitrate in rainfall, mg/L, and PCP is rainfall in cm. RN is added to the nitrate in soil layer 1, SNO3_1 , where it is available for runoff, uptake, and leaching.

Since separate $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ pools are maintained, and nitrification is simulated separately from ammonification, nitrate and ammonia fertilizers are distinguished in application. For example, ammonium nitrate fertilizer is 16.5% ammonia and 16.5% nitrate. Application of 400 kg/ha fertilizer would result in 66 kg/ha added to AMON and 66 kg/ha added to SNO3. Fertilizer and animal waste applications can be applied on the surface, incorporated, injected, or applied as fertigation. The 400 kg/ha ammonium nitrate application may be broadcast on the surface (top dressed), or it may be broadcast and incorporated to some specified depth on the day of application or on some later specified date. Surface application of inorganic fertilizer is assumed to mix with the appropriate species in the surface layer of soil on the date of rainfall or tillage.

Ammonia volatilization--Losses of ammonia by volatilization from surface-applied animal waste are reported as high as 35% in a 5-day period (Midwest Plan Service, 1983; North Carolina State University, 1982; U. S. Soil Conservation Service, 1975). Loss to volatilization is 5% or less when animal waste is incorporated immediately after application. The ammonia content of animal waste and the losses are dependent upon methods of storing and handling the waste, and climatic conditions during storage and after application.

Waste utilization to supplement or replace inorganic fertilizer must consider these losses from the total available nitrogen (U. S. Soil Conservation Service, 1975).

Reddy et al. (1979) formulated an ammonia volatilization component for a nonpoint source pollution model. The process was related to air temperature, and it was thought that the process should continue for a week. Daily volatilization, VOLN, kg/ha, is expressed as

$$VOLN = (AWNH) [1 - \exp(-k_v t)] \quad [112]$$

where AWNH is ammonia in animal waste, kg/ha, k_v is volatilization rate constant, and t is time in days. The volatilization rate constant is

$$k_v = 0.409 (1.08)^{ATP-20} \quad [113]$$

where ATP is the mean daily air temperature, EC, and the reference temperature is 20EC. It is assumed that volatilization is operative only for surface-applied solid, slurry, and liquid animal waste. For solid and slurry application, volatilization continues over a 7-day period or until tillage or rainfall occurs. If a solid or slurry is incorporated on the day of application, $t = 6$ hr in eqn. [110]. This assumes that the applied waste is incorporated in 6 hr. Some states require incorporation within 4 hr, but this is not a significant discrepancy between practice and model assumption. Volatilization is assumed to occur for 6 hr for applications of liquid manure (effluent) by irrigation. On a day of rainfall, the remaining AWNH is added to the ammonia in soil layer 1, AMON₁, and AWNH on the surface is set to zero to stop the process.

Volatilization of ammonia mineralized (ammonified) from crop residue and animal waste (other than the soluble ammonia) is not simulated in **GLEAMS**. Likewise, volatilization of ammonia in animal waste incorporated into the soil is not considered in the model, but it is added directly into the AMON pool of the respective soil layers from incorporation.

Phosphorus Component: The phosphorus component of the **CREAMS** model was only a surface response model (Frere et al., 1980). It was assumed that the normal buffering capacity of soils was such that adsorbed phosphorus was the principal concern in water quality problems associated with lakes. However, this is not entirely true, and heavy phosphorus loadings on sandy soils with low buffering capacities may result in labile phosphorus movement to shallow groundwater or into drainage canals and lakes. High application rates of animal waste on sandy soils, such as with dairy operations in south Florida (Knisel et al., 1985), may cause high losses into off-site water bodies via drainage canals.

Alternate management practices are needed on problem areas to reduce the edge-of-field or bottom-of-root zone phosphorus loadings. In order to adequately assess management strategies, well formulated phosphorus processes are needed in a management oriented model such as **GLEAMS**.

A simplified phosphorus model was developed by Jones et al. (1984) and Sharpley et al. (1984) to assess long-term soil erosion and crop productivity. The model was incorporated into the EPIC model (Sharpley and Williams, 1990) and was successfully applied over a wide range of soils, crops, and climatic regions. Since the model represents a state-of-the-art phosphorus model, and it is consistent with other components of **GLEAMS**, it was largely incorporated intact in the **GLEAMS** nutrient component. About the only modification is in the mineralization of organic phosphorus in animal waste. Since most of the phosphorus processes parallel those in the nitrogen component, many of the equations given above for nitrogen will be cited or repeated in this section to adequately describe the model.

The phosphorus component is depicted in Fig. 2 with the various transformations shown. The similarities with the nitrogen component can be seen by comparing Fig. 2 with Fig. 1. As shown in Fig. 2, the component includes three soil phosphorus pools: a mineralizable organic humus P pool (SORGP), an active mineral P pool (PMINP), and an long-term stable mineral P pool (SOILP). Analogous to the nitrogen component, a fresh organic phosphorus pool (FOP) represents the mineralizable crop root residue, and that in surface residue (RESDP). Organic phosphorus in animal waste (ORGPW) is represented in the model. Plant available and mobile labile phosphorus is represented in the model (Fig. 2) by PLAB.

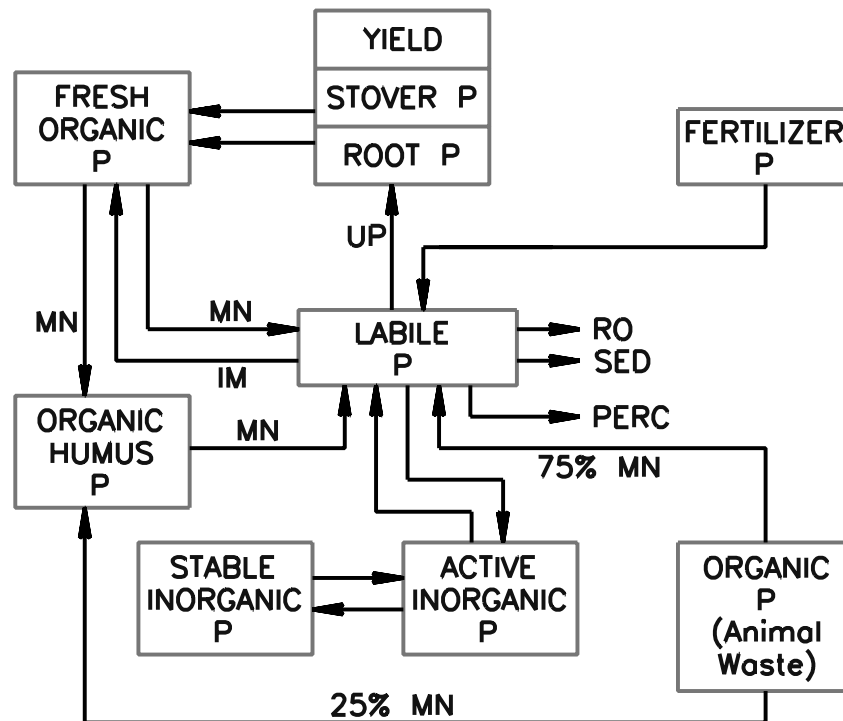


Figure 2. Schematic representation of the phosphorus component.

Like the nitrogen component, the various pools of phosphorus are primarily distinguished by different carbon:phosphorus (C:P) ratios. The fresh organic phosphorus (FOP) root residue and surface residue generally have C:P ratios greater than 200 while that for SORGP is in the range of 125 to 200. There is a flow between active and stable mineral phosphorus pools, and a flow between active mineral P and labile P. Flow between the mineral P pools maintain a long-term stable system with the stable pool (SOILP) four times the size of the active mineral pool (PMINP) at equilibrium. Also, the PMINP is active in immobilization of labile P by sorption when PLAB gets large from fertilizer or manure application, or by mineralization. Phosphorus sorption is a function of soil characteristics.

Mineralization--Phosphorus mineralization is a single-step first-order process (Jones et al., 1984), and follows the same general procedure as for nitrogen. Mineralization, RMP, kg/ha, from fresh organic phosphorus, FOP, kg/ha, is

$$RMP_i = (DCR_i) (FOP_i)$$

[114]

The decomposition of crop residue, DCR, was defined in eqn. [43] as a function of residue composition, and the C:N and C:P ratios, and the temperature and soil water factors (eqns. [44]-[47]). As in the EPIC model (Sharpley and Williams, 1990), 75% of RMP is added to the labile phosphorus pool, PLAB, kg/ha, and 25% is added to the organic humus phosphorus pool, SORGP, kg/ha (Jones et al, 1984).

As in the nitrogen component, phosphorus in surface residue, RESDP, is mineralized to soluble phosphorus, SOLP, by the same process as for FOP in eqn. [114]. The same ambient conditions of soil water in the surface layer and air temperature are used as in mineralization of RESDN to SOLNH.

Mineralization, PMN, kg/ha, from the organic humus phosphorus, SORGP, kg/ha, is defined as

$$PMN_i = (CMN) (SORGP_i) \left(\frac{POTMN_i}{SOILN_i} \right) [(SWFA_i) (TFA_i)]^{0.5} \quad [115]$$

where the soil water factor, SWFA, and temperature factor, TFA, are the same as defined in eqns. [35] and [36], respectively. Jones et al. (1984) used the ratio of active and stable soil nitrogen pools, POTMN and SOILN, respectively, to partition soil organic humus phosphorus into the mineralizable fraction.

Analogous to the flow between the active and stable nitrogen pools, a flow rate, MPR, kg/ha/d, is determined between active and stable mineral phosphorus, PMINP and SOILP, as

$$MPR_i = 0.1 (SWFA_i) \exp(0.115 T_i - 2.88) \left[PLAB_i - (PMINP_i) \left(\frac{PSP_i}{1 - PSP_i} \right) \right] \quad [116]$$

where SWFA is defined from eqn. [35], T is temperature, EC, and PSP is phosphorus sorption coefficient defined by Sharpley and Williams (1990) for calcareous soils as

$$PSP_i = 0.58 - 0.0061 CACO3_i \quad [117]$$

where CACO3 is the calcium carbonate concentration, µg/g. Sharpley and Williams (1990) gave phosphorus sorption coefficients for noncalcareous soils based upon degree of weathering. For slightly weathered soils, the sorption coefficient was defined as

$$PSP_i = 0.0054 BSAT_i + 0.116 PH_i - 0.73 \quad [118]$$

where BSAT is base saturation, percent, and PH is soil pH. For highly weathered soils, the coefficient is

$$PSP_i = 0.46 - 0.0916 \ln(CL_i) \quad [119]$$

where CL is clay content in percent. Jones et al. (1984) defined highly weathered soils as Oxisols, Ultisols, Quartzipsamments, Ultic subgroups of Alfisols, and acidic Ochrepts. PSP is constrained such that 0.05 ≤ PSP ≤ 0.75.

At equilibrium, the stable mineral phosphorus pool (SOILP) is assumed to be four times the active mineral pool (PMINP) (Sharpley and Williams, 1990). Flow between the pools is given as

$$ASPR_i = \omega_i (4 PMINP_i - SOILP_i) \quad [120]$$

T is a flow coefficient which is a function of PSP, and for calcareous soils,

$$\omega_i = 0.00076 \quad [121]$$

and for noncalcareous soils

$$\omega_i = \exp(-1.77 \text{ PSP}_i - 7.05) \quad [122]$$

When the flow estimated by eqn. [95] is positive, the daily amount is subtracted from PMINP and added to SOILP. Likewise, when the flow is negative, the flux is subtracted from SOILP and added to PMINP.

Like nitrogen, the mineralization rate for phosphorus in animal waste, PMNAW, kg/ha/d, is determined from the decomposition rate constant AWDCR from eqn. [47] as

$$\text{PMNAW}_i = (\text{AWDCR}_i) (\text{ORGW}_i) [(\text{SWFA}_i) (\text{TFA}_i)]^{0.5} \quad [123]$$

where ORGPW is the organic phosphorus in animal waste, kg/ha, and the soil water and temperature factors are defined in eqns. [35] and [36], respectively. In accordance with Bhat et al. (1981), 75% of PMNAW is added to PLAB and 25% is added to organic humus phosphorus, SORGP.

Immobilization--The high C:P ratios of crop residue, generally greater than 200, results in immobilization of plant-available labile phosphorus, PLAB (Jones et al., 1984). The same general procedure is followed as that for nitrogen except that only the one source of phosphorus is immobilized instead of the two in nitrogen, nitrate and ammonia. The immobilized P, WIMP, kg/ha, is

$$\text{WIMP}_i = (\text{DCR}_i) (\text{FRES}_i) [0.16 \text{ PLI}_i - (c_{\text{pfr}})_i] \quad [124]$$

where the decomposition of crop residue, DCR, is determined in eqn. [41]. The coefficient 0.16 in eqn. [124] results from assuming that carbon is 40% of fresh residue, and that 40% of the carbon is assimilated by soil microorganisms. The concentration of P in the fresh residue, c_{pfr} , kg/kg, is

$$(c_{\text{pfr}})_i = \frac{\text{FOP}_i}{\text{FRES}_i} \quad [125]$$

The labile phosphorus immobilization factor, PLI,

$$\begin{aligned} \text{PLI}_i &= 0.01 + 0.001 \text{ CPLAB}_i && \text{for } \text{CPLAB} \leq 10 \\ \text{PLI}_i &= 0.02 && \text{for } \text{CPLAB} > 10 \end{aligned} \quad [126]$$

where CPLAB is concentration of labile phosphorus, $\mu\text{g/g}$.

If WIMP exceeds 95% of PLAB, then DCRPR is calculated similar to that for nitrogen (eqn. [51]) as

$$\text{DCRPR}_i = \frac{0.95 \text{ PLAB}_i}{\text{FRES}_i [0.16 \text{ PLI}_i - (c_{\text{pfr}})_i]} \quad [127]$$

Either phosphorus or nitrogen can limit immobilization because only a single value of DCRPR is used for residue decomposition, and the minimum of the two calculated values control. Immobilized P is subtracted from PLAB and added to FOP.

Surface immobilization of phosphorus follows the same procedure as that for nitrogen. The decomposition rate for surface residue, DCR_s , kg/ha/d, is

$$DCR_s = (CNP_s) (RC_s) [(SWFA_1) (TF_a)]^{0.5} \quad [128]$$

where TF_a is the temperature factor as calculated with eqn. [11] using mean daily air temperature. Immobilization is calculated as in eqn. [124]. If the calculated immobilization is greater than the available phosphorus, then $DCRPR_s$ is

$$DCRPR_s = \frac{0.95 (PLAB_1) + SOLP}{RESDW [0.16 PLI_1 - (C_{pfr})_s]} \quad [129]$$

where SOLP is the soluble phosphorus on the surface from mineralization or fertilization. The appropriate value of surface immobilization is subtracted from labile P in layer 1, $PLAB_1$, and added to P in the surface residue, RESDP.

Phosphorus in runoff, sediment, and percolation--Phosphorus is partially adsorbed to the soil clay fraction, and therefore the mathematical manipulations follow that for ammonia. Partitioning P between the soil and water phases is as given in eqn. [66], and the partitioning coefficient, CPKD, is related to the percent clay in the soil, CL, as

$$CPKD_i = 100 + 2.5 CL_i \quad [130]$$

The extraction coefficient for phosphorus, $\$p$, is determined from eqn. [67] for $CPKD_1$.

Assumptions presently made are that CPKD is related only to the clay content of soil and not to phosphorus status, degree of clay surface coverage by adsorbed P, or the nature of the surface. While this assumption may be valid for agri-cultural soils, CPKD may be overestimated for soils with inherently low adsorptive capacity receiving large phosphorus loadings such as from animal wastes. This aspect is currently receiving research attention, and eqn. [102] and related equations may be replaced with additional algorithms in the future.

The concentration of phosphorus in the surface layer of soil available for runoff and percolation into layer 2 is

$$(C_{av})_p = (CPLAB_i) \exp \left[\frac{-(F - ABST)}{CPKD_1 \left(\frac{1 - POR_1}{2.65} \right) + POR_1} \right] \quad [131]$$

where CPLAB is the concentration of labile phosphorus, $\mu\text{g/g}$, based upon the dry weight of the soil. The concentration in the water, mg/L, from eqn. [65], is

$$CPLABW_1 = \frac{(C_{av})_p \beta_p}{1 + (CPKD_1) \beta_p} \quad [132]$$

Labile phosphorus in runoff, ROLP, kg/ha, is

$$ROLP = 0.1 (CPLABW_1) (Q) \quad [133]$$

The sediment-associated labile P, SEDLP, kg/ha, is

$$SEDLP = 0.1 (SY) (ER) (CPKD_1) (CPLABW_1) \quad [134]$$

The initial mass of labile phosphorus available in layer 1, AVLPMs, kg/ha, is

$$AVLPMs_1 = (CPLAB_1) (SOILMS_1) \quad [135]$$

from which the percolation mass of phosphorus, PRLPMs, kg/ha, out of layer 1 is

$$PRLPMs_1 = AVLPMs_1 - [(C_{av})_p (SOILMS_1)] \quad [136]$$

and the percolation concentration, PERCLP, mg/L, out of layer 1 is

$$PERCLP_1 = \frac{0.1 PRLPMs_1}{PERC_1} \quad [137]$$

The labile phosphorus mass, PLAB, remaining in layer 1 after a runoff event is

$$PLAB_1 = (PLAB_1)_o - ROLP - SEDLP - PRLPMs_1 \quad [138]$$

For layers 2 through ncl, total number of computational layers,

$$PLAB_i = PLAB_i + [(PERCLP_{i-1}) (PERC_{i-1})] \quad [139]$$

Then after re-equilibration with the water mass, WM (eqn. [88]), the concentration in the water for further percolation, uptake, and evaporation, is

$$CPLABW_i = \frac{10 PLAB_i}{(CPKD_i) (SOILMS_i) + WM_i} \quad [140]$$

To complete the sediment phosphorus, loss from P in animal waste is

$$SEDOP = \frac{(SY) (ER) (ORG PW_1)}{SOILMS_1} \quad [141]$$

Loss from active mineral P is

$$SEDMP = \frac{(SY) (ER) (PMINP_1)}{SOILMS_1} \quad [142]$$

and from stable mineral P is

$$SEDSP = \frac{(SY) (ER) (SOILP_1)}{SOILMS_1} \quad [143]$$

and sediment humus P loss with sediment is

$$SEDHP = (SY) (ER) (SORGP_1) \quad [144]$$

The total sediment-associated phosphorus, SEDP, kg/ha, is

$$SEDP = SEDLP + SEDHP + SEDOP + SEDMP + SEDSP \quad [145]$$

Phosphorus uptake and evaporation--Data on crop nitrogen and phosphorus content were examined for a number of crops. Ratios of nitrogen:phosphorus are included in the model data statements for 78 crops. N:P varies from crop to crop averaging about 7:1. The optimum phosphorus content, for demand purposes, is estimated from the nitrogen content (CN in eqn. [95]) and the N:P ratio, NPR, as

$$CP = \frac{CN}{NPR} \quad [146]$$

and the total dry matter phosphorus, TDMP, kg/ha, is

$$TDMP = 0.01 (CP) (DM) \quad [147]$$

where DM is the dry matter determined by eqn. [97]. Then the phosphorus demand, DEMP, kg/ha, is determined as the difference between the TDMP values on successive days as

$$DEMP_d = TDMP_d - TDMP_{d-1} \quad [148]$$

Uptake of labile phosphorus, UPLP, kg/ha, is estimated for each layer where transpiration, TR, occurs from

$$UPLP_i = 0.1 (CPLABW_i) (TR_i) \quad [149]$$

where the concentration of labile P, CPLABW, is determined by eqn. [140]. The total uptake, UPP, kg/ha, is determined as the sum over all layers of transpiration, ntl,

$$UPP = \sum (UPLP_i) \quad \text{for } i=1, ntl \quad [150]$$

A demand factor for P, DMPFAC, is calculated as

$$DMPFAC = \frac{DEMP}{UPP} \quad [151]$$

An adjusted uptake, AJUPP, kg/ha, is calculated for each layer as

$$AJUPP_i = (UPLP_i) (DMPFAC) \quad [152]$$

The adjusted uptake is subtracted from PLAB for each layer. Unlike the nitrogen component, growth is not constrained for phosphorus deficiency.

Phosphorus is moved upward with evaporation one computational soil layer the same as with nitrogen and pesticides. The assumption is the same for phosphorus: upward movement one layer is by water flux, whereas further movement is assumed to be by vapor flux which is not considered in **GLEAMS**. Phosphorus loss is not allowed out of layer one by evaporation. The movement by evaporation, EVP_i , kg/ha, is estimated as

$$EVP_i = 0.1 (EVAP_i) (CPLABW_i) \quad [153]$$

where $EVAP$ is the water evaporation calculated in hydrology, and $CPLABW$ is calculated in eqn. [113]. EVP_i is subtracted from $PLAB_i$ and added to $PLAB_{i-1}$.

Fertilizer phosphorus--Inorganic phosphorus fertilizer is considered in the model to be plant-available labile P. It is further assumed to be instantaneously soluble, and upon application, the mass is added directly to the labile phosphorus pool (PLAB) in the soil. Although phosphorus fertilizer is normally incorporated into the soil, if it is surface-applied, the mass applied on the surface is added to the soluble P (SOLP) pool that is instantaneously moved into the soil surface layer with rain or irrigation. Solubility of different forms of P fertilizer are not considered.

Soil Temperature: Soil temperature has been shown above to be a modifier of nitrogen and phosphorus transformation rates. In the **CREAMS** model (Knisel, 1980), mean daily air temperature was used to adjust rate constants because it was thought that a time lag was the only major factor in temperature changes in the soil profile. That is, it was thought that mean daily soil temperatures approach mean daily air temperatures with less diurnal fluctuations and semi-annual lags. For most practical purposes, this was sufficient in **CREAMS** because the soil water was averaged over the entire root zone and between days of rainfall. These averaging schemes did not allow day-to-day changes in actual water states. Moreover, the mean daily air temperatures were also averaged between storm dates. These assumptions may cause some problems in climatic regions where the upper soil layers are frozen and transformation processes stop, while lower root-zone layers are above freezing and transformations continue.

Like several other elements in the **GLEAMS** model, soil temperature is relatively site specific. That is, in mountainous areas or in hilly terrain, slope aspect may have a dominant affect on near-surface soil temperatures. This is not peculiar to temperature: soil evaporation is affected by aspect, also. Thus, the water balance is different for south and north facing slopes. North facing slopes receive more snow in many cold regions. Since snow cover modifies soil temperature, and precipitation and evaporation differences are not functions of aspect in the model, it is not considered significant to include aspect in soil temperature.

Williams et al. (1990) adapted the concepts of Richardson's (1981) air temperature model to generate daily surface soil temperatures for bare ground. Daily air temperatures are estimated with a first-order Markov scheme using lag coefficients, and dampened the daily range on days with rainfall. Obviously this is an oversimplification of the technique, but details are not given in this paper. Williams et al. (1990) used daily maximum and minimum air temperatures to represent bare soil conditions, and adjusted the mean daily air temperature for surface cover to simulate the insulation effects of snow and/or crop biomass and residue. The surface soil temperatures were then manipulated as a function of soil depth and water content to dampen the day-to-day changes towards a long-term mean-annual air temperature at some depth. Further, the soil and water mass is much more efficient in heat storage than air, and a 5-day moving average scheme is used for the dependency model of soil temperature.

The average soil temperature, TSC , EC, on day d at the center of each soil layer i is

$$TSC_{(i,d)} = LAG [TSC_{(i,d-1)}] + (1.0 - LAG) [SDF_i (TAVGC - TGSC_d) + TGSC_d] \quad [154]$$

where LAG is the lag coefficient ranging from 0 to 1, SDF is a soil depth factor, TAVGC is the long-term mean-annual temperature in EC, and TGSC is the temperature at ground surface, EC. The soil depth factor in eqn. [154] is estimated as

$$SDF_i = \frac{SD_i}{SD_i + \exp(-0.867 - 2.08 SD_i)} \quad [155]$$

where

$$SD_i = \frac{DEP_i + DEP_{i-1}}{2.0 SDD} \quad [156]$$

where DEP is the depth, m, from the soil surface to the bottom of the soil computational layer, and SDD is the soil damping depth, m. It can be seen that near-surface temperatures are strongly influenced by the surface temperature, TGSC, and this influence gives way to TAVGC as SD increases. At SDD, the soil temperature is within about 5% of TAVGC.

The soil damping depth is a function of soil bulk density and water content. The bulk density factor, BDF, uses the mean density, BD, g/cm³, of the soil mass

$$BDF = 1.0 + \left[\frac{2.5 BD}{BD + \exp(6.53 - 5.63 BD)} \right] \quad [157]$$

The soil water factor, SWFT, is

$$SWFT = \frac{TSWC}{(0.356 - 0.144 BD) RD} \quad [158]$$

where TSWC is the total soil water, m, in the root zone depth, RD, m. Then the soil damping depth, SDD, m, (eqn. [156]) is

$$SDD = (BDF) \exp \left[\ln \left(\frac{0.5}{BDF} \right) \left(\frac{1 - SWFT}{1 + SWFT} \right)^2 \right] \quad [159]$$

In estimating the temperature of the ground surface, TGSC in eqn. [154], it is necessary to calculate the temperature of the bare ground surface, TBGSC, EC, and then estimate the effects of soil cover. The range of air temperature from maximum, TAXC, to minimum, TANC, usually is less on days with rainfall. Thus, the temperature of the bare ground surface on a wet day, TBGSWC, EC is

$$TBGSWC_d = TAXC_d + SCR (TAXC_d - TANC_d) \quad [160]$$

where SCR is a scaling factor ranging from 0 to 1, but best results were reported by Williams et al. (1990) with SCR = 0.1. A value of 1.0 would indicate a full range from maximum to minimum temperature for the day, d. The temperature of the bare ground surface on a dry day, TBGSDC, is

$$TBGSDC_d = \frac{\left(\frac{TAXC_d + TANC_d}{2} \right) - (ANWD_{mo}) (TBGSWC_d)}{1 - ANWD_{mo}} \quad [161]$$

where ANWD is the number of wet days, NWD, in month, mo, divided by the number of days in the month

$$ANWD_{mo} = \frac{NWD_{mo}}{ND_{mo}} \quad [162]$$

A 5-day moving average of bare soil surface temperature is calculated to estimate the soil system lag caused by soil heat storage. Thus, the final estimate of the temperature of bare ground surface, TBGSC, EC, is

$$TBGC_d = \sum_{n=0, 4} TBGSC_{d-n} \quad [163]$$

where TBGSC is the appropriate wet-day or dry-day bare ground surface temperature from eqn. [160] or [161].

If the soil surface is bare, i. e. no surface residue, no crop growing, and no snow cover, the temperature estimated with eqn. [163] becomes the temperature at the ground surface, TGSC, in eqn. [154]. If there is cover, an adjustment is made with a cover factor, CF, and

$$TGSC_d = (CF) (TBGC_{d-1}) + (1.0 - CF) (TBGC_d) \quad [164]$$

During the winter, the cover factor may be greater for the water content of snow than for surface residue and/or crop biomass, thus the cover factor, CF, is

$$CF = \max \begin{cases} COVER \\ SNOW \end{cases} \quad [165]$$

where COVER is

$$COVER = \frac{CV}{CV + \exp(7.563 - 1.297 \times 10^{-4} CV)} \quad [166]$$

CV, t/ha, is the sum of surface residue and above-ground crop biomass

$$CV = \frac{RESDW + 0.75 (TDM)}{1000} \quad [167]$$

RESDW is surface residue, kg/ha, and TDM is total dry matter, kg/ha. SNOW in eqn. [165] is

$$SNOW = \frac{SNO}{SNO + \exp(2.303 - 0.2197 SNO)} \quad [168]$$

where SNO is the water content of the snow cover, mm. If there is no snow, CF = COVER.

It can be seen from eqns. [164] to [168] that management practices may significantly affect the soil temperature and plant nutrient transformations. Thus, the interactions of soils, climate, and management are complex in nature.

Management Representations

Several new management representations or practices have been included in the new version of **GLEAMS** with the nutrient component. Some have already been discussed under the hydrology component, such as modification of the procedure for surface irrigation using the water content in the simulated rooting depth instead of the entire root zone. Other practices pertain more specifically to the nutrient component.

Fertigation and irrigation application of liquid animal waste and N and P: In the agricultural regions where center-pivot irrigation is used, liquid fertilizer may be applied in the irrigation water. Also, livestock operations such as swine production and dairying may use lagoons in their waste disposal systems, and lagoon effluent is applied to crop and pasture lands by irrigation (sometimes referred to locally as "manurigation"). These systems distribute soluble ammonia, nitrate, and labile phosphorus with irrigation. Irrigation water must be sufficient to move the fertilizer into the soil and to some finite rooting depth, hopefully without excess movement resulting in leaching of nutrients or potentially polluting surface and ground waters. The depth of irrigation water is user-specified, and the model calculates the water and chemical flux into, within, and (if any) through the root zone. With the appropriate addition of the respective nutrients at the surface, the same procedure is used as described in the respective components above to calculate the redistribution of water and chemicals. Since the form of material is liquid, the nutrients are soluble and are manipulated in the model as surface-applied SOLN, SOLNH, and SOLP. The model adds these fractions to the respective masses in the top 1 cm and redistributed as is rainfall nitrogen. If excess irrigation water is applied, any runoff, sediment yield, and associated nutrients are calculated.

In some areas, for example Nebraska sand hills, irrigation water may contain significant concentrations of nitrate-nitrogen and soluble phosphorus, up to 6 mg $\text{NO}_3\text{-N/L}$ and 3 mg $\text{PO}_4\text{P/L}$. Although these concentrations do not appear significant at first glance, consider that 50 cm irrigation water may be applied during the growing season of an annual crop. This addition would amount to 30 kg $\text{NO}_3\text{-N/ha}$ and 15 kg $\text{PO}_4\text{-P/ha}$ which are significant, and are taken into consideration in making fertilizer recommendations.

The nutrient component of **GLEAMS** allows input of irrigation N and P if it is thought to be significant. Just as with rainfall, nitrogen in irrigation water is assumed to be in the form of nitrate.

Tillage: Tillage operations accomplish two major functions in the nutrient component: (a) incorporate crop residue and/or animal waste on the surface, and (b) mix the incorporated materials and all of the various forms of nutrients in the plow depth. All tillage implements do not incorporate and mix to the same degree, nor are all operations made to the same depth. A relatively extensive list of tillage implements/practices are included in the model, with associated incorporation and mixing efficiencies, for user specification by number and input of tillage depth. The list includes those from EPIC (Sharpley and Williams, 1990) with some additional ones.

Incorporation and mixing are separately treated functions. For example, a moldboard plow may incorporate about 95% of surface material, but mixing is very low. A mixing efficiency of 1.0 indicates uniform mixing within the computational soil layers, while a mixing efficiency of zero indicates an inversion rather than mixing. A moldboard plow may have a mixing efficiency of zero or 1.0 depending upon material. For example, animal waste incorporated by moldboard may be inverted with the turning of a plow slice into the furrow. On the other extreme, if a meadow of tall grass, such as brome grass, is moldboarded, the mixing

efficiency may be 1.0 as the grass is turned into furrow. The model user may specify the mixing and incorporation efficiency.

Harvesting of crops removes the nitrogen and phosphorus with the harvestable portion of the crop. That portion is subtracted from the system for nitrogen and phosphorus balance. The amount of surface residue with its specific N and P is added to any surface residue that may already exist, if any. Also, the root residue with its respective N and P contents is distributed into the fresh organic nitrogen (FON) and fresh organic phosphorus (FOP) by soil computational layer with weighting factors dependent upon the root depth and number of computational soil layers. These amounts are added to any existing amounts of FON and FOP on the date of harvest.

Two common practices in the Southeast Coastal Plain that affect surface residue weight and N and P content are burning and baling. When small grain or cover crop is followed by another crop, for example, peanuts, at the time of harvest, the residue is burned. The second practice is the baling of residue after combining peanuts. Both practices remove the residue mass and associated N and P from the system, but does not affect the root residue. Doubtless, there probably is some organic matter in the surface soil layer lost to burning, but this is not considered.

Pesticides

The pesticide component of **GLEAMS** has been extensively described by Leonard et al. (1987), and the description is not repeated here. Other publications contain additional information as well (Knisel et al., 1989; Knisel et al., 1991; Leonard et al., 1989; and Leonard et al., 1990.)

SUMMARY

A plant nutrient component was developed for the **GLEAMS** model incorporating state-of-the-art process descriptions for nitrogen and phosphorus. Major processes include ammonification, nitrification, denitrification, uptake, fixation, leaching, and runoff of nitrogen; and mineralization, uptake, leaching, and runoff of phosphorus. Management alternatives include fertigation; application of animal waste as solid, slurry, or liquid through irrigation systems, and tillage.

Model validation will be presented in Part II of this paper. Readily-available observed data will be used for comparison with simulated values.

LIST OF SYMBOLS

ABST	Initial abstraction of rainfall, cm
AJUPNH	Adjusted uptake of ammonia-nitrogen, kg/ha
AJUPNO	Adjusted uptake of nitrate-nitrogen, kg/ha
AJUPP	Adjusted uptake of phosphorus, kg/ha
ALB	Albedo
AMON	NH ₄ -N mass in the soil, kg/ha
ANWD	Average number of wet days per month
AP	Coefficient
ASPR	Phosphorus flow rate between mineral pools, kg/ha/d
ATP	Air temperature, EC
AVLPMS	Available mass of labile phosphorus, kg/ha
AVNHMS	Available mass of ammonia, kg/ha
AVNOMS	Available mass of nitrate, kg/ha
AWNHN	Ammonia content in animal waste, kg/ha
BD	Soil bulk density, g/cm ³
BDF	Bulk density factor
BKN	Flow rate constant between soil nitrogen pools, kg/ha/d
BP	Coefficient
BSAT	Base saturation, %
C	Chemical concentration, µg/g
C1, C2	Empirical coefficients
C _{av}	Available chemical concentration in the soil, µg/g
CP	Coefficient, Julian date of the longest day of the year
C _s	Chemical concentration in the solid (soil) phase, µg/g
C _w	Chemical concentration in the solution (water) phase, mg/L
CACO3	Calcium carbonate content of the soil, µg/g
CCRD	Current crop rooting depth, cm
CF	Cover factor
CL	Clay content of the soil, %
CMN	Mineralization constant, kg/ha/d
CN	Concentration of nitrogen in crop biomass, %
CNH4S	Concentration of adsorbed ammonia on the soil, µg/g
CNH4W	Concentration of ammonia-nitrogen in the water, mg/L
CNHKD	Coefficient for partitioning ammonia on clay,
CNO3W	Concentration of nitrate-nitrogen in the water, mg/L
CNP	Carbon:nitrogen, carbon:phosphorus ratio of crop residue
CNR	Carbon:nitrogen ratio of crop residue
COVER	Soil cover, t/ha
CP	Concentration of phosphorus in crop biomass, %
CPLAB	Concentration of labile phosphorus in the soil, µg/g
CPLABW	Concentration of labile phosphorus in the water mg/L
CPR	Carbon:phosphorus ratio of crop residue
CV	Sum of crop residue on soil surface and above-ground crop biomass, t/ha
D	Depth of soil from the surface to the bottom of a soil layer, cm
DCR	Residue decay rate, kg/ha/d
DCRPR	Adjusted residue decay rate, kg/ha/d
DEMN	Daily optimum nitrogen demand of a crop, kg/ha
DEMP	Daily optimum phosphorus demand of a crop, kg/ha
DEP	Depth from soil surface to bottom of soil computational layer, m
DMNFAC	Nitrogen demand factor
DMPFAC	Phosphorus demand factor
DK	Active soil carbon decay rate, mg/g/d
DMR	Ratio of total dry matter to harvestable portion of crop
DNI	Denitrification, kg/ha
DT	Time increment when soil water exceeds field capacity, d
E _o	Potential evaporation, cm
E _p	Plant evaporation, cm
E _{pl}	Plant evaporation for limited soil water, cm
E _s	Soil evaporation, cm

E_{so}	Potential soil evaporation, cm
E_{tr}	Evapotranspiration for reference crop, mm/day
EL	Elevation, m
ELEV	Elevation above mean sea level, m
ER	Enrichment ratio of sediment
ET	Evapotranspiration, cm
EVAP	Depth of evaporation, cm
EVNH	Evaporation of ammonia-nitrogen, kg/ha
EVNO	Evaporation of nitrate-nitrogen, kg/ha
EVP	Evaporation of labile phosphorus, kg/ha
exp	Exponent or exponential function
F	Infiltration, cm
FC	Field capacity, volumetric water content at 10 or 33 kPa, cm/cm
FIXN	Nitrogen fixation, kg/ha
FON	Fresh organic (crop residue) nitrogen, kg/ha
FOP	Fresh organic (crop residue) phosphorus, kg/ha
FRACNH	Fraction of nitrogen immobilized as ammonia
FRACNO	Fraction of nitrogen immobilized as nitrate
FRES	Fresh crop residue, kg/ha
G_h	Heat flux density to the ground, MJ/m ² /day
H_o	Net solar radiation, gm-cal/cm ² /day
GRT	Crop growth ratio
K_1	Dimension coefficient
K_d	Partitioning coefficient between soil and water phases
K_s	Saturated conductivity, cm/h
LAT	Latitude, degrees
LAG	Lag coefficient
MN	Nitrogen mineralization (ammonification), kg/ha
MPR	Mineral phosphorus flow rate, kg/ha/d
ND	Number of days in the month
NIT	Nitrification, kg/ha
NPR	Nitrogen:phosphorus ratio in crop biomass
NWD	Number of wet days in the month
OF	Outflow of water from a soil layer, cm
OM	Organic matter content of soil, %
ORGNW	Organic nitrogen in animal waste, kg/ha
ORGPW	Organic phosphorus in animal waste, kg/ha
P	Atmospheric pressure, kPa
P_o	Atmospheric pressure at mean sea level
PCP	Precipitation depth, cm
PERC	Depth of water percolation, cm
PERCLP	Concentration of labile phosphorus in percolate, mg/L
PERCNH	Concentration of ammonia-nitrogen in percolate, mg/L
PERCNO	Concentration of nitrate-nitrogen in percolate, mg/L
PH	Soil pH
PLAB	Labile phosphorus mass in the soil, kg/ha
PLI	Labile phosphorus immobilization factor
PMINP	Active mineral phosphorus, kg/ha
PMN	Phosphorus mineralization from active mineral P, kg/ha
PMNAW	Phosphorus mineralization for animal waste
POR	Soil porosity, cm ³ /cm ³
POTLAI	Potential leaf area index for a crop, m ² /m ²
POTMN	Potentially mineralizable soil nitrogen, kg/ha
PRLPMS	Labile phosphorus mass in percolate, kg/ha
PRNHMS	Ammonia-nitrogen mass in percolate, kg/ha
PRNOMS	Nitrate-nitrogen mass in percolate, kg/ha
PSP	Phosphorus sorption coefficient
PY	Potential yield, kg/ha
Q	Runoff depth, cm
R	Total solar radiation, gm-cal/cm ² /day
R_b	Net out-going long-wave radiation, MJ/m ² /day

R_{bo}	Out-going (back) radiation on cloudless day, MJ ²
R_n	Net radiation, MJ/m ² /day
R_s	Observed daily radiation, MJ/m ²
RC	Residue composition factor
RCN	Concentration of nitrogen in rainfall, mg/L
RD	Effective root depth, m
RESDN	Nitrogen in crop residue on soil surface, kg/ha
RESDP	Phosphorus in crop residue on soil surface, kg/ha
RESDW	Crop residue mass on soil surface, kg/ha
RMN	Residue mineralization rate, kg/ha/d
RMP	Phosphorus mineralization from crop residue, kg/ha
RN	Nitrogen mass in rainfall, kg/ha
ROLP	Labile phosphorus in runoff, kg/ha
RON	Daily flow of nitrogen between mineralizable and stable soil nitrogen, kg/ha
RONH4	Ammonia-nitrogen in runoff, kg/ha
RONO3	Nitrate-nitrogen in runoff, kg/ha
RTN	Ratio of potentially mineralizable nitrogen to total soil nitrogen
SAT	Volumetric soil water content at saturation, cm/cm
SC	Active soil carbon for denitrification, mg/g
SCR	Scaling factor for air temperature range
SD	Soil depth function of damping depth
SDD	Soil temperature damping depth, m
SDF	Soil depth factor
SEDLP	Sediment associated labile phosphorus, kg/ha
SEDN	Total sediment-associated nitrogen, kg/ha
SEDMN	Sediment-associated mineralizable nitrogen, kg/ha
SEDMP	Sediment-associated mineralizable phosphorus, kg/ha
SEDNH	Sediment-associated ammonia, kg/ha
SEDON	Sediment-associated organic nitrogen, kg/ha
SEDOP	Sediment-associated organic phosphorus, kg/ha
SEDP	Total sediment-associated phosphorus, kg/ha
SEDSN	Sediment-associated stable soil nitrogen, kg/ha
SEDSP	Sediment-associated stable soil phosphorus, kg/ha
SFN	Stress factor for nitrogen deficiency
SM	Soil moisture depth, cm
SNO	Water-equivalent depth of snowpack, mm
SNO3	NO ₃ -N mass in the soil, kg/ha
SNOW	Snow cover factor
SOILMS	Soil mass, Mg/ha
SOILN	Stable soil nitrogen, kg/ha
SOILP	Stable soil phosphorus, kg/ha
SOLN	Soluble nitrate-nitrogen on the soil surface, kg/ha
SOLNH	Soluble ammonia-nitrogen on the soil surface, kg/ha
SOLP	Soluble phosphorus on the soil surface, kg/ha
SORGP	Soil organic humus phosphorus, kg/ha
ST	Soil water storage volume, cm
SUMLAI	Accumulated leaf area index, m ² /m ²
SW	Volumetric soil water content, cm/cm
SWC	Soil water content (depth), cm
SWFA	Soil water factor for ammonification
SWFD	Soil water factor for denitrification
SWFN	Soil water factor for nitrification
SWFT	Soil water factor for soil temperature
SY	Sediment yield, kg/ha
T	Soil temperature, EC
T_c	Temperature, EC
T_d	Dew point temperature, EC
T_k	Temperature, EK
T_n	Minimum temperature, EC
T_o	Absolute temperature, EK
T_x	Maximum temperature, EC

TANC	Minimum daily air temperature, EC
TAVGC	Mean annual air temperature, EC
TAXC	Maximum daily air temperature, EC
TBGC	Temperature bare ground, EC
TBGSDC	Temperature of bare ground surface on dry day, EC
TBGSWC	Temperature of bare ground surface on wet day, EC
TDM	Total dry matter, kg/ha
TDMN	Nitrogen in total dry matter, kg/ha
TDMP	Phosphorus in total dry matter, kg/ha
TF	Temperature factor
TFA	Temperature factor for ammonification
TFDN	Temperature factor for denitrification
TFN	Temperature factor for nitrification
TO	Temperature above 0EC
TR	Transpiration equivalent depth, cm
TRON	Total runoff loss of nitrogen, kg/ha
TSC	Soil temperature, EC
TSWC	Total soil water content of root depth, m
TUPN	Total adjusted uptake of nitrogen, kg/ha
U_{rh}	Wind speed at reference height, m/sec
U_z	Wind speed at height z, m/sec
UPFAC	Uptake factor for nitrogen
UPLP	Uptake of labile phosphorus, kg/ha
UPN	Uptake of nitrate- and ammonia-nitrogen, kg/ha
UPNH	Uptake of ammonia-nitrogen, kg/ha
UPNO	Uptake of nitrate-nitrogen, kg/ha
UPP	Total uptake of phosphorus, kg/ha
VOLN	Daily ammonia volatilization from animal waste, kg/ha
WIMN	Immobilization rate for nitrogen, kg/ha/d
WIMP	Immobilization rate for phosphorus, kg/ha/d
WM	Water mass (depth) in the soil, cm
WP	Volumetric soil water at wilting point (1500 kPa), cm/cm
YP	Yield potential for the harvestable portion of a crop, kg/ha
Z_{om}	Momentum roughness length, cm
Z_{ov}	Roughness length for heat and water vapor, cm
Z_p	Height of psychrometer and thermometer, cm
Z_w	Height of anemometer, cm
a	Subscript denoting air
c_{nfr}	Concentration of nitrogen in fresh residue, kg/kg
c_p	Specific heat of moist air at constant pressure, kJ EC/kg
c_{pfr}	Concentration of phosphorus in fresh residue, kg/kg
d	Subscript denoting day
d_c	Crop height parameter, cm
e	Exponent, 2.713
e_{z_o}	Saturation vapor pressure of air, kPa
e_z	Saturation vapor pressure of air at height z, kPa
exp	Exponent, 2.713
h_c	Crop height, cm
i	Subscript denoting computational soil layer
i	Subscript denoting initial condition
mo	Subscript denoting the number of the current month
ncl	Number of computational soil layers
nh	Subscript denoting ammonia
no	Subscript denoting nitrate
ntl	Number of transpiration layers
o	Subscript denoting initial time, t=0
p	Subscript denoting phosphorus
r_a	Diffusion resistance of the air layer, sec/m
r_{cc}	Crop canopy resistance, sec/m
rh	Reference height, cm
s	Subscript denoting surface

t	Time, (infiltration) hr, (time step) day
tt	Travel time of water through a soil layer, h
z	Height above ground, m
"	Adiabatic lapse rate
\$	Coefficient of extraction into surface runoff
\$ _{nh}	Coefficient of extraction for ammonia into surface runoff
\$ _p	Coefficient of extraction for phosphorus into surface runoff
) t	Time interval, h
F	Storage routing coefficient
F'	Constant, MJ/m ² /day/EK ⁴
T	Phosphorus flow coefficient
(Psychrometric constant, kPa/EC
(*	Psychrometric constant modified by the ratio of canopy resistance to atmospheric resistance, kPa/EC
)	Slope of saturation vapor pressure curve at the mean air temperature
)	Increment
,	Emmittance
8	Latent heat of vaporization, MJ/kg
D	Density of air, kg/cm ³

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