Application of a Nonpoint Source Pollution model to a Small Watershed in Virginia

by

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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
Master of Science
in
Agricultural Engineering

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June 19, 1991

Blacksburg, Virginia

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(ABSTRACT)

AGNPS, a nonpoint source pollution model, was selected to simulate sediment yield and chemical loadings from Owl Run watershed. The model was validated to demonstrate its applicability to Virginia Piedmont conditions. The validation was carried out by comparing simulation results with measured data including runoff, sediment yield, and nitrogen and phosphorus loadings to downstream water bodies. Statistical measures, including simple linear regression, determination of root mean square errors, and test on differences between simulated and measured data, were used in this study to evaluate errors. Results from these statistical procedures indicated that the errors between simulated and measured results are within acceptable limits.

An annualization procedure was used to provide the basis for evaluating the long-term impact of various BMPs. Critical areas in the watershed, which are responsible for majority of the pollutant loadings, were identified by the model using the annualization procedure. A FORTRAN program was developed to convert critical areas for individual events to ″annualized critical areas″ so that evaluations were made on long-term basis.

BMPs currently installed in Owl Run watershed and several alternative BMP implementation scenarios were simulated. Their impacts on reducing pollutant loadings and their cost effectiveness were evaluated by using the AGNPS model and the annualization procedure. The current BMP scenario will eventually reduce sediment yield, total nitrogen, and total phosphorus loadings by 26%, 32%, and 32%, respectively. Some of the proposed scenarios can reduce these pollutant loadings by up to 59%, 66%, and 67%, respectively.

Acknowledgements

Great thanks must go to Dr. Saied Mostaghimi for his academic, technical, and even English guidance as my advisor and graduate committee chairman. I am grateful to Dr. Conrad Heatwole and Dr. Harry Johnson for their guidance as my graduate committee members. Acknowledgement is extended to Jan Carr and Phil McClellan for their assistance with computer techniques and relevant data management work. Dr. U.S. Tim provided helpful comments, and Mr. Zheng Wang provided me with his excellent personal computer techniques. Finally, I would like to thank my family, especially my wife Yang Shi, my parents, and parents in law, for their patience, support, understanding and encouragement.

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Introduction

Nonpoint source (NPS) pollution, resulting from modern agricultural activities and urban developments, has been recognized as a significant source of water quality degradation in the United States. Agricultural nonpoint source pollution, which is diffuse in nature and dominated by natural processes, is responsible for a significant portion of pollution in large water bodies such as the Chesapeake Bay [USEPA, 1983]. Main types of agricultural NPS pollution include sediment, chemical fertilizers, pesticides, and animal wastes.

Soil erosion on nation's croplands occurs at an average annual rate of about 20 Mg/ha, twice the acceptable rate considered by some soil conservationists [Dempster and Sterna, 1979]. Soil erosion, accelerated by human activities on the land, causes numerous sediment-related water quality problems such as habitat alteration and other adverse effects on aquatic life; filling of water courses and decreasing of capacities of lakes and reservoirs; increasing the complexity and the cost of treating water supplies for municipalities and industries; and reducing the recreational value of water bodies. Many pollutants get absorbed to fine soil particles transported by surface runoff, and deteriorate the downstream water bodies. In the United States, over 4 billion tons of sediment are delivered into streams and rivers every year, about half of this amount originates from agricultural lands [Council on Environmental Quality, 1980].

Major NPS pollutants of concern are sediment, nitrogen (N) and phosphorus (P). Fertilizers, animal wastes, and crop residues are major sources of N and P. Excessive amount of soluble inorganic P and N causes eutrophication in water bodies like the Great Lakes and the Chesapeake Bay. Eutrophication, which is defined as explosive growth of aquatic plants, particularly algae, causes increased turbidity; reduced oxygen levels; taste and odor problems; and aesthetically decreases recreational values of surface waters. Excessive nitrate-N in water supplies can also cause animal and human health problems [Duttweiler and Nicholson, 1983]. Agricultural and urban runoff may also carry large amounts of toxic metal , pesticides, and other organic chemicals. These materials may result in water quality problems in water supplies, commercial and recreational fisheries, and decreased species in aquatic ecosystem.

To solve the nonpoint source pollution problems mentioned above, various approaches have been considered by agencies in charge of NPS pollution control. These approaches, intended to minimize the negative environmental effects of land use activities while maintaining the productivity of the land, include the use of agricultural best management practices, or BMPs. Important BMPs which reduce pollutant carriers such as surface runoff and sediment, include conservation tillage, terraces, contouring, and cover crops. Other BMPs intended to reduce pollutant concentrations involve the method, rate, timing, and formulation of fertilizers and pesticides. Such BMPs include integrated pest management and improved fertilizer and animal waste management. There are also structural BMPs which reduce pollutant delivery such as filter strips, ponds, grassed waterways, terraces, and contouring.

To put the measures and steps of solving nonpoint source pollution problems into practice, the effectiveness of the BMPs need to be evaluated first. In general, the most ideal way of evaluating the impact of management practices on NPS pollution control is the establishment of a comprehensive monitoring system. Such systems allow detailed data collection and analysis for the assessment of the effectiveness of BMPs. For most watersheds, however, it is not economical to install monitoring systems. Watershed models are powerful tools to carry out the task of BMP assessment. These models, however, need to be validated first to demonstrate their applicability on certain watersheds. The validation work has rarely been done for most distributed parameter models because of the need for excessive amount of field data for such models. The extensive data collected from the Owl Run watershed, located in Fauquire County, Virginia, makes it possible to validate distributed NPS models for Virginia's Piedmont conditions [Mostaghimi, et al., 1989].

Even if a monitoring system is installed in a watershed, it is unlikely that the "critical areas" can be demonstrated because of the diffuse characteristics of the nonpoint source pollution (nonpoint sources generally cannot be monitored at their points of origin, and their exact sources are difficult or impossible to trace). A critical area is defined as the small fraction of a watershed responsible for a majority amount of sediment and chemical loadings to downstream water bodies. Distributed parameter watershed models have the capability to identify the critical areas within the watershed. Therefore, if pollution control activities can be concentrated in these areas, greater water quality improvements can be expected with limited funds.

Objectives

The overall goal of this study was to investigate the applicability of a NPS pollution model to small watersheds in Virginia Piedmont areas. The specific objectives were:

a. To perform a critical review of existing distributed watershed models and select a suitable model for assessing NPS pollution in Virginia Piedmont areas. The model should have the ability to evaluate the effectiveness of specific BMPs in terms of pollutant reductions.

b. To validate the model by comparing the model predictions with the data collected from a small agricultural watershed in Virginia.

c. To use an annualization procedure to convert the event-based simulation results of the model to average annual results so that the BMPs effectiveness can be evaluated on a long-term average basis, and compare the annualized simulation results with long-term average annual values of recorded data.

d. To identify NPS pollution critical areas on the watershed and propose suitable BMPs for reducing annual pollutant loadings.

Literature Review

A classification of different models is discussed in this chapter in order to recognize relevant models by their specific characteristics. Widely accepted and used nonpoint source pollution models are reviewed and their advantages and limitations are discussed. Based on the review of models summarized in this chapter, a model is selected for the proposed study.

Classification of Models

To better understand, explain, and describe natural phenomena, variety of models have been developed to simulate real systems. Different criteria result in different classification of models, which reflect special interests or needs within a particular field of study. However, any model can be categorized as either a material or a mathematical model [Haan, 1982]. Material models can further be classified as either iconic or analog models, which have little to do with the topic of this study. Mathematical models, on the other hand, can be classified as either theoretical or empirical models (Fig. 1).

Theoretical models are based on equations which attempt to simulate the actual physical processes in a watershed. The governing physical laws and model structure may be well-understood, and sometimes this kind of models are called "white box" models [Haan, 1982]. Understanding of physical process theoretically, is an obvious advantage of these models. Empirical models are generally cause-and-effect models in which a mathematical expressions transform the system inputs, like precipitation, to outputs, such as runoff and pollutant loadings. This kind of model considers less or little physical laws because the physical laws are not well-known, or the physically-based model is too complicated and simplification of the model behavior is realistic. Therefore, this kind of models are also referred to as "black box" or conceptual models [Haan, 1982]. The advantages of empirical models include their simplicity, less data requirement than that of physical process models, and, therefore, more cost effective to use. These models, on the other hand, are difficult to improve and can not be extended beyond the range of data used in their development. Empirical models may easily be misapplied, and therefore, give the model developers and users less confidence.

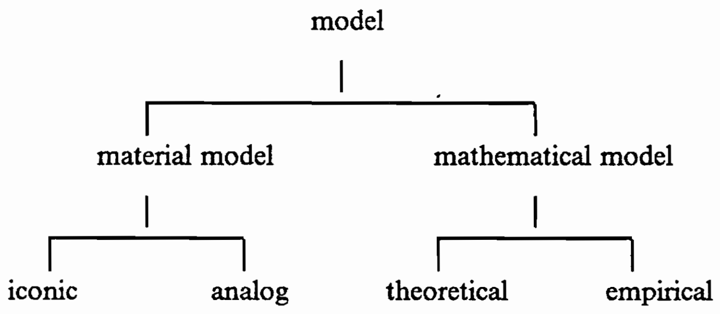

Figure 1. A classification of models.

Actually, there is no strict criteria between physical and empirical models since it is unrealistic to describe a real system thoroughly. Any physical model may include some empirical components.

It is clear, however, that the more the physical components are used in a model, the more confidence a modeler or a user will have in its application.

Most existing hydrology and water quality models are mathematical models supported by computers. These water quality models can be grouped into three general classes (Fig. 2) [Donigian, 1982]:

1. Runoff models;
2. Receiving water models; and
3. Groundwater models.

Runoff models simulate the movement of water and pollutants over and through the soil to stream channels. Receiving water quality models are those capable of simulating the flow of water and pollutants in rivers and reservoirs. Groundwater models simulate flow of water and pollutants in aquifers. Nonpoint source pollution models, to be discussed in this paper, are within the first category of this level of classification, ie., runoff models.

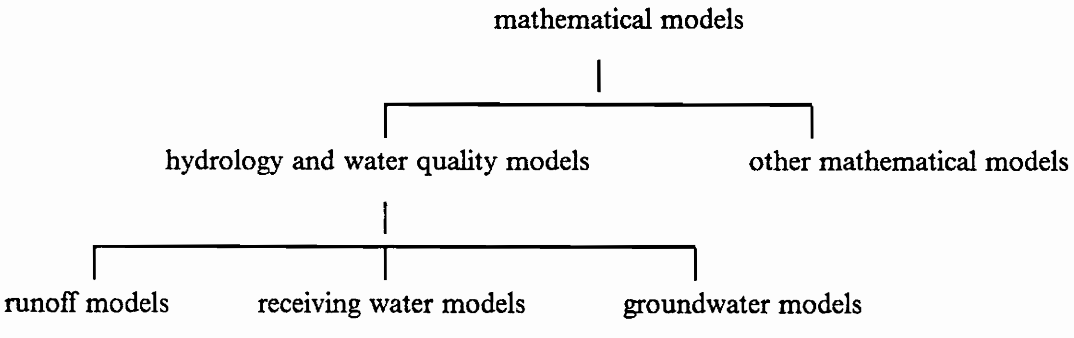

Figure 2. A classification of mathematical models.

Three levels of modeling can be identified according to model structure and modeling subject. 1) Individual process models; 2) component models; 3) Integrated watershed models [Ozgazielinska, 1976]. Individual process models describe one of the physical processes involved in the hydrologic cycle. Evaporation from free surface of water, flow in vadose zone, and unsteady surface flow are examples of individual process models. Component models include linked models of individual processes. These single process models can be run individually or simultaneously. Examples of component models include: evapotranspiration, direct surface runoff, erosion and subsurface flow. An integrated watershed model is a comprehensive model that consists of a set of linked component models and an operator that apportions the flow of water to the individual components in proper order. Such models are developed by combining components and have a well-defined structure. Most NPS models are integrated watershed models.

Mathematical hydrology and water quality models can also be classified according to the following criteria:

1. Static and dynamic models
2. Stochastic and deterministic models
3. Lumped and Distributed Parameter Models
4. Screening and hydrologic assessment models

Static models do not use time as an independent variable, i.e. the real system is simulated under the assumption of a steady-state condition, while dynamic models are time- dependent [Haan, 1982]. Dynamic models can also be event-based or continuous models. Event-based models attempt to simulate the hydrologic response during a storm event. They can better describe some of the processes in detail and ignore some processes like evapotranspiration. This kind of models, however, can not adequately represent long-term processes, and must select design storms to evaluate BMPs. Examples of event-based models include ANSWERS [Beaseley and Huggins, 1982], FESHM [Ross, et al., 1982], and AGNPS [Young, et al., 1985]. Continuous models characterize long term system response, and they are more appropriate for BMP risk assessment. The models can account for meteorologic variability. One main disadvantage of continuous models is that they have less details on individual events and some processes of interest may not be adequately described for storms. CREAMS [Knisel, 1980], ARM [Donigian and Davis, 1978], HSPF [Johanson et al., 1981] are examples of continuous NPS models.

A stochastic model considers the chance of occurrence of the variables and introduces the concept of probability into the model. This kind of model requires long term historical data or synthetic records such as precipitation, climatic, runoff, and sediment yield. If all the variables are not random, or the chance of occurrence is ignored and the model is considered to follow a definite law of certainty, the model will be a deterministic one [Chow, 1964]. Most of the NPS models are deterministic.

Lumped models simulate an area under the assumption that all the system's inputs and the parameters are uniform. They do not consider spatial variability of topography, soils and surface cover conditions. Therefore critical areas can not be identified by using this kind of models. Distributed parameter models, on the other hand, delineate a watershed into fine cells within which soil properties, crop conditions, and other characteristics of each element are considered to be homogeneous. The overall watershed response is obtained by integrating all the elemental responses. These elements are also influenced by inflows from and outflows to neighboring elements. Obviously, the computational effort required to use this kind of models is greater than those of lumped ones. But the models which consider spatial variability make it possible to delineate critical areas. The additional computation time is compensated by improved accuracy of simulation results.

Screening, or planning models, are useful for identifying problem areas within large basins and to make preliminary quantitative assessment of BMPs [Novotny, 1986]. Screening models are relatively simple and their predictions are accurate only within an order of magnitude [Novotny, 1986]. Universal Soil Loss Equations (USLE) [Wischmeier and Smith, 1978], and GAMES [Cook, et al., 1985; Madramootoo, et al., 1988] are examples of screening models. Hydrologic assessment models are much more complex and can be used to evaluate various conditions or alternative management scenarios. Hydrologic assessment models can also be subdivided into field-scale and watershed-scale models. Field-scale models are usually lumped models describing hydrologic processes within a field with uniform soils, crops, topography and weather condition. CREAMS [Knisel, 1980]; GLEAMS [Leonard, et at., 1987]; and NTRM [Shaffer, et al., 1983] are examples of field scale models. Watershed-scale hydrologic assessment models have a broad range of capabilities. Some of these models are event oriented while others are continuous simulation models. Distributed models have the ability to identify critical sources of NPS pollution in watersheds, and most of them can be used to simulate effectiveness of various BMP implementatios. Examples of watershed-scale hydrologic models include AGNPS [Young, et al., 1982]; ARM [Donigian and Davis, 1978]; ANSWERS [Beasely and Huggins, 1982]; and BASIN [Heatwole, et al., 1987].

Description of NPS models

WEPP

The USDA Water Erosion Prediction Project model (WEPP) was developed to generate new water erosion prediction technology for use in soil and water conservation, and environmental planning and assessment [Gilley, et al. 1988]. The WEPP model is a field size model for applying to areas as large as a few hundred hectares in size. A watershed version is under development which includes concentrated flow channels. The watershed version of the WEPP is a distributed model based on a descretization of the study area.

The main advantage of WEPP model is that it uses simple inputs which are commonly available and understood by personnel in local field offices. The model can also calculate sheet and rill erosion, ephemeral gully erosion, and accounts for effects of climate, soils, topography, and cropping management conditions on erosion and sediment transport. Furthermore, the model is easy to use and applicable to a broad range of conditions. The current version of the model does not have a chemical component. WEPP model has not been widely used or tested and verification is needed before application on a particular field. The model is in its final stages of development.

CREAMS

The CREAMS model (Chemicals Runoff and Erosion from Agricultural Management Systems) was developed by Agricultural Research Service for agricultural nonpoint source pollution control research and planning purposes [Knisel, 1980]. With respect to nonpoint sources of pollution, this model was developed specifically to simulate the response of field size areas. CREAMS is a comprehensive model for simulating long term average annual yields from a field. The model considers infiltration, snow melt, evapotranspiration, plant growth, sediment detachment and transport, nutrient and pesticides transport, and even leaching past the root zone [Knisel, 1980]. The model has two hydrology options: One option uses SCS runoff method, the other is an infiltration-based runoff component model. CREAMS has also a channel erosion and deposition component and can be used to evaluate alternative landuse practices and conservation measures [Decoursey, 1985]. The model employs concepts and algorithms representing natural processes, and most of the input parameters have a physical basis [Heatwole, Campbell, and Bottcher, 1987].

CREAMS has been verified with the data from many regions of the country, and has been widely used and distributed both nationally and internationally [Knisel and Svetlosanov, 1982]. The modified version of the model, CREAMS-WT, was developed to better represent the hydrology of flat, sandy, high-water-table fields [Heatwole et al., 1987]. Data from watersheds in South Florida flatwood regions were used for model development and verification. The model should also be applicable to Atlantic and Gulf Coastal Plain areas that have similar hydrologic conditions.

The application of CREAMS is limited to field size areas since it is a lumped parameter model and does not have the ability to consider spatial variability on a watershed scale. Therefore the model can not identify critical areas with a watershed.

HSPF

The Hydrologic Simulation Program Fortran (HSPF) is a continuous general model which was developed by Hydrocomp for the U.S. Environmental Protection Agency [Johanson et al., 1981;

Decoursey, 1985]. It is a modification of the Stanford Watershed Model-4 [Ccrawford and Linsley, 1966]. This general-purpose model simulates hydrology, sediment, pH, dissolved oxygen, organic matter, temperature, nutrients, pesticides, salts, bacteria and plankton from land surface entirely through a channel and reservoir system, including groundwater. HSPF consists of a set of modules arranged in a hierarchical structure which continuously simulates a comprehensive range of hydrologic and water quality processes.

HSPF was applied to a watershed in Iowa by Donigian et al. [1983] to predict water quality resulting from agricultural nonpoint sources. Their experiences with the model showed that HSPF provides a viable and flexible means of estimating the impacts of a wide range of BMPs.

Calibration of HSPF was a hard job, and problems with field-to-stream delivery were also mentioned by the authors. Formal training is recommended when necessary for those who attempt to use HSPF because of its complexity [Crowder, 1987]. The biggest drawback of the model is the empirical base of the many of its hydrologic parameters. Several years of recorded data are needed to obtain reliable input values for many of these parameters. Large amount of human efforts needed for application of the model is associated with data management and calibration of the parameter values. HSPF is a lumped model and can not be used to identify problem areas within a watershed.

FESHM

An event-oriented, distributed parameter hydrologic model, Finite Element Storm Hydrograph Model (FESHM), was developed and modified for simulating runoff in ungaged areas and for assisting in nonpoint source pollution control planning [Ross, 1978; Ross, Wolfe, et al., 1982]. The model has the ability to identify critically eroding areas within a watershed.

FESHM has two components: hydrology and sedimentation. Current version of the model does not have a nutrient or pesticide component. It divides the watershed into flow elements and the geographic information characteristics are lumped within each element. The finite element structure allows the model to route rainfall excess and sediment yield downstream. The governing flow equations of continuity and momentum were solved by the finite element numerical technique.

In subdividing a watershed, FESHM uses a procedure with two levels of discretization. Hydrologic Response Units (HRU's) are defined in determining rainfall excess, which are based on overlay of soil mapping units and land use maps. Elements used to route overland flow are defined based on the drainage and topographic characteristics of the watershed. The HRU's rainfall excess quantities are area-weighted within each flow element. This approach gives the model sufficient flexibility to alter the number and position of overland flow elements to reflect wide spatial variations in rainfall excess generation.

Alternative land management practices can be simulated in terms of runoff and sediment loss by using FESHM. The model simulates the management practices by changing the soil and cover condition parameters in the input data file. Sediment in streams, nutrient, and pesticide components are not available in the current version.

Difficulties were found in simulating low rainfall and low runoff events [Smith and Hebbert, 1979; Keith Beven, 1985]. This disadvantage of the model was ascribed to the lack of allowing runoff generated on a relatively impervious unit to reinfiltrate on other units downslope. The sediment transport component of the model has not been verified extensively. The sensitivity analysis of the model to input parameters was carried out by Shanholtz et al. [1981]. It was found that the model is most sensitive to the storage parameter in Holtan's infiltration equation and hydraulic roughness coefficients [Shanholtz, et al., 1981].

ANSWERS

Areal Nonpoint Source Watershed Environment Response Simulator (ANSWERS) is another distributed parameter, deterministic watershed model, which was developed originally by Purdue University for the EPA Great Lakes Program [Beasley, 1977]. The original version of the model predicts runoff and sediment loadings but not nutrients. A phosphorus transport component was incorporated into ANSWERS, and data from rainfall simulator plots were used to verify the model [Storm, 1987]. The phosphorus transport version of the model was used by Storm et. al. [1988] to demonstrate BMPs effects on increasing cost-effectiveness of cost-share funds for water quality improvement in the Nomini Creek watershed. ANSWERS divides watershed into a grid of small square cells. Infiltration, surface retention, soil moisture, sediment detachment and transport, and nutrient losses are calculated for each cell. These cellular responses are routed to cells downslope and finally to the watershed outlet.

ANSWERS can be used as a planning tool for quantitatively evaluating the benefits of various BMP scenarios for nonpoint source pollution control and even structural BMPs such as ponds, grass waterways, and parallel tile-outlet terraces [Beasley and Huggins, 1982]. Like other distributed watershed models, with its erosion submodel, ANSWERS can identify critical areas within a watershed. Another advantage of the model is that the hydrology component uses break-point rainfall data and deterministic equations to estimate infiltration, surface retention and detention, and percolation to predict rainfall excess.

One of the disadvantages of the ANSWERS model is that it does not consider channel erosion. It allows sediment degradation in channels only at the previously deposited areas. This limitation of the model would be a problem if channel erosion occurs significantly in watersheds. Like other distributed parameter watershed models, ANSWERS needs large amount of input data to describe the conditions within each element of the watershed. Since each element is like a lumped parameter watershed and requires about the same computation time as a lumped model does, the computer time needed for a distributed model is much greater than that of a lumped model. With the development of digital remote sensing techniques and other computerized inventory survey, this time consuming work, however, is being reduced considerably [Feezor et al. 1989].

AGNPS

Two Agricultural Nonpoint Source Pollution Models, AGNPS-I for areas from 500 to 25,000 acres and AGNPS-II for areas from 2.5 to 500 acres were developed in Minnesota [Young, et al., 1985]. Both of the models simulate runoff volume and peak rate, sediment detachment and transport, and nutrient and oxygen concentrations for single storm events.

AGNPS is a distributed parameter, event-based model. Hydrology, erosion, sediment transport, nitrogen, phosphorus and chemical oxygen demand transport are calculated for each cell. AGNPS can also consider point sources such as sediment from gullies, water, sediment, nutrient and chemical oxygen demand (COD) from animal feedlots, springs, and other point sources. Although AGNPS uses a cellular database like ANSWERS, the relationships used in each component calculation is much simpler than those used in ANSWERS such that AGNPS requires much less computational effort. Because of its simplicity, a PC version of AGNPS was developed by Young et al. [1985] to simulate watersheds with areas from 2.5 to 8,000 acres.

An apparent advantage of the model is that it can treat nutrient contributions from animal feedlots as point sources and route them with contributions from diffuse sources. Streambank, streambed, and gully erosion are also accounted for using estimated values as point sources. Sediment from these sources is added to upland sediment and considered in the transport phase of the model.

The main difficulty in using AGNPS is that the preparation of input data file is very time consuming. The total time required to collect input data for the model and enter the data into files requires 20 minutes per cell [Young, et al. 1987, Koelliker and Humbert, 1989]. Efforts were made by some researchers to develop software for interfacing geographic information systems with the AGNPS input data files [Hirschi, 1989].

The model has been tested for runoff estimations with data from 20 watersheds in the north central United States. Sediment yield estimates of the model with data from three watersheds in Iowa and Nebraska compared favorably with the measured values from the three watersheds [Young, et al., 1989]. The chemical component of AGNPS has not been tested on watershed scale because of lack of field data from watersheds. An annualization routine was also developed to evaluate long-term effects of BMPs on reducing pollution from nonpoint sources [Koelliker and Humbert, 1989].

SWRRB

The SWRRB model (Simulator for Water Resources in Rural Basins) was developed from CREAMS to predict the effect of management decisions on water and sediment yields within larger and more complex basins [Arnold, 1987].

The model was tested on more than ten large watersheds from eight Agricultural Research Service (ARS) locations throughout the United States. The results showed that SWRRB can be used to simulate water and sediment yields under a wide range of climatic conditions, soil properties, topography, landuse, and management practices [Arnold, 1987].

Recent improvements to the model include: 1). addition of a return flow component; 2). the incorporation of a component evaluating the effects of ponds and other reservoirs on water yield; 3). the addition of a weather model for long term simulation including rainfall, solar radiation and temperature; 4). the development of a different method to predict peak runoff rate; and 5). the addition of a simple flood routing component [Arnold, 1987].

The model is based on daily rainfall hydrology so it does not have the ability to model event-based storms. SWRRB does not have a chemical component to simulate transport of nutrients and pesticides. A recent study showed that the SWRRB and AGNPS obtained much better simulation results than CREAMS, EPIC, and ANSWERS. The data used were collected from several watersheds in Mississippi [Bingner, et al., 1989].

The model was expanded to allow simultaneous computations on several subbasins. The largest number of subbasins in the simulation by Arnold [1987] was five. It is unlikely that the model can be classified as a distributed parameter model. Thus the model does not have the ability to identify critical areas within a watershed.

GAMES

The Guelph model for evaluating effects of Agricultural Management Systems on Erosion and Sedimentation (GAMES) is an event-based model which was developed at the University of Guelph [Cook et al, 1985, Rudra et al, 1986, and Madramootoo et al., 1988]. GAMES is a distributed parameter model but its hydrologic response units are not elemental squares like that of

ANSWERS and AGNPS, these cells are irregular-shaped, which are delineated by natural and man-made boundaries such as soils, topography, and land use.

The principal inputs to the model are the rainfall erosion index (EI) and variables describing the soils, crops, and physical characteristics of each cell. The principal outputs from the model on a cellular level are gross erosion, sediment yield to the adjacent cells and sediment yield to the channel, total gross erosion, average erosion, and total sediment yield. No nutrient and pesticide components are available in the current version of the model. Since GAMES is simply a modification of a seasonal erosion and sediment yield model, no hydrologic output is available.

ARM

Agricultural Runoff Management (ARM) model [Donigian and Davis, 1978; Davis and Donigian, 1979] is a lumped parameter, continuous simulation model. ARM simulates runoff, sediment, phosphorus, nitrogen, and pesticide loadings to surface waters from both surface and subsurface sources. The hydrologic component of the model is an overland flow version of the Stanford Watershed Model [Ross, 1970], which simulates small watersheds from 200 to 500 ha in size.

The main advantage of ARM model is its comprehensiveness. It estimates runoff, sediment, nutrient (N and P) and pesticides. The model has many drawbacks of lumped models, therefore the model has to assume uniform landuse, cropping management practices, soils, and topography. Furthermore, ARM is not suitable for modeling ungaged watersheds because it needs historical records of runoff and water quality for calibration. ARM model does not consider channel erosion.

Crowder (1987) reported that calibration of ARM is necessary for each application of the model. The author concluded that the model simulated monthly phosphorus loadings to runoff satisfactorily.

EPIC

Erosion Productivity Impact Calculator (EPIC) was developed by Williams et al. [1982] to determine the relationship between soil erosion and crop productivity. EPIC is a continuous model which simulates annual and perennial crop growth by predicting long term effects of soil erosion on crop production. The model simulates, on a daily basis, hydrologic condition, sediment loss, soil nutrient properties, soil temperature, effect of tillage, plant growth stage, and daily weather, if the daily data are not available.

The multi-year simulation capability of the EPIC model is its main advantage. It is able to run eleven different crops in a crop rotation schedule. Detailed description of the recent version of the model was given by Williams et al. [1988]. Validation work was done for crop yield and runoff components [Williams and Renard, 1985]. The model has been used to determine the impact of soil erosion for the 1985 Resource Conservation Act appraisal [Putman et al., 1988]. EPIC is a field size, lumped parameter model and does not simulate storm event effects. The model can not be applied to a watershed for identifying critical areas.

Summary

A distributed parameter, comprehensive watershed model is needed to investigate the impact of BMPs on surface water quality from Owl Run watershed. This watershed was selected for monitoring because of its topography, landuse, and soils, which are typical characteristics of watersheds in the northern part of Virginia. A monitoring system was installed in the watershed in 1986 and a substantial amount of water quality, quantity and landuse data necessary to validate the

Table 1. Summary of widely used NPS pollution models.

Model	Lumped /or Distributed	Event-based /or Continuous	Hydrology component	Sediment component	Chemical Component
GAMES	D	E		*	
WEPP	D	C	*	*	
FESHM	D	E	*	*	
ANSWERS	D	E	*	*	P and N
AGNPS	D	E	*	*	P and N
BASIN	D	C	*	*	Nutrients, pesticides
CREAMS	L	C	*	*	Nutrients, pesticides
SWRRB	L	C	*	*	
HSPF	L	C	*	*	Nutrients, pesticides
ARM	L	C	*	*	P, N, pesticide
EPIC	L	C	*	*	Nutrients, pesticides

* The model has a component corresponding to that column.

model have been collected during the last several years. The monitoring system will be described in the following chapter.

The use of a distributed parameter watershed model makes it possible to identify problem areas within the watershed, simulate water quality impacts of BMPs implemented within the watershed, and enhance the accuracy of simulations. The NPS models reviewed in this study were designed to simulate BMPs. In summary, the following criteria were used to select an appropriate NPS model for this study:

a) The model should have hydrology, sediment yield, and chemical loading components including nitrogen and phosphorus.

b) Relationships used in the components should be simple and widely accepted.

c) The model should have the ability to simulate different kinds of BMPs.

d) The model should be a distributed one to enable the identification of critical areas and simulate various BMPs implemented at different locations within the watershed.

e) Event-based models are preferred for this study since a comprehensive database exists for storm events on Owl Run watershed.

Table 1 gives a summary of selected NPS models and their major characteristics. As indicated in the table, the first six models are distributed parameter models, of which BASIN, ANSWERS, and AGNPS have all the necessary components mentioned in the above criteria, and all of them have the ability to simulated various BMPs, in addition, ANSWERS and AGNPS are event-based models.

Three years of comprehensive data was available from Owl Run watershed, including rainfall amount, runoff volume, sediment yield, total nitrogen and total phosphorus loadings for individual events. Therefore, it was thought that an event based model should be selected, and validated by using data from these storm events.

ANSWERS and AGNPS are believed to be the most applicable NPS models to our situation based on the review of the models and data available. AGNPS was selected for this study because of its widely accepted, simple relationships, user-friendly graphics functions, and comprehensiveness. AGNPS has been successfully tested for various conditions throughout the U.S. and more efforts are being made to interface the model with Geographic Information System (GIS) to allow more convenient applications. A detailed description of AGNPS is included in the next chapter.

The Agricultural Nonpoint Source Pollution Model (AGNPS)

Introduction

The event-based, distributed parameter model AGNPS simulates runoff volume, peak flow rate, sediment, and nutrient transport from agricultural watersheds. The nutrients considered include nitrogen (N) and phosphorus (P). Basic model components include hydrology, erosion, sediment, and chemical transport. The model also considers point sources of sediment, water sources, nutrients and chemical oxygen demand (COD) from animal feedlots, springs, and other point sources [Young, et al. 1989]. Sediment and chemicals from these sources are added to upland sediment and chemicals considered in the transport phase of the model. Water impoundments are also considered as areas of sediment deposition and adsorbed nutrients. AGNPS divides a watershed into uniform square areas and analysis can be made at any point within the watershed.

Koelliker and Humbert [1989] used the PC version (2.5) of AGNPS on five watersheds in northeast Kansas. An annualization routine was developed in the study to estimate average annual results rather than single event results for water quality planning purposes. The study confirmed the promising use of the AGNPS model to develop predictions for relative changes in yields as a result of specific changes in watershed conditions. There was not adequate data available to validate or calibrate the model. The study was based on a sedimentation survey of small reservoirs in Kansas for the year 1960 [Holland, 1971]. The predicted sediment and water yields agreed reasonably good with the measured data.

Several NPS models including AGNPS were used to simulate runoff and sediment yields from three watersheds in Mississippi [Bingner, et al., 1989]. In this study, the AGNPS model was modified to simulate system response continuously holding all of the parameters constant for a given year, except for rainfall, EI value and C factor used in the USLE. Simulated values by AGNPS were compared with measured values from a number of storm events, over several years, on each watershed. The comparison showed that no model worked very well for every situation of runoff and sediment yield on the watersheds. Results produced by AGNPS, however, were close to the measured values in many situations.

The AGNPS model was tested for runoff evaluations on 20 different watersheds in north central United States by Young, et al.[1989]. A regression analysis of the estimated peak runoff values on the observed values yielded a slope of 0.984, a good agreement between estimated and observed values. Testing for sediment yield estimates were carried out on three watersheds, with two of them being in Iowa, the other in Nebraska [Young, et al., 1989]. The estimation from the model compared favorably with the measured values from the three watersheds.

Data from seven different watershed in Minnesota collected over a 3-year period were used to test the chemical components of the AGNPS model [Young, et al., 1989]. The comparison of measured versus estimated N and P concentrations from 20 different sampling points in the seven watershed indicated that AGNPS provided realistic predictions of nutrients concentrations in runoff water. Major applications following the testing of the model were accomplished on two large watersheds in Minnesota [Young, et al., 1989] to identify critical areas within the watersheds, and evaluate BMP effectiveness.

As mentioned previously, data file preparation for AGNPS is a time consuming work. Young's estimate [1987] was 20 minutes per cell to collect necessary data and enter the data into the files. Researchers have tried to link Geographic Information Systems (GIS) to AGNPS model to save the laborious time [Feezor, et al., 1989; Needham and Baxter, 1989]. The interfacing GIS with AGNPS model can greatly enhance the efficiency of the model capabilities. In Feezor's study [1989], statistical evaluation of grid size comparison demonstrated that a user should use the smallest grid size available to obtain certain degree of accuracy. High level automation of data conversion is still expected to allow quick evaluation of alternative management practices.

The four components of the model, hydrology, soil erosion and sediment transport, chemical transport, and point sources are described in detail in the following sections.

Hydrology

The hydrology component of AGNPS utilizes SCS curve number method to estimate runoff volume of each element. This method was chosen because of its widespread use. The curve number depends upon landuse, soil type, soil moisture condition, and hydrologic soil condition. Therefore, the model has the advantage of being able to evaluate different management practices [USDA-SCS, 1972]. The basic relationship is as follows:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad \text{for} \qquad p > 0.2S \tag{1}$$

where Q is runoff volume, P is precipitation, and S is a retention parameter, all in mm. In practice, the retention parameter S is related to a runoff curve number, CN, which is defined in terms of landuse treatments, hydrologic condition, antecedent soil moisture, and soil type [USDA-SCS, 1972]:

$$S = \frac{25400}{CN} - 254 \tag{2}$$

The SCS curve numbers are based on the assumption that the initial abstraction equals 0.2S. Determination of curve numbers is a time consuming procedure requiring detailed data on land cover and soils.

The time needed for concentrated flow to occur, ie. the overland flow duration, is determined by the equation [USDA-SCS, 1972]:

$$\mathrm{OFT} = \frac{L_s}{V_0} \tag{3}$$

where OFT is the overland flow time in seconds; L_s is field slope length in m; and V_0 is overland flow velocity in m/sec. The velocity is calculated as:

$$V_0 = 10^{0.5 \times \log(100S_l) - SCC} \tag{4}$$

where S_l is land slope; and SCC is overland surface condition constant, an input parameter needed for each cell. The parameter is determined in terms of landuse and vegetation.

Peak runoff rate is also estimated for each cell using an empirical relationship proposed by Smith and Williams [1980].

$$Q_p = 3.79A^{0.7}CS^{0.16}Q^{0.903A^{0.017}}LW^{-0.19} \tag{5}$$

where Q_p is the peak flow rate in m^3/s; A is the drainage area in km^2; CS is channel slope in m/km; Q is the runoff volumes calculated above; and LW is watershed length/width ratio.

Erosion and Sediment Transport

The erosion and sediment transport component of AGNPS uses a modified form of the Universal Soil Loss Equation to estimate upland erosion for single storm events [Wischmeier, et al. 1978].

The USLE equation used in AGNPS is:

$$SL = (EI)KLSCP(SSF) \tag{6}$$

where SL is soil loss; EI is the energy index, which is the product of the total storm kinetic energy and maximum 30-minute intensity; K is soil erodibility factor; LS is topographic factor representing slope length and steepness; C is the crop and management factor; P is the supporting practice factor; and SSF is a factor to adjust for slope shape within each cell. All these factors are defined and calculated using procedures in USDA Agricultural Handbook 537 [Wischmeier and Smith, 1978]. Eroded soil are divided into five particle size classes -- clay, silt, small aggregates, large aggregates, and sand.

The detached sediment is routed from cell to cell throughout the watershed to the outlet after calculation of runoff and upland erosion. The method used for sediment routing involves equations for sediment transport and deposition described by Foster et al. [1981] and Lane [1982]. The basic routing equation, derived from the steady-state continuity equation is as follows:

$$Q_s(x) = Q_s(0) + Q_{s1}(x/L_r) - \int_0^x D(x)W dx \tag{7}$$

where $Q_s(x)$ is the sediment discharge at downstream end of channel reach; $Q_s(0)$ is the sediment discharge at upstream end of the channel reach; Q_{sl} is lateral sediment inflow; x is downslope distance; L_r is the reach length; D(x) is sediment deposition rate at point x; and W is the channel width. The sediment deposition rate is estimated as:

$$D(x) = [V_{ss}/q(x)][q_s(x) - g_s(x)] \tag{8}$$

where V_{ss} is particle fall velocity; q(x) is the discharge per unit width; $q_s(x)$ is sediment discharge per unit width; and $g_s(x)$ is the effective transport capacity per unit width. The effective transport capacity, g_s, is computed using a modification of the Bagnold stream power equation [Bagnold, 1966], as follows:

$$g_s(x) = fk\frac{\tau V^2(x)}{V_{ss}} \tag{9}$$

where f is an effective transport factor; k is transport capacity factor; τ is sheer stress determined by types of soil texture; and V is the average channel flow velocity determined by the Manning's equation. Sediment load for each of the five particle sizes is calculated using:

$$Q_s(x) = [\frac{2q(x)}{2q(x) + \delta x V_{ss}}][Q_s(0) + Q_{s1}\frac{x}{L} - \frac{Wx}{2}[\frac{V_{ss}}{q(0)}[q_s(0) - g_s(0)] - \frac{V_{ss}g_s(x)}{q(x)}]] \tag{10}$$

where $Q_s(x)$ is the particle discharge at the cell outlet and other symbols are as defined previously. This is the basic routing equation used in the sediment transport model.

Chemical Transport

The chemical component of the model estimates N, P, and COD transport throughout the watershed, using the procedures adapted from CREAMS [Frere, et al, 1980] and a feedlot evaluation model [Young, et al., 1982]. It calculates soluble and sediment-bound phases separately. Nutrient yield in the adsorbed phase is calculated using total sediment yield from a cell:

$$Nut_{sed} = (Nut_f) \times Q_s(x) \times ER \tag{11}$$

where Nut_{sed} is N or P transported by sediment; Nut_f is N or P content in the soil; and ER is enrichment ratio calculated as:

$$ER = 7.4 \times Q_s(x)^{-0.2} \times T_f \tag{12}$$

where $Q_s(x)$ is the sediment yield and T_f is an adjustment factor for different soil textures. The values for clay, silt, sand, and peat are 1.15, 1.00, 0.85, and 1.50 respectively [Young, et al., 1987; 1985].

Considering the effects of nutrient levels on rainfall, fertilization, and leaching, the soluble nutrients contained in runoff are estimated as follows:

$$Nut_{sol} = C_{nut} Nut_{ext} Q \tag{13}$$

where Nut_{sol} is the concentration of soluble N or P in the runoff; C_{nut} is mean concentration of soluble N or P at the soil surface during runoff; Nut_{ext} is an extraction coefficient of N and P moving into runoff [Frere, et al. 1980]; Q is the total runoff volume.

The COD considered in the model is assumed soluble and the soluble COD is assumed to accumulate without losses. Computation of COD values in runoff are based on runoff volumes obtained in the hydrology component and average concentration of COD in runoff is available in the literature [Young, et al., 1985], which is used as the basis for predicting COD concentration for each cell.

Point Source Inputs

Nutrient and COD concentrations contributed by animal feedlots are treated as point sources by the chemical component of the model. Contributions from point sources are then routed with contributions from nonpoint sources.

Chemical contributions from feedlots are estimated with a feedlot pollution evaluation system developed by Young et al. [1982]. The system divides an animal feedlot into three conceptual areas. Area 1 is the animal lot itself, area 2 is the drainage area upstream of the feedlot, and area 3 is the area from which runoff bypasses the feedlot (area 1) and joins the runoff from the feedlot at its outlet. The runoff from area 3 dilutes the concentrations of the pollutants in the runoff from the feedlot area. A buffer area is also defined, within area 3, as the area between the feedlot and its downstream waterbody. Inputs required by the model include the areas and curve numbers of the three areas, the surface condition constant, slope and flow length of the buffer area, and the number and type of animals in the feedlot. The system calculates the concentration and mass of nitrogen, phosphorus, and COD in the runoff, taking into account the dilution by the tributary water and attenuation through the buffer area.

Springs, waste water treatment plant discharges, and other point source inputs are accounted for by entering inflow rates and chemical concentrations to the cells where the point sources are located. Sediment from streambank, streambed, and gully erosion is calculated using estimated values as point sources and is added to the upland sediment. Sediment and runoff routing through impoundments are carried out using relations described by Laflen et al. [1978]. These relations were developed for impoundment terraces with pipe outlets. Impoundments reduce peak discharge rate, total volume of runoff, sediment yield, and chemical loadings.

Owl Run watershed

The Owl Run watershed, 1153 hectares in size, is located in Fauquier county, Virginia. The watershed is 8 km south of Warrenton, Virginia, and 65 km from Washington, D.C. (Figure 3). The Owl Run watershed was selected to be monitored, as part of the Chesapeake Bay program to evaluate the impact of animal waste BMPs on downstream water quality. The Owl Run watershed was chosen because of its high concentration of dairies and lack of animal waste management practices [Mostaghimi, et al., 1989]. The Owl Run Watershed/Water Quality Monitoring project was initiated in April 1986 to provide comprehensive assessment of the water quality as influenced by changes in landuse, agronomic and cultural practices in the watershed over a 10-year study period [Mostaghimi, et al., 1989]. Meteorological, hydrologic, biological, soil and water quality, and landuse information are being monitored at several sites within the watershed. A database management system for storage and retrieval of hydrologic and water quality information has also been established. The installation of the monitoring system makes it possible to evaluate the effectiveness of animal waste BMPs on improving the quality of water from the watershed. Figure 3 and figure 4 show the location of the watershed and the monitoring stations installed within the watershed.

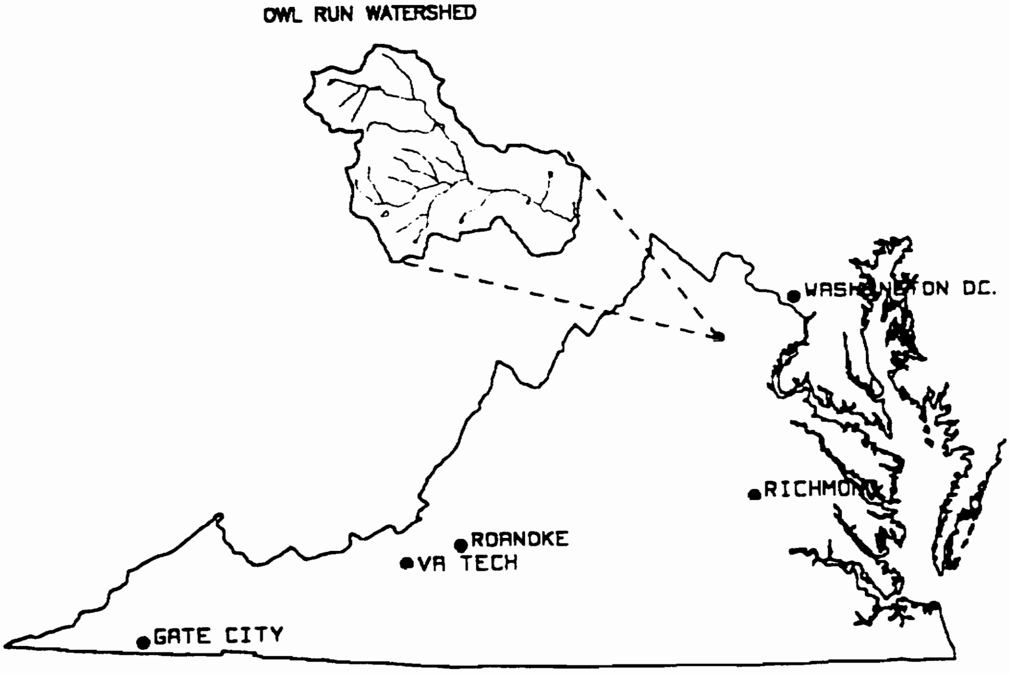

Figure 3. Location of Owl Run watershed.

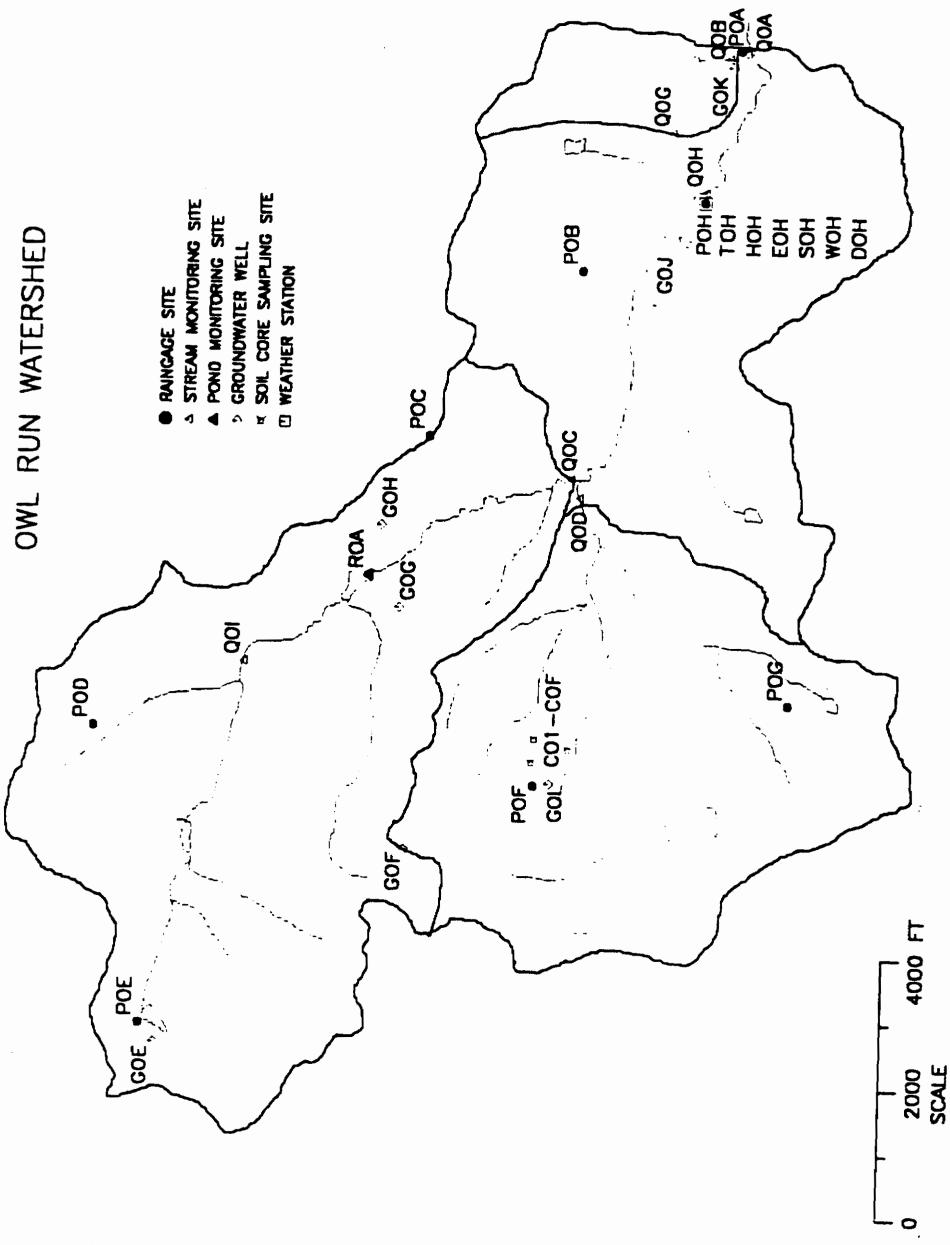

Figure 4. Monitoring stations installed within Owl Run watershed

Topography: Fauquier county is located in the Piedmount physiographic provinces. The Piedmount Plateau consists of 80% of the county. The Blue Ridge province in the northwestern part of the county includes the Blue Ridge Mountains and outlying foothills.

The terrain of the area is predominantly steep and rugged with large rocks strewing over and protruding from most of the mountain slope. Between the foothills are relatively narrow, rolling to hilly uplands, which are underlaid by granite rocks. Elevation of the mountains range from 275 m to 725 m above sea level. The valleys are of considerably lower elevation. Main rivers in the watershed are Rappahannock River, Goose Creek, and their tributaries originated in the Blue Ridge and its foothills. The northern and eastern parts of the Fauquier County are drained by parts of the Potomac River drainage system [USDA-SCS and VPI, 1956].

Climate: The climate of Fauquier county, Virginia, is of the humid continental type, with an average annual rainfall of about 104 cm. It is rather humid and hot in summer with highest temperatures around 32 °C to 35 °C. The extreme temperatures in winters are about -9 °C to -6 °C which are vigorous but not too severe. A typical characteristic of the winters is frequent cold spells of short duration. The average frost-free period is 189 days, expending from mid-April to late October [USDA-SCS and VPI, 1956].

Although large amount of rain occurs in spring and summer during the crop growing season, the distribution of the average annual rainfall in the county is fairly even throughout the year. Runoff is usually large during summer because of the rainfall intensity. Most of the well-drained upland soils in the area may actually absorb less moisture during summer season. Heavy thunderstorms and showers are frequent in summer, late spring, and early fall. Slowly drizzling rains and snow are main forms of winter precipitation. The wind velocity is greatest in the spring and the average over the year is 9.7 km/hr.

Soils: The soils on the watershed are mainly shallow silt loams, with Triassic shale being underneath. In some areas of the watershed the shale layer is exposed. Areas with high erosion rate are

Table 2. Soil types in the Owl Run watershed.

Soil type	Percent slope	Percent of the watershed area
Bowmansville silt loam	0 - 2	1.2
Bucks silt loam, undulating phase	2 - 7	16.3
Calverton silt loam, undulating phase	2 - 7	8.2
Croton silt loam	0 - 5	8.8
Kelly silt loam, level and undulating phase	2 - 7	2.4
Montalto silt loam, undulating moderately shallow phase	2 - 7	14.4
Montalto stony silt loam, rolling moderately shallow phase	7 - 14	2
Penn silt loam, undulating phase	2 - 7	35.7
penn silt loam, rolling phase	7 - 14	4.1
Rowland silt loam	0 - 2	2.9
Wadesboro silt loam, undulating phase	2 - 7	1.4
Other	0 - 25	2.6

reportedly from heavily cultivated fields [VDCHR, 1986]. Table 2 gives a summary of main soil types of the watershed. Penn, Bucks and Montalto associations are major soil series which account for 72.5% of the watershed area. Penn soils are shallow and excessively drained soils that occur predominantly on undulating to rolling relief. Slopes range from 2-7% for undulating phase and 7-14% for the rolling phase. Soil permeability is moderate, the water holding capacity is poor, and the internal drainage is medium to rapid. The color of Penn soils is reddish-brown with a purply cast, to dark reddish-brown. The Bucks soil series are moderately deep, well-drained upland soils derived from Triassic red shale and sandstone. The acidity of the Bucks Association soils is strong to very strong, the organic matter content is fairly high, and internal drainage is medium . The subsoils of the series are dark reddish-brown, and surface soils brown. Their slopes range from

2-7%. The Montalto soils were derived from fine-grained Triaasic diabase with medium to strong acidity. The slopes of the series range from 2-14%. The soils are moderately well supplied with organic matter and plant nutrients so that they are relatively fertile. Internal drainage is medium and erosion ranges from none on forest to moderate on agricultural areas [SCS, 1956]. The Montalto soils are moderately shallow and relatively dark and, therefore, warm and dry in the spring for early plowing. A spatial distribution of major soils types of the watershed is given in Figure 5.

Landuse: Agricultural fields cover more than 90% of the 1153 ha watershed area. The remaining 10% of the watershed is used for residential, commercial, and transportation purposes. Table 3 summarizes area percentages of the watershed for each landuse.

Table 3. Typical Landuses in the Owl Run watershed.

Land use category	Percentage of the watershed area
Conventional corn	15
No-till corn	11
Rotational hay	20
Pasture (active)	18
Pasture (idle)	7
Woodland	20
Non-agricultural	9

About 50% of the corn follows a rye cover or small grain rotation. Most of the hay fields are maintained as grass for 3 to 4 years, followed by one year corn production. The grass legume hay

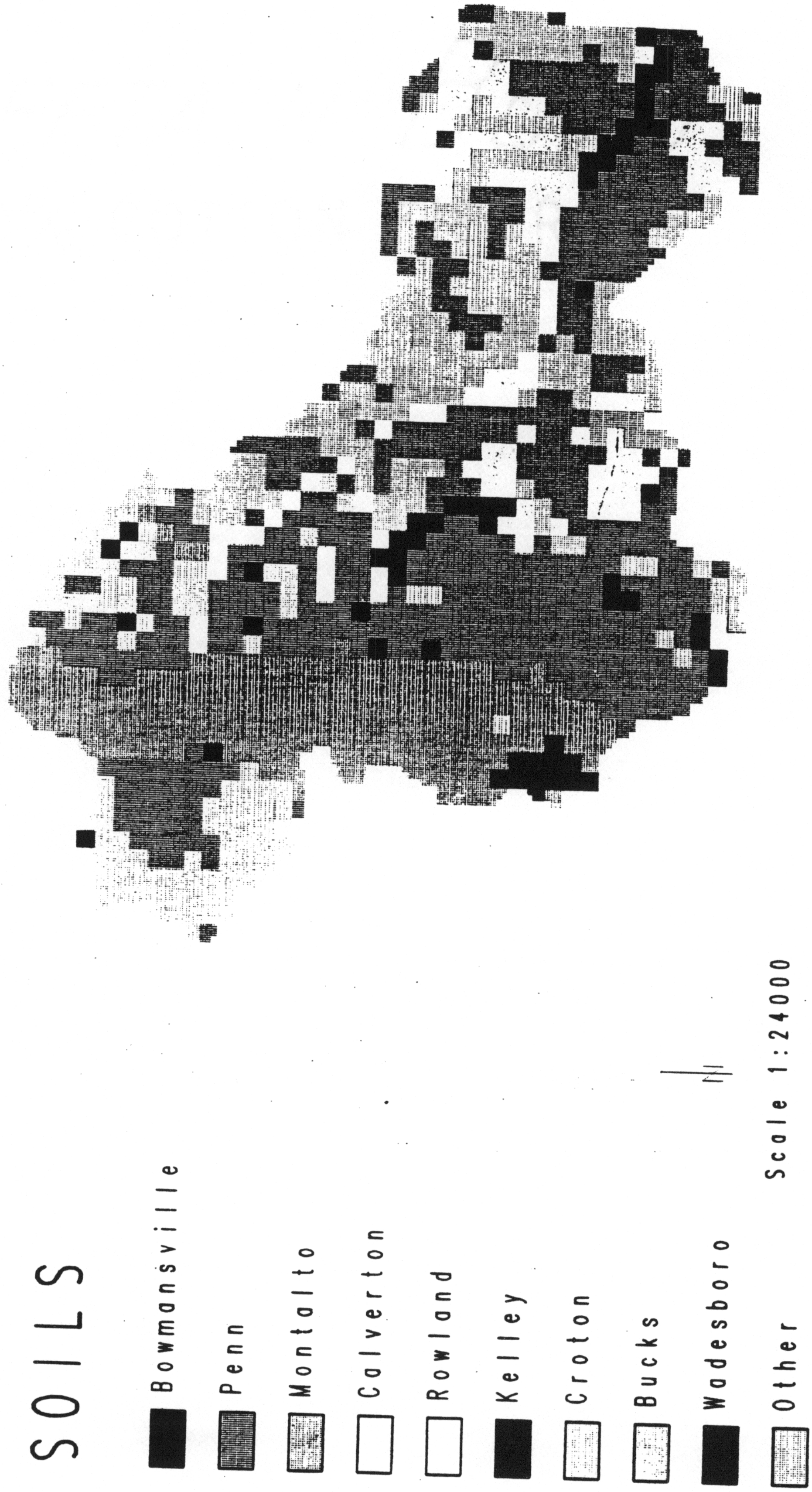

Figure 5. Types of soils in Owl Run watershed.

is planted with a small grain companion crop after the corn crop. Major landuses of the watershed are shown in figure 6.

The watershed has five major dairies in it, with only one of the operations having an animal waste storage facility at the time the monitoring was initiated in 1985. There are about 1000 milking cows, and 250 replacement heifers and dairy cows within the watershed. The fact that a large area must be left without protective vegetative cover over the winter to provide land for spreading manure, was one of the reasons responsible for the high erosion rate on much of the agricultural land and the high rate of pollutant loadings to downstream waterbody. The annual dairy waste produced in the watershed is approximately 14,600 cubic meters (3.9 million gallons). This volume includes wash water and runoff that comes into contact with the waste [VDCHR, 1986].

Corn production in the watershed with conventional and no-till practices covers about 26% of the watershed area. Typically, about 157 kg/ha of nitrogen, 32 kg/ha of phosphorus, and 56 kg/ha of potassium are applied to the corn crop. This includes the spring top dressing of the small grain. All commercial fertilizer applications on the agricultural lands are based on soil tests performed by Virginia Tech, local fertilizer dealers, and commercial laboratories.

The monitoring system: Several runoff and precipitation monitoring stations were installed in the watershed to better define and characterize the spatial variations of climatic and landuse variables related to pollutant losses from the watershed. As shown in figure 4, eight stations are located within the watershed named POA through POH, to collect precipitation data. Additional meteorological data are measured at station POH, including daily evaporation, daily wind direction and wind speed, air temperature, and relative humidity. Four station QOA, QOB, QOC, and QOD, were designed for monitoring surface water quality for the parameters listed in table 4. The main station, QOA, is installed at the outlet of the watershed to demonstrate the total watershed response to

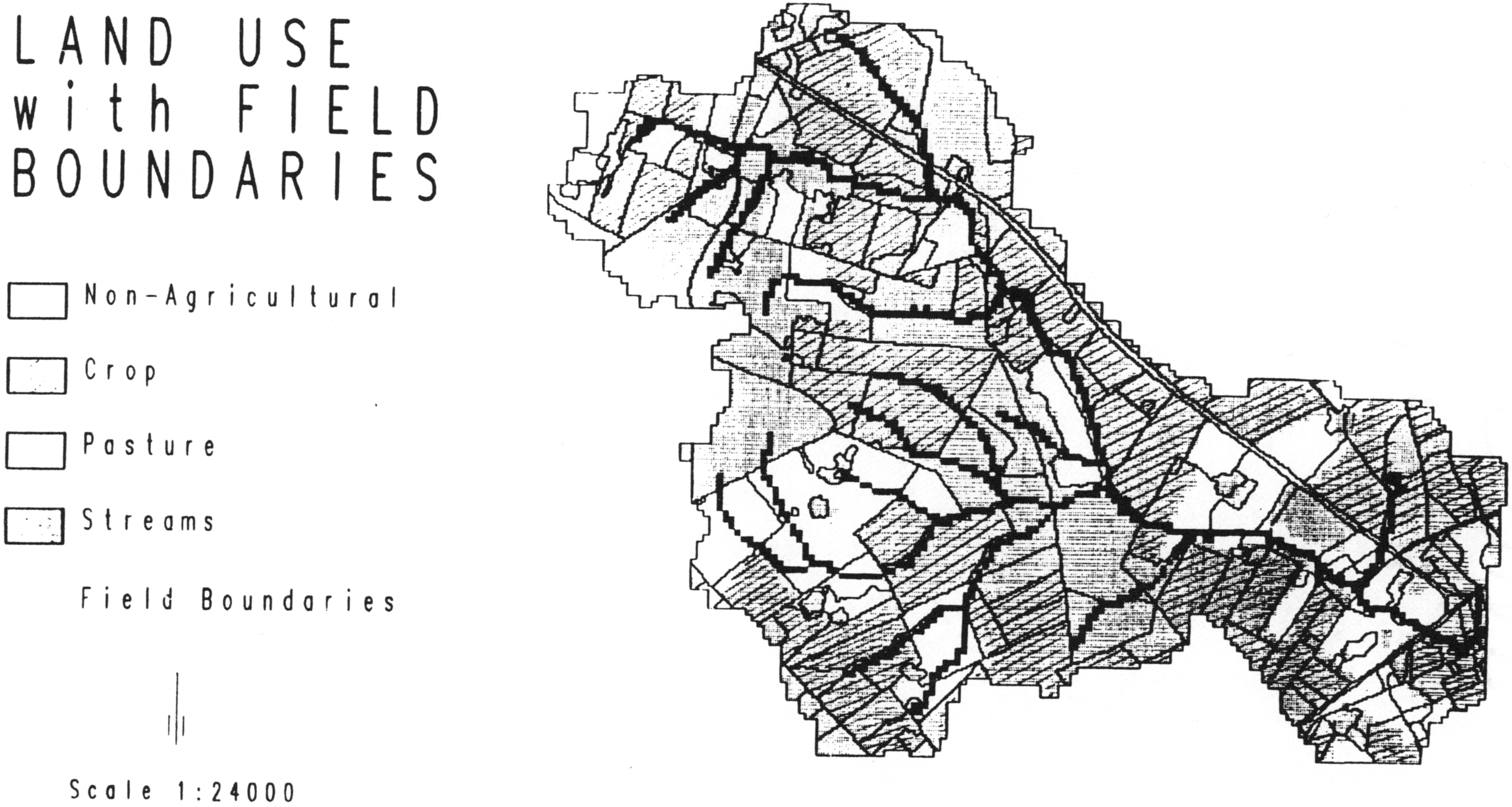

Figure 6. Major landuses of Owl Run watershed.

BMP implementations. Seven private groundwater wells were used to monitor groundwater quality, as GOE, GOF, GOG, GOH, GOI, GOJ, and GOK (Figure 4).

Five data layers of the watershed, elevations, stream networks, watershed boundaries, soil types, and general landuse, were digitized and stored in raster format into a database. The management of the database, including digitization, error checking and correction of the data were performed by the Virginia Geographic Information System (VirGIS) laborary, located in the Agricultural Engineering Department at Virginia Tech [Shanholtz, et al., 1987]. Soil and landuse survey program of the monitoring project provided the basis for monthly landuse survey and quarterly soil sampling on the watershed. The landuse survey provides a comprehensive documentation of agricultural and animal waste management practices implemented on the watershed.

Table 4. Soil and water quality parameters monitored at the Owl Run Watershed

Parameter	Surface water	Ground water	Atmospheric precipitation	Soils
Total Suspended Solids (TSS)	X		X	
Nitrate-Nitrogen ($NO_3 - N$)	X	X	X	X
Ammonium-Nitrogen ($NH_4 - N$)	X	X	X	X
Total Kjeldahl Nitrogen (TKN)	X	X	X	X
Soluble TKN (TKN_{sol})	X	X	X	
Total Nitrogen (TN)	X	X	X	X
Total Phosphorus (TP)	X	X	X	X
Filterable TP	X	X	X	
Total soluble Phosphorus (P_{sol})	X	X	X	
Orthophosphorus ($PO_4 - P$)	X	X	X	X
Chemical Oxygen Demand (COD)	X			
Herbicides: Atrazin, Dual, Paraquat, Princep, Lorox, Lasso, etc.	X	X		
Insecticides: Sevin, Malathion, Pydrin, etc.	X	X		
Biological monitoring of protozoan diversity and bacteria levels	X			

1. Adapted from S. Mostaghimi, et al., Watershed/Water Quality Monitoring for Evaluating Animal Waste BMP Effectiveness - Owl Run Watershed pre-BMP Evaluation, 1989. Report No. O-P1-8906.

The pre-BMP implementation phase of the monitoring project ended in 1989. BMPs installed on the watershed include no-till, grassed waterways, vegetative filter strips, CRP (conservation resource program), animal waste storage facilities, fencing, and stip cropping. The post-BMP implementation phase of the project will continue to be monitored for several years to evaluate both the short term and long term impact of the practices.

The Owl Run watershed monitoring project makes it possible to develop, verify, or validate various nonpoint source pollution models with the abundant meteorological, hydrological, land use, soil and water quality data available. The database management system established by the project can greatly enhance the usability of the data collected for model verification and BMP evaluations.

Model Validation

It is necessary to validate a model before applying it to a specific area. Validation of a model is defined as demonstrating its applicability by identifying the accuracy of the parameters selected for the study area. Complete model validation requires testing over the full range of conditions for which the model simulates [Hern, et al., 1987]. There are generally two major steps involved in model validation. First, the correctness of the selected model parameters needs to be determined by comparing model predictions with measured watershed response from a series of record, and calibrating the selected input parameters, if necessary. The second step is to use the selected parameter set (or calibrated parameters) on a different series of record and determine simulation errors [Haan, et al., 1982; Young and Alward, 1983]. Therefore, two independent series of events need to be provided to carry out this procedure.

The purpose of this chapter is to demonstrate the AGNPS applicability to Virginia Piedmont conditions by comparing its predictions with data collected from the Owl Run watershed. As required by the validation procedure, two series of storms were selected from 1987, and 1988 records. The 1988 series of storms were used for evaluating the selected input parameters. The parameters obtained were then used on the second series (1987) with the same landuse and management conditions. The simulation results and the corresponding observed data are plotted against each other to present a visual view of the model performance. Both visual comparisons and statistical analysis were performed on simulation results of both storm series to evaluate the model's applicability.

Selection of the storm events

Over 100 storm events are observed on the Owl Run watershed each year. Among these events, only about 40% produced measurable runoff. The precipitation amounts for each of these storms are generally larger than 7 mm [Mostaghimi, et al., 1989]. For the purpose of data selection and analysis, storms greater than 7 mm in rainfall amount are defined as primary storms. To meet the requirement of statistical analysis and model validation, 11 of the 37 primary storm events which occurred during 1988 were selected randomly throughout the year for parameter evaluation and model testing. 12 primary events from 1987 were also selected, using the same procedure as 1988, to carry out the model validation procedure.

Preparation and evaluation of input parameter values

Over 20 input parameters for each cell are needed for AGNPS simulations. Of these parameters, some of them maintain the same value throughout the year and are not time dependent. These values include topographic data such as land slope, slope direction (aspect), channel slope, channel side slope, and soil properties including soil textures, erodibility factors, and hydrologic soil groups. Other parameters such as curve number, cropping factor and Manning's roughness coefficient are functions of crop types and other surface cover and vary with the time of the year.

The procedure used for preparation and evaluation of parameters in this study consisted of two steps. First, the input parameters for a watershed were selected homogeneously throughout the year, i.e. the parameters were assumed to be the same for different crop stages. This set of parameters depicts the average conditions on the watershed throughout the year. A series of events were simulated and the results were compared with the data collected from the Owl Run watershed. The model with homogeneous parameters underpredicted watershed responses for those storm events occurred during dormant season, and overpredicted the responses for the events during growing season. The second step was to divide the whole year into two different seasons, dormant and growing, in an attempt to refine the input parameter values. The period from May 15 through October 15 was defined for Owl Run as the growing season, and the rest of the year as dormant season. Input parameters with seasonal changes such as cropping factor in USLE, curve number, Manning's roughness coefficient, and surface condition constant were then prepared for the two seasons.

As a distributed watershed model, the size of the cells in AGNPS needs to be selected carefully. As mentioned in the literature review chapter, it takes about 20 minutes to collect and manage necessary data for the preparation of input parameters for each cell [Young, et al. 1987; Koelliker and Humbert, 1989]. The cell size for this study has to be selected carefully because the parameters used in this study are treated manually. Feezor and Hirschi [1989] suggested that the smallest size practical should be used to maintain the highest accuracy with AGNPS simulations. They used one-hectare cell size as the basic size and compared the simulation results with that of other larger cell sizes. The four-hectare size was found to cause an overall deviation less than 10 percent for the results of the basic cell size for both sediment yield and nutrient loadings. A four-hectare cell size was chosen for this study for the sake of both time-saving and necessary accuracy of the results.

Topographical parameters

Cell number, receiving cell number, land slope, slope shape, slope length, flow direction (aspect), channel slope, channel side slope, and channel type indicator were obtained from 1:24000 scale United States Geological Survey topographic map of Fauquire County, Virginia, which was digitized into VirGIS database [Shanholtz, et al., 1987].

Cell number and the receiving cell number are used by the model to identify the locations of the watershed behaviors. The other topographic parameters, together with the cell and receiving cell numbers, are used by the model to route the runoff, sediment, and chemicals downstream and to the watershed outlet.

Curve Number (CN)

The curve number is a key parameter used in SCS curve number method, which is adopted by the hydrology component of AGNPS to estimate surface runoff volume. This parameter is a function of several variables including landuse, hydrologic soil group, and antecedent soil moisture conditions. The landuse varies seasonally, the antecedent soil moisture condition varies from event to event, while the hydrologic soil group remains constant. Curve numbers were determined using the procedures outlined in the Engineering Handbook, Section 4 -- Hydrology [USDA-SCS, 1972]. A simple computer program was developed to calculate a CN for each cell based on landuse, antecedent soil moisture condition, and soil property. With the incorporation of this software program into AGNPS, the CN values in the input file of the model could be replaced by landuse, soil hydrologic group, and antecedent soil moisture condition, which are available as different data layers of a typical GIS.

Average parameter values for growing and dormant seasons are 79 and 87, respectively, ranging from 66 to 91, and from 71 to 94. Conditions used for selection of the parameters are given in Table 5.

Cropping factor (C)

The Universal Soil Loss Equation (USLE) is used in the erosion component of the model as described in the AGNPS chapter. The C factor used in USLE is closely related to crop types, growing seasons, and the amount of residue left on soil surface. A detailed landuse monitoring program is very helpful to determine the C value by using the classification tables in AGNPS User's Manual (Version 3.5) [Young, R.A., et al., 1989]. The landuse data used in this study is the general landuse map digitized into a VirGIS data base (Figure 6). Two basic sets of C values were prepared, one for the dormant season, and the other one for growing season, as used in the hydrology component. Conditions adopted for the two seasons and their average values were listed in Tables 5 6, respectively. The values are calculated by using the tables presented by Wischmeier and Smith [1978] according to the conditions listed in Table 5.

Support practice factor (P)

The P factor is another parameter used in the USLE. This is a key parameter to reflect the impact of various management practices on improving water quality related to nonpoint source pollution. The P parameter is defined by Wischmeier and Smith [1978] as the ratio of soil loss with a specific support practice to the corresponding loss with up-and-down-slope culture. The selection of the factor is based on various conservation practices [Wischmeier and Smith, 1978] which are related to the time of the year. For simulations of the events before 1989, when the pre-BMP phase of the monitoring project ended, a value of 1 is used to represent the conditions during that period. The support practices related to the P factor include contouring, contouring stripcropping, buffer stripcropping, and terracing. Any of these practices can be simulated by the model for post-BMP period using the procedures described by Wischmeier and Smith [1978].

Manning's roughness coefficient (n)

This factor is used in sediment routing component of the AGNPS, in which the Bagnold stream power equation is used to evaluate effective sediment transport capacity. Manning's roughness coefficient is used in calculating the average velocity of flow in the equation. Roughness coefficients for different landuse conditions for each storm were selected using the AGNPS User's Guide for channelized flow and overland flow. For those cells where there was no definable channel, roughness coefficients appropriate for the landuse of the cells were selected for the main surface condition. Average n values and their corresponding conditions for the two seasons used in this study are also listed in Tables 5 and 6.

Table 5. Conditions for which AGNPS parameters were selected for Owl Run simulations.

Parameter	Season	Hay	NT * corn	CT * corn	Pasture	Woodland
CN [1]	dormant	small grains straight - poor	row crop-straight + CST - poor *	row crop - straight row - poor	fallow-straight	woods - poor
	growing	small grain straight - good	row crop-straight + CST - good *	row crop-straight row - good	pasture - fair	woods - good
C [2]	dormant	grain after grain - SB	NT plant in crop residue	RdR, spring TP * fallow	permanent pasture - 60% cover-weeds	managed woods 20% canopy
	growing	grain after grain	NT plant in crop residue	RdR, spring TP	permanent pasture - 60% cover-grass	managed woods 80% canopy
SCC [3]	dormant	rotational meadow	fallow	row crop - straight	pasture - fair	woodland
	growing	permanent meadow	row crop - contoured	row crop - straight	pasture - good	woodland
n [4]	dormant	grass - sparse	wheat straw - 1 ton/ac residue	smooth, bare	grass sparse	grass - good
	growing	grass - very dense	wheat straw 4 tons/ac residue	small grain - good 14 - inch rows	grass excellent	grass - extra
FL [5]	all seasons	no manure application	average manure N: 50 lb/a, P: 20 lb/a	average manure N: 50 lb/a, P: 20 lb/a	average manure N:50 lb/a, P: 20 lb/a	no manure application
FA [6]	all seasons	no manure application	chisel plow + planter	disk + planter row cultivator	planter	no manure application

* NT = no-till; CT = conventional tillage; CST = conservation tillage; TP = plowed with moldboard; RdR = crop residues removed.

1. CN = curve number; 2. C = Cropping factor in USLE; 3. SCC = surface condition constant; 4. n = Manning's roughness coefficient; 5. FL = Fertilization level; 6. FA = Fertilizer availability factor.

Table 6. Values of selected AGNPS parameters related to landuse in Owl Run watershed.

Landuse	Season	CN[1]	n[2]	C[3]	SCC[4]	FL[5]	FA[6]
Corn NT	Dormant	71 79 86 89	0.090	0.08	0.22	1	57
	Growing	64 75 82 85	0.250	0.06	0.29	1	57
Corn CT	Dormant	72 81 88 91	0.030	0.49	0.05	1	21
	Growing	67 78 85 89	0.200	0.22	0.05	1	21
Hay	Dormant	65 76 84 88	0.040	0.12	0.29	0	0
	Growing	63 75 83 87	0.300	0.04	0.59	0	0
Pasture	Dormant	77 86 91 94	0.040	0.09	0.15	1	85
	Growing	49 69 79 84	0.130	0.04	0.22	1	85
Idle	Dormant	65 76 84 88	0.040	0.09	0.15	0	0
	Growing	63 75 83 87	0.130	0.04	0.22	0	0
Forest	Dormant	44 66 77 83	0.080	0.01	0.29	0	0
	Growing	25 55 70 77	0.350	0.01	0.29	0	0
Water	Both	100	0.990	0.00	0.00	0	0

1. Curve numbers corresponding to the four hydrologic soil groups A, B, C, and D, from left to right. 2. Manning's roughness coefficient; 3. Cropping factor in USLE; 4. Surface condition constant; 5. Fertilization level; 6. Fertilizer availability factor.

Fertilization level and availability factor

These two parameters are used by the model to estimate the N and P concentrations in the runoff and the sediment. The fertilization level used in the nutrient component of the model designates a level of fertilization in the field at the time of chemical application. This factor is not well explained in AGNPS User's guide because of the various sources of nutrients and complex nutrient transformation processes. According to Novotny and Chesters [1981], about 46% of soil nitrogen comes from fertilizer application, 7% from manure application, 17% from crop residue and 20% from nitrogen fixation from the atmosphere.

To determine appropriate values for both of the factors, calibration was performed by comparing the simulation results with the observed data. The procedure and the criteria used for calibration is discussed in the Model Calibration Section.

It is suggested by the AGNPS User's Guide that, for a manure applied field, low fertilization level (50 lb/ac N and 20 lb/ac P) for average manure application, and medium fertilization (100 lb/ac N and 40 lb/ac P) for a heavy application of manure be assumed for the model input. Tables 5 and 6 list the average values for the manure applied fields and the conditions adapted for different landuses, respectively, which were determined through calibration.

Fertilizer availability factor denotes the percent of fertilizer left in the top 1 centimeter of soil at the time of the storm. This value changes with time because of the processes of chemical volatilization, crop uptake, decay or attenuation, leaching to ground water, and losses to runoff water. Therefore, the magnitude of this parameter is related to many factors such as different types of cultivation activities, the methods of chemical application, meteorological conditions including temperature, moisture, wind speed, amount and intensity of precipitation, or combinations of various conditions [Young, et al., 1985]. Wheras the only factor considered in the user's manual for determination of this availability factor is the type of cultivation activities. Detailed landuse data is expected to make the parameters evaluated as realistic as possible. Values and corresponding cultivation activities used for this study were determined by assuming that there are two cultivation activities within each of the two periods selected for the year, representing average conditions for that period. Minor adjustments for this parameter were also made through calibration (refer to Calibration Section). Conditions and final values used are also listed in Tables 5 and 6, respectively.

Soil erodibility factor (K)

Some soil surveys include the soil erodibility factor, K, for different layers of the soils. For Owl Run watershed, the latest version of soil survey is the Fauquir County Soil Survey published in 1956 [USDA-SCS, 1956]. This soil survey does not present the soil erodibility factors. The K factors used for AGNPS input were identified by using the procedure outlined by Novotny and Chesters [1981], which is based on organic matter content and textural classes of the soils. This is a simplification of the relationship developed by Wischmeier and Mannering [1969] on 55 soils in the United States. The relationship is represented by an empirical equation with 24 variables (15 soil properties and their combinations including organic matter content, aggregation index, thickness of granular material, structure, antecedent soil moisture, etc.).

Surface condition constant (SCC)

This parameter is based on the condition of the landuse at the time of storms. This parameter is used to make adjustments for the time it takes for overland flow to channelize in the sediment and chemical routing components of the model. The values for various landuse and the two seasons used in this study were obtained using the procedure similar to that of curve numbers outlined in the AGNPS User's Guide [Young, et al., 1985]. The conditions used for the determination of the values in Table 5, and the selected values are listed in Table 6.

Chemical oxygen demand (COD) factor

The value of this factor is based on the landuse of the individual cells. It represents the average COD concentration of the runoff from the cell. The AGNPS User's Guide provides the values of the factor for various landuses, which were based on estimates of background concentrations from several northern states of the United States.

Statistical analysis

Errors from a variety of sources may be involved in modeling efforts. Measurement of observed data, preparation of model parameters, and approximations and assumptions of physical relationships adopted by the model are major sources of the errors. Wrong conclusions may be based on these uncertainties. Statistical analysis provides a measurement of model accuracy by identifying the total variation caused by the errors involved.

Several statistical methods are used in this study to evaluate the model performance and to provide further understanding of the model's applicability to Virginia's conditions. The statistical procedures used in this study include:

1. Regression analysis;
2. Root mean square error (rms);
3. Comparison of means between the observed and simulated results.

Regression analysis:

A simple linear regression line can be obtained by least square method

$$Y_i = a + bX_i + e_i \qquad i = 1,2, \ldots\ldots, n. \tag{14}$$

in which Y_i is the ith value of simulation; n is the number of simulations within a series; X_i is the observed value; a is the intercept, b is the slope of the regression line; and e_i, is a random variable representing errors around the regression line. A first impression can be obtained by drawing the points of simulation and the regression line on a figure with X coordinate being the observed values and Y coordinate the simulated values. Several statistics can be computed from the regression Equation (14) [Haan, 1977]. The coefficient of determination, R^2, is the ratio of the sum of squares due to regression to the total sum of squares. It measures the ability of the regression line to explain variations in the dependent variable. If the regression equation perfectly predicted every value of Y_i, or $e_i = 0$ for every i, the R^2 would be 1. On the other hand, if none of the variations in Y can be explained by the regression equation, the value would be zero. The closer the R^2 is to 1, the better is the relationship between simulated and observed values.

An estimate of the intercept and slope of the linear regression line can be obtained by using the least square method. A slope of less than 1 means that the model underestimates the watershed response, especially for large values, and a slope greater than 1 indicates overestimation. An negative intercept means that the model underestimates the watershed behavior, at least for small events, and vice versa.

To test the significance of the slope and intercept, the null hypotheses on the intercept and the slope can be written as:

$$H_0\text{: } a = 0 \tag{15 a}$$

$$H_0\text{: } b = 1 \tag{15 b}$$

where a is the intercept and b is the slope. The test statistics, a/S_a and $(b-1)/S_b$, are distributed as student's t with n-2 degrees-of-freedom. S_a^2 and S_b^2 are variances of the intercept and the slope, respectively. These tests should be conducted as two-tailed tests with 5% probability significance level on each side ($t_{\alpha/2=0.05}$). A SAS simple linear regression program can be used to test H_0: a = 0, H_0: b = 0, but not H_0: b = 1. Therefore hypothesis test on slope of 1:1 (or b = 1) was performed manually in this study. Nonsignificant tests (null hypotheses are accepted) of equations 15 a and 15 b provide confidence to the modeler and demonstrates the applicability of the model to the study area. In reality, it is impossible to obtain an exact 1:1 regression line with a zero intercept. Evaluation of b, a, and R^2 provide additional levels of insight when comparing the model prediction with the observed data.

While the coefficient of determination, R^2, as mentioned above, provides a visual evaluation of overall relationship between simulated and measured data, drawing confidence interval lines along the obtained regression line gives the modeler or readers further information to evaluate the model from the viewpoint of confidence intervals. For a certain level of confidence, the narrower the band area between the confidence interval lines, the better the sample data represents the population. The ultimate case is the coincidence of the two confidence interval lines on the regression line, which means that there is no random error between the predicted and observed values.

The relationship used for calculating confidence intervals on the regression lines are given by:

$$L = y - S_y t_{1-\alpha/2,\, n-2} \tag{16 a}$$

$$U = y + S_y t_{1-\alpha/2,\, n-2} \tag{16 b}$$

$$S_y = s\sqrt{1/n + (x - \bar{x})/\sum(x - \bar{x})} \qquad (16\,c)$$

where L and U are lower and upper confidence limits of the regression line, respectively; y and x are coordinates of simulation points; s is the standard deviation of random variable e_i in equation (14); $\bar{x}$ is the mean value of observed results; and α is the level of confidence [C.T. Haan. 1977].

Since our work is based on samples, all the statistic parameters (a, b, R^2) are random variables with certain probability distribution functions. The regression line is also a random variable as a function of the random variables. For a continuous random variable, the probability that the variable equals to a certain value is zero. The concept of confidence interval make it possible to evaluate the variation of the errors involved in the simulation.

Root mean square (rms) error:

The root mean square error provides a pooled measure of differences between the observed and simulated watershed response [Thomann, 1982]:

$$\text{rms} = \sqrt{\sum_{i=1}^{n} \frac{D_i^2}{n}} \qquad (17)$$

where D_i is the difference between the observed and simulated values, and n is the number of pairs of comparisons. The rms represents the standard error of estimate of model prediction and provides a direct estimate of model errors. The rms is also statistically well-behaved (identical, and independently distributed as normal). If expressed as a ratio to the mean value of the observed or simulated results data (whichever is smaller), the root mean square error represents a type of relative error and some researchers call this normalized quantity of the coefficient of variation (CV) [Young, and Alward, 1983]. A relative error is especially useful when comparisons are being made between different models. The disadvantage of the rms is that it does not reflect the impact of the magnitude of variables.

Comparison of means between observed and simulated results:

A hypothesis test on the differences between observed and simulated values can be performed under the null hypothesis: $H_{0:}\ \overline{D} = 0$. Where $\overline{D}$ is the mean of the differences between the measured and predicted values [Thomann, 1982]. The test statistic, t_{obs}, is distributed as a student's t probability density function with a degree-of-freedom of n - 1 :

$$t_{obs} = \frac{\overline{D} - d}{S/\sqrt{n-1}} \tag{18}$$

where d is the true difference expected between model prediction and the observed values which is assumed to be zero, and S is a pooled value of the standard deviations of simulated and measured data. A significant result of this test (the null hypothesis $H_{0:}\ \overline{D} = 0$ is rejected) at certain level, say 5%, means that there is some apparent difference between the model prediction and the measured watershed response. A nonsignificant result (accepted the null hypothesis) gives us some confidence that there is not enough evidence to criticize the overall model prediction.

All the three procedures mentioned above were used to validate the applicability of the model to the study area. These methods evaluate the model credibility from different statistical viewpoints. The rms error assess the overall model credibility by providing direct measure of model errors.The test for comparison of means answers the question whether the difference between the simulation results and the observed data is statistically acceptable. The parameters involved in the simple linear regression procedure measure the errors related to the magnitude of the water quality problem, and give the confidence intervals on the simulation results.

For hypothesis test problems, the criteria used to validate models are within the framework of statistical analyses [Yang and Alward, 1983; Thomann, 1982]. A 5% significance level is widely agreed to be reasonable to determine the validity of models. For direct error estimate procedures, the criteria used by some researchers [Hedden, 1986] are: a) for screening applications, the model(s) should be able to replicate observed field data within an order of magnitude; and b) for site-specific applications, the prediction of the model(s) should be able to match the measured data within a factor of two. Nevertheless, some scientists indicate that the site-specific criteria might not be met easily by even the best models using carefully measured site-specific parameters [Smith, M.C., et al., 1989].

Calibration

Calibration of AGNPS simulation was performed to closely approximate the observed runoff volume, sediment yield, and nutrient loadings from the watershed. Such calibration allows for reasonable estimate of input parameters for the model. Relevant parameters for model calibration included curve number in the hydrology component; C factor, surface cover condition factor, and Manning's roughness coefficient used in soil erosion and sediment transport component; and fertilization level and fertilizer availability factors in chemical loading component of the model.

Because of the error accumulation from runoff and sediment yield to nutrient loadings, the accuracy of the hydrology and sediment simulations will influence the nutrient loading component. Therefore the calibration procedure was performed on the hydrology, soil erosion and sediment transport, and then the nutrient loading components.

These parameters were calibrated using the 1988 data series and the results were evaluated by using the statistical measures and criteria mentioned previously in this section. The parameters were adjusted according to the sensitivity analysis made by Young et al. [1985]. Various tables for determination of the parameters collected in the AGNPS user's manual were used to assure that the parameters were adjusted within reasonable ranges. Once the selected parameter were calibrated to within the satisfactory criteria, they were used for the 1987 data to evaluate the results using the same statistical procedures. All of the calibrated input parameter values were realistic and within the published ranges. Conditions and the corresponding adjusted parameter values are listed in Tables 5 and 6, respectively.

Results and discussion

The procedures outlined for model validation required simulations to be performed on both 1987 and 1988 data series selected for this study. The magnitude and date of occurrence of the selected storm events are listed in tables 7 and 8 for the two series, respectively. The model input parameters were prepared for both the growing season and the dormant season as defined previously in this chapter. The growing season parameter set was used to simulate those events occurred during the crop growth period in the area, and the dormant season set was used for those events occurred during the rest of the year.

All the three statistical methods explained in previous section were used on the two series of storms. The parameters selected for the first series (1988) were tested by these methods and calibrated to the measured data. Simulations were then performed for 1987 events and the results were tested by the same statistical procedures. The root mean square errors (rms) were examined first because the corresponding relative error (coefficients of variation, CV) can be used to compare directly with the criteria suggested by some investigators [Hedden, 1986]. As defined in equation (17), rms represents the overall average error between the observed and simulated results. The CV is the ratio of rms to the observed or simulated mean value (whichever is smaller). Therefore, the criterion of within "a factor of two" will be satisfied when the ratio is less than 1 for site specific simulations, and the criterion of within "an order of magnitude" will be met when the CV value is less than 9. According to these criteria [Hedden, 1986; Smith, et al., 1989], if the model simulates the watershed response within a factor of two, the simple linear regression procedure and testing on differences of means will give further confidence of the model credibility. When the relative error is outside of a factor of two (CV is greater than 1), the simple linear regression analyses and the tests on means can be used to diagnose the simulation problems.

Simulation results and direct comparisons with the observed data for runoff volume, peak flow rate, sediment yield, total nitrogen, and total phosphorus concentrations at the watershed outlet, are tabulated in tables 7 and 8 for 1988 and 1987 data sets, respectively. The two tables also include values of root mean squares, coefficient of variation and parameters of simple linear regressions (intercept, slope, and coefficient of determination). Test results on the intercept, slope and differences of means for various parameters are listed in tables 9 and 10 for 1988 and 1987 data sets, respectively. Simulation results for the two storm series are also plotted against the observed data in figures 7 through 11 for 1988 series, and figures 12 through 16 for 1987 series. Regression lines and 95% confidence intervals along the lines are also plotted in the figures corresponding to each of the parameters.

The runoff volumes predicted by the model compared favorably with the observed data. As shown in figure 7 and figure 12 (runoff volume simulations for 1988 and 1987), simulation points are well distributed along the regression lines, with intercepts and slopes being nearly zero and 1, respectively. The confidence interval along the regression lines lie very close to the regression lines. These results indicate that the regression lines, which are random variables, will fall between the interval lines, 95% of the time. The relative errors evaluated in terms of CV values were 0.15, and 0.29 for 1988 and 1987 (tables 7 and 8), respectively, well within the criterion of "a factor of two". R^2 values of the two series presented in tables 7 and 8 (0.99 and 0.97, respectively) are large enough to demonstrate suitability of the relationship used in the hydrologic component of the model. The hypotheses of zero intercept and 1:1 slope were accepted at the 5% significance level (tables 9 and 10). This indicates that the simulation results consistently agreed with the observed data. Tests on the means of simulated and measured runoff showed no significant differences (tables 9 and 10) so that the hydrology component was validated with further confidence.

Peak flow rates were generally overpredicted by the model. The overall relative errors (expressed by CV) were 1.02 and 1.39 for 1988 and 1987, which were just over the "a factor of two" criteria. The Discrepancies between the observed and simulated peak flow rates increase proportionally with the magnitude of the storm events. Slopes of 1.39 and 1.55 were computed by the regression analyses for 1988 and 1987 events, respectively, which means the error increases proportionally with the magnitude of the storms. Hypothesis tests on differences between the mean values of observed peaks and simulated peaks were rejected at the 5% significance level, indicating that significant errors do exist between the simulated and observed peak flow rate. The discrepancies between the

Table 7. Summary of Owl Run Simulations for 1988.

Event	Rainfall (mm)	Runoff volume (mm)		Peak Rate (mm/h)		TSS (T)		TN (ppm)		TP (ppm)	
		predicted	observed	predicted	observed	predicted	observed	predicted	observed	predicted	observed
01/25	13.91	2.29	2.21	0.56	0.18	11.4	12.2	9.9	14.3	2.1	0.7
02/02	22.78	5.59	6.37	1.33	1.03	60.0	77.8	9.9	7.9	2.6	1.4
02/11	13.72	1.52	2.07	0.37	0.16	10.1	6.9	11.3	7.9	2.6	1.3
03/04	12.95	1.52	1.02	0.37	0.11	8.7	5.9	10.6	9.9	2.6	1.1
03/26	19.28	1.52	1.30	0.37	0.26	11.5	7.5	11.3	8.9	2.6	2.8
04/06	33.92	2.54	3.40	0.59	0.14	19.4	15.0	8.7	11.8	2.3	0.8
05/04	65.67	10.16	9.26	0.46	0.45	94.0	88.9	10.3	14.3	3.1	2.3
05/18	26.24	2.79	1.53	0.69	0.31	11.1	22.9	14.9	12.0	2.5	2.4
07/23	9.14	0.25	0.28	0.04	0.05	5.0	1.7	19.9	22.5	6.3	5.1
11/05	10.36	0.25	0.50	0.07	0.06	8.2	3.0	20.6	23.7	7.1	7.0
11/27	28.45	2.54	2.95	0.59	0.19	15.2	9.8	9.2	9.5	2.8	1.7
Mean	23.31	2.82	2.81	0.50	0.27	23.1	22.9	12.4	13.0	3.3	2.4
rms *		0.65		0.28		7.41		2.89		1.08	
cv		0.25		1.05		0.32		0.22		0.45	
intercept		0.017		0.206		2.895		4.038		1.335	
slope		1.009		1.079		0.885		0.646		0.824	
n **		11		11		11		11		11	
R^2		0.937		0.728		0.932		0.682		0.897	

* Root mean square.

** Number of simulations used in the statistics.

Table 8. Summary of Owl Run Simulations for 1987.

Event	Rainfall (mm)	Runoff volume (mm)		Peak Rate (mm/h)		TSS (T)		TN (ppm)		TP (ppm)	
		predicted	observed	predicted	observed	predicted	observed	predicted	observed	predicted	observed
02/22	26.04	6.10	10.51	1.41	0.15	22.2	17.9	19.7	8.2	4.2	3.2
04/15	59.51	27.90	27.32	5.96	2.85	43.9	46.8	11.6	11.8	2.5	3.1
06/01	9.18	0.00	0.48	0.04	0.01	2.3	0.8	10.7	8.1	2.3	2.8
06/21	12.30	0.25	0.43	0.07	0.02	3.0	0.5	19.9	16.9	5.3	2.4
06/26	6.79	0.00	0.26	0.01	0.01	1.9	0.2	11.2	18.5	3.4	3.0
09/11	29.21	6.60	5.87	1.45	0.94	23.2	22.5	18.3	11.5	2.8	1.9
09/19	20.83	0.35	0.79	0.07	0.09	2.9	0.8	12.7	6.7	2.9	1.1
10/03	14.22	0.25	0.23	0.04	0.02	2.4	0.1	8.8	4.9	2.1	0.9
12/10	16.51	3.30	3.41	0.79	0.59	16.4	22.4	9.3	8.7	2.1	0.8
12/15	19.30	4.32	5.59	1.05	0.47	18.3	15.4	8.8	7.4	1.8	0.6
12/25	10.41	0.76	1.31	0.20	0.10	5.7	3.3	8.9	5.2	1.9	0.6
12/28	12.70	3.30	3.83	0.79	0.36	13.3	14.9	9.3	6.9	1.8	0.9
Mean	19.75	4.43	5.00	0.99	0.47	13.0	12.1	12.4	9.6	2.7	1.8
rms *		1.39		1.00		2.90		5.17		1.33	
cv		0.28		2.15		0.24		0.54		0.74	
intercept		-0.555		0.094		2.266		0.464		1.327	
slope		0.996		1.551		0.881		0.871		0.594	
n **		12		12		12		12		12	
R^2		0.969		0.929		0.962		0.402		0.549	

* Root mean square error.

** Number of simulations used in the statistics.

Table 9. Test of intercept, slope, and differences between simulated and observed data (1988).

Categories			Runoff volume	Peak runoff	TSS	TN	TP
Intercept	H_0: $a=0$	a *	0.017	0.206	2.895	4.038	1.335
		SE **	0.316	0.077	2.798	1.909	0.268
		t_{obs}	0.054	2.675	1.035	2.115	4.980
		$t_{(n-2),95}$	2.228	2.228	2.228	2.228	2.228
		conclusion	accepted	accepted	accepted	accepted	rejected
Slope	H_0: $b=1$	b *	1.009	1.079	0.885	0.646	0.824
		SE **	0.083	0.205	0.076	0.137	0.088
		t_{obs}	0.108	0.385	1.513	2.583	2.000
		$t_{(n-2),95}$	2.228	2.228	2.228	2.228	2.228
		conclusion	accepted	accepted	accepted	rejected	accepted
Differences	H_0: $D=0$	$\overline{D}$	0.007	0.227	0.273	-0.555	0.909
		S	0.879	0.108	9.261	2.971	1.580
		t_{obs}	0.008	2.102	0.029	-0.619	1.567
		$t_{(n-1),95}$	2.228	2.228	2.228	-2.228	2.228
		conclusion	accepted	accepted	accepted	accepted	accepted

* Intercept and slope obtained by least square estimate.

** Standard error.

Table 10. Test of intercept, slope, and differences between simulated and observed data (1987).

Categories			Runoff volume	Peak runoff	TSS	TN	TP
Intercept	H_0: $a = 0$	a *	-0.555	0.094	2.226	4.604	1.327
		SE **	0.482	0.193	0.960	3.343	0.306
		t_{obs}	-1.151	0.478	2.319	1.352	4.337
		$t_{(n-2),95}$	-2.201	2.201	2.201	2.201	2.201
		conclusion	accepted	accepted	rejected	accepted	rejected
Slope	H_0: $b = 1$	b *	0.996	1.551	0.881	0.871	0.590
		SE **	0.054	0.129	0.058	0.354	0.156
		t_{obs}	0.074	4.271	2.052	0.364	2.628
		$t_{(n-2),95}$	2.201	2.201	2.201	2.201	2.201
		conclusion	accepted	rejected	accepted	accepted	rejected
Differences	H_0: $D = 0$	$\overline{D}$	-0.575	0.532	0.825	2.867	0.907
		S	2.332	0.393	4.072	1.309	0.389
		t_{obs}	-0.246	1.354	0.203	2.197	2.356
		$t_{(n-1),95}$	-2.201	2.201	2.201	2.201	2.201
		conclusion	accepted	accepted	accepted	accepted	rejected

* Intercept and slope obtained by least square estimate.

** Standard error.

simulated and observed peak runoff rates can be partially due to the empirical nature of the relationship used in AGNPS for calculating the peak rates. The empirical equation used to predict peak flow in AGNPS (equation (5) in this study) was developed using data from 304 storms occurred on 56 watersheds located in 14 states [Knisel, et al., 1980]. The watershed sizes ranged from less than 100 ha to over 6000 ha, and the exponents for drainage area A and runoff volume Q in equation (5) vary with the sizes of watersheds. The current version of AGNPS does not have the capability of adjusting these two parameters for specific applications.

The erosion and sediment yield predictions of the model agreed well with the measured data. The coefficients of variation, CVs in tables 7 and 8 for TSS (total suspended sediment), were quite small and easily within "a factor of two" (less than 1). The coefficients of determinations, R^2, were 0.94 and 0.96 for 1988 and 1987, respectively. This simply means that the random errors are only 6 and 4 percent of the total variations. These values of R^2 for sediment yield are smaller than those for runoff because errors within the hydrology components of AGNPS could have been accumulated into the erosion and sediment routing components. The hypotheses that the intercepts of the regression lines are zero were accepted for both data series, however the test on slope for the 1988 data was rejected. Therefore, it can be concluded that there are some minor errors which associated with AGNPS predictions of TSS increase proportionally with the storm magnitude. The overall differences between the simulated and measured data of the two series were not significant (Tables 9 and 10). This demonstrated further that the sediment yield component is acceptable for our study area. Large differences between simulated and observed sediment yield can be found for some big storms occurred during the two years (table 7). The energy intensity value EI, used in the USLE, may not be evenly distributed spatially throughout the watershed. The current version of AGNPS does not take into account the spatial variation of the EI values within a watershed. The model uses only one EI value for the whole watershed. This uncertainty was incorporated into the modeling results because Thiessen average EI values were used as input. Errors from hydrology and soil erosion and sediment transport components were accumulated into the following nutrient loading component.

Results from nutrient modeling were acceptable. The CVs were 0.22 and 0.44 for nitrogen, and 0.43 and 0.74 for phosphorus for the 1988 and 1987 series (tables 7 and 8). The confidence interval bands around the regression lines (figures 10, 11, 15, and 16) are wider than those of the the other parameters tested. This variability is understandable because of larger random errors in equation (14) accumulated from the hydrology and sediment components. The R^2 values for the two nutrient analysis are smaller that those for runoff volumes and sediment yields. This is also explained by the error accumulation. The student t tests on means of nitrogen concentrations were accepted for both 1988 and 1987 data (tables 9 and 10). The t test on means of phosphorus concentration for 1988 was accepted, but the for 1987 was rejected. Although the difference is significant, the calculated t observation was just slightly out of the confidence interval, which can still be considered to be close to the population mean (tables 9 and 10).

Intercepts larger than 0 and slopes smaller than 1 were identified by the hypothesis tests for both N and P values. In dealing with the chemical movement, the AGNPS model assumes a constant rate of nutrient movement into runoff (0.075 for both nitrogen and phosphorus). This assumption neglects the time it takes for the nutrients to reach equilibrium between the adsorbed and soluble phases. The component also uses constant values to evaluate the original nutrients in the soil water (5 ppm for nitrogen and 2 ppm for phosphorus). A constant rate is also used to account for the nitrogen content in the precipitation. These simplifications make it difficult to simulate low concentrations of chemicals in runoff.

Several high values of nitrogen concentration were recorded during fall season of 1988. Similar results were also obtained for phosphorus during late fall of 1987. The time variable used in this study has only two 'values', the dormant season and the growing season, which are still not refined enough to closely simulate time-dependent processes such as chemical application timings. The relationship used in AGNPS nutrient model does not consider some of the transformation processes of the nutrients like volatilization, degradation, and crop uptake. Detailed information is also needed for evaluating and calibrating the two input parameters for the nutrient component, fertilization level and availability factor.

As discussed above, simulation results of runoff, sediment yield, and nutrient loadings, agreed reasonably with the observed data. The relative errors are within a factor of two, which is suitable for site specific applications, and the overall differences of means between observed and simulated results are negligible as indicated by the hypothesis tests. Though discrepancies were found between simulated and observed peak flow rates, they do not have significant impacts on the sediment simulation. Based on the comparison of simulated and observed data, it is concluded that AGNPS is applicable to predicting the impact of agricultural activities on NPS pollutant loadings from watersheds in Virginia Piedmont areas.

Conclusions

The applicability of AGNPS to Owl Run watershed was examined. Statistical analyses were used to demonstrate the model's validity. Criteria for model acceptability were discussed and used in the model validation. Two basic seasons, dormant and growing seasons, were used in this study to account for seasonal variations. Two series of storm events occurred in 1987 and 1988 were used in the validation procedure. Statistical procedures including regression analyses, and comparison of means were performed on the simulation results. The following conclusions are made:

1. Parameters of AGNPS prepared were validated to the study area so that the model is applicable to the Virginia Piedmont conditions.

2. Parameters should be prepared for different seasons, the more stages within the year to be considered, the more accurate simulations could be expected. Calibration was necessary in this study because two seasons are still not enough to describe variations of parameters within the year.

3. Relative error analysis performed by root mean square errors demonstrated that the parameters prepared for the two seasons are acceptable for long term evaluation of management practices since the results satisfied the criteria agreed by researchers mentioned in this section.

4. Results of runoff volume agreed well with the observed data while discrepancies were found between simulated and observed peak flow values.

5. The sediment yield compared well with the observed data. The results would improve if spatial distribution of precipitation and erosion indices could be considered by the model.

6. The simulations for nitrogen and phosphorus concentrations in runoff at the watershed outlet agreed reasonably well with the measured data. Discrepancies were found between the simulated and observed nutrient loadings for a few specific events because the effect of the timing of the chemical applications could not be incorporated into the model since only two seasons were assigned for the year. Constants used by the model to estimate the original nutrient contents in the soil, and the extraction rate of chemical movement into runoff, introduced errors in the simulation results.

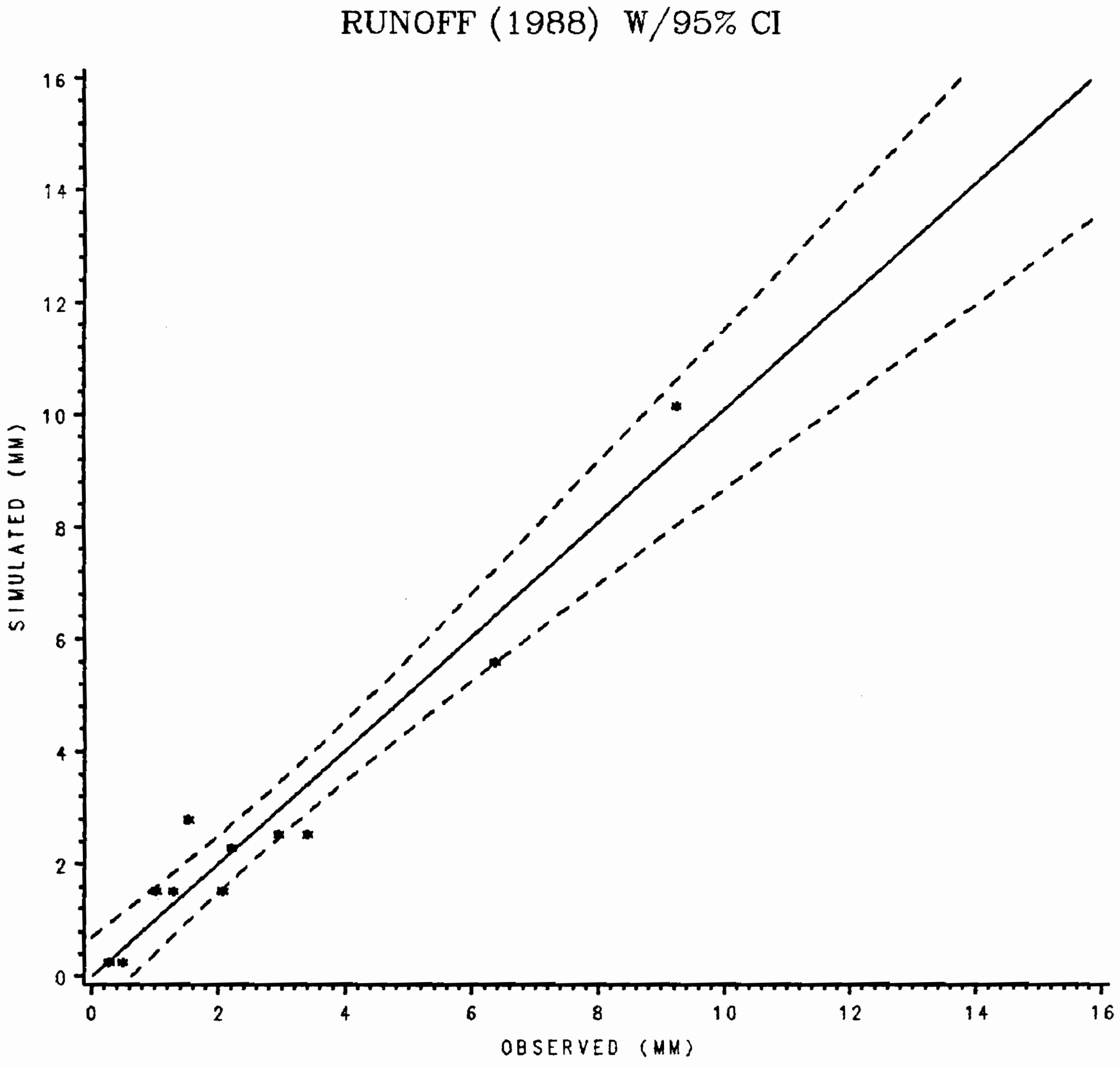

Figure 7. Regression analysis for runoff simulation (Owl Run watershed 1988)

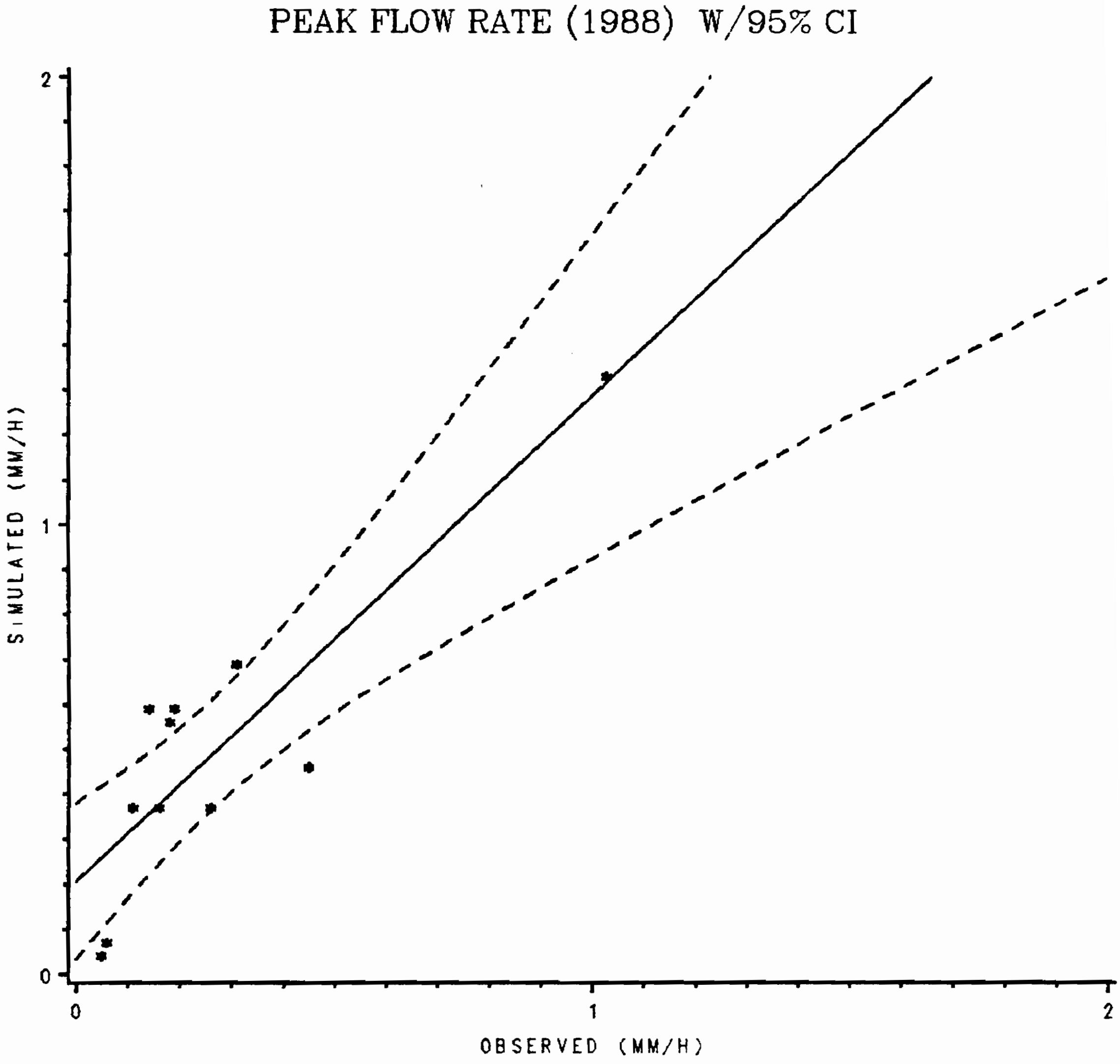

Figure 8. Regression analysis for peak rate simulation (Owl Run watershed 1988)

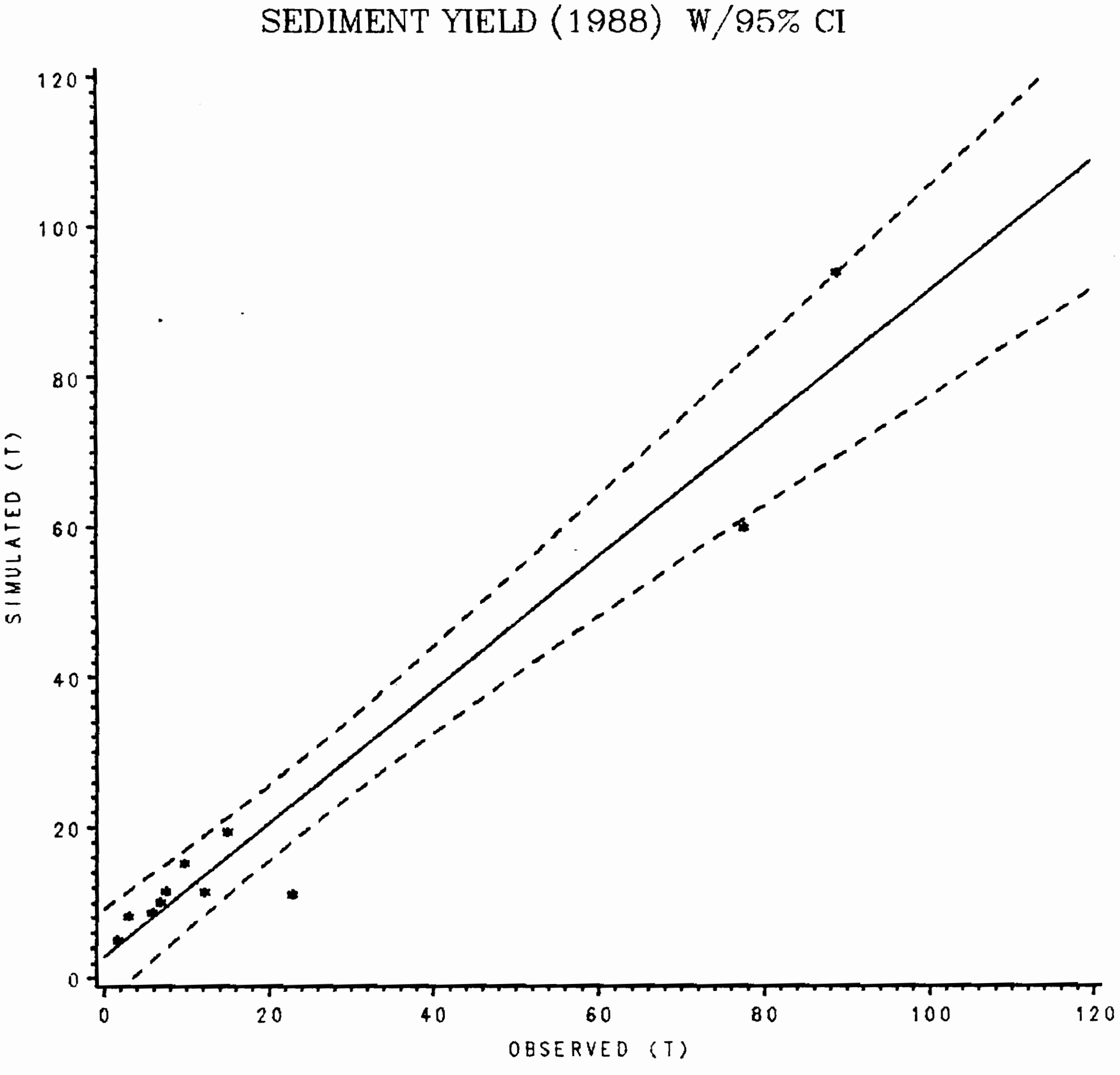

Figure 9. Regression analysis for sediment yield simulation (Owl Run watershed 1988).

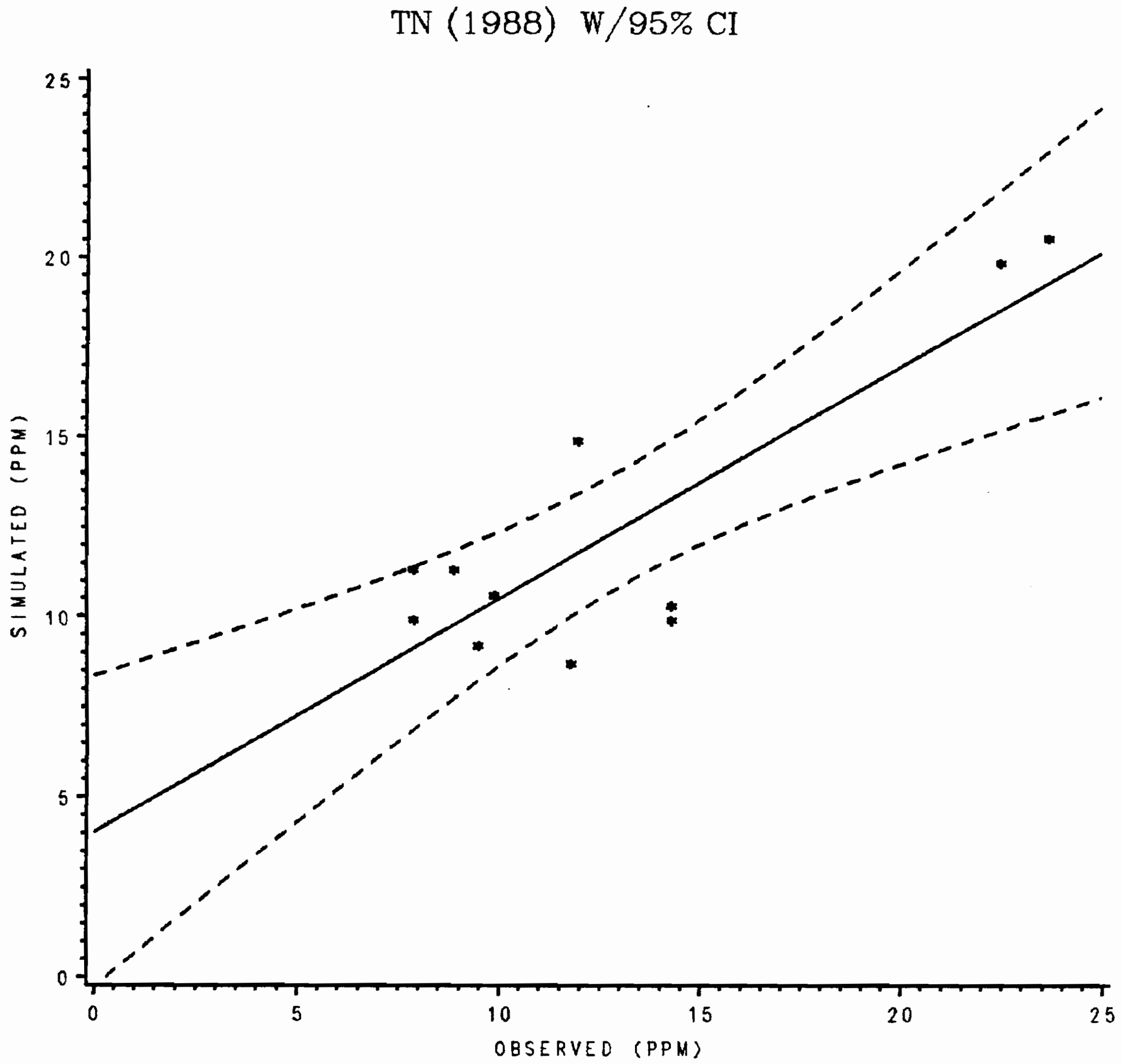

Figure 10. Regression analysis for total N loading simulation (Owl Run watershed 1988).

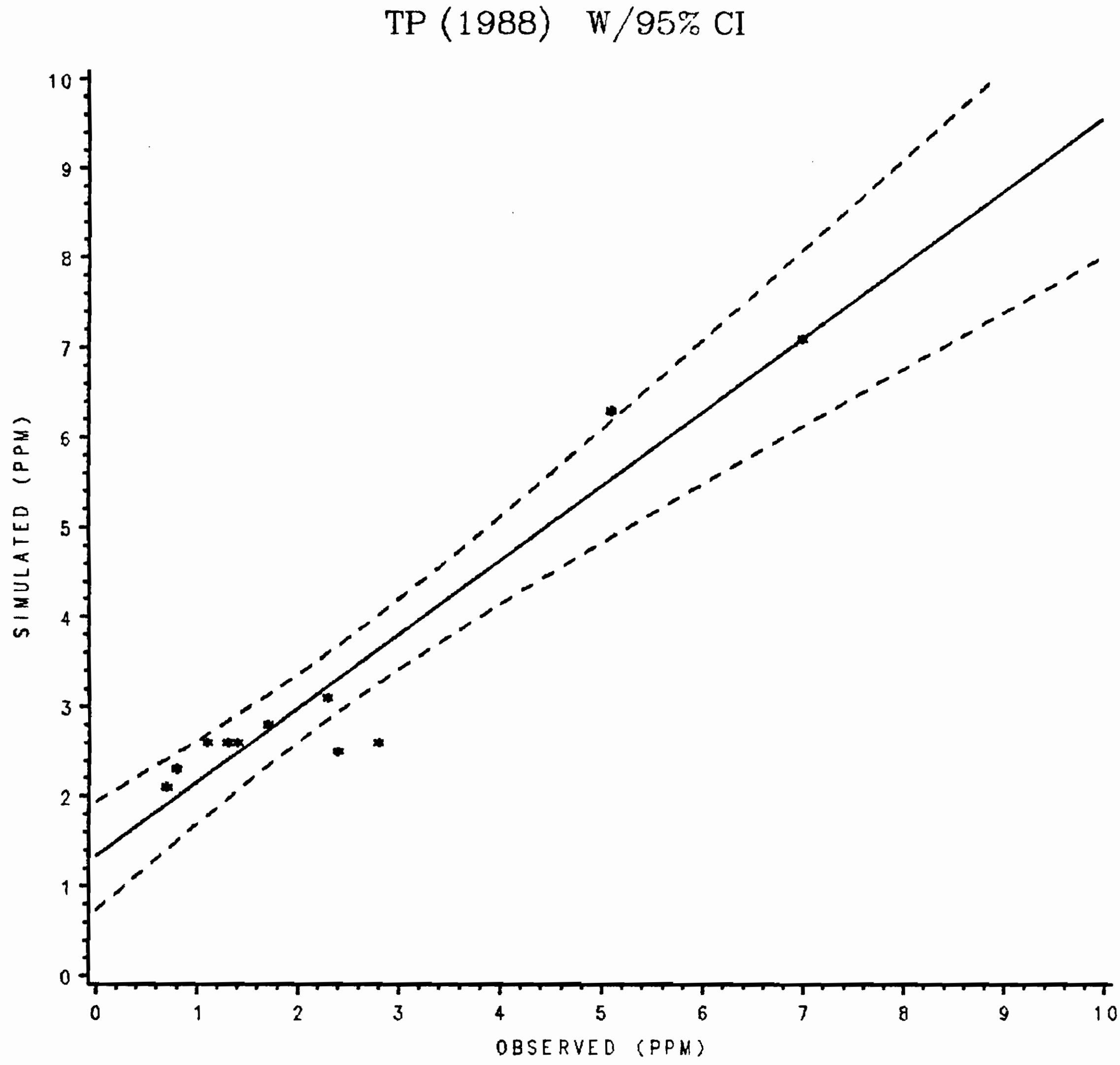

Figure 11. Regression analysis for total P loading simulation (Owl Run watershed 1988).

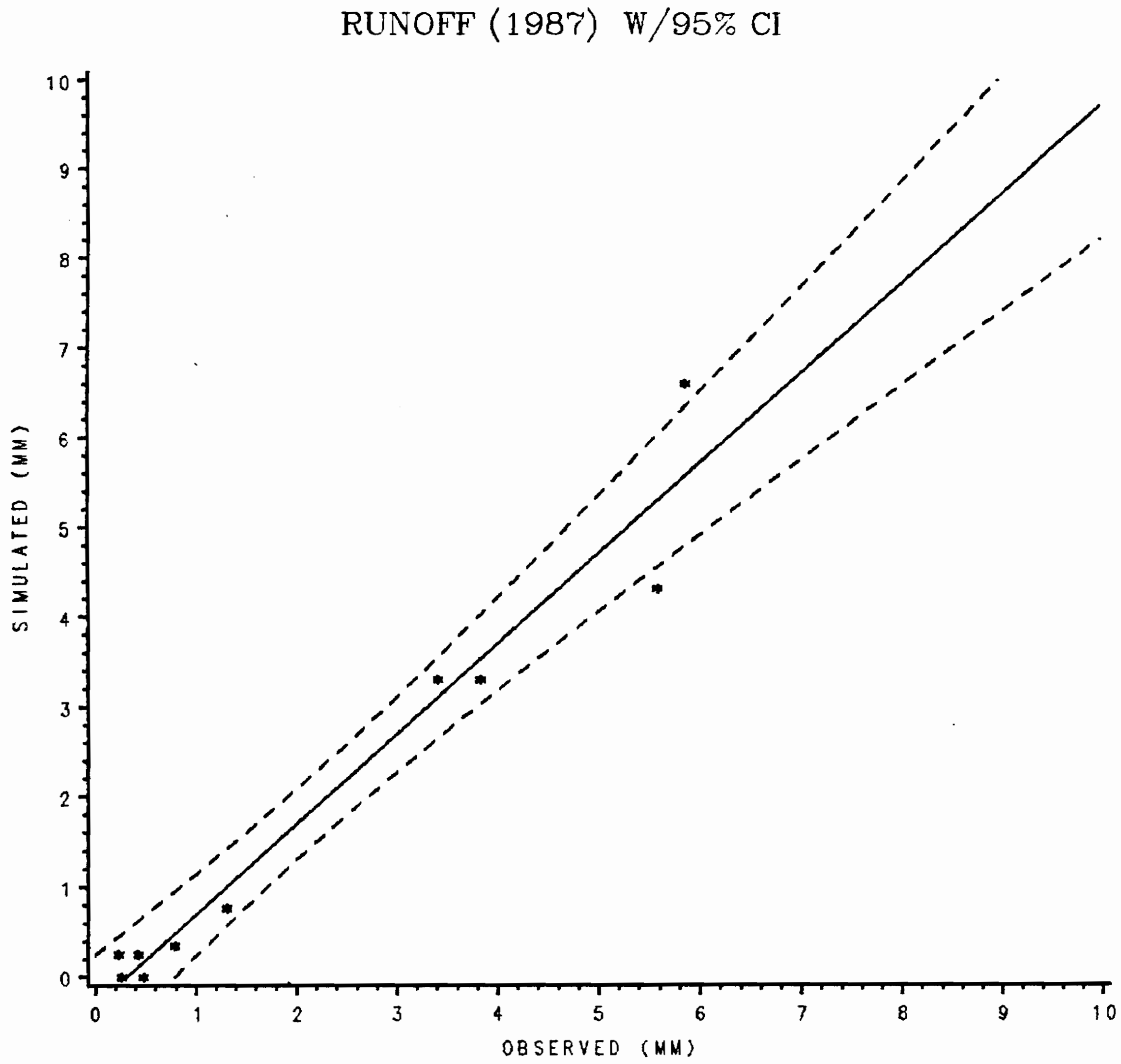

Figure 12. Regression analysis for runoff simulation (Owl Run watershed 1987)

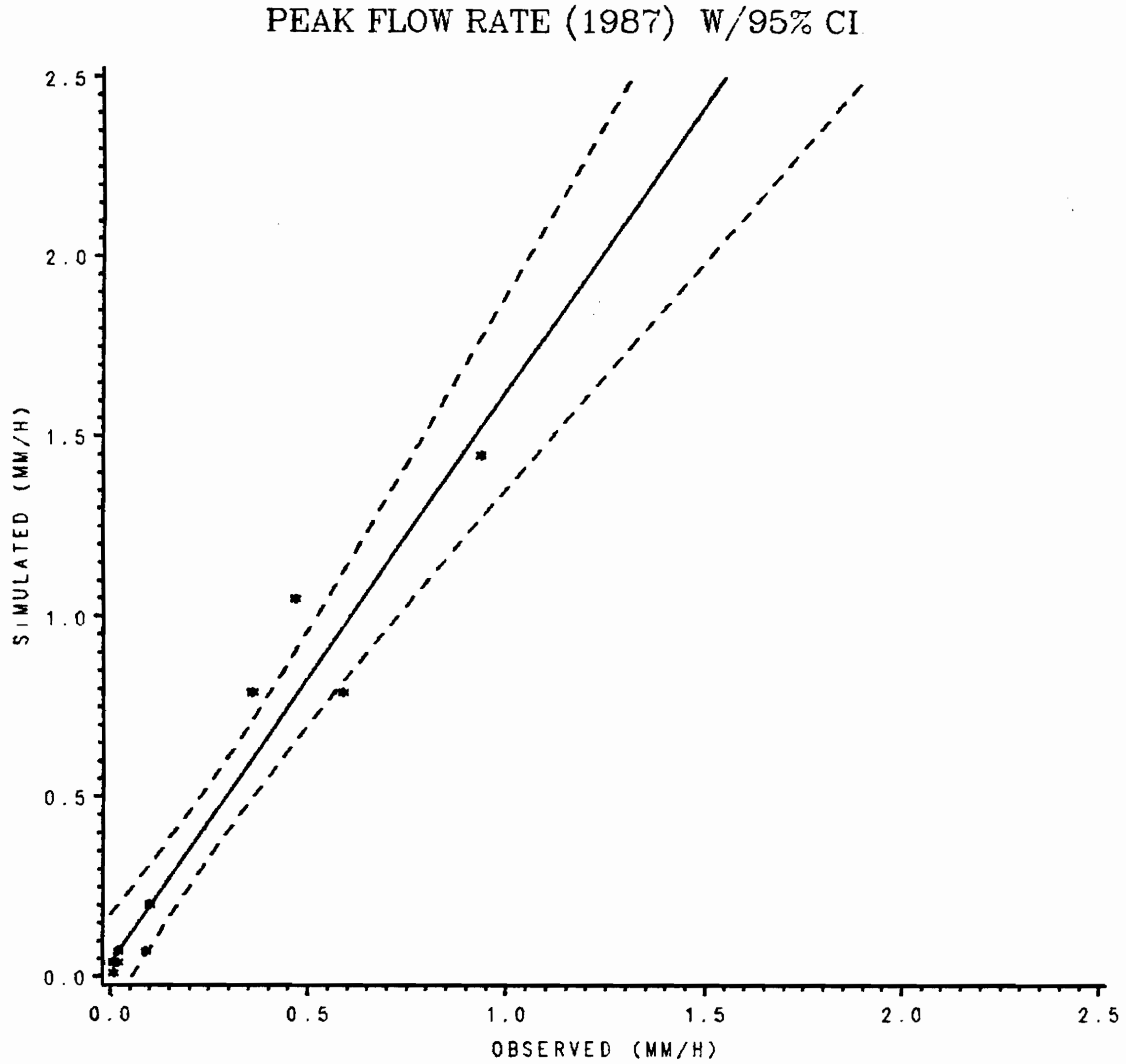

Figure 13. Regression analysis for peak rate simulation (Owl Run watershed 1987)

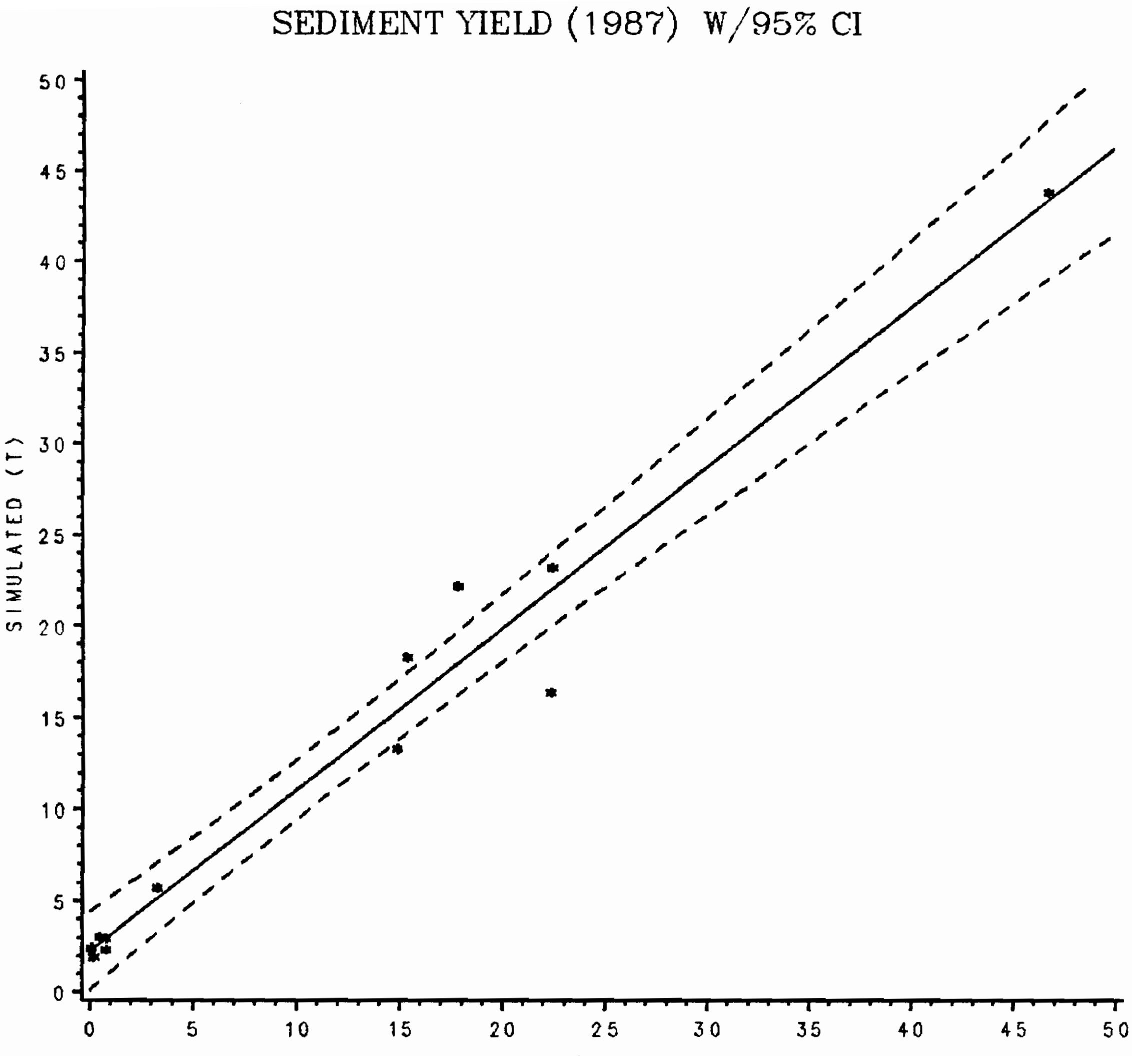

Figure 14. Regression analysis for sediment yield simulation (Owl Run watershed 1987).

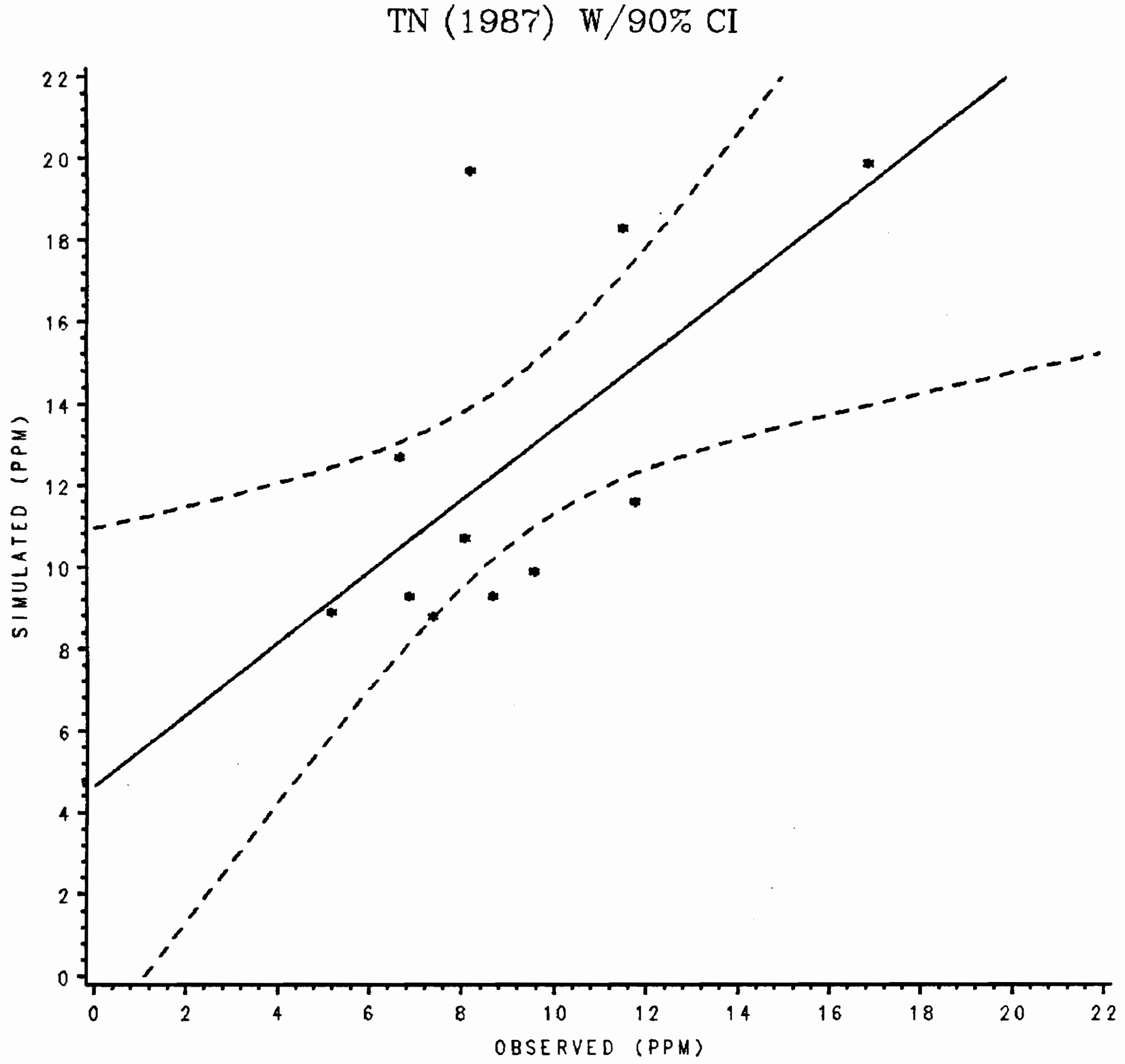

Figure 15. Regression analysis for total N loading simulation (Owl Run watershed 1987).

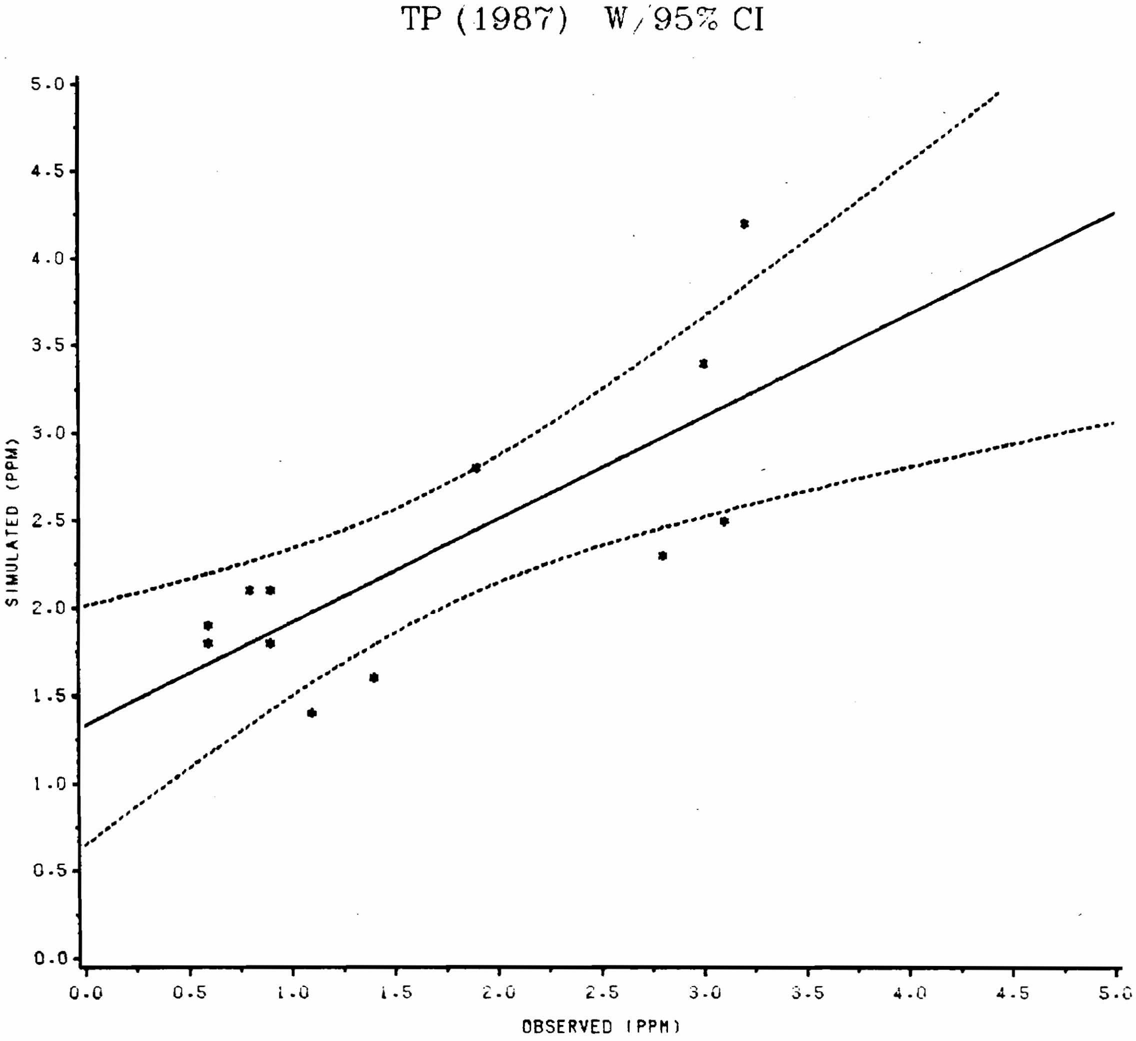

Figure 16. Regression analysis for total P loading simulation (Owl Run watershed 1987).

Annualization procedure

To evaluate the effectiveness of various BMPs on downstream water quality, representative storms, their magnitude and intensity, and their probability of occurrences need to be known, so that the contributions of these storms to the average annual runoff, sediment yield, and chemical loadings to downstream water bodies can be estimated. A big storm event may cause large amount of pollutant losses in runoff, but its contribution to the average annual total loadings may not be significant because of its low frequency of occurrence. Whereas relatively small events may cause significant contributions because of their high frequency of occurrences [Koelliker and Humbert, 1989]. Therefore, individual storm events can not be used directly to evaluate long-term system response. An annualization procedure is necessary to convert simulation results from event-based water quality models for evaluating the long-term impacts of BMPs. Figure 24 shows comparison of simulated and observed (from the 3-year data) distribution of contribution to runoff volume. The comparisons provided by both of the table (Table 13) and the figure (Figure 24) further validated the parameters used in this study.

The annualization procedure explained in this section includes frequency analysis of rainfall amounts and corresponding rainfall erosion indices (EI values in USLE), selection of representative events based on the frequency analysis, simulation, and summarization of these events.

Frequency analysis

As discussed in the last chapter, "primary events" (storm events with 24 hour rainfall amount being equal to or greater than 7 mm in depth) may cause measurable runoff, sediment yield, and chemical loadings. The data used in the frequency analysis for rainfall amount include a three-year period of primary events, collected from Owl Run watershed during 1987 to 1989. In the annualization procedure, storm events with all probabilities or return periods are required to summarize contributions of different storms to annual pollutant loadings. Therefore, the data collected from Owl Run watershed is too short to make a reliable frequency analysis, especially when extrapolation is needed to determine the probability of occurrences of extremely large events [Linsley, 1988]. For this reason, results of a rainfall frequency analysis from a nearby station located in Culpeper County, Virginia were used to extend the short record [Shanholtz and Lillard, 1973]. The assumption made here is that the Owl Run watershed has similar meteorological conditions as those of Culpeper county. The Culpeper series contains a ten-year period of record. This series was mainly used for events with return periods of longer than two years.

The erosivity index of a storm event, EI, is calculated using the equation [Foster, G.R., et al., 1981]:

$$EI = I \sum_{j=1}^{n} (0.119 + 0.0873 \log_{10}(i_j)) D_j \qquad (19)$$

Where n is the number of time segments into which a storm is divided; I is the maximum 30-minute rainfall intensity in mm/hr; i_j is the intensity during the jth time segment in mm/hr; and D_j is the depth of rainfall for the jth increment of the storm hyetograph. Frequency analysis for EI values were also performed using the three-year data collected from Owl Run watershed. A 22-year rainfall record for Richmond, Virginia [Wischmeier and Smith, 1978] was used to calculate EI values associated with larger events. The relationship between the probability of occurrence and return period can be written as [Chow, 1964]:

$$P = \frac{1}{mT} \tag{20}$$

where P is the probability of occurrences of primary events being greater than or equal to certain value; m is the average number of the primary events during a year, or the annual frequency of occurrence; and T is the return period in years.

In frequency analysis of hydrologic data, theoretical curve-fitting is needed to interpret the past record of hydrologic events in terms of future probability of occurrences. Theoretical frequency distributions extensively used in rainfall frequency studies include Pearson type-I and type-III distributions [Pearson, 1930; Foster, 1924], Type-I extreme distribution [Gumbel, 1941; Chow, 1953], and lognormal distribution [Chow, 1955].

Log-normal frequency distribution functions are found to be well fitted with the recorded hydrological data [Chow, 1955]. A log-normal distribution is a transformed normal distribution in which the variable is replaced by its logarithmic value. The probability density function of the distribution is

$$P(x) = \frac{1}{e^y \sigma_y \sqrt{2\pi}} e^{-\frac{(y-\mu_y)^2}{2\sigma_y^2}} \tag{21}$$

where x is the variable (rainfall amount or EI value); y = ln x is normally distributed, with μ_y and σ_y being the mean and standard deviation of y. While the statistical parameters for the variable x, including mean, coefficient of variation and coefficient of skewness (μ, C_v and C_s), can be evaluated by the complicated theoretical equations derived by Chow [1954], simplified procedures are widely used in the engineering field of applied hydrology. This is because of the errors involved in the data collection and enlarged by the calculation of higher power orders in the sophisticated equations. One of the simplified procedures is based on the trial and error method. The statistical parameter mean, μ, is represented by the arithmetical mean of the recorded data $\bar{x}$; the initial value of the coefficient of variation C_v can be the calculated by using the standard deviation divided by the mean value of x. The coefficient of skewness, C_s, was evaluated by assigning an initial value, say $3C_v$ or

$2C_v$, and using curve fitting. The probabilities of the variable are calculated by using the table provided by Chow [1964].

In this study, a log-normal distribution function with mean, $\bar{x} = 18$ mm, and coefficient of variations, $C_v = 0.8$, was found to be a good fitted theoretical curve for rainfall amounts. Another log-normal frequency distribution function with mean, $\overline{EI} = 51.7$ MJ.mm/ha/hr, and $C_v = 1.7$, was fitted to the rainfall erosion index data. The results of the two frequency analysis for rainfall amounts and EI values are shown in Figures 17 and 18, separately.

Selection of representative events

In order to estimate the average annual values from single storm simulations, a series of representative storm events should be selected for use in the annualization simulation. The assumption made in the annualization procedure is that each storm contributes to a portion of the average annual amount based on its frequency of occurrence [Koelliker and Humbert, 1989]. A representative storm to be used for AGNPS simulation is characterized by an amount of rainfall and an EI value.

A series of eleven different storms were selected with occurrence probabilities ranging from 0.0005 [return period, T, of 50 years, equation (20)] to 0.5 (return period, T, of 0.05 years). The rainfall and EI frequency curves were divided into eleven frequency intervals intervals such that the whole probability region (between 0 and 1) was represented (table 11). These eleven intervals on each of the curves were also selected such that the differences in the magnitudes of neighboring representative storms were not very large, in order to reduce the errors involved in the descretization of continuous variables. The more representative storms selected, the more accurate simulation results can be expected. The average rainfall amount and EI value on each of the eleven intervals were used in the AGNPS simulations as the two characteristics of each representative storm event corresponding to that probability interval. For example, the two values for the third

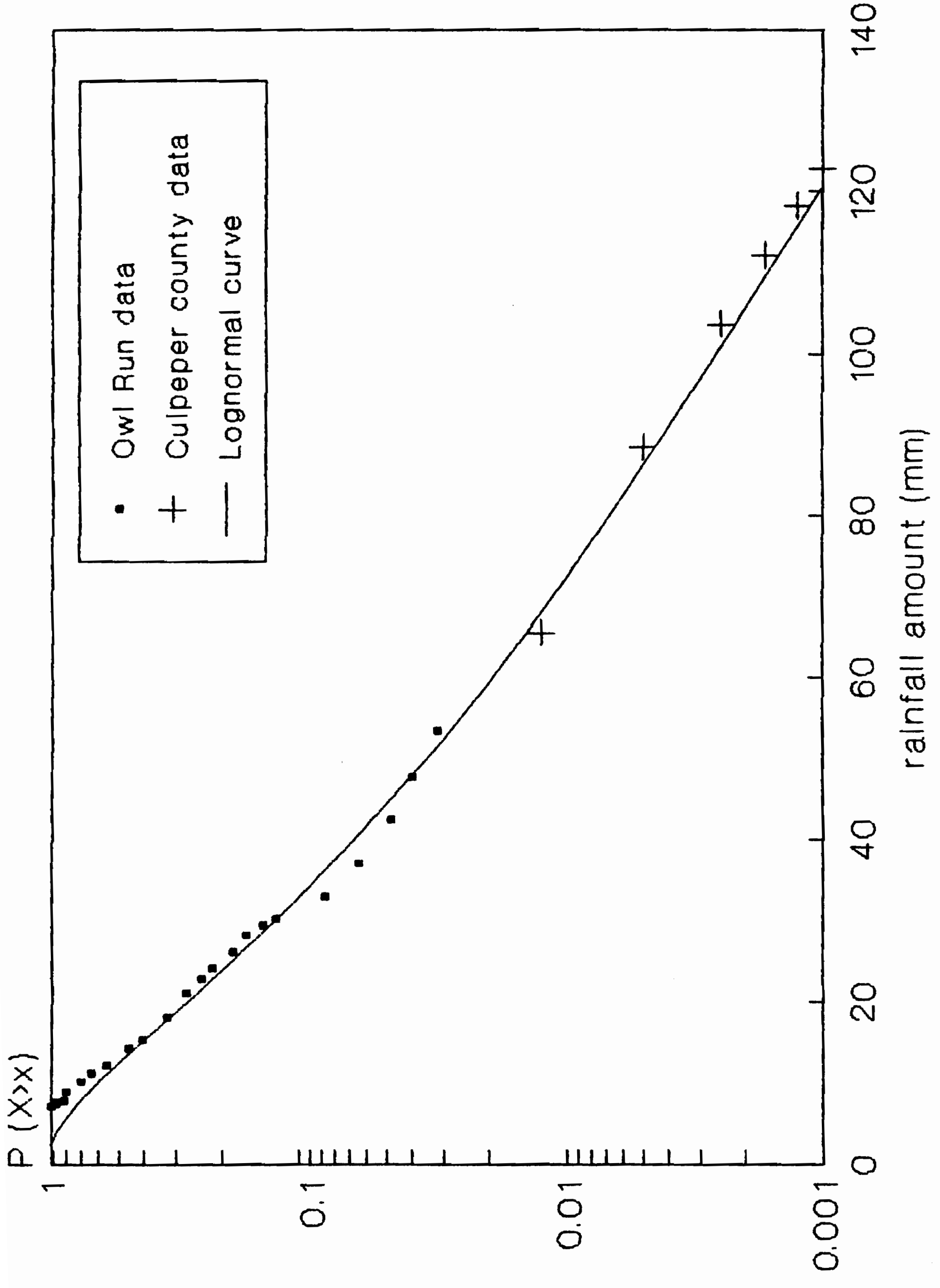

Figure 17. Frequency analysis of rainfall amount for Owl Run watershed.

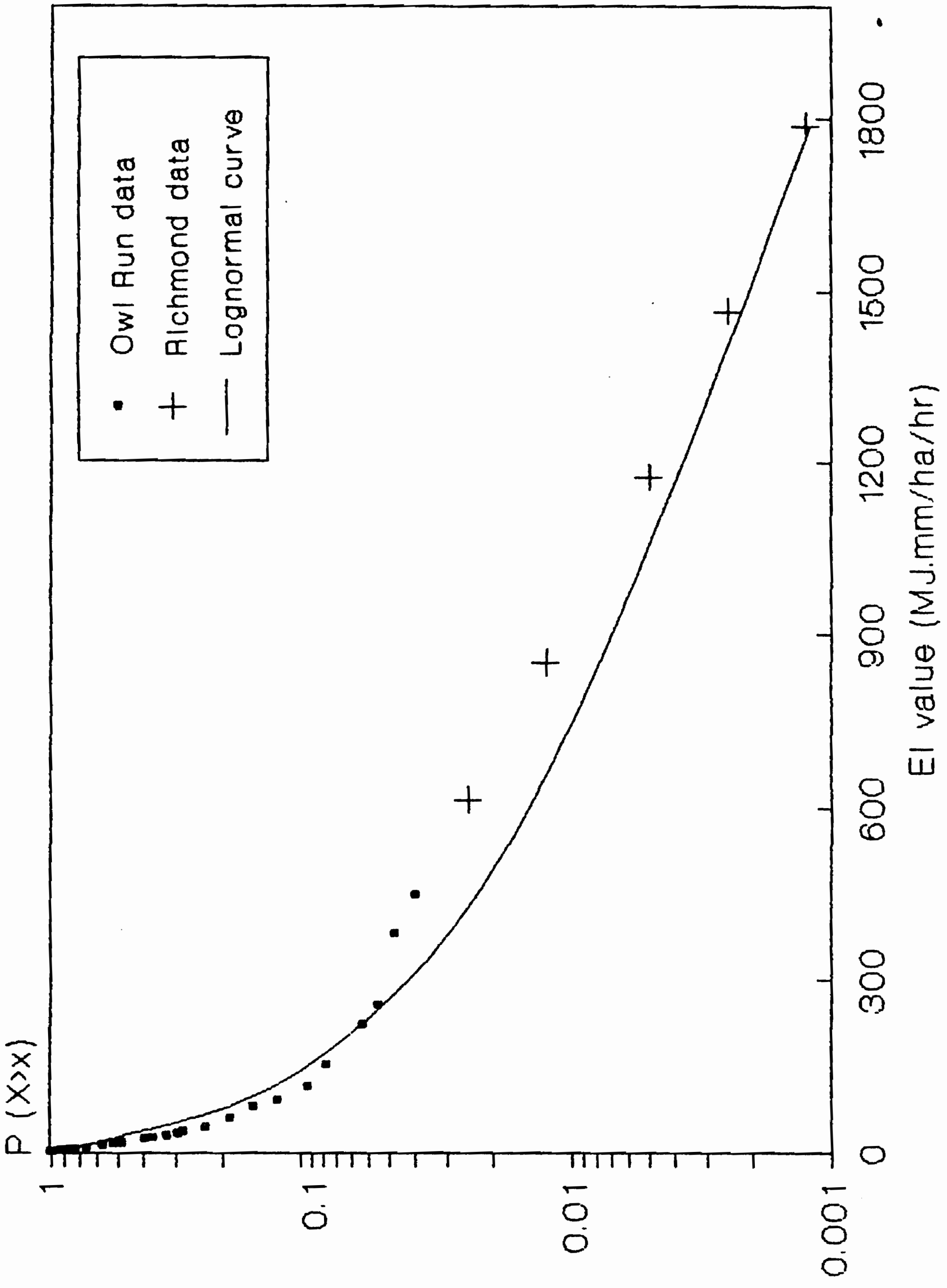

Figure 18. Frequency analysis of EI values for Owl Run watershed.

representative event (i = 3) required by AGNPS input were R_3 = 28.4 mm and EI_3 = 78 MJ.mm/ha/hr. R_3 is the average value of rainfall amount on the 3rd interval of the frequency curve in Figure 17 (table 11); EI_3 is the average value of erosion index on the 3rd interval of the EI frequency curve in Figure 18 (table 11); both of the two values have the same probability of occurrence, P_3 = 0.15 (return period T = 0.1667 years for annual occurrence frequency P_3, m = 6 times), which is used in weighing the annual contributions of this representative event.

Simulation and summarization

With the representative storm events selected following the procedures described in the last section, direct AGNPS simulations were made and summarized to find the average annual results.

Let n be the number of probability intervals into which the whole probability region is divided (or the number of representative storm events to be used in the annualization procedure), the annual contribution of all representative storms can be expressed as:

$$Ct = m\sum_{i=1}^{n} f(R_i, EI_i)P_i \tag{22}$$

where Ct is the annualized simulation result contributed by all the representative storms; R_i and EI_i are rainfall amount and erosion index of the i th representative storm event, i = 1,2, ... ,n (n = 11 in this study); m is the average number of primary storms occurring during a year, or the annual frequency of occurrence of all possible events; P_i is the interval probability corresponding to the i th representative storm; and $f(R_i, EI_i)$ is the AGNPS simulation result for each storm with input of R_i and EI_i. Ct could be runoff, sediment yield, or any of the chemical loadings simulated by AGNPS. Since a representative storm may occur during any season of the year, it should be simulated for each season and summarized as:

$$f(R_i, EI_i) = \sum_{j=1}^{k} f_j(R_i, EI_i, Para_j)Ps_{ij} \tag{23}$$

where k is the number of seasons used for a year (k = 2 in this study, for dormant and growing seasons); $Para_j$ denotes all the parameters used for the j th season's simulation such as CN, C factors in USLE, etc.; and $f_j(R_i, EI_i, Para_j)$ is the direct simulation result of the i th representative event for the j th season simulation, it could be runoff, sediment yield, or nutrient loadings. The $f_j(R_i, EI_i, Para_j)$ values corresponding to runoff, sediment yield, and chemical loadings for the two seasons are listed in Table 7 and table 8. Ps_{ij} is the percentage of the i th representative storm occurring during the j th season. Values of Ps_{ij} are also listed in Tables 11 and 12. The probability of a storm event occurring during different seasons is not evenly distributed. Generally, small events occur in dormant season more than in growing season, while extremely large events occur most of the time during growing season. The probabilities of the storm events occurring during the two seasons were calculated in percentages using the three-year period data from Owl Run watershed. These percentages are listed in table 11 and table 12.

The probability of the representative event P_i, in equation (22); annual frequency of occurrence, mP_i, in equation(22); the average rainfall amount, R_i; and the rainfall erosion index value, EI_i, corresponding to each frequency interval, i, were taken from the two frequency curves in Figures 17 and 18. A summary of these values are also listed in Tables 11 and 12.

Runoff, sediment yield, total nitrogen loading, total phosphorus loading, and total chemical oxygen demand loading, were simulated to estimate the contributions of storms with different magnitudes and frequencies. The outputs from each simulation run $f_j(R_i, EI_i, Para_j)$, multiplied by the corresponding occurrence frequency (mP_i), and weighted by the seasonal percentage (P_{ij}), give the annual contributions made by each representative storm. Figures 20 through 23 show the contributions of every representative storm to the annual average (in percentage) runoff, sediment yield, total nitrogen loading, and total phosphorus loading, corresponding to the rainfall amount and the annual occurrence frequency of the event.

Table 11. Summary of contributions of representative events to runoff and sediment yield.

Interval number (i)	1	2	3	4	5	6	7	8	9	10	11		$\sum_{i=1}^{11}$
Return period (yr)	0.025	0.05	0.1	0.25	0.5	1	2	5	10	20	50	∞	
$P(X \geq x_i)$	1.000	0.5	0.25	0.1	0.05	0.025	0.0125	0.005	0.0025	0.00125	0.0005	0.0	
$P(x_{i+1} \geq X \geq x_i)$ [a]	0.50	0.25	0.15	0.05	0.025	0.0125	0.0075	0.0025	0.00125	0.00075	0.0005		1
Frequency [b]	20	10	6	2	1	0.5	0.3	0.1	0.05	0.03	0.02		40
Rainfall (mm)	10.7	19.1	28.4	36.8	48.3	60.7	77.0	93.0	105.9	120.9	142.2		
EI (MJ.mm/ha/hr)	10	31	78	204	340	524	865	1208	1566	2025	2468		
growing season [c]	27%	45%	63%	67%	75%	75%	100%	100%	100%	100%	100%		
dormant season [c]	73%	55%	37%	33%	25%	25%	0 %	0 %	0 %	0 %	0 %		
GSS[d] Runoff (mm)	0.00	1.27	3.30	7.37	12.45	19.81	29.97	43.18	53.09	65.28	82.30		
DSS[e] Runoff (mm)	0.51	3.81	7.37	13.46	20.57	29.97	-	-	-	-	-		
Contribution to (mm)	7.4	26.7	28.8	18.8	14.5	11.2	9.0	4.3	2.7	2.0	1.6		127.0
annual runoff (%)	5.8	21.0	22.7	14.8	11.4	8.8	7.1	3.4	2.1	1.5	1.3		100
GSS[d] Sediment (T)	2.1	8.0	17.6	43.5	78.0	133.1	242.1	379.0	523.2	723.5	954.1		
DSS[e] Sediment (T)	5.7	19.6	44.7	116.4	212.5	365.6	-	-	-	-	-		
Contribution to (T)	93.6	143.9	165.9	135.1	111.6	95.6	72.6	37.9	26.2	21.7	19.1		923.0
annual sediment (%)	10.1	15.6	18.0	14.6	12.1	10.4	7.9	4.0	2.8	2.4	2.1		100

a. Interval probability, P_i in equation (22).
b. Annual occurrence frequency of the i th representative event, mP_i, (m = 40, annual occurrence frequency of all primary events).
c. Ps_{ij} in equation (23), percentage of the i th representative event occurs during the i th season.
d. Growing Season Simulation of AGNPS.
e. Dormant Season Simulation of AGNPS.

Relationship between rainfall amount and erosion index

Rainfall amount and its corresponding EI value are required by the AGNPS model as inputs for each individual storm event simulation. Storms with same magnitude of rainfall amount may result in a different EI value because of both temporal and spatial variations in rainfall intensity. Therefore, a frequency analysis of two dimensional distribution, or determination of their joint distribution, may be ideal in selecting the two values as the model input. In this study a simplified procedure was used by selecting rainfall amounts and EI values from the two individually-analyzed frequency curves. In doing this, it was assumed that events with same amount of rainfall have same EI value. For example, the rainfall amount taken from the rainfall frequency curve in Figure 17 between $0.1 > P \geq 0.05$ was averaged as 36.83 mm on interval number 4; the corresponding EI value was taken from EI frequency curve in Figure 18, with average value of 204 MJ.mm/ha/hr on the same probability interval. The probability of this representative event occurring within this interval is $0.1 - 0.05 = 0.05$, which is used as the weight [P_4 in equation (22)] in summarizing the simulation results.

The rainfall amounts recorded in Owl Run watershed during the 3-year period are plotted against their EI values in Figure 19. Rainfall amounts and EI values of representative events taken from the two frequency curves are also plotted on the same figure. The line joining the points of representative events passes through the scattered recorded data points. This line represents the averaged EI values for each representative rainfall amount. As mentioned above, only the representative storm events were used in the simulation.

Table 12. Summary of contributions of representative storms to TN, TP, and COD loadings.

Interval number (i)	1	2	3	4	5	6	7	8	9	10	11		$\sum_{i=1}^{11}$
Return period (yr)	0.025	0.05	0.1	0.25	0.5	1	2	5	10	20	50	∞	
$P(X \geq x_i)$	1.000	0.5	0.25	0.1	0.05	0.025	0.0125	0.005	0.0025	0.00125	0.0005	0.0	
$P(x_{i+1} \geq X \geq x_i)$ [a]	0.50	0.25	0.15	0.05	0.025	0.0125	0.0075	0.0025	0.00125	0.00075	0.0005		1
Frequency [b]	20	10	6	2	1	0.5	0.3	0.1	0.05	0.03	0.02		40
Rainfall (mm)	10.7	19.1	28.4	36.8	48.3	60.7	77.0	93.0	105.9	120.9	142.2		
EI (MJ.mm/ha/hr)	10	31	78	204	340	524	865	1208	1566	2025	2468		
growing season[c]	27%	45%	63%	67%	75%	75%	100%	100%	100%	100%	100%		
dormant season[c]	73%	55%	37%	33%	25%	25%	0 %	0 %	0 %	0 %	0 %		
GSS [d] Total N (kg)	26	277	581	1017	1452	1967	2614	3314	3856	4489	5242		
DSS [e] Total N (kg)	224	1004	1677	2628	3552	4688	-	-	-	-	-		
Contribution to (kg)	3420	6767	5919	3097	1997	1324	784	331	193	135	105		24052
annual total N (%)	14.2	28.1	24.6	12.9	8.2	5.5	3.3	1.4	0.8	0.6	0.4		100
GSS [d] Total P (kg)	13	79	145	251	357	502	700	924	1122	1360	1611		
DSS [e] Total P (kg)	53	224	383	634	885	1228	-	-	-	-	-		
Contribution to (kg)	842	1591	1399	754	489	342	210	92	56	41	32		5849
annual total P (%)	14.4	27.2	23.9	12.9	8.4	5.8	3.6	1.6	1.0	0.7	0.6		100
GSS [d] Total COD (T)	0.2	1.9	4.7	10.0	16.6	26.2	39.0	55.0	66.9	81.3	100.8		
DSS [e] Total COD (T)	0.8	4.7	9.3	16.8	25.4	37.1	-	-	-	-	-		
Contribution to (T)	12.1	34.3	38.4	24.5	18.8	14.4	11.7	5.5	3.3	2.4	2.0		167.5
annual total COD (%)	7.2	20.5	22.9	14.6	11.2	8.6	7.0	3.3	2.0	1.5	1.2		100

a. Interval probability, P_i in equation (22).

b. Annual occurrence frequency of the i th representative event, mP_i, (m = 40, annual occurrence frequency of all primary events).

c. Ps_{ij} in equation (23), percentage of the i th representative event occurs during the i th season.

d. Growing Season Simulation of AGNPS.

e. Dormant Season Simulation of AGNPS.

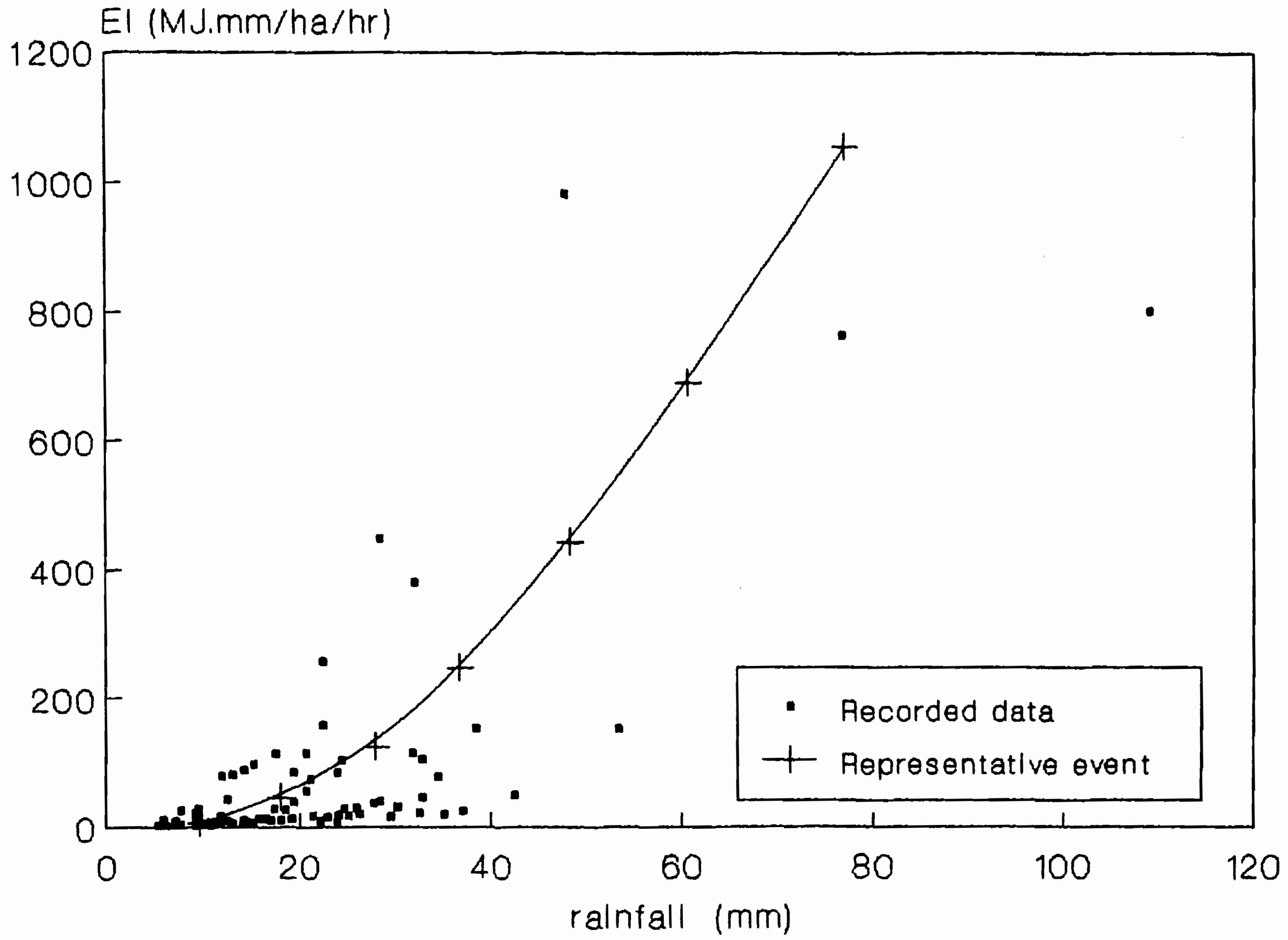

Figure 19. Relationship between rainfall amounts and corresponding EI values.

Results and discussion

As described in the previous chapter, AGNPS parameters related to landuse and surface cover conditions were prepared for different seasons; parameters related to topography and soils were prepared for the whole year; antecedent soil moisture conditions for determination of curve numbers was assumed to be condition-II as used in the validation of the model. The simulation results obtained from AGNPS using the annualization procedure were compared with the observed data from the Owl Run watershed [Mostaghimi, et al., 1989]. Table 13 shows the average annual simulation results compared with the data collected during each individual year and the average of the three years from the Owl Run watershed. Distributions of contributions to annual runoff volume were also compared between the simulated results and the 3-year observed data (Figure 24). As shown in Figure 24, the observed and simulated distribution agree reasonably well and indicate the validity of the distribution used in the annualization procedure.

Generally, the results compared favorably with the observed data. The annual average sediment yield, and total nitrogen loadings were slightly overestimated, while the total phosphorus loadings were underestimated. One possible reason for the discrepancy between the simulated and observed value is that the extreme values of rainfall erosion index data from Richmond, Virginia, was used in the EI frequency analysis for Owl Run watershed. The rainfall intensity in Richmond, Virginia, is generally larger than that in Fauquier County, Virginia [Herschfield, 1961]. In addition, fertilization levels and fertilizer availability factors are required by AGNPS as input parameters for individual events. This is a major weakness of event-based models, since the parameters have to be prepared for the entire season as average conditions in long-term simulations, which is more or less subjective. The data reported by Mostaghimi et. al. [1989] indicate that high concentrations of nitrogen and phosphorus were detected shortly after the chemical applications on the field. This phenomenon is difficult to simulate by using representative storms. A great amount of variability in the observed data was found among individual years. It should be noted that the annual prediction values made AGNPS are well within the ranges represented by the recorded data from the Owl

Run watershed for the three years of the study. Once sufficient amount of data is collected, such discrepancies can be minimized by comparing the simulation results with the observed average annual results.

From the results displayed in Figures 20 through 23, it can be noted that, events with annual occurrence frequencies of 6 to 10 times/year (return periods of 0.1667 to 0.1 years), are responsible for majority of the annual pollutant loadings. Therefore, more attentions should be made in designing BMPs sensitive to these small events.

The annualization procedure provides a basis for evaluating long-term effectiveness of various BMPs. For identification of critical areas within a watershed, the concept of perennial effects should still be considered. The critical areas in this study were identified by using the annualization procedure explained in this section. A computer program was developed to summarize the AGNPS′ output files with different representative storm′s input on a cell basis. Comparisons of annualized critical areas identified for the circumstances before and after a BMP implementation scenario are discussed in the next chapter.

Table 13. Comparison of annualization simulations with recorded data from Owl Run watershed.

Categories	AGNPS	Observed data			
	Annual simulation	Three year average	1987	1988	1989
Rain fall (mm)	772	757	765	418	1089
Runoff volume (mm)	127	168	198	67	239
Runoff/rain fall	0.16	0.22	0.26	0.16	0.22
Sediment yield (T) (T/ha)	 940 0.805	 719 0.624	 579 0.50	 485 0.42	 1092 0.95
TN loading (kg) (kg/ha)	 24153 20.9	 20689 17.9	 29500 25.6	 10323 9.0	 22245 19.3
TP loading (kg) (kg/ha)	 5856 5.08	 6319 5.48	 11600 10.1	 3457 3.0	 3899 3.4

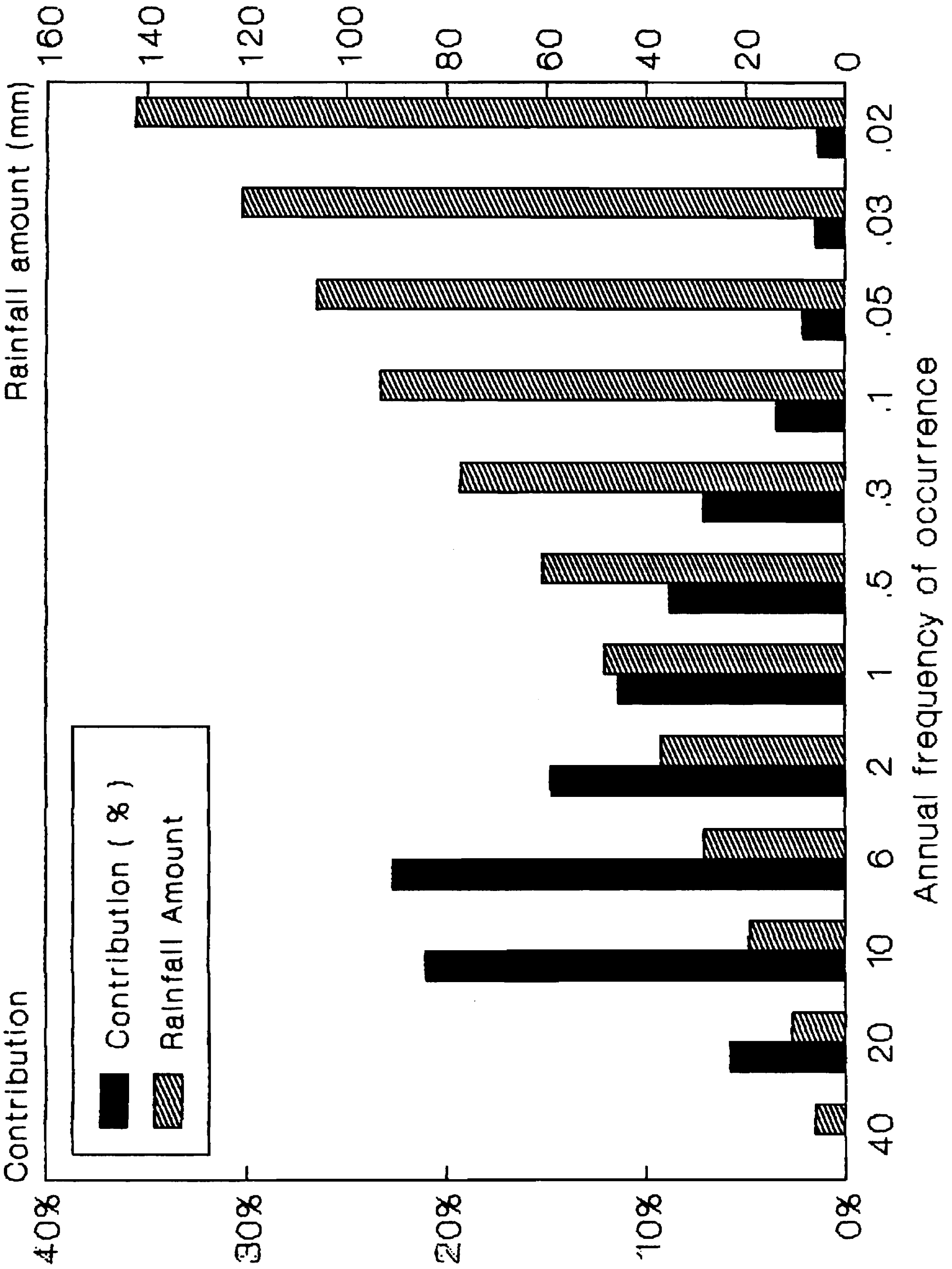

Figure 20. Contribution of representative storm events to annual runoff volume.

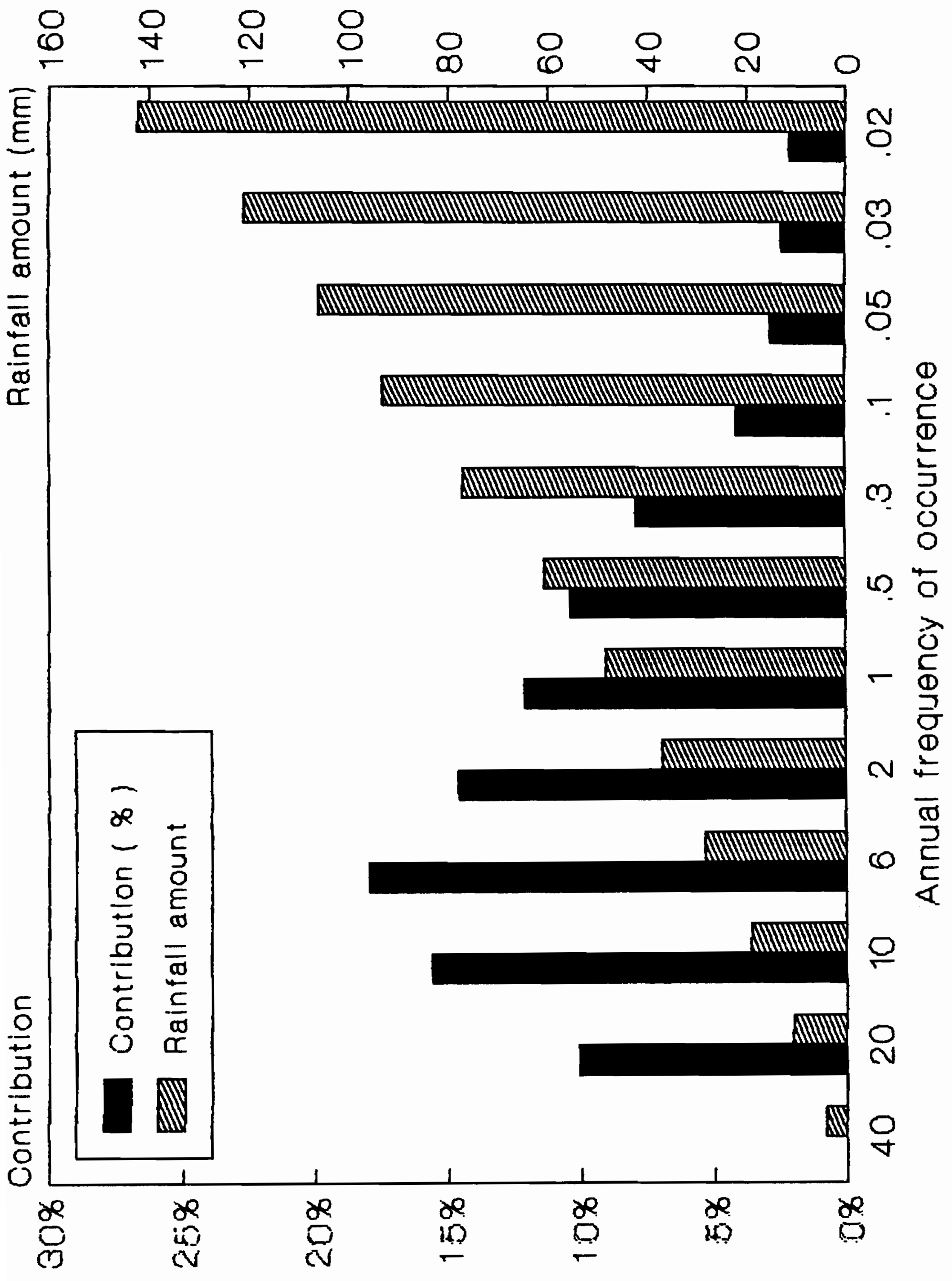

Figure 21. Contribution of representative storm events to annual sediment yield.

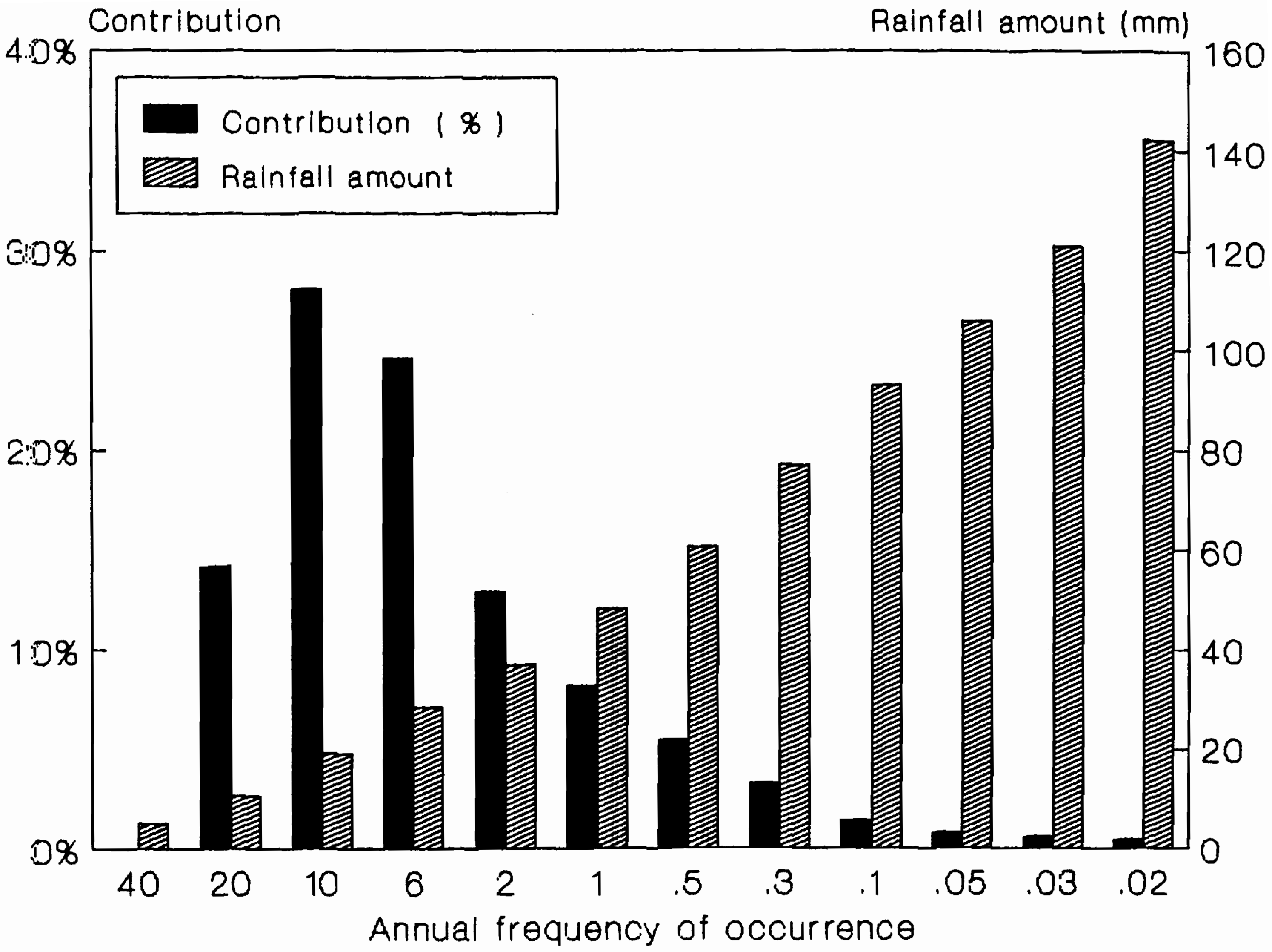

Figure 22. Contribution of representative storm events to annual total N loading.

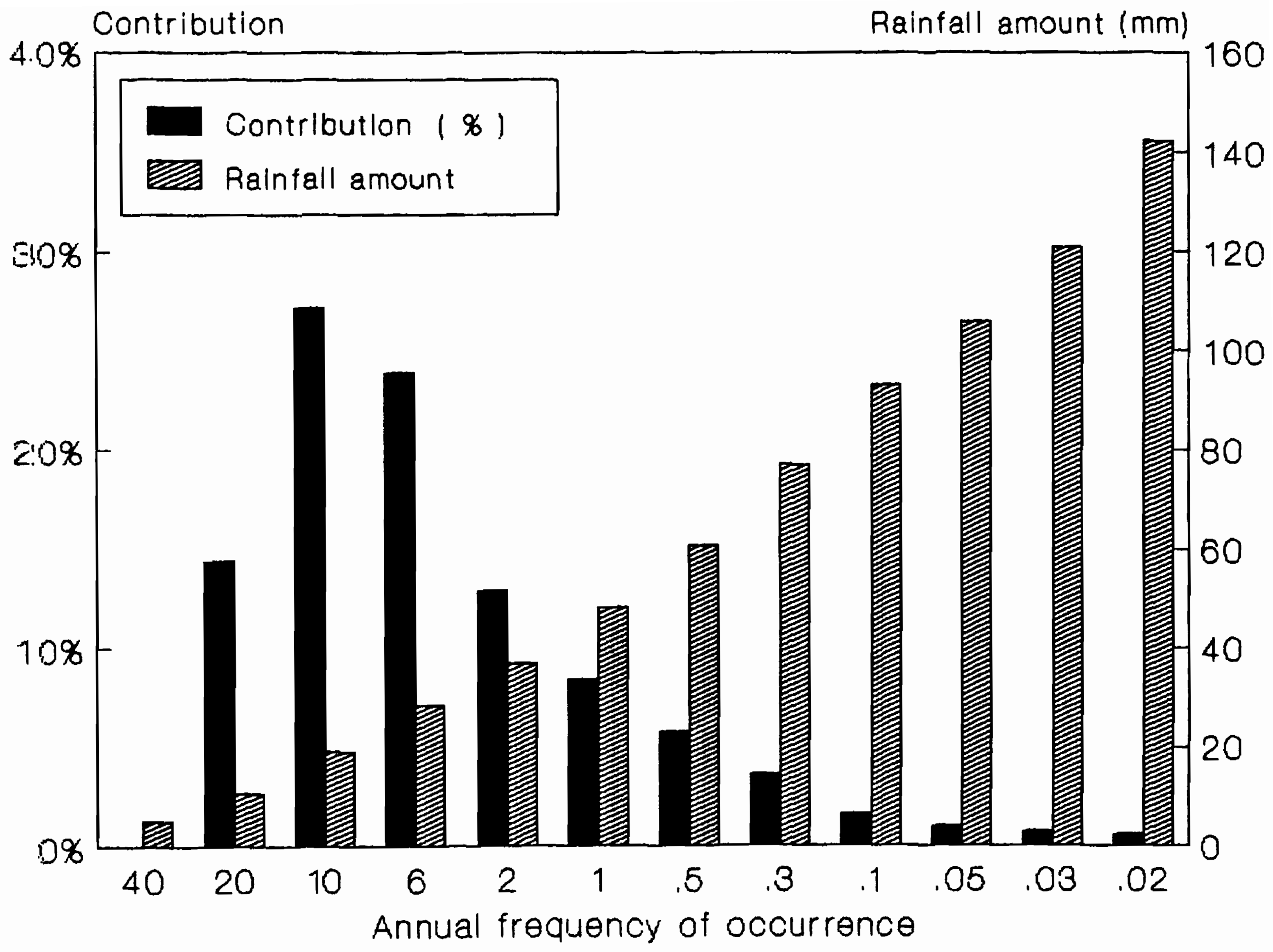

Figure 23. Contribution of representative storm events to annual total P loading.

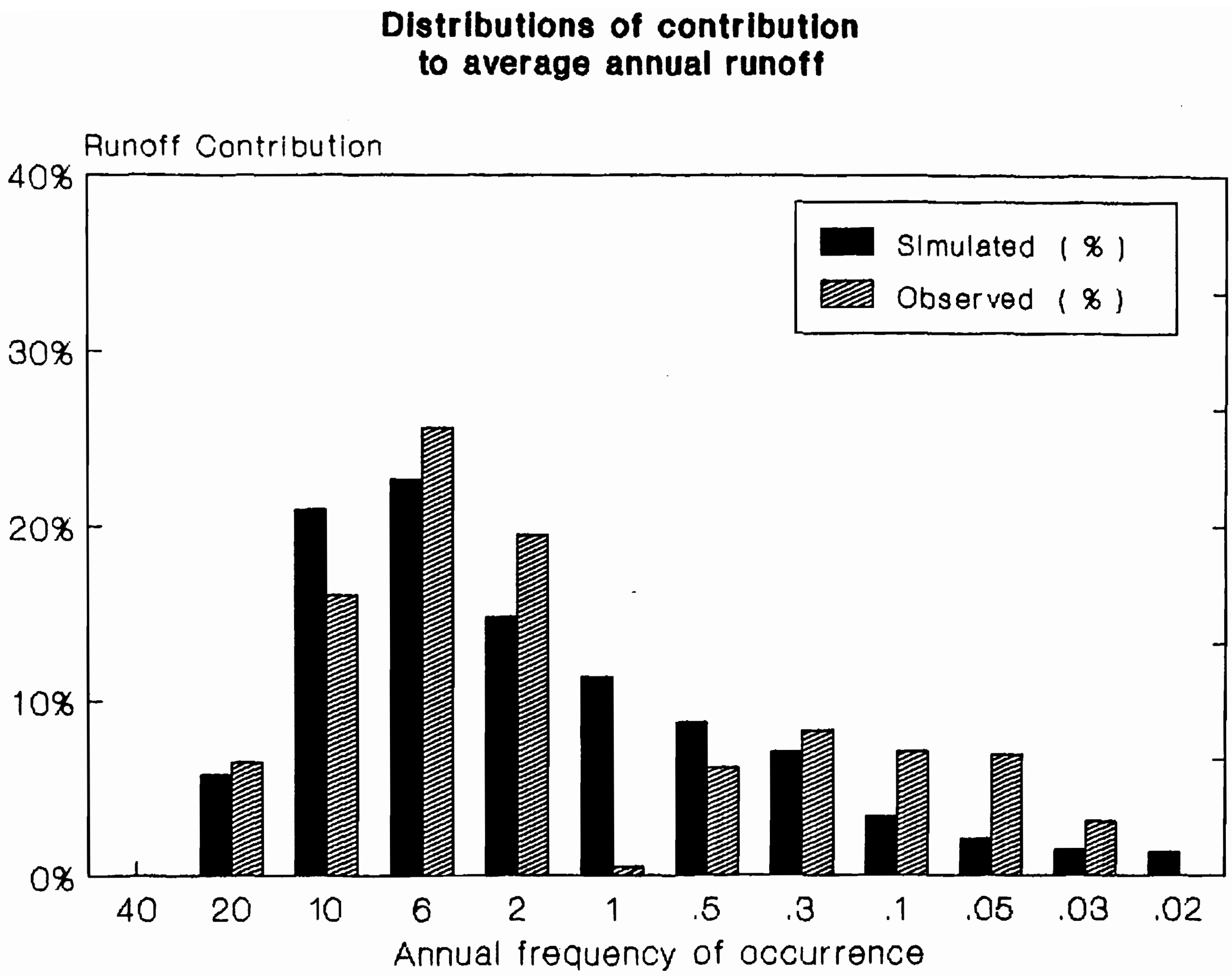

Figure 24. Comparison of contributions of storm events to annual runoff at various frequency of occurrences.

BMP simulation for Owl Run watershed

The purpose of this chapter is to evaluate the impacts of hypothetical implementation of BMPs on surface water quality in Owl Run watershed using the AGNPS model along with the annualization procedure. All the scenarios (currently intalled and proposed) were simulated using the annualized version of the model. The cell size and the input parameters for the model were the same as used in the model validation and the annualization sections.

The following seven BMP scenarios were simulated and their long term impacts on reducing pollutant loadings are discussed in the following sections:

1. Present scenario (BMPs currently installed in the watershed);
2. No-till practice on critical areas;
3. CRP (Conservation resources program) on critical areas;
4. Installation of animal waste storage facilities;
5. No-till on critical areas plus animal waste facilities;
6. No-till on all agricultural land plus animal waste facilities;
7. All cropland converted to pastureland plus animal waste facilities.

Scenario description

Present scenario (Scenario No.1)

As part of the cost-share program implemented by the Virginia Department of Conservation and Recreation, Division of Soil and Water Conservation (VDCR-DSWC), a combination of BMPs were installed in the Owl Run watershed. The BMPs installed include no-till, strip cropping, CRP, grassed waterways, animal waste storage structures, vegetative filter strips (VFS), and fencing. The areas and locations of these practices are shown in figure 25.

As illustrated in figure 25, no-till was implemented on about 150 ha of corn, or 13 percent of the entire watershed area. For no-till crop fields, the crops are planted in the previous crop residue with minimum soil disturbance. This practice results in decrease in the curve numbers and C factors to reduce surface runoff and soil erosion, and would increase the Manning's n and surface condition constant to increase the resistance of the land surface to the overland flow. The no-till practice also increases the fertilizer availability factor, which has negative effects on improving water quality.

The strip cropping practice was implemented on about 50 ha of crop land within the watershed (4.5 percent of the watershed in area). A stripcropping system refers to growing crops in a systematic arrangement of strips or bands across the general land slope to reduce water erosion and nutrient losses [VDCR-DSWC, 1990]. Like no-till, this practice decreases the curve numbers and C factors, increases the surface condition constant and Manning's roughness coefficient, but does not influence the fertilizer availability factor.

Conservation reserve program (CRP) requires that highly erodible cropland be retired for a period of 10 years. While the "reforestation of erodible cropland and pastureland" is an eligible Virginia state cost-share program, the CRP in Owl Run watershed was implemented as converting highly erodible lands (annual sediment erosion rate exceeding the tolerance limit, T) to grasslands. This practice is enforced on about 12 ha area within the watershed. Cells on which CRP is implemented are simulated as hayland.

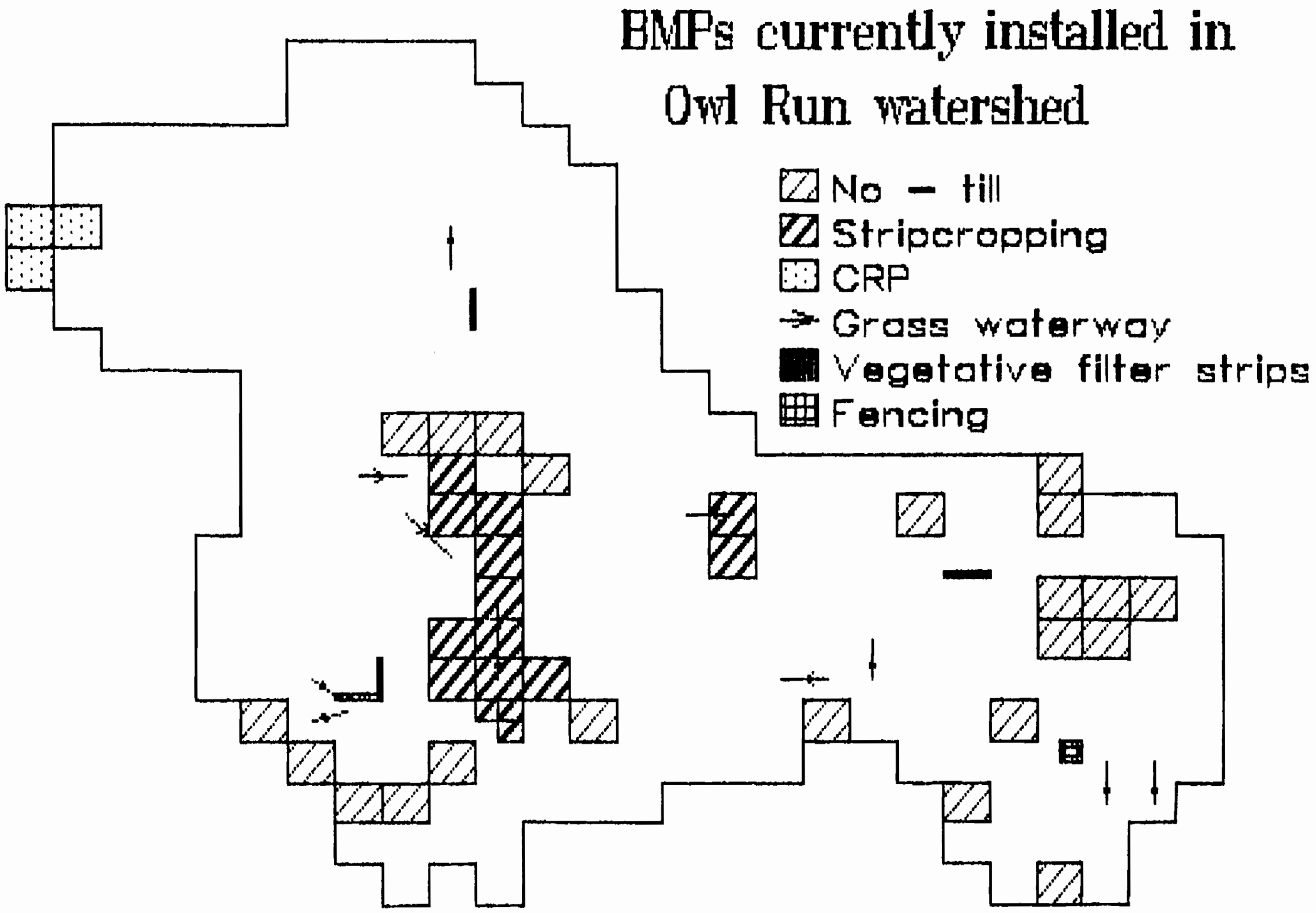

Figure 25. BMPs currently installed in Owl Run watershed.

A grassed waterway, or sod way is "a natural or constructed waterway, shaped or graded and established in suitable vegetation, to safely convey water across areas of concentrated flow" [VDCR-DSWC, 1990]. There are about 2.1 km of grassed waterways currently installed in the watershed.

The Virginia agricultural BMP cost-share program [VDCR-DSWC, 1990] describes animal waste control facilities as "a planned system designed to manage liquid and solid waste from areas where livestock and poultry are concentrated to improve water quality by storing and spreading waste at the proper time, rate and location". The animal waste storage facilities installed near five dairy cow feedlots and a hog lot in the watershed now have an annual storage capacity of 16810 tons, which is enough to handle the annual production of the livestock manure (17000 tons/year). This allows the appropriate timing and rate of the manure application. Simulation of animal waste facilities are accomplished by assigning appropriate values for fertilization levels and fertilizer availability factors (reasonable application rate and timing).

Vegetative filter strips, or grass filter strips are defined in VDCR-DSWC [1990] as vegetative buffers that are located along the banks of water courses to filter runoff, anchor soil particles and protect banks against scour and erosion. About 1.2 km of grass filter strips are installed within the watershed for nonpoint source pollutant control from about 29 ha of cropland. Cells where VFS was installed were subdivided into subcells using the routine in the AGNPS version 3.51 or higher, with the finest level at 12.5 m^2 (82 ft × 82 ft). Parameters related to grass were assigned to the areas where VFS located as described later in this section.

A pond and some of the stream banks (about 1.8 km in length) are fenced to protect water quality by reducing the direct manure loadings by animals. The Virginia agricultural BMP cost-share program for fencing practice has the following requirements for qualification of application: 1. The fence is 20 feet away (minimum) from the stream; 2. There is adequate vegetation between the stream and the water body to serve as an effective buffer to improve the water quality; 3. The stream is fenced on both sides. Like the procedure used for the simulation of filter strips, cells where fencing is applied need to be divided into subcells. The fine cells on the stream side of the fence are assigned parameters (of AGNPS input) for grass fields, and those on the other side of the fence are given values of the parameters as for pastureland.

No-till practice on critical areas (Scenario No.2)

This scenario assumes that no-till practice be implemented on all the critical areas (high erodible areas with annual sediment yield being greater than 22.4 tons/ha) identified by the AGNPS model with the annualization procedure. The total critical area identified within the watershed was 68 ha. in the watershed.

CRP on critical areas (Scenario No.3)

Like scenario no.2, the CRP practice is to be enforced on the critical areas to evaluate the impacts of this scenario on improving water quality. As defined in the first scenario description in this chapter, the conservation resource program requires that highly erodible croplands be retired for a period of 10 years. The highly erodible lands (critical areas identified according to the annual sediment yield) are to be replaced by grass land.

Animal waste storage facilities (Scenario No.4)

This option evaluates the net effects of pollutant reductions due to the installation of animal waste storage structures for handling livestock manure applications. There were about 80 ha of field in the watershed on which heavy rate of manure was applied before the installation of the animal waste storage facilities. As mentioned above, the five dairy waste and one hog waste storage facilities have enough capacity to handle the animal waste of 6 tons/day (total solids).

No-till on critical areas plus animal waste facilities (Scenario No.5)

While the no-till practice is implemented on the critical areas, the manure is managed to prevent over-application and to provide appropriate timing of application on the agricultural fields. This option simulates the cumulative effects of the two practices on water quality.

No-till on all agricultural land plus animal waste facilities (Scenario No.6)

The difference between this BMP scenario and scenario no.5 is that, instead of the critical areas, the no-till practice is applied on all agricultural lands including no-till on pastureland and hayland. The animal waste storage facilities play the same role as that of scenario no.4.

All cropland converted to pastureland plus animal waste facilities (Scenario No.7)

In this hypothetical scenario, all the cropland in the watershed is to be changed to pastureland under the assumption that the capacity of the animal waste facilities is enough to treat the waste from all the livestock in the watershed.

Simulation procedures for each of the BMPs

No-till

For the cells on which no-till is implemented, parameters including curve numbers (CN), C factors, surface condition constant (SCC), and Manning's roughness coefficients (n) were adjusted from conventional conditions to appropriate values corresponding to the practice. A summary of parameters used for simulating the no-till practice on cropland, pastureland, and hayland is given in table 14 for both dormant and growing seasons. The sources from which these parameters were estimated are the same as those used in the model validation procedure.

Table 14. Summary of parameters for no-till simulation.

		dormant season		growing season	
landuse	parameter	conventional	no-till	conventional	no-till
corn	CN *	72 81 88 91	71 79 86 89	67 78 85 89	64 75 82 85
	C	0.49	0.08	0.22	0.06
	n	0.03	0.09	0.20	0.25
	SCC **	0.05	0.22	0.05	0.29
	FA ***	21	57	21	57
pasture	CN *	77 86 91 94	49 69 79 84	68 79 86 89	39 61 74 80
	C	0.09	0.07	0.04	0.04
	n	0.04	0.06	0.13	0.13
	SCC **	0.15	0.21	0.22	0.22
	FA ***	85	85	85	85
hayland	CN *	65 76 84 88	64 74 82 86	63 75 83 87	60 72 80 84
	C	0.12	0.10	0.04	0.04
	n	0.04	0.06	0.30	0.30
	SCC **	0.29	0.32	0.59	0.59
	FA ***	0	0	0	0

* Curve numbers corresponding to the four hydrological soil groups A, B, C, and D.
** Surface condition constant.
*** Fertilization availability factor.

Strip cropping

This practice was simulated as row crops (corn) in half of the area, with small grains in between.

The strip width used in the simulation was an average value of 30 meters determined by the average land slope (3.46 %) of the watershed [Wischmeier and Smith, 1978]. The curve numbers for stripcropping cells were obtained from the CREAMS manual [USDA-SCS, 1984] for the conditions listed in table 15 for both dormant and growing seasons. The C factors used for strip cropping simulation were 0.05 and 0.02 for dormant season and growing season, respectively (corn in sod-based systems) as suggested by Wischmeier and Smith [1978].

The P factors for the stripcropping practice was determined using the same source as for strip cropping spacing and C factors [Wischmeier and Smith, 1978]. The P factor is also related to the average slope of the land. The selected values for the two seasons are listed in table 15. The Manning's n and surface condition constant were also adjusted to appropriate values corresponding to the stripcropping practice [USDA-SCS, 1984]. These two values are also listed in table 15.

Table 15. Summary of parameters for stripcropping simulation.

parameter	dormant season	growing season
CN[1]	row crop-straight-CST-poor * small grain-straight-CST-poor 68 77 84 88	row crop-straight-CST-good * small grain-straight-CST-good 62 74 81 85
C	0.05	0.02
P	0.45	0.45
n	0.13	0.20
SCC[2]	0.29	0.29
FA[2]	57	21

* CST, conservation tillage.

[1] Curve numbers corresponding to the four hydrological soil groups.

[2] Surface condition constant.

[3] Fertilization availability factor.

CRP

Under the conservation reserve program (CRP), highly erodible cropland are retired for a period of 10 years. The CRP is enforced on about 12 ha within the watershed. The retired croplands maintain a condition of ungrazed pasture. AGNPS input parameters used for this simulation, CN, C, SCC, and n were set to be the same as those of hayland as listed in table 14. The fertilization level is assumed to be 0.

Grassed waterways

About 2.1 km of grassed waterways are currently installed in the watershed. At the locations where grass waterways were installed, the value of Manning's roughness coefficient for channelized flow was adjusted from 0.048 to 0.060 [USDA-SCS, 1984]. It is assumed that gully sources do not exist any more at these locations for post-BMP simulations.

Animal waste structures

Before the installation of animal waste storage facilities, the fertilization levels and availability factors in AGNPS were chosen to be 2, and 100, respectively, as suggested by the AGNPS manual. These values represent frequent applications of manure at high rate so that the pollutants contained in the wastes are readily available to runoff. With the installation of the animal waste structures, manure spreading is handled at proper time, rate and locations as required by the cost-sharing program [VDCR - DSWC, 1990].

There are about 1000 dairy cows and 250 replacement heifers in the watershed [Mostaghimi, et al., 1989]. Annual waste production of these animals is 17100 tons. The capacity of currently installed animal waste storage facilities is 16810 ton, which is enough to handle the manure application at appropriate rate, timing and locations required by the cost-sharing program. The values of fertilization level were reduced to 1 for the post-BMP simulation, and the fertilizer availability factors were reduced to regular values for different landuses as listed in tables 14 and 15.

VFS

As indicated previously, for the AGNPS simulations performed in this study the basic cell size was 4 ha (200 m × 200 m). At the locations where VFS and fencing are installed, the cells were subdivided into up to 3 layers of subcells. Each cell at the finest level is 12.5 × 12.5 m^2 (82 ft × 82 ft), which is small enough to simulate VFS. The parameter values for the cells located on VFS were the same as grassland as listed in table 14. Base simulations were made without the subdivision of cells. Errors between the results of simulations before and after subdivision can be expected because of the routing process. Simulations were conducted to examine the effects of subdividing cell sizes on the AGNPS output. As shown in table 16, the errors from subdivision of cells for both VFS and fencing are negligible as compared to pre-subdivision scenario. The results indicated that the procedure and the level of the subdivision (9 out of 294 cells were subdivided) are valid and will not impact the AGNPS simulations. Comparisons of critical areas before and after the subdivision of necessary cells can be found in Appendix E.

Fencing

Cells on which the fencing practice was implemented for reducing animal's access to streams and ponds were divided into 12.5 × 12.5 m^2 subcells as those for VFS. When a storm occurs, manures left on the river bed and around ponds have direct contact with water flow. This direct loading can easily be reduced by confining the animals within the fenced areas. The effectiveness of this practice was demonstrated on wetlands in Florida [Heatwole, et al., 1987].

The fencing activity was simulated by changing the direct nutrient load on cells of stream bank or pond to zero.

Table 16. Comparison of simulations before and after the subdivisions of cells for VFS and fencing

	Runoff (mm)	TSS (T/ha)	TN (kg/ha)	TP (kg/ha)
before subdividing	126.9	0.831	20.88	5.10
after subdividing	126.1	0.805	20.95	5.08
errors (%)	0.7	1.9	0.3	0.4

Results and discussion

The 1987 Chesapeake Bay Agreement stated that, by the year 2000, at least a 40 percent reduction in nitrogen and phosphorus entering the main stem of the Chesapeake Bay is to be achieved due to the implementation of a basin-wide BMP strategy [U.S. EPA, 1983].

As mentioned at the beginning of this chapter, seven BMP scenarios were simulated using the annualization procedure to evaluate their long term impacts on reducing nonpoint source pollution losses. Results are compared to the pre-BMP scenario in terms of percent reductions in pollutant loadings. The long term simulation results along with total cost of each scenario and cost per unit for each scenario are given in table 18.

The conditions and corresponding parameters used for the pre-BMP simulations were described in model validation and annualization sections (Tables 5 and 6). The pre-BMP simulation results are provided in annualization section (Tables 11, 12, and 13), and are also listed in table 18 for comparison purposes.

The costs to the State of Viginia for no-till, stripcropping, installation of animal waste facilities, and other various BMP implementations were adapted from the Virginia Agricultural BMP Cost Share Program [VDCR-DSWC, 1990]. Analyses related to cost effectiveness of BMP implementations were made based on the state of Virginia cost-share payments for various practices.

Table 17 lists Virginia state cost share rates for major BMPs. The current state funding rate for implementing no-till practice is \$37/ha/year. Cost for stripcropping systems is \$74/ha/year. The CRP was implemented under the title ″Reforestation of Erodible Crop and Pastureland″, and ″Protective for Specialty Cropland″ in the Virginia Agricultural BMP Cost Share Program. Eligible lands are those on which the soil loss may exceed the tolerance limit, T. The one-time payment for reforestation is \$185/ha, or \$18.5/ha/year, considering the 10 year land retirement for CRP. The annual maintenance cost can be estimated under the title ″Protective Cover for Specialty Cropland″ in the Virginia cost-share program, for which the state payment rate is \$24.7/ha/year. Therefore the total annual funds for CRP are \$43.2/ha/year. The state cost share payment for the construction and maintenance of a liquid animal waste storage and associated components is $20,000 per year, and $7,500 per year for solid waste storage facilities. There are five animal production operations in the watershed, and the total annual cost for animal waste facilities was ($20,000 + $7,500) × 5 = $137,500. For conversion of cropland to pastureland, no implicit activity is available. The assumption made here is that the same rate as CRP is applicable ($43.2 per year for establishment and maintenance).

Table 17. Virginia state cost-share rate for major BMPs.

Practice	DSWC[1] Specification number	State cost-share Amount	% of total cost
no-till	SL-15	$37/ha/year	100%
CRP	FR-1 & SL-8	$43.2/ha/year	100%
stripcropping	SL-3	$74/ha/year	100%
crop/pasture conversion	SL-11	$43.2/ha/year	75%
animal waste facilities	WP-4	$27,500/operation/year	75%

1. Division of Soil and Water Conservation, Virginia Department of Conservation and Recreation.

For the currently installed BMP scenario (scenario no.1), runoff, average annual sediment yield, total nitrogen loading, and total phosphorus loading were reduced by 9.4 %, 26.4 %, 31.8 %, and 32.1 %, respectively, compared with the pre-BMP simulation results. This means more efforts must be made to accomplish the 40% pollutant reduction goal. The other six BMP scenarios presented in this study are aimed at investigating the impact of alternative strategies in reducing nonpoint source pollutant loadings (table 18).

Table 18. Annual pollutant reductions by different BMP scenarios.

Simulation scenarios	State cost-share ($/yr)	Runoff (mm)	TSS (T/ha)	TN (kg/ha)	TP (kg/ha)
Pre-BMP		126.9	0.805	20.9	5.08
BMP scenario no. 1[1]	146,842	115.0	0.589	14.9	3.44
Reductions		9.4 %	26.4 %	31.8 %	32.1 %
Reduction cost[8]			38	21	78
BMP scenario no. 2[2]	2,516	123.8	0.678	19.4	4.58
Reductions		2.4 %	13.5 %	9.3 %	9.4 %
Reduction cost[8]			18	2	5
BMP scenario no. 3[3]	2,940	118.7	0.657	18.1	4.14
Reductions		6 .5 %	17.9 %	13.3 %	18.3 %
Reduction cost[8]			17	1	3
BMP scenario no. 4[4]	137,500	126.9	0.805	14.7	3.72
Reductions		0 %	0 %	29.4 %	26.6 %
Reduction cost[8]			-	19	89
BMP scenario no. 5[5]	140,016	123.8	0.678	14.5	3.50
Reductions		2.4 %	13.5 %	30.1 %	30.8 %
Reduction cost[8]			18	19	78
BMP scenario no. 6[6]	156,654	84.1	0.379	8.37	2.19
Reductions		33.7 %	52.9 %	59.8 %	56.7 %
Reduction cost[8]			39	11	47
BMP scenario no. 7[7]	160,372	68.3	0.330	7.16	1.66
Reductions		46.2 %	58.8 %	65.6 %	67.2 %
Reduction cost[8]			42	10	41

1. Combination of BMPs currently installed within the watershed.
2. No-till practice on critical areas (68 ha).
3. Conservation resources program (CRP) on critical areas (68 ha).
4. Animal waste storage facilities.
5. No-till on critical areas (68 ha) plus animal waste structures.
6. No-till on cropland (518 ha) plus animal waste structures.
7. All cropland (530 ha) converted to pastureland plus animal waste structures.
8. The unit is $/T for TSS, and $/kg for TN and TP.

Scenario no.2 simulates the net effects of no-till on critical areas only (cells for which annual sediment yield exceeds 22.4 metric tons per ha). This scenario seems to be very cost-effective compared with scenario no.1. Under scenario no.2 the reduction costs were $18/Mg/ha for sediment, $2/Kg/ha for nitrogen, and $5/Kg/ha for phosphorus. A main disadvantage of this scenario is that the amounts of pollutant reductions are far less than the 40% reduction goal (13.5 %, 9.3 % and 9.4 % reductions for sediment yield, nitrogen and phosphorus loadings, respectively, table 18).

Scenario no.3 was designed to evaluate the impact of CRP practice on the same critical areas as those of scenario no.2. The pollutant reductions for this scenario were 17.9 %, 13.3 %, and 18.3 % for sediment yield, nitrogen and phosphorus loadings, respectively. These reduction rates are higher than those reported for scenario no.2 (no-till practice on critical areas), and is the most effective scenario for reducing pollutant loadings. The costs per unit pollutant reduction were $17/Mg/ha for sediment, $1/Kg/ha for nitrogen, and $3/Kg/ha for phosphorus.

Scenario no.4 evaluates the impact of the installation of the animal waste storage facilities on nutrient reductions. The cost of this practice is very high -- $137,500 for the installation and maintenance per year for the five dairy operations. The unit costs for pollutant reductions are also much higher than those of no-till and CRP scenarios (no.2 and no.3), respectively, but the practice does reduce a great amount of pollutants loadings, 29.4% for N and 26.6% for P respectively. The costs of the animal waste structures were actually even higher than those figures used in this study because of the implementation problems encountered [Mclellen, 1990].

Scenario no.5 considers the effects of the combination of no-till and animal waste structures on reducing nonpoint source pollution. The pollutant reductions are about the same as those of the current BMPs, 30.1 % and 30.8 % for nitrogen and phosphorus, respectively, but the total cost is less than scenario no.1 ($140,016 vs $146,842). Obviously, the reductions made by this scenario are still not enough to meet the 40% goal.

None of the above five scenarios met the 40% reduction requirement. Therefore, two additional scenarios were considered to explore the possibilities for fulfilment of the goal. Scenario no.6 assesses no-till practice on all of the agricultural land plus the installation of animal waste facilities, and scenario no.7 considers a hypothetical situation where all the croplands are converted to pastureland in addition to the installation of animal waste structures. It should be noted that these two scenarios may not be as practical as the ones already discussed. As shown in table 18, the sediment, nitrogen, and phosphorus loadings could be reduced by 52.6 %, 59.8 %, and 56.7 % for scenario no.6, and 58.8 %, 65.6 %, and 67.2 % for scenario no.7, respectively. The costs per kg reduction of nitrogen and phosphorus for both of the scenarios are much less than the costs reported for the currently installed BMPs in the watershed. Of the two scenarios, scenario no.6 is more realistic. On the other hand, converting large areas of cropland to pastureland under scenario no.7 would not be practical since additional manure storage facilities would be needed. As reported in table 18, the installation of animal waste storage structures are very costly.

Based on the above discussions, the best scenarios for Owl Run watershed may be the installation of animal waste facilities in combination with other BMPs such as no-till, stripcropping, and CRP, on critical areas. Most of these scenarios, however, do not meet the stated goal of 40% reduction in pollutant loadings. Based on the results presented here, it is clear that the BMPs installed on critical areas are very cost-effective. One strategy for achieving larger percentage pollutant reductions would be to redefine the critical areas (i.e. to a level less than the "T" value). This strategy would call for implementation of BMPs on a larger portion of the watershed and, thus, is expected to result in greater reductions in pollutant loadings.

The annualized critical areas identified in this study summarizes the output files of AGNPS on individual cell basis. Figures 26 and figure 27 compare the changes of sediment yield critical areas made by current BMP scenario. The criteria for identifying the critical areas is designated at level A, or 22.4 T/ha/year. Figures 28 and 29 compare, at a lower level (level B, or 19.0 T/ha/year), annualized critical areas of sediment yield with and without BMPs currently implemented. Critical areas set at C level (sediment yield greater than 15.7 T/ha/year) are also identified by the model and the annualization procedure (figures 30 and 31). The alternative scenarios no.2, no.3 and no.5 were proposed and simulated based on figure 25. These figures indicate that, with the implementation of current BMPs, there are still some areas from which the pollutant loadings are significant. Therefore, redefinition of critical areas to lower "T" values would result in a greater percentage of the watershed area being identified as problem areas. Implementation of BMP on these problem areas is expected to significantly reduce nonpoint source pollutant losses.

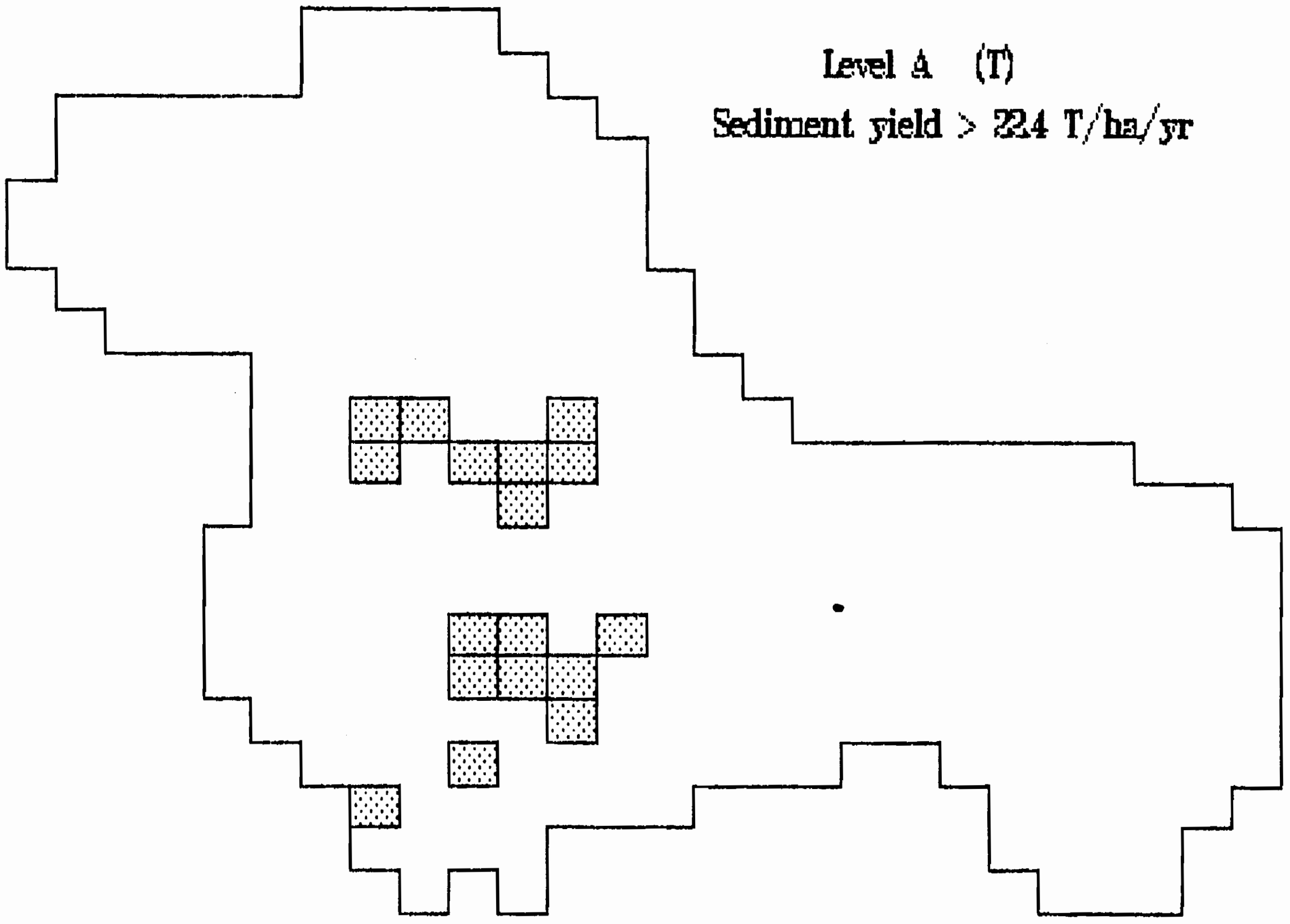

Figure 26. Critical areas identified for Pre-BMP phase of the Owl Run watershed.

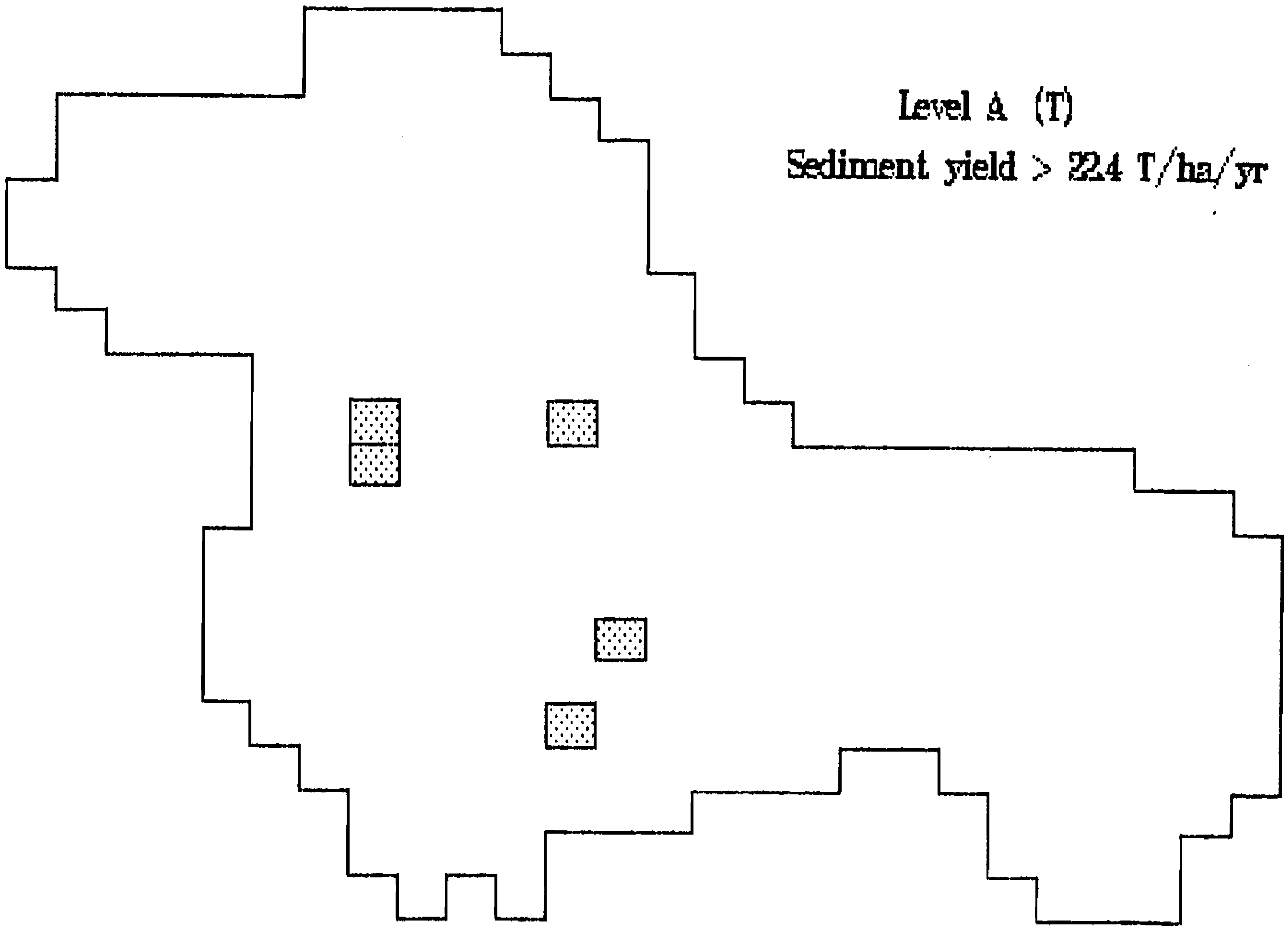

Figure 27. Critical areas identified for Post-BMP phase of the Owl Run watershed.

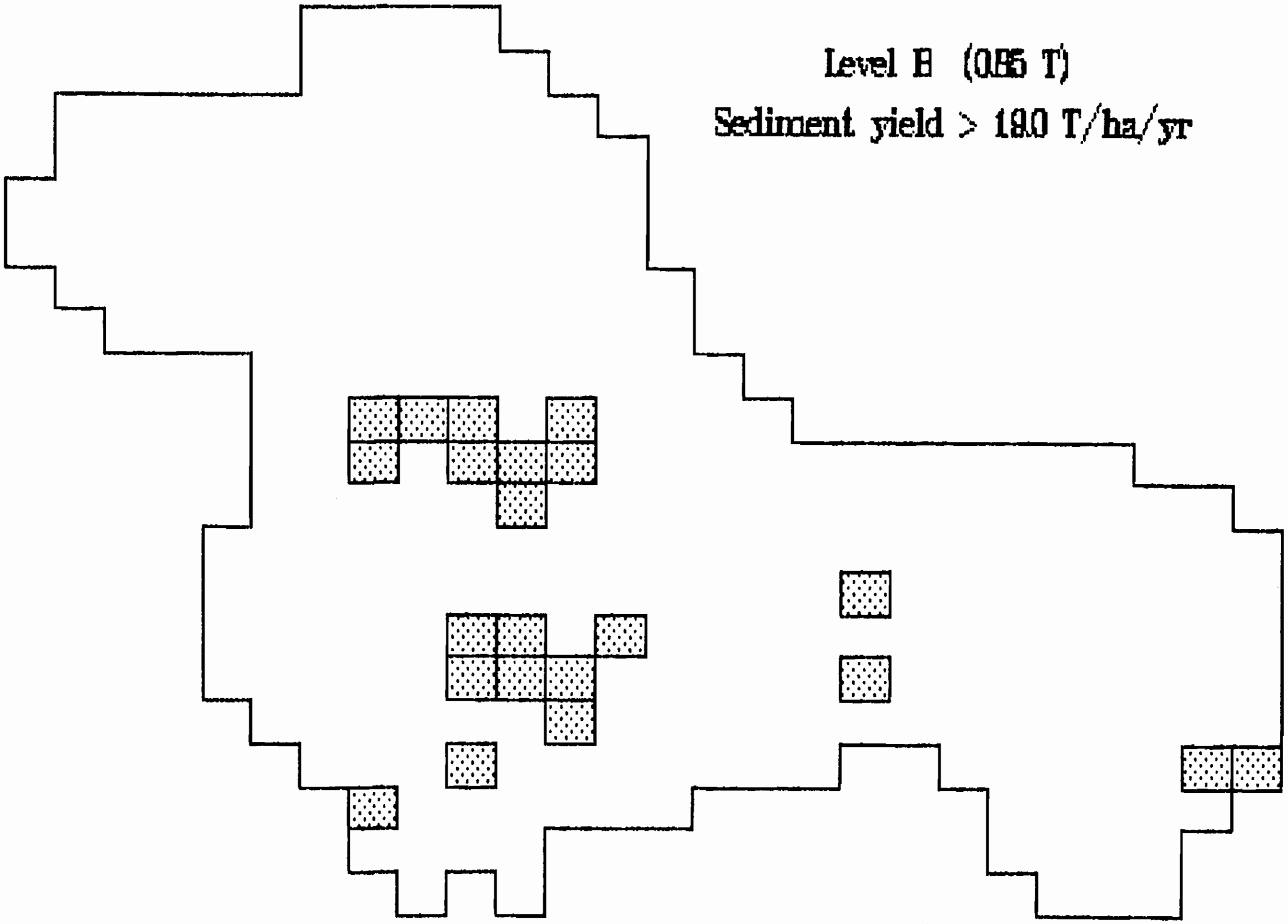

Figure 28. Critical areas identified for Pre-BMP phase of the Owl Run watershed.

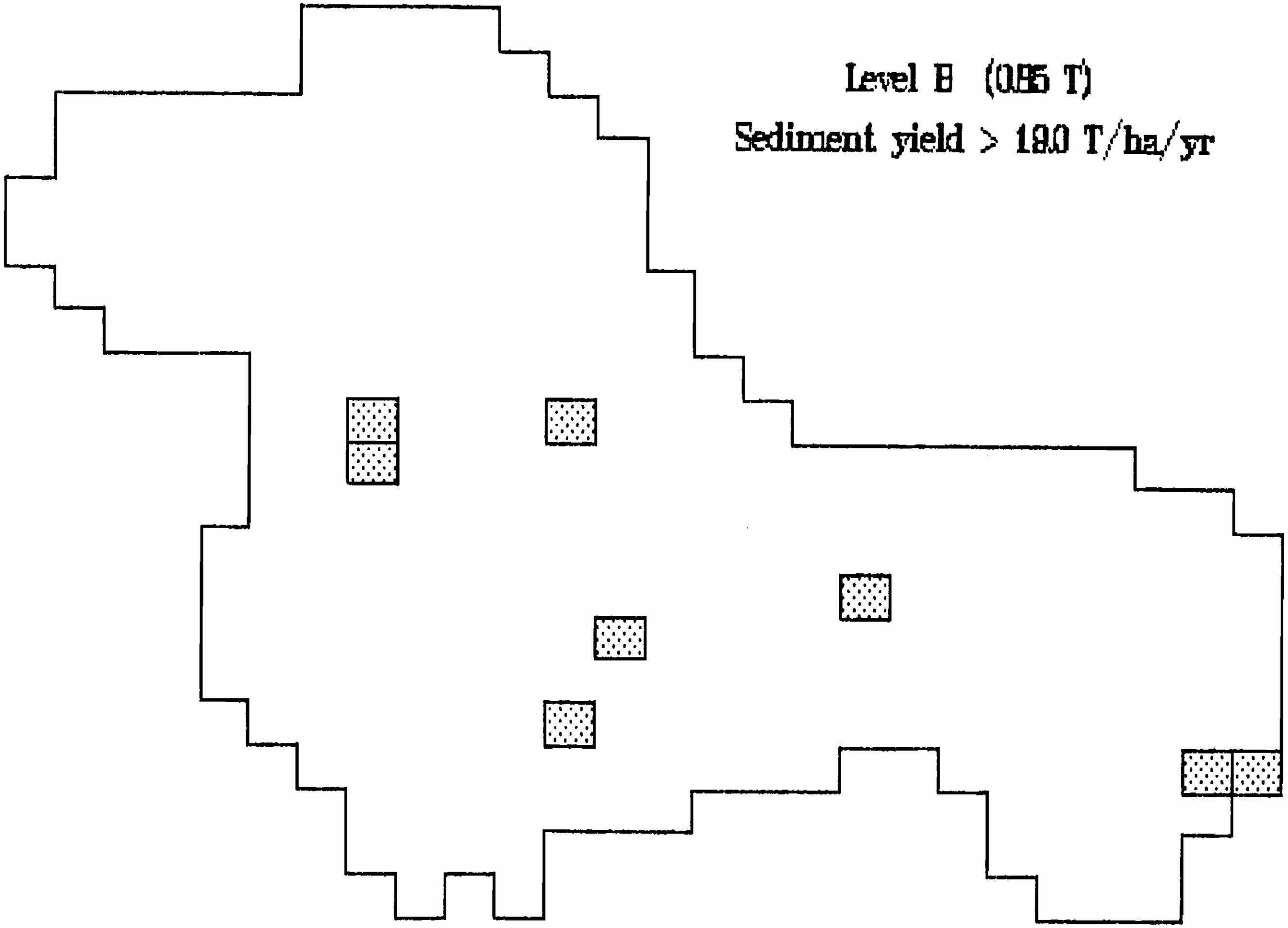

Figure 29. Critical areas identified for Post-BMP phase of the Owl Run watershed.

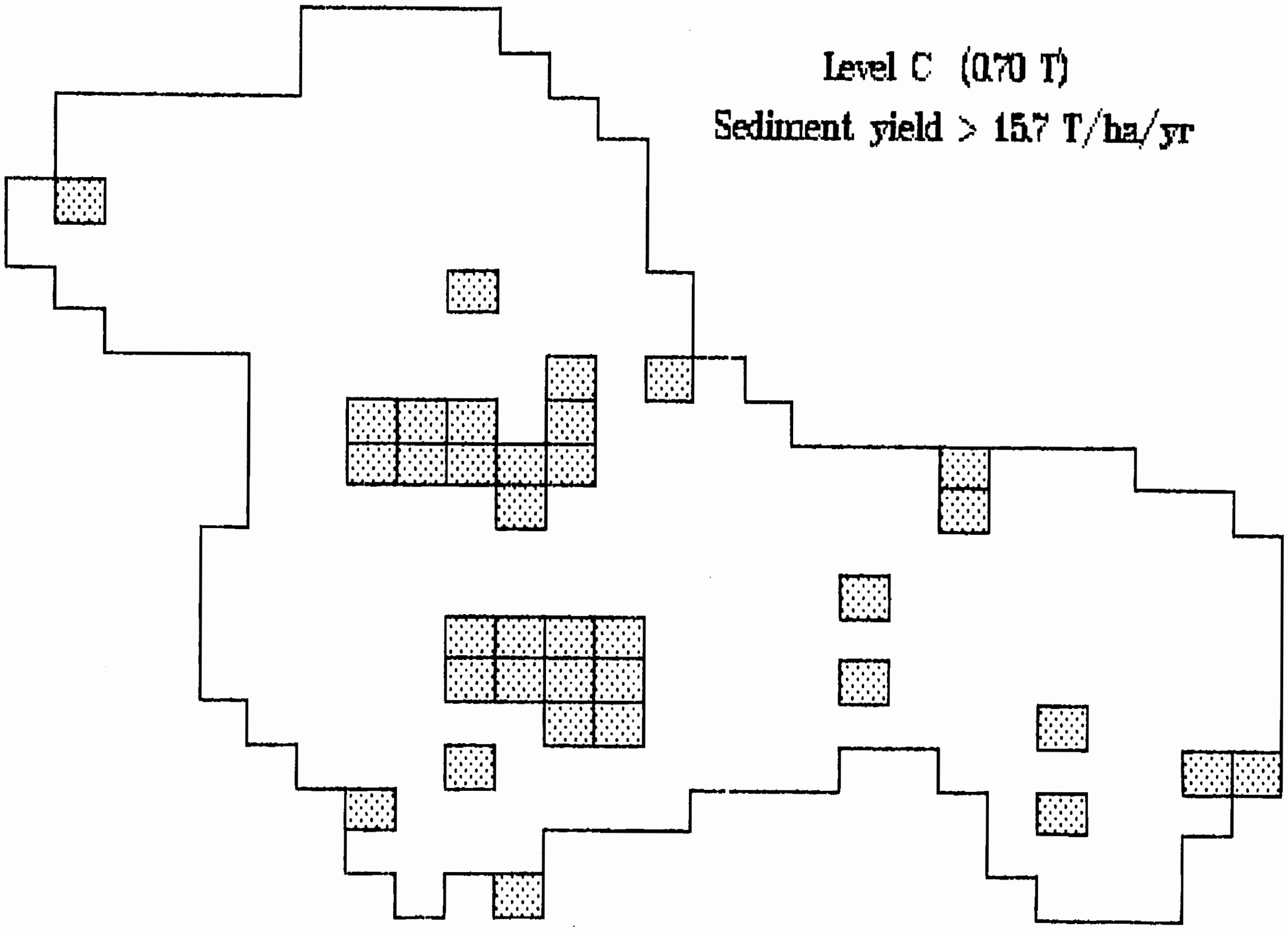

Figure 30. Critical areas identified for Pre-BMP phase of the Owl Run watershed.

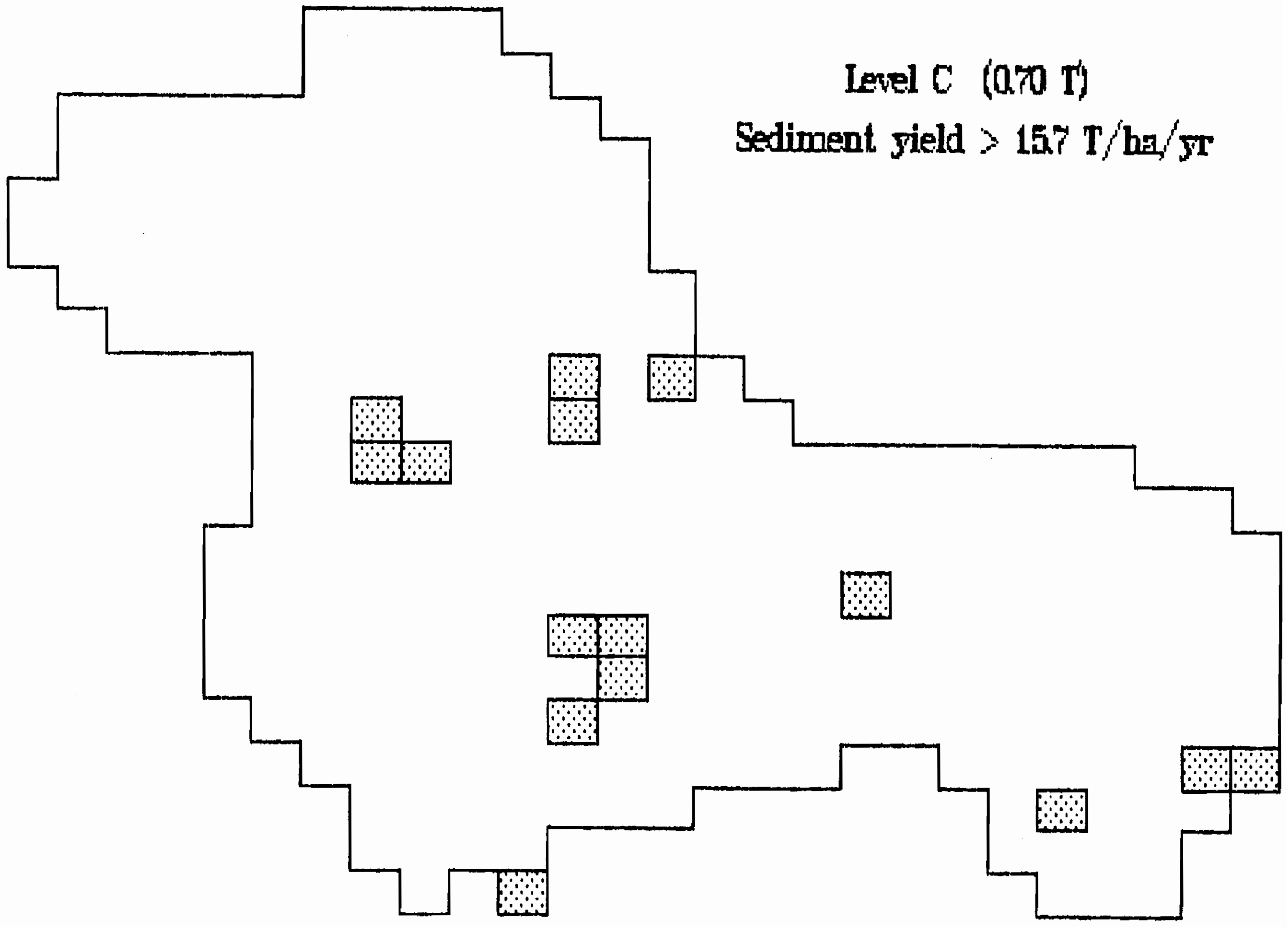

Figure 31. Critical areas identified for Post-BMP phase of the Owl Run watershed.

Summary and conclusions

The overall goal of this study was to investigate the applicability of an appropriate NPS pollution model to small watersheds in Virginia Piedmont areas. Several distributed watershed models were reviewed and a suitable model, AGNPS, which has the ability to evaluate effectiveness of specific BMPs, was selected for this study. The model has been widely accepted because of its simplicity, comprehensiveness, ability to consider spatial variability of watershed characteristics, and its ability to identify critical areas study areas.

The model was validated by comparing model predictions with data collected from a small agricultural watershed in the area. The data used for validation were recorded by a meteorological, hydrological, and water quality monitoring system installed in the Owl Run watershed.

An annualization procedure was used to convert the event based simulation results of the model to average annual results so that the BMP effectiveness was evaluated on a long-term basis. The long-term simulation results were also compared with recorded average annual data from the study watershed. Nonpoint source pollution critical areas on the watershed were identified by using the model and the annualization procedure, and some applicable BMPs were proposed, based on the critical areas, for reducing pollutant loadings. The effectiveness of the proposed BMP scenarios were then evaluated by the model.

The annualization procedure was applied under several assumptions. Surface cover conditions for preparation of model parameters were assumed to be uniform within each period considered for the year; the antecedent soil moisture condition-II was used to represent the average antecedent soil moisture conditions; and rainfall and EI values were considered to be uniformly distributed throughout the watershed.

The following conclusions were made from this study:

Runoff, sediment yield, nitrogen and phosphorus loadings predicted by AGNPS compared reasonably well with the observed data as indicated by simple linear regression analyses, comparison of mean values, and relative errors represented by root mean square (rms) error methods.

The applicability of the annualization procedure for AGNPS to the study area was demonstrated by comparing simulated runoff volume, sediment yield, and N and P loadings with those collected from the watershed during a three-year period. Relative errors of 23.5%, 14.3%, and 8.9% were calculated for sediment yield, N and P loadings for the average three year data collected from the watershed.

The impact of BMPs currently installed in watershed, as well as those of six proposed BMP scenarios on reducing nonpoint source pollutant loadings to the streams were simulated with AGNPS. The expected average long-term reductions in pollutant loadings due to the implementation of current BMPs were 31.8% for N, 32.1% for P, and 26.4% for sediment.

Scenario no.2 and no.3, proposed for evaluating impact of no-till or CRP implementations on critical areas, were found to be the most cost effective in reducing pollutant loadings. The no-till scenario (no.2) could reduce sediment yield by 13.5%, and N and P losses by 9.2% and 9.4%, respectively, with the costs of $18/T/year for sediment, $2/kg/year for N loss, and $5/kg/year for P loss. Scenario no.3 reduces sediment by 17.9%, N by 13.3%, and P by 18.3%, with reduction costs of $17/T/year, $1/kg/year, and $3/kg/year for sediment yield, N, and P losses, respectively. Animal waste facility scenario (no.4) has the largest impact on reducing N and P loadings (29.4% and

26.6%, respectively), but fairly high unit reduction costs of $19.5/kg for N, and $89.0/kg for P. The total annual cost for this scenario is $137,500.

The most effective and practical scenario seems to be somewhere between scenarios no.5 (no-till on critical areas plus animal waste facilities) and no.6 (no-till on all agricultural land plus animal waste facilities). Scenario no.6 could reduce N and P loadings by 59.8% and 56.7%, respectively, which meets the 40% reduction goal, with a total annual cost of $155,654, just slightly higher than that of the current scenario. It should be noted, however, that the Chesapeake Bay agreement has recommended reducing nutrients loadings to the Bay by 40 percent to protect long-term water quality. Nutrients loadings from small watersheds located in the headwaters of the Bay, such as Owl Run watershed, however, may need to be reduced by a larger percentage to achieve this goal. Due to the complexity of the procedures involved, however, it is not possible to accurately estimate the percent reduction needed at the headwaters.

It should be mentioned that input data preparation for distributed model parameters such as those of AGNPS is very time consuming and difficulties will arise in determing accurate values for some parameters. Based on the results obtained from this study, however, it appears that AGNPS is a suitable model for application to Virginia Piedmont conditions.

Recommendations

The following recommendations are presented for further research on application of NPS pollution models to small watersheds:

1. A mainframe version of AGNPS is necessary because of the large computation load and memory space requirement. For annualized simulations performed in this study, the average long term values of pollutant loadings were obtained based on a two dimensional analysis of seasonal variation and magnitude of storms (i.e. the probability distributions of the model output were functions of seasonal variation and magnitude of the representative events). If the frequency analyses of antecedent soil moisture conditions and/or other factors are taken into account, the computation time will increase substantially.

2. In this study , two seasons, dormant and growing, were used for hydrologic and water quality simulation. To better describe the seasonal variations of the parameters related to surface cover conditions, more seasonal stages (periods) within the year should be considered.

3. Better relationships between rainfall amount and erosion index of storm events need to be explored. Representative storm events can be analyzed as two dimensional joint frequency distributions of rainfall amount and erosion index for each storm event.

4. The seasonal variability of antecedent soil moisture conditions needs to be investigated. In this study the average condition (condition-II) as classified by the National Engineering Handbook, section-4 [USDA-SCS, 1972] was assumed. Frequency analysis of this parameter will help reduce errors in using the annualization procedure.

5. Additional research is necessary on determining the fertilization levels and availability factors for AGNPS. Relationship between the levels and the rate of animal waste or chemical fertilizer application needs to clarified and the values need to be categorized in more detail.

6. Simulation of individual BMPs using AGNPS needs to be validated. This requires long term monitoring data to compare with the simulation results.

7. A technique based on operations research, expert system, or other system analysis or optimization theories is useful to identify feasible BMP combinations and select the best ones

8. Interfacing AGNPS input files with GIS is necessary to make more efficient analyses with smaller cell sizes.

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Appendix A. Variable Glossary

Variable	Type	unit	Description
FREQ	RA[1]	times/yr	Annual occurrence frequency
PS	RA	--	Seasonal occurrence probability
G1	IA[2]	--	Cell number
G2	IA	--	Cell division indicator
G3	IA	acre	Drainage area
G4	RA	inch	Overland runoff
G5	RA	inch	Upstream runoff
G6	IA	cfs	Upstream peak flow
G7	RA	inch	Downstream runoff
G8	IA	cfs	Downstream peak flow
G9	RA	%	Upstream runoff percentage
M1	RA	ton/a[3]	Cell erosion
M2	RA	ton	Sediment inflow
M3	RA	ton	Sediment yield generated within the cell
M4	RA	ton	Sediment yield at the cell outlet
GM5	IA	%	Sediment deposition
SEDI	RA	T[4]	Annual sediment yield at watershed outlet
NITR	RA	Kg	Annual nitrogen loading at watershed outlet
PHOS	RA	Kg	Annual phosphorus loading at watershed outlet
RD	RA	inch	Dormant season runoff

SD	RA	ton	Dormant season sediment
ND	RA	lb	Dormant season nitrogen loading
PD	RA	lb	Dormant season phosphorus loading
CODD	RA	1000 lbs	Dormant season COD loading
RG	RA	inch	Growing season runoff
SG	RA	ton	Growing season sediment
NG	RA	lb	Growing season nitrogen loading
PG	RA	lb	Growing season phosphorus loading
CODG	RA	1000 lbs	Growing season COD loading
RDOR	RA	mm	Dormant season runoff
SDOR	RA	T	Dormant season sediment
NDOR	RA	Kg	Dormant season nitrogen loading
PDOR	RA	Kg	Dormant season phosphorus loading
CODDOR	RA	1000 Kgs	Dormant season COD loading
RDOR	RA	mm	Growing season runoff
SDOR	RA	T	Growing season sediment
NDOR	RA	Kg	Growing season nitrogen loading
PDOR	RA	Kg	Growing season phosphorus loading
CODDOR	RA	1000 Kgs	Growing season COD loading
G4[5]	RA	lb/a	Sediment bound nitrogen within the cell
G5[5]	RA	lb/a	Sediment bound nitrogen at cell outlet
G9[5]	RA	lb/a	Water soluble nitrogen within the cell
G7[5]	RA	lb/a	Water soluble nitrogen at cell outlet
G8[5]	IA	ppm	Nitrogen concentration
PH1	RA	lb/a	Sediment bound phosphorus within the cell
PH2	RA	lb/a	Sediment bound phosphorus at cell outlet
PH3	RA	lb/a	Water soluble phosphorus within the cell
PH4	RA	lb/a	Water soluble phosphorus at cell outlet
PH5	IA	ppm	Phosphorus concentration
COD1	RA	lb/a	Water soluble phosphorus within the cell
COD2	RA	lb/a	Water soluble phosphorus at cell outlet
COD3	IA	ppm	Phosphorus concentration

---

[1] real array

[2] Integer array

[3] English unit

[4] Metric unit

[5] Reused variable in the loop for dormant season calculation.

Appendix B. Program Listing of Annualization Procedure

```
C                ANNUALIZATION PROCEDURE FOR AGNPS
C
C                            10/18/90
C
C
C   This program is part of the annualization procedure for AGNPS
C simulation. The program summarizes 17 output files with different
C magnitude of storm events. The outputs of this program include a
C similar file as a regular AGNPS output, 'result.w', and a small
C summary output file, 'sum.w'. The file 'result.w' can be used to
C show annualized critical areas for various pollutants including
C annual average sediment yield, nitrogen, and phosphorus loadings
C at user defined levels. This file must be used together with the
C AGNPS graphix device. The file 'sum.w' shows directly the annual
C average runoff, sediment yield, nitrogen, phosphorus, and chemical
C oxygen demand loadings at the outlet of the watershed. In
C addition to the 17 AGNPS output files, a file named 'f.ps' is
C also required to input the results of storm frequency analysis.
C   This program was written in the FORTRAN language standard for
C Microsoft's Optimizing Compiler (Version 4.0, 1987) and may need
C to be modified if other compilers are used. All variables are defined
C in Appendix A. The program may be easily modified to evaluate
C different watershed by expanding or modifying the main program and
C having appropriate 'f.ps' file.
C
$      storage 2:
       character a*80,a3*3,aa(5)*80
       integer G1(17),G2(17), G3(17),G6(17),G8(17),gm5(6,17)
       real G4(17),G5(17),G7(17),G9(17)          ,freq(11),ps(2,11)
       real m1(6,17),m2(6,17),m3(6,17),m4(6,17)
       real ph1(17),ph2(17),ph3(17),ph4(17),        cod1(17),cod2(17)
```

```
       integer                              ph5(17),      cod3(17)
       real sedi(800), nitr(800), phos(800)
       real rdor(11),sdor(11),ndor(11),pdor(11),coddor(11)
       real  rgro(6), sgro(6), ngro(6), pgro(6), codgro(6)
       real rd(11),sd(11),nd(11),pd(11),codd(11)
       real rg(11),sg(11),ng(11),pg(11),codg(11)
       real rc(11),sc(11),nc(11),pc(11),codc(11)
       open(1,file='bmp_g1.nps')
       open(2,file='bmp_g2.nps')
       open(3,file='bmp_g3.nps')
       open(4,file='bmp_g4.nps')
       open(5,file='bmp_g5.nps')
       open(6,file='bmp_g6.nps')
       open(7,file='bmp_g7.nps')
       open(8,file='bmp_g8.nps')
       open(9,file='bmp_g9.nps')
       open(10,file='bmp_g10.nps')
       open(11,file='bmp_g11.nps')
       open(12,file='f.ps')
       open(99,file='result.w',status='new')
       open(98,file='sum.w',status='new')

       do 30 i=1,11
       read(12,*) freq(i),ps(1,i),ps(2,i)
       write(98,50) freq(i),ps(1,i),ps(2,i)
  50   format(f8.3,f10.3,f10.3,'   freq, ps(1,i),ps(2,i)')
  30   continue
       do 10 ifile=1,11
       do 10 i=1,22
       read(ifile,2) a
 10    continue
 2     format(a80)

       jj=0
       do 70 i=1,11
 70    G1(i)=0
 100   fm3=0.0
       pcell=1.0
       do 22 ifile=1,11
       read(ifile,*) G1(ifile),   G2(ifile),  G3(ifile),G4(ifile),
     + G5(ifile),G6(ifile),G7(ifile),G8(ifile),G9(ifile)
111    format(i1,1x,a3,i3,2f5.2, i2,f5.2,i2,f5.1)
112    format(i2,1x,a3,i3,2f5.2, i2,f5.2,i2,f5.1)
113    format(i3,1x,a3,i3,2f5.2, i2,f5.2,i2,f5.1)
c    TREATMENT OF SUBDIVISIONS
c      if(              ) pcell=1.0/4.0
c      goto 26
c      if(              ) pcell=1.0/16.0
c      goto 26
c      if(              ) pcell=1.0/64.0
```

```
 26    continue
c      if(G1(ifile).gt.9) goto 180
c      if(G1(ifile).gt.99) goto 181
c      write(98,111) G1(ifile),   G2(ifile),  G3(ifile),G4(ifile),
c    + G5(ifile),G6(ifile),G7(ifile),G8(ifile),G9(ifile)
c      write(*,113) G1(ifile),   G2(ifile),  G3(ifile),G4(ifile),
c    + G5(ifile),G6(ifile),G7(ifile),G8(ifile),G9(ifile)
c      goto 86
c180    write(98,112) G1(ifile),   G2(ifile),  G3(ifile),G4(ifile),
c    + G5(ifile),G6(ifile),G7(ifile),G8(ifile),G9(ifile)
c      goto 86
c181    write(98,113) G1(ifile),   G2(ifile),  G3(ifile),G4(ifile),
c    + G5(ifile),G6(ifile),G7(ifile),G8(ifile),G9(ifile)
c86    continue

       do 20 ir=1,6
       read(ifile,*) m1(ir,ifile),m2(ir,ifile),m3(ir,ifile),
     + m4(ir,ifile),gm5(ir,ifile)
 20    continue
       fm3=fm3+m3(6,ifile)*freq(ifile)*ps(1,ifile)*pcell
       if(G1(ifile).ne.251) goto 22
       rd(ifile)=g7(ifile)*freq(ifile)*ps(1,ifile)*pcell
       sd(ifile)=m4(6,ifile)*freq(ifile)*ps(1,ifile)*pcell
       rdor(ifile)=g7(ifile)*pcell*25.4
       sdor(ifile)=m4(6,ifile)*pcell*0.9072
 22    continue
       jj=jj+1
       sedi(jj)=fm3
       write(*,7) jj
 7     format(i5)
       if(G1(11).lt.294) goto 100
       jj=0

c   TREATMENT OF NUTRIENTS
       do 71 ifile=1,11
       read(ifile,2) a
       read(ifile,2) a
 71    G1(i)=0
  200  fni=0.0
       fph=0.0
       pcell=1.0
       do 282 ifile=1,11
       read(ifile,*) G1(ifile),   G2(ifile),  G3(ifile),
     +   G4(ifile),G5(ifile),G9(ifile),G7(ifile),G8(ifile)
       read(ifile,*) ph1(ifile),  ph2(ifile), ph3(ifile),ph4(ifile),
     + ph5(ifile),cod1(ifile),cod2(ifile),cod3(ifile)
c     TREATMENT OF SUBDIVISIONS
c      if(               ) pcell=1.0/4.0
c      goto 226
c      if(               ) pcell=1.0/16.0
```

```
c       goto 226
c       if(              ) pcell=1.0/64.0
 226    continue

        fni=fni+(G5(ifile)+G7(ifile))*freq(ifile)*ps(1,ifile)*pcell
        fph=fph+(ph2(ifile)+ph4(ifile))*freq(ifile)*ps(1,ifile)*pcell
        if(G1(ifile).ne.251) goto 282
        nd(ifile)=(G5(ifile)+G7(ifile))*freq(ifile)*ps(1,ifile)*pcell
        pd(ifile)=(ph2(ifile)+ph4(ifile))*freq(ifile)*ps(1,ifile)*pcell
        codd(ifile)=cod2(ifile)*freq(ifile)*ps(1,ifile)*pcell
        ndor(ifile)=(G5(ifile)+G7(ifile))*pcell*0.4536*2911.0
        pdor(ifile)=(ph2(ifile)+ph4(ifile))*pcell*0.4536*2911.0
        coddor(ifile)=cod2(ifile)*pcell*0.4536/1000.0*2911.0
 282    continue
        jj=jj+1
        nitr(jj)=fni
        phos(jj)=fph
        write(*,7) jj
        if(G1(11).lt.294) goto 200

289     continue
        jj=0
        do 284 i=1,11
284     close(i)
        open(1,file='bmp_d1.nps')
        open(2,file='bmp_d2.nps')
        open(3,file='bmp_d3.nps')
        open(4,file='bmp_d4.nps')
        open(5,file='bmp_d5.nps')
        open(6,file='bmp_d6.nps')

        do 310 ifile=1,6
        do 310 i=1,22
        read(ifile,2) a
        if(ifile.gt.1) goto 310
        write(99,2) a
310     continue

        do 72 i=1,6
 72     G1(i)=0
 300    fm3=0.0
        pcell=1.0
        do 322 ifile=1,6
        read(ifile,*) G1(ifile),   G2(ifile),  G3(ifile),G4(ifile),
      + G5(ifile),G6(ifile),G7(ifile),G8(ifile),G9(ifile)
c     TREATMENT OF SUBDIVISIONS
c       if(              ) pcell=1.0/4.0
c       goto 26
c       if(              ) pcell=1.0/16.0
```

```
c      goto 26
c      if(              ) pcell=1.0/64.0
 326   continue

       do 320 irow=1,5
       read(ifile,2) aa(irow)
320    continue
       irow=6
       read(ifile,*) m1(irow,ifile),m2(irow,ifile),m3(irow,ifile),
     + m4(irow,ifile),gm5(irow,ifile)
       fm3=fm3+m3(6,ifile)*freq(ifile)*ps(2,ifile)*pcell
       if(g1(ifile).ne.251) goto 322
       rg(ifile)=g7(ifile)*freq(ifile)*ps(2,ifile)*pcell
       sg(ifile)=m4(6,ifile)*freq(ifile)*ps(2,ifile)*pcell
       rgro(ifile)=g7(ifile)*pcell*25.4
       sgro(ifile)=m4(6,ifile)*pcell*0.9072
322    continue
       jj=jj+1
       fm3=(fm3+sedi(jj))*0.9072/4.0
       if(fm3.lt.1.00) fm3=1.04

       if(g3(1).gt.99) g3(1)=99
       if(g3(1).lt.10) g3(1)=10
       if(g6(1).gt.9) g6(1)=9
       if(g8(1).gt.9) g8(1)=9
       if((g4(1).gt.9.99).or.(g4(1).lt.1.00)) g4(1)=1.04
       if((g5(1).gt.9.99).or.(g5(1).lt.1.00)) g5(1)=1.04
       if((g7(1).gt.9.99).or.(g7(1).lt.1.00)) g7(1)=1.04
       if((g9(1).gt.99.9).or.(g9(1).lt.10.0)) g9(1)=44.4
       if((G1(1).gt.9).and.(G1(1).lt.100)) goto 360
       if(G1(1).gt.99) goto 361
       call zh(G2(1),a3)
       write(99,111)  G1(1),a3,G3(1),G4(1),G5(1),G6(1),
     +                                  G7(1),G8(1),G9(1)
       goto 366
       call zh(G2(1),a3)
 360   write(99,112)  G1(1),a3,G3(1),G4(1),G5(1),G6(1),
     +                                  G7(1),G8(1),G9(1)
       goto 366
       call zh(G2(1),a3)
 361   write(99,113)  G1(1),a3,G3(1),G4(1),G5(1),G6(1),
     +                                  G7(1),G8(1),G9(1)
 366   continue


       do 390 ir=1,5
       write(99,2) aa(ir)
390    continue
       ir=6
       if((m1(6,1).gt.9.99).or.(m1(6,1).lt.1.00)) m1(6,1)=1.04
```

```
       if((m2(6,1).gt.9.99).or.(m2(6,1).lt.1.00)) m2(6,1)=1.04
       if((m3(6,1).gt.9.99).or.(m3(6,1).lt.1.00)) m3(6,1)=1.04
       if((gm5(6,1).gt.99).or.(gm5(6,1).lt.10)) gm5(6,1)=44
114    format(f4.2,2f5.2,f5.2 ,i3)
115    format(f4.2,2f5.2,f6.2 ,i3)
116    format(f4.2,2f5.2,f7.2 ,i3)
117    format(f4.2,2f5.2,f8.2 ,i3)
       if(fm3.lt.99.99) goto 370
       if(fm3.lt.999.99) goto  316
       write(99,117) m1(ir,1),m2(ir,1), m3(ir,1),fm3, gm5(ir,1)
       goto 379
316    write(99,116) m1(ir,1),m2(ir,1), m3(ir,1),fm3, gm5(ir,1)
       goto 379
370    if(fm3.lt.10.00) goto 314
       write(99,115) m1(ir,1),m2(ir,1), m3(ir,1),fm3, gm5(ir,1)
       goto 379
314    write(99,114) m1(ir,1),m2(ir,1), m3(ir,1),fm3, gm5(ir,1)
379    continue
       write(*,7) jj
       if(G1(6).lt.294) goto 300
       write(99,93)
       write(99,94)
 93    format('****')
 94    format('NUTRIENT')

c   TREATMENT OF NUTRIENTS
       do 73 i=1,6
       read(i,2) a
       read(i,2) a
 73    G1(i)=0
       jj=0
  400  fni=0.0
       fph=0.0
       pcell=1.0
       do 422 ifile=1,6
       read(ifile,*) G1(ifile),   G2(ifile),  G3(ifile),
     +   G4(ifile),G5(ifile),G9(ifile),G7(ifile),G8(ifile)
       read(ifile,*) ph1(ifile),  ph2(ifile), ph3(ifile),ph4(ifile),
     + ph5(ifile),cod1(ifile),cod2(ifile),cod3(ifile)
c    TREATMENT OF SUBDIVISIONS
c      if(               ) pcell=1.0/4.0
c      goto 226
c      if(               ) pcell=1.0/16.0
c      goto 226
c      if(               ) pcell=1.0/64.0
 426   continue

       fni=fni+(G5(ifile)+G7(ifile))*freq(ifile)*ps(2,ifile)*pcell
       fph=fph+(ph2(ifile)+ph4(ifile))
     +                       *freq(ifile)*ps(2,ifile)*pcell
```

```
      if(g1(ifile).ne.251) goto 422
      ng(ifile)=(G5(ifile)+G7(ifile))*freq(ifile)*ps(2,ifile)*pcell
      pg(ifile)=(ph2(ifile)+ph4(ifile))*freq(ifile)*ps(2,ifile)*pcell
      codg(ifile)=cod2(ifile)*freq(ifile)*ps(2,ifile)*pcell
      ngro(ifile)=(G5(ifile)+G7(ifile))*pcell*0.4536*2911.0
      pgro(ifile)=(ph2(ifile)+ph4(ifile))*pcell*0.4536*2911.0
      codgro(ifile)=cod2(ifile)*pcell*0.4536/1000.0*2911.0
 422  continue
      jj=jj+1
      fni=(fni+nitr(jj))*1.12085
      fph=(fph+phos(jj))*1.12085

      if(g3(1).gt.99) g3(1)=99
      if(g3(1).lt.10) g3(1)=10
      if((g4(1).gt.9.99).or.(g4(1).lt.1.00)) g4(1)=1.04
      if((g5(1).gt.9.99).or.(g5(1).lt.1.00)) g5(1)=1.04
      if((g9(1).gt.9.99).or.(g9(1).lt.1.00)) g9(1)=1.04
      if(g8(1).gt.9) g8(1)=9
      if((ph1(1).gt.9.99).or.(ph1(1).lt.1.00)) ph1(1)=1.04
      if((ph2(1).gt.9.99).or.(ph2(1).lt.1.00)) ph2(1)=1.04
      if((ph3(1).gt.9.99).or.(ph3(1).lt.1.00)) ph3(1)=1.04
      if((cod1(1).gt.9.99).or.(cod1(1).lt.1.00)) cod1(1)=4.44
      if((cod2(1).gt.9.99).or.(cod2(1).lt.1.00)) cod2(1)=4.44
      if((cod3(1).gt.99).or.(cod3(1).lt.10)) cod3(1)=44
      if(ph5(1).gt.9) ph5(1)=9

211   format(i1,1x,a3,i3,3f5.2,f5.2,i2)
221   format(i1,1x,a3,i3,3f5.2,f6.2,i2)
231   format(i1,1x,a3,i3,3f5.2,f7.2,i2)
241   format(i1,1x,a3,i3,3f5.2,f8.2,i2)
251   format(i1,1x,a3,i3,3f5.2,f9.2,i2)
212   format(i2,1x,a3,i3,3f5.2,f5.2,i2)
222   format(i2,1x,a3,i3,3f5.2,f6.2,i2)
232   format(i2,1x,a3,i3,3f5.2,f7.2,i2)
242   format(i2,1x,a3,i3,3f5.2,f8.2,i2)
252   format(i2,1x,a3,i3,3f5.2,f9.2,i2)
213   format(i3,1x,a3,i3,3f5.2,f5.2,i2)
223   format(i3,1x,a3,i3,3f5.2,f6.2,i2)
233   format(i3,1x,a3,i3,3f5.2,f7.2,i2)
243   format(i3,1x,a3,i3,3f5.2,f8.2,i2)
253   format(i3,1x,a3,i3,3f5.2,f9.2,i2)
214   format(f4.2,2f5.2,f5.2,i2,2f5.2,i3)
224   format(f4.2,2f5.2,f6.2,i2,2f5.2,i3)
234   format(f4.2,2f5.2,f7.2,i2,2f5.2,i3)
244   format(f4.2,2f5.2,f8.2,i2,2f5.2,i3)
      fni=fni*100.0
      fph=fph*100.0
      if(fni.lt.1.00) fni=1.04
      if(fph.lt.1.00) fph=1.04
      assign 214 to kp
```

```
        if(fph.lt.10.00) goto 591
        assign 224 to kp
        if(fph.lt.100.00) goto 591
        assign 234 to kp
        if(fph.lt.1000.00) goto 591
        assign 244 to kp
591     continue
        if((G1(1).gt.9).and.(G1(1).lt.100)) goto 560
        if(G1(1).gt.99) goto 561
        call zh(G2(1),a3)
        assign 211 to kn
        if(fni.lt.10.00) goto 592
        assign 221 to kn
        if(fni.lt.100.00) goto 592
        assign 231 to kn
        if(fni.lt.1000.00) goto 592
        assign 241 to kn
        if(fni.lt.10000.00) goto 592
        assign 251 to kn
592     continue
        write(99,kn) G1(1),a3,G3(1),  G4(1),G5(1),G9(1), fni, G8(1)
        write(99,kp) ph1(1),ph2(1),ph3(1),   fph,
     +                             ph5(1),cod1(1),cod2(1),cod3(1)
        goto 526
560     assign 212 to kn
        if(fni.lt.10.00) goto 593
        assign 222 to kn
        if(fni.lt.100.00) goto 593
        assign 232 to kn
        if(fni.lt.1000.00) goto 593
        assign 242 to kn
        if(fni.lt.10000.00) goto 593
        assign 252 to kn
593     continue
        call zh(G2(1),a3)
        write(99,kn) G1(1),a3,G3(1),  G4(1),G5(1),G9(1), fni, G8(1)
        write(99,kp) ph1(1),ph2(1),ph3(1),   fph,
     +                             ph5(1),cod1(1),cod2(1),cod3(1)
        goto 526
561     assign 213 to kn
        if(fni.lt.10.00) goto 594
        assign 223 to kn
        if(fni.lt.100.00) goto 594
        assign 233 to kn
        if(fni.lt.1000.00) goto 594
        assign 243 to kn
        if(fni.lt.10000.00) goto 594
        assign 253 to kn
594     continue
        call zh(G2(1),a3)
```

```
      write(99,kn) G1(1),a3,G3(1),  G4(1),G5(1),G9(1), fni, G8(1)
      write(99,kp) ph1(1),ph2(1),ph3(1),   fph,
     +                              ph5(1),cod1(1),cod2(1),cod3(1)
526   continue
      write(*,7) jj
      if(G1(6).lt.294) goto 400
      write(99,93)

      do 610 i=1,6
      rd(i)=(rd(i)+rg(i))*25.4
      sd(i)=(sd(i)+sg(i))*0.9072
      nd(i)=(nd(i)+ng(i))*2911*0.4536
      pd(i)=(pd(i)+pg(i))*2911*0.4536
 610  codd(i)=(codd(i)+codg(i))*2911*0.4536/1000.0
      do 611 i=7,11
      rd(i)=rd(i)*25.4
      sd(i)=sd(i)*0.9072
      nd(i)=nd(i)*2911*0.4536
      pd(i)=pd(i)*2911*0.4536
 611  codd(i)=codd(i)*2911*0.4536/1000.0
      run=0.0
      sed=0.0
      tn=0.0
      tp=0.0
      tcod=0.0
      do 612 i=1,11
      run=run+rd(i)
      sed=sed+sd(i)
      tn=tn+nd(i)
      tp=tp+pd(i)
 612  tcod=tcod+codd(i)
      do 613 i=1,11
      rc(i)=rd(i)/run*100.0
      sc(i)=sd(i)/sed*100.0
      nc(i)=nd(i)/tn*100.0
      pc(i)=pd(i)/tp*100.0
 613  codc(i)=codd(i)/tcod*100.0

      write(98,621)  rd,run, rc
 621  format(/11f6.1,f8.1/11f6.1)
      write(98,622)  sd,sed, sc
 622  format(/11f6.1,f8.1/11f6.1)
      write(98,623)  nd,tn, nc
 623  format(/11f6.0,f9.0/11f6.1)
      write(98,624)  pd,tp, pc
 624  format(/11f6.0,f9.0/11f6.1)
      write(98,625)  codd,tcod, codc
 625  format(/11f6.1,f9.1/11f6.1)

      write(98,631)  rdor,rgro
```

```
 631   format(///8X,'DIRECT SIMULATION'//2f6.3,2f6.2,7f6.2/
     +  f6.3,5f6.2)
       write(98,632)  sdor,sgro
 632   format(/11f6.1/11f6.1)
       write(98,633)  ndor,ngro
 633   format(/3f5.0,4f6.0,4f7.0/11f6.0)
       write(98,634)  pdor, pgro
 634   format(/7f6.0,4f7.0/11f6.0)
       write(98,635)  coddor,codgro
 635   format(/11f6.1/11f6.1)

       end
c
       subroutine zh(n,a3)
       character a3*3,b(3),b3*3
       equivalence (b(1),b3)
       i1=n/100+48
       i2=mod(n,100)/10+48
       i3=mod(mod(n,10),10)+48
       b(1)=CHAR(I1)
       B(2)=char(i2)
       b(3)=char(i3)
       a3=b3
       end
```

Vita

Yang Wang was born on May 30, 1955 in Beijing, China. He received a B.Eng. degree in Agricultural Water Resource Engineering from North China Institute of Water Conservancy and Hydropower, Handan, Hebei Province, China in February, 1981. He was an assistant engineer in the Northwest Research Institute of Water Resources Engineering, Yangling, Shaanxi Province, China for two years and then entered the graduate school of the same college for two and half years graduate study. He received the M.Eng. degree in July, 1986. He worked as a research engineer in the same research institute in northwest China for another two years before entering Virginia Tech to pursue an MS in Agricultural Engineering in August, 1988. He plans to begin studies in January, 1991 towards a PhD at another university in the United States.