Development of a Continuous, Physically-Based, Distributed Parameter, Nonpoint Source Model
by
Faycal Bouracui

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APPROVED

Theo A. Dillaha III, Chairman

Conrad D. Heatwole Saied Mostaghimi

G. V. Loganathan J. W. Gilliam

John V. Perumpral

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Faycal Bouraoui

Theo A. Dillaha III, Chairman
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(ABSTRACT)

ANSWERS, an event-oriented, distributed parameter nonpoint source pollution model for simulating runoff and sediment transport was modified to develop a continuous nonpoint source model to simulate runoff, erosion, transport of dissolved and sediment-bound nutrients, and nutrient transformations. The model was developed for use by nonpoint source pollution managers to study the long-term effectiveness of best management practices (BMPs) in reducing runoff, sediment, and nutrient losses from agricultural watersheds.

The Holtan's infiltration equation used in the original version of ANSWERS was replaced by the physically-based Green-Ampt infiltration equation. Soil evaporation and plant transpiration were modeled separately using the Ritchie equation. If soil moisture exceeds field capacity, the model computes percolation based on the degree of soil saturation. Nutrient losses include nitrate, sediment-bound and dissolved ammonium, sediment-bound TKN, and sediment-bound and dissolved phosphorus. A linear equilibrium is assumed between dissolved and sediment-bound phases of ammonium and phosphorus. Nutrient loss is assumed to occur only from the upper cm of the soil profile.

The model simulates transformations and interactions between four nitrogen pools including stable organic N, active organic N, nitrate and ammonium. Transformations of nitrogen include mineralization simulated as a combination of ammonification and nitrification, denitrification, and plant uptake of ammonium and nitrate. The model maintains a dynamic equilibrium between stable and active organic N pools.

The model simulates transformations and interactions between four phosphorus pools including
stable mineral P, active mineral P, soil organic P and labile P. Transformation of phosphorus include mineralization from the organic P pool. An equilibrium is maintained between stable and active mineral P and between active mineral P and labile P. Plant uptake of labile P is also simulated.

The model was validated on two watersheds in Georgia, and performed well in predicting runoff, sediment, nitrate, dissolved ammonium, sediment-bound TKN, dissolved and sediment-bound phosphorus from both watershed. The model did not perform as well in predicting sediment-bound ammonium losses from either watershed. A validation was then conducted on a watershed in Virginia. The model performed well on the watershed in Virginia for the largest storms, and the cumulative prediction for runoff, sediment yield, nitrate, ammonium, sediment-bound TKN, and orthophosphorus were within 40% of the measured values.

A practical application of the model was then demonstrated. The model was run for eight years on a 200 ha watershed in Virginia. Potential critical area were selected, and best management practices were implemented using six different targeting schemes. Targeting was found to significantly increase the efficiency of BMPs application with respect to water quality. The model also showed that fields that had very high sediment and nutrient yields did not always have large impacts on yields at the watershed level. Targeting, therefore, must identify fields that not only have high sediment yields, but also high delivery functions.
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INTRODUCTION

Nonpoint source (NPS) pollution is the most significant source of water quality problems in the United States (USEPA, 1993). To control NPS pollution, state and federal agencies developed a variety of programs, but most, particularly those dealing with agricultural NPS pollution control, were voluntary. Adoption of voluntary NPS pollution measures has not been very effective and NPS pollution continues to be the Nation's primary source of impaired water quality (USEPA, 1993). In the past few years, Congress and the federal government have begun to promote regulatory approaches to NPS pollution control. The first major regulatory program was the Coastal Zone Act Reauthorization Amendments of 1990 (CZARA). This act, for the first time required states to develop enforceable NPS pollution control programs in coastal areas of the United States. Recently, Congress began work on a new Clean Water Act (CWA). According to USEPA Administrator Carol Browner, the most significant aspect of the new CWA will be regulations to control NPS pollution (Blankenship, 1994). Early indications are that the CWA will expand the NPS programs developed under CZARA to the rest of the Nation.

Voluntary NPS programs of the past and current and pending regulatory legislation rely heavily on the use of management measures or "Best Management Practices" (BMPs) to mitigate NPS pollution problems. Best management practices can be defined under CZARA as "economically achievable measures for the control of the addition of pollutants from existing and new categories and classes of NPS pollution, which reflect the greatest degree of pollutant reduction achievable through the application of the best available nonpoint pollution control practices, technologies, processes, siting criteria, operating methods, or other alternatives" (USEPA, 1993). These BMPs may be structural, but most are management oriented and are intended to minimize water quality problems while still permitting productive use of the land. The principal difficulty in selecting appropriate systems of BMPs for a particular site is that BMP effectiveness varies from site to site due to spatial and temporal variations in site specific conditions such as soils, topography, climate, and landuse. Thus, a system of BMPs may be very effective for controlling NPS pollution at one site but the same BMPs may be ineffective at another site (Dilaha, 1990). Consequently, if BMPs are to be used effectively for NPS pollution control, a means must be identified to estimate their effectiveness for site specific conditions. If not, inappropriate BMPs will be applied, NPS pollution will not be controlled and the limited resources available for NPS pollution control will
be wasted. This dissertation describes the development of a NPS planning model that may be used for estimating the site specific effectiveness of select agricultural BMPs in reducing sediment and nutrient loss from agricultural areas.

Nonpoint source pollution can be classified into two broad categories according to its origin: rural and urban. Rural NPS pollution is the result of human disturbance of existing ecosystems and the resultant release of sediments, pesticides, nutrients, and other pollutants. Disturbances include logging, mining, and agricultural activities. Urban NPS pollution is the result of industrial activities, transportation, litter, poor management of pesticides and fertilizers on lawns and gardens, septic tanks, etc. The principal NPS pollutants are sediments, nutrients, pesticides, bacteria, heavy metals, chemicals, and oxygen demanding organic wastes. The NPS pollutants causing the most widespread water quality problems are nutrients and sediments from agricultural and urban runoff (Blankenship, 1994).

All the areas of a given watershed do not contribute equally to NPS pollution. Numerous studies have indicated that, for many watersheds, a few critical areas are responsible for a disproportionate amount of the pollutant yield from the watershed. (Dillaha, 1990; Storm et al., 1988). Consequently, NPS pollution control resources should be targeted on these critical areas to maximize improvements in downstream water quality if funding is limited (Maas et al., 1985; Dickinson et al., 1990). Targeting funds for implementation of conservation and management practices on critical areas is physically effective and economically efficient, and allows the development of efficient strategies to reduce pollution at minimum cost. According to Dickinson et al. (1990), targeting NPS pollution resources has the potential to triple pollutant reduction, substantially reduce funding requirements, and minimize the extent of area affected negatively by restrictive land practices.

Efficient NPS pollution control planning not only requires the means to determine total pollutant loading, but also the means to identify the critical areas within watersheds or farms that are responsible for the largest off-site losses. With the increased use and development of personal computers, modeling of agricultural watersheds and the associated NPS pollution has become the accepted and standard technology to quantify NPS pollution. There are a number of available models that can be used to simulate the hydrological cycle and the transport of pollutants from
agricultural watersheds. Different types of models have been developed, ranging from simple equations to complex integrated models. The complex integrated models can be divided into two classes: lumped parameter and distributed parameter models.

Distributed parameter models have several major advantages over lumped parameter models for NPS pollution assessment. Their principal advantages are that they can more accurately represent the effects of spatial variability of watershed features, and that they can estimate pollutant losses at different locations within the watershed. The major disadvantage of distributed parameter models is that their data requirements are higher and their use is often associated with time consuming data collection and large computer memory requirements and execution times.

Only a few distributed parameter watershed scale models are available for NPS modeling. These include ANSWERS (Huggins and Monke, 1966; Dillaha and Beasley, 1983), FESHM (Ross et al., 1982) and AGNPS (Young et al., 1987). AGNPS is probably the most widely used distributed parameter NPS model. It has a good user’s manual and user support is provided the USDA-ARS. AGNPS is a distributed parameter, event-oriented, watershed scale model developed to simulate runoff, sediment and erosion, nitrogen and phosphorus losses from agricultural watersheds. AGNPS uses empirical equations to model runoff (SCS curve number approach) and erosion (modified USLE). The use of the curve number limits the ability of the model to simulate the impact of different BMP’s on runoff, sediment and nutrient losses. FESHM is a distributed parameter, physically-based, event-oriented, watershed scale model, developed to simulate runoff, erosion and sediment transport from ungaged watersheds. ANSWERS is a watershed scale, distributed parameter, event-oriented, physically-based model, developed to predict runoff, erosion and sediment transport from ungaged watersheds. Both FESHM and ANSWERS models use the empirical Holtan’s equation to model infiltration. FESHM has received very limited validation, while ANSWERS has been validated for many conditions and used successfully for best management practice evaluation (Amin Sichani, 1982; Storm et al., 1988; Thomas and Beasley, 1986; DeRoo et al., 1992). All three distributed parameter models are event-oriented and can not be used to simulate the long-term effectiveness of BMPs for NPS pollution control. Furthermore, the existing versions of FESHM and ANSWERS do not simulate nutrient transport and fate.

There are currently no continuous simulation, physically-based, distributed parameter, NPS
watershed models available for evaluating the long-term effectiveness of BMPs for NPS pollution control. Effective simulation of the spatial and temporal variability of NPS pollution; delineation of critical areas; and assessment of the long-term effectiveness of BMPs for NPS pollutant reduction in ungaged watersheds would be greatly facilitated by the use of a distributed parameter, continuous simulation model. The development of such a model was the goal of this research.

OBJECTIVES

The overall goal of this research was to develop a long-term, continuous simulation, physically-based, distributed parameter watershed model for evaluating the effectiveness of select BMPs in reducing losses of sediment and nutrients from agricultural watersheds. The specific objectives of this research were to:

1) Select an existing distributed parameter watershed model to serve as a basis for the development of a long-term, continuous simulation, physically-based, distributed parameter watershed model for NPS pollution assessment.

2) Incorporate a physically-based infiltration model into the selected distributed parameter model to better represent the effects of BMPs on infiltration and runoff.

3) Develop a phosphorus transport and fate model for the NPS assessment model to simulate dissolved and sediment-bound inorganic phosphorus transport.

4) Develop a nitrogen transport and fate model for the NPS assessment model to simulate dissolved nitrate and ammonium transport and sediment-bound organic nitrogen and ammonium transport.

5) Convert the selected NPS assessment model into a long-term, continuous simulation model by incorporating crop growth, soil moisture and evapotranspiration components into the model.

6) Investigate the sensitivity of the model’s output to newly incorporated model
parameters to identify those model parameters requiring the most careful estimation.

7) Validate the model by comparing its predictions of runoff and sediment and nutrient losses with measured data from field and watershed scale studies.

8) Demonstrate the use of the model for NPS planning on a watershed scale.
LITERATURE REVIEW

MODELING NONPOINT SOURCE POLLUTION

INTRODUCTION

Nonpoint source pollution has emerged as a environmental priority and efforts are focusing on developing methods to quantify and determine pollutant loadings and the effects of NPS pollution. Since NPS pollution includes several interrelated processes, an integrated modeling approach is necessary. Novotny (1986), divided the history of hydrologic NPS modeling into four periods.

The first period, the "precomputer age", covered the first half of the century. During this period, many mathematical models were formulated. These included empirical equations (Horton, 1940) as well as physically-based models such as the Green-Ampt infiltration equation (Green and Ampt, 1911). In the 1950's and 1960's, the SCS curve number method for determining runoff (Soil Conservation Service, 1956), and the Universal Soil Loss Equation (USLE) (Wishmeier and Smith, 1978) were developed.

The second period, which covers the 1960's, witnessed the development of computer models (Novotny, 1986). Many people look upon this period as the golden age of hydrology. Due to the expense of computers at the time, only a few universities and agencies developed and used computer models. The Stanford Watershed model, developed by Crawford and Linsley in 1966, was one of the first comprehensive hydrologic models and was later used as the basis for many other hydrologic models.

As the computing costs decreased and computers became more widely available, a new generation of models were developed to assess and quantify NPS pollution. ANSWERS (Beasley et al., 1980), ACTMO (Frere et al., 1975), NPS (Donigian and Crawford, 1976), ARM (Donigian and Davis, 1978), and CREAMS (Knisel, 1980) are among the models developed during the model generation period, which corresponds roughly to the 1970's. Novotny indicates that the success of these early models was limited.
The last or current period, the implementation period, corresponds to the age of inexpensive microcomputers. During this period, few new models have been developed and the focus has been on adapting existing models for personal computers and work stations. The latest trend in NPS modeling is the integration of available models with knowledge-based and geographical information systems to produce models with enhanced capabilities regarding input generation, data manipulation and acquisition, and graphical display of output.

MODELING AND NONPOINT SOURCE POLLUTION

Modeling is defined by Wight (1988) as the process of organizing, synthesizing, and integrating component parts into a realistic representation of the prototype. The importance of modeling has been recognized by the USDA, and in an effort to justify the use of models, USDA (1978) lists the following benefits of modeling:

- Models help sharpen the definition of hypotheses,
- Models help define and categorize the state of knowledge,
- Models provide an analytical mechanism for studying the system of interest,
- Models can be used to simulate experiments instead of conducting the experiments on the watershed itself,
- Models can be used to plan efficient experiments,
- Models provide a key for determining the progress of research,
- Models provide a method for disseminating information, and
- Models can be used for prediction.

Furthermore, models are useful tools that increase the level of understanding, and provide information and direction for future research. Models also allow long time frame systems to be studied in compressed time, or alternatively, to study in expanded time the system of interest (Law and Kelton, 1982). Models also allow better control of the experimental conditions than is possible with real life experiments. Furthermore, models allow the study of a system without disturbing it (Law and Kelton, 1982).

states that:

- models are sophisticated tools for water resources analyses,
- models improve the informational background necessary for decision making, and
- models are also an inexpensive and efficient management technique.

Models can be used to analyze management alternatives economically. According to DeCoursey (1985), hydrologic models can be used in watershed research programs to:

- "structure data collection,
- study site response,
- select and evaluate parameters,
- determine the accuracy in evaluating input variables and parameters, and
- study the significance of spatial and temporal variability of physical features".

Models can be categorized into three classes:

- empirical models,
- conceptual models, and
- physical models.

Empirical models or black box models contain non physically-based transfer functions to transform input data to output data. These models are often referred to as cause and effect models where the physical processes taking place are not simulated. This type of model is relatively simple, requires little data and can be used for extrapolation. But it is important to note that extrapolating beyond the range of available information especially for outlier, or extreme events, may lead to highly erroneous results.

Conceptual models can be defined as semi-physical models since they simulate physical processes using major simplifications. Each physical component of the system or process is modeled in a simplified manner. This approach is used when information or general knowledge of the processes taking place is lacking.

Physically-based models try to simulate the internal mechanisms of the system using a theoretical approach without using major simplifications. These models use physical parameters that can be
either measured or determined using appropriate equations. Thus, in theory this type of model does not require calibration.

LUMPED AND DISTRIBUTED MODELS

Nonpoint source models are usually divided into screening models and hydrologic assessment models (Novotny, 1986). Screening models are used to identify critical areas that contribute the most to the total loading of pollutants. The models used in screening analysis give only a general approximation of the pollution problem. The uncertainty of output associated with this type of models is large and the accuracy is typically around an order of magnitude. Site specific hydrologic assessment models simulate the actual conditions of a watershed without as many restrictive assumptions as are used in screening type models. The accuracy of hydrologic assessment models are typically within factor of two to ten. Hydrological assessment models are further divided into lumped and distributed models.

Lumped Models
Lumping is often associated with averaging. The modeling of a catchment using a lumped approach can be done by using the dimensions of depth and time. Spatial variation of rainfall, topography, management practices, soil types, etc, is assumed to have no influence on the catchment response for a given rainfall event. The whole catchment is assumed to be homogeneous, and all the potential variations are lumped (averaged) together. Thus, the degree of accuracy of the model is expected to vary with the degree of non homogeneity of the catchment (Huggins and Monke, 1966). Lumped models provide a unique output for the whole watershed. They do not provide any information regarding the spatial behavior of the outputs. Lumped models usually use empirical equations and may require historical data for calibration.

Distributed Models
Distributed models take into account the spatial variability of watershed characteristics. Distributed models discretize the watershed into units which are assumed homogeneous. All the hydrologic, climatic and management parameters are assumed homogeneous within each cell, but may vary from cell to cell. The dynamics of the simulated processes are then described at each point within the watershed, and the outputs from each cell are routed to the watershed outlet. For
additional information regarding distributed models, the reader is referred to Beven (1985).

**Distributed Models Versus Lumped Models**

Lumped models often require calibration using historic data, fitting, and averaging of the input. The process of calibration makes the use of lumped models site specific and reduces their transferability to other watersheds (Beven, 1985).

Distributed models provide output at the watershed outlet and at any desired location within the watershed. Distributed models can be used to identify critical areas most to NPS pollution. Distributed models are attractive for NPS modeling, however their use presents some disadvantages. Distributed models require considerable computer resources, and extensive data collection and preparation (Baun et al., 1986, Storm et al., 1988). Validation is desirable at both the watershed and cell level, but data to validate at the cell level is seldom available.

**Event-Based and Continuous Models**

Hydrologic assessment models are further divided into continuous and event-based models. Event-based models are used to assess the impact of management practices on water quality for specific design storms. Continuous models are used to determine the long-term impact of management scenario alternatives on water quality. Event-based models do not have to simulate crop growth and evapotranspiration. However, they require initial estimates of soil moisture, nutrient concentration and cover conditions. Errors in these initial estimates can result in significant errors in model output.

**Model Selection**

The primary goal involved with model selection is the definition of the problem to be addressed, and the determination of the potential models that could be used to simulate the desired processes. Additional consideration include data availability, accuracy of the output required and the marginal cost of different models (is it worth spending additional time using distributed models for the additional accuracy gained?). Assumptions and limitations should always be taken into consideration during model selection. Previous model validation and study results should play a key role in determining which model to use.
EXISTING NONPOINT SOURCE MODELS

ACTMO
The Agricultural Transport Model (Frere et al., 1975) is a continuous model that can be applied to agricultural watersheds with one or more catchments. ACTMO was developed primarily for the analysis of agricultural fertilizers and pesticides. The three-dimensional discretization of the watershed used by ACTMO limits its applicability to small watersheds. The hydrologic model used is that of USDAHL-74 (Holtan, 1975). It computes infiltration, runoff, interflow, evapotranspiration, snowmelt, and snow accumulation. The USLE is used to estimate erosion. Both rill and interrill erosion are simulated but sedimentation is not allowed in channels. The model divides the chemicals into adsorbed and dissolved phases using a linear isotherm. The model is not currently supported or commonly used.

FEHSM
The Finite Element Storm Hydrograph Model (Judah, 1973; Ross, 1975, 1978) is a distributed parameter, event-oriented, watershed scale model. The model discretizes the watershed into homogeneous hydrologic response units. The model was developed to predict flow from ungaged areas and then was updated to include erosion and sediment transport processes. The hydrology component includes two parts. The first part determines the precipitation excess based on the Holtan (1961) infiltration equation. The second part routes the precipitation excess along overland flow and channel flow elements using an approximation of the kinematic wave theory. The erosion component considers detachment by raindrop impact and detachment due to overland flow using an approach developed by Beasley (1977). The model simulates the transport of different particle size classes. The model does not consider sedimentation in stream channels and does not include a nutrient component. The model is not supported and has not been widely used for NPS planning.

ARM
Agricultural Runoff Management Model (Davis and Donigian, 1979; Donigian, 1976; Donigian and Davis, 1978) is a continuous lumped model that was developed to predict pollutant losses from agricultural areas. It includes four major components: hydrology, erosion, nutrient, and pesticide transport. The model does not incorporate channel routing and, thus, should not be used.
on areas larger than 5 km². The hydrologic model used was derived from the Stanford Watershed Model (Crawford and Linsley, 1966). It includes interception, runoff, snowmelt, groundwater and interflow. The model requires two years of historic data to conduct the required calibration. Erosion and sediment transport are computed using Negev’s equations. Pollutant degradation is described using first order decay equations and the model simulates both sediment-bound and dissolved nitrogen and phosphorus.

NPS
The NonPoint Source (NPS) model (Donigian and Crawford, 1976) is a field-scale, continuous model. It was developed to simulate nonpoint source loads from urban and rural areas. It includes three major components: hydrology, erosion, and nonpoint source pollutant loads. The hydrologic runoff portion of the model is that of the Stanford Watershed Model (Crawford and Linsley, 1966). The model does not include channel routing, thus its use should be limited to areas less than 5 km². Three to five years of historic data are required to calibrate the model. Pollutant loading is estimated using potency factors.

CREAMS
The Chemical, Runoff, and Erosion from Agricultural Management Systems (Knisel, 1980) is a continuous, field-scale model applicable to homogeneous areas. It was developed to estimate pollutant loadings from agricultural fields. The CREAMS model consists of three major components: hydrology, erosion/sedimentation, and chemistry. The hydrology component estimates runoff volume and peak rate, infiltration, evapotranspiration, and percolation. CREAMS offers two options to determine runoff: the SCS curve number method when only daily rainfall data is available, and the Green-Ampt (Green and Ampt, 1911) infiltration approach when breakpoint rainfall data is available. Soil detachment is based on the modified USLE equation (MUSLE). The nutrient submodel considers both sediment-bound and dissolved nutrients. Dissolved nutrient loss is determined using an extraction coefficient. Dissolved nutrients are lost only from the upper centimeter of soil. Sediment-bound nutrient loss is determined using an enrichment ratio. CREAMS has an excellent users manual and was supported until recently by the USDA-ARS. CREAMS has been used extensively in NPS modeling studies.

LITERATURE REVIEW
**HSPF**

The Hydrological Simulation Program Fortran (Johanson et al., 1984) is a continuous, lumped, watershed scale model. It was developed to simulate the hydrology, erosion, sediment transport, nutrient and pesticide movement, salts, dissolved oxygen, from both urban and rural areas. The model allows the division of the watershed into land segments of uniform characteristics. The model uses a version of the Stanford Watershed Model (Crawford and Linsley, 1966) to simulate surface flow, subsurface flow and interflow. The model takes into account snow accumulation and snowmelt. The chemical and erosion components are identical to those described in the ARM section. HSPF requires between 3 and 5 years of historic data for calibration. Good model documentation and users manuals are available. The model is supported by the U.S. EPA. HSPF is one of the most difficult NPS models to learn but is still one of the most commonly used models for NPS planning.

**EPIC**

The Erosion Productivity Impact Calculator (Williams et al., 1983; Sharpley and Williams, 1990) is a field scale (1 ha), continuous simulation model. It was developed to determine the effects of soil erosion on soil productivity throughout the United States. The model includes hydrologic, erosion and sedimentation, plant growth and nutrient cycling components. Runoff is estimated using the SCS curve number method. Erosion is based on the Modified USLE (Williams, 1975). The EPIC model simulates nitrogen and phosphorus cycles. Dissolved nutrients are lost only from the top centimeter of the soil profile. Sediment-bound nutrient losses are determined using loading functions. EPIC and its submodels are commonly used for NPS planning purposes and user support is provided by the USDA-ARS.

**AGNPS**

Agricultural Non-Point-Source Pollution Model (AGNPS) (Young et al., 1987) is a distributed parameter, event-oriented, watershed scale model. AGNPS was developed to simulate runoff, erosion and sediment, nitrogen, phosphorus, and chemical oxygen demand (COD) losses from agricultural watersheds in Minnesota. AGNPS has also been used successfully in other states. Runoff is computed using the SCS curve number method. The upland erosion is computed using the modified USLE equation. The nutrient transport component is similar to that in CREAMS (Frete et al., 1980).
GLEAMS
The Groundwater Loading Effects of Agricultural Management Systems (Leonard et al., 1987) is a field-scale model based on the CREAMS model. The original model was developed to predict pesticides losses, but nutrient transport and transformations were later added (Knisel et al., 1993). The hydrology and sediment subroutines in GLEAMS were taken from the CREAMS model. Sediment-bound and dissolved nutrient losses are determined using a partition coefficient. Dissolved nutrient losses are assumed to occur from the upper centimeter of the soil profile. The nutrient model is based on the EPIC model (Sharpley and Williams, 1990). GLEAMS is widely used for NPS planning and user support is provided by the USDA-ARS.

SHE
The System Hydrologique Europeen (Abbott et al., 1986) is a distributed parameter, physically-based, continuous watershed scale model. The model discretizes the watershed into an orthogonal grid network. The model simulates snowmelt, evapotranspiration, overland and channel flow, unsaturated and saturated subsurface flow. Overland and channel flow are simulated using a simplification of the St. Venant equations, unsaturated flow is simulated using Richards equation, and the saturated flow is represented by a two-dimensional Boussinesq equation. The SHE model requires considerable computing resources.

ANSWERS
The Areal Nonpoint Source Watershed Environmental Response Simulation, ANSWERS, (Beasley et al., 1982) is a watershed scale, distributed parameter, event-oriented, physically-based model. ANSWERS was developed to simulate the impacts of watershed management practices on runoff and sediment loss. The original model (Huggins and Monke, 1966) included surface water hydrology only. The model was expanded to include erosion and sediment transport by Beasley et al. (1980). The sediment transport model was later updated to simulate sediment detachment and transport of mixed particle sizes (Dillaha and Beasley, 1983). Other researchers then added phosphorus (P) transport components (Amin Sichani, 1982; Storm et al., 1988), and an attempt to incorporate nitrogen (N) transport was also made (Dillaha et al., 1988).

The ANSWERS model was first validated on the Black Creek watershed in Indiana (Beasley et al., 1980; 1982). In these studies, the model's output, including runoff and sediment yield,
compared favorably with measured runoff and sediment yields. In later research, it was found that the USLE and ANSWERS predictions in estimating soil loss, on topographically nonuniform field and farm units, although different, were comparable considering the different approaches taken by the two models (Griffin et al., 1988). In another study ANSWERS was found to be in good agreement with measured runoff and sediment yield from two small watersheds in Iowa (Park et al., 1982). The P transport component developed by Amin Sichani (1982) was validated successfully with data from the Black Creek watershed. Storm et al. (1988) developed a similar P transport model that was validated successfully on experimental plots in Virginia.

The ANSWERS model has also been modified to simulate forest hydrology (Thomas and Beasley, 1986). The model was tested successfully on forested watersheds in Mississippi and North Carolina. The model did not perform well for watersheds with high baseflow. This is expected since the model, being event-oriented, is not designed to predict baseflow. The ANSWERS model was used in Nebraska to study the influence of best management practices (BMP's) on the hydrologic response of a 2046 hectare agricultural watershed (Razavian, 1990). The watershed was divided into 1,135 elements, calibrated for one rainfall event and validated successfully for two additional events.

A study conducted by the Wisconsin Department of Planning (Baun et al., 1986) reported that ANSWERS poorly represented runoff and sediment yield from very large watersheds in Wisconsin. The sediment transport algorithm was reported to be unresponsive to changes in land cover and distance of overland flow and the report suggested that ANSWERS was impractical for large watersheds. A review of the Wisconsin study, however, reveals that the authors attempted to apply the ANSWERS model to conditions for which it was not developed ie. heterogeneous 16 hectare cells. ANSWERS' developers state that the model should only be used with cells with uniform soils and landuse and cell sizes of one hectare or less are generally recommended. Larger cell sizes violate the basic assumptions of the model and cause problems with the numerical solution technique used to simulate overland flow.

The ANSWERS model was also tested successfully in Australia (Connolly et al., 1991; Silbum et al., 1990), although some modifications were required to better simulate infiltration in Australia soils. The ANSWERS model was used with Monte Carlo procedures to evaluate the impact of

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spatial variability of the infiltration parameters on the predicted runoff and erosion on a watershed in the Netherlands (De Roo et al., 1992). The author found that storms of low intensities were more difficult to simulate than storms with high intensities. This is understandable since ANSWERS was developed to simulate runoff for extreme events.

Of the reviewed models, ANSWERS is the only model well suited for evaluation of BMP’s on watershed scale because it is a distributed model and it can be used to simulate the spatial variability of a watershed, and because it does not rely on the curve number to simulate runoff. It can simulate the response of each cell to different cover conditions and management practices. Furthermore, the structured approach used in the development of the model facilitates the incorporation of new components. In addition, the ANSWERS model has been subjected to extensive validation and has been found to work for different management practices and climatic conditions. Furthermore, ANSWERS uses a process oriented infiltration equation which uses rainfall intensity as an input. Thus, the incorporation of a physically-based infiltration equation that uses breakpoint rainfall data is more appropriate in the ANSWERS model, which was designed to be sensitive to rainfall intensity and which allows the use of small time step rather than a daily time step.

NITROGEN

Nitrogen (N) is an important plant nutrient and is required by non-leguminous plants in larger amounts than other nutrients. It is one of the four major constituents of proteins (carbon, hydrogen, oxygen, and nitrogen). The concentration of N in the soils ranges from 0.07 to 0.3%, or about 1500 to 6000 kg/ha in the top 15 cm of soil (Novotny and Chester, 1981). Sources of N include microbial and chemical reactions, geological weathering, and precipitation. Atmospheric contribution of N ranges between 6 and 11 kg/ha per year (Van Der Leeden, 1990). Nitrogen can be present in either organic or inorganic forms and in either dissolved or particulate forms. Most soil N is in the organic form (90%) and is composed of humic, fulvic, amino, and nucleic acids and amino sugars. The organic N that is not available to plants is present principally in a particulate form.

The inorganic forms of N include nitrate (NO$_3^-$), nitrite (NO$_2^-$), exchangeable ammonium (NH$_4^+$),
fixed ammonium, and N gases (N₂, NOₓ). Nitrate and ammonium (in its exchangeable form), are available to plants and can be lost through leaching. Nitrate and nitrite are usually dissolved in the soil water. Since nitrite is usually present in minute quantities in most soils and accumulates only under anaerobic conditions, it is often neglected in soil N models. Under most conditions, nitrite is almost instantaneously transformed to nitrate. The recommended maximum concentration of nitrate in drinking water is 10 mg/L. The fixation of ammonium occurs when certain cations of clay minerals with expanding lattices such as montmorillonite are replaced by the NH₄⁺ ion. Fixed ammonium is not available for plant uptake and represents most of the inorganic N present in the soil.

Almost all soil N is present as organic matter or is sorbed by clays in the case of ammonium. The major means of N loss are plant harvesting, erosion and leaching of nitrate. Sediment-bound N is transported mainly by finer soil particles. Dissolved N, principally nitrate, is lost mainly through percolation during extremely wet months. Dissolved N losses may be very high in agricultural areas with subsurface tile drainage (Bottcher, 1981). The following sections will briefly describe the major processes involved in the N cycle.

NITROGEN CYCLE

A summary of the processes involved in the N cycle are given in Figure 1. According to Keeney (1983) the key biological transformations of N are:

- Immobilization,
- Ammonification,
- Nitrification,
- Denitrification, and
- Nitrogen fixation.

The major chemical transformations involving N include:

- Volatilization,
- Ammonium exchange,
- Ammonium fixation, and
- Chemical denitrification.
Figure 1. Flow chart for the nitrogen cycle (adapted from Keeney, 1983).
Ammonification and Nitrification

A dynamic equilibrium exists between organic and inorganic forms of N. Mineralization is the transformation of organic N to mineral N (NH$_4^+$, NO$_3^-$, and NO$_2^-$). Immobilization is the reverse process. Net mineralization, which is defined as the amount of mineralized N minus the immobilized N, varies between 2 and 4 % of the total soil N (Bartholomew. 1965). Mineralization is the result of two consecutive processes: ammonification and nitrification. The ammonification process controls the mineralization rate. Ammonification is the process by which organic N is transformed to NH$_4^+$. Nitrification is the oxidation of ammonium to nitrite and nitrate.

Novotny and Chester (1981), reported three different mechanisms to produce ammonium from organic N. These include:

- chemically or biologically from extracellular organic N compounds (urea),
- from living cell matter during endogenous respiration, and
- from dead and lysed cells.

Nitrification is a key process in the N cycle because it transforms relatively immobile ammonium into easily leached nitrates. Nitrification occurs only under aerobic conditions. The nitrification process occurs in two stages and can be summarized as follows:

\[
\text{(organicN} \rightarrow) \quad \text{NH}_4^+ \rightarrow \text{NO}_2^- \rightarrow \text{NO}_3^-
\]

(1)

During the first step, chemoautotroph bacteria, *Nitrosomas*, transform the ammonium into nitrite. *Nitrobacter* bacteria then rapidly convert the nitrite to nitrate. Since the conversion of nitrite to nitrate is faster than the transformation of ammonium to nitrite, little or no nitrite accumulates, except under high pH conditions (Alexander, 1965). The overall nitrification process generates 2H$^+$ per N, which may lead to acidification under certain conditions. High levels of nitrite have been reported in alkaline soils (Sprent, 1987). The optimal temperature for nitrification is around 22°C, and this process ceases at temperatures above 45°C and below 10°C (Zanoni, 1969). Other factors affecting the nitrification process include soil pH and moisture.
Immobilization

Immobilization is the reverse reaction of mineralization. It is the transformation and assimilation of inorganic N (ammonium and nitrate) by plants and microorganisms to organic N compounds. The ammonium ion is immobilized preferentially to nitrate ion (Broadbent, 1968). The amount of N available at any time is a function of the reaction rate of the two opposite processes, immobilization and mineralization. The factors affecting the amount of net mineralized N include temperature, type of substrate, moisture and aeration status. Keeney (1983), citing Bartholomew (1965) and Black (1968), states that during the decomposition of organic materials, the C/N ratio controls the net mineralization rate. For high C/N ratios, the organic matter is carbonaceous, and there is more energy for growth than N for synthesis, resulting in net immobilization for an extended period of time. Conversely, proteinaceous materials (low C/N) are associated with rapid net mineralization. Microbial degradation of residue, continues until the C/N reaches that of organic matter which is around 10.

Denitrification

Denitrification is the reduction of NO$_3^-$ or NO$_2^-$ to gaseous N compounds including N$_2$, O and N$_2$, mainly N$_2$. This process occurs under anaerobic conditions (i.e. limited oxygen supply). Nitrate and nitrite act as terminal electron acceptors. In addition to the presence of water, organic matter is necessary, as a source of electrons and energy for denitrification to occur. This process is accomplished by heterotrophic bacteria (bacteria obtaining food primarily from organic matter) and occurs in soils with low hydraulic conductivity, or during extended saturation periods. This process occurs over a wide range of temperatures and pH. The complete reduction of 2NO$_3^-$ to N$_2$ generates 2OH$^-$ ions, which may increase soil pH. Even in non saturated soils, anaerobic conditions may prevail in some microsites, thus supporting denitrification (Sprent, 1987).

Nitrogen Fixation

Nitrogen fixation is defined as the reduction of N$_2$ to NH$_3$, which is used quickly in the synthesis of organic N compounds. The enzymatic complex involved with the biological fixation is nitrogenase. The reaction leading to nitrogen fixation involves the simultaneous reductions of N gas and protons and can be described by:
\[ 8 \text{H}^+ + \text{N}_2 \rightarrow 2 \text{NH}_3 + \text{H}_2 \]

Nitrogen fixers obtain energy from either organic matter or photosynthesis by a host plant. Fixation rates are usually small, but higher rates are possible, especially when the nitrogen-fixing bacteria operate in symbiosis with plants (Singer and Munns, 1991). Most of N fixation involves legumes nodulated by \textit{Rhizobium} and non-legumes nodulated by \textit{Frankia}. Singer and Munns (1991) state that the symbiotic associations are effective for three reasons: 1) the plant provides ample energy through photosynthesis, 2) the plant assimilates ammonium that would otherwise inhibit fixation, and 3) root nodules provide suitable conditions including protection from free oxygen.

\textbf{Volatilization}

Ammonia volatilization is the transformation of \( \text{NH}_4^+ \) to gaseous ammonia (\( \text{NH}_3 \)). The gaseous ammonia is then released to the atmosphere. The volatilization process is controlled by the differences in pressures of soil ammonia and air ammonia. The process of volatilization can be represented as:

\[ \text{NH}_4^+ + \text{OH}^- \rightarrow \text{NH}_3 + \text{H}_2\text{O} \]

The previous reaction shows that the volatilization process is accompanied by soil acidification. Factors affecting the volatilization process include pH, temperature and cation exchange capacity, and all other factors affecting ammonium concentration in the soil. When ammonia is applied as fertilizer, the form of ammonia applied and the method of application will affect the volatilization rate.

\textbf{Chemical Denitrification}

Chemical denitrification or chemodenitrification is the reaction of \( \text{NO}_3^- \) with soil constituents at acid pH or high temperature to produce \( \text{N}_2 \). Some experiments conducted by Smith and Chalk (1980) have shown that chemodenitrification is not only limited to acidic soils, but can also occur at pH higher than 7.5.

\textbf{Ammonium Fixation}

Ammonium fixation is the process by which ammonium is trapped between the layers of
expending minerals such as montmorillonite. This form of N is not exchangeable and is unavailable to plants (Haynes et al., 1986).

**Ammonium Exchange**
Ammonium, being positively charged, can be adsorbed to clay and organic matter by the process of cation exchange. This process is reversible and results in an equilibrium between NH$_4^+$ adsorbed to clays and organic matter and NH$_4^+$ present in soil solution.

**Factors Influencing Nitrogen Transformation**
Soil moisture, soil temperature, aeration, pH and cation exchange capacity are among the many factors affecting the N cycle. All reactions involving N affect ambient pH because different forms of N carry different electric charges. In return, pH also affects the rate of N transformation. Denitrification rates are optimum between pH's of 7 and 8. But the process continues up to a pH as high as 11, however denitrification ceases when pH drops below 3.5. An increase in pH results in an increase in volatilization. Optimum nitrification occurs at temperature around 22 °C (Zanoni, 1969), while N fixation is optimum between 10 and 15 °C (Sprent, 1987). An increase in temperature results in an increase of volatilization. Volatilization is also greatly affected by soil moisture. Soil moisture affects ammonium concentration, which in turn controls volatilization rates. Nitrification rates are more affected by water stress than mineralization rate, thus increased levels of ammonium can be observed during the early stages of soil drying (Sprent, 1987).

**NITROGEN TRANSPORT**

**Loss of Nitrogen through Runoff**
Most of the N leaving watersheds through surface runoff is attached to finer soil particles. Novotny and Chester (1981) reported enrichment ratios for organic N or N adsorbed onto organic matter ranging from 2 to 4. These enrichment ratios are similar to those of the enrichment ratio for organic matter. Menzel (1980) found enrichment ratios varying from 2.5 to 7.5. Surface runoff also contains dissolved forms of N including NH$_4^+$ and NO$_3^-$.

**Leaching of Nitrogen**
Seepage or the loss of N through leaching is a major pathway for available N loss from...
agricultural areas. There are three major processes involved with the transport of nitrate through the soil profile:

- convection or bulk flow which results in the movement of dissolved substances with the flow of water,
- molecular diffusion which results in the movement of nitrate due to the concentration gradient, and
- hydrodynamic dispersion in the soil due to the heterogeneity and internal structure of the soil.

Factors Influencing Nitrogen Losses

The key to control N loss is better N management. According to Keeney (1983), excessive accumulation of N in ground and surface waters, and excessive loss on NH₃ or N₂O to the atmosphere occur when the natural capacity of a system to cycle N is exceeded. Among the means to reduce N pollution is the implementation of best management practices (BMP's). Among those, Keeney (1983) notes that soil conservation practices are very effective because limiting erosion will reduce particulate organic N loss. A second category of BMP's is related to water conservation. Increasing water use efficiency will limit the potential transport of nitrate to the ground water by limiting deep percolation. No-till has been proven useful in reducing mineralization and production of nitrate, as well as limiting erosion between cropping seasons (Sprent, 1987). However, conservation tillage practices are often associated with an increased use of herbicides and surface applied chemicals (D'Itri, 1985). A third category mentioned by Keeney (1983) includes cropping sequence and cover crops. Appropriate and well planned rotations will limit the amount of N required to grow crops. Using cover crops after harvesting reduces erosion and also allows the uptake of additional N, which otherwise could be lost through leaching or erosion.

Split application of N, where the amount of fertilizer applied is directly related to the amount required by the crop can reduce the amount of fertilizer used. Sprent (1987) criticizes the use of fertilizer in the autumn in temperate climates, because nitrification continues over the winter. Then, during the spring, warm moist soils are subject to nitrate leaching and denitrification. Keeney (1983) also mentions the use of slow release fertilizers to limit N pollution. Slow release fertilizers limit the amount of N lost through volatilization, leaching and denitrification. Fertilizer
placement also exhibits advantages in controlling N pollution. Application of urea to the soil surface may result in large losses of gaseous NH₃. Additional BMP's include foliar application of fertilizer and the use of nitrification and urease inhibitors. Much of the N fertilizer used in the U.S. is in the form of urea. Plants can uptake urea, but urea uptake is generally limited due to the presence of the urease enzyme. Urease causes the hydrolysis of urea and produces ammonia, which can be lost through volatilization. Volatilization losses can be reduced by the use of urease inhibitors. Nitrification inhibitors can also be used to reduce nitrification, and thus limiting nitrate leaching (Sprint, 1987). Reducing nitrate leaching can also be achieved through the use of legumes and other nitrogen fixing plants (Sprint, 1987). However leguminous plants have high mineralization rates upon death which may cause a surge of nitrate in leachate. If more nitrogen is removed with the crop during harvest than was fixed during the growing season, there will be a net loss of soil nitrogen. This deficit in nitrogen may accentuated by the net immobilization resulting from the high C:N ratio of residues (Sprint, 1987).

NITROGEN TRANSFORMATION MODELING

Several models have been developed to describe the N cycle (Dutt et al., 1970; Dutt et al., 1972; Mehran and Tanji, 1974; Duffy, 1975; Frissel and Van Veen, 1978; Watts and Hanks, 1978). A more extensive list of the models developed to describe the N cycle is given by Tanji (1982).

Dutt Model

The Dutt model (Dutt et al., 1972) is a complete representation of the N cycle. The model describes urea hydrolysis, nitrification, mineralization, immobilization of NO₃⁻ and NH₄⁺, and the adsorption-desorption processes of NH₄⁺. Inputs of N include addition of fertilizers: organic N, urea, NO₃⁻ and NH₄⁺. Outputs include uptake of N by plants, leaching of nitrate and nitrite, and leaching of urea. Losses of N in runoff are not considered. Transformations of N are modeled using regression equations. Dutt et al. (1972) described the nitrification rate using the following empirical equation:

\[
Y = 4.64 + 0.00162 \ T \ (\text{NH}_4^+) + 0.00162 \ \log(\text{NH}_4^+) - 2.51 \ \log(\text{NO}_3^-)
\]

(4)

where Y is the nitrification rate (ppm/day), NH₄⁺ is the ammonium concentration (ppm), NO₃⁻ is the nitrate concentration (ppm), and T is the temperature in °C.
The nitrate immobilization rate was described as:

\[ \text{NIR} = 0.049 + \frac{1.52 \ T}{(N_o)^3} + 3.23 \times 10^{-5} \exp(T) - 0.0049 \ T \frac{\text{NO}_3^-}{N_o} \]  

(5)

where NIR represents the net immobilization rate (ppm/day) and \( N_o \) is the organic nitrogen concentration (ppm). The net mineralization rate (NMR) is expressed as:

\[ \text{NMR} = 0.0892 + 0.00216 \ T + 0.027 \ N_o + 0.382 \ \log(\text{NH}_4^+) \]  

(6)

**Mehri and Tanji Model**

The processes modeled in the Mehri and Tanji model (Mehran and Tanji, 1974) include nitrification, denitrification, mineralization, immobilization and plant uptake. These processes were modeled using irreversible first order kinetics equations, which can be expressed as:

\[ \frac{dN}{dt} = -K \ N \]  

(7)

where \( K \) represents the first order rate constant and \( N \) represents the concentration of the species of interest. A reversible first order kinetics equation was used to describe the exchange of \( \text{NH}_4^+ \). Both reversible and irreversible models were coupled and solved simultaneously:

\[ \frac{d[N_c]}{dt} = -\sum_{i=1}^{n} K_i [N_c] + \sum_{j=1}^{m} K_j [N_m] \]  

(8)

where \( N_c \) is the concentration of \( N \) species of interest, \( N_m \) is the concentration of other \( N \) species, and \( K_i \) and \( K_j \) are the first order rate equations. Other researchers (Beek and Frisell, 1973; Hage and Amberger, 1974; Davidson et al., 1978; Donigian and Davis, 1978) have also used first order kinetics to model \( N \) cycle.

**CREAMS Nitrogen Submodel**

The CREAMS N submodel (Knisel, 1980) simulates mineralization, denitrification, plant uptake of nitrogen, and leaching of nitrate. The amount of mineralized \( N \) is determined by:

\[ \text{MN} = \text{POTM} \frac{\text{AWC}}{\text{FC}} \left( 1 - \exp \left( -\text{DAYS TK} \right) \right) \]  

(9)

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where:

TK = temperature coefficient,
AWC = average volumetric content (cm/cm),
FC = field capacity (cm/cm),
POTM = potentially mineralizable nitrogen in the soil (kg/ha),
MN = mineralization (kg/ha/d), and
DAYS = time between storms (day).

The temperature coefficient is expressed as a function of the average temperature during the period as follows:

\[ TK = \exp \left( 15.807 - \frac{6350}{TA} \right) \]  \hspace{1cm} (10)

where TA is the average temperature during the period in °K. The denitrification process is modeled using the following equation:

\[ DNI = NO_3 \left( 1 - \exp \left( DKT \times (DT - 0.5) \right) \right) \]  \hspace{1cm} (11)

where:

DNI = amount of denitrification (kg/ha),
NO_3 = nitrate in the root zone (kg/ha),
DT = duration of drainage since the last storm (days), and
DKT = temperature adjusted rate constant.

The temperature adjusted rate constant is expressed as:

\[ DKT = \exp \left( 0.0693 \times ATP + DB \right) \]  \hspace{1cm} (12)

where ATP is the average temperature in °C during the mineralization process. The parameter DB is determined by:

\[ DB = \ln(24 \times 0.011 \times SC + 0.0025)) - 2.4255 \]  \hspace{1cm} (13)

where SC is the amount of soil carbon (mg-C/g-soil). The value of SC can be determined from the amount of organic matter as follows:

\[ SC = \frac{OM}{0.1724} \]  \hspace{1cm} (14)

where OM is the percent soil organic matter content. Plant N uptake (nitrate only) is simulated
using two possible approaches. The first option assumes that N uptake is a function of plant water use, which in turn determines the amount of dry matter production. Dry matter production is estimated by:

$$\text{DM}_i = \frac{\sum \text{WU}_i}{\text{PWU}} \times \text{YP} \times \text{K}$$  \hspace{1cm} (15)

where:
- $$\text{DM}_i$$ = dry matter production on day $$i$$ (kg/ha),
- $$\text{WU}_i$$ = daily plant water use on day $$i$$ (mm),
- $$\text{PWU}$$ = total plant water use for the growing season (mm),
- $$\text{YP}$$ = crop yield potential (kg/ha), and
- $$\text{K}$$ = ratio of dry matter to crop yield at maturity.

Dry matter production is then used to estimate N concentration in plants by:

$$c = \min \left\{ b_1 \left( \frac{\text{DM}_i}{\text{TDM}} \right)^{b_2}, b_3 \left( \frac{\text{DM}_i}{\text{TDM}} \right)^{b_4} \right\}$$  \hspace{1cm} (16)

where $$c$$ is the N concentration in plants (kg/kg), TDM is the dry matter production for the growing season (kg) and $$b_1$$, $$b_2$$, $$b_3$$, and $$b_4$$ are crop constants defined by Smith et al. (1980). The accumulated N uptake, since the beginning of the growing season, on day $$i$$ is given by the product of N plant concentration and dry matter production as follows:

$$\text{UN}_i = c \times \text{DM}_i$$  \hspace{1cm} (17)

where $$\text{UN}_i$$ is the accumulated N uptake for day $$i$$. The daily plant uptake can be determined by taking the difference between $$\text{UN}_i$$ and $$\text{UN}_{i-1}$$. In case the coefficients $$b_1$$, $$b_2$$, $$b_3$$, and $$b_4$$ are not available, CREAMS offers a second option which approximates the plant N uptake process by a normal probability curve:

$$\text{PUN} = 1 - 0.5 \times S^{-4}$$  \hspace{1cm} (18)

where:
\[ S = 1.0 + 0.0196854 \times X + 0.115194 \times X^2 + 0.000344 \times X^3 + 0.01957 \times X^4 \] \tag{19}

where:

\[ X = \frac{(T - M)}{SD} \] \tag{20}

where:

- PUN = fraction of potential annual uptake by T days of growth,
- M = days required to take up 50\% of the annual amount, and
- SD = number of days between 50\% and 84\% uptake.

The amount of N uptake between storms is computed by:

\[ UN = (PUN - PPUN) \times PU \times TR \] \tag{21}

where:

- UN = N uptake between storms (kg/ha),
- PPUN = value of PUN for the previous storm,
- PU = potential annual N uptake (kg/ha), and
- TR = ratio of actual to potential transpiration.

**EPIC Nitrogen Submodel**

The EPIC model (Sharpley and Williams, 1990) was developed to assess long-term soil productivity and to evaluate best management strategies to preserve soil productivity. The EPIC model simulates the complete N cycle. Soil organic matter and organic N are partitioned into fresh and stable pools. Mineralization occurs from fresh organic N and from active organic N associated with humus. Mineralization from the fresh organic pool is simulated by:

\[ RMN = DCR \times FON \] \tag{22}

where:

- RMN = mineralization rate (kg/ha/day),
- FON = fresh organic N (kg/ha), and
- DCR = decay rate constant (day\(^{-1}\)).

The decay rate constant is expressed as:

\[ DCR = CNP \times RC \times \left( \frac{SWF}{FC} \right)^{0.5} \times FON \] \tag{23}

- CNP = C:N ratio factor.
SWF = soil water factor,
TF = temperature water factor,
FC = soil water content (mm), and
RC = residue composition factor.

Soil water factor is determined by:

$$SWF = \frac{SW}{POR}$$  \hspace{3cm} (24)

where SW represents water content in a specific layer (mm) and POR is the total porosity (mm). For temperatures less than 0, the temperature factor (TF) is zero. For positive temperatures, TF is:

$$TF = \frac{T}{T + \exp (9.93 - 0.312 T)}$$  \hspace{3cm} (25)

where T is the soil temperature (°C). The factor CNP is computed with the equation:

$$CNP = \min \left\{ \begin{array}{ll}
\exp [0.693 \times (CNR - 25)/25] & \rightarrow \mathcal{N} \\
\exp [0.693 \times (CPR - 200)/200] & \rightarrow \mathcal{P} \\
1.0 & 
\end{array} \right. $$  \hspace{3cm} (26)

where CNR is the C:N ratio and CPR is the C:P ratio. Mineralization from the active mineral pool is estimated by:

$$HMN = CMN \times ON_s \times (SWF \times TF)^{0.5} \left( \frac{BD}{BDP} \right)^2$$  \hspace{3cm} (27)

where:
- HMN = humus mineralization (kg/ha/day),
- ON$_s$ = active organic N associated with humus (kg/ha),
- CMN = humus transformation rate constant (0.0003 d$^{-1}$),
- BD = settled bulk density (t/m$^3$), and
- BDP = bulk density as affected by tillage (t/m$^3$).

The EPIC model maintains a balance between the stable and active organic N pools, and transformation from stable to active pool is computed daily. Denitrification is estimated by:

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\[ DN = WNO_3 \left(1 - \exp\left(-1.4 \, TF \, C\right)\right) \]  

where:
- \( WNO_3 \) = is the amount of nitrate contained in a specific soil layer at the end of a day (kg/ha),
- \( DN \) = denitrification rate (kg/ha/day), and
- \( C \) = organic carbon content (%).

The EPIC model uses a modification of the PAPRAN model (Seligman and Keulen, 1981) to determine immobilization. Daily crop N uptake is based on the daily N demand and is determined as the difference between the actual plant N content and the potential N content. The optimal crop N concentration is estimated as:

\[ c = b_1 + b_2 \exp\left(-b_3 \, \text{HUI}\right) \]  

where:
- \( c \) = optimal N concentration (kg/t),
- \( b_1, b_2 \text{ and } b_3 \) = crop parameters, and
- \( \text{HUI} \) = fraction of the growing season.

The N demand is then determined by the following equation:

\[ \text{UND}_i = c \, B_i - \sum_{k=1}^{i-1} \text{UN}_k \]  

where:
- \( \text{UND}_i \) = daily crop N demand for day \( i \) (kg/ha/d),
- \( B \) = accumulated biomass at day \( i \) (kg/t), and
- \( \text{UN} \) = actual N uptake rate (kg/ha/d).

The soil N available for plant uptake is estimated by:

\[ \text{UNS}_i = \sum_{j=1}^{m} u_{ij} \left( \frac{WNO_{3j}}{SW_j} \right) \]  

where:
- \( \text{UNS}_i \) = soil N available for plant uptake (kg/ha/d),
- \( u_j \) = water use rate (mm/d) for layer \( j \),
- \( WNO_{3j} \) = nitrate present in layer \( j \) (kg/ha),
- \( SW_j \) = soil water content (mm), and
m = number of soil layers.

The actual uptake of N is then given by:

\[
UN_{ji} = u_{ji} \left( \frac{WNO_{3ji}}{SW_j} \right) \left( \frac{UND_i}{UNS_i} \right)
\]  

(32)

where \( UN_{ji} \) is the adjusted uptake rate for layer \( j \) on day \( i \) and other parameters are as previously defined.

**GLEAMS Nitrogen Submodel**

GLEAMS (Knisel et al., 1993) uses identical equations to those used in EPIC to model mineralization from organic N and plant residue, and plant uptake. However, unlike EPIC, GLEAMS assumes a two step mineralization process. GLEAMS simulates mineralization as the combination of ammonification and nitrification.

**SEDIMENT-BOUND NITROGEN TRANSPORT MODELING**

More than 90% of the total N is attached to soil particles and consequently modeling the loss of sediment-bound N is extremely important. Sediment-bound forms of N include organic N, fixed and adsorbed ammonium. The Langmuir isotherm (Langmuir, 1918) is often used to express the equilibrium between the adsorbed and dissolved phases of a chemical. It can be expressed as:

\[
\frac{X}{M} = \frac{Q \cdot C \cdot b}{1 + C \cdot b}
\]  

(33)

where:
- \( \frac{X}{M} \) = amount of adsorbed chemical per unit weight of adsorbent,
- \( C \) = equilibrium concentration of dissolved adsorbate,
- \( Q \) = adsorption maximum, and
- \( b \) = measure of the intensity of the sorption.

This equation can be reduced to a linear relationship whenever \( C \) is relatively small compared to \( 1/b \). The Freundlich adsorption isotherm (Freundlich, 1926) is also used to describe the equilibrium between sediment bound and dissolved species. It is expressed as:
\[
\frac{X}{M} = K C^{1/n}
\]

(34)

where \( K \) and \( n \) are constants. The Freundlich isotherm reduces to a linear relationship when \( n \) is equal to one.

In the CREAMS model, the loss of \( N \) through sediment transport is determined using an enrichment ratio as follows:

\[
SEDN = SOILN SED ER
\]

(35)

where:

- \( SEDN \) = nitrogen transported with sediment (kg/ha),
- \( SOILN \) = nitrogen content of soil (kg-N/kg-soil),
- \( SED \) = amount of sediment (kg/ha), and
- \( ER \) = enrichment ratio.

The enrichment ratio is predicted by:

\[
ER = a SED^b
\]

(36)

where \( a \) and \( b \) are fitted values. Menzel (1980) proposed the following relationship to determine the enrichment ratio:

\[
\ln(ER) = 2 - 0.2 \ln(SED)
\]

(37)

Williams (1979) also uses an enrichment ratio to determine the yield of organic \( N \):

\[
Y_{ON} = 0.0001 Y N_{ORG} ER
\]

(38)

where:

- \( Y_{ON} \) = organic \( N \) yield (kg),
- \( Y \) = sediment yield (kg),
- \( N_{ORG} \) = soil organic \( N \) content (ppm), and
- \( ER \) = enrichment ratio.

The EPIC model (Sharpley and Williams, 1990) also uses the enrichment ratio approach to model organic \( N \) transport by sediment. The upper limit of the enrichment ratio is given by the inverse of the delivery ratio. The delivery ratio is estimated by:

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\[
DR = \left( \frac{q_p}{r_p} \right)^{0.56}
\]  

(39)

where:
- \( DR \) = delivery ratio,
- \( q_p \) = peak runoff rate (mm/hr), and
- \( r_p \) = peak rainfall excess rate (mm/hr).

The lower limit of the enrichment ratio is 1. The enrichment ratio is then determined by:

\[
ER = X_1 \, SED^{X_1}
\]  

(40)

where \( X_2 \) is determined by:

\[
X_2 = - \frac{\log \left( \frac{1}{DR} \right)}{2.699}
\]  

(41)

and \( X_1 \) by:

\[
X_1 = \frac{1}{0.25 X_1}
\]  

(42)

The hydrological models ARM and NPS both use potency factors to determine the amount of pollutant lost through runoff. The potency factor is an arbitrary factor of proportionality that can be related to the enrichment ratio. The potency factor is:

\[
Y_i = POT_i \, Y_s
\]  

(43)

where:
- \( Y_i \) = loading of pollutant \( i \),
- \( Y_s \) = loading of sediment, and
- \( POT_i \) = potency factor.

Comparing the previous equation with equation (35), one can derive the relationship between the potency factor and the enrichment ratio:
POT = SOILN ER

where SOILN represents the nutrient content of the soil.

DISSOLVED NITROGEN TRANSPORT MODELING

Modeling dissolved N is complex since it is necessary to model three different processes: convection, diffusion, and dispersion. Convection also called advection, refers to solute transport due to mass flow only. The water and the pollutant of interest move due to the existence of a hydraulic gradient. Haynes et al. (1986) describe the process of nitrate movement by convection using the following equation:

$$\frac{\partial c}{\partial t} = -U \frac{\partial c}{\partial x}$$

(45)

where:

- $c$ = concentration of NO$_3^-$ (µg/mL),
- $U$ = average pore velocity (cm/day),
- $t$ = time (days), and
- $x$ = linear distance in the direction of the flow (cm).

Dispersion results in the movement of contaminants and pollutants due to heterogeneities present in the porous media. The process is the result of: 1) the flow velocity within a single pore is not uniform, it is faster at the pore center; 2) large variability of pore sizes results in large variations in pore water velocities; 3) and large variations in pore length due to the tortuosity of pore geometry (Haynes et al., 1986). This process is also referred to as hydrodynamic dispersion.

Diffusion is the movement of contaminants in the direction of their concentration gradient. The flux occurs from areas of high concentration to areas of low concentration. Movement of diffusion can be expressed as:

$$\frac{\partial c}{\partial t} = D_e \frac{\partial^2 c}{\partial x^2}$$

(46)

where $D_e$ represents the effective diffusion coefficient (cm$^2$/day). In most cases, the processes of convection and hydrodynamic dispersion mask the diffusion phenomena, and diffusion is often
neglected.

The combined effect of the three processes can be described as:

$$\frac{\partial c}{\partial t} = E \frac{\partial^2 c}{\partial x^2} - U \frac{\partial c}{\partial t}$$

(47)

where $E$ is the dispersion or apparent diffusion coefficient. It is expressed as the sum of diffusion plus mechanical dispersion:

$$E = D_s + m U$$

(48)

where $m$ is the dispersivity. Frissel and Van Veen (1981) developed a simplified transport model:

$$\frac{dc}{dt} = E \frac{c_i - c_{i-1}}{l} + L_e \frac{c_i + c_{i-1}}{2}$$

(49)

where:

$L_e$ = the leaching efficiency factor, and

$l$ = distance between midpoints of adjacent soil layers $i$ and $i-1$.

Frere et al. (1975) describe the dispersion of nitrate at any depth using the following equation:

$$c = \frac{A U}{\sqrt{4 \pi D d}} \exp \left( - \frac{d - x}{(4 D d)^{0.5}} \right)$$

(50)

where:

$c$ = solution concentration at depth $x$ (ppm),

$A$ = amount of chemical (kg/ha),

$U$ = conversion factor,

$x$ = depth (cm),

$d$ = average depth of chemical movement (cm), and

$D$ = dispersion coefficient.

When the pollutant is mixed in a layer of thickness $AP$, and when the infiltrating front is at a depth $D$, the concentration of the pollutant at a distance $x$ from the front is given by (Frere et al. (1975):

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\[ C(x) = \frac{C_i}{2} \left( \text{erfc} \left( \frac{0.5 \ AP + x}{\sqrt{4 \ D \ d}} \right) + \text{erfc} \left( \frac{0.5 \ AP - x}{\sqrt{4 \ D \ d}} \right) \right) \]  

(51)

where:

- \( AP \) = depth of mixing of chemical (cm),
- \( x \) = distance from the infiltrating front (cm), and
- \( C_i \) = initial concentration (ppm).

CREAMS models nitrate loss using an extraction coefficient:

\[ R\text{ONO}_3 = C_{\text{av}} \cdot \text{EXKNO}_3 \cdot Q \]  

(52)

where:

- \( R\text{ONO}_3 \) = amount of dissolved \( P \) lost through runoff (kg),
- \( C_{\text{av}} \) = average \( \text{NO}_3 \) soil solution concentration during infiltration (kg/m\(^3\)),
- \( \text{EXKNO}_3 \) = extraction coefficient for \( \text{NO}_3 \), and
- \( Q \) = runoff (m\(^3\)).

The same approach is used in EPIC and GLEAMS to determine loss of nitrate and dissolved ammonium in runoff and infiltration.

**PHOSPHORUS**

**FORMS OF PHOSPHORUS PRESENT IN THE SOIL**

Phosphorus is another important nutrient necessary for plant growth. However, in excess in surface waters, \( P \) is a nuisance and the principal cause of eutrophication in many freshwater bodies. Phosphorus is believed to be the major limiting nutrient for plant growth in lakes. Cropland contributes 1.56 million tons of \( P \) per year to receiving waters (Van Der Leeden, 1990). The recommended level of \( P \) to control biological nuisance growth and eutrophication is 0.05 ppm at the confluence of streams and reservoirs or lakes, and 0.025 ppm within reservoirs or lakes.

Phosphorus can be divided into organic and inorganic \( P \). The inorganic \( P \) is mainly particulate
(sediment-bound) due to its sorptivity characteristics, but it is in equilibrium with dissolved inorganic P that is available for plant uptake. More than 200 inorganic P compounds, mainly polyphosphates have been identified. The organic fraction of P becomes available for plant uptake once mineralization occurs. The mineral apatite, especially calcium fluorapatite ($\text{Ca}_{10} (\text{PO}_4)_6 \text{F}_2$) is the primary source of P. Phosphorus can also be divided into particulate and dissolved phases.

**Particulate Phosphorus**

Phosphorus bound to soil particles is referred to as particulate or sediment-bound P. Nelson and Logan (1983) classified particulate P into four categories:

- adsorbed-labile P or exchangeable P,
- organic P including phytins and phospholipids,
- precipitates, the products of reaction of fertilizers with calcium, iron, aluminum and other cations, and
- minerals, including amorphous (uncrystalline) and crystalline minerals with calcium, aluminum, iron and other cations.

Organic P concentration is usually high in surface soils due to the accumulation of organic matter (McElroy et al., 1976). Soil P is readily immobilized due to its sorptivity characteristics. In acid soils, the availability of P is diminished because of the formation of iron and aluminum phosphates. In alkaline soils, the availability of P is reduced because of the formation of tricalcium phosphate (McElroy et al., 1976).

**Dissolved Phosphorus**

Dissolved P consists of both organic and inorganic forms including orthophosphate and polyphosphate. The main compounds found in solution include $\text{PO}_4^{3-}$, $\text{H}_3\text{PO}_4$, $\text{H}_2\text{PO}_4^-$, and $\text{HPO}_4^{2-}$. At high pH, polyphosphate can precipitate with metallic ions, including $\text{Ca}^{2+}$, $\text{Al}^{3+}$ and $\text{Fe}^{3+}$. Dissolved inorganic phosphate, also called bioavailable P, is the portion available to plants. The bioavailability of particulate P is a function of the kinetics involved in the conversion of particulate P to dissolved inorganic P.
PHOSPHORUS CYCLE

Many reactions and mechanisms regulate and control the composition and forms of P present in the soil. A summary of the processes involved in the P cycle is given in Figure 2. According to Syers and Iskandar (1981), P concentration in soil solution is influenced by four processes:

- immobilization / mineralization,
- sorption / desorption,
- precipitation / dissolution, and
- plant uptake.

Mineralization and Immobilization

Mineralization of P is the process by which organic P in plant residues and other organic material is decomposed by microorganisms and transformed into phosphate ion. The amount of organic P varies from soil to soil but is generally 20 to 90% of total P (Black and Goring, 1953). Three forms or organic P have been identified: inositol phosphate, nucleic acids, and phospholipids. Immobilization of P is the uptake of phosphate ion from the soil solution and its incorporation in cytoplasm as organic P. Once the microbes die, the P is then subject to mineralization. At C:P ratio less than 200:1, the phosphate ion is released directly to the soil solution and is available for plant uptake. Mineralization of P can be rapid, however the decomposition of some organic materials may take a longer time. According to Nelson and Logan (1983), the total conversion of organic P to inorganic P is complete within 3 to 4 years. At a C:P ratio of about 300:1, excessive microbial growth occurs, resulting in immobilization of P. Overall, net mineralization occurs (mineralization is larger than immobilization) independently of the C:P ratio. Humus contains 0.25 to 0.5% organic P, and about 1 to 4% of humus present in the soil layer is decomposed. Since humus is characterized by C:P ratios between 100 and 200:1, large amounts of phosphate ion can be released to soil solution from humic materials (Nelson and Logan, 1983).

Desorption/Sorption Processes

The adsorption process is not to be confused with the absorption. Absorption is the penetration and incorporation of P into the solid phase. Adsorption is defined as a physiochemical process that results in the immobilization and retention of P on soil particle surfaces. Both reactions together form the sorption process. Desorption is the inverse reaction and results in the release
Figure 2. Flow chart for the phosphorus cycle (adapted from Novotny and Chester, 1981).
of P from the solid phase. These two reactions control the partition of P between the sediment-bound and dissolved phases. Hydrous oxides of iron and aluminum are the major components involved in the sorption of P by soils (formation of mononuclear complexes). The sorption of P to clay particles is assumed to be similar to that involving P and hydrous oxides of iron and aluminum. The reactions explaining the sorption of phosphate and hydrous oxide of iron have been given by Ryden et al. (1977):

\[(\text{Fe-OH}) (\text{Fe-OH}_2^+) + \text{H}_2\text{PO}_4^- \rightarrow (\text{Fe-OH}) (\text{Fe-H}_2\text{PO}_4^-) + \text{H}_2\text{O} \quad (53)\]

and

\[(\text{Fe-OH}) (\text{Fe-OH}) + \text{H}_2\text{PO}_4^- \rightarrow (\text{Fe-OH}) (\text{Fe-H}_2\text{PO}_4^-) + \text{OH}^- \quad (54)\]

Syers and Iskandar (1981) note that Equation 54 shows that sorption of P to soil surfaces does not necessarily result in an increase in the negative charge of the surface. Usually, P is assumed to be adsorbed to clay and organic matter particles and little P is in solution. The amount of P lost through leaching is minimal (Ryden et al., 1973), with little or no contamination of ground water. The sorption reactions are mainly controlled by soil characteristics and the solubility of the compounds involved in the reactions. Analyzing results of several studies conducted to study the effect of pH on the sorption-desorption processes, Syers and Iskandar (1981) concluded that these results were somewhat contradictory and that the effects of pH on the sorption desorption process were not fully understood. However, in general it was found that an increase in pH results in a decrease in the amount of sorbed P. Anions may also compete with P for sorption sites and may influence the amount of sorbed P (Syers and Iskandar, 1981).

**Precipitation and Dissolution**

According to Snoeyink and Jenkins (1980), dissolution is the major factor affecting composition of natural water. Orthophosphate and polyphosphate, being negatively charged, react readily with cations to form precipitates. These precipitates can either be amorphous (characterized by a crystal structure not well organized) or crystalline. In alkaline or calcareous soils (high pH), P is known to precipitate with calcium to form dicalcium and tricalcium phosphate. Even though these precipitates can be adsorbed at the surface of CaCO$_3$ or clay saturated with calcium, these precipitates have a large surface area in contact with soil solution, and thus, P may be released.
in solution slowly. For soils rich in clay and organic matter (low pH), P precipitates with Fe and Al. These precipitates can be quite insoluble and not available for plant uptake. Although the precipitation and dissolution processes can be used to describe the interaction of P with soil components, Syers and Iskandar (1981) find that these interactions are better explained by sorption-desorption reactions.

**Plant Uptake of Phosphorus**

Plant available forms of P (inorganic dissolved phase), include HPO$_4^{2-}$ or H$_2$PO$_4^-$ (depending on the pH). Phosphorus is intercepted by the root hairs first and then transported to the root by mass flow and diffusion (Nelson and Logan, 1983). Diffusion of P is the primary means of transport of P to the plant root. The amount of P removed by plants varies from 24 kg/ha for soybeans (yield of soybeans being 3.39 ton/ha) to 50 kg/ha for corn having a yield of 50 tons/ha.

**Fertilization**

Dissolved inorganic P concentration is very low in soils. Most of the P is attached to soil particles in organic forms. Application of fertilizers is used to increase the amount of available P. However, when P is applied to soils, it rapidly binds with soil particles and organic matter, and is unavailable. The rate of conversion of P from available to less available forms depends upon the method of application, the type of fertilizer, solubility of the fertilizer, pH, and cultural and conservation practices.

**Factors Affecting Phosphorus Transformations**

Young et al. (1985) classified the factors affecting P transformation and availability into two categories: chemical characteristics and physical characteristics. Forms of soil P and soil pH are among the major chemical characteristics that affect P availability. The soil pH affects the forms of phosphate ion present in the soil. For pH between 5 and 7.2, H$_2$PO$_4^-$ is the dominant ionic form, whereas for pH between 7.2 and 9 the dominant form is HPO$_4^{2-}$. This is of major importance since the former ion is the specie more readily taken up by plants. Furthermore, pH affects solubility of different P compounds and precipitation reactions (see previous section). Adjustment of soil pH (liming of acid soil) is commonly used to increase P availability to plants. The major physical characteristics affecting P transformation are aeration, temperature and moisture. Aeration affects microbial growth, which in turn controls organic matter decomposition.
(P mineralization). Furthermore, aeration controls the oxidative state of inorganic P compounds. Anaerobic conditions that prevail in paddy rice transform ferric phosphate to the much more soluble and thus more available ferrous phosphate (Young et al., 1985). The effect of temperature is attributed to decreased mineralization rate at lower temperature and to a slower diffusion rate to root surfaces. Soil moisture content also affects the diffusion of P to the root surface. A major aspect to consider in P transformation is the low mobility of P. According to Young et al. (1985), dissolved P does not move more than 2 or 3 cm from fertilizer granules due to the most soil’s high sorptive capacity.

PHOSPHORUS TRANSPORT

Loss of Phosphorus in Runoff
As discussed previously, P is usually transported in its particulate form. Up to 90% of the P loss from agricultural fields in grain is lost in the particulate form (Nelson and Logan, 1983) through sediment transport. Runoff has two roles in the transport of sediment and P: particle detachment and particle transport. The process of erosion is selective for finer particles. These finer particles are responsible for most of the P transport because P is usually preferentially adsorbed to the clay fraction in soils. The finer particles, particularly clay, have larger surfaces of adsorption, and the clay fraction contains much of the organic matter and hydrous oxides (iron and aluminum) that can bind P (Nelson and Logan, 1983). The enrichment ratio for particulate P varies from 1 to 10 depending on watershed size and soil characteristics. Enrichment of P is higher than the enrichment ratio of clay and organic matter: about 1.5 to 2 times higher than that for clay or organic matter (Stoltenberg and White, 1953).

Loss of Phosphate Through Leaching
Only a small fraction of the P in the soil is present in the dissolved phase. Phosphorus is mainly bound to the fine soil particles. However, some dissolved P is transported with runoff, and small amounts of P can reach the ground water through leaching. The amount of percolating P is controlled by the P adsorptive capacity of the soils above the aquifer (Nelson and Logan, 1983). Some P can reach the water table through preferential flow where the dissolved P has little interaction with the soil matrix, and reduced chance of being adsorbed to soil particles. Transport of dissolved P involves the same processes as those described for N: convection, diffusion and
hydrodynamic dispersion.

Factors Influencing Phosphorus Losses
The same approach used in controlling nitrogen losses is used to control P losses. However, more attention is focused on controlling erosion since P loss is mostly in the particulate form.

PHOSPHORUS TRANSPORT MODELING

Due to the complexity of the P cycle and the large number of reactions involving phosphorus compounds, most of NPS models limit their simulation of the P cycle and transformations to adsorption/desorption processes. Two approaches have usually been used to describe the sorption/desorption reactions. The first approach assumes an instantaneous and complete equilibrium between dissolved and adsorbed P. The second approach assumes nonequilibrium conditions.

Equilibrium Models
The Langmuir and Freundlich isotherms are among the most popular equilibrium models. The Langmuir isotherm assumes constant energy of sorption and interaction between sorbed molecules. Thus the Langmuir isotherm is usually restricted to monolayer sorption. Syers et al. (1973) found that more than one type of adsorption site, associated with a different bonding energy, was usually involved in P sorption process, and suggested a modified Langmuir isotherm to describe P adsorption:

$$S = S_{\text{max}} \left( \frac{1}{k' C} + 1 \right) + S_{\text{max}} \left( \frac{1}{k'' C} + 1 \right)$$

where $k'$ and $k''$ are the respective affinity parameters for the two different types of sorption sites.
The Freundlich isotherm (Equation 34) can also be used to model P sorption/desorption processes. For soil containing residual phosphate (native labile P) both isotherms should be modified by subtracting the amount of residual P (Mansel and Selim, 1981).

Non Equilibrium Models
The previously described approaches are based on the assumption that an equilibrium is reached
instantaneously between dissolved and solid phase. However, research has shown that desorption of P is characterized by an initial rapid rate (few hours), followed by much slower rates (days) (Ryden et al., 1977). Enfield (1974) proposed a kinetic approach for modeling P sorption from soil solution:

\[
\frac{\partial S}{\partial t} = a \cdot C^b \cdot S^d
\]

where \(t\) represents time and \(a\) and \(b\) are constants. Kuo and Lotse (1974) incorporated time in the Freundlich isotherm (Equation 34) to yield:

\[
S = K \cdot (k \cdot C^N \cdot t^{\frac{1}{M}}) \equiv K \cdot C_0 \cdot t^{\frac{1}{M}}
\]

where \(N/M\) is equal to \(1/n\) in Equation 34 and \(C_0\) represents the initial P concentration. Sharpley et al. (1981) developed an extraction function which is expressed as:

\[
P_d = K \cdot t^\alpha \cdot WS^\beta \cdot P_{ex}
\]

where:
- \(P_d\) = cumulative P desorbed (μg-P/g soil),
- \(P_{ex}\) = initial extractable P level of the soil (μg-P/g soil),
- \(t\) = time of contact (minutes),
- \(WS\) = water to soil ratio (cm³/g), and
- \(K, \alpha, \beta\) = empirical constants specific to soil type.

Relationships between \(K, \alpha, \beta\) and soil organic carbon and clay content have been developed by Sharpley (1983).

**Particulate Phosphorus**

Hagin and Amberger (1974), and McElroy et al. (1976) modelled particulate P using a loading function similar to Equation 35. The total P loading is expressed as:

\[
P = SY \cdot PC \cdot ERP
\]

where:
- \(P\) = total P loading (kg/ha),
- \(SY\) = sediment yield carried by runoff (kg/ha),
- \(PC\) = concentration of P in surface layer (kg/100 kg-soil), and
- \(ERP\) = P enrichment ratio.
Enrichment ratio is defined as the ratio of sorbed P from the eroded sediment and from the original soil. Menzel (1980) proposed the following relationship to determine ERP:

\[ \ln(ERP) = 2.00 - 0.2 \ln(SD) \]  

where SD represents the sediment yield in kg/ha.

Sharpley (1980) used a relationship similar to Menzel’s:

\[ \ln(ERP) = 2.48 - 0.27 \ln(SD) \]  

Massey et al. (1953) proposed the following relationship to determine the enrichment ratio for P:

\[ \ln(ERP) = 0.319 + 0.25 (-\ln(SYR)) + 0.98 \ln(-\ln(SY)) \]  

where SYR represents the sediment loss expressed in ton per acre inch of runoff.

**CREAMS Phosphorus Model**

The CREAMS model does not simulate mineralization of P and assumes a linear relationship between adsorbed and sediment-bound P. Phosphorus lost through erosion is modeled using an enrichment ratio. Dissolved P transported in runoff is computed using an extraction coefficient:

\[ ROP = C_{av} \times EXKP_2 \times Q \]  

where:

- \( ROP \) = amount of dissolved P lost through runoff (kg),
- \( C_{av} \) = average P soil solution concentration during infiltration (kg/m³),
- \( EXKP_2 \) = extraction coefficient for P, and
- \( Q \) = runoff (m³)

**EPIC Phosphorus Model**

The EPIC model divides phosphorous into an organic and inorganic pools. The organic pool consists of fresh organic P and P associated with humus. Mineralization of P occurs from within these two pools. Mineralization from the fresh organic pool is determined by:

\[ RMP = DCR \times FOP \]  

where:

- \( RMP \) = mineralization of fresh organic P for a certain layer (kg/ha/d),
- \( DCR \) = daily critical rate
- \( FOP \) = fraction of organic P

**LITERATURE REVIEW**
FOP = fresh organic P in crop residue (kg/ha), and
DCR = decay rate constant.

Mineralization from organic P associated with humus is computed by:

\[ HMP = \frac{CMN \cdot ON \cdot OP \cdot (SWF \cdot TF)^{0.5} \cdot BD^5}{ON \cdot BD^5} \]  \hspace{1cm} (65)

where:

- HMP = humus P mineralization rate (kg/ha/d),
- ON = stable organic N, and
- OP = organic P content of the soil (kg/ha).

The EPIC model divides the mineral P into three pools including labile, active and stable mineral pools. Fertilizer P is assumed labile at application, but is quickly converted to the active mineral pool. EPIC maintains an equilibrium between active mineral and stable mineral pools. EPIC also maintains an equilibrium between active mineral P and labile P. The flow between active and stable mineral pools is given by:

\[ MPR = 0.1 \cdot SWF \left( \frac{AP - MP \cdot \frac{PSP}{1 - PSP}}{1 - PSP} \right) \cdot \exp(0.115 \cdot T - 2.88) \]  \hspace{1cm} (66)

where:

- MPR = mineral P flow (kg/ha/d),
- T = soil temperature (°C),
- MP = active mineral pool (kg/ha),
- PSP = sorption coefficient function of chemical and physical properties of the soil, and
- AP = labile P (kg/ha).

The flow direction is regulated by the difference computed between the labile P and MP PSP/(1-PSP). If the difference is positive, the flow is from the labile P to the active mineral P. If the difference is negative, the flow reverses and goes from the active mineral P to labile P. Plant uptake of P is similar to that described for N (Equations 29-32).

**INfiltration**

Infiltration is defined as the entry of water through the air-soil interface. Infiltration is one of the key components of the hydrologic cycle. Modeling infiltration accurately is crucial in the determination of the amount of runoff and the soil water distribution during and after a rainfall.
event. Infiltration is a complex process and many factors affect infiltration rate. Soil properties have a major impact on infiltration rate. Infiltration rates tend to increase with coarser texture soils. Antecedent soil moisture affects infiltration rate. At low moisture content, initial infiltration rates are extremely high and are limited by rainfall rate. Once a soil becomes saturated, infiltration is solely dependent on soil characteristics, such as saturated hydraulic conductivity. Formation of a surface crust has also been proven to affect infiltration rates. Edwards and Larson (1969) observed that the saturated hydraulic conductivity of a surface layer decreased from 19 mm/hr to 2 mm/hr during the first two hours of rainfall simulation. The formation of a surface crust is affected by the vegetal and residue cover present at the soil surface.

There are two basic approaches to model the infiltration process. Infiltration can be modeled using an empirical approach. Empirical equations include the Kostiakov (Kostiakov, 1932), the Horton (Horton, 1940), and the Holtan (Holtan, 1961) equations. These equations may require calibration with measured data from the watershed of interest or similar watersheds. An alternative empirical approach is the SCS curve number approach (USDA, 1972). This equation can be used on ungaged watersheds but its accuracy is limited.

Infiltration can also be modeled using a physically based approach. The physically-based infiltration equations include the Green-Ampt (Green and Ampt, 1911), the modified Green-Ampt (Mein and Larson, 1971), and the Philip equations (Philip, 1957). Physically-based equations have the advantage that their parameters can be determined from soil properties and vegetal cover information and do not require calibration. Infiltration can also be modeled using numerical solutions to the physically-based differential equation governing infiltration, also referred to as the Richards equation (1931). This type of approach is difficult to implement on watershed scale models due to the large data and computer resources required to solve the differential equations involved.

INfiltration MODEL REVIEW

Infiltration methods that have been used extensively in hydrologic modeling include the Holtan (Holtan, 1961) infiltration equation, the Green-Ampt (Green and Ampt, 1911) infiltration equation, and the SCS curve number method (USDA, 1972).
Holts Infiltration Equation

The ANSWERS model uses a modified form of the Holts infiltration equation (Overton, 1964) to simulate the infiltration process. It can be expressed as:

$$F_{\text{MAX}} = FC + A \left( \frac{PIV}{TP} \right)^p$$  \hspace{1cm} (67)

where:

- $F_{\text{MAX}} = \text{infiltration capacity with surface inundated (cm/hr)}$,
- $FC = \text{steady state infiltration capacity (cm/hr)}$,
- $A = \text{maximum infiltration capacity in excess of FC (cm/hr)}$,
- $TP = \text{total porosity within the control depth (cm)}$,
- $PIV = \text{air remaining in the control depth before saturation (cm)}$, and
- $p = \text{empirical coefficient}$.

Six infiltration parameters have to be specified for each type of soil: total porosity, field capacity, control zone depth, steady state infiltration rate, and the two coefficients $A$ and $P$. Two major problems result from the use of Holts's equation. The first problem is the determination of $A$ and $P$. One can either use data available in literature or conduct soils tests to fit and determine these two coefficients. They are usually determined graphically by fitting predicted and measured infiltration data. The second major problem is the selection of the control zone depth. Huggins and Monke (1966) found that the control zone depth varied with cover conditions. A usual approach is to consider the control zone depth to be the depth of the A horizon. Smith (1976) comments that the Holts equation does not agree with hydraulic principles since the infiltration rate depends on the control zone depth. Baun et al. (1986) showed that runoff volume is extremely sensitive to the selection of the control zone depth. A decrease in the control depth by 33% increased the runoff volume by 87%, while an increase in the control depth by 33% decreased runoff volume by 28% (Baun et al. 1986). In the ANSWERS model, once the control zone is filled with water, then water in excess of field capacity can drain using the following equation (Huggins and Monke, 1966):

$$DR = FC \left( 1 - \frac{PIV}{GWC} \right)^3$$  \hspace{1cm} (68)

where:

- $DR = \text{drainage rate of water from the control zone (cm/hr)}$, and
- $GWC = \text{gravitational water capacity of the control zone (cm)}$.  

LITERATURE REVIEW
In ANSWERS, water drained from the control zone moves into a pool where it becomes available for tile and/or base flow.

**SCS Curve Number Method**

One of the most widely used methods to determine runoff (and infiltration) is the SCS curve number method (USDA, 1972). It was developed from data collected by the Soil Conservation Service during the late 1930's and early 1940's. The assumption is that the ratio of actual retention and maximum retention is equal to the ratio of runoff and effective precipitation (rainfall minus initial abstraction). This relationship can be expressed as:

\[
\frac{Q}{(P - I)} = \frac{F}{S}
\]  \hspace{1cm} (69)

where:

- \( Q \) = runoff volume (cm).
- \( P \) = daily precipitation (cm).
- \( I \) = initial abstraction (interception, surface retention and detention), (cm).
- \( F \) = actual retention (cm), and
- \( S \) = maximum retention (cm).

When \( P \rightarrow \infty \), the actual retention is equal to the maximum retention and both ratio \( P/(Q-I) \) and \( F/S \) are equal to one. When the rainfall approaches the initial abstraction, there is no water left for surface storage and the two ratios \( P/(Q-I) \) and \( F/S \) are equal (close) to zero. This relationship holds for the two extreme points and is assumed to hold for any intermediary point. The other relationship used, expresses that once runoff begins, all rainfall becomes either runoff or actual retention. This is expressed as:

\[
(P - I) = F + Q
\]  \hspace{1cm} (70)

Then combining Equations 69 and 70 one can derive the SCS runoff equation:

\[
Q = \frac{(P - I)^2}{(P - I + S)}
\]  \hspace{1cm} (71)

When precipitation is less than interception, the runoff volume is equal to zero. The collected data was then used to derive the following empirical relationship:

**LITERATURE REVIEW**
\[ I = 0.2 \ S \] \hspace{1cm} (72)

The most widely used equation is obtained by combining Equations 71 and 72, which yields:

\[ Q = \frac{(P - 0.2 \ S)^2}{(P + 0.8 \ S)} \] \hspace{1cm} (73)

Thus the only term required to use the SCS curve number is the maximum retention parameter. This parameter was related to a curve number (CN) by:

\[ CN = 2.34 \frac{1000}{S + 10} \] \hspace{1cm} (74)

The determination of the curve number has been widely discussed in the literature and is available for general categories of landuse. This approach was improved by Williams and Laseur (1976) by allowing the curve number to vary continuously with soil moisture.

The curve number method has been widely used because of its simplicity, and because it relates runoff to soil type, management practices, vegetation cover and density, antecedent soil moisture content, and hydrologic conditions of the watershed. Furthermore, it does not require breakpoint rainfall data. However, limitations inherent to the model make the SCS curve number method less desirable for use in hydrologic modeling.

One of the major limitations of the runoff curve number method is that the runoff is not related to time or in other terms runoff is not related to rainfall intensity or duration of the storm. This may present a major limitation for discontinuous or storms of duration larger than one day. For discontinuous storms with period of no rain longer than one hour, a new higher curve number should be selected based on the change in soil moisture content for the next period of rainfall (Rallison and Miller, 1981). Furthermore, as implemented in most models, the curve number does not change with variation in vegetal cover or management practices. It just varies with soil moisture.

Research has shown that the curve number varies with storm duration and that additional curve numbers should be developed (Rallison and Miller, 1981). Furthermore, curve numbers are not available for all areas in the United States, and many landuses lack available curve number. 

LITERATURE REVIEW
instance rangelands and forested areas in some part of the United States do not have curve numbers (Rallison and Miller, 1981). Furthermore, the curve number was developed to predict runoff from small agricultural watersheds. Thus the application of the SCS curve number method to large watersheds may be inappropriate.

Kostiakov Infiltration Equation

The Kostiakov equation (1932) can be expressed as:

\[ F = a \cdot t^b \]  \hspace{1cm} (75)

where:
- \( F \) = cumulative infiltration (cm),
- \( t \) = time since beginning of infiltration, and
- \( a, b \) = constants.

The simplicity of the equation made its use popular in flood irrigation studies. This equation requires data for calibration.

Horton Infiltration Equation

Horton (1940) proposed a three parameter infiltration equation:

\[ f = f_c + (f_0 - f_c) e^{-kt} \]  \hspace{1cm} (76)

where:
- \( f \) = infiltration rate (cm/hr)
- \( f_c \) = final infiltration rate (cm/hr)
- \( f_0 \) = initial infiltration rate (cm/hr), and
- \( K \) = constant dependent on soil type and soil moisture content.

Theoretically, \( f_c \) should remain constant at a given location, however the value of \( f_c \) changes from storm to storm.

Green-Ampt Infiltration Equation

Lately, the Green-Ampt infiltration equation has received increased attention in hydrological modeling because of the improvements made in the determination of the parameters. The Green-Ampt infiltration equation is a physically-based formula derived from Darcy’s law (Darcy, 1856). It assumes a homogeneous soil profile and a uniform distribution of the soil moisture throughout.
the soil profile. The infiltration process is modeled as a saturation wetting front crossing the soil profile. The soil moisture behind the wetting front is at saturation, while the soil moisture ahead of the wetting front is equal to the antecedent soil moisture content. The basic Green-Ampt equation to compute cumulative infiltration is:

\[ K_s t = F - N_s \ln \left( 1 + \frac{F}{N_s} \right) \]  \hspace{1cm} (77)

where:
- \( K_s \) = saturated hydraulic conductivity (cm/hr),
- \( t \) = time (hr),
- \( F \) = cumulative infiltration (cm), and
- \( N_s \) = effective matrix potential (cm).

The effective matrix potential is defined as the product of the available porosity and the wetting front capillary potential and can be expressed as:

\[ N_s = (CP - ASM) S_f \]  \hspace{1cm} (78)

where:
- \( CP \) = porosity corrected for air and rocks (vol/vol),
- \( ASM \) = antecedent soil water (vol/vol), and
- \( S_f \) = wetting front capillary potential (cm).

The wetting front capillary potential represents the suction gradient which pulls the water from the saturated zone to the unsaturated zone (the two zones are separated by the wetting front). The infiltration rate can then be obtained by differentiating Equation 77 with respect to time. This leads to the following expression of the infiltration rate:

\[ f = K_s \left( 1 + \frac{N_s}{F} \right) \]  \hspace{1cm} (79)

where \( f \) represents the infiltration rate (cm/hr). The original Green-Ampt equation was developed considering that the surface was ponded when infiltration started. The equation was modified by Mein and Larson (1971) to consider ponding. Prior to ponding, the infiltration rate is equal to the rainfall rate. After ponding, the infiltration rate and cumulative infiltration can be determined.
using Equations 77 and 79. Ponding occurs when the rainfall rate is equal to the infiltration rate. Thus, from Equation 77, one can derive the cumulative infiltration when ponding occurs:

$$F_p = \frac{N_s}{\frac{R}{K_s} - 1}$$  \hspace{1cm} (80)

The time of ponding ($t_p$) is then determined by dividing the cumulative depth ($F_p$) by the rainfall rate ($R$). An equivalent time ($t_p'$) which corresponds to the time required to infiltrate $F_p$ under ponded conditions, is computed using Equation 76. The Mein and Larson (1971) infiltration equation can then be expressed as:

$$K_s (t - t_p + t'_p) = F - N_s \ln \left( 1 + \frac{F}{N_s} \right)$$  \hspace{1cm} (81)

**Philip's Equation**

Philip (1957) solved the partial differential equation of soil moisture flow and used the first two terms of the infinite series solution as an approximation for infiltration rate:

$$f = \frac{S}{2} t^{-1/2} + C$$  \hspace{1cm} (82)

where:

- $f$ = infiltration rate (cm/hr),
- $S$ = soil sorptivity (cm hr$^{0.5}$),
- $t$ = time since beginning of infiltration (hr), and
- $C$ = constant dependent on soil characteristics and moisture condition (cm/hr).

The Philip equation was developed for a deep homogeneous soil, with uniform initial moisture content and for a ponded surface.

**Richards Equation**

The Richards equation (Richards, 1931) was derived from a combination of Darcy's law and the continuity equation. It can be expressed as:
\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D(\theta) \frac{\partial \theta}{\partial z}\right) + \frac{\partial K}{\partial z}
\]

where:

\[
\begin{align*}
\theta &= \text{volumetric soil water content}, \\
t &= \text{time}, \\
D(\theta) &= \text{soil water diffusivity}, \\
K &= \text{hydraulic conductivity, and} \\
z &= \text{distance from an arbitrary reference plane}.
\end{align*}
\]

Many researchers have numerically solved Richards equation. Smith and Whoolhisier (1971) solved Richards equation for rainfall ponding surface conditions and Whisler and Klute (1965) solved the equation for nonuniform initial moisture content.

SUMMARY

Many techniques are available for determining infiltration, but only few tests have been conducted to evaluate all these infiltration equations simultaneously for identical experimental conditions. Skaggs et al. (1969) evaluated the Green-Ampt, Horton, Philip and Holtan infiltration equations for several different soils, at varying initial soil moisture and surface conditions. All the equations performed satisfactorily, especially for short duration simulations. However, the authors emphasized the difficulty of determining accurately the value of the control depth for the Holtan equation. According to Skaggs et al. (1969), the control depth is affected by surface compaction and crustling, and the control depth is less than the depth of the A horizon for shallow soils. A study conducted by Whisler and Bouwer (1970) concluded that the Green-Ampt method performed better than the Philip equation and is easier to use. During the same study, Whisler and Bouwer (1970) found that numerical solutions to the Richards equation were in closer agreement with the observed data than the Philip and Green-Ampt equations. However, applicability of the Richards equation to watershed modeling is limited due to the enormous computation time required to solve the equation and the difficulty associated with the determination of the parameters involved in the Richards equation.
EVAPOTRANSPIRATION

INTRODUCTION

Evapotranspiration (ET) is a combination of two processes: evaporation and transpiration. Evaporation can be defined as the net rate of water transfer from the liquid to the gaseous phase. Transpiration is the transfer of water vapor by the plants through their stomatal system to the atmosphere. Evapotranspiration, which is the variable of interest in most hydrological models, is the combination of evaporation and transpiration.

Evapotranspiration is an extremely important hydrologic component. More than 50% of the total amount of rain is returned to the atmosphere through ET. Evapotranspiration is also an important aspect of hydrological modeling, especially when simulating watershed hydrology on a continuous basis. Event oriented models do not consider ET, since during rainfall events ET is negligible. But in continuous models, ET is a major process that depletes soil moisture and affects soil moisture redistribution. Modeling ET is therefore a necessity for continuous models.

Evapotranspiration is controlled by energy input and water availability. Saxton and McGuinness (1982) found that three sets of variables should be considered to compute ET: variables related to the determination of potential ET, variables related to the plant and soil-water interaction, and variables related to the soil-water characteristics.

Potential ET is the amount of water lost when water is not limiting plant growth and development. Potential ET is defined by Penman (1956) as "the amount of water transpired per unit time by a short green crop, completely shading the ground, of uniform height and never short of water". It is controlled only by meteorological factors. Net radiation is the primary climatic factor controlling ET (Jensen, 1973). Solar radiation provides the necessary heat for water evaporation and transpiration (evaporation of water requires 585 cal g⁻¹ at 20° C). Evaporation from the soil can be divided into two stages. During the first stage, water is not limiting and evaporation is affected by hydraulic properties of the soil and the amount of energy available. During the second stage, also referred to as the falling stage, the evaporation rate is no longer controlled by meteorological factors, but rather by soil characteristics, especially hydraulic conductivity (Jensen,
1973). Some authors consider a third stage, which corresponds to a stage where water is limiting, and evaporation occurs at a constant rate (Gardner and Hillel, 1962). There are several methods to estimate potential ET and they can be classified into five categories:

- evaporation method,
- radiation method,
- temperature method,
- humidity method, and
- combination method.

EVAPORATION METHOD

Pan Evaporation

Pan evaporation is among the oldest methods to estimate potential ET. Potential ET (PET) is found by multiplying pan evaporation (PE) from a standardized pan by a pan coefficient $C_{ET}$. Thus, PET can be expressed as:

$$PET = C_{ET} \times PE$$  \hspace{1cm} (84)

The coefficient $C_{ET}$ is used to adjust for the higher exposure and lower reflectance of free evaporating surface compared to a well wetted vegetated surface. Extensive research has been conducted to determine $C_{ET}$ and values can be found in the literature. Empirical equations were also developed to relate the pan coefficient to climatological data (Penman, 1948; Christiansen, 1968).

TEMPERATURE METHOD

Several methods were developed to compute ET based on a vertical energy budget of a vegetated surface.

Blaney-Criddle Method

Blaney-Criddle (1966) developed a formula relating potential evaporation to the mean monthly temperature. This formula is widely used for irrigation planning in arid regions of the western U.S. and is expressed as:
\[ \text{PET} = k \, p \, \frac{45.7 \, t + 813}{100} \]  

(85)

where:

- \( \text{PET} \) = potential ET (mm),
- \( k \) = consumptive-use coefficient,
- \( p \) = mean monthly annual daytime hours of the year (%), and
- \( t \) = mean monthly temperature (°K).

The coefficient \( k \) represents the effects of the climate and plant growth on ET.

**Thornthwaite Method**

Thornthwaite (1948) expressed ET as a function of mean monthly temperature. This equation was developed for valleys of the east central U.S. One of the assumptions of the method is that the rate of ET is not affected by advection of moist or dry air. Jensen (1973) cautions about the use of the Thornthwaite equation in arid or semi-arid climates. The Thornthwaite equation can be expressed as:

\[ \text{PET} = 1.6 \, L_d \left( \frac{10 \, T}{I} \right)^a \]  

(86)

where:

- \( \text{PET} \) = evapotranspiration (30 day),
- \( L_d \) = daytime hours,
- \( T \) = mean monthly temperature (°C), and
- \( I \) = heat index (based on temperature).

The value of \( a \) is determined by:

\[ a = 0.000000675 \, I^3 - 0.0000771 \, I^2 + 0.01792 \, I + 0.49239 \]  

(87)

**RADIATION METHODS**

**Jensen and Haise Method**

The Jensen and Haise (1963) equation was developed to estimate PET in high altitude regions of...
the western U.S. It can be expressed as:

$$\text{PET} = (0.025 \ T + 0.078) \ R_s$$  \hspace{1cm} (88)

where:
- $\text{PET}$ = potential evapotranspiration (cm/day),
- $T$ = mean air temperature ($^\circ$C), and
- $R_s$ = solar radiation (cm/day).

This equation should be used to estimate PET for periods of 5 days or longer.

**Turc Method**

Turc (1961) proposed the following relationship:

$$\text{PET} = 0.40 \ T \frac{R_s + 50}{T + 15}$$  \hspace{1cm} (89)

where:
- $\text{PET}$ = evapotranspiration (mm/month),
- $T$ = mean monthly air temperature ($^\circ$C), and
- $R_s$ = solar radiation (l).

This equation assumes a mean relative humidity higher than 50%, which is the case in most temperate climates. Turc also developed an equation for average relative humidity less than 50%.

**HUMIDITY METHOD**

**Halstead Method**

Halstead (1951) expressed evapotranspiration as a function of the saturation deficit:

$$\text{ETP} = d_i (q_{\text{max}} - q_{\text{min}})$$  \hspace{1cm} (90)

where:
- $\text{ETP}$ = mm/month,
- $q_{\text{max}}$ = saturation absolute humidity at maximum air temperature,
- $q_{\text{min}}$ = saturation absolute humidity at minimum air temperature, and
- $d_i$ = fraction of annual daylight hours.
COMBINATION METHOD

Penman Equation

Penman (1948 and 1956) developed an equation which combines both the aerodynamic profile method and the vertical energy budget method. Penman relates the potential evapotranspiration to temperature, humidity, wind velocity, vapor pressure, and solar radiation. Penman's equation can be expressed as:

\[
\text{PET} = \frac{E R_n + \frac{(7.12 d_s U_s)}{\ln \left( \frac{Z_a - d}{Z_0} \right)}}{583 (1 + E)}
\]  

(91)

where:

- \( \text{PET} \) = evapotranspiration (cm/day),
- \( E \) = slope of psychometric saturation line over psychometric constant,
- \( R_n \) = net radiation (cal/cm\(^2\)/day),
- \( d_s \) = vapor pressure deficit (bars),
- \( U_s \) = horizontal wind movement at elevation \( Z_a \) (km/day),
- \( Z_a \) = anemometer height above soil (cm),
- \( d \) = wind profile displacement height (cm), and
- \( Z_0 \) = wind profile roughness height (cm).

Ritchie's Method

One of the most implemented evapotranspiration methods in hydrological models is Ritchie's method (Ritchie, 1972), an approximation of the Penman combination equation. It neglects wind speed and potential ET is determined based on the leaf area index. Ritchie's model computes soil evaporation and plant transpiration separately. Evapotranspiration is computed by:

\[
E_0 = \frac{0.0504 H_0 \Delta}{0.65 + \Delta}
\]  

(92)

where:

- \( E_0 \) = potential evapotranspiration (cm),
- \( H_0 \) = net solar radiation (l), and
- \( \Delta \) = slope of the saturation vapor pressure curve at the mean air temperature.

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\[ \Delta = \frac{5304}{T^2} \exp \left( 21.55 - \frac{5304}{T} \right) \] (93)

where \( T \) is the daily temperature (°K).

The net solar radiation is determined by:

\[ H_0 = \frac{(1 - \lambda) \, R}{c} \] (94)

where:
- \( R \) = daily solar radiation (l),
- \( \lambda \) = albedo, and
- \( c \) = 22.95.

Soil evaporation is assumed to take place in two different stages. In the first or constant rate stage, soil evaporation is just limited by the amount of energy available. Thus, the soil is evaporating at a rate at least equal to the potential evaporation rate. The potential soil evaporation is computed by:

\[ E_{so} = E_0 \, e^{(-0.4 \, \text{LAI})} \] (95)

where:
- \( E_{so} \) = potential soil evaporation (cm), and
- \( \text{LAI} \) = leaf area index (ratio of plant leaf area and soil surface area).

The soil during the first stage evaporates at the potential rate. The upper limit of the first stage, \( U \), is determined by:

\[ U = 0.9 \, (\alpha_s - 3)^{0.42} \] (96)

where:
- \( U \) = first stage upper limit (cm), and
- \( \alpha_s \) = soil evaporation parameter (cm/day^{0.5}).

The soil evaporation parameter depends on soil water transmission characteristics. When the cumulative soil evaporation exceeds the upper limit of first stage (U), the second stage begins.

The second stage begins when the surface starts to dry, and water from within the soil starts to evaporate. During the second stage, also called the falling rate stage, the soil evaporation rate is
given by:

\[ E_s = \alpha_n \left( t^{0.5} - (t - 1)^{0.5} \right) \]  

(97)

where:

- \( E_s \) = soil evaporation rate for day \( t \) (cm/day), and
- \( t \) = number of days since stage two evaporation started (days).

The potential plant transpiration, \( EP_0 \), is given by:

\[ EP_0 = \frac{E_0 \cdot LAI}{3} \quad 0 \leq LAI \leq 3 \]  

(98)

and

\[ EP_0 = E_0 - E_s \quad \text{LAI} > 3 \]  

(99)

If soil moisture is a limiting factor, the plant transpiration is reduced to:

\[ E_p = \frac{EP_0 \cdot SW}{0.25 \cdot FC} \quad \text{SW} \leq 0.25 \cdot FC \]  

(100)

where:

- \( E_p \) = plant transpiration (cm),
- \( SW \) = current soil water in the root zone (cm), and
- \( FC \) = field capacity of the soil (cm).

SUMMARY

Jensen (1973) conducted an extensive review of 15 different ET modeling techniques. The results show that the combination methods are the best in most climatic conditions. Penman ranked fifth out of fifteen in predicting ET from coastal areas, and second in inland arid to semi-arid climates. However, Jensen (1973) recommended local calibration of the wind and vapor deficit component. Pruitt and Doreenboos (1977) insist upon the need of local calibration of ET equations in order to produce reliable estimates of ET.
MODEL DEVELOPMENT

INTRODUCTION

Based on the results of the literature review, the ANSWERS model was selected as the best available model from which to develop the proposed distributed parameter, continuous simulation, NPS planning model. ANSWERS was selected because it has sound, process-oriented hydrologic and sediment transport models and because its structured design facilitates incorporation of new components. AGNPS was judged to be unsuitable because it is dependent on the curve number method to estimate runoff and its sediment model is based on the empirical Modified Universal Soil Loss Equation. FESHM was not selected because it is not currently a supported model and it has not been widely used.

THE ANSWERS MODEL

ANSWERS (Beasley et al., 1980; 1982; Dillaha and Beasley, 1982; Storm et al., 1988) is a process-oriented, distributed parameter, event-oriented model developed to simulate the effects of BMPs on runoff and sediment loss in agricultural watersheds. The following description of the version of the ANSWERS model used in this research is taken largely from the ANSWERS User’s Manual (Beasley and Huggins, 1981). For a more detailed description of the hydrologic and sediment transport portions of the ANSWERS model, the reader is referred to the ANSWERS User’s Manual or Dillaha and Beasley (1982). In addition to the components of the ANSWERS model described below, the public version of the ANSWERS model also contains components for simulating interflow, tile flow and select structural BMPs. These components were not included in the model developed in this research because they were judged to be too inaccurate due to their lack of a process-oriented or even empirical basis.

The ANSWERS model is based on the hypothesis that: "At every point within a watershed, relationships exist between water flow rates and those hydrologic parameters which govern them e.g., rainfall intensity, infiltration, topography, soil type, etc. Furthermore, these flow rates can be utilized in conjunction with appropriate component relationships as the basis for modeling other transport-related phenomena such as soil erosion and chemical movement within that watershed"
(Beasley and Huggins, 1981). To apply this approach in a practical manner, ANSWERS relaxes the point concept to refer to watershed elements up to one hectare in size. An element is defined as a homogeneous area within which all hydrologically significant parameters are approximately uniform. A watershed is modeled as a matrix of these square elements. The square element shape was selected to simplify data file preparation and computations.

Component relationships representing important physical processes are used to characterize the movement of water and sediment within and from each individual element. Parameter values vary in an unrestricted manner between elements; thus, any degree of spatial variability within a watershed can be represented. Outflow from each element is integrated to obtain overall watershed response. Element interaction occurs because surface flow (overland and channel), flow in tile lines and groundwater flow from each element becomes inflow to its adjacent elements. Pollutants are generated and transported by these flows and by raindrop impact.

HYDROLOGIC MODEL

Hydrologic processes represented in the ANSWERS model are depicted in Figure 3. After rainfall begins, some precipitation is intercepted by the vegetal canopy until the interception storage potential is satisfied. As rainfall proceeds, infiltration decreases until it equals the rainfall rate. At this point water begins to accumulate on the surface in micro-depressions. Once the capacity of the micro-depressions is exceeded, runoff begins. The accumulated water in excess of surface retention capacity, surface detention, produces surface runoff. When rainfall ceases, the water in surface detention begins to dissipate until surface runoff ceases altogether. However, infiltration continues until all the depressional water has infiltrated. Infiltration is modeled using Holan’s infiltration equation (Equation 67) described in the literature review. Water in the soil moisture control zone in excess of field capacity drains from the control zone in accordance with Equation 68.

The net rainfall rate reaching the ground surface is dependent on the user specified pluviograph(s) and on interception. Each element has a raingage identifier identifying the raingage that determines the storm pattern for that particular element. Up to 4 raingages are permitted, but typically only one is used.
Figure 3. Flow chart for the hydrology component of the ANSWERS model.
Surface detention is the water volume which must build up to sustain overland flow. Detention depth is calculated as the total volume of surface water in an element, minus the retention volume (which can only infiltrate), divided by the area of the element. This implies that the entire specified retention volume of an element be filled before any water becomes available for surface detention and runoff. ANSWERS uses a surface detention model developed by Huggins and Monke (1966) to describe the surface storage potential of a surface as a function of the water depth on the soil surface.

Mathematically, each element's hydraulic response is computed, as a function of time, by an explicit, backward difference solution of the continuity equation combined with a stage-discharge relationship. Manning's equation is used as the stage-discharge equation for both overland and channel flow routing. The hydraulic radius in Manning's equation is assumed equal to the average detention depth in the element.

In ANSWERS, a watershed is divided into an irregular matrix of square elements. Every element acts as an overland flow plane with a user specified slope and slope direction. Channel elements collect flow from overland flow elements and route the runoff to the watershed outlet. Elements with channel flow act as dual elements. These elements act as ordinary overland flow elements, with the restriction that all overland flow from the element passes into the element's channel element. Channel elements are described in terms of their slope, width and Manning's roughness coefficient. Typically, rather than having a unique set of values for each channel segment, they are grouped into reaches with similar coefficients.

SEDIMENT MODEL

The version of the ANSWERS model used in this research uses the expanded sediment transport model that simulates differential detachment and transport of the various particle size classes. The expanded sediment transport model is based on the Yalin (1963) model and is described in detail by Dillaha (1981) and Dillaha and Beasley (1983) and in the ANSWERS User's Manual (Beasley and Huggins, 1981).

Soil detachment, transport, and deposition are modeled as a function of the precipitation and the
runoff process. Sediment detachment and transport are the result of raindrop impact and overland flow. Detachment by raindrop impact occurs throughout a storm, even when there is no overland flow. Soil particles detached prior to initiation of overland flow are assumed to reattach to the soil mass. Detachment of soil particles by overland flow occurs when the shear stress due to overland flow exceeds the gravitational and cohesive forces of the soil mass. Detachment of soil particles by raindrop impact and by overland flow are calculated using relationships developed by Meyer and Wischmeier (1969).

Whether or not a detached soil particle moves, depends on the sediment load in the flow and the flow’s sediment transport capacity. Sediment leaving an element is assumed to be transported as either overland flow or channel flow. All sediment from an element either moves into an element’s channel element, if a channel is present, or to adjacent downslope elements if no channel is specified.

Once a soil particle has been detached, sufficient energy must be available to transport it or the particle will be deposited. The transport of sediment by overland flow is self-regulating, i.e. soil particle detachment by overland flow does not occur unless there is excess energy available in addition to the amount required to transport suspended sediments. Within an element the material available for transport is the combination of that detached within the element and that which enters with inflow from adjacent elements.

Once the available detached sediment within an element is known, the transport capacity is computed. If it is insufficient to carry the available material, the excess is deposited in the element. The overall accounting relationship for this process is the differential form of the continuity equation as applied above to water flow. Sediment carried out of an element is apportioned between adjacent elements in direct proportion to the overland flow flowing to adjacent cells.

In the ANSWERS model, sediment is transported in two related forms: bedload and suspended load. Bedload is assumed to moves along the bottom of the flow by saltation, rolling and sliding and is assumed to be composed of the larger soil particles (sand, gravel, and aggregates). Bedload transport is highly transport dependent and a decrease in transport capacity is assumed to result
in the immediate deposition of the excess bedload.

Suspended load is assumed to be distributed throughout the flow depth and a decrease in the transport capacity does not result in an immediate deposition of suspended sediment. This delay is the result of the small fall velocities of most suspended particles. Fines such as clay size particles have such small fall velocities, that they are effectively permanently suspended. In the ANSWERS model, primary clay and silt less than 10 microns in diameter, are considered to be washload and are not allowed to deposit unless the flow rate was zero. This means that the yield of primary clay and small silt particles is determined entirely by their weight fraction in the original soil mass and the total amount of detachment.

The fraction of particles larger than 10 microns that are deposited when there is a transport capacity deficit is calculated using an equation developed to describe the settling efficiency of discrete particles in water (Weber, 1972). The rate at which sediment is transported by flow is assumed to be a function of both the sediment supply rate and the transport capacity of the flow. The net rate of movement is proportional to the lesser of the transport or the rate at which the particles are available for transport.

Sediment transport in the ANSWERS model is calculated using a modification of Yalin's equation (Yalin, 1963). Yalin's equation was developed to describe bedload transport of uniform, cohesionless grains over a movable bed for steady, uniform flow of a viscous fluid. Foster and Meyer (1972) developed a method by which Yalin's equation could be used to predict the transport capacity of each particle size class in a mixed sediment. This procedure is used in the ANSWERS expanded sediment transport model.

A flow chart of the ANSWERS extended sediment transport is presented in Figure 4. The basic assumptions of the ANSWERS sediment transport model are:

1. The particle size distribution of detached sediment is the same as the weight fractions of the soil particles in the original soil mass (no enrichment during detachment).
2. Rainfall detachment is not limited by the transport capacity of the flow.
3. Flow detachment occurs only if there is excess transport capacity and can never exceed
Figure 4. Flow chart for the sediment detachment and transport (Dilaha, 1981)
the transport capacity excess.
4. Deposition and flow detachment never occur at the same time for the same particle.
5. Washload transport is independent of the transport capacity of the flow and does not influence the transport of the larger particles.
6. Deposited sediment requires the same amount of energy as in the original detachment to become redetached.
7. Enrichment is controlled by the deposition process.
8. The rate at which a particle will deposit is proportional to its fall velocity.
9. Channel erosion does not occur.

INfiltration Component

The ANSWERS model currently uses the Holtan infiltration equation. A major problem with the use of the Holtan equation is the selection of the control zone depth. Huggins and Monke (1966) found that the control zone depth was a function of cover conditions. The ANSWERS user's manual recommends use of one half of the A horizon depth as the control zone depth. Another model using Holtan's method, FESHM (Ross et al., 1982), considers the control zone depth to be the depth of the A horizon. The subjectivity in the choice of the control zone depth is a major limitation of Holtan's equation. In addition to the problem regarding the selection of the appropriate control depth, Smith (1976) suggests that Holtan's equation does not agree with hydraulic principles since the infiltration rate depends on the control zone depth. This may present a major limitation when using ANSWERS on ungaged watersheds, and an alternative approach to simulate infiltration seems appropriate.

None of the empirical equations mentioned in the previous chapter, including the Kostiakov (Kostiakov, 1932) and Horton (Horton, 1940) infiltration equations, were considered potential replacements for Holtan's equation because these methods require calibration, and they have never been used for modeling infiltration on large watersheds. The SCS curve number method was not selected either because it is does not consider the effects of rainfall intensity on infiltration. In addition, the curve number has no physical significance and values have not been developed for common management practices. Thus, it is very difficult, if not impossible, to accurately reflect the effects of BMPs on infiltration using the curve number approach.
The Richards equation was not selected because its use is impractical due to numerical complexity, computer requirements, and the difficulty involved in the determination of soil parameters. It would also be difficult to estimate the effects of BMPs on the Richards equation parameters.

The Green-Ampt infiltration equation was chosen for implementation in the ANSWERS model for three major reasons: it is a physically-based approach, computationally efficient, and its parameters can be determined from readily available soil and vegetal cover information. Furthermore, it has been tested for a wide variety of conditions, and it has successfully simulated the effects of different management practices on infiltration. The CREAMS model was run using the Green-Ampt option to simulate runoff on 9 different watersheds located in five states. The annual mean runoff $R^2$ ranged from 0.63 to 0.898. Rawls and Brakensiek (1986) used 330 runoff events from 17 watersheds to compare the predictions of the Green-Ampt and Curve number approaches. Management practices present on the different watersheds included mulching and contouring. The $R^2$ between the measured runoff and the runoff predicted by the Green-Ampt infiltration equation was 0.76 on cropland, 0.51 on pasture, and 0.66 on areas with combined cropland and pasture. The following section describes the version of Green-Ampt infiltration model that was incorporated into the ANSWERS model.

Green-Ampt computes infiltration by:

$$K_e = F - N_s \ln \left( 1 + \frac{F}{N_s} \right)$$  \hspace{1cm} (101)

where:

- $K_e$ = effective saturated hydraulic conductivity (cm/hr),
- $t$ = time (hr),
- $F$ = cumulative infiltration (cm), and
- $N_s$ = effective matrix potential (cm).

The effective hydraulic conductivity is a function of the saturated hydraulic conductivity. The saturated hydraulic conductivity can be estimated from field tests or values found in the literature. Saturated hydraulic conductivity can also be determined from soil properties using the following statistical regression equation developed by Rawls and Baumer (1989):
\[ K_s = 0.0002 \ C^2 \ \frac{(CP - RW)^3}{(1 - CP)^2} \left( \frac{BD}{RW} \right)^2 \]  

where:

- \( K_s \) = saturated hydraulic conductivity (cm/hr),
- \( CP \) = effective porosity (cm),
- \( BD \) = bulk density (g/cm\(^3\)),
- \( RW \) = residual soil water (cm), and
- \( C \) = soil texture coefficient.

The soil texture coefficient is determined using an equation developed by Rawls and Baume (1989):

\[
C = -0.17 + 0.181 \ CL - 0.00000069 \ SA^2 \ CL^2 \\
- 0.0000041 \ SA^2 \ SI^2 + 0.000118 \ SA^2 \ BD^2 \\
+ 0.00069 \ CL^2 \ BD^2 + 0.000049 \ SA^2 \ CL^2 \\
- 0.000085 \ SI \ CL^2
\]  

where:

- \( CL \) = clay fraction (%),
- \( SA \) = sand fraction (%), and
- \( SI \) = silt fraction (%).

The saturated hydraulic conductivity is adjusted to account for the influence of the vegetal cover that affects the speed and kinetic energy of impacting raindrops and surface crusting. The effective hydraulic conductivity for an area under canopy cover \( (K_c) \) is computed using the following equation (Rawls et al., 1989):

\[
K_c = K_s \ C_t \left[ \frac{B_c}{A_c} C_t + MPF \left(1 - \frac{B_c}{A_c} \right) \right]
\]  

where:

- \( MPF \) = macroporosity factor,
- \( B_c \) = bare area under canopy (%),
- \( A_c \) = canopy area (%),
- \( C_t \) = crust reduction factor, and
- \( C_f \) = canopy factor.

The macroporosity factor is determined by:
MPF \approx \exp (0.96 - 0.032 \text{ SA} + 0.04 \text{ CL} - 0.032 \text{ BD}) \quad (105)

where all the parameters are as previously defined. The crust reduction factor is computed as (Brakensiek and Rawls, 1983):

\[
C_r = \frac{L}{L - Z_c + \frac{Z_c}{SC} + \frac{b}{b}} \quad (106)
\]

where:

- \(L\) = average depth to wetting front (cm),
- \(Z_c\) = crust thickness (assumed to be 1 cm),
- \(SC\) = correction factor for partial saturation of the subcrust soil, and
- \(b\) = crust factor.

The average depth to the wetting front, \(L\), is expressed as (Rawls et al., 1989):

\[
L = 14.7 - 0.0015 \text{ SA}^2 - 0.3 \text{ CL BD} \quad (107)
\]

The correction factor for partial saturation of the subcrust soil (SC) is determined by (Rawls et al., 1989):

\[
SC = 0.736 + 0.0019 \text{ SA} \quad (108)
\]

The crust factor, \(b\), is computed by (Rawls et al., 1989):

\[
b = 0.0099 - 0.0721 Z_c + 0.0000068 \text{ SA}^2 \\
+ 0.000021 \text{ SA}^2 Z_c - 0.000315 S Z_c^2 \quad (109)
\]

The canopy factor used to determine the hydraulic conductivity in the area under canopy is defined as (Rawls et al., 1989):

\[
C_f = 1 + \frac{A_c}{A_0 + A_c} \quad (110)
\]

where \(A_0\) represents the area outside the canopy in percent. The effective hydraulic conductivity for the area outside the canopy (\(K_0\)) is computed by (Rawls et al., 1989):

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\[ K_0 = K_0 \left[ \frac{B_0}{A_0} C_r + MPF \left( 1 - \frac{B_c}{A_c} \right) \right] \]  

(111)

where \( B_0 \) represents the bare area outside canopy in percent. The total effective hydraulic conductivity is determined by combining Equations 104 and 111:

\[ K_e = A_c \frac{K_C}{A_0} + A_0 \frac{K_0}{A_0} \]  

(112)

The effective matrix potential, \( N_m \), is defined as the product of the available porosity (difference between the porosity corrected for rocks and the antecedent soil moisture content) and the wetting front capillary potential, \( S_f \) (Brakensiek et al., 1986):

\[ N_m = (CP - ASM) S_f \]  

(113)

where:

\( CP \) = effective porosity (vol/vol),
\( ASM \) = antecedent soil water (vol/vol), and
\( S_f \) = wetting front capillary potential (cm).

The available effective porosity, \( CP \), is determined by (Brakensiek and Rawls, 1983):

\[ CP = POR \ast CFC \ast EAC \]  

(114)

where:

\( POR \) = total porosity (vol/vol),
\( CFC \) = correction for coarse fragments, and
\( EAC \) = correction for entrapped air.

Brakensiek et al. (1986) developed an equation to compute CFC:

\[ CFC = 1.0 - \frac{VCF}{100} \]  

(115)

where \( VCF \) represents the volume of coarse fragments ( > 2mm). It is determined by:

\[ VCF = \frac{100 \frac{WCF}{2.65}}{100 - \frac{WCF}{BD} + \frac{WCF}{2.65}} \]  

(116)

where \( WCF \) represents the coarse fragment fraction (%).
The correction for entrapped air was expressed by Rawls and Baumer (1989) as:

\[ EAC = 1.0 - \frac{3.8 + 0.00019 \ \text{CL}^2 - 0.337 \ \text{SA} + 0.126 \ \text{CEC} + \frac{\text{OM} \ \text{SA}^2}{200}}{100} \]  

(117)

where:
- \( \text{OM} \) = organic matter content (%), and
- \( \text{CEC} \) = cation exchange capacity.

The cation exchange capacity, \( \text{CEC} \), is determined by:

\[ \text{CEC} = \frac{1}{6} (0.0059 \ \text{CL} + 0.041) \]  

(118)

The capillary potential at the wetting front is determined using an empirical equation developed by Rawls and Brakensiek (1985):

\[ S_r = \exp (x) \]  

(119)

where:

\[ x = 6.531 - 7.33 \ \text{POR} + 15.8 \ \text{CL}^2 + 3.81 \ \text{POR}^2 + \]  
\[ 3.40 \ \text{CL} \ \text{SA} - 4.98 \ \text{SA} \ \text{POR} + 16.1 \ \text{SA}^2 \ \text{POR}^2 + \]  
\[ 16.0 \ \text{CL}^2 \ \text{POR}^2 - 14.0 \ \text{SA}^2 \ \text{CL} - 34.8 \ \text{CL}^2 \ \text{POR} - \]  
\[ 8.0 \ \text{SA}^2 \ \text{POR} \]  

(120)

At each time step, Equation 101 is solved using Newton’s iteration technique to determine the cumulative infiltration depth, \( F \). The infiltration rate is obtained by differentiating \( F \) with respect to time. The resulting expression for the infiltration rate is:

\[ f = K_s \left( 1 + \frac{N_s}{F} \right) \]  

(121)

where \( f \) is the infiltration rate (cm/hr). The original Green-Ampt equation was developed considering that the surface was ponded when infiltration started. The equation was modified by Mein and Larson (1971) to consider infiltration under unponged conditions. Prior to ponding, infiltration is equal to the rainfall rate. After ponding, infiltration can be determined using Equations 101 and 121. Ponding occurs when the rainfall rate is equal to the infiltration rate. The cumulative infiltration at ponding, \( F_p \), is determined by Equation 80. The time of ponding,
t_p is determined by dividing the cumulative depth of infiltration at ponding by the rainfall rate and is expressed as follows:

\[ t_p = \frac{F_p}{R} \]  \hspace{1cm} (122)

where R represents the rainfall rate (cm/hr). An equivalent time to ponding, \( t'_p \), which represents the time it would take to infiltrate \( F_p \) under ponded conditions is computed by:

\[ t'_p = \frac{F_p - N_s \ln \left( 1 + \frac{F_p}{N_s} \right)}{K_s} \]  \hspace{1cm} (123)

The Mein and Larson (1971) infiltration equation can then be expressed as:

\[ K_s (t - t_p + t'_p) = F - N_s \ln \left( 1 + \frac{F}{N_s} \right) \]  \hspace{1cm} (124)

If soil moisture content exceeds field capacity, there is potential for percolation. The rate of percolation depends on the amount of water in excess of field capacity. The percolation component was taken from the WEPP model (Savabi et al., 1989). The hydraulic conductivity which regulates the travel time of water through the soil matrix varies from \( K_s \) at saturation, to zero at field capacity and is expressed as:

\[ RKFC = KS \theta (-2.6SS / \log(FCAP)) \]  \hspace{1cm} (125)

where:

- \( RKFC \) = adjusted hydraulic conductivity (cm/hr),
- \( \theta \) = soil moisture content (% saturation), and
- \( FCAP \) = field capacity (% saturation).

Travel time of water through the soil layer is computed using a linear storage equation:

\[ t = \frac{\theta - FCAP}{RKFC} \text{ POR} \]  \hspace{1cm} (126)

where \( t \) represents the travel time in hours and POR represents the porosity in cm. The percolation during the travel time is then determined using an exponential function:
\[
DR = (\theta - FCAP) \left[ 1 - \exp\left(-\frac{\Delta t}{t}\right) \right]
\]

where:
\[
\begin{align*}
DR & = \text{percolation rate (cm/hr), and} \\
\Delta t & = \text{time increment (hr)}. \\
\end{align*}
\]

**EVAPOTRANSPIRATION MODEL**

Evapotranspiration was added to make ANSWERS a continuous model. Several methods are available for determining ET, including pan evaporation, Ture (Ture, 1961), and Thornwaite (Thornwaite, 1948) methods. However, these methods require local calibration to estimate evapotranspiration accurately. Furthermore, none of these methods give estimates of both soil evaporation and plant transpiration. As discussed in the literature review, Jensen (1973) concluded that the combination methods are the best methods for estimating ET in most climatic conditions. The Ritchie method (Ritchie, 1972) was selected over the Penman method (Penman, 1946), because it is a simpler model and requires fewer input parameters. Furthermore, Ritchie's approach has been used extensively in hydrologic models (CREAMS, EPIC, WEPP). The only inputs required to determine ET are daily temperature, solar radiation, and leaf area index. Since Ritchie's model is so widely used, values of the leaf area index are readily available for important crops. Furthermore, Ritchie's model separates plant transpiration and soil evaporation. Plant transpiration is a major factor in the determination of plant nutrient uptake, which affects the amount of nutrients available for leaching and loss in runoff.

Ritchie's method is among the most commonly used methods to model ET. It has been used extensively in field scale and watershed scale models. It computes evaporation and transpiration separately. Potential ET is computed using Equation 92. Potential ET is partitioned between soil evaporation and plant transpiration. Potential soil evaporation is based on the leaf area index and is determined by Equation 95. Leaf area index is input to the model and is used to simulate plant growth. Soil evaporation is assumed to occur in two different stages. The upper limit of the first stage evaporation is given by Equation 96. The upper limit is based on the soil evaporation parameter. The soil evaporation parameter, also called soil transmissivity, depends on soil texture and is given by Savabie et al. (1989) as:

**MODEL DEVELOPMENT**
α = 4.165 + 0.02456 SA - 0.01703 CL - 0.0004 SA² \quad (128)

During the first stage, the soil evaporates at potential evaporation until the accumulative evaporative depth reaches the first stage upper limit. The second stage starts once the surface starts to dry, and water from within the soil starts to evaporate. During the second stage, also called the falling rate stage, the soil evaporation rate depends on the number of days since the second stage started and the soil evaporation parameter. The evaporation during the second stage is determined by Equation 97. Evaporation affects the soil profile to a depth, which is referred to as maximum evaporative depth, \( d_x \) (cm), and is given by Savabi et al. (1989) as:

\[ d_x = 9 - 0.077 \text{ CL} + 0.0006 \text{ SA}^2 \quad (129) \]

If there is not enough water present in the maximum evaporative depth to meet the evaporation needs, evaporation is reduced accordingly.

Plant potential transpiration is computed separately from soil evaporation and is determined by Equations 98 and 99 based on the leaf area index. Transpiration cannot exceed the amount of available water present in the root zone. The root depth, according to plant development stage, is given by Borg and Williams (1986):

\[ R_d = R_dx \left( 0.5 + 0.5\sin \left( 3.03 \left( \frac{D_p}{D_m} \right) - 1.47 \right) \right) \quad (130) \]

where:
- \( R_d \) = root depth (cm),
- \( R_dx \) = maximum root depth (cm),
- \( D_m \) = number of days to reach maturity, and
- \( D_p \) = number of days after planting.

If the root zone depth exceeds the simulated soil depth, plant evaporation is reduced using an exponential function (Savabi et al., 1989) as follows:
\[ PEP_e = \frac{E_{po}}{1 - exp(-V)} \left( 1 - exp \left( -\frac{V \ D}{R_d} \right) \right) \] (131)

where:

- \( PEP_e \) = adjusted potential evapotranspiration (cm),
- \( D \) = depth of the soil profile (cm), and
- \( V \) = rate-depth parameter.

A default value of 3.065 (default value used in WEPP) was selected. This value assumes that 30% of total water use come from the top 10% of the root zone (Savabi et al., 1989).

**NUTRIENT MODEL**

A key factor involved in the selection of an approach for modeling nutrient transport and transformation was its accuracy and simplicity. Most of the models developed for modeling the N and P cycles are detailed field scale models. Since ANSWERS was modified into a continuous simulation model, it was difficult to include detailed nutrient components because of the computational requirements. Nutrient fate and transport in the new version of ANSWERS are simulated using equations presented in the latest version of GLEAMS, which was inspired by the EPIC model (Sharpley and Williams, 1990). The major N pools simulated are active organic N, ammonium, and nitrate. Mineralization is simulated as in GLEAMS and EPIC. However, EPIC simulates mineralization as a single-step process. Mineralization from the active organic pool contributes directly to the nitrate pool. GLEAMS assumes a two-step mineralization process. First, mineralization from the active organic N pool to the ammonium pool, and then nitrification, from the ammonium to the nitrate pool. But testing of the approach used in the GLEAMS model to simulate nitrification resulted in excessive nitrification and a rapid disappearance of the ammonium pool. Consequently, a different approach developed by Duffy et al. (1975) was selected because of its simplicity. Denitrification was simulated using the approach in EPIC and GLEAMS. An approach similar to that of GLEAMS was used to simulate loss of dissolved nutrients in runoff and infiltration. Transport of sediment-bound organic N, ammonium and phosphate is similar to the method described by Storm et al. (1988) and Dilla et al. (1988). The pools simulated include labile P, active organic P, stable inorganic P and active inorganic P. Mineralization of organic P is simulated as in GLEAMS. The dissolved and sediment-bound P are simulated using the same approaches as those used for sediment-bound and dissolved N.
SEDIMENT-BOUND NUTRIENT MODEL

No changes were made to the sediment detachment and transport models in ANSWERS. However, the model was modified to allow seasonal variation of the C factor. The C factor (crop management factor) is varied from a maximum value at planting day to a minimum value when plants reach maturity. The C factor is assumed to vary linearly between these two values based on the leaf area index. The soil erosivity (K factor) was assumed constant and to not vary with time.

Identical approaches are used to determine sediment-bound P and N. Generic equations based on the conservation of mass are derived as follows. The conservation of mass can be expressed as:

\[ P_1 - P_0 = \frac{dP}{dt} \]  

(132)

or in the discrete form:

\[ P_{i+1} - P_{i} + 2 \frac{P_1}{dt} = P_{\text{PPT}} = P_{o2} - P_\pi + 2 \frac{P_2}{dt} \]  

(133)

where:
- \( P_1 \) = sediment-bound nutrient specie inflow (kg/s),
- \( P_0 \) = sediment-bound nutrient specie outflow (kg/s),
- \( P \) = sediment-bound nutrient specie in transit (kg),
- \( dt \) = time step (s), and
- 1,2 = initial and final value for the time increment.

The value of PPT represents the sum of the initial values of the nutrient specie under consideration. An initial test is done on the discharge at the end of the time interval. If the discharge is equal to zero, and all the sediment is deposited, no outflow occurs and no nutrients leave the cell. Referring to \( P_\pi \) as \( P_1 \), and \( P_2/dt \) as \( P_2 \) Equation 133 becomes:

\[ P_{\text{PPT}} = 2 \frac{P_2}{dt} - P_1 \]  

(134)

The nutrient in transit is then:
\[ P_2 = \frac{\text{PPT} + \text{PI}}{2} \]  

(135)

For the following time step, since there is no outflow or storage occurring, the value of PPT is set to PI.

If the discharge is positive, there is potential nutrient outflow. The input of nutrients comes from adjacent cells and/or from within the cell. Sediment-bound nutrient is generated with newly detached sediment. The amount of sediment-bound nutrient added from within the cell is expressed as:

\[ \text{PCELL} = \text{PO} \times \text{SEDNEW} \]  

(136)

where:
- \( \text{PCELL} \) = newly generated sediment-bound nutrient (kg/s),
- \( \text{SEDNEW} \) = newly generated sediment (kg/s), and
- \( \text{PO} \) = concentration of the nutrient in the cell soil (kg/kg-soil).

The sediment-bound nutrient inflow, \( P_{i2} \), is determined by:

\[ P_{i2} = \text{PI} + \text{PCELL} \]  

(137)

where PI represents the inflow from adjacent cells. The outflow of sediment-bound nutrient is determined as the concentration of sediment-bound nutrient in storage multiplied by the runoff volume which can be expressed as:

\[ P_{o2} = \frac{P_2}{S} \times Q \]  

(138)

where \( S \) represents the storage volume at the end of the time increment. The amount of sediment-bound nutrient in transit is computed by:

\[ P_2 = \frac{\text{PPT} + P_{i2}}{1 + x_i} \]  

(139)

where \( x_i \) represents the ratio of runoff and storage volume. A new value of PPT is computed for the following time increment as:
\[
PPT = P_{o1} + P_{o2} (1 - x_i)
\] (140)

These calculations are repeated at each time step for each particle size class separately. The initial nutrient content of the soil is distributed among the different particle size classes according to the specific area of the particles, such that:

\[
PSSA = \frac{P_0 \times 10^{-9}}{SSAT}
\] (141)

where:
- \(PSSA\) = nutrient content of the soil (kg/m²),
- \(P_0\) = total nutrient content of the original soil (µg/g-soil), and
- \(SSAT\) = specific surface area of the original soil (m²/g).

The concentration of nutrient for each particle class size (\(P_{0i}\)) is then determined by:

\[
P_{0i} = SSA_i \times PSSA
\] (142)

where \(SSA_i\) represents the specific surface area for particle size class \(i\).

The basic assumptions of the sediment-bound nutrient model are:

1. The sediment transport model assumptions are correct,
2. The sediment-bound nutrients are distributed proportionally between the different soil particle size classes according to the specific surface area of the particle size classes, and
3. There is no transfer of sediment-bound nutrient between different particle size classes during a storm.

**DISSOLVED NUTRIENT MODEL**

The dissolved nutrient component is also based on a mass balance approach. The dissolved component differs from the sediment-bound component in that the input of dissolved nutrient comes from the mixing of rainfall with dissolved nutrient present in the portion of the soil that interacts with surface runoff, the effective depth of interaction, (EDI). The amount of available dissolved nutrient was derived from the procedure used in the GLEAMS model. It is assumed that during and after a storm event, there is a linear dynamic equilibrium between the dissolved
and sediment-bound phases of ammonium and labile P. Knisel et al. (1993) suggested the following equation to determine the chemical concentration available in runoff:

\[ c_{av} = c \exp \left( -\frac{(F - ABS)}{K (1 - POR) 2.65 + POR} \right) \]  

(143)

where:
- \( c_{av} \) = available nutrient concentration in runoff and infiltration (µg/g),
- \( c \) = nutrient concentration in the surface layer (µg/g),
- \( K \) = partition coefficient,
- \( ABS \) = initial abstraction (cm),
- \( F \) = cumulative infiltration (cm), and
- \( POR \) = total porosity of surface layer (cm).

Sharpley and Williams (1990) suggested the following equation to determine \( c_{av} \) for nitrate:

\[ c_{av} = c \exp \left( -\frac{Q}{POR - WP} \right) \]  

(144)

The approach used is similar to that described by Sharpley and Williams (1990) and Knisel et al. (1993). This equation was developed for use on a daily time step. It was adjusted to simulate the smaller time step used in ANSWERS by:

\[ c_{av} = c \exp (-X_I) \]  

(145)

where \( X_I \) is determined as:

\[ X_I = \frac{(Q + FIL + S) DT}{POR + 2.65 (1 - POR) K} \]  

(146)

where:
- \( Q \) = runoff rate m³/s,
- \( FIL \) = infiltration rate m³/s,
- \( S \) = storage rate m³/s, and
- \( DT \) = time increment s.

The concentration of nutrient in solution is given by Leonard et al. (1987) as:

\[ c_s = \frac{c_{av} \beta}{1 + K \beta} \]  

(147)
where:
\[ c_s = \text{concentration of nutrient in solution (\(\mu g/g\)), and} \]
\[ \beta = \text{extraction coefficient}. \]

The extraction coefficient is given by Leonard et al. (1987) as a function of \(K\) by:

\[
\begin{align*}
\beta &= 0.5 & K &\leq 1 \\
\beta &= 0.598 \exp (-0.179 \ K) & 1 < K \leq 10 \\
\beta &= 0.1 & K > 10
\end{align*}
\]  

(148)

A mass balance approach similar to that used for the sediment-bound nutrient is applied for dissolved nutrient. The mass balance can be expressed as:

\[
SN_{i1} - SN_{o1} + 2 \frac{SN_{i1}}{dt} = SNPT = SN_{o2} - SN_{i2} + 2 \frac{SN_{i2}}{dt}
\]

(149)

where:
\[
\begin{align*}
SN_i &= \text{dissolved nutrient specie inflow (kg/s)}, \\
SN_o &= \text{dissolved nutrient specie outflow (kg/s)}, \\
SN &= \text{dissolved nutrient specie in transit (kg)}, \\
dt &= \text{time step (s), and} \\
I,2 &= \text{initial and final value for the time increment.}
\end{align*}
\]

The value of \(SNPT\) represents the sum of the initial values of the nutrient specie under consideration. The inflow of dissolved nutrients is the sum of incoming dissolved nutrient from adjacent cells and from dissolved nutrient generated within the cell. Thus, \(SN_i\) can be expressed as:

\[
SN_{i2} = SN_i + c_s (Q + FIL)
\]

(150)

where \(SN_i\) represents the inflow of dissolved nutrient from adjacent cells.

The amount of dissolved nutrient in transit is computed by:

\[
SN_2 = \frac{SNPT + SN_{i2}}{1 + x_2}
\]

(151)

where \(x_2\) represents the ratio of runoff plus infiltration and storage volume. The outflow of dissolved nutrient, \(SN_{o2}\), is:
\[ SN_{o2} = SN_{2} x_{3} \]  \hspace{1cm} (152)

where \( x_{3} \) represents the ratio of runoff and storage volume. The new value of SNPT is determined by:

\[ SNPT = SN_{I2} + SN_{o2} (1 - x_{2}) \]  \hspace{1cm} (153)

**NITROGEN MODEL**

The nitrogen transport model simulates sediment-bound and dissolved ammonium, nitrate and sediment-bound TKN. A summary of the processes involved is given in Figure 5.

**Sediment-Bound Ammonium**

Initial concentration of sediment-bound ammonium is distributed among the different particle sizes in proportion to the specific surface areas of the particle size classes using Equations 141 and 142. If no outflow occurs, sediment-bound ammonium in transit is determined using Equation 135. If outflow occurs, Equations 138 and 139 are used to determine the outflow and storage of sediment-bound ammonium. An enrichment ratio of five was used for both ammonium and sediment-bound TKN.

**Dissolved Ammonium**

At each time step, the concentration of dissolved ammonium is determined using Equation 147. The partition coefficient for ammonium is given by Knisel et al. (1993) by:

\[ K_{Am} = 1.34 + 0.083 \text{ CL} \]  \hspace{1cm} (154)

where \( K_{Am} \) represents the partition coefficient for ammonium. Outflow of dissolved ammonium is determined using Equation 152.

**Nitrate**

Unlike ammonium, nitrate is not attached to soil particles and is always in solution. Nitrate moves through the soil profile with infiltrating and percolating waters. In modeling nitrate the partitioning coefficient is set to zero and the extraction coefficient is to 0.5 (Equation 148). Thus,
Figure 5. Flow chart for nutrient loss paths.
the concentration of nitrate available for runoff and infiltration is determined by Equation 147 as:

\[ c_{\text{av}} = 0.5 \, c_{\text{NO}_3} \exp (-X_1) \]  \hspace{1cm} (155)

where \( X_1 \) is determined from Equation 146 for \( K = 0 \) as:

\[ X_1 = \frac{(Q + F I L + S) \, DT}{F O R} \]  \hspace{1cm} (156)

A mass balance approach described with Equations 149 to 153 is used to model nitrate movement with runoff and infiltration.

**PHOSPHORUS MODEL**

A summary of the P transport model is given in Figure 5. The new version of ANSWERS models sediment-bound and dissolved labile phosphorus.

**Sediment-Bound Phosphorus**

A mass balance approach is used to model sediment-bound labile P transport. At each time step, if no outflow occurs, sediment-bound P in transit is computed using Equation 135. If outflow occurs, the outflow of sediment-bound P and P in storage are determined using Equations 138 and 139. The initial concentration of P among the different particle size classes is determined using Equations 141 and 142.

**Dissolved Phosphorus**

At each time step, the concentration of available dissolved P is determined using Equation 147. The partition coefficient for P is given by Knisel et al. (1993):

\[ K_{\text{Phos}} = 100 + 2.5 \, CL \]  \hspace{1cm} (157)

where \( K_{\text{Phos}} \) represents the partition coefficient for phosphorus. Since value of \( K_{\text{Phos}} \) is greater than 100 (Equation 157), the extraction coefficient for phosphorus is equal to 0.1 (Equation 148). A value of the dissolved labile P outflow and storage are determined at each time step using Equations 152 and 151, respectively. Equation 153 is then used to determine a new value of
SNPT for the dissolved labile P.

The infiltration and nutrient transport components including N and P transport components are used only during rainfall events. If no rainfall occurs on a particular day the infiltration and nutrient transport subroutines are not called and the program calls the evapotranspiration, percolation and nutrient transformation routines.

NUTRIENT TRANSFORMATION MODEL

The new version of ANSWERS simulates transformations of N and P. A summary of the transformations considered for N is given in Figure 6.

Nitrogen Transformation
ANSWERS divides soil N into several pools. These include active organic pool, stable organic, fresh organic, nitrate and ammonium pools (Figure 6). The N transformation component was adapted from GLEAMS (Knisel et al., 1993). The model simulates mineralization, which is assumed to be a two-stage process. During the first stage of mineralization, also called ammonification, the active soil organic N (potentially mineralizable N) is transformed to ammonium. The pool of mineralizable organic N is characterized with a C:N ratio between 12 and 25 and a half-life of a few years. The other pool of organic N, the stable pool, has a C:N ratio less than 12. These two pools are dynamic and a constant exchange exists between the stable and mineralizable pools. The procedure used to describe the flow between these two pools in GLEAMS was adapted from the EPIC model (Sharpley and Williams, 1990), and is described below. A ratio is defined to determine the fraction of potentially mineralizable N and total soil organic N as follows:

\[
RTN = \frac{POTMIN}{POTMIN + SOILN}
\]  

(158)

where:

- POTMIN = potentially mineralizable N (kg/ha), and
- SOILN = stable soil N (kg/ha).

The flux between the stable and active organic pools is determined as:

MODEL DEVELOPMENT
Figure 6. Flow chart for the simulated nitrogen cycle.
POTSO = BKN \{POTMIN RTN - SOILN\} \hspace{1cm} (159)

where:

\begin{align*}
POTSO &= \text{daily flow between active and stable organic pools (kg/ha/day)}, \\
BKN &= \text{rate constant (10}^5 \text{ kg/ha/day), (Sharpley and Williams, 1990).}
\end{align*}

If POTSO is positive, then the flux occurs from the active pool to the stable pool, otherwise the flux occurs from the stable pool to the active pool. Mineralization (ammonification) is determined by:

\begin{align*}
MIN &= CMN \ POTMIN \ [SWFA \ TEMPFA]^{0.5} \\
&= \text{mineralization rate (kg/ha/day),} \\
CMN &= \text{mineralization constant (0.0003 kg/ha/day), (Sharpley and Williams, 1990),} \\
SWFA &= \text{soil water factor for ammonification, and} \\
TEMPFA &= \text{temperature factor for ammonification.}
\end{align*}

The mineralized nitrogen, MIN, is added to the total amount of ammonium, AMON. The soil water factor is determined by:

\begin{align*}
\text{SWFA} &= \frac{\text{SW} - \text{WP}}{\text{FC} - \text{WP}} \quad \text{SW} \leq \text{FC} \hspace{1cm} (161)
\end{align*}

where:

\begin{align*}
\text{SW} &= \text{volumetric soil water content (cm/cm),} \\
\text{WP} &= \text{volumetric water content at 1500 KPa (cm/cm), and} \\
\text{FC} &= \text{volumetric water content at 33 KPa (cm/cm).}
\end{align*}

If the soil water content exceeds field capacity, ammonification does not occur and SWFA is set to zero. For positive soil temperatures, the temperature factor for ammonification is determined by:

\begin{align*}
TEMPFA &= \frac{T}{T + \exp (9.93 - 0.312 \ T)} \hspace{1cm} (162)
\end{align*}

where T represents the soil temperature, °C. For negative soil temperatures, TEMPFA is set to zero and no ammonification occurs.

The second stage of mineralization also called nitrification was adapted from Duffy et al. (1975).
Eighty percent of the added ammonium fertilizer is assumed to nitrify within 20 days. Then nitrification is assumed to occur at the constant rate of 0.005 mg-N/day/cm². The amount of nitrified ammonium is added to the total amount of nitrate and subtracted from the total amount of ammonium.

Denitrification is the reduction of nitrate to nitrate gases and is assumed to occur when soil water exceeds field capacity. It is considered to be a first order process, and is based on the amount of active soil carbon. The amount of active soil carbon was derived from the active N organic pool by Frere et al. (1980) as:

\[
SC = \frac{18 \text{ POTMIN}}{\text{SOILMA}} \times \frac{\nu_{\text{soil}}}{\nu_{\text{N}}} \tag{163}
\]

where SC represents the active soil carbon (mg/g) and SOILMA is the soil mass (kg/ha). The denitrification rate is determined by:

\[
\text{DNI} = \exp \left( -DK \ \text{TEMPFD} \ SWFD \right) \tag{164}
\]

where:
- DNI = denitrification rate (kg/ha/day),
- DK = daily decay rate of soil organic carbon,
- SWFD = soil water factor for denitrification, and
- TEMPFD = temperature factor for denitrification.

The daily decay rate DK of soil organic carbon is determined as:

\[
DK = 0.0528 \ SC + 0.1008 \tag{165}
\]

The temperature factor for denitrification is computed identically to the temperature factor for ammonification. Denitrification is assumed to start once soil water content is 10% above field capacity. Thus, the soil water factor for denitrification can be expressed as:

\[
\text{SWFD} = \frac{SW - [FC + 0.10 \ (\text{SAT} - FC)]}{\text{SAT} - [FC + 0.10 \ (\text{SAT} - FC)]} \tag{166}
\]

When denitrification occurs, it is subtracted from the nitrate pool.

Between storm events, it is assumed that a linear relationship exists between sediment-bound and
dissolved ammonium and can be expressed as:

\[ K_{Am} = \frac{\text{ANSOIL}}{\text{SOILMA}} - \frac{\text{SZNH4}}{\text{WATVOL}} \]  

(167)

where:

- \( K_{Am} \) = partition coefficient for ammonium,
- \( \text{ANSOIL} \) = sediment-bound ammonium (kg),
- \( \text{SZNH4} \) = dissolved ammonium (kg), and
- \( \text{WATVOL} \) = represent water volume (kg/ha).

The value of \( K_{Am} \) is determined by Equation 154. AMON, the total amount of ammonium (kg), can be expressed as:

\[ \text{AMON} = \text{ANSOIL} + \text{ANWAT} \]  

(168)

\( \text{SZNH4} \) can be determined as:

\[ \text{SZNH4} = \frac{\text{AMON}}{1 + \frac{K_{Am} \text{ WATVOL}}{\text{SOILMA}}} \]  

(169)

and \( \text{ANSOIL} \) is determined by:

\[ \text{ANSOIL} = K_{Am} \text{ SZNH4} \frac{\text{SOILMA}}{\text{WATVOL}} \]  

(170)

Dissolved N is lost through runoff, percolation and denitrification. Another major pathway of N loss is plant uptake. Runoff losses of N occurs only during a storm. Other N losses (percolation, denitrification, and plant uptake) are computed on a daily basis. The amount of nitrate lost through percolation is assumed to be proportional to the amount of water percolating and is computed by:

\[ \text{PERNO3} = \text{SZNO3} \frac{\text{DR}}{\text{WATVOL}} \]  

(171)

where \( \text{DR} \) is the daily percolation (kg/ha) and \( \text{PERNO3} \) represents the amount of nitrate lost
through percolation (kg). The amount of nitrate lost through percolation is subtracted from the total amount of nitrate.

The plant uptake component was taken from the GLEAMS model, which in turn was adapted from the EPIC model. The EPIC model simulates the uptake of nitrate while GLEAMS simulates both nitrate and ammonium uptake. The potential nitrate uptake is the product of nitrate concentration in the root zone and transpiration. It is expressed as:

\[ \text{UPNO3} = \text{PEP} \left( \frac{\text{SZNO3}}{\text{WATVOL}} \right) \]  \hspace{1cm} (172)

where PEP is plant transpiration (cm) and UPNO3 represents the total nitrate uptake (kg). The potential ammonium uptake is expressed in an identical manner:

\[ \text{UPNH4} = \text{PEP} \left( \frac{\text{SZNH4}}{\text{WATVOL}} \right) \]  \hspace{1cm} (173)

where UPNH4 is the total ammonium uptake. The total potential N uptake is expressed as:

\[ \text{TUPTN} = \text{UPNH4} + \text{UPNO3} \]  \hspace{1cm} (174)

where TUPTN is the total potential N uptake. The potential N uptake is then compared with the daily N demand. The concentration of N in plant biomass is determined by:

\[ \text{CN} = C_1 \left( \frac{\text{SUMLAI}}{\text{POTLAI}} \right)^{C_2} \]  \hspace{1cm} (175)

where:

- \text{CN} = \text{concentration of N (\% crop biomass),}
- \text{SUMLAI} = \text{accumulated leaf area index (m}^2/ \text{m}^2),
- \text{POTLAI} = \text{potential accumulated leaf area index on the day of harvest (m}^2/ \text{m}^2),
- \text{C}_1 \text{ and } C_2 = \text{plant dependent empirical coefficients.}

The values of \text{C}_1 \text{ and } C_2 \text{ are given by Knisel et al. (1993). The ratio of SUMLAI and POTLAI, also called growth ratio, is used to calculate the total dry matter as:}

\[ \text{DM} = \text{PGRT YP DMY} \]  \hspace{1cm} (176)

where:

- \text{PGRT} = \text{plant growth ratio,}
YP = yield potential (kg/ha).
DMY = ratio of total dry matter to harvestable yield, and
DM = total dry matter (kg/ha).

The total dry matter N for a given day is then determined by multiplying the total dry matter by the concentration of N in dry matter:

\[ TDMN1 = DM \frac{CN}{100} \]  \hspace{1cm} (177)

where TDMN1 is the total dry matter N (kg/ha). The daily N demand is then computed by:

\[ TDMN = TDMN1 - TDMN2 \]  \hspace{1cm} (178)

where:
- TDMN = daily N demand (kg/ha), and
- TDMN2 = total dry matter N for the previous day (kg/ha).

A demand factor (DEMFAC) is then determined:

\[ DEMFAC = \frac{TDMN}{TUPTN} \]  \hspace{1cm} (179)

The ammonium uptake is adjusted by:

\[ UPNH4 = UPNH4 \times DEMFAC \]

and the nitrate uptake is adjusted to:

\[ UPNO3 = UPNO3 \times DEMFAC \]  \hspace{1cm} (181)

This procedure allows N uptake to be distributed according to the relative size of the dissolved ammonium and nitrate pools.

**Phosphorus Transformation**

The simulated soil phosphorus pools include an active organic P pool, a labile P pool, an active mineral pool, an inactive mineral pool, and a fresh organic P pool (Figure 7). The ratio of potentially mineralizable P to total organic P is assumed to be identical to the ratio of potentially mineralizable N to soil organic N (Knisel et al., 1993). The potentially mineralizable P is determined as the product of soil organic P and the ratio of active and stable soil organic N.
Figure 7. Flow chart for the simulated phosphorus cycle.
Mineralization rate is determined as:

\[
\text{MINP} = \text{CMN SORGP} \left( \frac{\text{POTMIN}}{\text{POTMIN} + \text{SOILN}} \right) [\text{SWFA TEMPFA}]^{0.5} \tag{182}
\]

where:

\[
\begin{align*}
\text{MINP} & \quad = \text{mineralization rate (kg/ha/day), and} \\
\text{SORGP} & \quad = \text{soil organic P (kg/ha).}
\end{align*}
\]

The variables SWFA, TEMPFA, CMN, POTMIN, and SOILN are as defined previously. The amount of mineralized P is added to the amount of labile P. The active and stable inorganic P pools are dynamic, and at equilibrium, the stable mineral P pool is assumed to be four times larger than the active mineral P pool (Sharpley and Williams, 1990). The equilibrium between the active mineral P pool and the labile P pool is described by Equation 66. At the end of each day, the labile P is partitioned into sediment-bound and labile P. Dissolved labile P is available for plant uptake, and can be lost through leaching. However, due to the large adsorptivity of P, the P losses through percolation are neglected. The amount of dissolved labile P is given by:

\[
\text{PSOL} = \frac{\text{PLAB}}{1 + \frac{K_{\text{P}_{\text{till}}}}{\text{WATVOL}} \cdot \frac{\text{SOILMA}}{SOILMA}} \tag{183}
\]

where PSOL represents dissolved labile P (kg), and the sediment-bound labile P is the computed as the difference between the total amount of labile P and the dissolved labile P and can be expressed as:

\[
\text{POSOIL} = \text{PLAB} - \text{PSOL} \tag{184}
\]

The uptake of dissolved labile P is computed in an identical manner to that of nitrate and dissolved ammonium. The uptake of labile P is then subtracted from the total pool of labile P. For additional details regarding fate and transport of P and N the reader is referred to the GLEAMS user's manual (Knisel et al., 1993) and the EPIC user's manual (Sharpley and Williams, 1990).
CONCLUSION

The ANSWERS model was modified from an event-based model to a continuous model to simulate runoff, erosion, transport of dissolved and sediment-bound nutrients, and transformation of nitrogen and phosphorus pools for ungaged watersheds. A complete flow chart of the modified model is given in Figure 8. Holtan's infiltration equation was replaced by the widely used and physically-based Green-Ampt equation. Soil evaporation and plant transpiration were modeled separately using Ritchie's equation. A nutrient transformation and nutrient transport were added to the ANSWERS model. The nutrient transformation model was adapted from the GLEAMS and EPIC models. Nitrification was taken from the Duffy et al. (1975) model. Transport of dissolved nutrients was modeled using an extraction coefficient. The sediment-bound nutrient transport component is similar to that used by Storm et al. (1988).
Figure 8. Flow chart for the modified ANSWERS model.
MODEL VALIDATION

A major component of model development is validation. Validation is the process in which predicted data are compared with measured data. McKeon and Segna (1987) investigated selection criterion for mathematical models used in exposure assessment. Depending on the type of model used, different degrees of accuracy are expected. Screening level analyses, are defined by McKeon and Segna (1987) as studies where validation (and calibration) data is limited, and the error associated with this type of model is expected to be large. For this type of analysis, predicted data is around an order of magnitude of the measured data (McKeon and Segna, 1987). For detailed level assessment analysis, the uncertainty of model output is reduced because of the availability of data required during the validation (calibration process). This type of analysis yields output within a factor of 10 of the measured data. Heatwole et al. (1991) suggest that good hydrologic assessment model prediction should be within a factor of 2 of observed values if model parameters are measured on-site or if the model is calibrated. For the purposes of this validation study, the modified ANSWERS model will be considered successfully validated if model predictions are within a factor of 2 of the long-term cumulative measured values.

Only a few studies have been conducted to simultaneously measure runoff, sediment and nutrient loading as affected by BMP’s on agricultural watersheds. Thus, data availability for ANSWERS validation was limited. Data considered for the validation study were obtained from both field and watershed scale monitoring studies. Smith et al. (1978) conducted research to study the effects of management practices on water quality on small watersheds. Mostaghimi et al. (1989) studied the effects of implementing best management practices on water quality at the watershed scale. In the first part of the validation, ANSWERS was tested using small watershed data collected by Smith et al. (1978). This database, which has been widely used for validating NPS models such as CREAMS, GLEAMS, and NPS, is more comprehensive than the data usually collected at the watershed scale level. In the second part of the validation study, ANSWERS was validated using data collected from a large heterogeneous watershed by Mostaghimi et al. (1989).

SMALL WATERSHED VALIDATION STUDY

Input data used to validate the ANSWERS model were collected at the Southern Piedmont
Conservation Research Center located near Watkinsville, GA. The data were collected from 1973 to 1975 as part of a project to measure the persistence of pesticides as affected by application methods, soil composition and climatic conditions (Smith et al., 1978). In 1974, additional funding of the project allowed the measurement of nutrient transport from two of the four experimental plots. The site was located in the Southern Piedmont physiographic region between the Southern Appalachian Mountains and the Southern Coastal Plains and characterized by a gently rolling relief. Annual temperature ranges from 14 to 18°C, and annual precipitation ranges from 115 to 140 cm. The study area consisted of four field-watershed plots (P1, P2, P3 and P4). P2 and P4 watersheds only were used in the validation study because nutrient data were not collected from the P1 and P3 watersheds. Soils in the P2 watershed include Cecil sandy loam soil (62%), Cecil sandy clay loam soil (28%) and Cecil loam (10%). The P4 watershed soils included Cecil sandy clay loam (73%) and Cecil sandy loam (27%). The P4 watershed also contained terrace channels which were graded towards a grassed waterway with slopes of 1 to 2 percent. Three years of climatic data were collected and include breakpoint rainfall data, pan evaporation and wind speed. The P2 and P4 watersheds had separate raingages.

Since the ANSWERS model is intended for use on ungauged watershed, no calibration was conducted during the selection of the input parameters. Measured average air temperature and breakpoint rainfall data were available for input to the model. However, soil temperatures were not available. It was assumed that soil temperature was equal to air temperature. Furthermore, there was no information regarding solar radiation. Solar radiation is necessary to simulate evapotranspiration. A synthetic daily solar radiation record was generated using CLIGEN (Nicks, 1985), a synthetic climate generator. Soil texture, management practices, landuse, and fertilizer applications were reported by Smith et al. (1978) and are summarized in Table 1. Concentration of available P, total N and total P were obtained from Smith et al. (1978). The remainder of the required nutrient input was estimated from available data. The value of potentially mineralizable N was taken from Stanford and Smith (1978). If data regarding potentially mineralizable N is not available, it can be estimated from soil total N, and soil organic N present in the soil surface (Knisel, 1980). Soil ammonium and nitrate were initialized to concentrations of 2 µg NH4/g-soil and 10 µg NO3/g-soil, respectively, according to the default values suggested by GLEAMS. Since the model was run one year prior to the beginning of the validation period, these initial values should not affect the long-term ammonium and nitrate pool sizes. The stable organic N
Table 1. Management practices for P2 and P4 watersheds.

<table>
<thead>
<tr>
<th>Date</th>
<th>P2</th>
<th>P4</th>
</tr>
</thead>
<tbody>
<tr>
<td>04-25-1974</td>
<td>watershed tilled with chisel (20 cm deep)</td>
<td>watershed tilled with chisel (20 cm deep)</td>
</tr>
<tr>
<td>04-29-1974</td>
<td>plant corn fertilizier application and incorporation with disk harrow (15 cm) NH4-N 38 kg PO4-P 33 kg</td>
<td>plant corn fertilizier application and incorporation with disk harrow (15 cm) NH4-N 38 kg PO4-P 33 kg</td>
</tr>
<tr>
<td>06-11-1974</td>
<td>fertilizer application and incorporation with disk harrow (15 cm) NH4-N 107 kg</td>
<td>fertilizer application and incorporation with disk harrow (15 cm) NH4-N 100 kg</td>
</tr>
<tr>
<td>09-16-1974</td>
<td>harvest corn</td>
<td>harvest corn</td>
</tr>
<tr>
<td>10-19-1974</td>
<td>---</td>
<td>plant rye</td>
</tr>
<tr>
<td>04-15-1975</td>
<td>---</td>
<td>harvest rye</td>
</tr>
<tr>
<td>04-24-1975</td>
<td>fertilizer application and incorporation with disk harrow (15 cm) NH4-N 11 kg NO3 11 kg PO4-P 21 kg</td>
<td>fertilizer application and incorporation with disk harrow (15 cm) NH4-N 11 kg NO3 11 kg PO4-P 31 kg</td>
</tr>
<tr>
<td>05-14-1975</td>
<td>---</td>
<td>plow and plant corn</td>
</tr>
<tr>
<td>05-21-1974</td>
<td>plow and plant corn</td>
<td>---</td>
</tr>
<tr>
<td>06-25-1975</td>
<td>fertilizer application and incorporation with disk harrow (15 cm) NH4-N 112 kg</td>
<td>fertilizer application and incorporation with disk harrow (15 cm) NH4-N 112 kg</td>
</tr>
<tr>
<td>10-03-1975</td>
<td>harvest corn</td>
<td>---</td>
</tr>
<tr>
<td>10-30-1975</td>
<td>---</td>
<td>harvest corn</td>
</tr>
</tbody>
</table>
pool was estimated by subtracting the potentially mineralizable N, ammonium and nitrate pools from the total N pool. Soil organic P was determined using the following equation developed by Sharp et al. (1984) that relates the soil organic P to the total N:

\[
\text{SORGP} = 44.64 + 1130 \text{TN}
\]  

(185)

where SORGP represents soil organic P in μg/g and TN is the total N (percent). The concentration of available P was provided by Smith et al. (1978). The model was run for thirty months from May 1973 to September 1975. Model predictions are presented only for the period from May 1974 to September 1975 because this is the period when nutrient data was collected. A complete listing of the model input parameters for the validation run is presented in Appendix B. Figures 9 and 10 show how the P2 and P4 watersheds were discretized into the format required by ANSWERS. The 1.4 ha P2 watershed was discretized into 89 cells of 0.0157 ha each. The 1.3 ha P4 watershed was divided into 278 cells of 0.0047 ha each in order to better represent the channel network. Two types of channels were simulated on the P4 watershed. The first type of channel collects water from the terraces and carries it to the second type of channel which is a grassed waterway. Slope was assumed uniform for each terrace. Soil type for each cell was determined by overlying the watershed grid with the soil type map. Land use was uniform for both watersheds and varies with time only.

In reviewing the validation results it is important to remember that these results were obtained without calibration. Best estimates of model input parameters were made prior to running the model and parameter values were not changed later to improve model predictions. Since the model is intended for use without calibration, calibration during the validation study was deemed inappropriate.

RUNOFF

The results for cumulative runoff are shown in Figure 11 for the P2 watershed, and Figure 12 for the P4 watershed. Overall, the model predicted total runoff well, but there was a tendency to overpredict total runoff on the P4 watershed. However, as shown in Figure 12, most of the overprediction occurred during the first three months of the simulation. In general the model was in very close agreement with the predicted runoff. The model closely reproduced the trend of
Figure 9. P2 watershed flow path and channel network.
Figure 10. P4 watershed flow path and channel network.
Figure 11. Measured vs. predicted cumulative runoff, P2 watershed.
Figure 12. Measured vs. predicted cumulative runoff, P4 watershed.
monthly runoff on both watersheds (Figures 13 and 14). Overall, the model was better in predicting runoff from the P2 watershed than from the P4 watershed. Cumulative runoff predictions were within 3% of the measured value for P2 (Figure 15) and within 35% for P4 (Figure 16). The better performance of the model on the P2 watershed may be due to poor initial characterization of the effects of the terraces on infiltration and runoff parameters on the P4 watershed. However, since calibration was not allowed, initial parameter estimates and watershed characterization were not changed. The good performance of the runoff on both watersheds is a good indication of the general performance of the water balance model components, including runoff, infiltration, ET, and percolation. Since no data were available for testing the ET and percolation components independently, the results of the runoff/infiltration model were assumed to reflect the overall performance of the water component of ANSWERS.

SEDIMENT

The model underpredicted total sediment loss for the P2 watershed (Figure 17). The model performed well in predicting the total load of sediment loss for the P4 watershed (Figure 18). The sediment yield prediction for P4 is surprising since runoff was overpredicted by 35%. The model reproduced the trend of monthly sediment losses on the P2 and P4 watersheds well (Figures 19 and 20). The model predicted the occurrence of two large sediment events in June 1974 and June 1975 for the P2 watershed. However, the model underpredicted the sediment load from the second event. This can be explained by the fact that these two events occurred during similar periods with identical cover and crop development stage, both rainfall events had similar intensity patterns (first event produced more rainfall than the second event) and both resulted in similar runoff amounts. Thus, the model predicted similar sediment loads for both events. However, the measured sediment load for the second event was four times higher than for the first event. On the P4 watershed the model overpredicted sediment loss for the first three months of the simulation. The overprediction of sediment loss during that period may be attributed to the overprediction of runoff. The model underpredicted sediment loss during March 1975, and this underprediction is probably due to the underprediction of runoff during that month. Overall the model performed better in predicting monthly trends of sediment loss on the P2 watershed than on the P4 watershed. This improved performance can be explained by the fact that the model predicted monthly runoff from the P2 watershed better than it did from the P4 watershed. Thus,
Figure 13. Measured vs. predicted monthly runoff, P2 watershed.
Figure 14. Measured vs. predicted monthly runoff, P4 watershed.
Figure 15. Ratio between measured and predicted runoff, sediment, nitrate, sediment-bound ammonium, dissolved ammonium, sediment-bound TKN, and dissolved inorganic P for the P2 watershed.
Figure 16. Ratio between measured and predicted runoff, sediment, nitrate, sediment-bound ammonium, dissolved ammonium, sediment-bound TKN, and dissolved inorganic P for the P4 watershed.
Figure 17. Measured vs. predicted cumulative sediment loadings, P2 watershed.
Figure 18. Measured vs. predicted cumulative sediment loadings, P4 watershed.
Figure 19. Measured vs. predicted monthly sediment loadings, P2 watershed.
Figure 20. Measured vs. predicted monthly sediment loadings, P4 watershed.
better estimates of runoff from the P4 watershed could improve the estimates of sediment loss. Overall, long-term predictions of sediment loss were within 68% of the measured values for the P2 watershed (Figure 15) and within 12% for the P4 watershed (Figure 16).

NITRATE

The model did well in predicting total cumulative nitrate losses and monthly nitrate losses (Figures 21, 22, 23, and 24) on both watersheds. For the P2 watershed, the model underpredicted the nitrate losses occurring in June 1975, and was in very close agreement with the measured nitrate losses for all the other months of the validation period. The underprediction can be explained by the fact that the model predicted very high initial infiltration rates during the major storm that occurred during June 1975, thus, most of the nitrate present in the effective depth of interaction (upper 1 cm) was lost through infiltration. The model also underpredicted nitrate losses in March 1975 for the P4 (Figure 24) which may indicate that the model may have underestimated mineralization and ammonification occurring during the winter season for both watersheds. Corn residue was incorporated in the soil, and residue mineralization may have replenished the inorganic N pools (nitrate and ammonium) during the winter. The ANSWERS model does not simulate crop residue mineralization. The amount of N present in the residue is added to the potentially mineralizable N pool. An additional reason for the underprediction of nitrate loss on the P4 watershed, may be due to the presence of the winter crop which may have depleted the nitrate and ammonium pool. Overall the model predicted cumulative nitrate losses well for both watersheds. The model predictions of cumulative nitrate loss were within 37% of the measured values for the P2 watershed (Figure 15) and 15% for the P4 watershed (Figure 16).

DISSOLVED AMMONIUM

The model predicted very well the total dissolved ammonium loss through runoff for the P2 and P4 watersheds (Figures 25 and 26). Model predictions of cumulative dissolved ammonium loss were within 34% and 14% for the P2 and P4 watersheds, respectively (Figures 15 and 16). The model reproduced very well the trend on monthly loss of dissolved ammonium for both watersheds (Figures 27 and 28). The model overpredicted dissolved ammonium loss from the P4 watershed during July 1974 (Figure 28). This overprediction can be explained by the large overprediction of runoff during that month. Even though the model performed well on the P4 watershed, an overprediction of dissolved ammonium loss was expected since the runoff was
Figure 21. Measured vs. predicted cumulative NO3 loadings, P2 watershed.
Figure 22. Measured vs. predicted cumulative NO3 loadings, P4 watershed.
Figure 23. Measured vs. predicted monthly NO3 loadings, P2 watershed.
Figure 24. Measured vs. predicted monthly NO3 loadings, P4 watershed.
Figure 25. Measured vs. predicted cumulative dissolved NH4 loadings, P2 watershed.
Figure 26. Measured vs. predicted cumulative dissolved NH4 loadings, P4 watershed.
Figure 27. Measured vs. predicted monthly dissolved NH4 loadings, P2 watershed.
Figure 28. Measured vs. predicted monthly dissolved NH4 loadings, P4 watershed.
overpredicted. This may indicate an underprediction of the ammonium pool for the P4 watershed.

SEDIMENT-BOUND AMMONIUM

The model poorly predicted sediment-bound ammonium loss from both watersheds (Figure 29 and 30). The model performed extremely poorly in predicting the trend of monthly sediment-bound ammonium loss (Figure 31 and 32). In almost all cases, model predictions were lower than the observed values. A close analysis of the measured data shows that more than 50% of the loss of sediment ammonium for P2 watershed occurred during June and July 1975. Twenty days before the large runoff event that occurred in June 1975, ammonium fertilizer was applied. All fertilizer is assumed to be distributed evenly in the plow layer. The higher measured value of sediment-bound ammonium may be due to residual ammonium in the top layer of soil. In addition, the measured sediment-bound ammonium values are also higher than expected. For the storm that occurred in June 1975, losses of sediment-bound ammonium represented about half the loss of sediment-bound TKN, which is an extremely high value. For several later storms, the measured sediment-bound NH4 losses were higher than measured sediment-bound TKN losses. This is not possible since the TKN test includes NH4 and this that indicates the measured ammonium or TKN values are incorrect. The large storm that occurred in July 1975 followed a large application of NH4-N fertilizer a month earlier. The measured loss of sediment-bound ammonium was much larger than the predicted. This may be due also to the presence of residual fertilizer in the surface layer. For the P4 watershed, most of the sediment-bound ammonium losses occurred in February and March 1975. These months accounted for more than 50% of the total loss of sediment-bound ammonium. However, for the storm that occurred in February 1974, the measured sediment-bound ammonium value is questionable since it is six times higher than that measured for sediment-bound TKN. Further analysis of the measured data indicates that a potential source of error may be the partition coefficient used in the model to determine the equilibrium between sediment-bound and dissolved ammonium. Total loss of sediment-bound ammonium for the P2 watershed is 2900 g which were transported by 9500 kg of sediment. Total loss of dissolved ammonium is 2700 g transported by 3600 m³ of runoff. Thus, computing a partition for measured sediment-bound and dissolved ammonium results in a partition coefficient of 410. An identical calculation on the P4 watershed gives a value for the partition coefficient of 1820. The partition coefficient for ammonium used in the model was around 2 (see equation 154). Thus the major problem in the sediment-bound ammonium component may be that the measured data suggests a partition coefficient much higher than that used in the model, or that the enrichment ratio used in the model should be much higher (enrichment ratio used in the model is equal to 5). However,
Figure 29. Measured vs. predicted cumulative sediment-bound NH4 loadings, P2 watershed.
Figure 30. Measured vs. predicted cumulative sediment-bound NH4 loadings, P4 watershed.
Figure 31. Measured vs. predicted monthly sediment-bound NH4 loadings, P2 watershed.
Figure 32. Measured vs. predicted monthly sediment-bound NH₄ loadings, P4 watershed.
it is difficult to make conclusion in this case because of suspected errors in the reported ammonium data. Overall the model underpredicted long-term sediment-bound ammonium losses by a factor of 20 for P2 (Figure 15) and a factor of 39 for P4 (Figure 16).

SEDIMENT-BOUND TKN

The model predicted sediment-bound TKN loss on the P2 and P4 watersheds (Figure 33 and 34) well. Overall, the model underestimated total loss of sediment-bound TKN on the P2 watershed by 22% (Figure 15). This was expected since sediment loss was underpredicted (Figure 17). The model overpredicted the sediment-bound TKN loss on the P4 watershed by 25% (Figure 16) and this may be due to the overprediction of sediment (Figure 15). The model did reasonably well in simulating monthly losses of sediment-bound TKN from the P2 watershed (Figure 35), but not as well with the P4 watershed (Figure 36). Since sediment-bound TKN is the largest pool of N, and since it is a very stable pool, the model predicted that sediment and sediment-bound TKN loss trends are closely correlated (Figures 19 and 33 for P2 and Figures 20 and 34 for P4). Thus, the model predicts that the main sediment-bound TKN losses will coincide with the major sediment loss events for the P2 watershed. However, the peak measured sediment-bound TKN loss did not coincide with the major sediment yield events and the trends between measured sediment losses and measured sediment-bound TKN losses were different. The same observation was made for the P4 watershed. The model predicted similar trends between the sediment losses and sediment-bound TKN losses. As with P2, the major losses of sediment-bound TKN from P4 were predicted to occur during the storms that produced the most sediment. The major loss of sediment-bound TKN from the P4 watershed occurred in February 1975. For that particular month, sediment was underpredicted by more than 50% which may have resulted in an underprediction of sediment-bound TKN by at least 50%. The same underprediction of sediment loads for the months of December 1974 and January 1975 may have resulted in the underprediction of sediment-bound TKN for P4 watershed. For the P4 watershed, the 1975 cropping season resulted in higher measured losses of sediment-bound ammonium than sediment-bound TKN losses, indicating again that either the measured ammonium or TKN values are in error. For the P2 watershed, the large overprediction of sediment-bound TKN loss for June 1974 is mainly due to the large overprediction of sediment losses for that month. The underprediction of sediment-bound TKN losses for June 1975 can also be explained by the poor prediction of sediment losses for that month. For July 1975, measured and predicted sediment losses were similar, and still the model overpredicted sediment-bound TKN losses. However, the measured sediment-bound TKN losses
Figure 33. Measured vs. predicted cumulative sediment-bound TKN loadings, P2 watershed.
Figure 34. Measured vs. predicted cumulative sediment-bound TKN loadings, P4 watershed.
Figure 35. Measured vs. predicted monthly sediment-bound TKN loadings, P2 watershed.
Figure 36. Measured vs. predicted monthly sediment-bound TKN loadings, P4 watershed.
were unexpectedly high. Considering the 1975 cropping season only, July 1975 accounted for 14% of the sediment losses while it accounted for 60% of the sediment-bound TKN losses. Furthermore, two storms occurred in July 1975, only eleven days apart, both produced similar sediment loads. However, the amount of measured sediment-bound TKN losses differed by a factor of 17. This does not seem reasonable and indicates that the measured TKN values are probably inaccurate.

**DISSOLVED PO4**

The model did extremely well in predicting losses of dissolved phosphate from the P2 watershed (Figure 37) while the losses of dissolved phosphate from the P4 watershed were underpredicted (Figure 38). Model predictions of total dissolved P loss were within 9% of the predicted values for the P2 watershed (Figure 15). Cumulative dissolved P losses were underpredicted by 73% for the P4 watershed (Figure 16). The model did well in predicting monthly trends of phosphate loss from P2 (Figure 39). The underprediction from the P4 watershed resulted mainly from the rainfall event that occurred in March 1975. The measured loss of dissolved phosphate was about 160 grams, while the predicted loss was around 10 grams (Figure 40). During that event, the measured runoff accounted for about 55% of the total rainfall, while the predicted runoff accounted for only 40% of the rainfall. Thus, the model predicted more phosphate being leached through the surface soil layer. One of the problems may be the use of an extraction factor based on the infiltration and runoff rate. The model may have performed well in predicting runoff and infiltration amounts, but may not have predicted very accurately runoff and infiltration rates. The model may be very sensitive to infiltration and runoff rates. Underprediction of nitrate and dissolved ammonium occurred during the same period on both watersheds. Furthermore, the presence of a winter crop on the P4 watershed may have depleted the labile P pool. The model performance could be improved by simulating crop residue mineralization. Crop mineralization can be extremely high, especially when large amounts of residue are left. In the P4 watershed, large amounts of residue of corn were incorporated in the soil, and may have replenished the phosphate pool during the winter. Thus, during the early spring storms, more phosphate was lost than predicted. The same observation can be made for the P2 watershed, where the amount of phosphate was underpredicted during the early spring storms (Figure 39).
Figure 37. Measured vs. predicted cumulative PO4 loadings, P2 watershed.
Figure 38. Measured vs. predicted cumulative PO4 loadings, P4 watershed.
Figure 39. Measured vs. predicted monthly PO4 loadings, P2 watershed.
Figure 40. Measured vs. predicted monthly PO4 loadings, P4 watershed.
SUMMARY

The model was tested on two separate watersheds using data collected by Smith et al. (1978). The model was run for a period of thirty months. Predicted values of runoff, sediment, nitrate, dissolved and sediment-bound ammonium, sediment-bound TKN, and dissolved labile P were compared with measured data. Overall, the model did well in predicting runoff from the P2 watershed, while runoff was overpredicted on the P4 watershed. The model succeeded in reproducing the monthly trend of runoff from both watersheds. The model predicted sediment loss from both watersheds well. The model did very well in predicting total losses of nitrate and dissolved ammonium from both watersheds. The model also reproduced well seasonal trends of nitrate and dissolved ammonium loss. The model did not predict the sediment-bound ammonium loss well on either watershed, and did not reproduce monthly trends of sediment-bound ammonium loss. The model predicted sediment-bound TKN loss well. It did well in predicting dissolved phosphate loss on the P2 watershed, while it underpredicted dissolved phosphate loss on the P4 watershed. Overall, the model was successfully validated for predicting cumulative runoff, sediment, dissolved ammonium, sediment-bound TKN, and dissolved inorganic P losses from both watersheds. The model failed to predict total sediment-bound ammonium losses from either watersheds. However, the measured sediment-bound ammonium data shows some inaccuracy, and it also indicates that the use of a higher enrichment ratio for ammonium may be appropriate.

LARGE WATERSHED VALIDATION STUDY

The Owl Run watershed is located in Fauquier County, Virginia and contains 1153 hectares. Table 2 lists the percentage of land falling into different landuse categories. The major crops are corn, hay and pasture. Non agricultural areas cover less than 30% of the watershed. The watershed contains five major dairies with 1000 milking cows and one replacement heifer operation with 250 replacement heifers and dairy cows. Owl Run watershed has a humid continental climate with an average annual precipitation of 104 cm. The watershed soils are mainly silt loam. Penn silt loam (fine-loamy, mixed, mesic Typic Hapludults) is the major soil in the watershed (40% of the watershed) and is characterized by moderate permeability with slopes ranging from 2-7% for the undulating phase and 7-14% for the rolling phase. Buck silt loam (fine-loamy, mixed, mesicUltic Hapludalfs) is the second most predominant soil. It covers 16.3% of the watershed and is characterized by a moderate permeability and slopes ranging from 2-7%.
Table 2. Landuse for Owl Run (QOA) watershed (%).

<table>
<thead>
<tr>
<th>Landuse</th>
<th>QOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional-till corn</td>
<td>8.2</td>
</tr>
<tr>
<td>No-till corn</td>
<td>2.3</td>
</tr>
<tr>
<td>Small grain</td>
<td>7.0</td>
</tr>
<tr>
<td>Hayland</td>
<td>20.1</td>
</tr>
<tr>
<td>Pasture</td>
<td>15.9</td>
</tr>
<tr>
<td>Homesite</td>
<td>6.7</td>
</tr>
<tr>
<td>Forest</td>
<td>26.0</td>
</tr>
<tr>
<td>Corn contour-strip cropping</td>
<td>2.3</td>
</tr>
<tr>
<td>Idled pasture</td>
<td>6.1</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>0.6</td>
</tr>
<tr>
<td>Farmstead</td>
<td>1.4</td>
</tr>
<tr>
<td>Loafing lot</td>
<td>1.8</td>
</tr>
<tr>
<td>Wetland</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Montalto soils (fine, mixed, mesic Ultic Hapludalfs), which cover 14.4% of the watershed, have moderate permeability with slopes ranging from 2-14%.

The Owl Run watershed contains four water quality monitoring stations QOA, QOB, QOC, and QOD. The main station QOA is located at the watershed outlet and drains 1153 ha. Station QOB (45 ha drainage) collects runoff water from the town of Calverton and one dairy operation. Station QOC (462 ha drainage) collects runoff water from agricultural land. Runoff collected at station QOD (328 ha drainage) includes runoff from agricultural lands and from dairy operations. There is no baseflow during dry periods at any of the monitoring stations. Runoff collected at the monitoring stations is analyzed for total suspended solids, nitrate, ammonium, TKN, dissolved TKN, total P, total dissolved P, and orthophosphorus. Meteorological variables (precipitation, daily evaporation, wind direction and speed, air temperature, relative humidity) are collected at a main weather station in the watershed and precipitation data is collected at seven additional sites within or bounding the watershed. Additional information on the Owl Run monitoring project and systems are reported by Mostaghimi et al. (1989).

The model was run for a full corn growing season for a period of five months, from May 1991 to September 1991. The Owl Run watershed is characterized by the presence of dairy operations and a lack of good animal waste management practices (Mostaghimi et al., 1989). The ANSWERS model at the present stage of development does not simulate surface application of manure. Furthermore, little is known regarding the amount and location of manure applied to the soil. A large portion of the nutrient monitored at the watershed outlet appears to be coming from the dairy operations, or simply from cropland to which manure has been applied. According to Mostaghimi et al. (1989), 14,600 m³ of dairy waste are produced annually in the watershed. This includes both wash water volume and runoff coming in contact with the dairy waste. To simulate the presence of dairy operations in the watershed, 250 kg/ha of ammonium was assumed to be applied to the pastures on September 4 1991. About 200 kg/ha of nitrogen was applied on the corn fields on May 1, 1991. Furthermore, about twenty percent of the watershed is woodland and 10% of the watershed is non-agricultural. Thus, the simulation of these landuses is subject to errors since the ANSWERS model was intended to be used to simulate such landuses. Some of the internal parameters used by the ANSWERS model were calibrated to better represent the observed sediment yield. The detachment coefficient by rainfall was divided by 100, and the coefficient for detachment by overland flow was divided by 150. The results are reported for the storms that produced runoff during the simulation period and are given in Table 3.
Table 3. Runoff, sediment yield, nitrate, ammonium, orthophosphorus and sediment-bound TKN loadings for the Owl Run watershed.

<table>
<thead>
<tr>
<th></th>
<th>Rainfall</th>
<th>Runoff</th>
<th>Sediment</th>
<th>NO₃</th>
<th>NH₄</th>
<th>PO₄</th>
<th>TKN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mm)</td>
<td>(mm)</td>
<td>(kg)</td>
<td>(kg)</td>
<td>(kg)</td>
<td>(kg)</td>
<td>(kg)</td>
</tr>
<tr>
<td>07-26-91</td>
<td>59</td>
<td>1.2</td>
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RUNOFF

The model represented runoff volume for four of the five reported storms very well. The model underpredicted runoff for the storm occurring on September 24 by 86%, which is the smallest storm reported during the simulation period. This is expected since ANSWERS was originally developed to predict runoff from extreme storms. DeRoo (1991) also reported that the ANSWERS model performed better for larger storms. The predictions of the model are very encouraging, since during the development of the input file, little information was available regarding the characteristics of the channel network. Furthermore, it appears that ANSWERS handled the hydrology of the forested and urban areas adequately. These results confirm the ability of ANSWERS to represent and simulate the effects of different land cover on runoff. Furthermore, in a previous research conducted on the Owl Run watershed for the same simulation ANSWERS was used successfully in predicting runoff volume and in producing accurate hydrographs at different points within the watershed (Bouraoui et al., 1993). Overall the model predicted well cumulative runoff loss from the Owl Run watershed. The predicted cumulative runoff was within 7% of the measured value (Table 3).

SEDIMENT

The model did not perform as well in predicting sediment yield as it did in predicting runoff (Table 3). The model underpredicted sediment yield for four of the five storms (07-26-91, 09-04-91, 09-18-91, and 09-24-91). Three out of the four underpredictions of sediment yield (07-26-91, 09-04-91, and 09-24-91) correspond to an underprediction in runoff amount. For the storm that occurred on September 18, 1991, the predicted value was within 20% of the predicted. For the storm that occurred on August 9, 1991, the sediment was overpredicted by 65% even though the runoff was slightly underpredicted. The model predicted cumulative sediment loss within 12% of the measured value.

NITRATE

The model underpredicted nitrate loadings for all storms. The model predicted that the largest loss would occur on August 8, 1991, which is the largest storm occurring during the simulation period. For that particular storm, the predicted nitrate was within 17% of the measured value. For the four remaining storms, nitrate loading was underpredicted by about 60% or more. This
underprediction may be attributable to the fact that ANSWERS does not simulate runoff occurring from dairy operations, which is a major contributor to total nutrient loadings in the Owl Run watershed. The presence of dairy operations will result in high nutrient loading, even during small storms. Overall, long-term prediction of nitrate loss was within 30% of the measured value.

AMMONIUM

The model, as for nitrate, did not reproduce the ammonium loadings well (Table 3). The model predicted that the major loss of ammonium would occur during the largest runoff event (August 9, 1991). However, the measured data indicate that the major losses occurred the subsequent months for smaller runoff events. This illustrates the high variability of nutrient loss due to the presence of the dairy operations. Model prediction of cumulative ammonium loss was within 12% of the measured value.

SEDIMENT-BOUND TKN

Overall, the model performed better in predicting sediment-bound TKN losses from the watershed than any other nutrient. The model did not perform extremely well in predicting total sediment-bound TKN loadings, however, when comparing measured and predicted sediment-bound TKN concentration (g TKN/kg soil) the model predicted 16, 14, 18, 15, and 15 g-TKN/kg-sediment and the measured concentrations are 14, 13, 21, 13, and 21 g-TKN/kg-sediment for the storms occurring on July 26, August 8, September 4, September 18 and September 24, 1991, respectively. This indicates that the performance of the model in predicting sediment-bound TKN can be improved with better predicted estimates of sediment yield. Thus, the model has the ability to reproduce nitrogen losses from large watersheds. The predicted cumulative sediment-bound TKN loss was within 39% of the measured value.

DISSOLVED PO4

The model predicted the amount of dissolved phosphorus occurring during the largest storm well. The predicted P loss was within 13% of the measured value. However, for all four smaller storms, the model underpredicted P loss by 91, 86, 68 and 98%. However, during the largest event, the effects of the dairy operations have relatively smaller impact with respect to the total loadings of nutrients (including P), thus the performance of the model is expected to be better.
during the largest storms. For the storms that occurred September 24, 1991, the underprediction of dissolved P is largely due to the underprediction of runoff volume. Overall, the model performed the best for the larger storms, when the effects of nutrient loading from the dairy operation are expected to have less influence on the total loadings. Model prediction for cumulative dissolved inorganic P losses were within 6% of the measured values.

SUMMARY

The model was successfully validated on a large watershed in Virginia for predicting cumulative runoff, sediment, nitrate, ammonium, sediment-bound TKN, and dissolved inorganic P losses. Cumulative predictions of runoff, sediment yield, nitrate, ammonium, orthophosphorus, and sediment-bound TKN losses were all within 40% of the measured values. For individual storms, the model predicted runoff amount and sediment yield relatively well. However the model did not perform as well in predicting nutrient loading although predictions were generally within a factor of 2 of observed values. Part of the performance of the model is attributable to the presence of dairy operations that the model does not simulate. The prediction of sediment-bound TKN can be improved by predicting sediment losses more accurately. The model predicted that the major loss of nitrate, phosphorus and sediment-bound TKN occurred during the largest storm. During the large storm occurring on August 9, 1991, the model performed well in predicting nitrate and phosphate losses. The overprediction of sediment-bound TKN is due mainly to the overprediction of sediment.
SENSITIVITY ANALYSIS

INTRODUCTION

The ANSWERS model was modified into a continuous, physically-based nonpoint source model and tested on two small watersheds in Georgia and a large watershed in Virginia. Modifications made included the addition of many new variables and parameters. Therefore, a logical step after model development and testing is sensitivity analysis. Sensitivity analysis can be defined as the relative changes in the model predictions with respect to changes in the model input (Orlob, 1983). It is usually conducted by taking the derivative of model outputs with respect to given input parameters, and assumes that all other model input parameters remain constant. Sensitivity analysis allows the determination of the relative sensitivity of model parameters on model outputs, and the effects of uncertainty in input parameter estimates on model outputs. This allows increased attention to be given to the determination of the sensitive parameters, in order to obtain more accurate output values. Sensitivity analysis also gives an indication of the accuracy of the output. Sensitivity analysis also allows a better understanding of the interrelationships of the parameters, and gives an indication on how they affect the processes they are involved with.

The P2 watershed (Watkinsville, Georgia) was selected to conduct the sensitivity analysis. The base input file used for the sensitivity analysis is the same input file used for the validation run. The model was run for 870 days (3 full corn growing seasons). Since the outputs (cumulative losses at the end of the simulation period) were not expected to vary linearly with the input parameters, the sensitivity was determined at six different levels. The selected parameters were increased and decreased by 10, 25 and 50%. Parameter sensitivity was determined by dividing the output obtained with increased (decreased) input parameter minus the output obtained during the base run by the output value of the base run.

The first part of the sensitivity analysis was focused on determining the effects of hydraulic conductivity and soil texture (clay and silt content of the soil) on the new infiltration model, and consequently on runoff and sediment. Since this part of the sensitivity analysis focused on the effect of hydraulic conductivity on runoff and sediment, even when clay and silt content were changed, the particle size distribution of the soil was not modified. The effects of nutrient loss as affected by the clay and silt content are also reported. The effects of important evapotranspiration parameters on runoff and sediment were then studied. The third part of the
sensitivity analysis focused on the new nutrient models by studying the effects of varying the nutrient input parameters on the nutrient loss.

RUNOFF

The soil parameters selected for the sensitivity analysis are soil clay and silt content. Sand was not included in the sensitivity analysis, because the soils covering the P2 watershed were mostly loam, silt loam and clay loam soils. Thus, sand was the largest fraction present in these soils. Thus a variation of 10% of the sand content would induce a change of more than 50% for the silt and clay content.

The sensitivity of runoff to changes in the clay and silt content is shown in Figure 41. The model was very sensitive to variations in the clay content of the soil. An increase in the clay content always increased runoff, and a decrease in the clay content always decreased runoff. This was expected since clay content directly affects the hydraulic conductivity, which in turn determines infiltration rates. An increase in the clay content of the soil resulted in a decrease in the hydraulic conductivity of the soil, resulting in lower infiltration rates which increased runoff volumes. Lower clay content resulted in higher hydraulic conductivities, which resulted in decreased runoff. Runoff was less sensitive to silt than clay content. A 50% increase in the silt content resulted in an increase of 22% of the runoff volume, while an increase in the clay content of 50% resulted in an increase in the runoff volume by 45%.

The sensitivity of the runoff volume to variations of the depth of the soil horizon simulated was also studied. One of the major limitations of the previous version of the ANSWERS model was the use of Holtan’s infiltration equation (Holtan, 1961) and its associated control depth. Runoff volume was dependent upon the selection of the control depth. The new version of the ANSWERS model uses the Green-Ampt infiltration equation rather than the Holtan’s equation. The model assumes a single homogeneous soil layer. The depth of this layer should be based upon soil characteristics and cultural practices. The depth of the soil layer (PIV) was assumed to be 20 cm, the depth of the plow layer. This depth was increased and decreased by 10, 25 and 50%. The results of the sensitivity analysis are shown in Figure 41. The runoff volume was not sensitive to increases in the soil zone depth. Decreases of the soil zone depth (PIV) by 10 and 25% resulted in little change in the runoff volume. A decrease in the soil depth by 50% resulted in an increase in the runoff volume by 18%. This increase was expected, because the shallower

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Figure 41. Sensitivity analysis of depth of soil zone (PIV), and clay (CLAY) and silt (SILT) content on runoff volume.
the soil zone depth, the faster soil moisture increases and percolation starts. This results in lower infiltration rates and higher runoff rates. The model is now much less sensitive to variations of the soil zone depth with respect to runoff volume, than the previous version of the model.

Runoff volume is also related to evapotranspiration, since both infiltration and evapotranspiration are involved simultaneously in the soil water balance. Evapotranspiration is driven by the air temperature, solar radiation and leaf area index. The sensitivity of the runoff volume to variations in temperature, solar radiation and leaf area index is shown in Figure 42. Note that in the validation run, soil and air temperatures are assumed the same because of missing soil temperature data. Runoff volume was insensitive to decrease in air temperature. A decrease in air temperature by 50% decreased runoff volume by only 1%. An increase in soil and air temperature by 50% increased runoff volume by 13%. The sensitivity of runoff volume to variations in solar radiation and leaf area index is similar to that of temperature. An increase in the leaf area index and daily solar radiation always decreased runoff, and a reduction of LAI and solar radiation always resulted in an increase of the runoff volume. This is expected since an increase in LAI and solar radiation increases evapotranspiration, resulting in a drier soil, and less runoff. A decrease in the LAI by 50% increased runoff by 13%, while a decrease in the solar radiation by 50% increased runoff volume by 18%. The runoff volume was the most sensitive to solar radiation.

The findings of this sensitivity analysis are confirmed by Lane and Ferreira (1980), who conducted a sensitivity analysis of the runoff volume from the P2 watershed to LAI, solar radiation and temperature using the CREAMS model (CREAMS uses the same method as ANSWERS to compute evapotranspiration). Values of the leaf area index were decreased by 25 and 50% and then increased by 25 and 50% throughout the growing season of corn. The CREAMS model was not very sensitive to variations in the leaf area index (LAI). A decrease in the LAI of 50% resulted in an increase in the runoff volume by 7.6%, while an increase in the LAI of 50% reduced the runoff volume by 2.8%. Variation of the mean monthly temperature by 50% and -50% resulted in variation of the runoff volume of 13% and -3.3%, respectively. Runoff volume was the most sensitive to solar radiation where a decrease in the solar radiation by 50% increased runoff volume by 21.7%. An increase in the solar radiation by 50% decreased runoff volume by 5.4%. For further details regarding this sensitivity analysis, the reader is referred to Lane and Ferreira (1980).
Figure 42. Sensitivity analysis of air temperature (TEMP), solar radiation (RADI) and leaf area index (LAI) on runoff volume.
SEDIMENT

Sediment yield is directly related to the runoff volume, and is expected to vary in a similar manner as the runoff volume. Sediment yield was the most sensitive to variation in the clay content (Figure 43). A variation in the clay content by 50% increased the sediment loss by 52%. Sediment yield was slightly more sensitive to variations in the clay and silt content than runoff. The selection of the soil depth did not affect greatly the amount of sediment loss. This sensitivity analysis shows that great care has to be taken when choosing the clay content of the soil. Clay content greatly affects runoff volume and sediment loss. The sensitivity analysis also shows that runoff volume and sediment loss are highly correlated as expected.

Additional parameters of the ANSWERS model affect runoff volume and sediment loss. For details concerning the sensitivity of runoff and sediment yield to these parameters, the reader is referred to Baun et al. (1986).

NITROGEN

The input parameters included in the sensitivity analysis of N output include potentially mineralizable N (POTMIN), stable organic N (SOILN), initial concentration of ammonium (AMON) and initial concentration of nitrate (NO3). The output considered in the sensitivity analysis include nitrate in runoff, nitrate in percolation from the infiltration control zone, dissolved and sediment-bound ammonium, and sediment-bound TKN.

NITRATE

Nitrate loss in runoff was insensitive to small variations of the potentially mineralizable N (Figure 44). A large increase in POTMIN (+50%) resulted in an increase in nitrate loss in runoff by 3%, while a decrease in POTMIN by 50% decreased the nitrate loss in runoff by 4%. This indicates that the mineralization rate in ANSWERS is very low, and even large increases in the potentially mineralizable N pool will not result in higher ammonium, and thus nitrate concentrations. The low sensitivity of nitrate loss to initial ammonium concentration was expected since the initial amount of ammonium involved is relatively small compared to the total amount of ammonium involved during the total period of the simulation. This is illustrated by the fact that the major differences between the base run nitrate loss and the nitrate loss obtained with modified initial
Figure 43. Sensitivity analysis of depth of soil zone (PIV), and clay (CLAY) and silt (SILT) content on sediment yield.
Figure 44. Sensitivity analysis of initial nitrate (NO3), stable organic N (SOILN), active organic N (POTMIN), ammonium (AMON) on nitrate loss in surface runoff.
ammonium concentration occurred during the initial storms of the simulation period. The model was more sensitive to the initial concentration of nitrate than to the initial concentration of ammonium. This is expected since nitrate is lost directly to runoff, while ammonium must undergo nitrification before it can be lost in runoff as nitrate. Overall, nitrate loss in runoff was insensitive to the initial concentration of nitrate, since an increase by 50% of the initial concentration of nitrate increased nitrate loss in runoff by only 7%. This was expected since the initial concentration of nitrate is very small compared to the total amount of nitrate involved during the simulation period. The major difference of nitrate loss between the base run, and the run with modified initial nitrate concentration occurred during the initial storms of the simulation period.

The influence of soil parameters on nitrate loss through runoff are shown in Figure 45. The parameters that had the biggest impact on runoff also affected nitrate loss in runoff the most. Nitrate loss was most sensitive to the clay content of the soil. An increase in the clay content by 50% increased nitrate loss in runoff by 102% (runoff was increased by 45%). Overall, the nitrate was much more sensitive to clay variation than runoff. This higher sensitivity can be explained by the non linear equation used to determine nitrate loss in runoff. Furthermore this higher sensitivity can be explained by the fact that an increase in the clay content of the soil increased the amount of runoff by 45%. Increased runoff resulted in smaller percolation rates, thus less nitrate was lost through percolation, and more nitrate was available to be transported by runoff. Silt content affected nitrate loss in a manner similar to that for runoff. Nitrate loss was more sensitive to variations in silt content than runoff. This higher sensitivity can be explained by the fact that increased runoff volumes result in smaller percolation volumes, thus less nitrate is lost in percolation and more nitrate is lost in runoff. Thus, increased runoff volumes not only increase nitrate loss in runoff but also increase the amount of nitrate available to be transported by runoff because of the smaller percolation rates. This is illustrated by Figure 46, which represents the sensitivity of nitrate loss through percolation to different soil parameters. The amount of percolating nitrate varies inversely with runoff. An increase in runoff decreases nitrate loss in percolation, and a decrease in runoff volume increases percolating nitrate. The amount of nitrate lost through percolation was most sensitive to the clay content of the soil. An increase in the clay content by 50% resulted in a decrease in the amount of nitrate lost through percolation by 20% (runoff was increased by 20%). Nitrate loss through percolation is more sensitive to variations in clay content than nitrate loss in runoff. This can be explained by the fact that the amount of nitrate lost through percolation is much higher than that lost in runoff. Thus, small variations in
Figure 45. Sensitivity analysis of depth of soil zone (PIV), and clay (CLAY) and silt (SILT) content on nitrate loss in surface runoff.
Figure 46. Sensitivity analysis of depth of soil zone (PIV), and clay (CLAY) and silt (SILT) content on nitrate leaching from the soil zone.
the amount of percolating nitrate greatly affect the amount of nitrate in the upper soil zone interacting with surface runoff, which in turn controls nitrate loss in runoff.

**DISSOLVED AMMONIUM**

Dissolved ammonium was insensitive to variations in the nitrogen input parameters (Figure 47). Dissolved ammonium was insensitive to variations of POTMIN. An increase in POTMIN by 50% increased dissolved ammonium loss with runoff by 5%. This confirms that the mineralization rate predicted by ANSWERS is very small, thus the amount of POTMIN will not affect greatly the amount of dissolved ammonium carried with runoff. Total loss of dissolved ammonium was also insensitive to the initial concentration of ammonium. Ammonium is partially sediment-bound, and thus all ammonium is not available to be lost dissolved in runoff. Furthermore, the initial concentration of ammonium is very small compared to the total amount of ammonium involved during the simulation. Thus, the initial concentration of ammonium will have a minor impact on the total loss of dissolved ammonium. The concentration of nitrate or stable organic N had little or no influence on the amount of dissolved ammonium loss.

The dissolved ammonium loss varied in a similar manner to runoff to variations in the clay and silt content of the soil (Figure 48). Increased runoff resulted in increased dissolved ammonium loss, and decreased runoff decreased dissolved ammonium loss. The dissolved ammonium loss was the most sensitive to variations of the clay content of the soil. Sensitivity of dissolved ammonium loss and runoff to clay content variations are in the same range. An increase in 50% in the clay content increased the dissolved ammonium loss by 59% while runoff was increased by 46%. Dissolved ammonium loss was much less sensitive than nitrate loss to variations in clay and silt content. This is expected, since the model does not allow movement of dissolved ammonium via percolation.

**SEDIMENT-BOUND AMMONIUM**

The sensitivity of the sediment-bound ammonium to the initial nitrogen parameters is shown in Figure 49. Sediment-bound ammonium loss was not affected by variations in POTMIN. An increase in POTMIN by 50% increased the sediment-bound ammonium loss by 2%. This is attributable to the small mineralization rates predicted by ANSWERS. The sediment-bound ammonium loss was more sensitive to the initial concentration of ammonium. An increase by
Figure 47. Sensitivity analysis of initial nitrate (NO3), stable organic N (SOILN), active organic N (POTMIN), ammonium (AMON) on dissolved ammonium loss in surface runoff.
Figure 48. Sensitivity analysis of depth of soil zone (PTV), and clay (CLAY) and silt (SILT) content on dissolved ammonium loss in surface runoff.
Figure 49. Sensitivity analysis of initial nitrate (NO3), stable organic N (SOILN), active organic N (POTMIN), ammonium (AMON) on sediment-bound ammonium loss.
50% of the initial ammonium concentration, resulted in an increase in sediment-bound ammonium loss of 10%. However, the major differences between the base run and the run with increased ammonium concentration (50%) occurred during the early storms of the simulation period. Later, during the simulation little or no difference was observed between the base run sediment-bound ammonium loss and the modified run sediment-bound ammonium loss because the soil N pools had stabilized. The concentration of stable soil organic N (SOILN) had no effect on sediment-bound ammonium loss. This is due to the fact that there is no direct relationship between ammonium and stable organic N. There is an equilibrium between the stable and active organic N, but an increase in the stable organic N is buffered by the active organic N pool. Furthermore, since ANSWERS predicts very small mineralization rates, an increase in the stable organic N will hardly have any effects on the ammonium pool, including the sediment-bound ammonium pool.

Nitrate has very little influence on the sediment-ammonium loss. An increase in the nitrate pool results in an increase in sediment-bound ammonium loss and a decrease in the nitrate pool results in a decrease in the sediment-bound ammonium loss (the same observation can be made for the dissolved ammonium loss). This is explained by the fact that a decrease in the nitrate pool, will decrease the amount of nitrate taken up by plant, thus the plant will uptake more ammonium, causing the depletion of the ammonium pool. Thus, a decrease in the nitrate pool will cause a decrease of dissolved and sediment-bound ammonium losses.

The sediment-bound ammonium loss responded to variations in the clay and silt content in a manner similar to runoff and sediment losses (Figure 50). Sediment-bound ammonium was the most sensitive to variations in the clay content of the soil. An increase in the clay content by 50% increased sediment-bound ammonium loss by 63% (sediment was increased by 52%). Sediment-bound ammonium was much less sensitive in variations in the silt content.

SEDIMENT-BOUND TKN

Sediment-bound TKN was more sensitive to the concentration of stable organic N (SOILN) than the concentration of active organic N (POTMIN) (Figure 51). An increase in POTMIN by 50% increased sediment-bound ammonium loss by 14%, while an increase in the stable organic N by 50% increased the sediment-bound ammonium loss by 33%. TKN is defined as total N minus nitrate. On the P2 watershed, stable organic N was the largest N pool. It is thus expected to have the most influence upon sediment-bound TKN loss. The active organic N pool, which is the second largest N pool, was expected to have a lesser influence than SOILN. Ammonium, which

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Figure 50. Sensitivity analysis of depth of soil zone (PIV), and clay (CLAY) and silt (SILT) content on sediment-bound ammonium loss.
Figure 51. Sensitivity analysis of initial nitrate (NO3), stable organic N (SOILN), active organic N (POTMIN), ammonium (AMON) on sediment-bound TKN loss.
is the smallest pool composing TKN, was expected to have minimal influence upon sediment-bound TKN losses. Furthermore, the ammonium pool is very instable and subject to quick transformations. The ammonium pool varies from high concentrations following fertilizer application, to zero during the maximum plant growth period. Furthermore, the nitrification rate is much higher than the mineralization rate. Thus, all mineralized N is quickly transformed to nitrate. Even high additions of ammonium fertilizer, are followed by quick nitrification of the ammonium pool (20 days in ANSWERS).

The effects of varying soil parameters on sediment-bound ammonium-loss are shown in Figure 52. The sediment-bound ammonium loss is the most sensitive to clay content. Effects of soil parameters on sediment-bound TKN loss are identical to the effects of the soil parameters on sediment loss. This is expected, since TKN is a very large, stable pool, not subject to quick changes (like the ammonium pool).

PHOSPHORUS

SEDIMENT-BOUND PO4

Phosphorus parameters investigated during the sensitivity analysis include organic P (SORGP), active mineral P (PMINP), stable mineral P (SOILP), and labile P (PLAB). The sensitivity of sediment-bound P to variations in the P inputs considered is presented in Figure 53. Sediment-bound P was insensitive to variations in SORGP because of ANSWERS’s low mineralization rates for soil organic P. This is expected since the N and P mineralization rates were assumed to be the same (Knisel et al., 1993). A 50% increase in SORGP increased sediment-bound P loss by less than 2%. Sediment-bound P loss was also insensitive to variation in the active mineral pool. A 50% increase in PMINP, increased sediment-bound P loss by 3%. This low sensitivity is explained by the equilibrium between the stable and active mineral P pools. The stable mineral P pool is assumed four times larger than the active organic P pool. Thus any increase in PMINP, is quickly transformed to SOILP, and thus little active mineral P will contribute to the labile P pool. The sediment-bound P loss was insensitive to variations in the stable mineral P pool. Little of the added stable mineral P will contribute to the active mineral P pool (25%), and thus little of the added stable mineral P will be transformed to labile P. Sediment-bound P loss was the most sensitive to the initial concentration of labile P. An increase in PLAB by 50% increased sediment-bound P loss by almost 30%. A decrease in PLAB by 50% decreased the amount of
Figure 52. Sensitivity analysis of depth of soil zone (PIV), and clay (CLAY) and silt (SILT) content on sediment-bound TKN loss.
Figure 53. Sensitivity analysis of initial labile P (PLAB), stable inorganic P (SOILP), active inorganic P (PMINP), organic P (SORGP) on sediment-bound P loss.
sediment-bound P loss by 30%. Most of the differences in sediment-bound P loss occurring between the base run and the run with modified initial PLAB concentration occurred during the initial storms of the simulation. After the initial storms, little or no difference was observed.

The effects of varying the soil parameters upon sediment-bound P loss are shown in Figure 54. As expected, the sediment-bound P loss is the most sensitive to factors affecting sediment loss. Sediment-bound P loss was the most sensitive to clay content variations. An increase in the clay content by 50% increased the sediment-bound P loss by 38%. Most of the increase in sediment-bound P loss is due to the increased sediment yield. As expected, sediment-bound P loss was less sensitive to variations in silt content, because sediment loss was affected less by variations in the silt content.

DISSOLVED PO4

Dissolved labile P sensitivity to variations in the P input parameters is similar to that of sediment-bound P loss (Figure 55). Dissolved labile P loss was relatively insensitive to variations in soil organic P, and stable and active mineral P. Increases in SORGP, PMINP, and SOILP by 50% increased the dissolved labile P loss by 2, 4, and 4%, respectively. This low sensitivity of dissolved labile P is explained by the same reasons given to explain the low sensitivity of sediment-bound P to P input parameters. Dissolved labile P was the most sensitive to the initial value of PLAB. An increase in PLAB by 50% increased dissolved P loss by 22%. However, the major differences between the base run dissolved labile P loss and the dissolved labile P loss obtained when increasing PLAB concentrations, occurred during the first large storms of the simulation period. After two or three months of simulation, the base run dissolved labile P loss and the dissolved labile P obtained with the modified PLAB concentration were identical.

The effects of modifying the clay and silt content upon the dissolved labile P loss are shown in Figure 56. Dissolved labile P loss is less sensitive than runoff to variations in clay content. A 50% increase in the clay content of the soil increased dissolved labile P loss by 22% while it increased runoff by 46%. This difference is explained by the fact that increasing the clay content increases the runoff volume, but it also increases the partition coefficient of phosphorus. Thus increasing clay content increases runoff volume, but decreases the amount of dissolved labile P that can be lost through runoff. Thus, clay content has opposite effects on the runoff volume and dissolved labile P available to be transported by runoff. As a consequence, dissolved labile P is
Figure 54. Sensitivity analysis of depth of soil zone (PIV), and clay (CLAY) and silt (SILT) content on sediment-bound P loss.
Figure 55. Sensitivity analysis of initial labile P (PLAB), stable inorganic P (SOILP), active inorganic P (PMINP), organic P (SORGP) on dissolved P loss in surface runoff.
Figure 56.  Sensitivity analysis of depth of soil zone (PIV), and clay (CLAY) and silt (SILT) content on dissolved P loss in surface runoff.
expected to be less sensitive to variations in silt content. An increase in the silt content will decrease the sand and clay content of the soil. A smaller clay content results in a smaller partition coefficient for P and increased dissolved labile P in the soil. Consequently, a large increase in the silt content will not only increase the runoff volume, but it will also increase the amount of dissolved labile P available for runoff. This explains why dissolved labile P loss is more sensitive to silt content variation than runoff. The opposite effects of silt content on runoff volume and partition coefficient are best illustrated when the silt content of the soil is decreased by 50%. When silt content was decreased by 50%, runoff decreased by 3%, and dissolved labile P decreased by 18%. This large difference is explained by the fact that decreasing the silt content decreased the equilibrium constant of P and more dissolved labile P was consequently available for loss in runoff.

CONCLUSION

The sensitivity analysis showed that the clay and silt contents are very sensitive parameters in the ANSWERS model. Clay and silt are the parameters affecting runoff and sediment loss the most. Thus, they have a major impact on nutrients transported with runoff and sediment. Initial concentrations of nutrients did not have a large impact on the total nutrient losses. An increase (decrease) of the initial nutrient concentration resulted in an increase (decrease) of the nutrient loss only for storms early in the simulation period. After a few months, the initial concentration of nutrients stabilized and had little effect on nutrient loss. The sensitivity analysis also indicates that runoff volume is no longer very sensitive to soil depth parameter.

Great care should be taken in selecting the clay and silt content of the soil, because as shown by the sensitivity analysis, they greatly affect runoff and sediment volume. However, the sensitivity was conducted for extreme cases, and usually estimates of the clay and silt content of a particular soil can be estimated accurately, or within an order of one (which is the range covered by the sensitivity analysis).
MODEL APPLICATION

The ANSWERS model was modified to a comprehensive, physically-based, continuous, watershed scale nonpoint source pollution model. The model was validated on two small watersheds in Georgia and on a large watershed in Virginia. Model predictions were generally with a factor of one of observed data and the model was judged adequate for planning purposes. This part of the research focuses on a practical demonstration of how the model can be used to predict the long-term effectiveness of BMPs on runoff, sediment, and nutrient losses for planning purposes.

The model was run on the Nomini Creek watershed in Westmoreland County, Virginia. The watershed contains approximately 1505 hectares of which half is agricultural, primarily row crops, and the remainder is forested. The major crops in the watershed include corn, soybeans, wheat and barley. Westmoreland County has a humid continental climate, with 100 cm of annual precipitation. The major soils in Nomini Creek watershed are Suffolk and Rumford series. The Suffolk series (coarse-loamy, siliceous, thermic, Typic Hapludult) covers 58% of the watershed and is characterized by a sandy loam texture with moderate permeability and slopes ranging from 0 to 6%. The Rumford soils (coarse-loamy, siliceous, thermic, Typic Hapludult), cover approximately 33% of the watershed, and are classified as sandy loam soils, with moderately to steep slopes (0 to 50%) and by moderately rapid permeability.

Surface water quality is monitored at two stations QN1 and QN2. The main station, QN1, is located at the watershed outlet. Runoff collected at QN1 is strongly influenced by the presence of marshes and swamps located upstream of QN1. Station QN2 drains a 225 ha agricultural subwatershed. There is a significant baseflow at both stations due to springs and high water tables. Additional information regarding the Nomini Creek data collection and data analysis procedures are given by Mostaghimi et al. (1988). The model was run on the QN2 subwatershed, which is not affected by swamps and marshes (landuses that ANSWERS does not simulate). Figure 57 represents the percentage of land falling in different landuse categories. An eight year climatic data record was generated using CLIGEN (Nicks, 1985). The daily rainfall data were then transformed into breakpoint rainfall using desegregation routines used in the WEPP model (Lane and Nearing, 1989). The watershed was divided into uniform 1 ha cells. In the first step, the model was run using the predominant crop rotation found in the area. Management practices,
Figure 57. Nomini Creek, QN2 subwatershed landuse categories.
landuse and fertilizer application for the Nomini Creek watershed are summarized in Table 4.

The model was run for 8 years (four full rotations) to identify areas that are likely responsible for the greatest sediment and nutrient losses (critical areas). The potentially critical areas were identified based on their simulated soil loss. The second step consisted of implementing conservation tillage on 10%, 20%, 30% and 100% of the agricultural areas. The implementation was done with the constraint of respecting field boundaries (conservation till was applied at the field level rather than at the cell basis). Conservation tillage is defined as a tillage practice which leaves at least 30% of the soil surface covered with residue after planting. Different types of conservation tillage include no-till, ridge till, and chisel system. The major effect of conservation tillage practices is to reduce erosion. Residues buffer and reduce the energy of impacting raindrops on the soil. Furthermore, by increasing surface roughness, residue increases infiltration and reduces erosion by overland flow. Conservation tillage is expected to increase infiltration and decrease erosion production from those areas which contribute the most total sediment loading of the watershed. Conservation tillage is simulated by varying the model parameters which are influenced by conservation tillage. These parameters included roughness coefficient, maximum roughness height, Manning’s n for overland flow, and the crop management factor. These factors were changed in accordance with the values used by Baun et al. (1986). Other parameters are also affected by conservation tillage, especially soil parameters such as bulk density and soil temperature. However, since the model does not currently allow variations in these parameters, their effects were not simulated.

The model was run six times: one run consisted of all the crop land area being in conventional tillage (Run 1) and then conservation tillage was applied to 8.5 (Run 2), 21.5 (Run 3), 32.7 (Runs 4 and 5) and 100% (Run 6) of the cropland. The model was run twice with 32.7% of the cropland converted to conservation tillage, because for each of the 32.7% runs, a different farm was selected for conversion to conservation tillage. One farm had higher sediment yields but was farther away from the watershed outlet than the second farm. In the conservation tillage scenarios, conservation was applied to the fields with the highest sediment yields first. As the percentage of conservation tillage was increased, conservation tillage was expanded to fields with progressively lower sediment yields. The results for the different targeting schemes are shown in Table 5. In order to better understand the contribution of each area to the total loss of sediment and nutrients from the watershed, a unit reduction was computed.
<table>
<thead>
<tr>
<th>Date</th>
<th>Management Practice</th>
<th>Fertilizer Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>04-30-1980</td>
<td>watershed conventionally tilled (Run 1)</td>
<td>fertilizer application and incorporation with</td>
</tr>
<tr>
<td></td>
<td>chisel (20 cm deep) (Runs 2-6)</td>
<td>NH₄-N 80 kg NO₃ 80 kg PO₄-P 60 kg</td>
</tr>
<tr>
<td>05-01-1980</td>
<td>plant corn</td>
<td></td>
</tr>
<tr>
<td>10-31-1980</td>
<td>harvest corn</td>
<td>fertilizer application and incorporation with</td>
</tr>
<tr>
<td>11-01-1980</td>
<td>plant small grain</td>
<td>NH₄-N 40 kg NO₃ 60 kg PO₄-P 20 kg</td>
</tr>
<tr>
<td>06-30-1981</td>
<td>harvest small grain</td>
<td></td>
</tr>
<tr>
<td>07-01-1981</td>
<td>planting soybean</td>
<td>fertilizer application and incorporation with</td>
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<tr>
<td></td>
<td></td>
<td>NH₄-N 40 kg NO₃ 60 kg PO₄-P 20 kg</td>
</tr>
<tr>
<td>10-31-1981</td>
<td>harvest soybean</td>
<td></td>
</tr>
<tr>
<td>11-01-1981</td>
<td>fallow</td>
<td></td>
</tr>
</tbody>
</table>
The unit reduction represents the percentage reduction of sediment and nutrient loss at the watershed outlet divided by the percent area of the watershed converted to conservation tillage. An efficient scenario is indicated by unit reduction larger than 100. The unit reductions for the different targeting levels are shown in Table 6.

Converting all cropland from a conventional tillage to conservation tillage (Run 6) decreased watershed sediment yield by 56% (Table 5). This large decrease resulted in unit reduction of 162%, which means that converting from conventional to conservation tillage is a very efficient way of reducing sediment, since converting 33% of the watershed area from conventional to conservation tillage practice decreased overall watershed yield by 56%. However, conversion of all fields to conservation tillage was the least efficient management scenario in terms of unit reductions (unit reduction is 162). The most efficient unit reduction was obtained when converting the fields that had the highest sediment yields (unit reduction is 430). Thus, Run 1 was about 2.5 times more efficient than Run 6 in reducing overall sediment yield of the watershed. This illustrates how targeting is an efficient method for reducing sediment losses.

The model predicted that conversion from conventional to conservation tillage was much less efficient in reducing dissolved nutrients than sediment-bound nutrients. This is primarily the result of the small reduction in runoff (12%) that was obtained from conversion from conventional to conservation tillage. This small reduction in runoff is partially the result of the low predicted runoff with conventional tillage (annual runoff of 85.5 mm or about 8.5% of precipitation).

The model predicted that converting agricultural areas from conventional to conservation tillage practice would increase nitrate leaching in the converted areas. Figure 58 shows the percent increase in nitrate leaching due to the implementation of conservation tillage. Predicted nitrate leaching increased by as much as 7%.

Table 6 shows that targeting conservation tillage to 8.5% of the cropland with the highest erosion rates was the most efficient (in terms of unit reduction) in reducing total losses of both sediment-bound and dissolved nutrients. This indicates that targeting of BMP's to fields with high sediment yields may result in the highest decrease per unit area in sediment and nutrient load. However, this may not always be the case as illustrated in Runs 4 and 5 where 32.7% of the agricultural land was converted from conventional to conservation tillage. The two runs differ by the location of the farm selected for implementation of conservation tillage. The farm selected for Run 4 was
Table 5. Percentage reduction in total runoff, sediment and nutrient losses at the watershed outlet due to the implementation of conservation tillage practice on critical fields.

<table>
<thead>
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<th>Run</th>
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<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Percentage cropland area converted to conservation tillage</td>
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</tr>
<tr>
<td>Base Value</td>
<td></td>
</tr>
<tr>
<td>Runoff 1</td>
<td>68.5</td>
</tr>
<tr>
<td>Sediment 2</td>
<td>7341</td>
</tr>
<tr>
<td>NO₃⁻ 3</td>
<td>22</td>
</tr>
<tr>
<td>Dis NH₄⁺ 3</td>
<td>556</td>
</tr>
<tr>
<td>Sed NH₄⁺ 3</td>
<td>74</td>
</tr>
<tr>
<td>Sed TKN 3</td>
<td>12025</td>
</tr>
<tr>
<td>Total P 1</td>
<td>1714</td>
</tr>
</tbody>
</table>

¹ mm/year, ² kg/ha-yr, ³ kg/yr
Table 6. Unit reduction in total runoff, sediment and nutrient losses at the watershed outlet due to the implementation of conservation tillage practice on critical fields.

<table>
<thead>
<tr>
<th></th>
<th>Run</th>
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<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
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<tr>
<td>Percentage area converted to conservation tillage</td>
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<td></td>
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</tr>
<tr>
<td>0</td>
<td>8.5</td>
<td>21.5</td>
<td>32.7</td>
<td>32.7</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Base Value</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Runoff</td>
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<td>16</td>
<td>12</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
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<td>218</td>
<td>244</td>
<td>162</td>
</tr>
<tr>
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<td>21</td>
<td>24</td>
<td>16</td>
<td>27</td>
<td>11</td>
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<tr>
<td>Dis NH₄⁺</td>
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<td>2</td>
<td>9</td>
<td>8</td>
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<td>7</td>
</tr>
<tr>
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<td>138</td>
<td>101</td>
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<tr>
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<td>236</td>
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<td>171</td>
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<tr>
<td>Total P</td>
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<td>175</td>
<td>156</td>
<td>122</td>
<td>146</td>
<td>92</td>
</tr>
</tbody>
</table>

1 mm/year, 2 kg/ha-yr, 3 kg/yr
Figure 58. Percentage increase in nitrate leaching due to the conversion from conventional to conservation tillage.
located further upstream than the farm selected for Run 5. Even though the Run 4 farm had higher sediment yield than the Run 5 farm, conservation tillage was more efficient in reducing sediment loss on the Run 5 farm. This illustrates a crucial point when selecting critical areas. High sediment and nutrient losses from upland areas may not reach the watershed outlet. If conditions are right, they may be deposited or lost through infiltration before reaching the watershed outlet. Thus, implementation of BMPs in these areas may not always result in the expected pollutant reductions. This indicates that selection of critical areas involves more than just the selection of areas with high sediment and nutrient yields. Implementation of conservation tillage on such areas will reduce the onsite sediment and nutrient yields but may not reduce the overall watershed sediment and nutrient yields.

If the purpose of BMP implementation is the overall reduction of the sediment and nutrients leaving the watershed rather than losses from specific fields, then additional factors should be taken into consideration. Such factors include landuse, surface cover, and soil characteristics of areas that runoff must cross before reaching the watercourse or watershed outlet. It may be necessary to run the model many times to estimate delivery functions relating the amount of contaminant leaving a cell to the total amount of sediment and nutrient leaving the watershed. Thus, cells with very high delivery functions, which means a very high percentage of the sediment and nutrient leaving a cell reaches the watershed outlet, combined with areas with high cellular pollutant yields would indicate on which cells the implementation of BMP’s would be the most efficient.

Economic factors must also be considered. It may be more economical to implement BMP’s on some areas than others. Another important aspect in the critical area selection is the environmental problem to be addressed. Table 6 indicates that different areas have different efficiencies in controlling sediment, sediment-bound nutrients and dissolved nutrient losses. Run 2 was more efficient than Runs 3 and 5 in controlling sediment and sediment-bound nutrient losses, but was less efficient in controlling dissolved nutrient losses. Thus, BMP’s must be tailored for the particular pollutant of concern.

Even though the problem of selecting critical areas appears to be very complex, it could be done efficiently using optimization techniques, linear and non-linear programming. The first step is to define an objective function that includes both the desired pollutant loading objective, and the funds allocated for reducing the pollutant loadings. The second step is to develop constraint
functions that include the total amount of sediment and nutrient leaving a cell, delivery functions, and economic considerations. Then, based on this constraints and objective function, the areas best suited for BMP implementation can be determined.

This section of the research focused on a practical application of the model. The model was used to identify potentially critical areas that contribute disproportionately to total losses of sediment and nutrients. Conservation tillage was implemented at four targeting levels on 10, 20, 30 and 100% of the agricultural land. Areas associated with high sediment yield and nutrient losses were shown to not necessarily be the areas controlling losses from the watershed. For instance, two identical fields with the same nutrient and sediment yields were shown to contribute differently to the total loss of sediment and nutrients from the watershed due to different deposition and trapping of contaminants between the source areas and the watershed outlet. The model was sensitive enough to predict that two areas with identical sediment and pollutant losses could contribute differently to the pollutant loading leaving the watershed. Thus, the model can be used to determine delivery functions for each field. It was suggested that these delivery functions, along with economic considerations could be used with optimization techniques to identify fields where BMP’s can be most economically applied and still meet water quality objectives.
SUMMARY AND CONCLUSION

SUMMARY

A comprehensive, distributed, continuous, physically-based watershed scale, nonpoint source pollution management model was developed for planning purposes. The model is intended for use without calibration. The model simulates nitrate, dissolved and sediment-bound ammonium, sediment-bound TKN, dissolved and sediment-bound P loss during rainfall events, in addition to runoff, erosion and sediment transport. The model also predicts the amount of nitrate leaving the soil zone during and between rainfall events. The model maintains a daily water balance by computing percolation and evapotranspiration on a daily basis. A daily nutrient mass balance is also maintained. The model is not intended for making absolute predictions. It is intended for use by planners, and its main purpose is to represent the relative effectiveness of alternative management practices in reducing runoff, sediment and nutrient losses from agricultural watersheds.

The model was developed for use by nonpoint source pollution managers. The model is intended to study the long-term effectiveness of best management practices in controlling runoff, sediment and nutrient losses from agricultural lands. The model is best used in a two step process. First, the model is run to identify potentially critical source areas in the watershed. During the second step, the model simulates alternative land use scenarios, and quantifies the effectiveness of the alternative management scenarios in reducing pollutant loadings to the desired level.

The model can also be run on an event basis to assess the effectiveness of BMP’s in reducing NPS pollution loading from single design storms. Furthermore, the model can be run on a single design storm basis to estimate the required dimensions of structures such as ponds, grass waterways, and infiltration areas. The model is suitable for use on watersheds up to 2000 ha in size. On smaller watersheds, the model can be used with a finer grid to represent minor variations in soils, topography and cropping systems. These heterogeneities can not be represented by the current generation of field-scale models. Spatial input data required by the model is obtained from soil, topographic and land use maps or photos. Other parameters can be estimated from literature sources based on soil, cropping and management systems employed.

The new infiltration model uses the Green-Ampt infiltration equation. The previous version of
ANSWERS used Holtan's infiltration equation, which required the use of a control depth. With the Holtan equation, runoff and infiltration were extremely sensitive to the selection of the soil depth which was difficult to define. Principal advantages of the Green-Ampt infiltration equation are that it is not sensitive to the control depth and its parameters are determined from readily available soil and land use information.

During a rainfall event, the model assumes that dissolved nutrients are lost from the upper centimeter of the soil profile. A linear equilibrium is assumed between the dissolved and sediment-bound phases of ammonium and phosphorus. The partition coefficient for ammonium and phosphorus are determined as a function of the clay content of the soil. Nitrate, dissolved ammonium and dissolved P loss in runoff are determined using an extraction coefficient. The nitrate loss in percolation is computed as the product of nitrate concentration in the soil zone and the volume of water leaving the soil zone via percolation.

Between rainfall events, the ANSWERS model maintains a water balance. Evapotranspiration is computed using Richie's method and plant evaporation and plant transpiration are computed separately. If soil moisture exceeds field capacity, the model computes percolation. Percolation varies according to the degree of saturation, zero when soil moisture is close to field capacity, to a maximum rate when the soil profile is saturated.

The model simulates four nitrogen pools including active soil organic N, stable organic N, nitrate, and ammonium and interactions between the pools using relationships from the EPIC and GLEAMS models. Mineralization, including both ammonification and nitrification, from the active soil organic N pool is considered and a dynamic equilibrium is maintained between the stable and active organic N pools. Denitrification is permitted when soil moisture exceeds field capacity.

The model simulates four separate P pools: soil organic P, stable mineral P, active mineral P and labile P, and maintains an equilibrium between active and stable mineral P and between active mineral P and labile P. Mineralization of the soil organic P is simulated. Plant uptake of ammonium, nitrate and labile P is computed on a daily basis based on the daily plant demand and nutrient availability.

The model was first validated using data from two monitored fields in Georgia. The two
watersheds are characterized by two different land management systems. The first field was characterized by conventional till corn planted on the contour, and the second field had conventional till corn planted on the contour with terraces and grassed waterways. The model was validated for runoff, sediment yield, nitrate, dissolved and sediment-bound ammonium, and dissolved and sediment-bound labile P loss. No monitored data were available regarding evapotranspiration and nutrient transformations. When the model was run for twenty-five months, the model simulated runoff and nutrient loss well, and was assumed to simulate evapotranspiration and nutrient transformation equally well. The model was next validated on a large watershed in Virginia. The model was run for five months, and the model predictions were compared with observed runoff, sediment, dissolved and sediment-bound nutrient loss. Model predictions were within a factor of 10 of the observed values for the smaller storms and within a factor of 1 for the larger storms.

The use of the model as a planning tool was then demonstrated. The model was run for eight years on a watershed in Virginia to identify potentially critical sources of NPS pollution. The use of the model in evaluating alternative management practice scenarios to minimize pollutant losses from the potentially critical source areas was demonstrated.

CONCLUSION

The model performed well on the two watersheds in Georgia (P2 and P4) in simulating runoff and sediment. The model performed better in predicting runoff from P2 than P4, which may be attributable to the presence of terraces and grassed waterways on the P4 watershed. Since no calibration was allowed during the validation runs, the effects of terraces and grassed waterways on surface runoff may not have been well represented. Predicted long-term cumulative runoff was with 10 and 55% of observed values for P2 and P4 watersheds, respectively. The model simulated nitrate, dissolved ammonium, sediment-bound TKN, dissolved P losses on both watersheds well. Predicted values were within 50% of observed values for nitrate, dissolved ammonium, and sediment-bound TKN, and within 100% of observed values for dissolved P. The model did not perform well in predicting sediment-bound ammonium on either watershed. Sediment-bound ammonium was underpredicted on both watersheds by up to 3000%. This underprediction may be due to the low partition coefficient used to describe the equilibrium between sediment-bound and dissolved ammonium. The quality of the observed data was also questioned, since for several storms, measured sediment-bound ammonium was higher than

SUMMARY AND CONCLUSION
sediment-bound TKN. This is not theoretically possible since ammonium is a subset of TKN. Another source of error may be the equations used to describe mineralization between rainfall events.

Overall the model appeared to perform well in predicting runoff, sediment and nutrient losses on a continuous basis. Long-term cumulative predictions were generally well within a factor of ten of observed predictions, which meets the criteria of good planning model as defined by the EPA. The new ANSWERS model uses a multitude of regression equations to describe nutrient transformations and nutrient transport. Unfortunately, data is not available to validate the individual equations. The validity and reliability of the individual equations used has not determined but the overall model appears adequate for planning purposes. The equations used to describe nutrient transformations are empirical statistical equations. Thus, it is expected that the model will perform better for watersheds with certain landuses and soil types than others. However, the validation study demonstrated the versatility of the model, and its ability to represent and simulate heterogeneous watersheds, with a variety of landuses, types and management practices. Furthermore, with a limited amount of input information, the model was able to simulate runoff and sediment, and nutrient loss from a large watershed in Virginia.

This version of ANSWERS is a first attempt at the development of a comprehensive, distributed, continuous nonpoint source model. The model was developed and ran on a VAX (VMS operating system V5.5-2) machine. Running the program on the Owl Run watershed (1100 one hectare cells), for a 5 month period required approximately five hours. This is a major problem with the current version of the model but the model code is rather crude and could be improved greatly by a professional programmer. The model will run faster on a 486 PC but this was not attempted. Thus, at the current stage of development, it is impracticable to run the model on the Owl Run watershed for a duration of 10 years. The creation of the required spatial data files by hand is also very time consuming and tedious but is well suited for use with a GIS. The use of a GIS would greatly facilitate data input and manipulation. Furthermore, a GIS would be a great tool for model output visualization. ANSWERS should also be integrated with an expert system to reduce the amount of input information that the user has to provide. Even when integrated with these powerful tools, ANSWERS as currently coded is not well adapted for large watersheds (>2000 ha) nor for extremely long simulations. Some algorithms used by the model should be rewritten to be more efficient, and faster alternatives to simulate sediment, nutrient transformation and loss should be investigated. For example, the model currently spends a great deal of time.

SUMMARY AND CONCLUSION
simulating the vast majority of precipitation events that do not produce runoff. The model should be revised so that all precipitation from small storms that are not likely to produce runoff are immediately added to the soil moisture pool. This would probably reduce execution time by an order of magnitude.

Currently, the modified ANSWERS model is the only continuous, distributed, comprehensive watershed-scale nonpoint source planning model available. The model has the ability to estimate runoff, sediment, and nutrient loss for a variety of watersheds and conditions. The algorithms used by the model to simulate infiltration, nutrient losses have been used by other models, and have been subjected to validation. However, no data was available to validate the individual nutrient transformation equations.

The validation performed on the Owl Run watershed illustrated some potential problems that model users may encounter when running the model on large watersheds. Many large agricultural watersheds include landuses that ANSWERS does not currently simulate. For example, ANSWERS was not designed to simulate forested areas, landuses that occupy 20% of the Owl Run watershed and about 50% of the Nomini Creek watershed. The model also poorly represents alternative fertilizer application methods. Routines to simulate animal waste application or management are not included. This is an important limitation in watersheds such as Owl Run where dairy operations are a large contributor to the total nutrient loading. All these limitations need to be addressed in future versions to make ANSWERS a stronger and more robust watershed model.

In spite of these limitations, ANSWERS was shown to be a useful and state-of-the-art planning tool for assessing the impact of different management alternatives on runoff, sediment and nutrient loadings. Furthermore, the model was successfully validated for predicting runoff, sediment and nutrient losses from agricultural watersheds where the data required to run the model and describe the watershed is available.
RECOMMENDATIONS FOR FUTURE RESEARCH

The ANSWERS model is a large and complex model. Since the model was designed to run for watersheds up to 2000 ha, many assumptions and simplifications were made. There is room for improving the model, and the research revealed many limitations in the current version of ANSWERS and in the status of nonpoint source pollution from large agricultural watersheds in general. Thus, the following recommendations are made for further research to improve the model and further advance the status of hydrologic watershed modeling.

One of the major limitations of the present version of ANSWERS is the amount of computer time required to run the model on large watersheds for long-term simulations. This problem arises from the approach used by ANSWERS to solve the continuity equation. ANSWERS requires a small time step to minimize errors in the solution of the continuity equation. To minimize errors, ANSWERS requires a time step of 60 seconds or less. Even during non-runoff producing precipitation events, ANSWERS runs the entire rainfall period with a 60-second time step. It would be very useful and time efficient to determine the threshold value at which storms produce runoff. Thus, for non-runoff producing rainfall events, the precipitation amount could be added directly to the soil moisture pool without calling the infiltration, erosion and sediment transport, and nutrient loss routines. Another possible improvement may involve alternative solution techniques that permit larger time steps. Furthermore, at present, ANSWERS produces a hydrograph and a pollutograph for all nutrients and sediment for each storm. It may be appropriate to modify the model to compute cumulative losses at the end of each storm. This might reduce the computer execution time and it would definitely reduce memory requirements.

Another limitation encountered during this research is related to the fact that ANSWERS simulates only one soil layer, in which soil moisture, nutrient concentration, and soil characteristics are assumed homogeneous. It was therefore impossible to model changes in the soil profile with respect to nutrient concentrations, soil properties, etc. This is a problem, especially when modeling nitrate, an extremely mobile specie, which moves downward with infiltrating and percolating water, and moves upward with water lost through transpiration. The effect of layering is extremely important, especially when simulating the nutrient content of the upper centimeter of soil. In the current version of ANSWERS, the upper centimeter is used to quantify the amount of nutrient that can be lost in surface runoff. As soon as a storm is over, the upper centimeter is assumed to have the same concentration of nutrient as the rest of the soil profile. This may cause
a problem when two large storms occur close to each other. The model would be expected to overpredict nutrient loss for the second storm, since even if the first storm depletes the nutrient content of the upper layer centimeter, the following day the upper layer is replenished since it is assumed to have the same concentration as the rest of the soil profile. Thus, introducing additional soil layers with varying properties would improve the prediction of nutrient loss. However, the addition of multiple soil layers would require additional computer memory, and increase execution time. It may be appropriate to reduce the number of overland cells that ANSWERS can simulate (maximum of 2000) in order to introduce soil layers. The introduction of soil layers will enable ANSWERS to predict nitrate leaching below the root zone better. In its present form, ANSWERS predicts only the amount of nitrate leaving the soil zone (not the root zone). Furthermore, simulating the layering of nutrient concentrations in the soil profile would improve the simulation of plant uptake of nutrients.

Another important step in the improvement of the ANSWERS model would be the introduction of a pesticide component. Since the procedures used to simulate the nutrients were inspired by those used to simulate pesticides in the CREAMS and GLEAMS models, a pesticide component could be easily incorporated using relationships similar to those used to simulate nutrient losses. Furthermore, with the addition of soil layers, the model could predict the amount of pesticide lost in surface runoff and sediment, and the potential amount of pesticide leaving the root zone.

During the research it was also apparent that ANSWERS input file creation was impractical by hand and that the model should be integrated with a GIS. In fact, the data file for the Owl Run watershed was created using files developed with the Virginia Geographic Information System (VirGIS). Special software was developed to manipulate and transform the raster based input files developed from VirGIS to create the ANSWERS input file. For the long-term simulation, software was developed to read data from a CLIGEN output file and to convert the data to the desired format. Practical use of the ANSWERS model will require software to generate long-term climatic data (including breakpoint rainfall data) along with a GIS to facilitate data input file creation and manipulation. Furthermore, the GIS would be useful in visualizing model output. In addition, with the use of a GIS, the user could easily select and manipulate identified critical areas where the implementation of BMP's is required. Along with a GIS, an expert system could be used to link with different databases to assemble the required input parameter files. Furthermore, the expert system could also help the user in selecting the appropriate parameters values. Expert systems can also facilitate output interpretation. It is possible that the expert

Recommendations for Future Research
system could even identify critical areas and then suggest appropriate BMP's for reducing pollutant loadings to the required level.

Other research needs include the incorporation of a soil temperature model. During the long-term simulation, climatic data was generated using CLIGEN, however CLIGEN does not generate soil temperatures. It was assumed that soil temperature was equal to air temperature. However, in order to improve the estimates of nutrient transformation rates, algorithms to generate soil temperature should be investigated. It is also very important to validate the individual nutrient transformation models separately to assess their validity. It appears that the model may have underpredicted mineralization rates and used a low partition coefficient for ammonium. Thus, it may be appropriate to investigate other approaches to simulate mineralization. The model could also be improved by introducing mineralization of residue, which may also solve the problem of low mineralization rates. Furthermore, new equations, or additional validation of the equations used to predict partition coefficients for phosphorus and ammonium may be necessary. In addition, no feedback currently exists between the ANSWERS nutrient component and the water component models. Water stress reduces nutrient uptake, however, nutrient stress has no effect on water uptake. Plant growth is simulated by using the leaf area index. Introducing a more sophisticated and more accurate plant growth component would improve estimates of water uptake, nutrient uptake, and allow simulation of the effects of nutrient stress on water uptake.

Extensive research should also be conducted on how to represent the effect of different BMP's on the ANSWERS parameters. This would allow better representation of the effects of BMP's on runoff, sediment and nutrient loss. The results of this research could be incorporated in the expert system to help in input file creation.

New algorithms for computing erosion and sediment transport should be investigated. The present version of ANSWERS does not compute channel erosion, which may be a major contributor to total erosion in certain areas. Furthermore, the model does not simulate base flow and interflow which may be a problem on watersheds such as Nomini Creek, where interflow and base flow are major contributors to total runoff. ANSWERS does not currently simulate some common practices and structures such as ponds, wetlands, and filter strips. The model does not simulate irrigation, or input of fertilizer in rainfall (irrigation) either. The model does simulate application of fertilizer and manure but they are assumed to be uniformly applied in the soil zone and the method of application and the location of application of fertilizer is not considered. The current
version of ANSWERS allows crop parameters to be dynamic, however, soil parameters are
assumed constant. The model does not consider soil compaction, and the effect of tillage and
management practices on soil characteristics. Processes to simulate these effects should be
investigated and considered for incorporation into the model.
REFERENCES


REFERENCES


REFERENCES


REFERENCES 195
Leonard, R. A., W. G. Knisel, and D. A. Still. 1987. GLEAMS: ground-water loading effects of agricultural management systems. Trans. of the ASAE 30(5):1403-1418.


Office of Technology Assessment. 1982. Use of models for water resources management, planning, and policy. Washington, D. C.


REFERENCES


# APPENDICES

## APPENDIX A: VARIABLE GLOSSARY

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- **FILTS**: Infiltration capacity for element i (m³/s),
- **FLIN**: Net rate of flow into an element less losses (m³/s),
- **FLINS**: Storage, inflow and outflow for element i at start of time increment (m³/s),
- **FLODEP**: Depth of flow in element or channel (m),
- **FMAX**: Maximum infiltration capacity, surface inundated (m³/s),
- **FPBAR**: not used
- **FRA**: Fraction of catchment area covered by rain gauge i,
- **FV**: Fall velocity of particle type i (m/s),
- **FWA**: Fraction of surface area of element covered by water,
- **GAM**: Coefficient used in the Ritchie's equation,
- **GRF**: Fractional rate of baseflow release,
- **GWC**: Volume of air filled pore space at field capacity for soil i (m),
- **HU**: Maximum height differential on soil surface (mm),
- **ICR**: Number of cropping practices,
- **IEL**: Array for data manipulation,
- **IG**: Alphanumeric number for rain gauge,
- **II**: Number of channel segments,
- **iROT**: IROT(2i) represents the cover for a specific rotation, IROT(2i+1) represents the end of IROT(2i) (YearDay) for instance 2 1973123 represents cover number 2 until Julian day 123 for the year 1973,
- **IROT1**: Number of all possible rotations,
- **IRR**: Number of rainfall intensity readings for rain gauge i,
- **IS**: Soil type for current element,
- **ISR**: Number of soil types,
- **ISTRIL**: Comparator for sensing presence of drain tile in element,
- **ISTRUC**: Counter for structural practices,
- **ITEMP**: Array for input data manipulation,
- **ITR**: Rainfall histogram counter,
- **IX**: Constant to indicate presence of a channel in an element,
- **IY**: Segment number on segmented discharge curve,
- **I1-3**: Counter,
- **J, JK**: Counters,
- **JMAX**: Dimension in IEL,
- **JS**: Column number for last column on current element row plus 1,
- **JTR**: Current rainfall intensity histogram period for rain gauge i,
- **J1-3**: Counters,
- **K**: Number of values in rainfall hyetograph and surface type of current element,
- **KK**: Soil type for current element,
- **KPR**: Number of time increment routings between print lines,
- **K1**: Counter,
- **KE**: Effective saturated hydraulic conductivity (mm/hr),
- **KS**: Saturated hydraulic conductivity (mm/hr),
- **L**: Number of last element in row and a counter,
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<tr>
<td>SE1-2</td>
<td>R ARRAY</td>
<td>Rate of sediment movement from element with and without flow detachment (kg/s),</td>
<td></td>
</tr>
<tr>
<td>SF</td>
<td>R VARIABLE</td>
<td>Segment factor. Maximum projected catchment discharge,</td>
<td></td>
</tr>
<tr>
<td>SG</td>
<td>R ARRAY</td>
<td>Specific gravity of particle type i,</td>
<td></td>
</tr>
<tr>
<td>SGD2</td>
<td>R VARIABLE</td>
<td>SQRT (AGRAV/2),</td>
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</tr>
<tr>
<td>SI</td>
<td>R EQV ARRAY</td>
<td>Rate of sediment inflow into element i from adjacent elements (kg/s),</td>
<td></td>
</tr>
<tr>
<td>SIG</td>
<td>R VARIABLE</td>
<td>Sum of SI values for all particle classes (kg/s),</td>
<td></td>
</tr>
<tr>
<td>SIGMA</td>
<td>R VARIABLE</td>
<td>Coefficient in transport equation,</td>
<td></td>
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<tr>
<td>SIMDUR</td>
<td>R VARIABLE</td>
<td>Simulation duration (days),</td>
<td></td>
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<tr>
<td>SKDR</td>
<td>R ARRAY</td>
<td>Erosion parameter for soil type i,</td>
<td></td>
</tr>
<tr>
<td>SL</td>
<td>R ARRAY</td>
<td>Slope of overland flow element or channel segment i,</td>
<td></td>
</tr>
<tr>
<td>SMAX</td>
<td>R VARIABLE</td>
<td>Final accumulated sediment loss from catchment (kg),</td>
<td></td>
</tr>
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</table>

**APPENDICES**
<table>
<thead>
<tr>
<th>SMDIR</th>
<th>R</th>
<th>VARIABLE</th>
<th>S-DIR,</th>
</tr>
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<tr>
<td>SMIN</td>
<td>R</td>
<td>VARIABLE</td>
<td>Minimum elemental and channel slope in watershed,</td>
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<tr>
<td>SOIL</td>
<td>I</td>
<td>EQV ARRAY</td>
<td>Soil type for element i,</td>
</tr>
<tr>
<td>SOIVOL</td>
<td>R</td>
<td>ARRAY</td>
<td>Soil mass of the soil layer (kg),</td>
</tr>
<tr>
<td>SOILN</td>
<td>R</td>
<td>ARRAY</td>
<td>Stable organic N (kg/ha),</td>
</tr>
<tr>
<td>SOILP</td>
<td>R</td>
<td>ARRAY</td>
<td>Stable soil phosphorus (kg/ha),</td>
</tr>
<tr>
<td>SOTEMP</td>
<td>I</td>
<td>VARIABLE</td>
<td>Soil temperature (°C),</td>
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<tr>
<td>SORGP</td>
<td>R</td>
<td>ARRAY</td>
<td>Soil organic phosphorus (kg/ha),</td>
</tr>
<tr>
<td>SP2</td>
<td>R</td>
<td>ARRAY</td>
<td>Outflow of dissolved P (kg/s),</td>
</tr>
<tr>
<td>SPADEP</td>
<td>R</td>
<td>VARIABLE</td>
<td>Maximum elemental aggradation value (kg/ha),</td>
</tr>
<tr>
<td>SPAERO</td>
<td>R</td>
<td>VARIABLE</td>
<td>Minimum elemental aggradation value (kg/ha),</td>
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<tr>
<td>SPASD</td>
<td>R</td>
<td>VARIABLE</td>
<td>Standard deviation of SEL,</td>
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<tr>
<td>SPASS</td>
<td>R</td>
<td>VARIABLE</td>
<td>Variable used in determining SPASD,</td>
</tr>
<tr>
<td>SPASUM</td>
<td>R</td>
<td>VARIABLE</td>
<td>Sum of SEL values used to calculate SPASD,</td>
</tr>
<tr>
<td>SPER</td>
<td>R</td>
<td>EQV ARRAY</td>
<td>Steady state infiltration rate (mm/h),</td>
</tr>
<tr>
<td>SPI</td>
<td>R</td>
<td>ARRAY</td>
<td>Inflow of dissolved phosphorus from adjacent cells (kg/s),</td>
</tr>
<tr>
<td>SPSSI</td>
<td>R</td>
<td>ARRAY</td>
<td>Accumulated dissolved P loss from catchment at print line i,</td>
</tr>
</tbody>
</table>

<p>| SPT    | R   | VARIABLE | Accumulated sediment loss from catchment at previous time (kg), |
| SR     | R   | ARRAY    | Rainfall rate from previous calculation (m³/s), |
| SRA    | R   | VARIABLE | Portion of sediment leaving element and flowing in a row direction, |
| SS     | R   | ARRAY    | Incremental increase in storage on element i, |
| SSA    | R   | ARRAY    | Specific surface area for particle size class j for soil type i (m²/g), |
| SSAT   | R   | ARRAY    | Total specific surface area for soil type i (m²/g), |
| SSCON  | R   | VARIABLE | Sediment concentration at print line i (mg/l), |
| SSI    | R   | VARIABLE | Accumulated sediment loss from catchment at print line i, |
| SSII   | R   | VARIABLE | Same as SSI, |
| SST    | R   | EQV ARRAY| Sum of initial values in sediment continuity equation (kg/s), |
| SSTOR  | R   | ARRAY    | Storage on element at end of time increment (m³/s), |
| SSIM1  | R   | VARIABLE | SSI at previous time step, |
| ST     | R   | ARRAY    | Silt content of the soil (%), |
| STD    | R   | VARIABLE | Total inflow into tile lines during DT, |
| STRUC  | R   | VARIABLE | Flag for existence of structure, |
| SUMLAI | R   | ARRAY    | Summation of the leaf area index from planting day to the current day of simulation, |
| SUMNHW | R   | ARRAY    | Accumulated dissolved ammonium loss for cell i for the entire length of the simulation (kg), |
| SUMNHS | R   | ARRAY    | Accumulated sediment-bound ammonium loss for cell i for the entire length of the simulation (kg), |
| SUMNO3 | R   | ARRAY    | Accumulated dissolved nitrate loss for cell i for the entire length of the simulation (kg), |
| SUMPO4 | R   | ARRAY    | Accumulated dissolved P loss for cell i for the entire length of the simulation (kg), |
| SUMTKN | R   | ARRAY    | Accumulated sediment-bound TKN loss for cell i for the entire length of the simulation (kg), |
| SUMXED | R   | ARRAY    | Accumulated sediment loss for cell i for the entire length of the simulation (kg), |</p>
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<thead>
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<th>Type</th>
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<td>SUR</td>
<td>R</td>
<td>Variable</td>
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<td>SWFA</td>
<td>R</td>
<td>Soil water factor for ammonification,</td>
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<tr>
<td>SWFDN</td>
<td>R</td>
<td>Soil water factor for denitrification,</td>
</tr>
<tr>
<td>SWH20</td>
<td>R</td>
<td>Specific weight water (kg/m$^3$),</td>
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<tr>
<td>T</td>
<td>R</td>
<td>Real time</td>
</tr>
<tr>
<td>TBAR</td>
<td>R</td>
<td>Percent of elements tiled</td>
</tr>
<tr>
<td>TC</td>
<td>R</td>
<td>Time of $i^{th}$ histogram period for rain gauge $i$,</td>
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<tr>
<td>TDMN2</td>
<td>R</td>
<td>Total dry matter N (kg/ha),</td>
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<tr>
<td>TDMP2</td>
<td>R</td>
<td>Total dry matter P (kg/ha),</td>
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<tr>
<td>TEMPC</td>
<td>I</td>
<td>Air temperature ($^\circ$C),</td>
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<td>TEMPFA</td>
<td>R</td>
<td>Temperature factor for ammonification,</td>
</tr>
<tr>
<td>TEMPK</td>
<td>R</td>
<td>Air temperature ($^\circ$K),</td>
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<td>TEST</td>
<td>R</td>
<td>Comparison for correct data input check</td>
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<td>TEST1</td>
<td>I</td>
<td>Flag indicating occurrence of ponding,</td>
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<tr>
<td>TETP</td>
<td>R</td>
<td>Sum of ES and PEP (mm),</td>
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<tr>
<td>TF</td>
<td>R</td>
<td>Sediment transport capacity (kg/s),</td>
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<tr>
<td>TFDN</td>
<td>R</td>
<td>Temperature factor for denitrification,</td>
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<td>TFMSE2</td>
<td>R</td>
<td>TF-SE2,</td>
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<td>TFXCES</td>
<td>R</td>
<td>Transport capacity excess (kg/s),</td>
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<tr>
<td>THETAR</td>
<td>R</td>
<td>Residual water (mm),</td>
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<tr>
<td>TIAL</td>
<td>I</td>
<td>Value of $i$ denotes element is tile drained,</td>
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<td>TIMPON</td>
<td>R</td>
<td>Time ponding (mn),</td>
</tr>
<tr>
<td>TPON</td>
<td>R</td>
<td>Equivalent time of ponding, represents the time it would take to infiltrate</td>
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<td></td>
<td>CUMPON under ponded conditions (mn),</td>
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<td>TINT</td>
<td>R</td>
<td>Time interval in hyetograph,</td>
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<td>TITLE</td>
<td>R</td>
<td>Simulation title,</td>
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<td>TKNSEL</td>
<td>R</td>
<td>Accumulated sediment-bound TKN loss in element $i$ for a given storm (kg/s),</td>
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<td>TMAX</td>
<td>R</td>
<td>Maximum time value given in any hyetograph,</td>
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<tr>
<td>TMIN</td>
<td>R</td>
<td>Minimum time value given in any hyetograph,</td>
</tr>
<tr>
<td>TP</td>
<td>R</td>
<td>Porosity for soil type $i$,</td>
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<tr>
<td>TRAP</td>
<td>R</td>
<td>Trap efficiency of ponds</td>
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<tr>
<td>TRANP</td>
<td>R</td>
<td>Phosphorus transfer between active and mineral P pools (kg),</td>
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<tr>
<td>TTIME</td>
<td>R</td>
<td>Time since stage 2 evaporation started (days),</td>
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<tr>
<td>TUPTN</td>
<td>R</td>
<td>Total uptake of N (kg),</td>
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<tr>
<td>UPNH4</td>
<td>R</td>
<td>Uptake of ammonium (kg/ha),</td>
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<tr>
<td>UPNO3</td>
<td>R</td>
<td>Uptake of nitrate (kg/ha),</td>
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<td>UPPHOS</td>
<td>R</td>
<td>Uptake of P (kg/ha),</td>
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<td>R</td>
<td>Comparison for units</td>
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<td>UNITS</td>
<td>R</td>
<td>Type of input-output units,</td>
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<td>VISCOS</td>
<td>R</td>
<td>Kinematic viscosity of water (m$^2$/s),</td>
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<td>VOL</td>
<td>R</td>
<td>Accumulated runoff depth from catchment,</td>
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<tr>
<td>VS</td>
<td>R</td>
<td>Simplification variable used in transport equation,</td>
</tr>
<tr>
<td>VSTAR</td>
<td>R</td>
<td>Shear velocity (m/s),</td>
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<td>WATVOL</td>
<td>R</td>
<td>Water present in the soil layer (L),</td>
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<td>WID</td>
<td>R</td>
<td>Width of type 1 channel (m),</td>
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<tr>
<td>X</td>
<td>R</td>
<td>Overland flow width across overland flow element (m),</td>
</tr>
<tr>
<td>Symbol</td>
<td>Type</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
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<tr>
<td>XF</td>
<td>R ARRAY</td>
<td>Variable used in the calculation of the capillary front potential.</td>
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<td>XDIR</td>
<td>R VARIABLE</td>
<td>Same of DIR.</td>
</tr>
<tr>
<td>XMOI</td>
<td>R ARRAY</td>
<td>Soil moisture (mm).</td>
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<tr>
<td>XPR</td>
<td>R VARIABLE</td>
<td>Real value of KPR.</td>
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<td>XR</td>
<td>R VARIABLE</td>
<td>Same as R.</td>
</tr>
<tr>
<td>XZW</td>
<td>R VARIABLE</td>
<td>Element or channel width (m).</td>
</tr>
<tr>
<td>X1-4</td>
<td>R VARIABLE</td>
<td>Simplifying variables used in SUBROUTINE SED.</td>
</tr>
<tr>
<td>Y</td>
<td>R VARIABLE</td>
<td>Number of appropriate increment on segmented discharge curve. Depth at initial value of this curve segment.</td>
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<tr>
<td>YALCON</td>
<td>R VARIABLE</td>
<td>Yalin's Constant.</td>
</tr>
<tr>
<td>YCR</td>
<td>R VARIABLE</td>
<td>Dimensionless critical shear stress from Shield's diagram.</td>
</tr>
<tr>
<td>YERBEG</td>
<td>R VARIABLE</td>
<td>Beginning year of the simulation.</td>
</tr>
<tr>
<td>YP</td>
<td>R ARRAY</td>
<td>Yield potential (kg/ha).</td>
</tr>
<tr>
<td>Z</td>
<td>R ARRAY</td>
<td>Macroporosity factor.</td>
</tr>
<tr>
<td>Z12</td>
<td>R VARIABLE</td>
<td>Rate of sediment inflow plus erosion at end of time increment, and</td>
</tr>
<tr>
<td>ZC</td>
<td>R ARRAY</td>
<td>Crust thickness, assumed to be 10 mm.</td>
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</tbody>
</table>
APPENDIX B: PROGRAM LISTING

ANSWERS

(DCPOWER)

DISTRIBUTED CONTINUOUS PREDICTION OF WATERSHED ENVIRONMENTAL RESPONSE

AUTHOR: Faycal Bouraoui

INCORPORATION OF NITROGEN AND PHOSPHORUS LOSSES AND transformations COMPONENTS

APRIL 2, 1994

AUTHOR: Theo A. Dillaha

DEVELOPMENT OF EXTENDED SEDIMENT MODEL

SEPTEMBER 1, 1981

INTEGRATION OF EXTENDED SEDIMENT MODEL FOR FORTRAN 77 COMPILER

AGRICULTURAL ENGINEERING DEPARTMENT, VIRGINIA TECH BLACKSBURG VIRGINIA 24061

IMPLICIT DOUBLE PRECISION (A-H,O-Z)

C

C **** MAXIMUM NUMBER OF SOIL TYPES IS 20.

C

COMMON /SOIL( A(20),P(20),FC(20),GWC(20),SKDR(20)
COMMON /GRAMPT/CL(20),SA(20),ST(20),GM(20),AC(20)
& AO(20),BC(20),BO(20),PHI(20),VCF(20),WCF(20),CFC(20),
& CEC(20),EAC(20),PHIC(20),XCF(20),PSF(20),CBF(20),
& THETAR(20),KS(20),CF(20),Z(20),LF(20),CS(20),SCF(20),
& CRC(20),KE(20),ZC(20),BD(20)

APPENDICES
COMMON /ETYPES/LAI(20,11),ESU(20),LAI1(20),POTLAI(20),EDX(20)
&S,UMLAI(20)
REAL SUMLAI
REAL LAI,ESU,S1EP,S2EP,TTIME,LAI1,EDX
COMMON /ASMF/,ASMBF(20),FCAP(20),TP(20),RESWAT(20),DFI(20)
INTEGER DAYBEG,SIMDUR,TEMPC,SOITEM,RADI,RAITES,YERBEG,RNUT

COMMON /ROT/IROT(20,41)
INTEGER IROT

COMMON /PHOS1/, P0SOIL(2000),SSA(20,8),SSAT(20),EDJ(2000),
&P0(2000,8),ER(8),STOLD(2000,8),SEDNEW(2000,8),PPT(2000,8),
&PI(2000,8),PSL(2000),STNEW(8),P2(8),PCHEL(2000,8),PE(8)
&,.DRFT

COMMON/NITRO1/, A0SOIL(2000),ANPT(2000,8),ANI(2000,8),
&ANSEL(2000),AN2(8),ANCELL(2000,8),ANE(8),ANO(2000,8)
&,.CNH(2000)

COMMON/NITRO2/, O0SOIL(2000),ONPT(2000,8),ONI(2000,8),
&ONSEL(2000),ON2(8),ONCELL(2000,8),ONE(8),ONO(2000,8)

COMMON /PLANTN/DATPLA(20),DATHAR(20),CP1(20),CP2(20),DMP(20)
&T,YP(20),ROTMAX(20),ROTDAY(20),CDFAL(20),RLAIMX(20),CDRK(20)
&.RES(20),RES2(20),RES90(20)
INTEGER DATPLA,DATHAR,ROTMAX,ROTDAY

DIMENSION PSSI(101),SPSSI(101),ANSSI(101),ONSSI(101)
&.ANHSI(101),ANO3SI(101)
COMMON /SOLUB/, SP2(2000),PEXT(2000),PK(20)
&.RALPHA(20),RBETA(20),ROAMA(20),SPI(2000),CGEN1(2000)


REAL NO3SEL,NHWSL,NHSS
REAL KS,KE

C **** MAXIMUM NUMBER OF SURFACE AND CROP TYPES IS 20
C
C COMMON /CROUGH/, ROUGH(20),HU(20),DIR(21),PIT(5,20),PER(20),CDR(20)

C **** MAXIMUM NUMBER OF RAINGAGES IS 8 WITH 35 VALUES PER CAGE.
C
C COMMON /CRGAGE/, RC(8,35),TC(8,35),R(8,20),FRA(8),JTR(8),RATE(8),SR
1(8),NF(8)
C
C ... PARAMETERS USED IN THE EXTENDED SED SUBROUTINE
C

APPENDICES
COMMON /ZSED/, NPART, NWASH, NWASH1
COMMON /ZSEDR/, VISCONS, AGR, SWH2O, YALCON, SE(8), VS(2000), DIA(8), SG1(8), FV(8), CY1(8), CY2(8), CY4(8), DIAAMM(8), EQSDIA(8), EDDMM(8), F(10, 8)
2, CE1, CE2, CE3, CE4, CE5, CE6

C
C **** MAXIMUM NUMBER OF OVERLAND ELEMENTS PLUS CHANNEL ELEMENTS
C **** IS 2000 = NMAX.
C
C ***** IT IS EXPECTED THAT ARRAY "IEL" (IN SUBROUTINE DATA) WILL
C ***** BE OF SUCH A SIZE THAT IT WILL OVERLAY (BE EQUIVALENCED TO)
C ***** THE SPACE IN ARRAYS SI AND QI TOGETHER. THEREFORE IT IS
C ***** NECESSARY THAT THESE TWO ARRAYS BE KEPT ADJACENT IN THEIR
C ***** COMMON BLOCK. NOTE: THE ACTUAL NUMBER OF ELEMENTS THAT
C ***** CAN BE DIMENSIONED IN IEL WILL DEPEND ON THE WORD LENGTH
C ***** OF THE MACHINE BEING USED, E.G. ON A MACHINE WHICH USES
C ***** A SINGLE WORD INTEGER AND A DOUBLE WORD REAL, THE NUMBER
C ***** OF ELEMENTS IN IEL CAN BE FOUR TIMES THE NUMBER OF ELEMENTS
C ***** IN ARRAY SI.
C
C
C ***** ARRAYS SI AND QI MUST BE DIMENSIONED TO A SIZE = NMAX+1STRUC+2
C ***** TO HOLD, IN ORDER, SEDIMENT AND FLOW FROM THE WATERSHED
C ***** OUTLET ELEMENT, STRUCTURAL PRACTICES AND ANY "LEAKY"
C ***** ELEMENTS.
C
C EQUIVALENCE (FLITS(1), CWID(1))
EQUIVALENCE (TIAL(1), RANE(1))
INTEGER SUR, TIAL(2000), RANE, SOIL
DIMENSION ASM, ASMILM(20), XMOI(2000), SOIVOL(20)
& , FCVOL(20), WP(20), RATEMX(20)

DIMENSION RNUTNI(20), RNUTAM(20), RNUTP(20)

COMMON /ASMP, ASMPER(2000)
REAL MINP
COMMON /PARTTI/ON, PKDA(20), PKDP(20), PSP(20)

C
C **** NUMBER OF PRINT AND PLOT POINTS IS 101 MAXIMUM.
C
DIMENSION T(101), Q1(101), RW(101), SSI(101), SSSCON(101), ER(8)
DIMENSION PP(14), QA(2000), TT(20)
CHARACTER*4 PP, QT
DATA PP(1), PP(2), PP(3), PP(4), PP(5), PP(6), PP(7), PP(8), PP(9), PP(10),
1 PP(11), PP(12), PP(13), PP(14)/ IN., HR., AC., PT., LB. /
2. 'FPM', 'AC', 'MM', 'H', 'HA', 'M', 'KG', 'MG/L', 'HA' /
C **** NEW TRANSPORT AND DETACHMENT CONSTANTS.
C
C **** DETACHMENT COEFFICIENT CE3 (RAINFALL) WAS INCREASED BY A FACTOR
C **** OF 4 IN THE MARCH 15, 1982 VERSION OF ANSWERS. THE REASON FOR
C **** THIS LARGE INCREASE WAS THAT A NUMBER OF THE RAINFALL

APPENDICES
C **** SIMULATOR
C **** PLOTS THAT WERE USED IN COEFFICIENT CALCULATION HAD DEPOSITION
C **** AREAS. HOWEVER, AFTER CLOSER EXAMINATION OF PHOTOGRAPHS AND
C **** SURVEY INFORMATION, THE DETACHMENT COEFFICIENT WAS DEEMED TO
C **** BE TOO HIGH. THUS, THE CURRENT ACCEPTED VALUE OF CE3 IS TWICE
C **** THE ORIGINAL VALUE (GASP-IV VERSION OF ANSWERS).
C **** DETACHMENT COEFFICIENT CE4 (FLOW) WAS INCREASED BY A FACTOR OF
C **** 50 IN THE MARCH 15, 1982 VERSION OF ANSWERS. THE REASON FOR
C **** THIS DRAMATIC INCREASE WAS SOME RAINFALL SIMULATOR DATA THAT
C **** SHOWED THE DIFFERENCE BETWEEN RAINFALL-ONLY AND RAINFALL PLUS
C **** UPSLOPE FLOW SEDIMENT YIELDS. WHILE THE YIELDS INCREASED
C **** SUBSTANTIALLY WITH THE INCREASED FLOW, IT APPEARS THAT THE
C **** MAJOR SOURCE OF SEDIMENT WAS WASHOFF OF UNATTACHED PARTICLES.
C **** NOT DETACHMENT OF COHESIVE PARTICLES. A RE-EXAMINATION OF THE
C **** FLOW DETACHMENT EQUATION HAS LED TO THE CONCLUSION THAT THE
C **** FLOW DETACHMENT COEFFICIENT SHOULD BE APPROXIMATELY 5 TIMES
C **** GREATER THAN THE ORIGINAL VALUE (NOT 50 TIMES).
C **** WHILE THE C AND K FACTORS IN THE USLE ARE USED TO DESCRIBE
C **** THE RELATIVE DEGREE OF ERODIBILITY OF A PARTICULAR SOIL IN
C **** THIS MODEL, THE IMPACTS OF SURFACE COMPACTION, ROUGHNESS,
C **** TEMPERATURE, ETC. ARE NOT TAKEN INTO ACCOUNT. THUS, WHILE
C **** THE EROSION EQUATIONS WORK FOR THOSE SOIL SERIES FOR WHICH
C **** WE HAVE RAINFALL SIMULATOR AND WATERSHED DATA, THEY MAY NOT
C **** DO AN ADEQUATE JOB ON OTHER TYPES OF TOPOGRAPHY, SOIL TEXTURE,
C **** SURFACE CONDITION, ETC. FOR THESE REASONS, CE3 AND CE4 SHOULD
C **** BE CONSIDERED AS POTENTIAL VARIABLES. RESEARCH NOW BEING
C **** CONDUCTED SHOULD YIELD BETTER DESCRIPTIONS OF THE DETACHMENT
C **** PROCESS AND THE COEFFICIENTS ASSOCIATED WITH IT. WHILE IT
C **** IS NOT POSSIBLE TO GIVE EXACT INSTRUCTIONS ON MODIFICATIONS
C **** THAT SHOULD BE MADE TO COEFFICIENTS WHEN SIMULATED AND
C **** OBSERVED RESULTS DON'T AGREE, WE WILL CERTAINLY BE WILLING TO
C **** DISCUSS THE PROBLEM AND MAKE SUGGESTIONS FOR LOGICAL MODEL
C **** MODIFICATIONS.
C C
C
C
C
C **** OPENING INPUT FILE--ANSWERS.INP
OPEN (UNIT=1, FILE='ANSWTI.OUT', STATUS='OLD')
OPEN (UNIT=8, FILE='NOMRAIOUT', STATUS='OLD')

C **** OPENING OUTPUT FILE--ANSWERS.OUT
OPEN (UNIT=2, FILE='QOA.OUT', STATUS='NEW')
CE1=5603.
CE2=4.26
CE3=62208.0
CE4=0.1
CE5=0.0833333
CE6=62.3174
READ (1.280) (TT(I),I=1,19)
WRITE (2,290) (TT(I),I=1,19)

C
C **** READ, TRANSFORM AND RETURN INPUT INFORMATION.
C
CALL DATA (NDT,KPR,N,CONV,CU,SR,IT,NN,ICR,NFI,CFI,ISTRUC,SS,TMIN,T
MAX,NR,DX,GR,NE,A,DD,A,DT,NAXM,C,DAYBE,G,
2SIMDUR,ISR,YBERG,CLAYAV)

CONFAY=DX*DX/10000.
DO 5550 J=1,N
K=SOIL(J)/256
ASMVOL(J)=ASMBF(K)*(TP1(K)/CU1)

APPENDICES 215
ASMPER(J)=ASMBF(K)
ASMLIM(K)=(FCAP1(K)-FC1(K))*(TP1(K)*CU1)*0.25+FC(K)*(TP1(K)*CU1)
WP(K)=FC(K)*TP1(K)*CU1
FCVOL(K)=FCAP1(K)*(TP1(K)*CU1)
SOIVOL(K)=DF1(K)*DX*DX*BD(K)
VOLSZ1(J)=EDI(J)*PHI(K)
VOLSZ1(J)=EDI(J)*BD(K)
VOLSZ(J)=EDI(J)*0.001*DX*DX*PHI(K)
5550 CONTINUE

*MAX RATE OF NITRIFICATION IS 100MG/KG/WEEK

DO 5551 J=1,ISR
RATEMX(J)=0.001*SOIVOL(J)/7.
5551 CONTINUE

DO 5532 JK=1,1CR
IF(DATPLA(JK).GT.DATHAR(JK)) DATHAR(JK)=DATHAR(JK)+365
LDATE=(DATHAR(JK)-DATPLA(JK))+1
RLEN=(DATHAR(JK)-DATPLA(JK)+1)/10.
DO 5531 LL=1,10
5531 CONTINUE
5532 CONTINUE

*LDATE REPRESENT GROWTH DURATION
POTLAI(JK)=(LAI(JK,LL1+1)+LAI(JK,LL1))/1)*0.5*RLEN
&+POTLAI(JK)
5535 CONTINUE
5532 CONTINUE

DO 5555 IDATE=1,SIMDUR

*GET LEAF AREA INDEX AND INTERPOLATE FOR A SPECIFIC DATE
*LDATE REPRESENT THE CURRENT DATA IN JULIAN CALENDAR

IF(LDAY.GE.365) THEN
  YERBEG=YERBEG+1
  DAYBEG=DAYBEG-365
ENDIF

LDAY=IDATE+DAYBEG-1

DO 5580 JK=1,1CR

*LDATE REPRESENT GROWTH DURATION
LDATE=(DATHAR(JK)-DATPLA(JK))-1
RLEN=(DATHAR(JK)-DATPLA(JK))/10.
LMODE=INT(((REAL(LDAY)-REAL(DATPLA(JK))+1)/REAL(LDATE))*10)+1
IF(LMODE.GT.11) GOTO 5580
RMODE=((REAL(LDAY)-REAL(DATPLA(JK))+1)/REAL(LDATE))*10+1.
IF(RMODE.LT.0) THEN
  LMODE=INT(((REAL(LDAY)-REAL(DATPLA(JK))+366)/REAL(LDATE))*10)+1
  RMODE=((REAL(LDAY)-REAL(DATPLA(JK))+366)/REAL(LDATE))*10+1.
ENDIF
IF(LMODE.GT.11) GOTO 5580
LAI(JK)=(LAI(JK,LMODE)+1)-LAI(JK,LMODE))*(RMODE-LMODE)
& LAI(JK,LMODE)
CDRI(JK)=CDRFL1(JK)+LAI(JK,LMODE)/RLAIMX(JK)*(CDRI(JK)
&-CDRFL1(JK))
IF(CDRI(JK).GT.CDRFAL(JK)) THEN
  WRITE(6,*)(JK,CDR(JK),CDRFL(JK))
STOP
ENDIF

*COMPUTING THE ROOT DEPTH FOR A GIVEN DAY
RDAY=REAL(LDAY)-REAL(DATPLA(JK))+1.
RDAYM=REAL(DATHAR(JK))-REAL(DATPLA(JK))+1.

APPENDICES

216
ROTMAX(JK)=\text{ROTMAX}(JK)\ast(0.5+0.5\ast\sin(3.03\ast(RDAYL/RDAYM)-1.47))

5580 CONTINUE

RAITES=0
RNUT=0
DO 5581 JK1=1,ICR
RNUTNI(JK1)=0.
RNUTAM(JK1)=0.
RNUTP(JK1)=0.
5581 CONTINUE
READ(8,5560) TEMPC,SOITEM,RADL,RAITES,RNUT
IF(RNUT.EQ.1) THEN
DO 5582 JK1=1,ICR
READ(8,6010) RNUTNI(JK1),RNUTAM(JK1),RNUTP(JK1)
RNUTNI(JK1)=RNUTNI(JK1)*CONFAY
RNUTAM(JK1)=RNUTAM(JK1)*CONFAY
RNUTP(JK1)=RNUTP(JK1)*CONFAY
5582 CONTINUE
ENDIF
PREMOI=0.
PREPTV=0.

*CHOOSE THE CORRECT COVER FOR THE GIVEN DAY

LDAY=0ERBEG*1000+ILDAY
DO 5586 J=1,N
K=MOD(SOIL(J),256)
DO 5585 J1111=3,21,2
IF(LDAY.LE.ROT(K,J1111)) THEN
INTI=0
SUR(J)=K*256+0
GOTO 5586
ENDIF
5585 CONTINUE
5586 CONTINUE

DO 6001 J=1,N
K=MOD(SOIL(J),256)
DO 6001 J1111=3,19,2
IF(LDAY.EQ.(ROT(K,J1111)+1)) THEN
SMULAI0=0.
LAI0=0.
INTI=0
RES(INTI+1)=0.25
RES90(INTI+1)=0.1
GOTO 6002
ENDIF
6001 CONTINUE

6002 J=MOD(SUR(19),256)
JAD=MOD(LDAY,60)
IF(JAD.EQ.0) WRITE(6,*) 'SIMULATING ', YERBEG,LDAY
IF (RAITES.EQ.1) THEN
DO 6000 J=1,N
K=SOIL(J)/256
PIV(J)=(1-ASMVOL(J)+RESWAT(K))*CU1+TP1(K)*TP1(K)/DT
ASMPER(J)=ASMVOL(J)*CU1+TP1(K)
APPENDICES 217
PREMOI=ASMPER(I)+PREMOI
PREP=PREPIV+PIV(I)
6000 CONTINUE
PREMOI=PREMOI/N
PREPIV=PREPIV/N
5570 CALL RAINF(A(NRG,FILTS,PP,N,CU1,CU2,CU,DT,TMIN,TMAX,KPR,NDT,
1 ISTRUC,NMAX,ICR,NN))

C
C **** COMPUTE THE PIECE-WISE LINEAR SEGMENTS FOR USE IN MANNING'S
C **** EQUATION.
C
SC=((SFC*CONV/5B)**.6)/300.
D=0.
DO 10 I=1,300
QA(I)=D**1.66667
10 D=D+SC
SC=1/SC

*-*

DX2=DX*DX

*-*

C
C **** INITIALIZE VARIABLES.
C
C **** SET RAINFALL INITIAL VALUES.
C
DO 20 I=1,NRG
JTR(I)=1
IF (TCA(I,1).EQ.TMIN) JTR(I)=2
SR(I)=0.
20 NFI=3
N1=N1+1
N2=N2-1
CHN=CHN-1

C
C **** EROSION CONSTANTS.
C
IF (IT.LE.0) GO TO 30
C
C **** METRIC UNITS.
C
* CE1 AND CE2 WERE NOT CORRECTED BECAUSE THEY ARE NOT
* USED ANYMORE
CE1=9.66155E+5
CE2=2.0847E+1
CE3=6.53864E+6

CE4=5.25545E+1
CE5=CE4
CE6=7.7419E-4
CE7=1.0E+3

C
C **** INITIALIZE VALUES.
C
30 VOL=0.
SS1(1)=0.
PSS1(1)=0.
SPSS1(1)=0.
ANSSI(1)=0.
ANHSSI(1)=0.
ONSSI(1)=0.
ANO3SI(1)=0.
SDR=0.
CHDR=0.
SSCON(1)=0.
RW(1)=0.
Q1(1)=0.
RMAX=0.
QMAX=0.
CMAX=0.
PREC=0.
DTM=DT/60.
T(1)=TMIN

C

C .. INITIALIZATION OF DATA EXTENDED SED SUBROUTINE

C

ERG=0.
DO 31 I1=1,8
31 ER(I1)=0.
YALCON=0.635

* * INITIALIZE VARIABLES FOR THE PHOSPHORUS COMPONENT

* *

tespla=0.
tesnh=0.
tesno3=0.
DO 32 M=1,N
isoi=x
ISOIL= SOIL(M)/256
PSSA=P0SOIL(M)/SSAT(ISOIL)

* * AMMONIUM AND ORGANIC N SEDIMENT BOUND ORIGINAL CONCENTRATION

* A0SOIL IS EXPRESSED IN KG

ANPSSA=A0SOIL(M)/SSAT(ISOIL)
ONPSSA=00SOIL(M)/SSAT(ISOIL)

DO 33 IC=1,NPART
PO(M,IC)=SSA(ISOIL,IC)*PSSA/F(ISOIL,IC)
ANO(M,IC)=SSA(ISOIL,IC)*ANPSSA/F(ISOIL,IC)
ONO(M,IC)=SSA(ISOIL,IC)*ONPSSA/F(ISOIL,IC)
ERP(IC)=0.
STOLD(M,IC)=0.
STNEW(IC)=0.

ANPT(M,IC)=0.
PPT(M,IC)=0.

ANI(M,IC)=0.0
PI(M,IC)=0.0

33 CONTINUE
T12=0.0
T13(M)=0.0

KK=SOIL(M)/256

RBITW(M)=0.
TPON(M)=0.
TIMPON(M)=0.
7ESTL(M)=0.
TESPLA = EDILAB(M) + TESPLA
TESNH4 = EDINH4(M) + TESNH4
TESNO3 = TESNO3 + EDINO3(M)

32 CONTINUE
TESPLA = TESPLA/N
TESNO3 = TESNO3/N
TESNH4 = TESNH4/N

C **** START COMPUTATION FOR EACH HYDROGRAPH PRINT LINE AT DT*KPR.

C DO 220 L = 2, NDT
LM1 = L - 1
T(L) = T(LM1)

C **** CONTINUITY EQUATION FOR TIME INCREMENTS DT.

C DO 170 J = 1, KPR
SPT = 0.

* PSPT ACCUMULATED SEDIMENTBOUND PHOSPHORUS LOSS
PSPT = 0.
DO 35 IC = 1, NPART
PSPT = PSPT + PI(NN, IC)
35 SPT = SPT + S(J, NN, IC)
T(L) = T(L) + DTM

C **** CALCULATE NET RAINFALL FOR EACH GAGE AND SURFACE CONDITION
C **** AND UPDATE INFIILTRATION CAPACITIES WITHIN GAGE AREA ON TIME OR
C **** NET RAINFALL CHANGE.

C DO 90 JJ = 1, NRG
NF(JJ) = NF(JJ) - 1
ITR = ITR(JJ)
ITRM1 = ITR - 1
IF (T(L) - TC(JJ, ITR)) 60, 60, 40
40 IF (T(L) - TMAX) 50, 230, 230
C

C **** NEW RAINFALL RATE, ALLOW FOR DTM BRIDGING TC VALUE.

C 50 DI = T(L) - TC(JJ, ITR)
ITRP1 = ITR + 1
RATE(JJ) = CU*(RC(JJ, ITRP1)) * DI + RC(JJ, ITR)*(DTM - DI))/DTM
ITR(JJ) = ITR(JJ) + 1
ITR = ITRP1

C **** ADD WHOLE HISTOGRAM BLOCK TO TOTAL PRECIPITATION IN
C **** PROPORTION TO WATERSHED AREA COVERED.

C PREC = PREC + RC(JJ, ITR) * (TC(JJ, ITR) - TC(JJ, ITR - 1)) * FRA(JJ)/60.
C
C **** CALCULATE NET RAINFALL FOR EACH COVER.

C 60 DO 70 I = 1, ICR
R(JJ, I) = R(JJ, I) + RATE(JJ) * PIT(JJ, I) / PER(JJ)
IF (R(JJ, I), EQ, SR(JJ) AND NF(JJ), GT, 0) GO TO 70
SK(JJ) = R(JJ, I)
NF(JJ) = NF(JJ)
70 CONTINUE
RATE(JJ)=RC(JJ,ITR)*CU
IF (NF(JJ),GT.0) GO TO 90

C
C **** CALCULATION OF INFILTRATION CAPACITY FOR EACH OVERLAND
C **** ELEMENT.
C
DO 80 M=1,N
IF (MOD(RANE(M),256),NE.JJ) GO TO 80
K=MOD(SUR(M),256)
KK=SOIL(M)/256
FILT(M)=FILT(PIV(M),FCAP1(KK),GWC(KK),DR(M),S(M),R(JJ,K)
1,CU2.ROUGH(KK),HiUK,NEXP,ASMPER(M),KE(KK,K),PSIF(KK),PHIC(KK),TH(L)
1,CU2,LF(KK),KS(KK),KK.KK.M,CUM1(M),RBIT0(M),TESTI(M),TIPON(M)
& TPON(M),FILTS(M),DT,CU1,TP1(KK),A(KK))
80 CONTINUE
NF(JJ)=NF
90 CONTINUE
C
C **** CONTINUITY EQUATION EXPLICIT SOLUTION FOR EACH ELEMENT DURING
C **** TIME INCREMENT, DT.
C
DO 170 M=1,N2
SSS(T)=S(M)+SS(M)
IF (SSS(T),LT.0.) SSS=0.
IF (M,GT.N) GO TO 100
C
C **** OVERLAND ELEMENT.
C
I=MOD(RANE(M),256)
K=MOD(SUR(M),256)
KK=SOIL(M)/256
SUPP=5*SSS+QI(M)+R(LK)
FIL=FILTS(M)
IF (FIL,GT.SUPP) FIL=SUPP
IF (FIL,LT.0.) FIL=0.0
IF (DR(M),LT.0.) DR(M)=0.
CUM1(M)=CUM1(M)+(FIL/CU)*(DT/3600.)
CNO3(M)=CNO3(M)+(DR(M)/CU)*(DT/3600)
PIV(M)=PIV(M)+DR(M)-FIL
SDR=SDR+DR(M)
FLIN=QI(M)+R(LK)-FIL
GO TO 110

C
C **** CHANNEL ELEMENT.
C
100 K=21
FLIN=QI(M)+CHDR+DIN(M)
C
C **** COMBINE INITIAL INFLOW, OUTFLOW AND STORAGE WITH ACCUMULATED
C **** INFLOW.
C
110 FHS=FLINS(M)+FLIN
IF (SSTOR.GT.DIR(K)) GO TO 130
C
C **** NO RUNOFF FROM ELEMENT.
C
120 S(M)=FHS
SS(S)=0.
FLINS(M)=FLIN+FHS
IF (Q(M).EQ.0.) GO TO 170
D=Q(M)

APPENDICES
Q(M)=0.
GO TO 150

C

**** DIRECT SOLUTION OF CONTINUITY EQUATION BY LINEARIZATION.

C

130 Y=SC*(SSTOR-DIR(K))
   IY=Y+1.
   IF (IY.LT.300) GO TO 140
   WRITE (2,330) M
   STOP

140 Y=IY-1
   QL=B(M)*QA(IY)
   QD=B(M)*(QA(IY+1)-QA(IY))
   SSTOR=(FHS(QL+QD*(Y+DIR(K))*SC))/(1+QD*SC)
   IF (SSTOR.LE.DIR(K)) GO TO 120
   Q2=QL+QD*((SSTOR-DIR(K))*SC-Y)
   D=Q2-Q(M)
   Q(M)=Q2
   SS(M)=SSTOR-S(M)
   S(M)=SSTOR
   FLINS(M)=FLIN+SSTOR-Q2

C

C......SEDIMENT CALCULATION.....

C

150 IF (M.LE.N) GO TO 156

C

C......COMPUTE TRANSPORT/DEPOSITION FOR CHANNEL FLOW

C

   CALL SED(CWID(M),0,0.0,M,N,KK,DX)
   CALL PBOUND(NPART,M)
   CALL SOLUBP(DX2.R(IK),KK,M,L,K,DT,T12,T11,SSTOR,FLM,SE,N
   & CUMIN1,CU,NPART)
   CALL AMMON(NPART,M)
   CALL WATNH(SSTOR,FLM,DT,N,CUMIN1,CU,KK,NPART)
   CALL NO3Z(SSTOR,FLM,DT,N,CUMIN1,CU)
   CALL ORGN(NPART,M)

.

   DO 151 IC=1,NPART
       SI(M,IC)=0.0
   151 CONTINUE

C

C......REMEMBER ALL CHANNEL FLOW MOVES WITH ITS "COLUMN" DESIGNATOR

C

   K=NC(M)
   QI(K)=QI(K)+D
   SP1(K)=SP1(K)+SP2(M)

   AI4H4(K)=AI4H4(K)+OUTNH4(M)
   AI4O3(K)=AI4O3(K)+OUTNO3(M)

   DO 152 IC=1,NPART
       PI(K,IC)=PI(K,IC)+PE(IC)
       AI4H4(K)=AI4H4(K)+AI4H4(IC)
       AI4O3(K)=AI4O3(K)+AI4O3(IC)
       SIC(K,IC)=SIC(K,IC)+SIC(IC)
   152 CONTINUE

   IF (M.NE.N2) GO TO 170
   DO 154 IC=1,NPART
       EI(IC)=EI(IC)+SE(IC)
   154 CONTINUE
154 CONTINUE
   GO TO 170
C
C......COMPUTE TRANSPORT/DEPOSITION FOR OVERLAND FLOW
C
156 C=CDR(K)*SKDR(KK)
   CALL SED(DX.R(IK),C.DIR(K),M,N,KK,DX)
   CALL PBOUND(NPART,M)
   CALL SOLUBP(DX2,R(IK),KK,M,I.K,D.T,712,L,T11,SSTOR,FIL,SE,N
   &.CUMIN1,CU,NPART)
   CALL AMMON(NPART,M)
   CALL WATNH(SSTOR,FIL,M,D.T,N,CUMIN1,CU,KK,NPART)
   CALL NO3Z(SSTOR,FIL,M,D.T,N,CUMIN1,CU)
   CALL ORGN(NPART,M)

*.  DO 157 IC=1,NPART
   SI(M,IC)=0.
157 CONTINUE
*.  C
C......PROPORTION OUTFLOW AND SEDIMENT TO DOWNSLOPE ADJACENT ROW
C.......AND COLUMN ELEMENTS.....
C
   IF(M.LT.N2) GO TO 160
   DO 158 IC=1,NPART
      ER(IC)=ER(IC)+SE(IC)
   158 CONTINUE
160 CONTINUE
DRA=D*RFL(M)
I=NR(M)
K=NC(M)
QI(I)=QI(I)+DRA
QI(K)=QI(K)+D-DRA
PSIRA=SP2(M)*RFL(M)
SPI(I)=SPI(I)+PSIRA
SPI(K)=SPI(K)+SP2(M)*PSIRA
ANH4(0)=ANH4(0)+OUTNH4(M)*RFL(M)
ANH4(K)=ANH4(K)+OUTNH4(M)-OUTNH4(M)*RFL(M)
AINO3(0)=AINO3(0)+OUTNO3(M)*RFL(M)
AINO3(K)=AINO3(K)+OUTNO3(M)-OUTNO3(M)*RFL(M)

   DO 162 IC=1,NPART
      PRA=PE(IC)*RFL(M)
      ANRA=ANE(IC)*RFL(M)
      ONRA=ONE(IC)*RFL(M)
      SRA=SE(IC)*RFL(M)
      PI(I.IC)=PI(I.IC)+PRA
      PI(K.IC)=PI(K.IC)+PE(IC)*PRA
      ANI(I.IC)=ANI(I.IC)+ANRA
      ANI(K.IC)=ANI(K.IC)+ANE(IC)*ANRA

APPENDICES
ONI(LIC)=ONI(LIC)+ONRA
ONI(K,IC)=ONI(K,IC)+ONE(IC)-ONRA

SI(LIC)=SI(LIC)+SRA
SI(K,IC)=SI(K,IC)+SE(IC)-SRA

162 CONTINUE
170 CONTINUE
   IF (CHN.LT.1 OR SDR.EQ.0.) GO TO 180

C
C ***** CALCULATE TILE DRAINAGE AND GROUNDWATER CONTRIBUTION.
C
XPR=KPR
CALL DRAIN (DR,DC,DIN,N,N1,N2,STD,TIAL,RFL,NR,NC)
SDR=SDR*STD*XPR
CHDR=SDR*GRF/XPR/CHN
SDR=SDR*(1.-GRF)

C
C ***** OUTPUT PRINT SECTION.
180 Q1(L)=Qi(NN)/CNV
   SIG=0.
   DO 185 IC=1,NPART
   SIG(SIG+SIG(NN,IC))
   SSI(L)=SIG*DT
   IF (Q1(NN).GT.0.) GO TO 190
   SCON(L)=0.
   GO TO 200
190 SCON(L)=(SIG-SPT)/(SIG-SPT+QR(NN)*CE6)*100000.
200 IF (Q1(L).GT.QMAX) QMAX=Q1(L)
   IF (SCON(L).GT.CMAX) CMAX=SCON(L)
   V entertain=Q1(L)
   RW(L)=0.
   DO 210 I=1,NRG
   J=JSR(I)
210 RW(L)=RW(L)+RC(IJ)*FRA(I)
   IF (RW(L).GT.RMAX) RMAX=RW(L)

* *DETERMINE PHOSPHORUS OUTPUT
* *
   PSIG=0.
   DO 215 IC=1,NPART
   PSIG=PSIG+Pi(NN,IC)
215 CONTINUE
   PSSI(L)=PSIG*DT*1.E+3
   SPSSI(L)=SFI(NN)*DT*1000.

* *DETERMINE NITROGEN OUTPUT
* *
   ANSIG=0.
   ONSIG=0.
   DO 216 IC=1,NPART
   ANSIG=ANSIG+ANi(NN,IC)
   ONSIG=ONSIG+ONi(NN,IC)
216 CONTINUE
   ANSSI(L)=ANSIG*DT*1.E+3

APPENDICES 224
ONSSI(L)=ONSIG*DT*1.E+3
CCONVERTING NITROGEN OUTPUT FROM KG TO G

ANH4S(L)=ANH4(NN)*1000.*DT
ANO3SI(L)=ANO3(NN)*1000.*DT

C
C***** PRINT ONE HYDROGRAPH LINE....
C
220 CONTINUE

222 FORMAT(1X,F7.1,5(1X,F12.4))
C
C***** END OF HYDROGRAPH. PRINT TOTAL RUNOFF AND RAINFALL.
C
L=NDT+1
230 VOL=(VOL-5*Q1(L-i))*DT*FLOAT(KPR)/3600.
X=SSI(L-1)/AREA
CONFAC=AREA*.1000.
CONFAC=CONFAC/1000.
VOL1F=VOL1F+VOL
VOL1X=VOL1X+X

IF(YEAR0,NE,YERBEG) THEN
WRITE(2,*)
WRITE(2,*)
WRITE(2,*) 'YEAR OF SIMULATION',YERBEG
WRITE(2,*)
YEAR0=YERBEG
ENDIF

IF(VOL.LE.0.01) THEN
RNO3=RNO3+ANO3SI(L-1)
RNH4S=RNH4S+ANH4SI(L-1)
RNH4SE=RNH4SE+ANSSI(L-1)
RPHOS=RPHOS+SPSSI(L-1)
RORGN=RORGN+ONSSI(L-1)
RSEDPA=RSEDPA+PSSI(L-1)
WRITE(2,229) LDAY,PREC,VOL1F,VOL1X,RNO3/1000.,RNH4S/1000.,
&RNH4SE/1000.,RPHOS/1000.,RSEDPA/1000.,RORGN/1000.
ELSE

RNO3=RNO3+ANO3SI(L-1)
RNH4S=RNH4S+ANH4SI(L-1)
RNH4SE=RNH4SE+ANSSI(L-1)
RPHOS=RPHOS+SPSSI(L-1)
RORGN=RORGN+ONSSI(L-1)
RSEDPA=RSEDPA+PSSI(L-1)
WRITE(2,229) LDAY,PREC,VOL1F,VOL1X,RNO3/1000.,RNH4S/1000.,
&RNH4SE/1000.,RPHOS/1000.,RSEDPA/1000.,RORGN/1000.
ENDIF

229 FORMAT(1X,3B1,1X,F5.0,1X,F6.1,1X,6(1X,F7.1),F10.0)
231 FORMAT(1X,3B1,1X,F10.0,1X,F10.0,1X,F10.0,1X,F10.5)
C
CC...PRINT PARTICLE SIZE DISTRIBUTION OF ERODED SEDIMENT....
C
C***** INDIVIDUAL ELEMENT SEDIMENT LOSS (-) OR GAIN (+).
C
APPENDICES 225
\[
X = \frac{10000}{DX/DX} \\
\text{IF (IT.EQ.0) } X = X \times 4.356
\]

C

**** OUTPUT INDIVIDUAL ELEMENT NET SEDIMENTATION AMOUNTS AND GROSS
C
**** STATISTICAL VALUES.
C

SPAERO=0.
SPADEP=0.
SPASUM=0.
SPASS=0.

C

**** COMPUTE STATISTICS ON OVERLAND FLOW ELEMENTAL SEDIMENT YIELDS.
C

DO 250 I=1,N
SEL(I)=SEL(I)*DT*X
NO3SEL(I)=NO3SEL(I)*X*DT
NHWSEL(I)=NHWSEL(I)*X*DT
NHSEL(I)=NHSEL(I)*X*DT
TKNSEL(I)=TKNSEL(I)*X*DT
PO4SEL(I)=PO4SEL(I)*X*DT
SUMSED(I)=SUMSED(I)+SEL(I)
SUMNO3(I)=SUMNO3(I)+NO3SEL(I)
SUMNHW(I)=SUMNHW(I)+NHWSEL(I)
SUMH(I)=SUMNHW(I)+NHSEL(I)
SUMTKN(I)=SUMTKN(I)+TKNSEL(I)
SUMPO4(I)=SUMPO4(I)+PO4SEL(I)

250 CONTINUE

C

**** NOW, OUTPUT NET DEPOSITION FOR CHANNEL AREAS.
C

J=N+1
DO 260 I=J,N2
260 SEL(I)=SEL(I)*DT
C

*COMPUTE NEW SOIL MOISTURE AFTER EVERY RAINFALL EVENT
*

DO 6003 J=1,N
K=SOIL(J)/256
ASMVOL(I)=(1-PIV(J)*DT/TP1(K))*TP1(K)/CU1-RESWAT(K)
ASMPER(I)=ASMVOL(I)*CU1/TP1(K)

6003 CONTINUE

*THE FOLLOWING ENDFIND INDICATES THE END OF THE IF RAITES=1
ENDFIND

CALL ETP11(TEMPC,RAD,L,ETPMM)
TETPR=0.
TOTPER=0.
TOTXMO=0.
DO 5590 J11=1,N
K=MOD(SUR(J11),256)
KK=SOIL(J11)/256
CALL EVAPO(LAI1(K),S1EP(J11),ESU(KK),TTIME(J11),S2EP(J11)
& ,ETPMM,L,PEP(J11),ES(J11),CUMIN1(J11))

*INITIALIZING THE INITIAL CUMULATIVE INFILTRATION TO ZERO
CUMIN1(J11)=0.
XMOI(J11)=ASMVOL(J11)+RESWAT(KK)*TP1(KK)/CU1

*EDX REPRESENTS THE MAXIMUM EVAPORATIVE DEPTH
RRATIO=EDX(KK)/DFI1(KK)) + XMOI(J11)-WP(KK)) IF(ES(J11)>RRATIO) ES(J11)=RRATIO

*REDUCE THE PLANT EVAPORATION ACCORDING TO THE ROOT DEPTH
IF(ROTDAY(KK)*DFI1(KK)) THEN
   ROTRAT=EXP(3.065*DFI1(KK)/ROTDAY(KK))
   ROTR(J11)=(1.-ROTAT)/(1.-EXP(-3.065))
   PEP(J11)=PEP(J11)*ROTR(J11)
ELSE
   ROTR(J11)=1.
ENDIF

CNH4(J11)=0.

*SOIL MOISTURE LIMITING
IF(XMOI(J11)<AT.WP(KK)) xmoi(J11)=wp(kk)
IF(XMOI(J11)<AT.ASMLM(KK)) THEN
   PEP(J11)=PEP(J11)*XMOI(J11)/ASMLM(KK)
   TETP=PEP(J11)+ES(J11)
   IF(XMOI(J11)<AT.WP(KK)) THEN
      ASMVOL(J11)=ASMVOL(J11)-TETP
      TETPPR=TETPPR+TETP
       ELSEIF (XMOI(J11)<AT.EQ.WP(KK)) THEN
      ES(J11)=0.
      PEP(J11)=0
      ELSE
         TETP=XMOI(J11)-WP(KK)
         PEP(J11)=PEP(J11)+TETP/(PEP(J11)+ES(J11))
         ES(J11)=ES(J11)+TETP/(PEP(J11)+ES(J11))
         ASMVOL(J11)=ASMVOL(J11)-TETP
         TETPPR=TETPPR+TETP
       ENDIF
TOTES=TOTES+ES(J11)
TOTE Pep=TOTE Pep+PEP(J11)
GOTO 5590
ENDIF

*SOIL MOISTURE NOT LIMITING
IF (XMOI(J11)<AT.FCVOL(KK)) THEN
   XMOI=MAX(0.0, XMOI(J11)-CU1*TP1(KK)
   PERCOL=0.
   CALL PERCO(XMOI(J11), KS(KK), FCVOL(KK), CU, PERCOL, FCAPI(KK)
   & XMOI2, TMAX, RAIRES, A(KK))
   ASMVOL(J11)=ASMVOL(J11)-TETP-PERCOL
   XMOI(J11)=ASMVOL(J11)-RESWAT(KK)*TP1(KK)/CU1

*CNH4 REPRESENTS THE LEACHING FRACTION OF NITROGEN
CNH4(J11)=(PERCOL+CNO3(J11))/(XMOI(J11)+TETP-PERCOL+CNO3(J11))
CNO3(J11)=0.
TETPPR=TETPPR+TETP
TOTPEP=TOTPER+PERCOL
TOTES=TOTES+ES(J11)
TOTPERP=TOTPER+PEP(J11)
PERCOL=0.
GOTO 5590
ENDIF

IF(XMOI(J11)<AT.WP(KK)) THEN
   ASMVOL(J11)=ASMVOL(J11)-TETP

APPENDICES
TETPPR = TETPPR + TETP
ELSE IF (XMOI(J11),EQ.WP(KK)) THEN
  ES(J11) = 0,
  PEP(J11) = 0
ELSE
  TETP = XMOI(J11),WP(KK)
  PEP(J11) = PEP(J11) + TETP
  ES(J11) = ES(J11) + TETP
  ASMVOL(J11) = ASMVOL(J11) - TETP
TETPPR = TETPPR + TETP
ENDIF
TOTES = TOTES + ES(J11)
TOTEP = TOTEP + PEP(J11)
TOTXMO = TOTXMO + XMOI(J11)

5590 CONTINUE

5591 FORMAT(1X,S/F10.5,1X))
     CALL NITRAN(ES,FCVOL,SOIVOL,XMOI,PEP,WP,N,TEMPC,ICR,
&
     RATEM,C,U,SOITEM,RNUTN,RNUTA,RNUTP,DF1,TP1)
IF(DATE.EQ.SIMDUR) THEN
  XCOR=365./SIMDUR
  WRITE(2,301)
  WRITE(2,302)
  WRITE(2,303)
301 FORMAT(4X,'%1X,75(*)'))
302 FORMAT(4X,30X,25H**** ANNUAL OUTPUT *****)
303 FORMAT(30X,25H**** ON A CELL BASIS *****))/
     WRITE(2,309)
  WRITE(2,308)
DO 5554 I=1,N
  WRITE (2,360) LSUMSED(I),XCOR,SUMNO3(I),XCOR,SUMNHW(I),XCOR,
&
  SUMNHI3(I),XCOR,LSUMTKN(I),XCOR,SUMPO4(I),XCOR,LCENO3(I),XCOR
5554 CONTINUE
ENDIF
5555 CONTINUE

C
C **** FORMATS.
C
280 FORMAT (19A4)
290 FORMAT (1H1.52H DISTRIBUTED HYDROLOGIC AND WATER QUALITY
&SIMULATION/16X,23H BY ANSWERS VER 4.940001/19A4)
300 FORMAT (1.15X,'OUTLET HYDROGRAPHS--VER 4.940001',/31X,'YIELD',9X,
1'CENTRATIONS ','A4',2X,' TIME','2X,'RAINFALL',2X,'RUNOFF','4X,'S
2EDIMENT','3X,'SEDIMENT' PHOSPHORUS SOLPHOS'/',1X,' MIN','2X,2A4,
31X,2A4,5X,4A18X,'(MG')',6X,'(G')')
399 FORMAT(1X,7HELE NO ),1X,9H SEDIMENT,1X,9H NO3 ,1X,9H SOL-NH4 , &
1X,9H SED-TKN ,1X,9H PO4 ,10H NO3 LEACH 
308 FORMAT(1X,7H ,1X,9H KG/HA ,1X,9H KG/HA ,1X,9H KG/HA,
&1X,9H KG/HA ,1X,9H KG/HA ,1X,9H KG/HA ,1X,9H KG/HA)
310 FORMAT (1X,F7.1,F8.2,F10.2F11.0,1X,F12.3X,F12.5)
311 FORMAT (1X,F7.1,F12.4X,F12.4X,F12.4X,F12.4X)
320 FORMAT (4X,28HRUNOFF VOLUME PREDICTED FROM,F7.2,A4,14H OF RAINFALL
=,F7.3,A4/15X,9HAVERAGE SOIL LOSS =,F7.3,1X,2A4)
330 FORMAT(4X,48HMEAN FLOW DEPTH GREATER THAN EXPECTED AT

APPENDICES 228
1 ELEMENT.
115/56H CONDITION OCCURRED BECAUSE THIS ELEMENT'S SLOPE IS MUCH, 31H 2 LESS THAN WATERSHED AVERAGE OR ,28H CIRCULAR FLOW PATTERNS ARE,
358H PRESENT IN THIS VICINITY. RECOMMENDED CORRECTIVE ACTION,.60H 4 INCREASE EXPECTED PEAK RUNOFF VALUE (SF) IN SUBROUTINE DATA,10H 5 OR MODIFY .24ELEM FLOW DIRECTIONS.)
340 FORMAT (1X,36H INDIVIDUAL ELEMENT NET SEDIMENTATION/4,4(2X,16HE
1 ELEMENT SEDIMENTATION)/4,4(2X,3HNO.,3X,244))
350 FORMAT (1X,'MAX EROSION RATE =',F7.0,24A,2X,'MAX DEPOSITION RATE =
1 ,F7.0,24A,4,2X,'STD. DEV. =',F7.0,24A,4//24X,'CHANNEL DEPOSITION
2 --',A4,4,4(24X,'NO. AMOUNT'))
360 FORMAT (17,1X,F9.0,6(1X,F9.3))
370 FORMAT (21H STRUCTURAL PRACTICE,'32H REDUCED TOTAL SEDIMENT YIE
1 LD BY F9.0,A4)
C 380 FORMAT (14,2F7.2,F7.0,13/12A4)
C 390 FORMAT (3F10.2,F10.0)
405 FORMAT(20X,26HPARTICLE SIZE DISTRIBUTION/
*24X,18HFO ERODED SEDIMENT/)
410 FORMAT(17X,15HPARTICLE CLASS,I1,2H =,F6,2,8H PERCENT)
C
5560 FORMAT(1X,14,I1,1X,14,I1,1X,14,I1,1X,11)
6010 FORMAT (1X,F9.4,1X,F9.4,1X,F9.4)
2570 FORMAT(2X,14,I1,1X,3X,F7.2,2X,F7.3,2X,F7.0,3X,F7.4,2X,F7.4,5X,
&F7.4,3X,F7.4,5X,F7.4,3X,F7.4,5X,F7.4)
2580 FORMAT(2X,14,I1,1X,3X,F7.2,2X,F7.3,2X,F7.0,3X,F7.3,2X,F7.3,5X,
&F7.3,3X,F7.3,5X,F7.3)
9000 END
SUBROUTINE DATA (NDT,KPRN,CONV,CU,ST,NN,ICR,NFL,CU2,ISTRUC,SB,
1TM,MIN,MAX,NG,DG,GRF,EXP,DC,PP,FRILS,CWID,AREA,DT,MAX,CU1,DAY BEG
2,SMF,SR,YEK,BG,CLAY)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C ***** SUBROUTINE TO INPUT WATERSHED DATA.
C
COMMON /ZSED/,NPART,NWASH,NWASH1
COMMON /ZSED/,VISCOS,AGR,AV,SWH20,YALCON,SE(8),VS(2000),DIAG(8),SG
1(8),FV(8),C1(8),C2(8),C4(8),DIAMM(8),EQSDIA(8),EDMM(8),F(10,8)
2,CE1,CE3,CE5,
COMMON /CUMIN/ CUMIN(2000),RTB(0) (2000),TEST(2000),MELON(0000),
& TAN(0000)
C
C ***** MAXIMUM NUMBER OF SOIL TYPES IS 20.
C
COMMON /COIL/,A(20),P(20),FC(20),GWC(20),SKDR(20)
COMMON /GMAT/,CL(20),SA(20),ST(20),OM(20),AC(20)
& _AO(20),BC(20),BO(20),PHI(20),VFC(20),WVF(20),CFC(20),
& CEC(20),EAC(20),PHIC(20),XF(20),PSIF(20),PBF(20),
& THETR(20),KS(20),CF(20),Z(20),LF(20),CS(20),SCF(20),
& CRC(20),KE(20),ZC(20),BD(20)
COMMON /ETPHES/ESU(20),LAI(20),POTLAI(20),EDX(20)
& SUMLAI(20)
COMMON /ROTS/ IROT(20,41)
INTEGER IROT
REAL KS,KE,LF,LAESU,LAI,EDX,SUMLAI
COMMON /PHOS/ POSOIL(2000),SSA(20,8),SSAT(20),EDOP(2000),
& P(2000,8),ERP(8),STOLD(2000,8),SEDNEW(2000,8),PPT(2000,8),
& P(2000,8),PSEL(2000),STNEW(8),P2(8),PCELL(2000,8),PE(8)
& DRFT

COMMON/NITRO1/ AOSOIL(2000),ANPT(2000,8),ANI(2000,8),
& ANSEL(2000),AN2(8),ANCCELL(2000,8),ANE(8),AN6(2000,8)
& _CNH(4200)

COMMON/NITRO2/ OOSOIL(2000),ONPT(2000,8),ONI(2000,8),
& ONSL(2000),ON2(8),ONCELL(2000,8),ONE(8),ON0(2000,8)

COMMON/SOLUB/ SP2(2000),PEXT(2000),PK(20)
& _RALPHA(20),RBETA(20),RGM7A(20),SP(2000),CGEN1(2000)


REAL MINP


COMMON /ASMF/ ASM5F(20),FCAP1(20),TP1(20),RESWAT(20),DF1(20)
DIMENSION TP(20), DF(20), ASM(20), FCAP(20)
C
C **** MAXIMUM NUMBER OF SURFACE AND CROP TYPES IS 20.
C
C COMMON /CRG/ROUGH(20),HU(20),DIR(21),PIT(20,20),PER(20),CDR(20)
C
C **** MAXIMUM NUMBER OF OVERLAND ELEMENTS PLUS CHANNEL ELEMENTS
C **** IS 50.
C
C ***** IT IS EXPECTED THAT ARRAY "IEL" (IN SUBROUTINE DATA) WILL
C ***** BE OF SUCH A SIZE THAT IT WILL OVERLAY (BE EQUIVALENCED TO)
C ***** THE SPACE IN ARRAYS SI AND QI TOGETHER. THEREFORE IT IS
C ***** NECESSARY THAT THESE TWO ARRAYS BE KEPT ADJACENT IN THEIR
C ***** COMMON BLOCK. NOTE: THE ACTUAL NUMBER OF ELEMENTS THAT
C ***** CAN BE DIMENSIONED IN IEL WILL DEPEND ON THE WORD LENGTH
C ***** OF THE MACHINE BEING USED, E.G. ON A MACHINE WHICH USES
C ***** A SINGLE WORD INTEGER AND A DOUBLE WORD REAL. THE NUMBER
C ***** OF ELEMENTS IN IEL CAN BE FOUR TIMES THE NUMBER OF ELEMENTS
C ***** IN ARRAY SI.
C
20,8),QI(2010),DIN(2000),ST(2000,8))
C
C ***** ARRAYS SI AND QI MUST BE DIMENSIONED TO A SIZE = NMAX+ISTRUC+2
C ***** TO HOLD, IN ORDER, SEDIMENT AND FLOW FROM THE WATERSHED
C ***** OUTLET ELEMENT, STRUCTURAL PRACTICES AND ANY "LEAKY"
C ***** ELEMENTS.
C
EQUIVALENCE (TP1(1),ST(1,1)),(DF1(1),ST(21,1)),(ASM1(1),ST(41,1))
EQUIVALENCE (FCAP1(1),ST(61,1)), (ITEMP1(1),ST(81,1))

APPENDICES

230
EQUIVALENCE (IRR(1),SST(101,1))
EQUIVALENCE (RN(1),SEL(1))
EQUIVALENCE (WID(1),SEL(41)), (CN(1),SEL(51))
EQUIVALENCE (CBAR(1),SEL(80)), (SPER(1),SEL(101)), (CROP(1,1),SEL
1(121)), (NSTRUC(1),SEL(161))
DIMENSION CROP(20,2), RN(20), DIRM(20), CBAR(20), SPER(20), NSTRUC
1(4), STRANAM(3,4)
EQUIVALENCE (DIRM(1),DIR(1))
COMMON / CROPAD/ DIRM2(20)

C **** MAXIMUM NUMBER OF RAINGAGES IS 4 WITH 35 VALUES PER GAGE.
C
COMMON /CRGAGE/ RC(8,35),TC(8,35),R(8,20),FRA(8),TJR(8),RATE(8),SR
1(8),NF(8)
DIMENSION IRR(4),IG(5),DATE(2)
EQUIVALENCE (IEL(1,1,1),SI(1,1))
DIMENSION IEL(3,103,20),ITEMP(20)
DIMENSION IELC(3,103,2),ITEMPC(2)
EQUIVALENCE (TIAL(1),RANE(1))
EQUIVALENCE (TIAL(1),RANE(1))
EQUIVALENCE (DIN(1),CHAN(1))
COMMON /PARTITION/PKDA(20),PKDP(20),PSP(20)
COMMON /PLANTN/DATPLA(20),DATHAR(20),CP!(20),CP2(20),DMY(20)
& ,YP(20),ROTMX(20),ROTDAY(20),CDRFAL(20),RLAIMX(20),CDRX(20)
& ,RES(20),RES20(20),RES90(20)

INTEGER SUR,SOIL,TIAL(2000),RANE,CHAN(2000),DATPLA,DATHAR
INTEGER DAYBE, SIMDUR, YERBEG, ROTMAX, ROTDAY

C **** MAXIMUM NUMBER OF CHANNEL TYPES IS 10.
C
DIMENSION WID(10), CN(10), PP(14), TITLE(11)
LOGICAL STRUC
CHARACTER*4 C1, C2, C3, C4, C5, C6, PRL, UN, UNITS, PR, TEST
CHARACTER*4 PP, TITLE, STRANAM, DATE
CHARACTER*2 IG, IELC, ITEMPC, ISTL
CHARACTER JBEQ
DATA C1,C2,C3,C4,C5,C6,PRL,UN/' RAI', ' SI'; ' SO'; ' SU'; ' CH',
1 ' EL', ' PRIN', ' METR'/
DATA ISTL/'TT'/

C **** NOW, STORE THE NAMES OF THE STRUCTURAL PRACTICES.
C
DATA STRANAM/'PTO ', ' TERR ', ' ASES ', ' POND ', ' S ', ' L ', ' AKES ', ' G ',
1 ' W ', ' ATER '
1 ' WAYS ', ' FIEL ', ' D BO ', ' RDER '/
STRUC=FALSE.

C **** NUMBER OF STRUCTURAL PRACTICES PERMITTED. ARRAYS STRANAM AND
C ***** NISTRUC MUST BE REDIMENSIONED IF STRUC IS MODIFIED. ALSO, THE
C ***** ADDITIONAL STRUCTURE NAMES MUST BE ADDED TO THE DATA
C ***** STATEMENT.
C
ISTRUC=4
IT=0
OUTSID=0.
TMAX=0.
TMIN=1.1E+10

C **** INPUT UNITS USED IN SIMULATION AND OUTPUT PRINT CONTROL.

APPENDICES
C
READ (1,830) UNITS,PK
C
C ****** INPUT NUMBER OF RAINGAGES AND DATE OF EVENT.
C
READ (1,810) TEST,NRG,DATE
IF (NRG.GT.8) GO TO 540
IF (TEST.NEC2) GO TO 580
READ (1,1666) DAYBEG,YERBEG
READ (1,1667) SIMDUR
DO 20 I=1,NRG
READ(1,830) IG(I)
20 CONTINUE
C
C ****** DEFINE DEFAULT SIMULATION REQUIREMENTS. MAXIMUM NUMBER OF
C ****** HYDROGRAPH PRINT POINTS IS 101 (THIS IS THE NUMBER THAT WILL BE
C ****** OUTPUT). NORMAL TIME STEP IS 60 SECONDS AND NORMAL TIME STEP
C ****** FOR INFILTRATION IS 180 SECONDS. MAXIMUM EXPECTED RUNOFF RATE
C ****** IS 2 INCHES (50.8 MM) PER HOUR. IF A SEGMENTED CURVE ERROR
C ****** OCCURS DURING SIMULATION, INCREASE SF BY 50 PERCENT UNTIL THAT
C ****** PROBLEM CEASES (IT MAY NOT BE THE ONLY PROBLEM, THOUGH).
C ****** FOR WATERSHEDS WITH LARGE ELEMENTS (GREATER THAN 5 ACRES),
C ****** MILD TOPOGRAPHY (LESS THAN 1 PERCENT AVERAGE SLOPES), OR
C ****** MANY ELEMENTS (MORE THAN 1000), THE SIMULATION TIME STEP, DT,
C ****** SHOULD BE INCREASED TO NO MORE THAN 300 SECONDS (5 MINUTES).
C ****** SIMILARLY, FOR SMALL ELEMENTS (LESS THAN 1 ACRE), SEvere
C ****** TOPOGRAPHY, OR WATERSHEDS WITH ONLY A FEW ELEMENTS, THE
C ****** SIMULATION TIME STEP SHOULD BE DECREASED TO 15 - 30 SECONDS.
C
C.... INPUT SIMULATION REQUIREMENTS
C
READ (1,810) TEST
IF (TEST.NE.C3) GOTO 580
READ (1,1030) NDT,DT,NFI,LF
C
IF (UNITS.EQ.UN) IT=7
IF (PRLEQ.F) WRITE(2,630) DT,NFI,LF,PE(II+1),PE(II+2)
NFI=NF2/IFIX(SNGL(DT))
C
C ****** INPUT INFILTRATION AND SOIL DATA.
C
READ (1,810) TEST
IF (TEST.NE.C3) GOTO 580
READ (1,780) ISR
IF (PRLEQ.F) WRITE (2,750) PE(II+1),PE(II+2),PE(II+1)
IF (ISR.GT.20) GO TO 530
ASMBAR=0.
FPBAR=0.
DO 60 I=1,ISR
READ (1,790) TP(I),FCAP(I),FC(I),A(I),P(I),DF(I),ASM(I),SKDR(I)
ASMBF(I)=ASM(I)
FCAPF(I)=FCAP(I)
DF(F)=DF(I)
SPER(I)=0.
READ(1,795) CL(I),SA(I),ST(I),OM(I),WCF(I)
READ(1,797) PK(I),RALPHA(I),RBETA(I),RGAMA(I)
C....
BD(I)=2.65*(1.-TP(I))
CC....WATER TEMPERATURE ASSUMED TO BE 20 DEG.C. (68 DEG.F.)....
CC....AT OTHER TEMPERATURES ADJUST VISCOS AND SWH2O.....

C
AGRAV=32.174
VISCOS=0.0000108
SWH2O=62.32
IF(UNITS.NE.UN) GO TO 58
AGRAV=8.8066352
VISCOS=0.000061003352832
C
SWH2O=9785.69088
SWH2O=999.1677535
58 CONTINUE
60 CONTINUE
C
DO 57 I=1,ISR
******************************************************************************
*ADITION THE CRUST THICKNESS ASSUMED TO BE 0.005M
ZC(I)=0.5
******************************************************************************

***********************************************************************

***POROSITY

*****************

PHI(I)=TP(I)

*****VOLUME OF COARSE FRAGMENT (>2MM)
VCF(I)=100.*(WCF(I)/2.65)/(100.-WCF(I)/BD(I))+(WCF(I)/2.65)
* WHERE WCF IS THE WEIGHT OF COARSE FRAGMENT (%)
****CORRECTION FACTOR FOR COARSE FRAGMENT
CFC(I)=1.0-(VCF(I)/100.0)

*******CATION EXCHANGE CAPACITY/%CLAY
CEC(I)=(.0059*CLC(I)+0.041)/(.6*CLC(I))
IF(CEC(I).LT.0.15) CEC(I)=0.15

*****CORRECTION FOR ENTRAPPED AIR
EAC(I)=1.0-(3.8+0.00019*CLC(I)**2-0.0337*SA(I)+0.126*CEC(I)
& *CLC(I)+OM(I)*SA(I)/200.)**2./100.

******************************************************************************

*****EFFECTIVE POROSITY

PHIC(I)=PHI(I)*CFC(I)*EAC(I)

******************************************************************************

*****CAPILLARY FRONT POTENTIAL

******************************************************************************

XF(I)=6.531-7.33*PHIC(I)+.001583*CLC(I)**2.0+3.81*PHIC(I)**2.0
& -.0488*SA(I)*PHIC(I)-.000799*SA(I)**2.0*PHIC(I)
& -.000140*SA(I)**2.0*CLC(I)-.00348*CLC(I)**2.0*PHIC(I)
& .00034*CLC(I)*SA(I)+.0016*CLC(I)**2.0*PHIC(I)**2.0
& .00161*SA(I)**2.0*PHIC(I)**2.0

******************************************************************************

PSIF(I)=EXP(XF(I))

******************************************************************************

*CONVERTING PSIF TO MM
PSIF(I)=10.*PSIF(I)

APPENDICES 233
*****CONSTANT C USED TO COMPUTE THE SATURATED HYDRAULIC CONDUCTIVITY

\[ \text{CBF}(i) = -0.17 + 0.181 \cdot \text{CL}(i) - 0.0000069 \cdot \text{SA}(i) + 2.0 \cdot \text{CL}(i)^2 + 2.0 \]
& \quad -0.0000041 \cdot \text{SA}(i) + 2.0 \cdot \text{ST}(i) + 2.0 + 0.000118 \cdot \text{SA}(i) + 2.0 \cdot \text{BD}(i) + 2.0
& \quad + 0.00069 \cdot \text{CL}(i) + 2.0 \cdot \text{BD}(i) + 2.0 + 0.000049 \cdot \text{SA}(i) + 2.0 \cdot \text{CL}(i)
& \quad - 0.000085 \cdot \text{ST}(i) \cdot \text{CL}(i)^2 + 2.0

****RESIDUAL SOIL WATER

\[ \text{THETAR}(i) = (0.2 + 0.1 \cdot \text{OM}(i) + 0.25 \cdot \text{CL}(i) \cdot \text{CEC}(i) + 0.45) \cdot (\text{BD}(i) / 100)
& \quad \cdot \text{EAC}(i) \cdot \text{FC}(i)
\]
& \quad \text{asmblf}(i) = \text{asmblf}(i) - (\text{thetar}(i) / \text{tp}(i))

RESWAT(i) = \text{THETAR}(i) / \text{TP}(i)

****

* UPPER STAGE OF SOIL EVAPORATION (MM DAY ** -0.5)

**

\[ \text{ESU}(i) = 9.4 \cdot (4.165 + 0.02456 \cdot \text{SA}(i) - 0.01703 \cdot \text{CL}(i) - 0.0004 \cdot \text{SA}(i))
& \quad \cdot (\text{SA}(i) - 3.5) \cdot 0.42
\]

ESU(i) = 9.4 \cdot (3.5 - 3) \cdot 0.42

*COMPUTE THE MAXIMUM EVAPORATIVE DEPTH

\[ \text{EDX}(i) = 90.77 \cdot \text{CL}(i) - 0.006 \cdot \text{SA}(i) \cdot \text{SA}(i)
\]

*****SATURATED HYDRAULIC CONDUCTIVITY

\[ \text{KS}(i) = \left(\text{PHIC}(i) - \text{THETAR}(i)\right)^2 \cdot (1 - \text{PHIC}(i))^{2.0}
& \quad \cdot (\text{BD}(i) / \text{THETAR}(i))^2 \cdot 0.0002 \cdot \text{CBF}(i)^{2.0}
\]

******MACROPOROSITY FACTOR

\[ \text{Z}(i) = \exp(0.96 - 0.32 \cdot \text{SA}(i) + 0.04 \cdot \text{CL}(i) - 0.032 \cdot \text{BD}(i))
\]

Z(i) = 0.4

* SEE WEPP MANUAL

******CRUST FACTOR

\[ \text{ZC}(i) = 1
\]
\[ \text{SCF}(i) = 0.0099 + 0.0212 \cdot \text{ZC}(i) + 0.0000068 \cdot \text{SA}(i)^2 + 0.0000212 \cdot \text{SA}(i)
& \quad + 2.0 \cdot \text{ZC}(i) + 0.000215 \cdot \text{SA}(i) \cdot \text{ZC}(i)^2
\]

******DEPTH TO WETTING FRONT

*** DEPTH TO WETTING FRONT MUST BE GREATER THAN CRUST DEPTH (1CM)

\[ \text{LF}(i) = 14.7 \cdot (0.0015 \cdot \text{SA}(i)^{2.0} - 0.3 \cdot \text{CL}(i) \cdot \text{BD}(i)
\]

IF(LF(i).LE.Z(i)) LF(i) = Z(i)

******CORRECTION FACTOR FOR PARTIAL SATURATION OF THE SUBCRAST SOIL

\[ \text{CS}(i) = 0.74 + 0.0019 \cdot \text{SA}(i)
\]

******CRUST REDUCTION FACTOR

\[ \text{CCK}(i) = \text{LF}(i) / \left(\text{LF}(i) - \text{ZC}(i)\right) / \text{CS}(i) + \text{ZC}(i) / \text{SCF}(i)
\]

*CONVERTING KEY TO CM/HR TO MM/HR

\[ \text{KS}(i) = \text{KS}(i) \times 10.
\]

\[ \text{LF}(i) = \text{LF}(i) \times 10.
\]

*COMPUTING PARTITION FACTOR FOR DISSOLVED AND ADSORBED AMMONIUM

\[ \text{PKDA}(i) = 1.34 + 0.083 \cdot \text{CL}(i)
\]

*COMPUTING PARTITION COEFFICIENT FOR PHOSPHORUS

\[ \text{PKDP}(i) = 100 + 2.5 \cdot \text{CL}(i)
\]

\[ \text{PSP}(i) = 0.46 - 0.0916 \cdot \log(\text{CL}(i))
\]

IF(PSP(i).LT.0.05) PSP(i) = 0.05

IF(PSP(i).GT.0.75) PSP(i) = 0.75

APPENDICES
C----
IF (PRI.EQ.PR) WRITE (2,640) LTP(I),FCAP(I),FC(I),KS(I),DF(I)
1,ASM(I),SKDR(I)

57 CONTINUE

C
C .... ADDITIONAL CALCULATIONS FOR EXTENDED SEDIMENT MODEL
C
WRITE(2,1040)
READ(1,1050) NPART,NWASH
WRITE(2,1060) NPART,NWASH
NWASH1=NWASH+1
IF(NWASH.EQ.NPART) NWASH1=1
VISCOS=1./VISCOS
READ(1,1070) DIAMM(IC),SG(IC),FV(IC),IC=1,NPART
DO 70 IC=1,NPART
   IF(UNITS.EQ.UN) GO TO 61
   DIA(IC)=DIAMM(IC)*.0032808399
   GO TO 62
61 DIA(IC)=DIAMM(IC)*0.001
62 IF(FV(IC).LE.0.00000001) GO TO 63
   GO TO 70
70 CONTINUE

C
CC........CALCULATION OF PARTICLE FALL VELOCITIES........
C
63 FV(IC)=AGRAV*(SG(IC)-1.)*VISCOS*DIA(IC)**2/18.
   X1=DIA(IC)*VISCOS
   REYN=FV(IC)*X1
   IF(REYN.LE.0.1) GO TO 70
   X2=DSQRT(4.*AGRAV*(SG(IC)-1.)*DIA(IC)/3.)
   DO 69 I=1,10
      CD=24./REYN+.3./DSQRT(REYN)+.34
      FV(IC)=X2/DSQRT(CD)
      REYN=FV(IC)*X1
   69 CONTINUE
70 CONTINUE

C
CC........CALCULATION OF EQUIVALENT SAND DIAMETERS.......
C
DO 78 IC=1,NPART
   IF(SG(IC).GT.2.645) GO TO 77
   X4=FV(IC)*VISCOS
   DS=DSQRT((10.90909091*FV(IC)/(AGRAV*VISCOS))
   REYN=X4*DS
   IF(REYN.LE.0.1) GO TO 76
   X3=FV(IC)**2/(AGRAV+2.2)
   DO 75 II=1,20
      DS=X3*(24./REYN+.3./DSQRT(REYN)+.34)
      REYN=X4*DS
   75 CONTINUE
76 EQSDIA(IC)=DS
   GO TO 78
77 EQUFDIA(IC)=DIAMM(IC)
78 CONTINUE
   X3=394.8
   IF(UNITS.EQ.UN) X3=1000.
   DO 79 IC=1,NPART

APPENDICES
79 EDMM(IC)=EQSDIA(IC)*X3
WRITE(2,1080)PP(TT+4)
WRITE(2,1090)(IC,DIAMM(IC),EDMM(IC),SG(IC),FV(IC),IC=1,NPART)
WRITE(2,1100)
DO 85 J=1,ISR
READ(1,1110)(P(I,J),I=1,NPART)
85 WRITE(2,1120),(F(I,J),I=1,NPART)

******************************************************************************

* INPUT SPECIFIC SURFACE AREA FOR PHOSPHORUS COMPONENT
* SPECIFIC SURFACE AREA MUST BE IN M^2/G

WRITE(2,*)'SPECIFIC AREA FOR DIFFERENT PARTICLE SIZE'
DO 86 J=1,ISR
READ(1,1111)SSAT(J),(SSA(J,I),I=1,NPART)
WRITE(2,1111)SSAT(J),(SSA(J,I),I=1,NPART)
86 CONTINUE

DO 81 I=1,ISR
SASA=0.
DO 88 J=1,NPART
SSA(J,I)=SSA(J,I)*F(J,I)
SASA=SASA+SSA(J,I)
88 CONTINUE
DO 82 I=1,NPART
SSA(J,I)=SSA(J,I)*SSAT(J)/SASA
82 CONTINUE
81 CONTINUE

******************************************************************************

C **** INPUT DRAINAGE AND GROUNDWATER CONSTANTS.
C
READ(1,980)NEXP,DC,GRF
IF (PRLEQ,PR) WRITE(2,990)NEXP,DC,PP(TT+1),GRF
C
C **** INPUT CROP AND SURFACE ROUGHNESS DATA.
C
READ(1,810)TEST
IF (TEST.NE.4) GO TO 580
READ(1,940)ICR
IF (PRLEQ,PR) WRITE(2,950)PP(TT+1),PP(TT+1),PP(TT+1)
IF (ICR.GT.20) GO TO 550
DO 87 I=1,ICR
CBA(I)=0.
READ(1,620)CROP(I,1),CROP(I,2),PIT(1,I),PER(I),ROUG(I),HU(I),RN
1(I),DIRM(I),CDR(I)
CDRK(I)=CDR(I)
DIRM2(I)=DIRM(I)
READ(1,623)AC(I),AO(I),BC(I),BO(I)
READ(1,624)(LAI(I,I11),I11=1,11)
READ(1,625)DATPLA(I),DATAR(I),CP1(I),CP2(I),DMY(I),YP(I)
& ,ROTMX(I),CDRFAL(I),RLAIDX(I)

******************************************************************************

* COMPUTE A EFFECTIVE HYDRAULIC CONDUCTIVITY FOR EACH SOIL CROP COMBINATION

****CANOPY FACTOR
CF(I)=1.+AC(I)/(AC(I)+AO(I))
DO 84 KKK=1,ISR

******************************************************************************
** EFFECTIVE HYDRAULIC CONDUCTIVITY
******************************************************************************

** SEARCHING FOR THE CORRECT HYDRAULIC CONDUCTIVITY
******************************************************************************

******************************************************************************

KE(KKK,J)= KS(KKK)*
& ( CF(I)*(AC(I)/100.)
& *(BC(I)*CRC(KKK)/AC(I)+Z(KKK)*(1-BC(I)/AC(I)))
& +(AO(I)/100.)
& *(BO(I)*CRC(KKK)/AO(I)+Z(KKK)*(1-BO(I)/AO(I))))
******************************************************************************

84 CONTINUE

IF (ROUGH(I),GT.1.0.OR.ROUGH(I),LE.0.) GO TO 590
IF (PRLEQ,PR) WRITE (2,969) LCROP(L1),CROP(L2),F1T(1,J),PER(I)
1,ROUGH(I),HU(I),RN(I),DRM(D),CDR(I)
87 CONTINUE

**

C INPUT ROTATION DESCRIPTION
READ(1,940) IROT1
DO 89 J=1,IROT1
READ(1,1890) IROT(I,1),(IROT(I,2111),I=1,41)
89 CONTINUE

C

C **** INPUT CHANNEL DATA.
C
C READ (1,810) TEST
IF (TEST.EQ.C6) GO TO 80
IF (TEST.NE.C5) GO TO 580
READ (1,920) M
IF (M.GT.10) GO TO 510
READ (1,760) (WID(I),CN(I),I=1,M)
IF (PRLEQ,PR) WRITE (2,6550) PP(I+4),(I,WID(I),CN(I),I=1,M)

C

C **** INPUT OUTFLOW ELEMENT POSITION.
C
READ (1,820) TEST,TITLE
IF (TEST.NE.C6) GO TO 580
80 READ (1,610) DX,NIOUT,NJOUT

C

C **** EVALUATE CONSTANTS FOR USE WITH METRIC OR ENGLISH UNITS.
C **** METRIC UNITS.
C
DX2=DX*DX
AREA=DX2/1.E+4
CU1=DX2/1.E+3
CU2=DT/DX2*500.
CU=DX2/3.6E+6
CONST=DX/(2./DT*DX2)**1.6667
IF (UNITS.EQ.UN) GO TO 90

C

C **** CONVERT TO ENGLISH UNITS.

APPENDICES
CU=CU1/0.012
CU2=CU2/0.012
CONST=1.485*CONST
AREA=AREA/4.3560

C **** INPUT INDIVIDUAL ELEMENT TOPOGRAPHICAL DATA.
C
* CHANGING ORIGINAL VALUE OF NPAR AND NPAR2 FROM 13 & 11 TO 20,18
90 NPAR=22
NPAR2=20

C **** CHANGE DIMENSION STATEMENT BELOW IF JMAX IS CHANGED.
C
JMAX=103
NMAX=2000
N=0
II=0
SCMIN=9.
SCMAX=0.
SCBAR=0.
SMIN=9.
SMAX=0.
SBAR=0.
TBAR=0.

DO 100 J=1,JMAX
100 IEL(3,J,3)=0
C
C **** INPUT FIRST ROW OF ELEMENTAL DATA.
C
* ADDED PHOSPHORUS INPUT ITEMP(12,13)

READ (1,680) (ITEMP(K),K=1,7),(ITEMPCL(K),L=1,2),(ITEMP(K),K=8,16)
READ(1,681) (ITEMP(K),K=17,20)

CALL RELEM (IEL,ITEMP,N,MOUT,NIOUT,NJOUT,NOUT,ISR,ICR,NMAX,JMAX,NPAR,
IELC,ITEMPC,NPAR2)

C **** PUT WATERSHED ELEMENTAL DATA INTO SINGLE DIMENSIONED ARRAYS.
C
110 CALL RELEM (IEL,ITEMP,N,MOUT,NIOUT,NJOUT,NJOUT,ISR,ICR,NMAX,JMAX,NPAR,
IELC,ITEMPC,NPAR2)
JS=IEL(2,1,2)
DG 270 J=1,JS
JMI=J-1
I=IEL(2,J,3)
IF (IEQJO) GO TO 270
SL(I)=FLOAT(IJO(2,J,4))/1000.
IF (SL(I),LT,SMIN) SMIN=SL(I)
IF (SL(I),GT,SMAX) SMAX=SL(I)
SBAR=SBAR+SL(I)
CHAN(I)=IEL(2,J,6)/100
IF (CHAN(I),GT,10) WRITE (2,1020) CHAN(I),I
SS(I)=FLOAT(IJO(2,J,8))/1000.

************************************************************************************
* PUT PHOSPHORUS AND NITROGEN INPUT VALUE INTO DIMENSIONED ARRAYS
* FSOL=INITIAL PHOSPHORUS CONTENT OF SOIL
* EDI EFFECTIVE DEPTH OF INTERACTION

APPENDICES 238
* INPUT ARE DONE IN KG/HA
* CONVERT EVERYTHING TO KG

CONFAY=DX*DX/10000.
SORGP(I)=IEL(2,J,12)
SORGP(I)=SORGP(I)*CONFAY
EDJ(I)=IEL(2,J,13)
PMNP(I)=IEL(2,J,14)
PMNP(I)=PMNP(I)*CONFAY
SOILP(I)=IEL(2,J,15)
SOILP(I)=SOILP(I)*CONFAY
PLAB(I)=IEL(2,J,16)
PLAB(I)=PLAB(I)*CONFAY
POTMIN(I)=IEL(2,J,17)
POTMIN(I)=POTMIN(I)*CONFAY
AMON(I)=IEL(2,J,18)
AMON(I)=AMON(I)*CONFAY
SOILN(I)=IEL(2,J,19)
SOILN(I)=SOILN(I)*CONFAY
SZN3(I)=IEL(2,J,20)
SZN3(I)=SZN3(I)*CONFAY

C
C **** IF CHANNEL SLOPE NOT SPECIFIED, ASSUME IT'S HALF OVERLAND SLOPE.
C
IF (SS(I).LE.0.) SS(I)=.50*SL(I)
TIAL(I)=0
IF (IELC(2,J,2).NE.1STL) GO TO 120
TIAL(I)=256
TBAR=TBAR+1.
120 M=FLOAT(IEL(2,J,5))/90.+1.
MM1=M-1
C
C **** EVALUATE OUTFLOW PROPORTIONS TO ADJACENT COLUMN AND ROW
C **** ELEMENTS.
C
ANG=(FLOAT(IEL(2,J,5))-90.*FLOAT(MM1))*0.01745329
X=SIN(ANG)*COS(ANG)
IX=CHAN(I)
IF (IX.EQ.0) GO TO 130
C
C **** EVALUATE CONVEYANCE FOR CHANNEL ELEMENTS.
C
II=II+1
CWID(ID)=WID(ID)
SS(I)=SS(I)
IF (SS(I).LT.SCMMIN) SCMMIN=SS(I)
IF (SS(I).GT.SCMMAX) SCMMAX=SS(I)
SCBAR=SCBAR+SS(I)
PIV(I)=CONST/CN(ID)/X*(DX/WID(ID)/X)**0.6667*DSQRT(SS(I))
C
C **** NOW DETERMINE THE ELEMENT(S) THAT RECEIVE OUTFLOW FROM THE
C **** CURRENT ELEMENT. NOTE: IS IS LEGAL FOR AN ELEMENT WITH A
C **** SHADOW CHANNEL ELEMENT TO SHOW FLOW, AT THIS TEST POINT, THAT
C **** WOULD OTHERWISE BE OUTSIDE THE CATCHMENT.
C
130 GO TO (140,150,145,140,140), M
140 IF ((J.GE.JMAX OR IEL(2,J+1,3).EQ.0).AND.CHAN(I).EQ.0.AND.IEL(2,J,15).NE.270.AND.I.NE.MOUT) WRITE (2,770) IEL(2,J,1),J
NR(I)=IEL(2,J,1,3)
GO TO (160,160,170,160,160), M
150 IF ((J.LE.1.OR.IEL(2,JM1,3).EQ.0).AND.IEL(2,J,5).NE.90.AND.I.NE.MO

APPENDICES 239
160 IF (IEL(1,J,3).EQ.0.AND.IEL(2,J,5).NE.0.AND.CHAN(I).EQ.0.AND.IEL(2,J,5).NE.360.AND.I1.NE.MOUT) WRITE (2,770) IEL(2,J,1),J
   770 NC(I)=IEL(1,J,3)
GO TO 180
170 IF (IEL(3,J,3).EQ.0.AND.IEL(2,J,5).NE.180.AND.I1.NE.MOUT.AND.CHAN(I).EQ.0) WRITE (2,770) IEL(2,J,1),J
   770 NC(I)=IEL(3,J,3)
180 IF (ANG.GT._78539816) GO TO 190
   190 RFL(I)=5*SN(ANG)/CS(ANG)
GO TO 200
200 GO TO (210,220,210,220,210), M
210 RFL(I)=1.-RFL(I)
C
C **** ELIMINATE FALSE RECEIVING ELEMENTS WHICH MAY CAUSE
C **** OUT-OF-RANGE
C **** SUBSCRIPTS FOR SOME BOUNDARY ELEMENTS.
C
220 IF (RFL(I).LT.0.001) NR(I)=NC(I)
   IF (RFL(I).GT.0.99) NC(I)=NR(I)
C
C **** "LEAKY" ELEMENTS (THOSE WITH PARTIAL FLOW OUTSIDE THE
C **** WATERSHED)
C **** MUST DIVERT THAT PARTIAL FLOW INTO A SPECIAL PSUEDO ELEMENT.
C
   IF (NC(I).GT.0.OR.I1.EQ.MOUT) GO TO 230
C
C **** THIS ELEMENT LEAKS, DIVERT IT INTO SPECIAL "BOTTOMLESS PIT".
C
   NC(I)=NMAX+ISTRUC+2
C
C **** ADD TO TOTAL NON-CONTRIBUTING AREA.
C
   OUTSID=OUTSID+1.-RFL(I)
230 IF (NR(I).GT.0.OR.I1.EQ.MOUT) GO TO 240
   NR(I)=NMAX+ISTRUC+2
   OUTSID=OUTSID+RFL(I)
C
C **** GET ROTATION NUMBER.
C
240 II=IEL(2,J,7)
   CBAR(II)=CBAR(II)+1.
C
C **** PUT ROTATION NUMBER IN LOW BYTE AND SOIL TYPE NUMBER
C **** IN NEXT BYTE OF (SOIL.SUR).
C
   K=MOD(I1,2)*6,100)
   SPER(K)=SPER(K)+1.
   SOIL(I)=(K*256)+I1
   SUR(I)=I1*256+IROT(II,2)
   ASMBAR=ASMBAR+ASM(K)
   FPBAR=FPBAR+FCAP(K)
   B(I)=CONST*DSQRT(SL(I))*X/RN(I)
C
C **** MAKE SPECIAL ADJUSTMENTS TO ACCOUNT FOR STRUCTURAL PRACTICES.
C **** BUT FIRST SEE IF ANY ARE PRESENT IN THIS ELEMENT.
C
   IF (IEL(2,J,1).NE.0) CALL STRUCT (II,NC(I),NR(I),RFL(I),IEL,JMAX,
C
   DO 250 K=1,NRG
   IF (IELC(2,J,1),EQ.IG(K)) GO TO 260
250 CONTINUE
   WRITE (2,600) IELC(2,J,1),IEL(2,J,1),J,IG(1)
   K=1
C
C ***** PUT RAINGAGE NUMBER IN LOW BYTE AND TILE NUMBER IN NEXT BYTE
C ***** OF (TIAL;RANE).
C
260 RANE(I)=TIAL(I)+K

270 CONTINUE
   JS=IELC(3,1,2)
   IF (ITEMP(3),.NE.999.AND.IEL(3,JS,1),.NE.ITEMP(1)) GO TO 110
   ITEMP(3)=999
   IF (JS.NE.JMAX) GO TO 110
   IF (N+ILGT.NMAX) GO TO 520
   X=N
   ASMBAR=ASMBAR/X
   FPBAR=FPBAR/X
   SB=AREA
   AREA=AREA*(X-OUTSID)
   CONV=CU*(X-OUTSID)
   SBAR=SBAR/X
   IF (ILGT:0) SCBAR=SCBAR/FLOAT(I)
   NN=N+1
C
C **** OUTPUT STATISTICAL SUMMARY OF WATERSHED CHARACTERISTICS.
C
   TBAR=TBAR/X
   WRITE (2,690) TTITLE,SB,PP(IT+3),N,II,AREA,PP(IT+3),SMIN,SBAR,SMAX,
   ISCMIN,SCBAR,SCMAX,TBAR,DC,PP(IT+1),ASMBAR,FPBAR,GRF,MOUT,NOUT,NJO
2UT
   WRITE (2,700) PP(IT+1),PP(IT+2)
   DC=DC*CU/24.
   SB=CONST*DSQR(SBAR)/RN(1)
   J=0
   DO 330 I=1,ICR
   IF (CBAR(I),.LE.0...AND.I,LT,ICR) GO TO 330
   CBAR(I)=CBAR(I)/X
   IF (J,GE.ISR) GO TO 320
330 J=J+1
   DO 300 J=J,ISR
   IF (SPER(J),.LE.0.) GO TO 300
   CLAYAV=CLAYAV+CL(JJ)*SPER(JJ)/100.

*FC REPRESENT THE WILTING POINT
   FPBAR=FC(JJ)
   SPER(JJ)=SPER(JJ)/X
   IF (CBAR(I),.LE.0.) GO TO 290
   WRITE (2,710) CROP(1,1),CROP(1,2),CBAR(1),PER(1),RN(I),CDR(I),JJ,S
1PER(JJ),KS(JJ),DF(JJ),SKDR(JJ)
   CBAR(I)=0.
   GO TO 310
290 WRITE (2,720) JJ,SPER(JJ),KS(JJ),DF(JJ),SKDR(JJ)
   GO TO 310

APPENDICES
241
300 CONTINUE
   J=ISR
   GO TO 320
310 J=J+1
   IF (I.LT.ISR) GO TO 330
   IF (J.LT.ISR) GO TO 280
320 IF (CBAR(J).GT.0.) WRITE (2,730) CROP(I,1),CROP(I,2),CBAR(I),PER(I)
   1),RN(I),CDR(I)
330 CONTINUE
   WRITE(2,1700)
   NR(MOUT)=NN
   NC(MOUT)=NN
   IF (I.LNE.0) GO TO 340
   N2=N
   GO TO 410
C
C ******** DETERMINE SHADOW ELEMENT CONTINUITY.
C ******** FIND CHANNEL SEGMENTS.
C
340 DO 350 I=1,N
   IF (CHAN(I).EQ.0) GO TO 350
C
C ******** USE THE ROW FLOW POINTER TO REMEMBER ORIGINAL ELEMENT NUMBER
C ******** OF THIS CHANNEL ELEMENT, SINCE THE FLOW COMPONENT IN THE ROW
C ******** DIRECTION IS 0.
C
   NR(NN)=I
   NN=NN+1
350 CONTINUE
C
C ******** MOVE CHANNEL PARAMETERS TO END OF ARRAYS.
C
   N2=NN-1
   N1=NN+1
   DO 390 I=N1,N2
   I=I-1
   B(I)=PTV(I)
   CWID(I)=CWID(I1)
   SL(I)=SST(I)
   J=NR(I)
   I1=NC(I)
   I2=NR(I)
390 CONTINUE
C
C ******** IF CERTAIN STRUCTURES ARE PRESENT IN AN ELEMENT WITH A SHADOW
C ******** ELEMENT, IT IS LIKELY THAT THE RECEIVING CHANNEL ELEMENT WILL
C ******** NOT BE GETTING THE MAJOR OUTFLOW.
C
   IF (I1.GT.NMAX) GO TO 360
   IF (I2.GT.NMAX) GO TO 380
C
C ******** THIS ELEMENT DOES NOT CONTAIN A STRUCTURE, THEREFORE, THE
C ******** RECEIVING CHANNEL ELEMENT SHOULD BE IN THE DIRECTION OF THE
C ******** PREDOMINANT FLOW COMPONENT.
C
   IF (RFL(J).LT.0.207107) GO TO 380
   IF (RFL(J).GT.0.792893) GO TO 360
C
C ******** FLOW DIRECTION IS PREDOMINANTLY DIAGONAL.
C ******** IF ROW FLOW DESTINATION NUMBER IS LESS THAN CURRENT ELEMENT
C ******** NUMBER, THE DIAGONAL POINTS TO THE LEFT AND THE DIAGONAL
C ******** DESTINATION ELEMENT CAN BE COMPUTED BY SUBTRACTING ONE FROM

APPENDICES
C ****** THE CONVENTIONAL OVERLAND FLOW COLUMN DESTINATION NUMBER.
C
   IF (I2.LT.J) GO TO 370
      I1=I1+1
   GO TO 380
360 I1=I2
   GO TO 380
370 I1=I1-1
C
C ****** MAKE CERTAIN THE RECEIVING ELEMENT IS A CHANNEL ELEMENT.
C
   380 IF (CHAN(I1).LT.1.AND.NE.MOUT) GO TO 560
C
C ****** TEMPORARILY ASSIGN THE ORIGINAL OVERLAND FLOW ELEMENT NUMBER
C ****** AS THE DESTINATION FOR THE SHADOW OUTFLOW. THIS IS NECESSARY
C ****** UNTIL NEW NUMBERS ARE ASSIGNED TO ALL SHADOW ELEMENTS.
C
      NC(I)=I1
C
C ****** MAKE ALL OVERLAND FLOW FROM THIS ELEMENT GO INTO ITS SHADOW
C ****** ELEMENT, UNLESS IT CONTAINS A STRUCTURAL PRACTICE.
C
      IF (NR(I).LE.NMAX) NR(I)=I
      IF (NC(I).LE.NMAX) NC(I)=I
390 CONTINUE
C
C ****** FIND REAL CHANNEL SEGMENT NUMBER INTO WHICH EACH CHANNEL
C ****** SEGMENT FLOWS.
C
      DO 400 J=N1,N2
         I=NC(J)
         NC(J)=NR(I)
      C
C ****** IF THIS ELEMENT CONTAINS A STRUCTURAL MEASURE, ITS CORRECT
C ****** CHANNEL ELEMENT NUMBER MAY BE PRESENT ONLY IN ARRAY NC.
C
      IF (NC(J).GT.NMAX) NC(I)=NC(I)
C
C ****** FORCE ALL CHANNEL FLOW TO USE ONLY COLUMN FLOW DIRECTIONS.
C
      400 RFL(J)=0.
      J=NR(MOUT)
      NC(J)=NN
C
C ****** OUTPUT DATA CONCERNING ANY STRUCTURAL PRACTICES.
C
      410 IF (.NOT.STRUC) GO TO 430
      WRITE (2,1000)
      DO 420 I=1,ISTRUC
         IF (NSTRUCT(I).NE.0) WRITE (2,1010) L,STRNAM(I,J),J=1,3,NSTRUCT(I)
      C
      420 CONTINUE
C
C ****** EVALUATE INITIAL CONDITIONS.
C
      430 DO 440 I=1,N2
         S(I)=0.
         440 FLINS(I)=0.
C
C ****** CONVERT SOIL CONSTANTS.
C
      DO 450 I=1,JSR
TP(I)=TP(I)*CU1*DF(I)
TP1(I)=TP(I)
450 GW(I)=(1.-FCAP(I))*TP(I)/DT
C
C **** INITIALIZE VALUES SPECIFIC TO INDIVIDUAL ELEMENTS.
C
Y=1./X
DO 460 I=1,N
K=2
IS=SOIL(I)/256
IC=MOD(SUR(I),256)
PIV(I)=(1.-ASM(IS))*TP(IS)/DT
460 CONTINUE
*
C
C **** CONTINUE FOR SURFACE INITIAL CONDITION.
C
C
CC....CALCULATION OF COEFFICIENTS FOR YALINS EQUATION.......
C
DO 505 IC=1,NPART
CY1(IC)=EQSDIA(IC)*VISCOS
CY2(IC)=1.65*AGRAB*EQSDIA(IC)
CY4(IC)=2.65*EQSDIA(IC)*SWH2O
505 CONTINUE
SGD2=DSQRT(AGRAB*.5)
DO 506 IC=1,N
K=MOD(SUR(IC),256)
VS(IC)=SGD2*DSQRT(SL(IC)*DT/DX2)
506 CONTINUE
IF(N2.EQ.N) GO TO 508
DO 507 IC=N1,N2
VS(IC)=SGD2*DSQRT(SL(IC)*DT/(DX*CWID(IC)))
507 CONTINUE
508 CONTINUE
RETURN
C
C **** ERROR MESSAGES.
C
510 WRITE (2,930)
STOP
520 WRITE (2,840)
STOP
530 WRITE (2,860)
STOP
540 WRITE (2,850)
STOP
550 WRITE (2,870)
STOP
560 WRITE (2,890) J
STOP
570 WRITE (2,900) NRG,J
STOP
580 WRITE (2,910) TEST
STOP
590 WRITE (2,970) ROUGH(I),CROP(L1),CROP(L2)
STOP
C
C **** FORMATS.
C
APPENDICES
244
600 FORMAT (1X,27HRAIN DATA MISSING FOR GAGE .A2,12H, AT ELEMENT.I4,1H
1,J4,7H: GAGE .A2,10H DATA USED)
610 FORMAT (16X,F7.2/I7X,F4.8)
620 FORMAT (11X,2A4.6F3.2F2.5F3.2X,F4.2.3F4.3.6X,F5.3,
**3X,F5.4)
623 FORMAT(1X,4(F4.1.1X))
624 FORMAT(1X,11(F4.2.1X))
625 FORMAT(1X,13.I13.IX,F4.2.1X,F6.3.1X,F5.2.1X,F7.1.1X,I3.1X,F5.4
&.1X,F4.2)
630 FORMAT (/1X,27HSIMULATION TIME INCREMENT =F6.18H SECONDS/I1X.
*38HINFLATION CAPACITY CALCULATED EVERY.I5,8H SECONDS/I1X,
**2HEXPECTED RUNOFF PEAK =F5.1.2A4)
640 FORMAT (142PFF.1F1.1.0PPF1.2X,F7.2,F9.1.2PPF1.0PPF9.2)
650 FORMAT (1X,18HCHANNEL PROPERTIES/I1X,4HPROPERTY,3H,5HWIDTH,3X,11HMANNI
1NG'S N9X(A4.4(F4.8.1F1.1.3))
660 FORMAT (/5X.3HRAINFALL HYETOGRAPH FOR EVENT OF .2A4)
670 FORMAT (/5X,12HGAGE NUMBER .A2/5X,11HTIME - MIN,.7X,15HRAINFALL RA
1TE -.2A4/(F1.4.1,F24.2))
681 FORMAT (315.I6)
690 FORMAT (/5X.11A4./5X.‘WATERSHED CHARACTERISTICS’/.,’ NUMBER OF’,
IF6.2.A4.' OVERLAND FLOW ELEMENTS =-I5./1X.'NUMBER OF CHANNEL SEG
2MENTS = I3./1X.'AREA OF CATCHMENT =-F8.1.A4./1X.'CATCHMENT SL
3PE: MIN =-.2F7.2.' AVE =-.F7.2.' MAX =-.F7.2.' PERCENT /1X
4CHANNEL SLOPE: MIN =-.F7.2.' AVE =-.F7.2.' MAX =-.F7.2.' PERCE
5NT./1X. ‘PERCENT OF AREA TILED =-.F6.1.' WITH A D.C. OF.-0PF5.2.A
64.’2A4.’/.' MEAN ANTECEDENT SOIL MOISTURE =-.2PF4.0.’ FIELD CAPA
7CY =-.F4.0.’ PERCENT SATURATION’/.’ GROUNDWATER RELEASE FRACTIO
8N =-.0PF7.4.1X.’OUTLET IS ELEMENT.I5.’ AT ROW.I4.’ COL.’I4)
700 FORMAT (/.’ SURFACE COVER/MANAGEMENT CONDITIONS.’/8X.’SOIL ASSOCIAT
ION PROPERTIES’/3X.’CROP PERCENT PERCENT N.’4X.’C.’5X.’NO. PER
2CENT KS.’4X.’ CONTROL ‘K.’/9X.’PRESENT COVER.’/18X.’PRE
3SENT.’2A4.8X.’ DEPTH MM’)
710 FORMAT (1X,2A4.2PF6.1.F7.0.PPF6.3,F7.4.I4,2PF7.1.1X,0PF7.2.8X,F8.1
1,F7.2)
720 FORMAT (122PF7.1.1X,0PF7.2.8X,F8.1,F7.2)
730 FORMAT (1X,2A4.2PF6.1.F7.0.PPF6.3,F6.2)
740 FORMAT (A1,F9.0,F10.0)
750 FORMAT (/1X.15HSOIL PROPERTIES/I1X,4HSOIL.2X,8HPOROSITY.2X,10HFIEL
1D CA.2X,2X2HWT. POINT HYDRAULIC.2X,7HCOREL,2X,10HANTECEDENT,
21X,‘HEROSITION’/7X.8H(PERCENT.3X.8H(PERCENT.3X.8H(PE
CENT.4X.’HCOREL.3X.4HZONE.5X.8HMOISTURE.3X.‘CONST.9X.5HVOL,’6X.8HSAT.’,
47X.‘HSAT.’/).6X.2A4.3X.I4.13‘(PERCENT SAT)
760 FORMAT (18X,F4.5,27X,F5.0)
770 FORMAT (8H ELEMENT.H4,1H,J4,27H FLOWS OUT OF THE WATERSHED)
780 FORMAT (18X,I4)
790 FORMAT (10X,F3.2.6X,F3.2.6X,F5.2.5X,F5.3,5X,F3.2.6X,F5.1.7X,F3.2.5
1,F3.2)
795 FORMAT (1X,5(F4.1.1X))
797 FORMAT (1X,4(F7.5.1X))
800 FORMAT (1X,4A,52X,A4)
810 FORMAT (A4,15X.I1.25X,2A4)
820 FORMAT (A4,24X.11A4)
830 FORMAT (16X,A2)
840 FORMAT (37H NUMBER OF SHED+CHAN ELEMENTS EXCEEDS,10H DIMENSION)
850 FORMAT (32H RAINFALL DATA EXCEEDS DIMENSION)
860 FORMAT (31H NO. OF SOILS EXCEEDS DIMENSION)
870 FORMAT (36H NO. OF CROPS EXCEEDS DIMENSION SPEC)
890 FORMAT (39HCHANNELS DISCONTINUOUS NEAR ELEMENT NO.,I5)
900 FORMAT (1X,37HYETOGRAPH DATA MISSING OR INCORRECT,24H FIRST
1COLUMN NOT 0 OR /I4,40H GAGES REQUESTED. BAD LINE BEGINS WITH: .A2)
910 FORMAT (24HINCORRECT INPUT SEQUENCE,36H OR HEADER CARD. CARD BEGIN
1NS WITHIN .A4)
920 FORMAT (30X,I3)
930 FORMAT (35H NO. OF CHANNEL TYPES EXCEEDS DIMENSION)
940 FORMAT (31X,I3)
950 FORMAT (7H COVER,20H MANAGEMENT PRACTICES,3X,4HCROP,6X,
19HMOT. PCT.,3X,7H PERCENT,2X,6H THROUGH,2X,6H THROUGH,2X,
29HMANNING'S,2X,9H MAX. RET.,2X,7HEROSION/11X,12H INTERCEPTION,
33X,4HCOVER,3X,6H COEFF.,2X,6HEIGHT,6X,1H HN,8X,5H DEPTH,5X,
46HCONST.,/14X,A4,25X,A4,16X,A4)
960 FORMAT (1X,I2,1X,A2,7F2.2,2PF12.0,0PF8.2,F8.1,F10.3,F10.2,F10.2)
970 FORMAT (20H ROUGHNESS COEFF. OF,F8.2,27H IS OUT OF RANGE FOR CROP:
1,2,A4)
980 FORMAT (20X,I2/39X,F5.2/31X,E10.3)
990 FORMAT (//X,19H DRAINAGE COEFF. =,12/I1X,22HTILE DRAINAGE COEFF. =
1,F5.2,A4,4H/5H/1X,30H GROUNDWATER RELEASE FRACTION =,E16.3)
1000 FORMAT (//X,28H STRUCTURAL MEASURES INCLUDED, /10X, 4HTYPE, 9X, 6H
1NUMBER)
1010 FORMAT (17X,I3,3A4,J6)
1020 FORMAT (1X,11H CHANNEL NO.,I5,15H AT ELEMENT NO.,J5)
1030 FORMAT (39X,I4/17X,F5.1/39X,I5/23X,F5.2)
1040 FORMAT (20X,31H PARTICLE SIZE DISTRIBUTION DATA/)
1050 FORMAT (36X,I2/36X,I2)
1060 FORMAT (14X,37H NUMBER OF PARTICLE SIZE CLASSES =,I2/
*14X,37H NUMBER OF WASHLOAD CLASSES =,I2)
1070 FORMAT (1X,F15.8,F15.3,F15.7)
1080 FORMAT (3X,HCLASS,3X,HDIA,MM,7X,9H QSAND,MM,10X,2HS3,3X,
*14H FALL VELOCITY.,/A4,2H/(S)
1090 FORMAT (5X,I1,4X,F6.3,2F15.3,F15.7)
1100 FORMAT (1X,8F6.3)
1111 FORMAT (1X,47H PARTICLE SIZE DISTRIBUTION OF SOILS AS DETACHED/
*2X,52HCLASS 1 2 3 4 5 6 7 8)
1120 FORMAT (1X,4H SOIL.,/I2,8F6.3)
1111 FORMAT (1X,9F8.4)
1166 FORMAT (1X,25X,I3,1X,I4)
1167 FORMAT (1X,28X,I4)
1700 FORMAT (///,30X,22H **** DAILY OUTPUT **** ///)
1710 FORMAT (2X,4H YEAR,1X,3H JUH,3X,8HRAINFALL,2X,6HRUNOFF,2X,8HSEDIMENT
&2X,6H NITRATE,2X,6H NITR. NH4,2X,8H SED.NH4,2X,8H SED. ORGN/
&7X,3H DAY,6X,2HM,7X,2HM,6X,5HKG/HA,5X,4HMG/L,5X,4HMG/L,5X
&4H/HA,5X,4H/HA,5X,5H/HA,5X,6HSED, P,8X,5H/LOG, P,8X,4H/HA,7X,
&4H/LOG)
1800 FORMAT (1X,I2,1X,5/(12,1X,I7,1X)/4X,S/(12,1X,I7,1X)/4X,S/(12,1X,I7,1X)
&/4X,S/(12,1X,I7,1X))
C
END
SUBROUTINE STRUCT (I1,NC,NR,RFL,IEL,JMAX,NPAR,NMAX,STRUC,NSTUC,I
1STUC,X,DX,WIDTH,SSL,S,LPIV,CN,CWID,CHAN,CONST,SL,ISMIN,SCMAX,S
2CBAR,ANG,IELC,NPAR2)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C***** SUBROUTINE TO ADJUST PARAMETERS TO REFLECT STRUCTURAL
C***** PRACTICES INSTALLED WITHIN AN ELEMENT.
C
DIMENSION IELC(3,JMAX,NPAR2), NSTURC(ISTRUC), WID(10), CN(10)
DIMENSION IELC(3,JMAX,2)
INTEGER CHAN, PRACT, LOGICAL STRUC, CHARACTER*2 IELC
C
C***** SWITCH TO APPROPRIATE HANDLER FOR EACH STRUCTURAL TYPE.

APPENDICES

246
C PRAC%=IEL(2,J,9)
IF (PRACT.GT.ISTRUC.OR.PRACT.LT.0) GO TO 90
STRU=.TRUE.
NSTRUC(PRACT)=NSTRUC(PRACT)+1
GO TO (10,60,70,80), PRACT
C
C ***** HANDLE PONDS AND TILE-OUTLET TERRACES BY USING A TRAP
C ***** EFFICIENCY APPROACH, FOR BOTH SEDIMENT AND WATER.
C
C ***** CASE 1 IS FOR A PTO.
C
10 TRAP=.90
C
C ***** CHECK FOR A POSSIBLE SHADOW CHANNEL ELEMENT.
C
20 IF (CHAN.EQ.0) GO TO 40
C
C ***** IT'S A CHANNEL ELEMENT, DOES IT REQUIRE DIAGONAL FLOW?
C
IF (ANG.LT..3926991.OR.ANG.GT.1.178097) GO TO 40
C
C ***** FLOW IS DIAGONAL, CHANGE DESTINATION ELEMENT NUMBEKS.
C
IF (NR.LT.1) GO TO 30
NR=NC+1
NC=NC+1
GO TO 40
30 NR=NC-1
NC=NC-1
C
C ***** THE PREDOMINANT OVERLAND DIRECTION IS MAINTAINED AND THAT
C ***** ELEMENT WILL RECEIVE THE UNTRAPPED FLOW AND SEDIMENT.
C
40 IF (RFL.GT.5) GO TO 50
RFL=TRAP
NR=NMAX+1+PRACT
RETURN
50 RFL=1-.TRAP
NC=NMAX+1+PRACT
RETURN
C
C ***** PONDS ARE SIMILAR TO PTO'S, BUT HAVE A HIGHER TRAP EFFICIENCY.
C
60 TRAP=.95
GO TO 20
C
C ***** GRASSED WATERWAYS DIRECTLY AFFECT ONLY THE VEGETATED AREA OF
C ***** THE ELEMENT IN WHICH THEY ARE LOCATED, BUT THEY MUST ALSO
C ***** ASSURE THAT THIS ELEMENT HAS A SHADOW CHANNEL ELEMENT.
C
70 IF (CHAN.NE.0) GO TO 80
C
C ***** CURRENT ELEMENT DOES NOT HAVE A SHADOW CHANNEL ELEMENT, MAKE C ***** ONE.
C
CHAN=IEL(2,J,11)
IF (CHAN.EQ.0) CHAN=1
II=II+1
CWID=WID(CHAN)
PIV=CONST/CN(CHAN)/X*(DX/CWID/X)**.6667*DSQRT(SSI)

APPENDICES 247
$SSI = SSI$

IF (SSI.LT.SCMIN) SCMIN = SSI
IF (SSI.GT.SCMAX) SCMAX = SSI
SCBAR = SCBAR + SSI

C

C **** NOW ACCOUNT FOR VEGETATED AREA BY REDUCING THE SEDIMENT
C **** DETACHMENT BY FLOW FOR THIS ELEMENT BY AN AMOUNT
C **** PROPORTIONAL TO THE VEGETATED AREA. SEDIMENT FLOW DETACHMENT IS
C **** DIRECTLY PROPORTIONAL TO THE OVERLAND SLOPE, ADJUST THAT
C **** PARAMETER.
C
C **** FIELD BORDERS HAVE A SIMILAR EFFECT TO THE VEGETATED AREA
C **** OF GRASSED WATERWAYS.
C
80 TRAP = FLOAT(IEL(2,J,10))/DX
IF (TRAP.GT.5) TRAP = .5
SL = SL * (1 - TRAP)
RETURN

C

C **** CHECK TO SEE IF IT'S A MANAGEMENT PRACTICE BEFORE SPOUTING OFF.
C
90 IF (PRACT.GT.10 AND PRACT.LT.13) RETURN
WRITE (2,100) IEL(2,19),IEL(2,J,1),J
RETURN

C

100 FORMAT (/4H PRACTICE NO..13,7H IN ROW..14,5H, COL..14,20H ILLEGAL A
1ND IGNORED)
C

END
SUBROUTINE DRAIN (DR,DC,DIN,N,N1,N2,STD,TIAL,RFL,NR,NC)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C ***** SUBROUTINE FOR SUBSURFACE DRAINAGE.
C
C
C **** SET ALL CHANNEL INFLOWS TO ZERO.
C
DO 10 I = N1, N2
10 DIN(I) = 0.
STD = 0.
C
C **** ROUTE DRAINAGE FROM TILES.
C
DO 50 I = 1, N
DRANE = 0.
IF (TIAL(I).LT.256) GO TO 40
IF (DR(I).GT.DC) GO TO 20
DRANE = DR(I)
GO TO 30
20 DRANE = DC
30 STD = STD + DRANE
40 DRANE = DRANE + DIN(I)
DD = RFL(I) * DRANE
J = NR(I)
K = NC(I)
DIN(J) = DIN(J) + DD
DIN(K) = DIN(K) - DD + DRANE
50 DIN(I) = 0.
RETURN

APPENDICES

248
C
END

FUNCTION FILT(PIV,FCAP1,GWC,DR,S,R,CU2,ROUGH,HU,NEXP,ASMPER,&
KE,PSIF,PHIC,T,CU,LF,Ks,kk,M,CUMIN1,RBIT0,TESTI,TIMPON,&
TPLON,FILTS,DT,CU1,TP1,AZRAT)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
REAL NS,KE,Ks
C
C ***** POTENTIAL INFILTRATION CAPACITY -- WHOLE SURFACE COVERED.
C
C IF (T.LE.O.) GOTO 50
C
C ***** UNSATURATED INFILTRATION ZONE.
C
******************************************************************************
******************************************************************************
******************************************************************************
****** EFFECTIVE MATRIX POTENTIAL
NS=PHIC*(1.0-ASMPER)*PSIF
******************************************************************************
******************************************************************************
******************************************************************************

**DETERMINE THE CUMULATIVE INFILTRATION USING THE NEWTON ITERATION
**TECHNIQUE
**KE*F=NS*LN(1+F/NS); G=(F-KE*F)/NS*LN((NS+F)/NS)
** DG/DF= 1-NS*(F+NS)/F+NS
** F2=F1-G1/(DG/DF1)

IF (T.EQ.0.) THEN
  FMAX=R
  TESTI=0
  GOTO 2
ENDIF
T2=T
RBIT=R/CU

IF ((R.EQ.0.) .AND. (TESTI.EQ.1)) .AND. (S.LT.0)) THEN
  FMAX=FILTS
  TESTI=0
  GOTO 2
ENDIF

IF((KE.GT.RBIT).AND.(TESTI.EQ.1)) .AND. (S.GT.0)) THEN
  TESTI=1
  GOTO 8
ELSE
  IF((KE.GT.RBIT).AND.(TESTI.EQ.1)) .AND. (S.LT.0)) THEN
    TESTI=0
    GOTO 2
ENDIF
ENDIF

IF(RBIT0.EQ.R) GOTO 111

IF((KE.LE.RBIT).AND.(TESTI.EQ.1)) THEN
  TESTI=1
  GOTO 8
ENDIF
IF(KE.GT.RBIT).AND.(TESTI.EQ.0)) THEN
   FMAX=FLTS
   IF(R.GT.0) FMAX=R
   TESTI=0
   GOTO 2
ENDIF

IF ((R.EQ.0).AND.(TESTI.EQ.1).AND.(S.LT.0)) THEN
   FMAX=FLTS
   TESTI=0
   GOTO 2
ENDIF

CUMPON=NS/((RBIT/KE)-1.)

IF((CUMPON-CUMIN1).LT.0.) THEN
   TIMPON=T2
   TPON=60*(((CUMIN1)-NS*DLOG(1.0+(CUMIN1)/NS))/KE
   GOTO 112
ENDIF

TIMPON=(CUMPON-CUMIN1)*60./RBIT*T2
TPON=60*((CUMPON)-NS*DLOG(1.0+(CUMPON)/NS))/KE
GOTO 112

111 CONTINUE
   IF (TESTI.EQ.1) GOTO 8

IF((KE.GE.RBIT).AND.(TESTI.EQ.0)) THEN
   FMAX=FLTS
   IF(R.GT.0) FMAX=R
   TESTI=0.
   TIMPON=0.
   TPON=0.
   GOTO 2
ENDIF

112 IF(T2.LT.TIMPON) then
   FMAX=R
   TESTI=0
   GOTO 2
ENDIF

8 T1=T2-TMIPS+TPON
IF(T1.LT.0.) THEN
   FMAX=FLTS
   GOTO 2
ENDIF
   TESTI=1

77 IF((CUMIN1.GT.0.) THEN
   CUMF=CUMIN1
   ELSE
   CUMF=0.1
ENDIF

APPENDICES
88  ZU1=(T1/60.)*KE*(CUMF-NS*DLOG(1.0-CUMF/NS))
    DEL=CUMF/(NS+CUMF)
    TEST=ZU1/DEL
    XX=CUMF+TEST
    IF(ABS(TEST).GT.0.000001) THEN
      CUMF=XX
    GOTO 88
    ENDIF
    CUMINF=CUMF

7  CONTINUE
    FMAX=KE*(1+NS/CUMINF)*CU
    ZXn=FMAX/CU
    FILT=FMAX

2  FILT=FMAX
888  FORMAT(12(F10.4,1X),F3.1,5(F10.4,1X))
    RBIT0=R
    CUMPON=0.
    IF (PIT) 30,40,10

10  IF (PIT.LT.GWC) GO TO 20
    DR=0.
    RETURN

*----------------------------------------------------------------------*
20  CONTINUE
    RKFC=KS*AZRAT*(1-PIV*DT/TP1)**(2.655/DLOG10(FCAP1))
    TI=(((1-PIV*DT/TP1)-FCAP1)*TP1/CU1)/RKFC

*  COMPUTING DRAINAGE FOR ONE HOUR
    ZFAY=1./TI
    IF(ZFAY.GT.7.5) TI=1./7.5.

    DR=(((1-PIV*DT/TP1)-FCAP1)*TP1/CU1)*(-EXP(-1./TI))*CU
    ASMF=(1-PIV*DT/TP1)*TP1/CU1

    RETURN

*----------------------------------------------------------------------*
C
C  ***** INfiltrATION ZONE SATURATED.
C
30  PIV=0.
40  RKFC=KS*AZRAT*(1-PIV*DT/TP1)**(2.655/DLOG10(FCAP1))
    TI=(((1-PIV*DT/TP1)-FCAP1)*TP1/CU1)/RKFC
    ZFAY=1./TI
    IF(ZFAY.GT.7.5) TI=1./7.5.

    DR=(((1-PIV*DT/TP1)-FCAP1)*TP1/CU1)*(-EXP(-1./TI))*CU

    FMAX=DR
    FILT=FMAX
    TESTI=1
    RETURN
C
END

FUNCTION RAIN(RATE,PIT,PER)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C  ***** DETERMINATION OF NET RAINFALL RATE.
C
APPENDICES  251
IF (PIT) 40,50,10
10 RIT=PER*RATE
   IF (RIT>PIT) 20,30,30
20 RAIN=RATE-RIT
    PIT=PIT-RIT
    RETURN
30 RAIN=RATE-PIT
    PIT=0.
    RETURN
40 PIT=0.
50 RAIN=RATE
    RETURN
END

C
C
CC.....SHIELDS DIAGRAM EXTENDED BY MANTZ (1977).......... 
C
FUNCTION SHIELD(REYN)
  IMPLICIT DOUBLE PRECISION (A-H,O-Z)
  IF(REYN.LE. 1.) GO TO 30
  IF(REYN.LE. 6.0) GO TO 46
  IF(REYN.LE. 20.) GO TO 50
  IF(REYN.LE.450.) GO TO 20

10  CONTINUE
  SHIELD=.06
  RETURN
20  SHIELD=DEXP(-3.9793+.19212*DLOG(REYN))
    RETURN
30  SHIELD=+.1*REYN**(1.3)
    RETURN
40  SHIELD=DEXP(-2.3026-.5546*DLOG(REYN))
    RETURN
50  SHIELD=0.033
    RETURN
END

C
SUBROUTINE SED(XZW,XR,CXDIR,M,N,KK,DX)
  IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
COMMON /HOS1/ P0SOI(2000),SSA(20,8),SSAT(20),EDI(2000),
       & PO(2000,8),ERP(8),STOLD(2000,8),SEDNEW(2000,8),PPT(2000,8),
       & PI(2000,8),PSL(2000),STNEW(8),P2(8),PCELL(2000,8),PE(8)
       & .DFT
COMMON /ZSEDI/ NPART,NWASH, NWASH1
COMMON /ZSEDR/ VISCOS,AGRAS,SWH2O,YALCON,SE(8),VS(2000),DIA(8),SG
       1(8),FV(8),CY1(8),CY2(8),CY4(8),DIANM(8),EQSDIA(8),EDMM(8),F(10,8)
       2,CE1,CE2,CE3,CE4,CE5,CE6
C
       20,8),Q(2010),DIN(2000),SST(2000,8)
C
DIMENSION SE1(8),SE2(8),DELTA(8),PS(8),TF(8),TFMSE2(8)
  *DS1(8),DS2(8),S22(8)
NP=1
   IF(QM.GT.0.) GO TO 30
C
C.....NO OUTFLOW. ALL SEDIMENT ASSUMED DEPOSITED.............
C
APPENDICES
GO TO 10
5 NP=NWASH1
10 CONTINUE
   DO 20 IC=NP,NPART
      SEL(M)=SEL(M)+.5*(SST(M,IC)+SI(M,IC))
      SST(M,IC)=SI(M,IC)

*DETERMINING THE NEWLY GENERATED SEDIMENT
   SEDNEW(M,IC)=0.
   STNEW(IC)=0.

   SE(IC)=0.
   C
   SI(M,IC)=0.

20 CONTINUE
   IF(NP.EQ.NWASH1.AND.NWASH.NE.0) GO TO 65
   RETURN
C
C........OUTFLOW........................................
C
C
30 CONTINUE
   SM fdir=S(M)-XDIR
   IF(SM fdir.LE.0.) GO TO 10
C
C........CALCULATE TRANSPORT CAPACITY FOR EACH ........
C.............PARTICLE SIZE CLASS......................
C
   SDEL=0.
   VSTAR=VS(M)*DSQRT(SM/dir)
   CY5=VSTAR*XZW
   DO 50 IC=NP,NPART
      RETN=CY1(IC)*VSTAR
      YCR=SHEILD(REYN)
      DELTA(IC)=VSTAR**2/(CY2(IC)*YCR)-1.0
      IF(DELTA(IC).LE.0.) GO TO 45
      SIGMA=1.65998*DELTA(IC)*DSQRT(YCR)
      PS(IC)=YALCON*DELTA(IC)*(1.-DLOG(1.+SIGMA)/SIGMA)
      SDEL=SDEL+DELTA(IC)
   GO TO 50
C
45 CONTINUE
   DELTA(IC)=0.
   PS(IC)=0.
   C
   SDEL=DELTA(IC)
50 CONTINUE
   IF(SDEL.LE.0.) GO TO 5
   DO 60 IC=NP,NPART
      TF(IC)=PS(IC)*DELTA(IC)/SDEL*CY5*CY4(IC)
   GO TO 60
C
65 CONTINUE
   AREA=DX*XZW
   IF(M.GT.N) GO TO 70
C
C....CALCULATE RAINFALL DETACHMENT & POTENTIAL FLOW DETACHMENT....
C
*REMEMBER TO REDUCE EROSION FOR PLOT BY 6%
* BECAUSE OF RAINFALL SIMULATOR DETR=(CEB*C*XR*XAR/AREA)**0.40
   DETR=(CEB*C*XR*XAR/AREA)
   DETF=CEB*C*SL(M)*Q(M)*DX
   GO TO 75
70 DETR=0.
    DETF=0.
75 CONTINUE
   DRFT=DETR+DETF
   X1=Q(M)/S(M)
   X2=1./(1.+X1)
   IF(NP.EQ.NWASH1.AND.NWASH.NE.0) GO TO 310
   X3=X1*X2
   X4=1./X1
   DO 80 IC=NWASH1,NPART
      DS2(IC)=S(M,IC)+F(KK,IC)*DETR
      DS2(IC)=DS1(IC)+F(KK,IC)*DETF
      S22(IC)=(SST(M,IC)+DS2(IC))*X2
      SE1(IC)=(SST(M,IC)+DS1(IC))*X3
      SE2(IC)=S22(IC)*X1
   80 CONTINUE
   C
   C........APPORTION ANY TRANSPORT EXCESS TO DEFICITS..........C
   C
   NPM=NPART-NWASH
   90 I1=0
      I2=0
      I3=0
      SDEL=0.
      TFXCES=0.
   DO 150 IC=NWASH1,NPART
      TFMSE2(IC)=TF(IC)-SE2(IC)
      IF(TFMSE2(IC)).LT.30,140,110
   100 CONTINUE
      I1=I1+1
      TFXCES=TFXCES+TFMSE2(IC)
      TF(IC)=SE2(IC)
      GO TO 150
   C
   C........TRANSPORT > SE2.........................C
   C
   110 I1=I1+1
      TFXCES+TFXCES+TFMSE2(IC)
      TF(IC)=SE2(IC)
      GO TO 150
   C
   C........TRANSPORT < SE2.........................C
   C
   i30 I3=I3+1
      SDEL=SDEL+DELTA(IC)
   140 I2=I2+1
   150 CONTINUE
      IF(SDEL.LE.0.) GO TO 200
      IF(I1.EQ.NPM.OR.I2.EQ.NPM.OR.I3.EQ.NPM) GO TO 200
   DO 160 IC=NWASH1,NPART
      IF(TFMSE2(IC).GE.0. OR DELTA(IC).LE.0.) GO TO 160
      TF(IC)=TF(IC)+TFXCES*DELTA(IC)/SDEL
      IF(I3.LT.1) GO TO 170
   160 CONTINUE
   GO TO 90
   170 IF(TF(IC).GT.SE2(IC)) TF(IC)=SE2(IC)
   C
   C........SOLVE CONTINUITY EQUATION FOR SEDIMENT TRANSPORT.....C
   C
   200 CONTINUE
   DO 300 IC=NWASH1,NPART
      IF(TF(IC).LT.SE1(IC)) GO TO 240
      IF(TF(IC).LT.SE2(IC)) GO TO 220
   C
   C..........MAXIMUM RAINFALL AND FLOW DETACHMENT............C
   C.............NO DEPOSITION..........................C
   C
      SST(M,IC)=DS2(IC)-SE2(IC)+S22(IC)

APPENDICES
254
SE(IC)=SE2(IC)
SEL(M)=SEL(M)-F(KK,IC)*DRFT

*DETERMINE THE NEWLY GENERATED SEDIMENT
SEDNEW(M,IC)=F(KK,IC)*DRFT
STNEW(IC)=S22(IC)/2.

*GO TO 290
C
C........MAXIMUM RAINFALL, PARTIAL FLOW DETACHMENT.........
C............NO DEPOSITION.............................
C
220 ZI2=TF(IC)*(1.+X4)-SST(M,IC)
SEL(M)=SEL(M)+SI(M,IC)-ZI2
SST(M,IC)=ZI2+TF(IC)*(X4-1.)
SE(IC)=TF(IC)

*DETERMINE THE NEWLY GENERATED SEDIMENT
SEDNEW(M,IC)=ZI2-SI(M,IC)
STNEW(IC)=TF(IC)*X4/2.

*GO TO 290
C
C........DEPOSITION, NO FLOW DETACHMENT..................
C
240 RE=FV(IC)*AREA/Q(M)
IF(RE.GT.1.) RE=1.
DP=RE*(SE1(IC)-TF(IC))
SE(IC)=SE1(IC)-DP
ZI2=SE(IC)*(1.+X4)-SST(M,IC)
IF(ZI2.LT.0.) ZI2=0.
SEL(M)=SEL(M)+SI(M,IC)-ZI2
SST(M,IC)=ZI2+SE(IC)*(X4-1.)

*DETERMINE THE NEWLY GENERATED SEDIMENT
SEDNEW(M,IC)=F(KK,IC)*DETR
STNEW(IC)=SE(IC)*X4/2.

*-- SI(M,IC)=0.
290 IF(SE(IC).LT.0.) SE(IC)=0.
IF(SST(M,IC).LT.0.) SST(M,IC)=0.
300 CONTINUE
IF(NWASH.EQ.0) GO TO 410
C
C....WASH LOAD CALCULATIONS...........................
C
310 CONTINUE
DO 400 IC=1,NWASH
DS=SI(M,IC)*F(KK,IC)*DRFT
S2=(SST(M,IC)+DS)*X2
SE(IC)=S2*X1
SST(M,IC)=DS-SE(IC)+S2
IF(SST(M,IC).LT.0.) SST(M,IC)=0.
SEL(M)=SEL(M)-F(KK,IC)*(DETR+DETF)

*DETERMINE THE NEWLY GENERATED SEDIMENT
SEDNEW(M,IC)=F(KK,IC)*DRFT
STNEW(IC)=S2/2.

*  
*  SI(M,IC)=0.
400 CONTINUE
410 CONTINUE

RETURN
END

SUBROUTINE RELEM (IEL,ITEMP,N,MOUT,NOUT,N,JOUT,ISR,ICR,NMAX,JMAX,N
1PAR,IELC,ITEMP,NPAR2)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C ******* SUBROUTINE TO SET UP NEXT ROW OF WATERSHED ELEMENTAL DATA.
C ****** INTO THE PROPER POSITION OF THE "3-ROW PER PASS" ARRAY.
C
DIMENSION IEL(3,JMAX,NPAR2),ITEMP(NPAR2)
DIMENSION IELC(3,JMAX,2),ITEMPC(2)
CHARACTER*2 IELC,ITEMPC
C
C **** "RIPEP" ROW 2 INTO ROW 1 AND ROW 3 INTO ROW 2, THEN ZERO
C ****** THE THIRD ROW.
C
DO 20 I=1,JMAX
   NZZ=NPAR-2
   DO 10 I=1,NZZ
      IEL(1,J,1)=IEL(2,J,1)
   10  IEL(2,J,1)=IEL(3,J,1)
   20  IEL(3,J,1)=0
DO 25 I=1,JMAX
DO 23 I=1,2
   IELC(1,J,1)=IELC(2,J,1)
   23  IELC(2,J,1)=IELC(3,J,1)
   25  CONTINUE
C
C ****** SET UP POSSIBLE LAST ROW TEST FLAG.
C
IEL(3,1,2)=JMAX
   IF (ITEMP(3,8,999)) RETURN
C
C ****** NOW TRANSFER CURRENT WATERSHED ELEMENTAL DATA INTO THE THIRD
C ****** ROW OF THE "3-ROW PER PASS" ARRAY.
C
C ****** IEL(1,J,3) CONTAINS THE POSITION NUMBER FOR THAT ELEMENT IN
C ****** THE SINGLE DIMENSION ARRAYS USED FOR SIMULATION ANALYSIS.
C ****** IEL(1,1,2) CONTAINS THE COLUMN NUMBER OF THE LAST WATERSHED
C ****** ELEMENT IN THE ROW.
C
30  J=ITEMP(2)
   K=MOD(ITEMP(5),100)
   ITEMP(6)=ITEMP(5)*100+K
   IF (K.LE.0.OR.K.GT.ISR) GO TO 80
   IF (ITEMP(7).LE.0.OR.ITEMP(7).GT.ICR) GO TO 90
   IF (J.GT.JMAX) GO TO 50
C
C ****** TRANSFER PARAMETER DATA FROM A SINGLE ELEMENT.
C
NZZ=NPAR-2
   DO 40 I=1,NZZ
   DO 40
40 IEL(3,J,1)=ITEMP(I)
   DO 45 I=1,2
45 IELC(3,J,1)=ITEMP(C(I))
C
C ***** REMEMBER AS POSSIBLE LAST ELEMENT IN CURRENT ROW.
C
   IEL(3,1,2)=J
C
C ***** REMEMBER ROW NUMBER OF THIS ELEMENT.
C
   IC=ITEMP(1)
C
C ***** SAVE ELEMENT'S SEQUENCE NUMBER.
C
   N=N+1
   IF (N.GT.NMAX) GO TO 60
   IEL(3,J,3)=N
   IF (ITEMP(1).EQ.NIOUT.AND.J.EQ.NJOUT) MOUT=N
   IF (ITEMP(3).NE.0) RETURN
C
C ***** NOW READ PARAMETERS FOR NEXT ELEMENT.
C
   READ(1,100) (ITEMP(K),K=1,7),(ITEMPC(L),L=1,2),(ITEMP(K),K=8,16)
   READ(1,101) (ITEMP(K),K=17,20)
   IF (ITEMP(1).LT.IC.OR.ITEMP(1).GT.IC+1.OR.(ITEMP(2).LE.J.AND.ITEMP(1).EQ.IC) GO TO 70
   IF (ITEMP(1).EQ.IC) GO TO 30
   RETURN
50 WRITE (2,110) ITEMP(1),J
   STOP
C
C ***** ERROR MESSAGES.
C
60 WRITE (2,120) ITEMP(1),J
   STOP
70 WRITE (2,130) ITEMP(1),ITEMP(2)
   STOP
80 WRITE (2,140) K,ITEMP(1),J
   STOP
90 WRITE (2,150) ITEMP(7),ITEMP(1),J
   STOP
C
100 FORMAT (2I3,I2,I3,3I4,3X,A2,1X,A2,2X,I4,I3,214,I6,I2,I5,I5)
101 FORMAT (3I5,I6)
110 FORMAT (23H COLUMN NO. FOR ELEMENT,I4,1H,,I4,24H EXCEEDS IEL() DIMENSION)
120 FORMAT (45H NO. OF ELEMENTS EXCEEDS DIMENSION AT ELEMENT,I4,1H,,I4)
130 FORMAT (40H ELEMENT DATA OUT OF SEQUENCE AT ELEMENT,I4,1H,,I4)
140 FORMAT (1X,9HSOIL TYPE,I4,22H SPECIFIED FOR ELEMENT,I4,1H,,I4,15H
   11S NOT DEFINED)
150 FORMAT (1X,9HCRP TYPE,I4,22H SPECIFIED FOR ELEMENT,I4,1H,,I4,15H
   11S NOT DEFINED)
C
C END

* SUBROUTINE TO DETERMINE SEDIMENT BOUND PHOSPHORUS

   SUBROUTINE PBOUND(NPART,M)

* 

APPENDICES
IMPLICIT DOUBLE PRECISION (A-H,O-Z)

* THIS SUBROUTINE DETERMINE SEDIMENT BOUND PHOSPHORUS USING
  * A CONSERVATION OF MASS APPROACH

COMMON /PHOS1/ POSOIL(2000),SSA(20,8),SSAT(20),ED(2000),
  & P0(2000),ERP(8),STOLD(2000,8),SEDNEW(2000,8),PPT(2000,8),
  & P(2000,8),PSEL(2000),STNEW(8),P2(8),PCELL(2000,8),PE(8)
  & JDFT

  20,8),Q1(2010),DIN(2000),SST(2000,8)

* OUTFLOW LARGER THAN ZERO, THERE IS POTENTIAL FOR SEDIMENT
  * DETACHMENT

IF (Q(M).LE.0.) GOTO 30

* DETERMINING THE NEWLY GENERATED SEDIMENT BOUND PHOSPHORUS

X1=Q(M)/S(M)

DO 10 IC=1,NPART
  IF (SI(M,IC).EQ.0.) PI(M,IC)=0.

  PCELL(M,IC)=P0(M,IC)*SEDNEW(M,IC)
  P2(IC)=(PPT(M,IC)+PI(M,IC)+PCELL(M,IC))/
  & (X1+1.)
  PE(IC)=P2(IC)*X1
  PPT(M,IC)=PI(M,IC)+PCELL(M,IC)-P2(IC)*X1
  &+P2(IC)
  PSEL(M)=SEDNEW(M,IC)+PSEL(M)
10  CONTINUE

GO TO 40

* NO OUTFLOW

30  DO 20 IC=1,NPART
  IF (SI(M,IC).EQ.0.) PI(M,IC)=0.

  P2(IC)=(PPT(M,IC)+PI(M,IC))/2.
  PE(IC)=0.0
  PPT(M,IC)=PI(M,IC)
20  CONTINUE

GO TO 40

40  CONTINUE

DO 50 IC=1,NPART
  PI(M,IC)=0.
50  CONTINUE

RETURN
END

* THIS SUBROUTINE IS USED TO DETERMINE SOLUBLE PHOSPHORUS

SUBROUTINE SOLUBP(DX2,X1R,KK,M,IK,DT,T12,L,T11,SSTOR,FIL,SE,N
  & ,CUMIN1,CU,NPART)
* THIS SUBROUTINE USES SIMPLE AVERAGES

IMPLIED DOUBLE PRECISION (A-H,O-Z)

* REAL R(8,20)


COMMON /GRAMPT/ CL(20),SA(20),ST(20),OM(20),AC(20)
& AO(20),BC(20),BO(20),PHI(20),VCF(20),WCF(20),CFC(20),
& CEC(20),EAC(20),PHIC(20),XF(20),PSIF(20),CBF(20),
& THETAR(20),KS(20),CF(20),Z(20),LF(20),CS(20),SCF(20),
& CRC(20),KE(20,20),ZC(20),BD(20)

COMMON /PHOSI/ PISOI(2000),SSA(20,8),SSAT(20),EDI(2000),
& P(2000,8),ERP(8),STOLD(2000,8),SEDNEW(2000,8),PPT(2000,8),
& PI(2000,8),PSEL(2000),STNEW(8),P2(8),PCELL(2000,8),PE(8)
& DRFT


& RALPHA(20),RBETA(20),RGAMA(20),SPI(2000),CGEN1(2000)


COMMON /PARTITION/PKDA(20),PKDP(20),PSP(20)


REAL NO3SEL,NHWSEL,NHSSEL

REAL MINP

X11=(Q(M)*FIL)/S(M)
X21=Q(M)/S(M)

IF(M.GT.N) GOTO 5

X12=(Q(M)*FIL+S(M))/((VOLSZ1(M)+(10-VOLSZ1(M)))*2.6*PKDP(KK))
& *CU*3600/DT)

X1=(Q(M)+FIL)/(S(M)+VOLSZ1(M)*CU*3600)/DT)
X2=(Q(M)/(S(M)+VOLSZ1(M)*CU*3600)/DT)
X3=(Q(M)+FIL)/(10-VOLSZ1(M))*2.6*CU*3600/DT)

SSTOR1=S(M)
IF(STOR1.LT.0) SSTOR1=0.

IF(Q(M).EQ.0.0).AND.(FIL.EQ.0.0)
& .AND.(SSTOR1.EQ.0.0)) GOTO 20

*EDINH4/M0 REPRESENT THE CONCENTRATION OF DISSOLVED

APPENDICES 259
*AMMONIUM IN EDI

5 IF (M.GT.N) THEN
   SP=(SPI(M)+SPSP(M))/(X11+1)
   SP2(M)=SP*X21
   SPSP(M)=SPI(M)+SP*(1-X11)
   IF(SPSP(M).LE.0.) SPSP(M)=0.
   GOTO 20
ENDIF

IF((Q(M).EQ.0).AND.(FIL.EQ.0).OR.(CUMIN1.EQ.0.)) THEN
   SP=(SPSP(M)+SPI(M))/2.
   SP2(M)=0.0
   SPSP(M)=SPI(M)
   GOTO 20
ENDIF

EXTFAC=EXP(-X12)*(0.1/(1+0.1*PKDP(KK)))

DO 10 IC=I,NPART
   OUPO4=OUPO4+PCELL(M,IC)*DT
10 CONTINUE

SPI=(SPI(M)+SPSP(M)+EDILAB(M)*EXTFAC*X3/DT)/(1+X1)
IF(SPI.LT.EXP(-90.)) THEN
   SP2(M)=0.
   GOTO 20
ENDIF

SP2(M)=SP*X2
SPSP(M)=SPI(M)+EDILAB(M)*EXTFAC*X3/DT+SP*(1-X1)
   IF(SPSP(M).LE.0.) SPSP(M)=0.
   IF (PSOL(M).LT.0.) PSOL(M)=0.
   EDILAB(M)=EDILAB(M)*(1-EXTFAC*X3-OUPO4)
   IF (EDILAB(M).LT.0.) EDILAB(M)=0.
   GOTO 20

20 CONTINUE
PO4SEL(M)=PO4SEL(M)+SP2(M)
SPI(M)=0.0
OUPO4=0.
RETURN
END

* SUBROUTINE TO DETERMINE SEDIMENT BOUND AMMONIUM

SUBROUTINE AMMON(NPART,M)
*
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
*/
THIS SUBROUTINE DETERMINE SEDIMENT BOUND NITROGEN USING
*/
A CONSERVATION OF MASS APPROACH
*
COMMON /PHOS1/ POSOIL(2000),SSA(20,8),SSAT(20),EDI(2000),
& PO(2000,8),ERP(8),STOLD(2000,8),SEDNEW(2000,8),PPT(2000,8),
& PI(2000,8),PSEL(2900),STNEW(8),P2(8),PCELL(2000,8),PE(8)
& .DRFT

APPENDICES 260
& ANSEL(2000),AN2(8),ANCCELL(2000,8),ANE(8),ANO(2000,8)


REAL NO3SEL,NHWSEL,NHSEL

* OUTFLOW LARGER THAN ZERO, THERE IS POTENTIAL FOR SEDIMENT
* DETACHMENT

   IF (Q(M),L.E.0.) GOTO 30

* DETERMINING THE NEWLY GENERATED SEDIMENT BOUND PHOSPHORUS

   X1=Q(M)/S(M)

   DO 10 IC=1,NPART

   IF (SI(M,IC),EQ.0.) ANI(M,IC)=0.

   ANCELL(M,IC)=AN0(M,IC)*SEDNEW(M,IC)
   AN2(IC)=ANPT(M,IC)+ANI(M,IC)+ANCCELL(M,IC))/
   & (X1+1.)
   ANE(IC)=AN2(IC)*X1
   ANSEL(M)=ANSEL(M)-ANCCELL(M,IC)+AN2(IC)
   ANPT(M,IC)=ANI(M,IC)+ANCCELL(M,IC)-AN2(IC)*X1
   & +AN2(IC)

10  CONTINUE
   GO TO 40

* NO OUTFLOW

30  DO 20 IC=1,NPART

   IF (SI(M,IC),EQ.0.) ANI(M,IC)=0.

   AN2(IC)=(ANPT(M,IC)+ANI(M,IC))/2.
   ANE(IC)=0.0
   ANSEL(M)=ANSEL(M)+AN2(IC)
   ANPT(M,IC)=ANI(M,IC)

20  CONTINUE
   GO TO 40

40  CONTINUE
   DO 50 IC=1,NPART

   ANI(M,IC)=0.
   NHSEL(M)=NHSEL(M)+ANE(IC)

50  CONTINUE
   RETURN
   END

APPENDICES

261
* SUBROUTINE TO DETERMINE SEDIMENT BOUND ORGANIC NITROGEN (AZOTE)

SUBROUTINE ORGN(NPART,M)

* IMPLICIT DOUBLE PRECISION (A-H,O-Z)

* THIS SUBROUTINE DETERMINE SEDIMENT BOUND ORGANIC N USING
* A CONSERVATION OF MASS APPROACH

COMMON /PHOS1/ POIL(2000),SSA(20),SSAT(20),EDI(2000),
& PO(2000,8),ERP(8),STOLD(2000,8),SEDNEW(2000,8),PPT(2000,8),
& P(2000,8),PSEL(2000),STNEW(8),P2(8),PCELL(2000,8),PE(8)
& .DRFT

COMMON/NITRO2/ OOSOIL(2000),ONPT(2000,8),ONI(2000,8),
& ONSEL(2000),ON2(8),ONCELL(2000,8),ON(8),ONO(2000,8)


REAL NO3SEL,NHWSEL,NHSSEL

* OUTFLOW LARGER THAN ZERO, THERE IS POTENTIAL FOR SEDIMENT
* DETACHMENT

IF (QM.LE.0.) GOTO 30

* DETERMINING THE NEWLY GENERATED SEDIMENT BOUND PHOSPHORUS

X1=Q(M)/S(M)

DO 10 IC=1,NPART

IF (SM=M,IC).EQ.0.) ONI(M,IC)=0.

ONCELL(M,IC)=ONO(M,IC)+SEDNEW(M,IC)
ON2IC=(ONPT(M,IC)+ONI(M,IC)+ONCELL(M,IC))/
& (X1+1.)
ONE(IC)=ON2(IC)*X1
ONSEL(M)=ONSEL(M)-ONCELL(M,IC)+ON2(IC)
ONPT(M,IC)=ONI(M,IC)+ONCELL(M,IC)-ON2(IC)*X1
& +ON2(IC)

10 CONTINUE
GO TO 40

* NO OUTFLOW

30 DO 20 IC=1,NPART

IF (SM=M,IC).EQ.0.) ONI(M,IC)=0.

ON2IC=(ONPT(M,IC)+ONI(M,IC))/2.
ONE=0.0
ONSEL(M)=ONSEL(M)+ON2(IC)

APPENDICES
ONPT(M,IC)=ONII(M,IC)

20 CONTINUE
GOTO 40

40 CONTINUE
DO 50 IC=1,NPART
ONII(M,IC)=0.
TKNSEL(M)=TKNSEL(M)+ONE(IC)
50 CONTINUE
RETURN
END

SUBROUTINE WATNH(SSTOR,FIL,M,DT,N,CUMINI,CU,KK,NPART)

IMPLICIT DOUBLE PRECISION (A-H,O-Z)

* THIS SUBROUTINE DETERMINES DISSOLVED AMMONIUM CONCENTRATION
* IT USES AN EXTRACTION FACTOR
* DEVELOPED BY KNISEL (1993, SEE GLEAMS MANUAL).


COMMON /PARTITION/PKDA(20),PKDP(20),PSP(20)

&ANSEL(2000),ANZ(8),ANCELL(2000,8),ANE(8),AN0(2000,8)
&.CNH4(2000)

REAL NOSEL,NHWS,NOSEL,NHSSEL

RBETA=0.598*EXP(-0.179*PKDA(KK))

X11=(Q(M)+FIL)/S(M)
X21=Q(M)/S(M)

IF((Q(M),EQ.0).AND.(FIL,EQ.0).OR.(CUMINI,EQ.0)) THEN
SPNH4=(STNH4(M)+AINH4(M))/2.
OUTNH4(M)=0.0
STNH4(M)=AINH4(M)
GOTO 20
ENDIF

IF(M.GT.N) GOTO 5

APPENDICES 263
IF((Q(M).EQ.0.0).AND.(FIL.EQ.0.0))
& .AND.(SSTOR1.EQ.0.0)) GOTO 20

X12=(Q(M)+FIL+S(M))/((VOLSZ1(M)+(10-VOLSZ1(M))*2.6*PKDA(KK)))
& *CU*3600/DT
X1=(Q(M)+FIL)/(S(M)+VOLSZ1(M)*CU*3600/DT)
X2=(Q(M)/S(M)+VOLSZ1(M)*CU*3600/DT)
X3=(Q(M)+FIL)/((10-VOLSZ1(M))*2.6*CU*3600/DT)

SSTOR1=S(M)
IF(SSTOR1.LT.0) SSTOR1=0.

*EDINH4(M) REPRESENT THE CONCENTRATION OF DISSOLVED
*AMMONIUM IN EDI

5 IF (M.GT.N) THEN
   SPNH4=(AINH4(M)+STONH4(M))/(X11+1)
   OUTNH4(M)=SPNH4*X21
   STONH4(M)=AINH4(M)+SPNH4*(1-X11)
   IF(STONH4(M).LE.0.) STONH4(M)=0.
   IF(OUTNH4(M).LE.0.) OUTNH4(M)=0.
   GOTO 20
ENDIF

EXTFAC=EXP(-X12)*RBETA/(1+RBETA*PKDA(KK))
DO 10 IC=1,NPART
OUNH4=OUNH4+ANCELL(M,IC)*DT
10 CONTINUE

SPNH4=(STONH4(M)+AINH4(M)+EDINH4(M)*EXTFAC*X3/DT)/(1+X1)
IF(SPNH4.LT.EXP(-50.)) THEN
   OUTNH4(M)=0.
   GOTO 20
ENDIF
OUTNH4(M)=SPNH4*X2
STONH4(M)=AINH4(M)+EDINH4(M)*EXTFAC*X3/DT+SPNH4*(1-X1)
IF(STONH4(M).LE.0.) STONH4(M)=0.
IF (SZNH4(M).LT.0) SZNH4(M)=0.
EDINH4(M)=EDINH4(M)*(1-EXTFAC*X3-OUNH4)
IF (EDINH4(M).LT.0.) EDINH4(M)=0.
GOTO 20

20 CONTINUE

NHWSL(M)=NHWSL(M)+OUTNH4(M)
OUNH4=0
AINH4(M)=0.0
RETURN
END

SUBROUTINE NO5Z(SSTOR,FIL,M,DT,N,CUMIN1,CU)

IMPLICIT DOUBLE PRECISION (A,H,O-Z)

APPENDICES 264
* THIS SUBROUTINE DETERMINES NITRATE CONCENTRATION
* IT USES AN EXTRACTION FACTOR
* DEVELOPED BY KNISSEL (1993. SEE GLEAMS MANUAL).


REAL NO3SEL,NHWSEL,NHSSEL

\[ X1_l = Q(M) + FIL_l / S(M) \]
\[ X2_l = Q(M) / S(M) \]

IF(M.GT.N) GOTO 5

IF(SSTOR1.LT.0) THEN
  SSTOR1=0,
  OUTNO3(M)=0,
  STONO3(M)=AINNO3(M)
GOTO 20
ENDIF

IF((Q(M).EQ.0.0).AND.(FIL.EQ.0.0)
&.AND.(SSTOR1.EQ.0.0)) GOTO 20

IF((Q(M).EQ.0.0).AND.(FIL.EQ.0.0).OR.(CUMIN1.EQ.0.0).
 THEN
  SPNO3=(STONO3(M)+AINNO3(M))/2.
  OUTNO3(M)=0.0
  STONO3(M)=AINNO3(M)
GOTO 20
ENDIF

\[ X1=(Q(M)+FIL)/(S(M)+VOLSZ1(M)*CU*3600/DT) \]
\[ X2=Q(M)/(S(M)+VOLSZ1(M)*CU*3600/DT) \]
\[ X12=(Q(M)+FIL+S(M))/(VOLSZ1(M)*CU*3600/DT) \]
\[ SSTOR1=S(M) \]
\[ X3=(Q(M)+FIL)/((10.-VOLSZ1(M))*2.6*CU*3600/DT) \]

5 IF (M.GT.N) THEN
  SPNO3=(AINNO3(M)+STONO3(M))/(X11+1)
  OUTNO3(M)=SPNO3*X21

APPENDICES 265
STONO3(M) = AINO3(M) + SPNO3*(1 - X1)
IF(STONO3(M),LE,0) STONO3(M) = 0.
IF(OUSNO3(M),LE,0) OUTNO3(M) = 0.
GOTO 20
ENDIF

EXTFAC = EXP(-X12)*0.5
SPNO3 = (STONO3(M) + AINO3(M) + EDINO3(M)*X3*EXTFAC/DT)/(1 + X11)
IF(SPNO3.LT.EXP(-50)) THEN
    OUTNO3(M) = 0.
    GOTO 20
ENDIF
OUTNO3(M) = SPNO3*X2
STONO3(M) = AINO3(M) + EDINO3(M)*EXTFAC*X3/DT + SPNO3*(1 - X1)
    IF(STONO3(M),LE,0) STONO3(M) = 0.
    EDINO3(M) = EDINO3(M)*X3*(1 - EXTFAC*X3)
    IF(EDINO3(M),LE,0) EDINO3(M) = 0.
    GOTO 20

20 CONTINUE
INO3SEL(M) = NO3SEL(M) + OUTNO3(M)
AINO3(M) = 0.0
RETURN
END

SUBROUTINE ETP11(TEMPC, RAD, LTEMPPM)
INTEGER TEMPC, RADI
DATA ALBED, GAM, 0.23, 0.68/
TEMPC = TEMPC + 273
LTEMPPM = 5304./TEMPC

* COMPUTING THE POTENTIAL ET ACCORDING TO RITCHE’S EQUATION

DELT = (LTEMPPM)/TEMPC*EXP(21.25 - LTEMPPM)
ETPM = 0.00128*(RAD*(1 - ALBED)/58.3)*(DELT*(DELT + GAM))
ETPM = ETPM*1000.
RETURN
END

SUBROUTINE EVAPO(LAI1, S1EP, ESU, TTIME, S2EP, ETPM, TETP, PEP, ES & CUMINF)

* COMPUTING SOIL EVAPORATION IN TWO STAGES
* FIRST STAGE ONLY ENERGY IS LIMITING, AND SOIL EVAPORATION
* IS EQUAL TO POTENTIAL SOIL EVAPORATION
* POTENTIAL SOIL EVAPORATION

REAL CUMINF, LAI1, S1EP, ESU, TTIME, S2EP, ES
PEP = ETPM*EXP(-0.4*LAI1)
* IF CUMULATIVE SOIL EVAPORATION IS LESS THAN UPPER LIMIT OF
* STAGE 1 (ESU), SOIL EP = POTENTIAL SOIL EP, ELSE STAGE 2 SOIL EP
* STARTS. DAY2 REPRESENTS THE NUMBER OF DAY SINCE STAGE 2 STARTED

APPENDICES 266
IF (S1EP.LT.ESU) THEN
   S1EP=AMAX1(0.,S1EP-CUMINF)
   S1EP=S1EP+PSEP
IF(S1EP.GT.ESU) THEN
   ES=PSEP-0.4*(S1EP-ESU)
   S2EP=0.6*(S1EP-ESU)
   TTIME=(S2EP/3.5)**2.
   GOTO 10
ELSE
   ES=PSEP
   GOTO 10
ENDIF
ELSE

   SB=CUMINF-S2EP
   IF (SB.LT.0.) THEN
      TTIME=TTIME+1
      ES=3.5*SQRT(TTIME)-S2EP
   ENDIF
   IF (CUMINF.GT.0.) THEN
      ESX=0.8*CUMINF
      IF(ESX.LE.ES) ESX=CUMINF+ES
      IF(ESX.GT.PSEP) ESX=PSEP
      ES=ESX
      ELSEIF (ES.GT.PSEP) THEN
      ES=PSEP
      ENDIF

   S2EP=S2EP+ES-CUMINF
   TTIME=(S2EP/3.5)**2
ELSE
   CUMINF=SB
   S1EP=ESU-SB
   TTIME=0
   S1EP=AMAX1(S1EP,0.)
   S1EP=S1EP+PSEP
IF(S1EP.GT.ESU) THEN
   ES=PSEP-0.4*(S1EP-ESU)
   S2EP=0.6*(S1EP-ESU)
   TTIME=(S2EP/3.5)**2.
ELSE
   ES=PSEP
ENDIF
ENDIF
ENDIF

10  ES=AMAX1(ES,0.)
* COMPUTING PLANT TRANSPARATION

IF (LAI.LT.3.) THEN
   PEP = ETPMM*LAII/3.
ELSE
   PEP = ETPMM
ENDIF

APPENDICES
TETP=ES+PEP
IF(TETPM,LT,TETP) THEN
TETP=TETPM
ES=TETP-PEP
ENDIF

RETURN
END

SUBROUTINE PERCO(XMO1,KS,FCVOL,CU,PERCOL,FCAP1,XMO12 &
TMAX,RATIES,AZRAT)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
REAL KS,TMAX,TDAY,FCVOL
INTEGER RATIES

RKFC=KS*AZRAT*XMO12**(-2.655/DLOG10(FCAP1))
XMO11=XMO1-FCVOL
T= XMO11/RKFC
*COMPUTING DRAINAGE FOR 24 HOURS
TDAY=24.
IF(RATIES.EQ.1) TDAY=AMAX1(0.,7.TDAY-TMAX/60.)
ZFAV=TDAY/T
IF(ZFAV.GT.75) ZFAV=75.
PERCOL=XMO11*(1.-EXP(-ZFAV))

RETURN
END

SUBROUTINE RAINFA(NRG,FILTS,PP,N,CU1,CU2,CU,DT,TMIN,TMAX &
KPR,NDT,ISTRUC,NMAX,ICR,NN)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)

COMMON /CSOIL/ A(20),P(20),FC(20),GWC(20),SKDR(20)
COMMON /CROAGE/ RC(8,35),TC(8,35),R(8,20),FRA(8),TTR(8),RATE(8),SR &
I(8),NF(8)
20),8,Q(2010),DIN(2000),SST(2000),S(8)
COMMON /CROUGH/ ROUGH(20),HU(20),DIR(21),PIT(5,20),PER(20),CDR(20)
& Lpom(2000)
COMMON /GRAMPT/ CL(20),SA(20),ST(20),OM(20),AC(20) &
& AO(20),BO(20),BO1(20),VF(20),WVF(20),CFC(20), &
& CEC(20),EAC(20),PHI(20),XP(20),PSIP(20),CBF(20), &
& THETAR(20),KS(20),CF(20),Z(20),LF(20),CS(20),SCF(20), &
& CRC(20),KE(20,20),ZC(20),BD(20)
DIMENSION IRR(5), IG(5), PP(14)
DIMENSION FILTS(2000)
COMMON /CROPAD/ DIRM2(20)
COMMON /ZSED/ NPART,NWASH,NWASH1
COMMON /ASMF/ ASMBF(20),FCAP1(20),TP1(20),RESWAT(20),DF1(20)
COMMON /ASMP/ ASMPER(2000)
CHARACTER*2 IG
CHARACTER*4 PP
CHARACTER JBEG
INTEGER SUR,SOIL,RANE
REAL KS,KE

APPENDICES
COMMON /PHOS1/, P0SOIL(2000), SSA(20,8), SSAT(20), EDI(2000),
& P0(2000,8), ERP(8), STOLD(2000,8), SEDNEW(2000,8), PPT(2000,8),
& PI(2000,8), PSEL(2000), STNEW(8), P2(8), PCELL(2000,8), PE(8)
& .DRFT

COMMON/NITRO1/, A0SOIL(2000), ANPT(2000,8), ANI(2000,8),
& ANSEL(2000), AN2(8), ANCELL(2000,8), ANE(8), AN0(2000,8)

COMMON/NITRO2/, COSOIL(2000), ONPT(2000,8), ONI(2000,8),
& ONSEL(2000), ON2(8), ONCELL(2000,8), ONE(8), ON0(2000,8)


COMMON /SOLUB/, SP2(2000), PEXT(2000,8), PK(20)
& .RALPHA(20), RBETA(20), RGSMA(20), SPI(2000), CGEN1(2000)

REAL NO3SEL, NHWSEL, NHSSSEL

C **** INPUT SEPARATE RAINFALL HYETOGRAHS FOR EACH RAINAGE.
C
TMAX=0.
TMN=1.E+10
DTMN=900.
TINT=DTMN
DO 20 I=1,NRG
FRA(I)=0.
* READ (8,830) IG(I)
* WRITE(6,*) IG(I)
K=2
KM=I
10 READ (8,740) JBE.G, TC(IK), RC(IK)
IF (K.GT.2) TINT=TC(IK)-TC(IKM1)
IF (TINT.LT.DTMN) DTMN=TINT
K=K+1
KM=K-1
IF (JBE.G.EQ.10 OR JBE.G.EQ.0) GO TO 10
IF (JBE.G.EQ.1) GO TO 570
IF (K.GT.35) GO TO 540
IF (TC(IK)-TC(IKM)) TMIN=TC(IK)
IF (TC(IKM1)-TMAX) TMAX=TC(IKM1)
20 IRK(I)=K
C
C **** INSERT SAME START AND FINISH TIME FOR EACH RAINAGE RECORD.
C
DO 30 I=1,NRG
K=IRK(I)
KM=K-1
TC(I,1)=TMN

APPENDICES
RC(I,1)=0.
IF (TC(I,KM1).EQ.TMAX) IRR(I)=IRR(I)-1
TC(I,K)=TMAX
30 RC(I,K)=0.

IT=7
DO 40 I=1,NRG
L=IRR(I)
40 CONTINUE

WRITE (2,670) IG(I),PP(IT+1),PP(IT+2),TC(I,K),RC(I,K),K=2,L
C **** RENUMBER RAINAGES TO 1,2,...,NRG IN ORDER OF HYETOGRAPH INPUTS.
C
      50 IF (DT.GT.DTMIN*60.) WRITE (2,880)
         51 KPR=(TMAX-TMIN)/DT/FLOAT(NDT)*60+1.

N2=NN-1
430 DO 440 I=1,N2
   440 S(I)=0.
440 FLINS(I)=0.

X=N
Y=1./X
DO 460 I=1,N
   460 K=2
   460 IS=S(N)-256
   460 IC=MOD(S(N),256)
J=MOD(KANE(I),256)
IF (TC(J,2).LT.(TMIN+1.1)) K=3
FRA(J)=FRA(J)+Y
SUPP=RC(J,K)*(1.-PER(J))*CU
X=FLAT(TP(J),FCAP(J),GWC(J),D(J),S(J),SUPP,CU2,ROUGH
1(J),H(J),NEXP,ASMPER(I),KE(I,J),PSDF(I),PHIC(I),TU(J),L,F(I)
2(I),KS(I),IC,J,LUMIN1(I),RBIT(I),TEST(I),TIMPON(I),TPON(I),
3,FILTS(I),DT,CU1,TP1(I),A(I)
FILTS(I)=X
IF (X.GT.SUPP) X=SUPP
460 FLINS(I)=SUPP-X
C
C **** CONVERT SURFACE VALUES.
C
    DO 480 I=1,ICR
    DIRM2(I)=0.10*HU(I)
    DO 470 I=1,NRC
    470 PIT(I,J)=PIT(I,J)+CU1/DT
    ADIR=HU(I)*ROUGH(I)*(DIRM2(I)/HU(I))*(1./ROUGH(I))
    480 DIR(I)=ADIR*2.*CU1/DT
C
C **** SET CHANNEL RETENTION TO ZERO.
C
    DIR(21)=0.
    J=NMAX+ISTRUC+2
    DO 500 I=1,J
    IF (I.GT.NMAX) GO TO 490
    Q(I)=0.
    SS(I)=0.
    SEL(I)=0.
    NOSSEI(I)=0.
    NHWSEL(I)=0.
    NHHSEL(I)=0.
    TKNSEL(I)=0.

APPENDICES 270
PO4SEL(I)=0.
PSEL(I)=0.
DO 484 IZ=1,NPART
484 SST(I,LIZ)=0.
PPT(LIZ)=0.
ANPT(LIZ)=0.
ONPT(LIZ)=0.
DIN(I)=0.
490 QI(I)=0.
AINO3(I)=0.
AINH4(I)=0.
SPI(I)=0.
DO 494 IZ=1,NPART
SI(LIZ)=0.
PI(LIZ)=0.
ANI(LIZ)=0.
494 ONI(LIZ)=0.
500 CONTINUE
RETURN

540 WRITE (2,850)
      STOP
570 WRITE (2,900) NRG,J
      STOP
C
C **** FORMATS.
C
600 FORMAT (1X,27HRAIN DATA MISSING FOR GAGE ,A2,12H, AT ELEMENT ,I4,1H
       1,14,7H: GAGE ,A2,10H DATA USED)
670 FORMAT (/5X,12HGAGE NUMBER ,A2/5X,11HTIME - MIN. ,7X,15HRAINFALL RA
       1TE ,-2A4/(F14.1,F24.2)
730 FORMAT (1X,2A4,2PF6.1,F7.0,0PF6.3,F6.2)
740 FORMAT (A1,F8.0,F10.0)
830 FORMAT (16X,A2)
850 FORMAT (32H RAINFALL DATA EXCEEDS DIMENSION)
880 FORMAT (47H ANALYSIS IS NOT ACCURATE IF RAINFALL INTENSITY,28H INT
       1ERVALS ARE LESS THAN DT.)
900 FORMAT (1X,37HYETOGRAPH DATA MISSING OR INCORRECT.,24H FIRST
       1COLUMN NOT 0 OR 1/4,40H GAGES REQUESTED. BAD LINE BEGINS WITH: ,A2)
C
END

SUBROUTINE NITRAN(ES,FCVOL,SOVOL,XMOL,PEP,WP,N,TEMP,ICR,
&  RATEMX,CU1,SOITEM,RNUTN,RNUTAM,RNUTP,DF1,TP1)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
*THIS SUBROUTINE INCLUDES NITROGEN TRANSFORMATION
* COMPUTING SOIL WATER COEFFICIENTS (SW)

REAL NIT,MIN

REAL MINP
COMMON /PHOS2/P0SOIL(2000),SSA(20,8),SSAT(20),EDI(2000),
& PO(2000,8),ERP(8),STOLD(2000,8),SEDNEW(2000,8),PPT(2000,8),

APPENDICES 271
& PI(2000,8), PSEL(2000), STNEW(8), P2(8), PCELL(2000,8), PE(8)
& .DRFT


COMMON/NITRO1/ A0SOIL(2000), ANP(2000,8), ANI(2000,8),
& ANSEL(2000), AN2(8), ANCELL(2000,8), ANE(8), ANO(2000,8)

COMMON/NITRO2/ O0SOIL(2000), ONPT(2000,8), ONI(2000,8),
& ONSEL(2000), ON2(8), ONCELL(2000,8), ONE(8), ONO(2000,8)


COMMON /GRAMPT/ CL(20), SA(20), ST(20), OM(20), AC(20)
& AO(20), BC(20), BO(20), PHI(20), VCF(20), WCF(20), CFC(20),
& CEC(20), EAC(20), PHIC(20), XF(20), PSIF(20), CBF(20),
& THETR(20), HS(20), CF(20), Z(20), LF(20), CS(20), SCF(20),
& CRC(20), KE(20,20), ZC(20), BD(20)

COMMON /ETPES/LAI(20,11), ESU(20), LAI(20), POTLAI(20), EDX(20)
& SUMLAI(20)
REAL LALESU, LAI, SUMLA, EDX

COMMON /PARTITION/PKDA(20), PKDP(20), PSP(20)

COMMON /PLANTN/DATPLA(20), DATHAR(20), CP1(20), CP2(20), DMY(20)
& YP(20), ROTMAX(20), ROTDAY(20), CDRFAL(20), RLAIMX(20), CDRK(20)
& RES(20), RES2(20), RES90(20)
INTEGER DATPLA, DATHAR, TEMPC, SOITEM, ROTMAX, ROTDAY

DIMENSION FCVOL(20), SOIVOL(20), TP1(20),
DIMENSION RNUTNI(20), RNUTAM(20), RNUTP(20), ILAI(20)
DIMENSION RNUTZ(20), ICOUN1(20)
INTEGER SUR, SOIL, RANE

*NOTE CU1=DX2/1000 CU1/10 WOULD CONVERT KG TO KG/HA
CONFAY=CU1/10.
DX2=CU1*1000.
*COMPUTE TEMPERATURE COEFFICIENT
IF(SOITEM.LE.0.) THEN
  TEMPFA=0.
ELSE
  TEMPFA=SOITEM/(SOITEM+EXP(9.93-0.312*SOITEM))
ENDIF

DO 9 I=1, ICR
  ILAI(I)=0
9 CONTINUE

DO 11 I=1, N
  MIC=MOD(SUR(I),256)
  ILAI(MIC)=1
11 CONTINUE

DO 20 I=1, ICR

APPENDICES 272
SUMLAI(I)=SUMLAI(I)+LA11(I)*ILAI(I)
20 CONTINUE

*ASSUME THAT NITRIFICATION OF AMMONIUM FERTILIZER TAKES 20 DAYS

  DO 2222 I=1,ICR
    IF(RNUTAM(I).GT.0.0) THEN
      RNUTZ(I)=RNUTAM(I)*0.8/20
      ICOUNT(I)=20
    ENDIF
    IF(ICOUNT(I).GT.0) THEN
      ICOUNT(I)=ICOUNT(I)-1
    ELSE
      RNUTZ(I)=0.
    ENDIF
  2222 CONTINUE

*COMPUTE TRANSFORMATION
*CMN=MINERALIZATION CONSTANT=0.0003KG/HA/D,POTMIN IS IN KG/HA
  CMN=0.0003
*BKN IS A RATE CONSTANT =0.00001KG/HA/DAY
  BKN=0.00001
  DO 1000 J=1,N
    MIC=MOD(SUR(J),256)
    MIS=SOIL(J)/256
    IF(XMOI(J).GT.FCVOL(MIS)) THEN
      SWFA=0.
    ELSE
      SWFA=(XMOI(J)-WP(MIS))/(FCVOL(MIS)-WP(MIS))
    ENDIF
    IF(XMOI(J).LT.WP(MIS)) THEN
      SWFN=0.
    ELSEIF(XMOI(J).LT.FCVOL(MIS)) THEN
      SWFN=(XMOI(J)-WP(MIS))/(FCVOL(MIS)-WP(MIS))
    ELSEIF(XMOI(J).LT.TP1(MIS)/CU1) THEN
      SWFN=1.*(XMOI(J)-FCVOL(MIS))/(TP1(MIS)/CU1-FCVOL(MIS))
    ELSE
      SWFN=0.
    ENDIF
    AMON(J)=AMON(J)+EDINH4(J)
    SZNO3(J)=SZNO3(J)+EDINO3(J)
  *ADD NUTRIENTS IF PRESENT
    AMON(J)=AMON(J)+RNUTAM(MIC)
    SZNO3(J)=SZNO3(J)+RNUTNI(MIC)
    PLAB(J)=PLAB(J)+RNUTP(MIC)
  CP11=5.0

*ADD RESIDUE TO SOIL ORGANIC N AND OSIL ORGANIC P
  IF(RES(J).GT.0.0) THEN
    RFON(J)=RFON(J)+RES(MIC)
  ENDIF

  POTMIN(J)=POTMIN(J)+RES(MIC)

APPENDICES 273
SORGP(I)=SORGP(I)+RES(MIC)/CP11

21 CONTINUE

*COMPUTE FLOW BETWEEN ACTIVE AND STABLE POOL
RTN=POTMIN(I)/(POTMIN(I)+SOILN(I))
POTSO=BKN*(POTMIN(I)*RTN-SOILN(I))
IF(POTSO.GT.POTMIN(I)) POTSO=POTMIN(I)
IF(<POTSO.GT.SOILN(I)) POTSO=SOILN(I)
POTMIN(I)=POTMIN(I)-POTSO
SOILN(I)=SOILN(I)+POTSO

*AMMONIFICATION

IF(POTMIN(I).LT.(0.01*CONFAY)) THEN
SOILN(I)=SOILN(I)+POTMIN(I)
POTMIN(I)=0.0
MIN(I)=0.0
ELSE
MIN(I)=CMN*POTMIN(I)*(SWFA*TEMPFA)**0.5
ENDIF
IF(MIN(I).LT.POTMIN(I)) MIN(I)=POTMIN(I)
POTMIN(I)=POTMIN(I)-MIN(I)
AMON(I)=MIN(I)+AMON(I)

*NITRIFICATION

IF(AMON(I).LT.(0.01*CONFAY)) THEN
IF(AMON(I).GT.0.) SZNO3(I)=SZNO3(I)+AMON(I)
AMON(I)=0.
NIT(I)=0.
ELSE
IF(RNUTZ(I).GT.0) THEN
NIT(I)=RNUTZ(I)
ELSE
NIT(I)=0.1*SOLVOL(MIS)/1000000
ENDIF

*THE MAX RATE MX IS 100MG/KG SOIL/WEEK
IF(NIT(I).GT.RATEMX(MIS)) NIT(I)=RATEMX(MIS)

IF(NIT(I).LT.AMON(I)) THEN
NIT(I)=AMON(I)
ENDIF
AMON(I)=AMON(I)-NIT(I)

IF(AMON(I).LT.(0.01*CONFAY)) THEN
IF(AMON(I).GT.0.) SZNO3(I)=SZNO3(I)+AMON(I)
AMON(I)=0.
ENDIF
ENDIF

SZNO3(I)=SZNO3(I)+NIT(I)

* COMPUTE DENITRIFICATION WHEN SOIL MOISTURE CONTENT EXCEEDS
* FIELD CAPACITY
RFCV=FCVOL(MIS)+0.1*(TP1(MIS)/CU1-FCVOL(MIS))
IF((AMON(I)+PEP(I)+ES(I)).GT.RFCV) THEN

APPENDICES 274
SC=18.*POTMIN(I)/(SOIVOL(MIS)/1000.)

*DAILY DECAY RATE
  DK=24.*(0.0022*SC+0.0042)
  TFDN=SOITEM/(SOITEM+EXP(5.93-0.321*SOITEM))
  SWFDN=(XMOI(I)+PEP(I)+ES(I)-RFCV)/(TP1(MIS)/CU1-RFCV)

*DENITRIFICATION
  DNI(I)=SZNO3(I)*(1-EXP(-DK*TFDN*SWFDN))
  IF(DNI(I).LT.0.) DNI(I)=0.
  IF(SZNO3(I).LT.DNI(I)) THEN
    DNI(I)=SZNO3(I)
    SZNO3(I)=0.0
  ELSE
    SZNO3(I)=SZNO3(I)-DNI(I)
  ENDIF
  ELSE
    DNI(I)=0.
  ENDIF

*DISTRIBUTE AMMONIUM BETWEEN ADSORBED AND DISSOLVED AMMONIUM
*THE EQUILIBRIUM CONSTANT IS BASED ON CLAY CONTENT ECNH4
*ALL COMPUTATION ARE BASED ON MASSES NOT ON CONCENTRATION
  WATVOL=XMOI(MIC)*CU1*1000.
  WATVOI=FCVOL(MIS)*CU1*1000.
  SZNH4(I)=AMON(I)*(1+PKDA(MIS)*SOIVOL(MIS)/WATVOL)
  A0SOIL(I)=AMON(I)-SZNH4(I)

*COMPUTING PLANT UPTAKE
*COMPUTE INTO SUBROUTINE DATA SUMALI AND POTLAI

  PGRT=SUMALI(MIC)/POTLAI(MIC)

*CONCENTRATION OF PLANT N IS IN PERCENT
  IF(SUMALI(MIC).EQ.0.) THEN
    CN=0.
    CP=0.
    GOTO 22
  ENDIF
  CN=CP1(MIC)*PGRT**CP2(MIC)
  CP=CN/CP11

*COMPUTING THE DRY MATTER CONTENT

  22  DM=PGRT*YP(MIC)*DMY(MIC)

    TDMN1=0.01*CN*DM
    TDMN=TDMN1-TDMN2(I)
    TDMP1=0.01*CP*DM
    TDMP=TDMP1-TDMP2(I)
  IF (TDMN.LT.0.) TDMN=0.
  IF (TDMP.LT.0.) TDMP=0.

    TDMN2(I)=TDMN1
    TDMP2(I)=TDMP1

*AMMONIUM AND NITRATE UPTAKE
  UPNH4(I)=PEP(I)*CU1*1000.*SZNH4(I)/WATVOL
  UPNO3(I)=PEP(I)*CU1*1000.*SZNO3(I)/WATVOL

APPENDICES
TUPTN=UPNH4(I)+UPNO3(I)
IF(TUPTN.GT.0.) THEN
  DEMFAC=TDN*CONFAY*ROTR(I)/TUPTN
  UPNH4(I)=UPNH4(I)*DEMFA
ENDF

IF(UPNH4(I).GT.SZNH4(I)) THEN
  UPNH4(I)=SZNH4(I)
  SZNH4(I)=0.
  AMON(I)=AMON(I)-UPNH4(I)
ELSE
  AMON(I)=AMON(I)-UPNH4(I)
  SZNH4(I)=SZNH4(I)-UPNH4(I)
ENDIF

UPNO3(I)=UPNO3(I)*DEMFA
IF(UPNO3(I).GT.SZNO3(I)) THEN
  UPNO3(I)=SZNO3(I)
  SZNO3(I)=0.
ELSE
  SZNO3(I)=SZNO3(I)-UPNO3(I)
ENDIF

*COMPUTE THE AMOUNT OF NITRATE LOST THROUGH LEACHING
* THE ACTUAL CONCENTRATION OF NITRATE THUS THE FRACTION OF NITRATE
* LOST THROUGH LEACHING IS ASSUMING COMPLETE MIXING

  CNO3(I)=SZNO3(I)*CNH4(I)
  CLENO3(I)=CLENO3(I)+CNO3(I)
  SZNO3(I)=SZNO3(I)*(-1.-CNH4(I))

*HERE SEDIMENT BOUND NITROGEN IS EXPRESSED IN KG P/KG SOIL
  A0SOIL(I)=5.0*A0SOIL(I)/SOIVOL(MIS)

  EDINO3(I)=SZNO3(I)*(VOLSZ(I)/PHI(MIS))*BD(MIS)*1000.
  &
  /SOIVOL(MIS)
  SZNO3(I)=SZNO3(I)=EDINO3(I)
  SZNH4(I)=AMON(I)*(-1.+PKDA(MIS)/SOIVOL(MIS)/WATVOL)

  RBETA=0.598*EXP(-0.179*PKDA(MIS))
  EDINH4(I)=AMON(I)*VOLSZ(I)/PHI(MIS)*BD(MIS)*1000.
  &
  /SOIVOL(MIS)
  AMON(I)=AMON(I)-EDINH4(I)

  OOSOIL(I)=5.0*(AMON(I)+POTMIN(I)+SOILN(I))/SOIVOL(MIS)

  PLAB(I)=PLAB(I)+EDILAB(I)

*PHOSPHORUS TRANSFORMATION

IF(SORGP(I).LE.0.01) THEN
  PLAB(I)=PLAB(I)+SORGP(I)
  MINP(I)=0.
  SORGP(I)=0.
ELSE
  MINP(I)=CMN*RTN*SORGP(I)*(SWFA*TEMPFA)**0.5
  IF(MINP(I).GT.SORGP(I)) MINP(I)=SORGP(I)
  SORGP(I)=SORGP(I)-MINP(I)

APPENDICES 276
PLAB(I)=PLAB(I)+MINP(I)
ENDIF

PTRANS=0.1*SWFA*EXP(0.115*SOITEM-2.88)*
& (PLAB(I)-MINP(I)*(PSP(MIS)/(1-PSP(MIS)))))
IF(PTRANS.GT.PLAB(I)) PTRANS=PLAB(I)
PLAB(I)=PLAB(I)-PTRANS
IF(PLAB(I).LE.0.0) PLAB(I)=0.
IF(PMINP(I).LE.0.0) PMINP(I)=0.
PMINP(I)=PMINP(I)+PTRANS

*COMPUTING THE TRANSFER BETWEEN STABLE AND ACTIVE P POOLS
TRANP=EXP(-1.77*PSP(MIS)-7.05)
& *(4.*PMINP(I)-SOILP(I))
IF(TRANP.GT.0.0) THEN
IF(TRANP.GT.PMINP(I)) TRANP=PMINP(I)
ELSE
IF(-TRANP.GT.SOILP(I)) TRANP=-SOILP(I)
ENDIF
SOILP(I)=SOILP(I)+TRANP
PMINP(I)=PMINP(I)-TRANP

*DISTRIBUTE PLAB BETWEEN SEDIMENT BOUND AND DISSOLVED PHASE
PSOL(I)=PLAB(I)/(1+PKDP(MIS)*SOIVOL(MIS)/WATVOL)
POSOL(I)=PLAB(I)-PSOL(I)
UPPHOS(I)=PEP(I)*CU1*1000.*PSOL(I)/WATVOL

IF((UPPHOS(I).GT.0.0)) THEN
DEMFAC=TDMP*CONFAY*ROTR(I)/UPPHOS(I)
UPPHOS(I)=UPPHOS(I)*DEMFAC
ENDIF

IF((UPPHOS(I).GT.PSOL(I)) THEN
UPPHOS(I)=PSOL(I)
PSOL(I)=0.
PLAB(I)=PLAB(I)-UPPHOS(I)
ELSE
PLAB(I)=PLAB(I)-UPPHOS(I)
PSOL(I)=PSOL(I)-UPPHOS(I)
ENDIF

PLAB(I)=PLAB(I)+POSOL(I)
PSOL(I)=PLAB(I)/(1+PKDP(MIS)*SOIVOL(MIS)/WATVOL)
POSOL(I)=PLAB(I)-PSOL(I)

EDILAB(I)=PLAB(I)*VOLSZ(I)/PHI(MIS)*BD(MIS)*1000.
& /SOIVOL(MIS)
POSOL(I)=5.*POSOL(I)/SOIVOL(MIS)
PLAB(I)=PLAB(I)-EDILAB(I)

CNO3(I)=0.
1000 CONTINUE

DO 1010 I=1,ICR
RES(I)=0.
1010 CONTINUE

APPENDICES
IF (ICOUNR.EQ.0) THEN
    ICOUNR=ICOUNR+1
    WRITE(2,*)' DAY RAIN RUNOFF SEDIMENT NO3 DIS-NH4
    & SED-NH4 DIS-PO4 SED-PO4 SED-TKN'
    WRITE(2,*)' MM MM KG/H A KG KG
    & KG KG KG KG'
    ELSE
    ICOUNR=ICOUNR+1
    ENDIF
2000 FORMAT(7(1X,F10.4))
END
APPENDIX C: SAMPLE INPUT FILE

P2 WATERSHED ELEMENTAL INPUT FILE

DATA FILE FOR P2 WATERSHED. GE. 05-01,73 SIMULATION.
METRIC UNITS ARE USED ON INPUT/OUTPUT
PRINT
RAINFALL DATA FOR 1 RAINGAUGES
BEGINNING JULIAN DAY OF SIMULATION 131 1973
DURATION OF SIMULATION DAYS 870
GAUGE NUMBER RI
SIMULATION CONSTANTS FOLLOW
NUMBER OF LINES OF HYDROGRAPH OUTPUT = 101
TIME INCREMENT = 60. SEC.
INFILTRATION CAPACITY CALCULATED EVERY 180, SECONDS
EXPECTED RUNOFF PEAK = 50. MM/HR
SOIL INFILTRATION, DRAINAGE AND GROUNDWATER CONSTANTS FOLLOW
NUMBER OF SOILS = 3
S 1, TP = .41, FP = .88, FC = .46, A = 1.000, P = .75, DF = 200.0, ASM = .99, K = .23
13. 64. 23.
13. 8. 0.174 0.662 1.
S 2, TP = .40, FP = .75, FC = .45, A = 1.000, P = .75, DF = 200.0, ASM = .99, K = .23
16. 64. 20.
18. 42. 40.
18. 8. 0.174 0.662 1.
S 3, TP = .40, FP = .65, FC = .27, A = 1.000, P = .75, DF = 200.0, ASM = .99, K = .23
18. 42. 40.
18. 8. 0.174 0.662 1.

PARTICLE SIZE AND TRANSPORT DATA FOLLOWS
NUMBER OF PARTICLE SIZE CLASSES = 4
NUMBER OF WASH LOAD CLASSES = 0
SIZE SPECIFIC GRAVITY FALL VELOCITY
0.002 2.65 0.0
0.200 2.65 0.0
0.400 1.60 0.0
0.650 2.65 0.0
0.130 0.340 0.300 0.230 1
0.160 0.340 0.300 0.200 2
0.180 0.220 0.200 0.140 3
4.5167 20.0000 0.0500 0.0500 4.0000
8.0667 20.0000 0.0500 0.0500 4.0000
8.3000 20.0000 0.0500 0.0500 4.0000
DRAINAGE EXponent = 3,
DRAINAGE COEFFICIENT FOR TILE DRAINS = 0.00 MM/24HR
GROUNDWATER RELEASE FRACTION = .000
SURFACE ROUGHNESS AND CROP CONSTANTS FOLLOW
NUMBER OF CROPS AND SURFACES = 5
C 1, CROP=CONCORN, PIT=.80, PER=.05, RC=.52, HU=60.0, N=.065, DIRM=.1000, C=.009
50.50. 50.50.
0.00 0.09 0.19 0.23 0.49 1.16 2.97 3.00 2.72 1.83 0.00
131 306 1.30 -0.264 2.50 9400. 900 0.570 3.00
C 2, CROP=FALLOW1, PIT=.80, PER=.05, RC=.52, HU=60.0, N=.065, DIRM=.1000, C=.015
50. 95. 5. 95.
0.00 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.00
307 128 1.30 -0.264 6.01 1. 1. 0.015 0.01
C 3, CROP=CONCORN, PIT=.80, PER=.05, RC=.52, HU=60.0, N=.065, DIRM=.1000, C=.009
56. 50. 50. 50.
0.00 0.09 0.19 0.23 0.49 1.16 2.97 3.00 2.72 1.83 0.00
129 259 1.30 -0.264 2.50 9400. 900 0.250 3.00
C 4, CROP=FALLOW2, PIT=.80, PER=.05, RC=.52, HU=60.0, N=.065, DIRM=.1000, C=.015
50. 95. 5. 95.

APPENDICES 279
0.60 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.00 100 90 60 70 75 80 85 90 95 100 1.0 0.015 0.01 C 5, CROP=CONCOR, PSTD=.80, PER=.05, RC=.52, HU=60.0, N=.065, DIRM=.001, C=.009 0.00 0.09 0.19 0.23 0.49 1.16 2.97 3.00 2.72 1.83 0.00 141 276 1.30 -0.264 2.50 9400.900 0.250 3.00 NUMBER OF ALL ROTATIONS = 1 1 1 19752306 2 1974128 3 1974259 4 1975140 5 1975276

| CHANNEL SPECIFICATIONS FOLLOW |
| NUMBER OF TYPES OF CHANNELS = 2. |
| CHANNEL 1 WIDTH = 5.0 M. ROUGHNESS COEFF. = .15 |
| CHANNEL 2 WIDTH = 2.0 M. ROUGHNESS COEFF. = .18 |
| ELEMENT SPECIFICATIONS FOR P2 WATERSHED |
| EACH ELEMENT IS 12.50 m. SQUARE |
| OUTFLOW FROM ROW 13 COLUMN 3 |
| 1 | 2 | 28 | 278 | 2 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 1 | 3 | 34 | 315 | 1 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 1 | 4 | 23 | 301 | 1 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 2 | 2 | 28 | 278 | 2 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 2 | 3 | 34 | 306 | 1 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 2 | 4 | 25 | 288 | 2 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 2 | 5 | 25 | 288 | 1 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 3 | 1 | 13 | 288 | 2 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 3 | 2 | 17 | 315 | 2 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 3 | 3 | 28 | 315 | 1 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 3 | 4 | 25 | 288 | 1 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 3 | 5 | 20 | 281 | 1 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 3 | 6 | 16 | 270 | 1 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 4 | 1 | 16 | 270 | 2 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 4 | 2 | 23 | 315 | 2 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 4 | 3 | 34 | 324 | 1 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 4 | 4 | 25 | 288 | 1 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 4 | 5 | 24 | 270 | 1 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 4 | 6 | 24 | 270 | 1 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 5 | 1 | 28 | 278 | 2 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |
| 5 | 2 | 36 | 297 | 2 | 1 | R1 | 0 | 24210 16 63 59 |
| 262 | 6 595 | 16 |

APPENDICES
| 92 | 34 | 32A | 1 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 93 | 23 | 301 | 3 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 94 | 16 | 270 | 103 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 95 | 30 | 203 | 1 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 96 | 36 | 186 | 1 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 97 | 25 | 162 | 1 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 98 | 29 | 124 | 2 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 99 | 30 | 180 | 2 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 101 | 20 | 28A | 2 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 102 | 46 | 323 | 2 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 103 | 25 | 288 | 2 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 104 | 17 | 225 | 10 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 105 | 36 | 174 | 1 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 106 | 41 | 169 | 1 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 107 | 38 | 162 | 1 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 108 | 29 | 146 | 2 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 109 | 23 | 121 | 2 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 111 | 25 | 288 | 2 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 112 | 40 | 323 | 2 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 113 | 16 | 270 | 102 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 114 | 32 | 180 | 1 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 115 | 46 | 165 | 1 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 116 | 43 | 158 | 1 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 117 | 38 | 162 | 1 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 118 | 25 | 162 | 2 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 119 | 18 | 153 | 2 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 121 | 38 | 360 | 2 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 122 | 40 | 307 | 2 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 123 | 23 | 270 | 101 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 124 | 44 | 185 | 1 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
| 262 | 6 | 595 | 16 |
| 125 | 48 | 180 | 1 | 1 | R1 | 0 | 24210 | 16 | 63 | 59 |
P4 WATERSHED ELEMENTAL INPUT FILE

DATA FILE FOR P4 WATERSHED, GE. 05-01.73 SIMULATION.
METRIC UNITS ARE USED ON INPUT/OUTPUT PRINT
RAINFALL DATA FOR 1 RAINGAUGES
BEGINNING JULIAN DAY OF SIMULATION 131 1973
DURATION OF SIMULATION DAYS 870
GAUGE NUMBER R1
SIMULATION CONSTANTS FOLLOW
NUMBER OF LINES OF HYDROGRAPH OUTPUT = 161
TIME_INCREMENT = 60, SEC.
INfiltration CAPACITY CALCULATED EVERY 180, SECONDS
EXPECTED RUNOFF PEAK = 50, MM/HR
SOIL INfiltration, DRAINAGE AND GROUNDWATER CONSTANTS FOLLOW
NUMBER OF SOILS = 2
S 1, TP = .41, FP = .88, FC = .46, A =1.000, P = .75, DF =200.0, ASM = .99, K = .23
15. 60. 25.
6.1 0.174 0.662 1.
S 2, TP = .40, FP = .75, FC = .45, A =1.000, P = .75, DF =200.0, ASM = .99, K = .23
17. 62. 21.
6.1 0.174 0.662 1.
PARTICLE SIZE AND TRANSPORT DATA FOLLOWS
NUMBER OF PARTICLE SIZE CLASSES = 4
NUMBER OF WASH LOAD CLASSES = 6
SIZE SPECIFIC GRAVITY FALL VELOCITY
0.002 2.65 0.0
0.200 2.65 0.0
0.400 1.60 0.0
0.050 2.65 0.0
0.150 0.300 0.300 0.200 1
0.170 0.310 0.310 0.210 2
4.5167 20.0000 0.0500 0.0500 4.0000 CREAMS PAGE 211
8.0667 20.0000 0.0500 0.0900 4.0000 TOTAL SPECIFIC
DRAINAGE EXponent = 3,
DRAINAGE COEFFICIENT FOR TILE DRAINS = 0.00 MM/24HR
GROUNDWATER RELEASE FRACTION = .000
SURFACE ROUGHNESS AND CROP CONSTANTS FOLLOW
NUMBER OF CROPS AND SURFACES = 5
C 1, CROP=CONCORN , PITT=.80, PER=.05, RC=.52,HU=60.0,N=.065,DIRM=1.000,C=.009
50.0 50. 50. 50.
0.00 0.09 0.19 0.23 0.49 1.16 2.97 3.00 2.72 1.83 0.00
131 305 1.30 -0.264 2.50 9400. 900 0.570 3.00
C 2, CROP= RYE , PITT=.30, PER=.05, RC=.52,HU=60.0,N=.065,DIRM=1.000,C=.065
50.0 50. 50. 50.
0.00 0.47 0.90 0.90 0.90 0.90 1.75 3.00 3.00 3.00 0.00
306 118 1.05 -0.290 3.00 1700. 300 0.150 3.00
C 3, CROP=CONCORN, PIT=.80, PER=.05, RC=.52, HU=60.0, N=.065, DIRM=1.000, C=.009
50.0 50. 50. 50.
0.00 0.09 0.19 0.23 0.49 1.16 2.97 3.00 2.72 1.83 0.00
119 259 1.30 -0.264 2.50 9400. 900 0.250 3.00
C 4, CROP=RYE, PIT=.80, PER=.05, RC=.52, HU=60.0, N=.065, DIRM=1.000, C=.065
50.0 50. 50. 50.
0.00 0.47 0.90 0.90 0.90 0.90 1.75 3.00 3.00 3.00 0.00
260 133 1.05 -0.290 3.00 1700. 300 0.150 3.00
C 5, CROP=CONCORN, PIT=.80, PER=.05, RC=.52, HU=60.0, N=.065, DIRM=1.000, C=.009
50.0 50. 50. 50.
0.00 0.09 0.19 0.23 0.49 1.16 2.97 3.00 2.72 1.83 0.00
134 303 1.30 -0.264 2.50 9400. 900 0.250 3.00
NUMBER OF ALL ROTATIONS = 1
1 1 197330 2 1974118 3 1974259 4 1975133 5 1975303

CHANNEL SPECIFICATIONS FOLLOW
NUMBER OF TYPES OF CHANNELS = 2,
CHANNEL 1 WIDTH = 5.0 M., ROUGHNESS COEFF. = .08
CHANNEL 2 WIDTH = 2.0 M., ROUGHNESS COEFF. = .18
ELEMENT SPECIFICATIONS FOR P4 WATERSHED, 1973 RUN
EACH ELEMENT IS 6.96 M. SQUARE
OUTFLOW FROM ROW 14 COLUMN 15
1 16 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
1 17 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
1 18 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
1 19 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
2 14 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
2 15 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
2 16 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
2 17 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
2 18 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
2 19 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
2 20 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
2 21 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
2 22 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
3 12 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
3 13 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
3 14 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
3 15 30 270 1 1 R1 0 24410 36 143 69
433 6 768 30
3 16 30 270 1 1 R1 0 24410 36 143 69
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3 17 30 270 1 1 R1 0 24410 36 143 69
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APPENDICES 292
P2 AND P4 WATERSHEDS WEATHER AND FERTILIZATION INPUT FILE (1 YEAR)

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APPENDIX D: SAMPLE OUTPUT FILE

NOMINI CREEK

1 DISTRIBUTED HYDROLOGIC AND WATER QUALITY SIMULATION
   BY ANSWERS VER 4.940001
   DATA FILE FOR FAUQUIER COUNTY, VA. 7-26-91 SIMULATION.

SIMULATION TIME INCREMENT = 60.0 SECONDS
INfiltration CAPACITY CALCULATED EVERY 180 SECONDS
EXPECTED RUNOFF PEAK =150.0 MM/h

SOIL PROPERTIES
SOIL POROSITY FIELD CAP. WILT. POINT HYDRAULIC CONTROL ANTECEDENT EROSION
( PERCENT PERCENT PERCENT CONDC. ZONE MOISTURE CONST. MM/H MM (PERCENT SAT)
VOL.) SAT.) SAT.)
1 41.0 48.0 0.22 13.58 150.0 36.0 0.26
2 40.0 50.0 0.22 11.23 150.0 36.0 0.28
3 39.0 51.0 0.22 18.57 150.0 36.0 0.32
4 41.0 50.0 0.22 12.38 150.0 36.0 0.32
5 41.0 41.9 0.21 35.80 150.0 36.0 0.30
6 41.0 32.0 0.16 72.82 150.0 36.0 0.34
7 41.0 36.0 0.18 14.49 150.0 36.0 0.22
8 35.0 71.0 0.35 6.37 150.0 36.0 0.37
9 38.0 71.0 0.35 8.67 150.0 36.0 0.37
10 36.0 53.0 0.22 6.36 150.0 36.0 0.20
11 36.0 53.0 0.22 3.10 150.0 36.0 0.20
12 41.0 54.0 0.22 11.57 150.0 36.0 0.32
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NUMBER OF WASHLOAD CLASSES = 1

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PARTICLE SIZE DISTRIBUTION OF SOILS AS DETACHED

CLASS 1 2 3 4 5 6 7 8
SOIL 1 0.060 0.010 0.070 0.410 0.450
SOIL 2 0.020 0.030 0.450 0.160 0.340
SOIL 3 0.040 0.090 0.190 0.290 0.390
SOIL 4 0.040 0.090 0.190 0.290 0.390
SOIL 5 0.030 0.110 0.320 0.200 0.340
SOIL 6 0.020 0.030 0.450 0.160 0.340
SOIL 7 0.020 0.030 0.450 0.160 0.340
SOIL 8 0.020 0.500 0.160 0.160 0.160
SOIL 9 0.020 0.500 0.160 0.160 0.160
SOIL10 0.020 0.190 0.350 0.160 0.280
SOIL11 0.020 0.190 0.350 0.160 0.280
SOIL12 0.050 0.170 0.090 0.360 0.330
SOIL13 0.050 0.170 0.090 0.360 0.330

SPECIFIC AREA FOR DIFFERENT PARTICLE SIZE
DRAINAGE EXPONENT = 3
TILE DRAINAGE COEFF. = 0.00 MM/24H
GROUNDWATER RELEASE FRACTION = 0.100E-02

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WESTMORLAND

WATERSHED CHARACTERISTICS

NUMBER OF 1.00 HA OVERLAND FLOW ELEMENTS = 212
NUMBER OF CHANNEL SEGMENTS = 21
AREA OF CATCHMENT = 212.0 HA
CATCHMENT SLOPE: MIN = 0.20 AVE = 2.74 MAX = 14.10 PERCENT
CHANNEL SLOPE: MIN = 0.50 AVE = i.21 MAX = 5.55 PERCENT
PERCENT OF AREA TILED = 0.0 WITH A D.C. OF 0.00 MM/24H
MEAN ANTECEDENT SOIL MOISTURE = 36., FIELD CAPACITY = 46. PERCENT SATURATION
GROUNDWATER RELEASE FRACTION = 0.0010
OUTLET IS ELEMENT  11 AT ROW 27 COL 25

SURFACE COVER/MANAGEMENT CONDITIONS

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**YEAR OF SIMULATION 1980**

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| 314 | 1.  | 0.8 | 22.1 | 1.3 | 0.5 | 0.1 | 0.3 | 1.0 | 48. |
| 315 | 1.  | 0.8 | 22.1 | 1.3 | 0.5 | 0.1 | 0.3 | 1.0 | 48. |
| 325 | 0.8 | 22.1 | 1.3 | 0.5 | 0.1 | 0.3 | 1.0 | 48. |
| 329 | 0.8 | 22.1 | 1.3 | 0.5 | 0.1 | 0.3 | 1.0 | 48. |
| 335 | 0.8 | 22.1 | 1.3 | 0.5 | 0.1 | 0.3 | 1.0 | 48. |
| 336 | 0.9 | 25.4 | 1.4 | 0.5 | 0.1 | 0.3 | 1.0 | 48. |
| 337 | 0.9 | 25.4 | 1.4 | 0.5 | 0.1 | 0.3 | 1.0 | 48. |
| 338 | 25. | 3.1 | 87.1 | 4.1 | 1.2 | 0.1 | 1.8 | 3.5 | 187. |
| 339 | 15. | 3.1 | 87.3 | 4.2 | 1.2 | 0.2 | 1.8 | 3.6 | 187. |
| 343 | 0.  | 3.1 | 87.3 | 4.2 | 1.2 | 0.2 | 1.8 | 3.6 | 187. |
| 355 | 16. | 3.2 | 87.6 | 4.2 | 1.2 | 0.2 | 1.8 | 3.6 | 190. |
| 356 | 1.  | 3.2 | 87.6 | 4.2 | 1.2 | 0.2 | 1.8 | 3.6 | 190. |
| 357 | 44. | 11.6 | 667.8 | 8.1 | 2.2 | 0.3 | 9.8 | 24.3 | 1377. |
| 364 | 17. | 11.6 | 667.9 | 8.1 | 2.2 | 0.3 | 9.8 | 24.5 | 1396. |
| 365 | 6.  | 11.6 | 667.9 | 8.1 | 2.2 | 0.3 | 9.8 | 24.5 | 1397. |

**YEAR OF SIMULATION 1981**

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| 25 | 11. | 667.9 | 8.1 | 2.2 | 0.3 | 9.8 | 24.5 | 1397. |
| 28 | 21. | 669.2 | 8.1 | 2.2 | 0.3 | 9.8 | 24.5 | 1400. |
| 29 | 0.  | 669.2 | 8.1 | 2.2 | 0.3 | 9.8 | 24.5 | 1400. |
| 31 | 6.  | 669.2 | 8.1 | 2.2 | 0.3 | 9.8 | 24.5 | 1400. |
| 32 | 7.  | 669.2 | 8.1 | 2.2 | 0.3 | 9.8 | 24.5 | 1400. |
| 33 | 9.  | 669.2 | 8.1 | 2.2 | 0.3 | 9.8 | 24.5 | 1400. |
| 53 | 23. | 683.7 | 8.1 | 2.2 | 0.3 | 10.0 | 25.0 | 1433. |
| 59 | 24. | 694.2 | 8.1 | 2.2 | 0.3 | 10.1 | 25.4 | 1456. |
| 69 | 22. | 706.1 | 8.1 | 2.2 | 0.3 | 10.1 | 25.8 | 1488. |
| 70 | 4.  | 706.1 | 8.1 | 2.2 | 0.3 | 10.1 | 25.8 | 1489. |
| 73 | 16. | 708.7 | 8.1 | 2.2 | 0.3 | 10.2 | 25.9 | 1495. |
| 73 | 17. | 708.7 | 8.1 | 2.2 | 0.3 | 10.2 | 25.9 | 1495. |
| 94 | 72. | 2776.9 | 8.2 | 2.3 | 0.6 | 27.0 | 83.4 | 5814. |
| 101 | 14. | 2777.9 | 8.2 | 2.3 | 0.6 | 27.0 | 87.3 | 6152. |
| 104 | 4.  | 2777.9 | 8.2 | 2.3 | 0.6 | 27.0 | 87.3 | 6152. |
| 105 | 18. | 2781.2 | 8.2 | 2.3 | 0.6 | 27.0 | 87.4 | 6163. |
| 117 | 0.  | 2781.2 | 8.2 | 2.3 | 0.6 | 27.0 | 87.4 | 6163. |
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| 125 | 25. | 2782.9 | 8.6 | 2.7 | 0.7 | 27.1 | 87.5 | 6167. |
| 135 | 12. | 2783.0 | 8.6 | 2.7 | 0.7 | 27.1 | 87.5 | 6168. |
| 136 | 18. | 2783.0 | 8.6 | 2.7 | 0.7 | 27.1 | 87.5 | 6168. |

APPENDICES 315
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**YEAR OF SIMULATION**

1983

**APPENDICES**

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266  53.  150.7  12500.2  71.3  513.5  101.9  104.6  299.3  28885.
270  45.  160.1  12936.7  72.8  557.7  104.5  111.3  306.8  29865.
287  33.  161.1  12966.2  73.1  561.0  104.7  111.6  307.4  29952.
288  37.  165.5  13164.9  74.3  581.7  105.6  114.2  310.6  30371.
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317  5.  167.7  13247.9  74.6  587.3  106.0  114.9  312.1  30557.
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YEAR OF SIMULATION

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Faycal Bouraoui was born on May 15, 1965 in Tunis, Tunisia, to Habib Bouraoui and Marguerite Robert. He received a Bachelor of Science in Agricultural Engineering from the National Agronomic Institute of Tunis, Tunisia, in June 1987. In December 1987, he joined Texas A&M University and obtained his Master’s Degree in Agricultural Engineering in June 1990, specializing in the Soil and Water area. In August 1990, he joined Virginia Tech as a graduate research assistant to continue his studies towards a Ph.D. degree. He is currently employed by the Virginia Tech Agricultural Engineering Department as research associate.