Applying Probabilistic Risk Assessment to Agricultural Nonpoint Source Pollution

by
Sharon Perkins Buck

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APPROVED:

Mary Leigh Wolfe, Chair   Saied Mostaghimi

Frank E. Woeste   Donald M. Vietor

John V. Perumpral
Department Head

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(ABSTRACT)

A probabilistic risk assessment (PRA) for the discharge of excessive nitrogen from nonpoint sources (NPSs) to a stream was performed for a small agricultural watershed in northern Virginia. Risk, by definition, is the product of the frequency of occurrence of an event and the consequences of that event. The purpose of this research was to determine the probability of occurrence of a nitrogen discharge event (i.e., frequency). The consequences of such a discharge event were not explicitly determined but were implicitly assumed to be negative in nature.

An event tree was developed to show the basic hydrologic processes at work in a small watershed. However, the event tree could not be used to discover the causes for nitrogen loss from the watershed. Therefore, a fault tree was developed for excessive nitrogen discharge in surface runoff on any day from agricultural sources. The development of the fault tree was found to be a useful exercise in understanding the intricate cause and effect relationships between agricultural practices and NPS pollution. Based on the results, the fault tree methodology might be used as an effective teaching or communication tool.

The fault tree was also evaluated quantitatively to determine a probability of occurrence for excessive nitrogen discharge to the stream on any day. Land use, fertilization, monitoring, and long-term weather records were used in conjunction with scientific judgment and expert opinion to establish the probabilities within the fault tree and to calculate the overall probability of nitrogen discharge to the stream on any day. The results obtained from the fault tree calculations tend to underestimate the importance of cropland best management practices (BMPs) over the long term, because the fault tree was developed on a daily basis (i.e., every day in a year has the same probability of a discharge event occurring). A more accurate depiction of the NPS pollution control problem was achieved by assuming the occurrence of a runoff event. A second fault tree was presented for the discharge of excessive nitrogen to the stream during a runoff event. The quantitative assessment of the new fault tree showed more clearly the impact of BMPs on reducing the likelihood of nitrogen discharge. A 0.15 decrease in the probability of nitrogen discharge during a runoff event was calculated for the Owl Run watershed from 1987 to 1993 due to the effects of BMPs installed during that time period. A 0.20 decrease was calculated for an Owl Run subwatershed for the same time period. This subwatershed isolated two major dairy operations and the effects of the BMPs installed for those dairies.

Despite the success of the fault tree in mirroring changes within the watershed, the amount of data and time required to perform the quantitative assessment may limit its use in the NPS pollution control field. The basic nature of the fault tree technique also limits its usefulness in the field. One such limitation is that degrees of events cannot be expressed. For example, a BMP is either present or not present on a fault tree. There can be no indication of how effective the BMP is in preventing NPS pollution without substantially increasing the level of detail displayed by the tree. Another limitation is that the ultimate result of the fault tree calculations is a probability of occurrence. This value is not as easily understood as the output of NPS pollution computer models, for example, where the output has specific meaning and units (e.g., milligrams of nitrogen per liter of runoff). The qualitative fault tree, however, has the advantage over computer models when it comes to understanding the concepts behind the technique and being able to see the cause and effect relationships at work in the watershed. Laypersons can understand the fault tree more easily than the complex computer code and intricate equations of models.

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Chapter 1: Introduction

1.1 Background

In recent years increasing attention has been paid to the effects of nonpoint sources of pollution on ground and surface water quality. Nonpoint sources (NPSs) are diffuse in nature and, therefore, more difficult to identify than point or pipe sources. One major source of nonpoint pollution is agriculture. NPS pollution problems can arise when excess chemical or organic fertilizers are added to crop or range lands. If nutrients applied in fertilizers, such as nitrogen and phosphorous, are not taken up by growing plants they can be washed into streams with runoff or leached into ground water. Once in the water, these nutrients can promote eutrophication of surface waters or degrade the quality of drinking water supplies.

Agriculture and other sources of NPS pollution are largely unregulated. Recent trends indicate that many groups would welcome more and rigorous regulation of the agriculture industry. The public and some regulatory agencies are demanding that the risks of agriculture be managed more stringently. New technologies, models, and programs must be developed to demonstrate to the public and the regulatory community that the risks inherent to agriculture are recognized, investigated, and managed.

The historical programs established to combat the NPS problems of erosion, sedimentation, and excessive nutrient applications have had some success with voluntary participation and through the use of government subsidies. Implementation of Best Management Practices (BMPs) has been the primary tool for reducing NPS pollution from agriculture. A BMP can be either structural (e.g., waste lagoons, sedimentation ponds), managerial (e.g., tillage practices, integrated pest management), or vegetative (e.g., cover crops, vegetative filter strips). Once a BMP has been chosen to achieve a specific purpose, resources and training are necessary to insure proper installation and operation.

Given the limitations of personnel and money facing all agricultural and environmental agencies, a method of targeting significant contributors to NPS pollution is needed. Realistically, every source of NPS pollution cannot be treated; therefore, priorities must be set to treat those areas which can bring about the largest reduction in NPS pollution for the least cost (Phillips, 1989). A voluntary system, such as the one described above, does not insure that the areas in need of special management receive it. In addition, economic studies have shown that in some instances the costs of implementing government-subsidized BMPs have exceeded the benefits to the community (Setia and Magleby, 1987). To avoid such mistakes in the future, some type of analytical pre-project assessment is necessary.

One method of system or project analysis that has gained popularity and credibility in the oil industry, energy industry, and other fields is Probabilistic Risk Assessment (PRA) (Goyal, 1986;

Rasmussen, 1981; Chen et al., 1993). PRA is used to estimate the risk of system failure or the occurrence of an undesirable event. Risk is quantified using the probabilities of occurrence for events which can lead up to the system failure. This research focused on calculating the risks associated with agricultural NPS pollution. If the actual probability of harm to the environment due to agricultural practices can be estimated, based on cultural practices and land use, then PRA might be a useful tool in determining both the placement and effectiveness of BMPs.

1.2 Objectives

The overall goal of this research was to determine the applicability of Probabilistic Risk Assessment (PRA) to agricultural NPS pollution. Because all forms of NPS pollution could not be studied, nitrogen was selected as the pollutant of interest. Nitrogen can be found in both dissolved and adsorbed forms, therefore, this selection would necessitate the study of both major pollutant pathways. A PRA of nitrogen losses was used as an indicator of the applicability of PRA to NPS pollution in general. To accomplish the overall goal, the following specific objectives were addressed:

1. To perform a qualitative assessment of the probability of nitrogen losses from a small agricultural watershed using PRA techniques;

2. To utilize the qualitative analysis from Objective 1 to perform a quantitative assessment for nitrogen losses from the agricultural watershed; and

3. To identify and investigate event probabilities which are difficult to quantify and which may be factors limiting the applicability of PRA to NPS pollution.

Chapter 2: Literature Review

Both risk and nonpoint source (NPS) pollution have been the subject of much research in recent years. This chapter presents the results of some of that research. The causes and effects of NPS pollution are explored through the example of the Chesapeake Bay. The concept of risk is introduced, and various popular methods for analyzing risk are detailed. Risk analysis is relatively new in the environmental arena. The limited research that has been conducted is presented.

2.1 Nonpoint Source Pollution

In their text on water quality, Novotny and Olem (1994, p. 13) define pollution as "a change in the physical, chemical, radiological, or biological quality of the resource (air, land, or water) caused by man or due to man's activities that is injurious to existing, intended, or potential uses of the resource." Sources of pollution may be either point or nonpoint. The statutory definitions of point and nonpoint pollution are not as obvious as they appear at first. However, point sources do have three general characteristics in common. Statutory point sources enter receiving waters at identifiable points, they carry pollutants, and they are regulated. In addition to the obvious examples of wastewater effluents, statutory point sources also include runoff from concentrated animal feeding operations. While runoff is traditionally considered to be a nonpoint source, Congress has chosen to regulate these confined animal operations as point sources (Novotny and Olem, 1994, p. 21).

Nonpoint sources of pollution are generally considered to be everything not defined as a point source. In general, NPS pollution is generated over a large area and transported overland to surface waters or by infiltration to shallow aquifers. Discharge of NPS pollution to water bodies is diffuse (i.e., exact points of entry cannot be determined) and at time intervals ultimately related to precipitation events. Examples of NPS pollution include runoff from agricultural or silvicultural activities, runoff from mines or construction sites, urban runoff, and leachate from septic tanks. The most significant pollutants from NPSs are suspended solids, toxic compounds, and nutrients. NPS pollution is difficult to monitor at its point of origin but can generally be diminished with improved land management techniques (Novotny and Olem, 1994, pp. 20-22).

The impact of NPS pollution from agriculture is tremendous. The U.S. Environmental Protection Agency estimated that in the early 1980s, NPS pollution from agricultural sources (i.e., cropland, pastureland, and rangeland) contributed more than 6.8 million tons of nitrogen and 2.6 million tons of phosphorus to U.S. surface waters each year (USEPA, 1984). The Chesapeake Bay is one example of a waterbody that has experienced significant degradation due to the effects of NPS pollution. In 1983, a USEPA study showed that 67 percent of the nitrogen and 39 percent of the phosphorus entering the Chesapeake Bay came from NPSs. In addition, cropland was estimated to be responsible for 60 percent of the nitrogen and 27 percent of the phosphorous from NPSs (USEPA, 1983). In a recent publication, however, agriculture was estimated to be responsible for 39 percent of all nitrogen and 49 percent of all phosphorous entering the Bay (USEPA, 1995).

In the early 1980s, it was recognized that the elevated levels of nutrients entering the Chesapeake Bay caused numerous ecological problems. The most noticeable and disturbing problems were algal blooms, accelerated eutrophication, and lower fish and oyster harvests. The result was the degradation of the Bay as a valuable economic and recreational resource. In an attempt to save the Bay, Virginia, Maryland, Pennsylvania, and Washington, D.C. committed to the Chesapeake Bay Agreement of 1983. This agreement targets the reduction of NPS pollution through cost-sharing programs.

A 1995 report on the Potomac River in Virginia, a tributary of the Chesapeake Bay, reported on the progress of nutrient reduction activities in the region. The data displayed in Table 2.1 show the extent of point and nonpoint contributions to controllable nutrient loads in 1985 and 1994. The report did not include uncontrollable, or background, discharges in the analysis.

The progress shown in Table 2.1 varies depending on which category is considered. The total phosphorous load was reduced by 26 percent. Phosphorous from point sources was decreased by 37 percent, whereas nonpoint contributions were down 21 percent. The total amount of nitrogen entering the Potomac River from Virginia was decreased by 6.5 percent. NPSs discharged 17 percent less nitrogen in 1994 as compared to 1985. Point sources, however, contributed 4 percent more nitrogen to the river. The increase in point source nitrogen discharge was the result of a 19 percent increase in wastewater flow due to population increases in the region. Although progress has been made, there is much more to be done to achieve the goal of a 40 percent reduction in nitrogen and phosphorous loads to the Bay set forth by the Chesapeake Bay Agreement.

Table 2.1: Nitrogen and phosphorous loads for the Potomac River Basin, Virginia (Virginia Department of Environmental Quality et al., 1995)

	1985 Load (millions lbs/yr and percent of total)			**1994 Load (millions lbs/yr and percent of total)**		
	Point Source	*Nonpoint Source*	*Total*	*Point Source*	*Nonpoint Source*	*Total*
Phosphorous	0.571 28%	1.483 72%	2.054	0.358 23%	1.170 77%	1.528
Nitrogen	10.062 49%	10.643 51%	20.705	10.504 54%	8.854 46%	19.358

2.2 Risk

Risk terminology is often confused and misused. In their text on probabilistic risk assessment, Henley and Kumamoto (1992, p. 9) define risk as "the probability of loss or injury to people and property". This definition is expressed by the following equation:

$$\textbf{Risk}\left[\frac{\text{Amount}}{\text{Year}}\right] = \textbf{Frequency}\left[\frac{\text{Events}}{\text{Year}}\right] \times \textbf{Consequence}\left[\frac{\text{Amount}}{\text{Event}}\right] \tag{1}$$

Therefore, a risk analysis, by its definition, combines a study of failure frequency with the consequences of a system failure. These consequences can be in terms of lives, property, or profits lost. The analysis of failure frequency due to any cause is termed a reliability analysis. Similarly, analyzing the frequency with which a particular event results in system failure is called a safety/hazard study (Henley and Kumamoto, 1992, p. 8).

Throughout the literature, the term risk is used synonymously with the frequency of event occurrence. In some situations, a risk analysis is conducted without an explicit consideration of consequences. Such implicit treatment of consequences leads to further confusion on the true meaning of risk. This research focused on determining the probability or frequency of NPS pollution discharge and, therefore, is technically considered a reliability analysis. The consequences of NPS pollution are not explicitly explored here but are assumed to be negative environmental impacts.

Other researchers have addressed the ecological and economic consequences of NPS pollution. Some of the more common water quality problems associated with agricultural NPS pollution include the following: increased turbidity (i.e., cloudiness caused by sediment delivery to waterways); increased levels of plant nutrients; increased levels of pesticides; increased levels of bacteria and organic matter from livestock (Novotny and Olem, 1994, pp. 681-686). All of these changes can have dramatic negative effects on the native vegetation and aquatic life of waterways. For example, bacteria and pesticides can kill certain aquatic species. Turbid water reduces the amount of light reaching submerged vegetation making photosynthesis difficult. Increased levels of nutrients feed fast-growing colonies of algae which not only block sunlight from the deeper waters but also deplete the levels of oxygen in the water. Severely depleted oxygen levels can leave fish and other aquatic life forms with nothing to breathe and could result in large scale fish-kills. Diseased and dying fishes can substantially decrease the economic value of waterbodies and the industries dependent on the harvest of aquatic species.

2.3 Risk Assessment Techniques

There are many different ways to assess risk. Some techniques are more scientific and quantitative than others. Not all methods analyze risk in a probabilistic manner as in this research. Each technique, however, has a specific purpose. Several techniques are described in the following sections.

2.3.1 Delphi Technique

The Delphi technique utilizes the practical and research experiences of professionals in the area of interest to assess levels of risk. Typically, the experts are asked to rate the risk level of certain activities under a set of initial conditions. The activities and conditions presented are general in nature and not site-specific. A scale of risk is established prior to convening the panel (e.g., a scale of one to five with five being the highest possible risk). Discussion is prompted until the panel can reach a consensus on the risk level of the activity. The information gained from the experts is recorded and can be used to analyze specific circumstances and sites (Lull et al., 1995).

2.3.2 Risk Indices

Another method used in risk analysis is the development of risk indices. Approaches vary widely; however, indices are usually based on measurable physical properties. An equation is developed to utilize these quantifiable characteristics and combine them into a single value or index. This index is then compared to some established standard to determine its risk level. The consequences of the event are implicitly assumed to be negative in most instances and are not directly addressed.

One example of a risk index is DRASTIC, a method for evaluating the relative potential for ground water pollution for any uniform region in the United States. The DRASTIC index, though not explicitly called a risk index, does assess pollution potential (i.e., the risk of ground water pollution occurrence under a given set of conditions). DRASTIC uses seven factors to determine pollution potential (Aller et al., 1987). Each factor is assigned a weight (X_W) indicating the importance of that factor in contributing to the risk of ground water pollution. The DRASTIC factors and their associated weights are shown in Table 2.2. Similar to the weights, the measured values for the physical properties associated with each factor are assigned a rating (X_R). An example of the ratings is given in Table 2.3 for "Depth to water table".

Table 2.2: DRASTIC factors and weights (Aller et al., 1987)

Factors (X)	**Weight (X_W)**
D - Depth to water table	5
R - net Recharge	4
A - Aquifer media	3
S - Soil media	2
T - Topography (slope)	1
I - Impact of the vadose zone media	5
C - Conductivity (hydraulic) of the aquifer	3

Table 2.3: Ratings for depth to water table (Aller et al., 1987)

Depth to water table (ft)	Rating (D_R)
0-5	10
5-15	9
15-30	7
30-50	5
50-75	3
75-100	2
100+	1

After the ratings have been determined for each DRASTIC factor, based on physical properties or measurements, the weights (X_W) and ratings (X_R) are combined using the following equation (Aller et al., 1987):

$$\text{DRASTIC Index} = D_R*D_W + R_R*R_W + A_R*A_W + S_R*S_W + T_R*T_W + I_R*I_W + C_R*C_W \qquad (2)$$

The DRASTIC Index indicates the vulnerability of ground water in the region to contamination by pollutants. The range of possible index values is 23 to 226. The determination of which index values indicate acceptable or unacceptable risk is left to the discretion of the user.

2.3.3 Probabilistic Risk Assessment

The methodology chosen for this research was Probabilistic Risk Assessment (PRA). This methodology is attractive to risk analysts because it provides a quantification of risk that can be used to directly compare a list of options. PRA has three general uses: to give overall estimates of risk for use in policy-making, to provide risk estimates for licensing and regulatory procedures, and to identify improvements (Linnerooth-Bayer and Wahlstrom, 1991). It has been debated that the emphasis of PRA should not be on the minimization or eradication of risk but rather the ability to manage risk. PRA encourages foresight and the recognition and management of risks. PRA can also provide a means of allocating limited resources (Starr, 1985).

PRA techniques are considered useful for complex systems but work best on structured and well-defined systems. In instances where systems are less defined and causal factors are difficult to quantify, PRA yields less precise or "soft" results. These "soft" results can still be quite useful, however. Qualitative analyses can provide a clearer picture of system interactions and environmental impacts (Linnerooth-Bayer and Wahlstrom, 1991). Even when quantitative data are available and risk values can be calculated, there are as yet no numerical guidelines or criteria for determining what level of risk is acceptable (Rasmussen, 1981; Lull et al., 1995).

2.3.3.1 Actuarial Method

Several PRA techniques are utilized in industry. One of the more accepted and less controversial techniques is the Actuarial Method. This method requires substantial experience with the system of interest and large quantities of data. The probability of failure is determined directly from historical information. Because this method is easily understood by lay persons, it is less controversial than many newer techniques. However, special care must be taken to adjust for future changes (i.e., changes in accident rates over time and advances in technology) (Rasmussen, 1981). In situations where the probability of failure is low, there may not be sufficient data available for the Actuarial Method to be useful. Newer techniques have been developed to combat this problem.

2.3.3.2 Tree Methods

Two of the newer PRA techniques are event tree and fault tree analysis. These two methods are often used in tandem because they are complementary. The tree techniques have been used extensively in a wide variety of industries. These methods allow the analyst to break down a complex system into its component pieces. The probabilities of occurrence for individual events are determined from experience, observation, or research and then combined algebraically to determine the ultimate probability of failure for the entire system (Pate-Cornell, 1984).

Event trees represent forward logic. An event tree begins with an initiating event and presents all possible outcomes of that event. Analysts use event trees to outline possible event sequences to see exactly what effect a given event will have on the total system. They are also used to break a complex problem into more manageable pieces. The probability of a certain event occurring is dependent on the probabilities of all other events preceding it in the event tree (Pate-Cornell, 1984). The individual probabilities must initially be determined by some external method, usually through fault tree analysis of single events (Henley and Kumamoto, 1992, p. 26).

Figure 2.1 is an example of an event tree developed for a dairy operation (Vietor and Johnson, 1995). The initiating event is the generation of wastewater during the cleaning of the milking parlor. The event tree follows the forward progress of the wastewater through the containment and irrigation system of the dairy farm. The wastewater is discharged from the milking parlor through an earthen channel to holding lagoons. While enroute to the lagoons, the water can either seep through the channel walls or be contained within the walls. If the wastewater seeps through the channel walls it is lost to the system as indicated by the extended line labeled "seep" on Figure 2.1. However, if the water is contained, it reaches Lagoon 1.

If Lagoon 1 is not full, the water is contained there and used for irrigation. Runoff occurs if irrigation rates are excessive, and the wastewater is lost from the system. Otherwise, the irrigation waters infiltrate and are taken up by crops or leached through the soil profile to groundwater. In both cases, the wastewater has reached its ultimate destination and exits the system. Returning to Lagoon 1, if the lagoon is full and overflows, the excess water enters Lagoon 2.

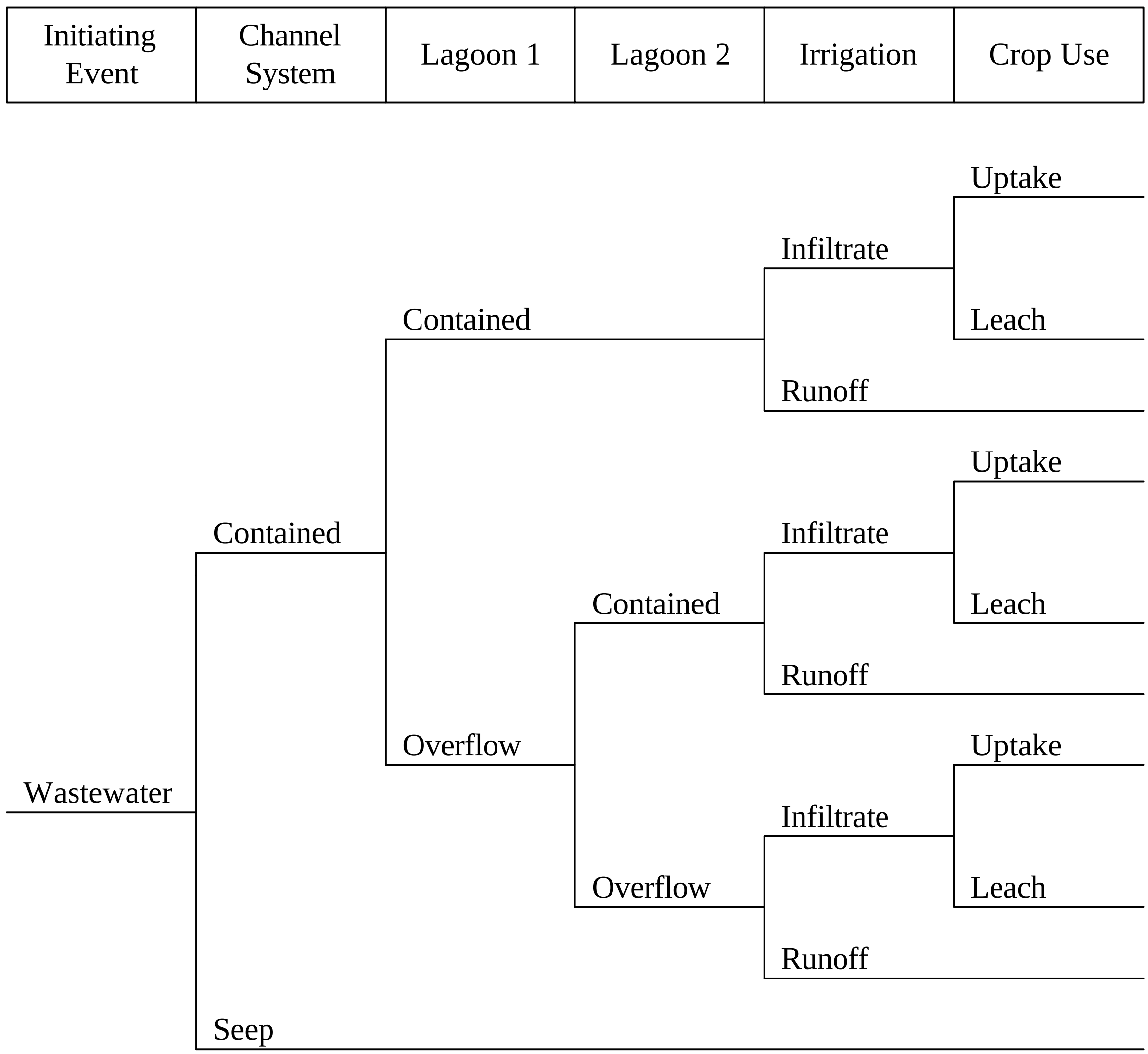
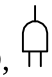


Figure 2.1: Event tree for dairy wastewater containment system (Vietor and Johnson, 1995)

At Lagoon 2, the water is either contained or the lagoon overflows, just as with Lagoon 1. If the water is contained in Lagoon 2, it is used as irrigation water and the processes described above for irrigation from Lagoon 1 are applied here as well. Overflow from Lagoon 2 has the same possible pathways, infiltration or runoff, as planned irrigation from Lagoon 2.

Unlike event trees, fault trees represent backward logic. The tree begins with a failure to the system or the occurrence of an undesirable event, called the top event. The failure is broken down into lower level events, or causes, connected by logic functions or gates (i.e., AND, , or OR,  gates). Figures 2.2A and 2.2B illustrate the use of gates in fault trees. Figure 2.2A is a simple fault tree utilizing an AND gate. Event A is the failure of interest or the top event. An AND gate located below Event A signifies that both Event B and Event C, the gate inputs, must occur for Event A to take place.

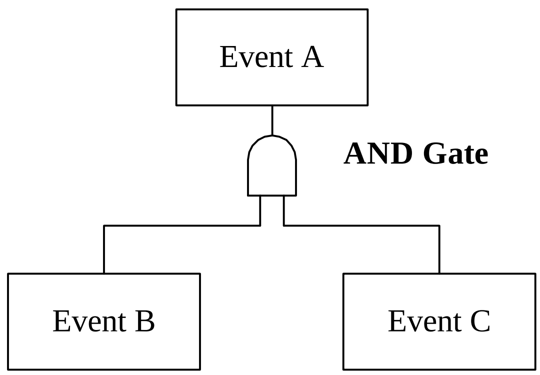


Figure 2.2A: A simple fault tree utilizing an AND gate

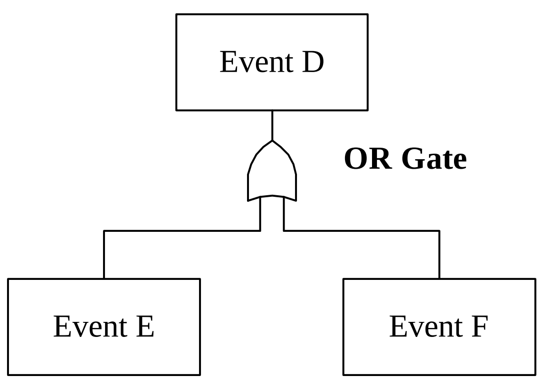


Figure 2.2B: A simple fault tree utilizing an OR gate

Similarly, Figure 2.2B shows an OR gate connecting inputs Events E and F to output Event D. The OR gate indicates that one or both of the input events must occur for Event D to occur. In complete fault trees, the input events in Figures 2.2A and 2.2B (i.e., Events B, C, E, and F) would also be broken down into their causal or input events. This process continues until the basic or primary faults, which cannot be broken down, are found.

The probability of the top event can be determined only if the probabilities of all basic faults are known from experience, experimentation, or estimation through modeling processes. When fault trees are used to evaluate dynamic systems, these basic event probabilities are determined for a selected period in time. Fault trees are static in nature but can be used to evaluate the condition of dynamic systems at a point in time. In such instances, fault trees represent a snapshot of the system, and basic event probabilities are calculated for the selected moment or period in time. These probabilities are then combined using Boolean algebra to find the probability of the top event. If the probability is unacceptable, analysis of the tree components assists in determining which factors or events can be altered to lower the probability of failure (Pate-Cornell, 1984).

Figure 2.3 is an example of a complete fault tree developed by Pate-Cornell (1984). The schematic (Figure 2.3A) illustrates an auxiliary feed water system (AFWS) for a nuclear power plant. The AFWS delivers water to the main reactor area. As seen in Figure 2.3B, the failure of interest is "auxiliary water supply system fails to deliver water to main system". The feed water system is divided into two subsystems: the water holding tanks and the pumping mechanisms. Both of these subsystems are essential to the operation of the AFWS (i.e., the two subsystems are shown in series in the schematic). If either of these subsystems becomes nonfunctional, the entire AFWS shuts down. Therefore, on the fault tree in Figure 2.3B "failure of subsystem 1" and "failure of subsystem 2" are inputs to an OR gate leading to the top event.

Next, the causes of failure for both subsystems must be examined. Subsystem 1 consists of two water holding tanks placed in parallel, indicating that only one functional tank is necessary for proper operation of Subsystem 1. Therefore, on the fault tree "failure of tank 1" and "failure of tank 2" are shown as inputs of an AND gate, because a rupture or failure of both tanks would be needed to cause the failure of Subsystem 1.

Subsystem 2 is only a little more difficult to analyze. Again, there are two portions of the subsystem in parallel indicating the use of an AND gate leading to the "failure of subsystem 2". One of the inputs to this AND gate is "failure of turbine pump", the event shown on the bottom portion of the schematic. The second input to the AND gate must represent the top portion of the schematic for subsystem 2 which shows a generator and an electric pump placed in series. As before, two devices in series indicates that each is essential to the operation of that portion of the system. Therefore, either the generator or the electric pump failing would cause the entire top portion of subsystem 2 to be nonfunctional. The failures associated with these two mechanisms are connected by an OR gate on the fault tree. This OR gate is an input to the AND gate for which “failure of turbine pump” is also an input. This configuration of events shows that for a failure of subsystem 2 to occur, the turbine pump AND either the generator OR the electric pump must fail coincidentally.

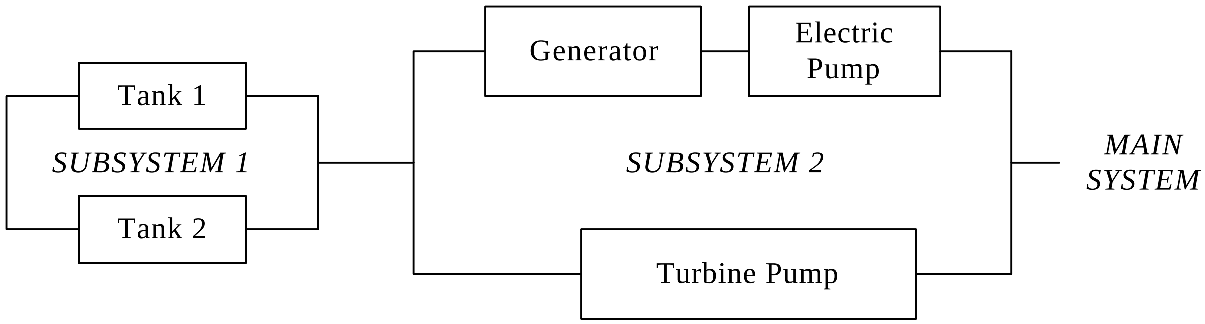


Figure 2.3A: Schematic of an auxiliary feed water system (Pate-Cornell, 1984)

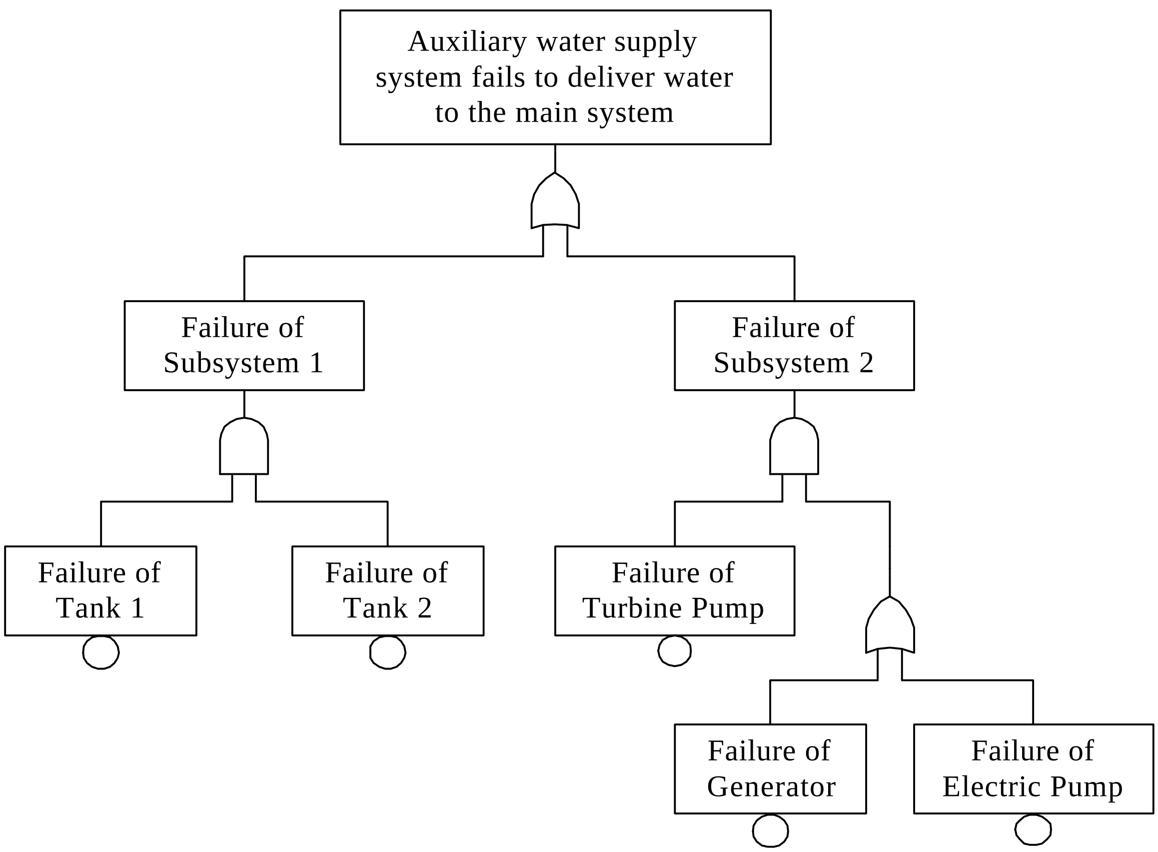


Figure 2.3B: Fault tree for failure of the auxiliary feed water system (Pate-Cornell, 1984)

2.4 Risk and Nonpoint Source Pollution

Work in the environmental arena with risk assessment techniques is only just beginning. The United States Environmental Protection Agency has published a set of generalized guidelines for conducting what it calls Ecological Risk Assessments. EPA defines an ecological risk assessment (ERA) as "a process that evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors" (USEPA, 1992). An ERA is not necessarily probabilistic in nature. It should also be noted that “environmental risk assessment” is a term frequently used in the literature. This term usually refers to hazards to human health as a result of environmental factors and does not address damage to the natural environment.

The advance of risk assessment techniques is of great interest to environmental policy-makers and regulatory agencies. A discussion of several studies in which risk has been applied to ecological problems follows. To date, there have been a limited number of such ecological risk studies. The studies described here do not necessarily conform to the USEPA’s Ecological Risk Assessment guidelines nor are they all probabilistic in nature.

Lull et al. (1995) developed a risk analysis procedure for use with Geographic Information Systems (GIS). The authors considered the risk of erosion due to the cumulative watershed effects of various forest harvesting processes. Cumulative watershed effects include hydrology, erosion and deposition, and biological responses. The Delphi technique was used to estimate the risk posed to water quality from harvesting activities. In this research, the experts were asked to quantify the risk of erosion due to forest harvesting practices given a certain land slope and soil erodibility level. Their discussions and decisions were based on their experience in soils and forestry. They ranked the risk of erosion on a scale of one to five, with five representing the greatest risk. The information gained from the panel of experts was then put into a GIS and applied spatially to two watersheds in Montana. This model was not validated. The authors recognized the need for validation through monitoring and called for the development of management guidelines based on the determined levels of risk. They view this technique of risk assessment as a way to evaluate watershed sensitivity to silvicultural activities.

Phillips (1989) proposed a spatial model for risk assessment in watersheds. The model can be used in conjunction with a standard dilution model to give a probabilistic estimate of the impacts at the basin mouth due to runoff from a specific upstream subwatershed. The example given in the article is that of finding the probability that a certain copper concentration will be exceeded at the mouth of an urbanized river due to the runoff from a subwatershed. Phillips stated that this type of risk assessment can be useful in targeting problem areas for improvement and risk reduction as well as for evaluating management and control options.

Teague et al. (1995) developed environmental risk indices to be used in comparing the effects of alternative production practices in western Oklahoma. They developed three indices; each incorporated a different level of detail about the chemical properties and environmental effects of pesticides. In the development of the Environmental Impact Quotient (EIQ), the authors considered only the chemical characteristics of the pesticide. The Chemical Environmental Index (CINDEX) included the chemical characteristics of the pesticide, as well as the quantities of pesticides, in grams per acre, lost to runoff and percolation. The third index, the Chemical Concentration Index (CONC) considered the characteristics of the pesticide in conjunction with the concentration of pesticide, in parts per million, lost to runoff or percolation. The authors see these indices as useful in comparing the effects of production practices and assessing the tradeoffs between environmental improvement and economic returns. They stated that because these indices address the multidimensionality of pesticide usage, the indices could be utilized to make specific pesticide prescriptions for individual farms or to formulate policy.

Johnson et al. (1995) applied event tree and fault tree analysis to land application of animal waste at a Texas dairy. A site-specific analysis of hazards and a qualitative risk assessment were performed. The local dairyman assisted in the development of the event and fault trees for his operation. The authors stated that the development of the trees helped in visualizing the system and improved understanding of system operation and the associated hazards. After assisting with development of the trees for his operation, the producer decided to purchase additional irrigation equipment to increase his irrigated acreage and reduce the risk of NPS pollution from runoff.

2.5 Summary

This chapter presented research detailing the tremendous impact of NPS pollution on water quality in the Chesapeake Bay. The basic concepts of risk assessment were presented, as well as several methodologies for risk analysis (e.g., Delphi technique, indices, PRA). As yet, a search of the literature has not revealed studies focused solely on the risks of agricultural NPS pollution. As the political climate surrounding agriculture continues to lead toward increased regulation, assessing the risks associated with agricultural practices may become essential. The question of how to determine that risk remains. Risk assessment is a common technique in some industries but its application is, as yet, very limited in agricultural NPS pollution. Research will be necessary to determine which risk assessment techniques can be effectively applied to the risks of agricultural NPS pollution. The proposed research seeks to determine if fault tree analysis is feasible for assessing risks associated with agriculture.

Chapter 3: Methodology

The following sections describe the basic methodology utilized for achieving the objectives of this research. Initial steps included selecting a suitable watershed for analysis and performing a qualitative assessment of that watershed. Elementary procedures for the quantitative assessment are also given in this chapter. However, a more detailed methodology for the quantitative assessment is presented in Chapter 4, because these procedures are dependent upon the results of the qualitative assessment. Criteria are also outlined for identifying events which could limit the use of PRA in agricultural NPS pollution control.

3.1 The Watershed

The first step in this research was to choose an appropriate watershed for study. A research team lead by Dr. Saied Mostaghimi of the Department of Biological Systems Engineering at Virginia Tech has studied two watersheds extensively; they are the Nomini Creek and Owl Run watersheds. The water quality in each watershed has been monitored for ten years as part of the vast research effort supporting the Chesapeake Bay Program. The Owl Run watershed was chosen for use in this research because its nonpoint source (NPS) pollution problems are surface water oriented. The ground water in Owl Run is of good quality and is not notably affected by the agricultural activities in the region (Mostaghimi et al., 1989). This research addresses the probability of nitrogen discharge to a stream via surface runoff. Therefore, a watershed with surface water and few groundwater problems is ideal. Ground water problems are one focus of the Nomini Creek research, making it unsuitable for this research.

The Owl Run watershed is located in Fauquier County, Virginia (Figure 3.1) and is part of the Potomac River basin and, therefore, the Chesapeake Bay basin. The watershed covers approximately 1153 hectares of predominantly agricultural land. About one quarter of the land is used for corn production. Some of this corn is followed by a rye cover crop and is in a four or five year rotation with a hay crop. Significant acreage is also dedicated to pasture. The watershed also includes five dairies with a total of nearly 1250 head of cattle. Only one of the dairies had any type of manure storage facility prior to 1989 (Mostaghimi et al., 1989).

Four runoff monitoring stations were established within the Owl Run watershed to gather runoff, sediment, nitrogen, and phosphorus data. Each station sampled from discrete storm events for every six centimeters change in stream stage. Station QOA (Figure 3.2) was at the main outlet of the Owl Run channel and monitored runoff from the entire watershed. Station QOB isolated the town of Calverton and one dairy. Station QOC sampled runoff from a large area of cropland and was intended to isolate the effects of cropland best management practices (BMPs). Station QOD isolated two major dairies and was intended to show the effects of waste management BMPs. In addition, eight precipitation stations (POA through POH, Figure 3.2) were established to measure the volume, quality, and intensity of rainfall in the watershed. Surveys of the local farmers also allowed the monitoring of land use and cultural practices within the watershed (Mostaghimi et al., 1989). Monitoring began in 1986 and concluded in 1996. The years prior to 1990 are considered the pre-BMP period. During and after 1990 a series of BMPs were installed in the watershed to mitigate the NPS pollution problem. Nutrient management, manure storage facilities, stream bank fencing, vegetative filter strips, and conservation tillage are some of the BMPs installed.

Two years of record were chosen for use in this research, 1987 and 1993. The year 1987 was chosen as a representative pre-BMP year. It was the first full year of monitoring within the watershed and before any action was taken to install BMPs. Similarly, 1993 was chosen as a representative post-BMP year. The installation of BMPs began in 1990 and continued into 1993. Some stream bank fencing was installed during October 1993 but was disregarded for this research, because it could not be applied to the entire year. By evaluating both a pre- and post-BMP year, the goal was to determine whether or not the fault tree would appropriately illustrate the effects of BMPs on the probability of nitrogen losses to the stream. In addition to analyzing the entire watershed for both pre- and post-BMP years, the dairy subwatershed, QOD, was analyzed separately to isolate the risk factors associated with dairy operations.

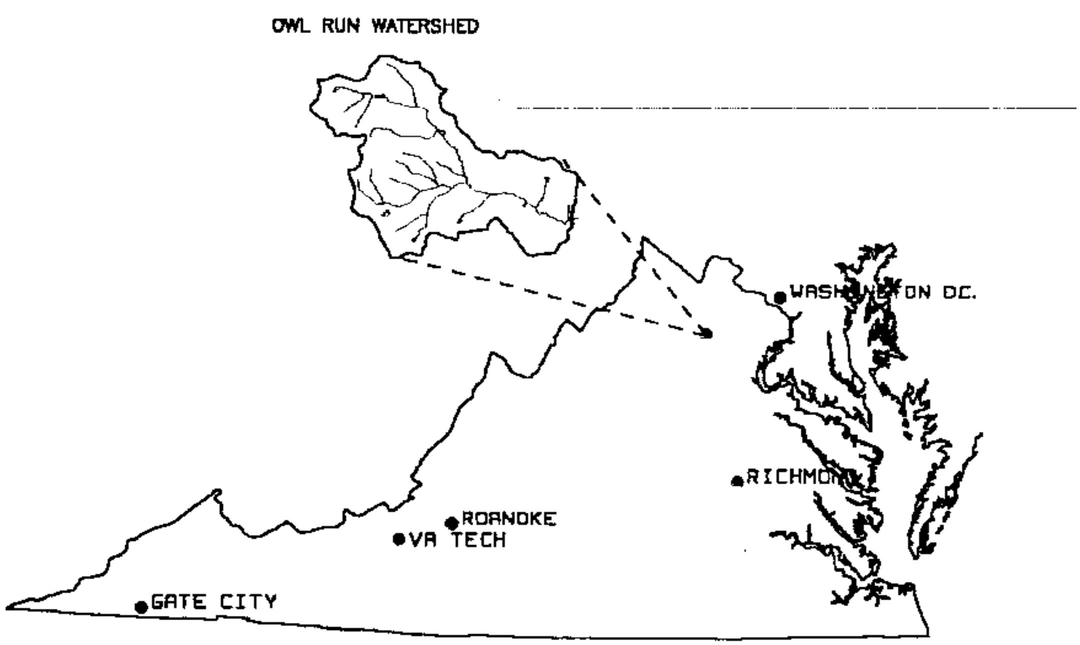


Figure 3.1: Location of the Owl Run watershed (Mostaghimi et al., 1989)

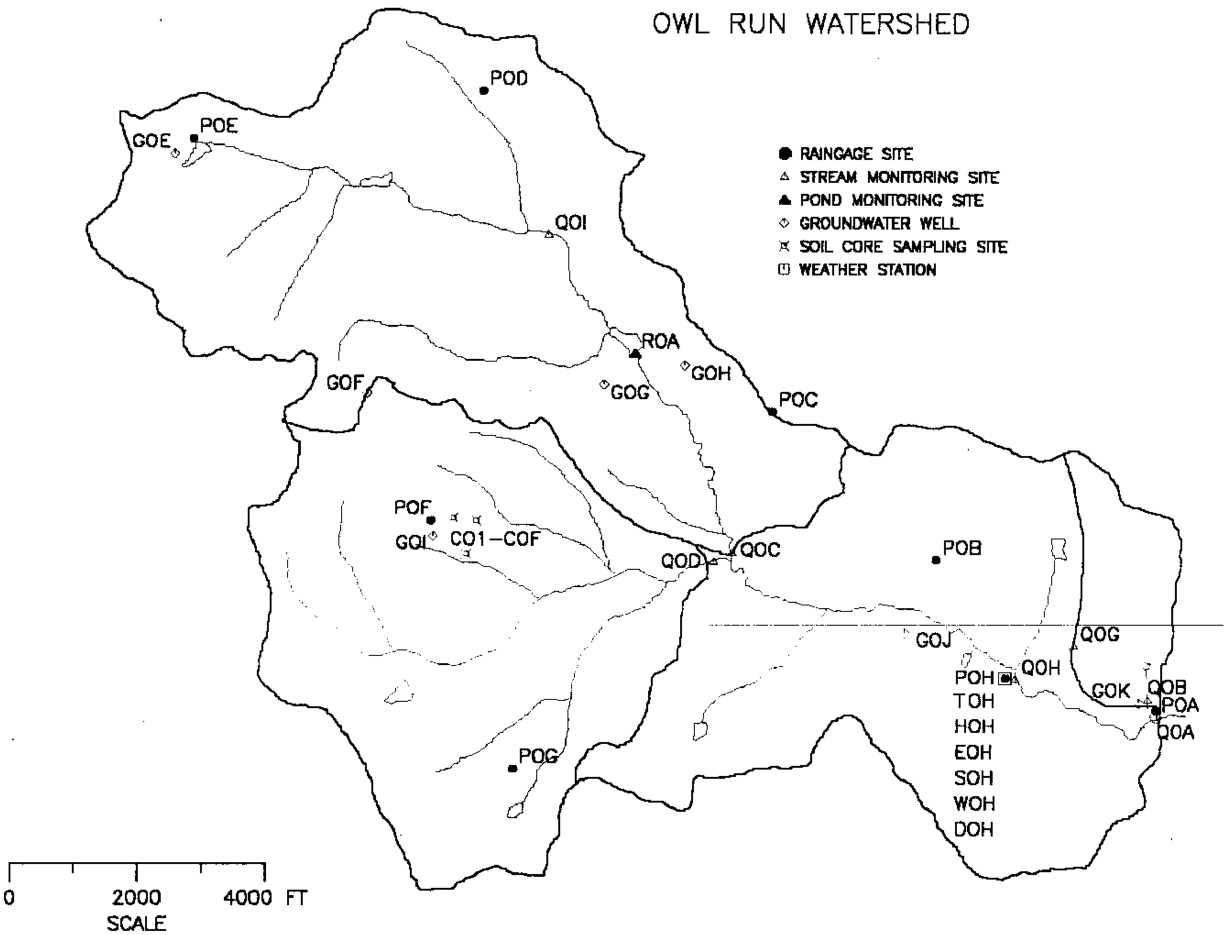


Figure 3.2: Location of monitoring stations within the Owl Run watershed (Mostaghimi et al., 1989)

3.2 Objective 1: Qualitative Assessment

The first specific objective was to conduct a qualitative assessment of the probability of nitrogen discharge to Owl Run in runoff water using PRA techniques. The qualitative assessment of nitrogen losses was conducted to determine if PRA techniques could adequately represent the concepts behind NPS pollution processes. An event tree and a fault tree were developed to perform this qualitative assessment.

3.2.1 Event Tree Development

As stated previously, event trees represent forward logic and express all possible outcomes for an initiating event. The initiating event chosen was "precipitation occurs" because precipitation is a cause of runoff and, therefore, NPS pollution. All events which could occur as a result of precipitation were included in the event tree in a logical order of occurrence. The event tree was developed to convey the basics of small watershed hydrology and, specifically, to show the origins of surface runoff. One major use for event trees is to characterize a system and divide it into logical parts which can then be analyzed in more detail using other methods (Pate-Cornell, 1984). This approach allowed the runoff event to be extracted from the event tree and developed into a fault tree for nitrogen discharge in surface runoff.

3.2.2 Fault Tree Development

The qualitative assessment process continued with the development of the fault tree. The fault tree for nitrogen discharge to Owl Run was developed based on the following information:

- the fault tree methodology outlined in the literature review,
- the general cultural practices and land uses within the Owl Run watershed, and
- general information on nitrogen processes, availability, and removal by runoff.

The event of interest, the top event of the fault tree, is "excessive nitrogen is discharged to Owl Run on any day". The term "excessive nitrogen" is used to indicate that the major focus of this research was not the natural, background levels of nitrogen discharged to the stream but rather the probabilities associated with preventable, manageable, or controllable discharges of nitrogen to Owl Run from agricultural activities.

Boundaries had to be established for the system being studied. It was decided that the events of interest (i.e., manageable and controllable events) were essentially confined to the condition and management of the soil surface. Therefore, the soil surface layer was chosen as the system boundary. Consequently, only surface runoff was considered. Any precipitation which infiltrated into the soil was not considered in development of the fault tree.

The major forms of available nitrogen from agricultural activities are ammonium (NH_4^+) and nitrate (NO_3^-) (Brady, 1990, p. 318). Both the adsorbed and soluble forms of these ions were considered. The major sources of these nitrogen forms in the Owl Run watershed are manure from dairy cattle within the watershed and inorganic fertilizers applied to cropland and pastures (Mostaghimi et al., 1989). Inorganic fertilizer usage and the dairies were examined to determine more specifically the causes of excess nitrogen availability for removal by runoff. The dairies were found to be a principal source of available nitrogen in three situations: cattle are allowed to enter the streambed; waste from confined animals is not contained and managed properly; and nutrient management precautions are lacking in the application of dairy waste. The nitrogen availability issues associated with inorganic fertilizer applications are also dependent on the lack of nutrient management. For most events addressing fertilizer application no distinction was made between inorganic fertilizer and manure (i.e., organic fertilizer). They were considered jointly. Events dealing with dairy management specifically address manure handling but not necessarily manure application.

The discharge of nitrogen to Owl Run is a result of not only the availability of nitrogen but also its transport. The transportation modes for both the soluble and adsorbed forms of nitrogen were studied. The two processes of interest are runoff and erosion. Runoff allowed to cross land with soluble nitrogen on the soil surface can dissolve and entrain ammonium and nitrate and discharge them to Owl Run. In this research all runoff was assumed to reach the stream.

Similarly, nitrogen adsorbed to the soil particles can reach the stream with the occurrence of a runoff event of sufficient magnitude to detach and transport the soil particles. Consequently, the factors contributing to runoff and erosion were closely examined. Attempts were made to determine basic causal events for runoff and erosion (e.g., precipitation, soil conditions, and cover factors). However, this approach proved impractical due to the level of detail needed to express the basic events on the fault tree. The amount of specific climatological and soil data necessary to define probabilities for these events was also a factor. Other alternatives for expressing the causes of runoff and erosion were sought. The decision was made to cease developing these events and designate them as undeveloped events. In essence, an undeveloped event is accepted as a basic event, and a probability of occurrence must be determined for it, just as for a basic event. The true causes of runoff and erosion were explored in the probability assignment phase of the research. This issue is discussed further in section 4.4.2 Threshold Values.

3.3 Objective 2: Quantitative Assessment

The second objective was to utilize the qualitative assessment as a basis to complete a quantitative assessment of risk. The fault tree technique was chosen to accomplish this objective early in the research process. The backward logic of fault trees fit well with the focus of this research. Fault trees could assist in discovering the multiple events and scenarios initiating NPS pollution. An event tree, however, could only follow the consequences of one initiating event.

Once the final fault tree had been developed, the probabilities of occurrence for all the basic events in the fault tree were sought. As state previously, the fault tree represents a snapshot of the system and should be evaluated for a specific time period. In this research, the fault tree was evaluated on a daily basis using average values from the years being studied.

Many of the basic events address land use issues; probabilities for these events were calculated from land use records for the selected pre- and post-BMP years. Other events address land management and cultural practices (e.g., BMPs installed, fertilizer type and usage, dairy operation practices). These probabilities were extracted from land use data gathered through farmer surveys and from the opinions of Owl Run experts (Pane, 1996-1997, and Mostaghimi, 1995-1996). Events involving the condition of the soils were more difficult to quantify. The soil survey for Fauquier County was used in conjunction with land use data, expert opinion, and professional judgment to establish the probabilities needed for soil condition events. A few events necessarily addressed the probabilities associated with rainfall and runoff events. Monitoring data from within the watershed as well as long term weather data were utilized to develop these probabilities.

The probabilities for individual events were calculated on either a time, area, or percentage basis. Land use and cultural practices are spread over an area. Therefore, it was logical that the probabilities for most of these events be developed on an area basis. In the case of stream fencing, the probabilities were developed on a length basis. Events dealing with cultural practices, and especially BMPs such as vegetated filter strips (VFS), were developed on either an area or percentage basis. If the area of land draining into the BMPs was known, the probability was developed on an area basis. However, if the presence of the BMP was considered more important than its size or the area draining into the BMP (e.g., the presence of a VFS or buffer between a loafing lot and the stream), the probability was determined on a percentage basis. For example, the probability that producers have installed a VFS is simply the percentage of dairies with that practice in place. One probability, however, was developed on a time basis. The presence of confined animals was based on the percent of total time that the dairy cattle spent in loafing lots.

Once all basic event probabilities had been developed, the probability of the top event, "excessive nitrogen is discharged to Owl Run on any day", was calculated using Boolean algebra. With Boolean algebra, the logic gates of the fault tree act as operators. An AND gate represents a multiplication sign, indicating that input events should be multiplied together to obtain the proper value for the output event. Similarly, an OR gate acts as an addition symbol, meaning that the input events should be summed (Pate-Cornell, 1984). Because the values represented in the fault tree are probabilities, at no time should a value greater than one be assigned. Occasionally, a value greater than one will result from an OR gate sum. In such cases the event should be assigned a probability of one. Following these guidelines, the calculation process was begun with the basic events at the bottom of the tree and was performed up through the tree until the top event probability was calculated.

3.4 Objective 3: Identifying Limiting Events

The purpose of Objective 3 was to identify the events for which developing probabilities is particularly difficult. After all basic event probabilities were calculated, the data and methodologies used in each case were compared. Events which meet any of the following criteria were identified as potential problems:

- the method for calculating a probability is unclear or difficult to select;
- probability calculations require data which are uncommon; or
- time required to perform calculations is excessive.

All decisions involving the criteria were based on the professional judgment of the researcher and comparisons with the other events quantified in this research.

3.5 Overall Objective

The overall goal of this research was to determine the usefulness of PRA in the NPS pollution control field. The simplicity or difficulty involved in a complete probabilistic analysis was central to the determination of usefulness. The methodology and results for each specific objective were reviewed in conjunction with the experiences of the researcher to achieve the overall objective.

3.6 Summary

The procedures for conducting this research were outlined in this chapter. The Owl Run watershed in Fauquier County, Virginia, was selected for analysis. A qualitative assessment of the probability of nitrogen discharge to Owl Run was performed through the development of an event tree and a fault tree. The fault tree was then analyzed quantitatively. As the process of quantifying probabilities concluded, events which proved difficult to quantify, for any reason, were analyzed. Their effect on the usefulness of PRA in agricultural NPS pollution control was evaluated.

Chapter 4: Results and Discussion

This chapter presents the results of the qualitative and quantitative analysis of nitrogen discharge to Owl Run. The event tree and fault tree are presented with explanation and discussion of the development of each tree. The calculations performed in quantifying event probabiliites are also detailed along with the results of those calculations. Issues related to the quantitative results and their implications for NPS pollution prevention are also discussed.

4.1 The Event Tree

The event tree developed during this research is shown in Figure 4.1. The initiating event is "precipitation occurs". Once precipitation reaches the ground it has one of three fates: infiltration into the soil, runoff to surface waters, or ponding on the soil surface. Infiltration occurs when the soil is not saturated and the rainfall rate does not exceed the infiltration capacity of the soil. Once infiltrated, the water can either be utilized by plants, flow subsurface to streams (interflow), or percolate to ground water.

If the soil is saturated or the rainfall rate exceeds the capacity of the soil to absorb it then runoff occurs. For the purposes of this research, all runoff was assumed to be overland flow. If, however, the saturated region is in a low lying area the water ponds until it evaporates or infiltrates into soil pores left vacant by the action of percolation. This infiltrated water has the potential routes of plant uptake, interflow, or ground water recharge. Runoff can occur, however, if additional rainfall causes the ponded region to be filled to capacity and overflow.

4.2 Discussion of Event Tree Development

The event tree (Figure 4.1) shows the basic hydrologic processes operating within a small watershed. Precipitation, ultimately, is used by plants, becomes ground water recharge, or enters surface waters as either interflow or surface runoff. The development of the event tree was straightforward with little confusion regarding the processes to be included.

The usefulness of the event tree for further risk analysis is very limited. The inherent nature of an event tree is to show the forward progress of events. This research was focused more on tracking the sources of NPS pollution in runoff. The event tree shows only that runoff can occur as a result of a precipitation event. It does not indicate any of the other factors affecting runoff (i.e., land use, soil condition) and was not developed to address the issue of nitrogen availability at all. A different type of analysis was necessary to determine the causes of nitrogen in runoff. Therefore, the runoff event was extracted from the event tree, expanded to include nitrogen discharge, and developed into a fault tree as described in the following sections.

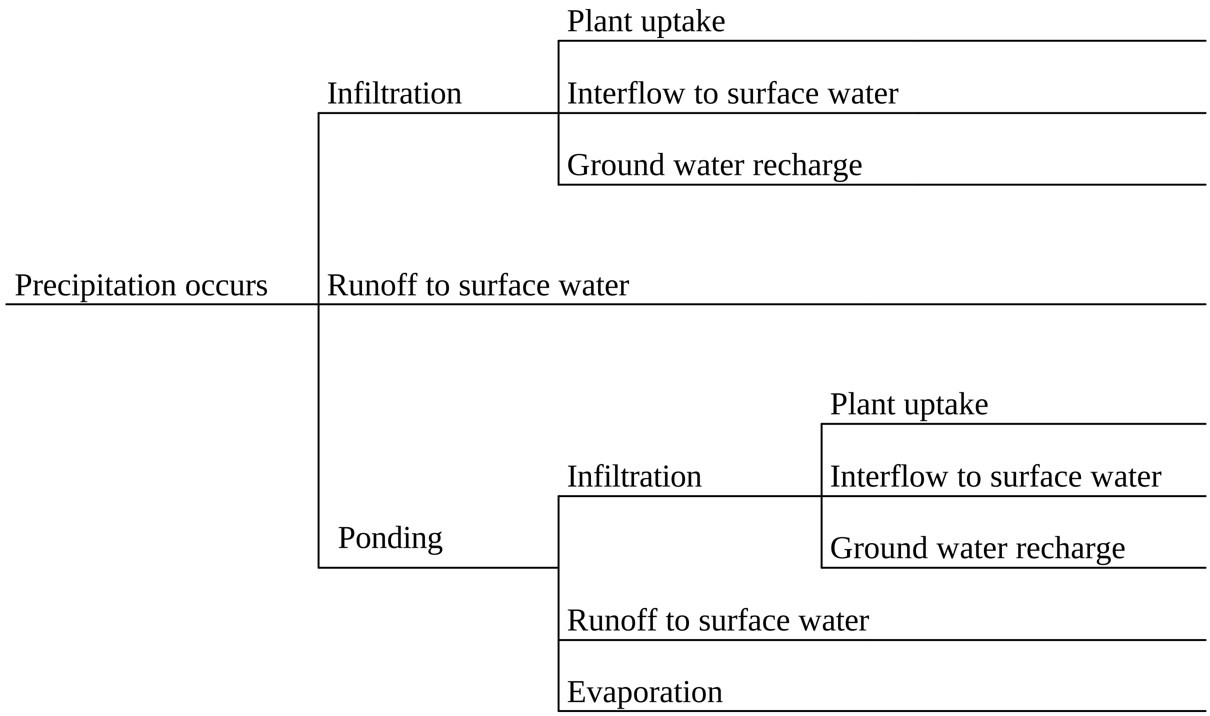
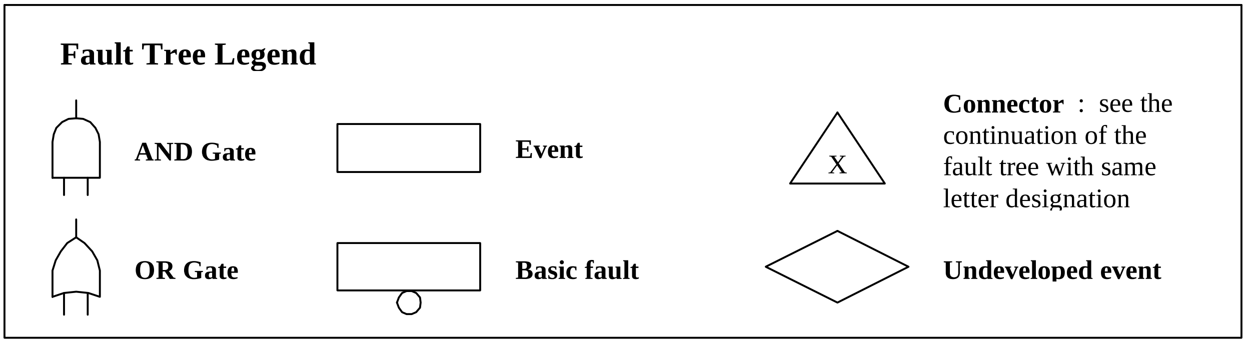


Figure 4.1: Event tree for the initiating event "Precipitation occurs"

4.3 The Fault Tree

A fault tree was developed to complete the qualitative analysis of nitrogen losses to Owl Run. The event of interest was "excessive nitrogen is discharged to Owl Run on any day" (Figure 4.2). The fault tree illustrates the causal factors of the top event and, ultimately, the basic causes of failure. Nitrogen in the soil may be found in either its dissolved or adsorbed form. Therefore, the second level on Figure 4.2 divides the tree into causes for the release of dissolved and adsorbed nitrogen. The events "cattle are in the stream and contribute N directly", "dissolved nitrogen discharged in surface runoff water" and "adsorbed nitrogen discharged in surface runoff water" are connected by an OR gate as any of these events would cause the presence of nitrogen in stream.



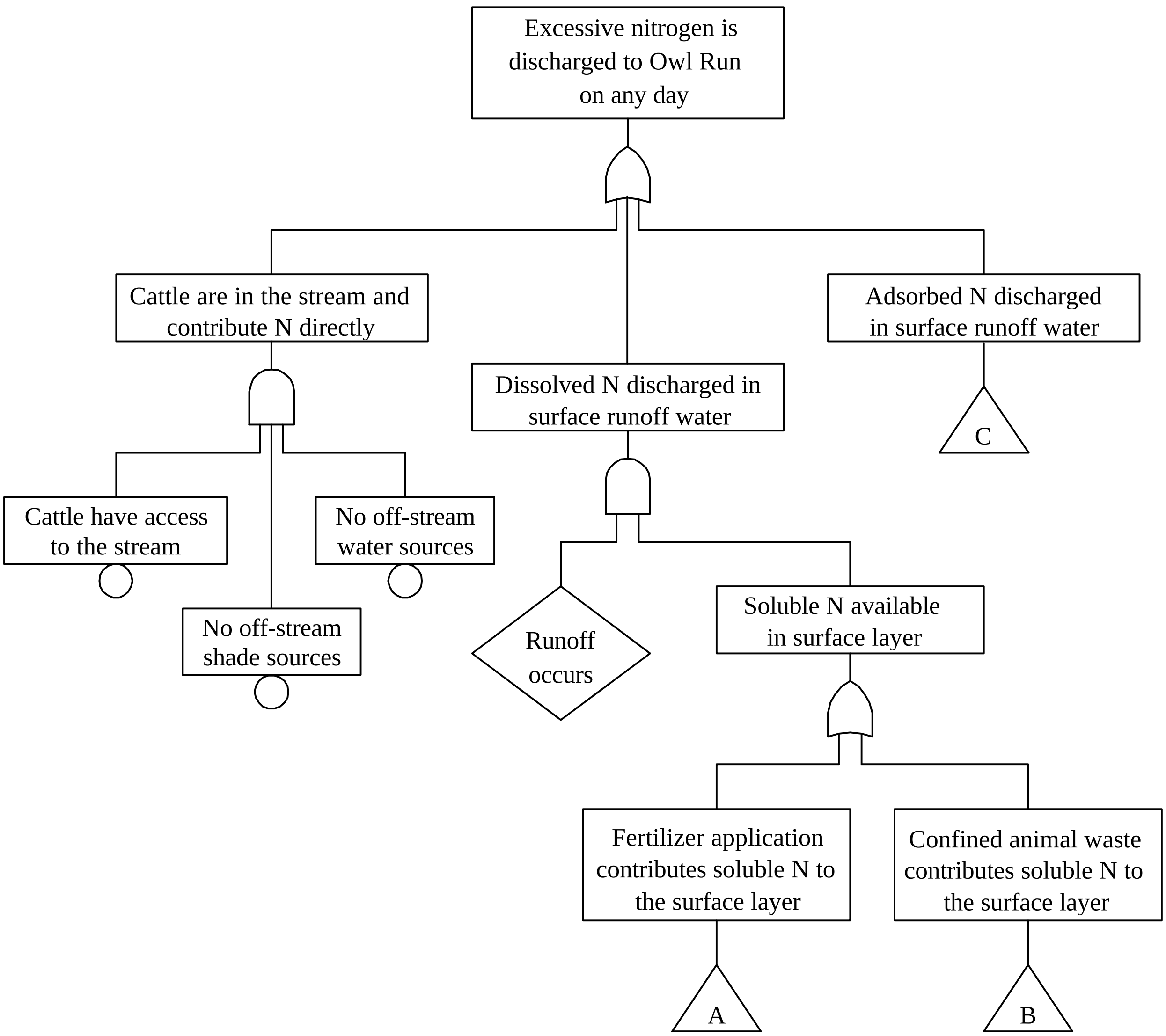


Figure 4.2: Fault tree for excessive nitrogen discharge to Owl Run

Cattle are in the stream and contribute N directly: This event refers to nitrogen deposited in the stream via animal excreta. It is assumed that if the cattle are in the stream, they defecate in the stream. Therefore, the event of importance is that the animals are in the stream. Cattle are most likely to be in the stream if the "cattle have access to the stream," there are "no off-stream shade sources," AND there are "no off-stream water sources." Studies have shown that if cattle have access to convenient water (Miner, et al., 1992; Sheffield, 1996) and shade (Collins, 1997) away from the stream, the cattle are much less likely to congregate in the stream area and, therefore, defecate in the stream. In many cases, off-stream water and shade sources are effective in keeping cattle out of streams without installing fencing.

Dissolved nitrogen: Following the dissolved nitrogen branch of the fault tree, the next level of events includes "runoff occurs" AND "soluble nitrogen is available in the surface layer". These events are connected by an AND gate as the runoff is necessary to dissolve and transport the soluble nitrogen.

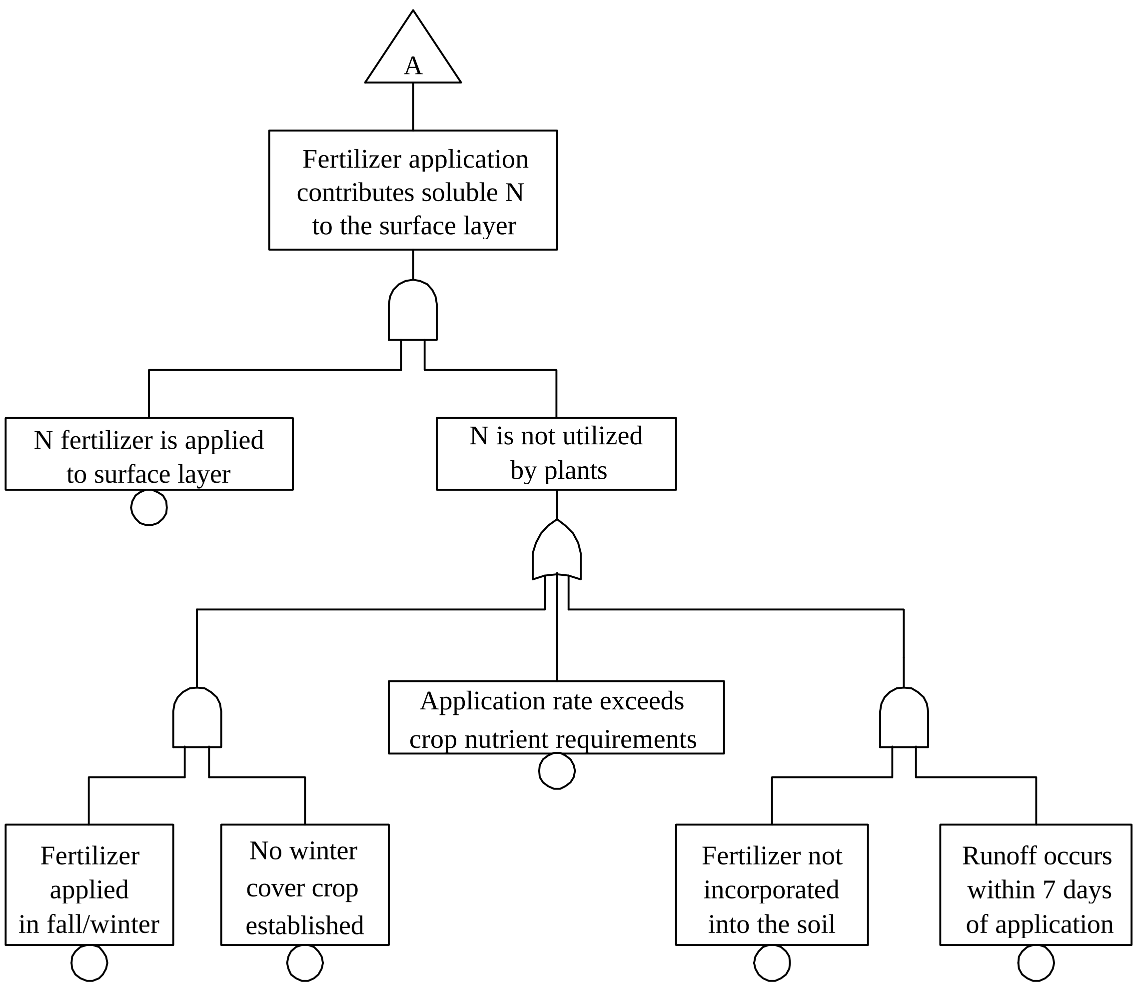


Figure 4.2: Fault tree for excessive nitrogen discharge to Owl Run (continued)

Runoff occurs: The cause of runoff is a rainfall event in which the rate of precipitation exceeds the infiltration rate of the soil. However, the causes of runoff are not explicitly included in the fault tree. The runoff event is an undeveloped event, represented by a diamond on the tree, and is treated as though it is a basic event. The details of why the runoff event was not developed further are discussed in section 4.4.2 Threshold Events and the process for assigning a probability to this event is described in section 4.6 Probability Assignment.

Soluble nitrogen is available in the surface layer: Returning to the "soluble nitrogen is available" branch of the fault tree, the sources of soluble nitrogen are “fertilizer application contributes soluble N to the surface layer” OR “confined animal waste contributes soluble N to the surface layer”.

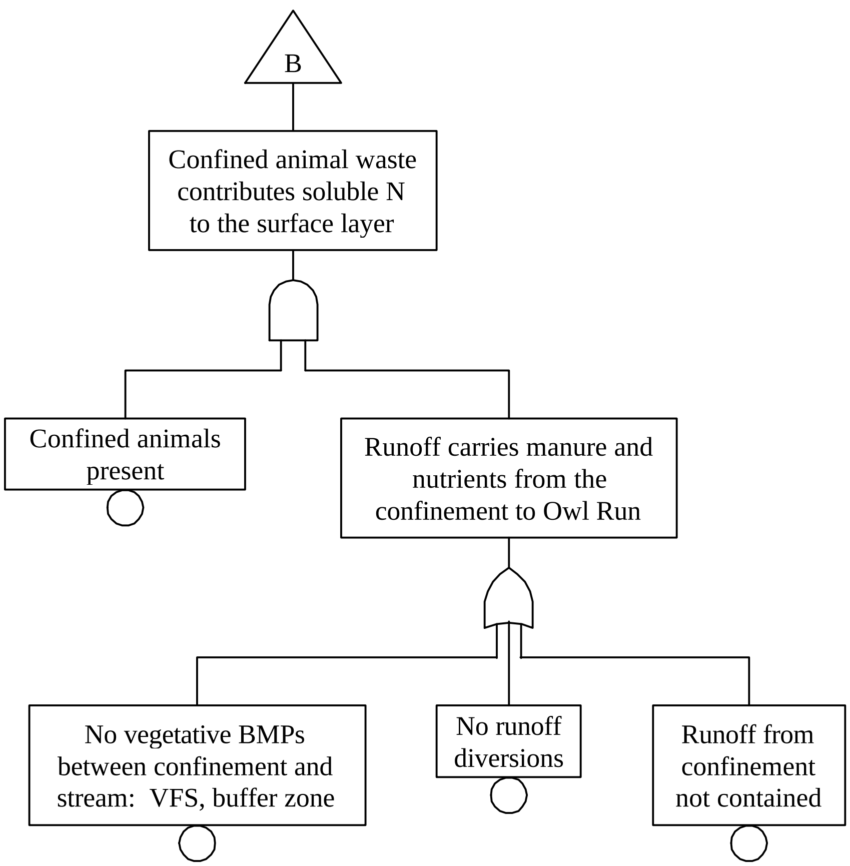


Figure 4.2: Fault tree for excessive nitrogen discharge to Owl Run (continued)

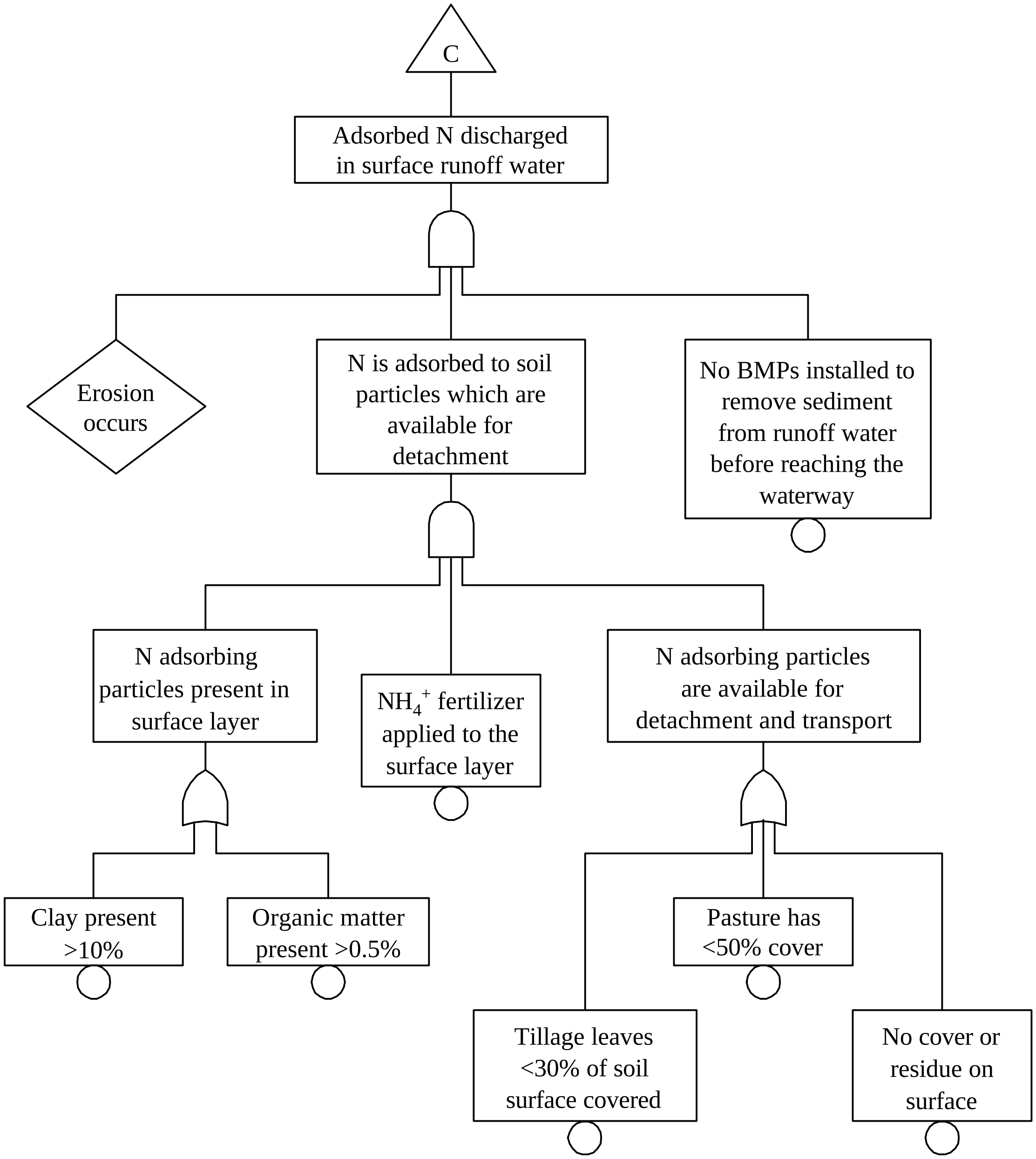


Figure 4.2: Fault tree for excessive nitrogen discharge to Owl Run (continued)

Fertilizer application contributes soluble N to the surface layer: Fertilizer contributions of soluble nitrogen are significant when "nitrogen fertilizer is applied to the surface layer" AND the "nitrogen is not utilized by plants". The nitrogen fertilizer may be either inorganic or animal manure.

Nitrogen is not utilized by plants: There are three instances shown in which nitrogen applied to the soil will not be utilized. These are as follows: the “fertilizer is applied in the fall or winter” AND there is “no winter cover crop established”; OR the “fertilizer is not incorporated into the soil” AND “runoff occurs within seven days of application”; OR the “application rate exceeds crop nutrient requirements”. Again, the fertilizer can be either organic or inorganic. The first of the instances listed is a seasonal consideration. If fertilizer is applied after the growing season and there is no crop planted to use the nutrients, i.e., a winter cover crop, the nutrients may be available for transport in runoff. This problem is compounded because other biological activity within the soil, e.g., microbial degradation, is slowed during the cooler seasons as well.

The next set of events contributing to non-utilization are that fertilizers are not incorporated into the soil and a runoff event occurs within seven days of fertilizer application. Nutrient management specialists advise farmers to incorporate fertilizers to prevent pollution problems and the loss of available nitrogen through volatilization (DSWC, 1993, p. 6-8; Tisdale et al., 1993, p. 151). The bulk of this volatilization occurs within the first seven days of exposure for manure (DSWC, 1993, p. 6-3). Therefore, if a runoff event occurs before the seventh day, a significantly higher concentration of soluble nitrogen is available on the soil surface to be transported by runoff. Incorporation of manure also prevents odor problems.

Finally, the application of excessive nutrients can also contribute to dissolved nitrogen releases into waterways. Even under optimum growth conditions, plants cannot utilize unlimited quantities of nutrients. Therefore, nitrogen applied in excess of plant and microbial needs may be lost to runoff.

Confined animal waste contributes soluble N to the surface layer: Animal contributions are most significant when livestock are confined or have direct access to waterways (Novotny and Olem, 1994, pp. 688-689). The issue of direct access to waterways was addressed at the top of the fault tree. The causal events for confined animal waste contributions are “confined animals present” AND “runoff carries manure and nutrients from the confinement to the stream”.

Runoff carries manure and nutrients: Three situations are given for the removal of manure and nutrients from the confinement to Owl Run. These situations include "no runoff diversions" OR "runoff from the confinement is not contained" OR "no vegetative BMPs established between confinement and stream". Runoff diversion refers to any practice which diverts clean runoff water around sites of animal confinement. Runoff water allowed to cross such confinements can entrain substantial quantities of dissolved nutrients, solid manure, and sediment. The second event refers to runoff which originates in the confinement area and is allowed to run off. Ideally, such runoff should be collected and stored for proper disposal and not allowed to enter waterways. The final event, "no vegetative BMPs established", refers to the presence of any other type of BMP which might serve to slow runoff from confined areas long enough to allow the runoff to infiltrate or the vegetation to extract nutrients from the runoff before it enters the stream.

Adsorbed nitrogen: The causes of the final level two event, "adsorbed nitrogen discharged in surface runoff water", are shown as "nitrogen is adsorbed to soil particles which are available for detachment" AND “erosion occurs” AND "no BMPs are installed to remove sediment from runoff water before reaching the waterway".

Erosion occurs: Erosion occurs when runoff has sufficient capacity to detach and transport soil particles to the waterway. The transport capacity of runoff depends on factors such as rainfall, land use, soil conditions, and slope length. However, like the runoff event, erosion remains an undeveloped event. It is considered a basic event for the purposes of this fault tree. The level of detail and amount of data necessary to thoroughly represent the factors affecting erosion (e.g., rainfall, soil conditions, slope length, etc.) were considered excessive for the purposes of this research. In addition, the detail necessary to dissect this event was considered to be disproportionate to the level of detail displayed in the remainder of the tree. Establishing a threshold for the occurrence of erosion was also an issue. Further discussion of decisions related to the level of detail and threshold values within the fault tree is presented later in sections 4.4.1 and 4.4.2.

Nitrogen is adsorbed to soil particles which are available for detachment: The fault tree shows three factors which influence the adsorption of nitrogen and the detachment of the soil to which it clings. These factors are as follows: “NH_4^+ fertilizer is applied to the surface layer”; AND “nitrogen adsorbing particles are present in the surface layer”; AND “nitrogen adsorbing particles are available for detachment and transport”.

NH_4^+ fertilizer is applied to the surface layer: When fertilizer is applied there are several fates awaiting NH_4^+ ions. The fate of interest here is that some NH_4^+ ions bind to exchange sites on organic matter and clays within the soil. Under moist conditions, however, the majority of NH_4^+ ions can be nitrified in a matter of one to three weeks (Tisdale, 1985, p. 134). The detail necessary to fully express the time and moisture dependence involved in the determination of whether NH_4^+ is nitrified or fixed to particles was considered beyond the scope of this research. Therefore, the occurrence of NH_4^+ fixation was based entirely upon the type of fertilizer applied.

Nitrogen adsorbing particles are present in the surface layer: The presence of either clay OR organic matter fulfills the requirement for nitrogen adsorbing particles. Threshold values were chosen to exclude soils with very low or negligible clay or organic matter content. Such soils would have very low adsorption capacities in the surface layer and, therefore, would not contribute significantly to adsorbed nitrogen releases into Owl Run on a regular basis. Based on the fact that sands, one of the soils with the lowest clay content, can have up to 10 percent clay content, a threshold of less than 10 percent clay was selected (Brady, 1990, p. 99). Soils with less than 0.5 percent organic matter were also excluded. This threshold for organic matter was selected because mineral soils generally contain between one and four percent organic matter, thus 0.5 percent organic matter content would be considered very low or negligible (Brady, 1990, p. 294).

Nitrogen adsorbing particles are available for detachment and transport: There are many factors which affect particle availability. One important factor is ground cover. For pasture land, researchers have found that if ground cover can be maintained at or above 50%, little erosion occurs regardless of the extent of livestock trampling (Smolen et al., 1990). Cover crops and conservation tillage have also been shown to reduce erosion on farmed land. They have been found to be 40 to 60 percent and 30 to 90 percent effective in reducing sediment yields, respectively (Novotny and Olem, 1994, pp. 691 and 697). The absence of such measures would, therefore, increase the availability of particles for transport. Each of these factors was included in the development of the fault tree as possible causes for sediment detachment and transport: "pasture has less than 50% cover"; "no cover or residue on surface"; and "tillage leaves less than 30% of the soil surface covered".

4.4 Discussion of Fault Tree Development

The fault tree was developed to more thoroughly explore the events and activities contributing to nitrogen discharge in surface runoff. The focus of the fault tree evolved as the research progressed. Initially, the tree was intended to be a complete and accurate scientific representation of the NPS pollution processes within the watershed. During the development, however, the level of detail necessary to cover all aspects of processes at work was deemed extreme. It was also found that representing the natural systems that are a vital part of the agricultural process was extremely difficult when using the rigid fault tree methodology. The evolution of the fault tree ended with the decision to develop a tree that communicates adequately the cause and effect of agricultural activities pertinent to nitrogen NPS pollution.

With this goal in mind, the events shown on the fault tree were limited to agricultural activities. Emphasis was placed on events which can be controlled by producers. Some events, like the occurrence of precipitation, cannot be directly affected by humans but were included in the tree because of their importance. For example, the occurrence of a rainfall event is essential to transport nitrogen from the land to the stream. Therefore, the precipitation event was included. Other events which cannot be significantly affected by management decisions and are not essential processes were not included in the fault tree.

Two difficult issues arose during development of the fault tree. These issues involved questions concerning the level of detail expressed in the fault tree, as mentioned previously, and the use of threshold values for events. Both issues were resolved as described in the following section.

4.4.1 Level of Detail

The question of how detailed the fault tree should be was resolved by analyzing what would make fault tree analysis most useful to the agricultural community. In most instances, expanding the level of detail represented in the fault tree would necessitate a more extensive data requirement for assigning probabilities. Large data requirements would hinder the usefulness of probabilistic risk assessment in an agricultural setting. The goal was to use only commonly-available information for the completion of the fault tree analysis. Another factor to be considered is the visual quality of the fault tree. Fault trees can be effective visual communication tools. Unnecessary, irrelevant, or confusing details placed on a tree can disorient the viewer and decrease the effectiveness of the tree in conveying ideas and concepts.

Events excluded from the fault tree, based on their level of detail, include the processes of the nitrogen cycle. Initially the entire nitrogen cycle was included in the fault tree. Causal factors for nitrification, ammonium fixation, and mineralization were identified and placed on the tree as major sources of available nitrogen. These events were removed from the tree as the fault tree development process continued. It was decided that because these events occur in the subsurface, they were not applicable to a fault tree with the soil surface as a boundary. Another factor in removing the subsurface nitrogen cycle from the fault tree was that these processes are not easily managed by producers. Quantifying probabilities for these processes would also require more specific data on long-term soil fertilization records and climatic conditions than would be easily accessible. For these reasons, the nitrogen cycle events were excluded. The process of nitrogen volatilization, however, was included in the fault tree, because it occurs at the soil surface. Volatilization was considered implicitly in the events depicting fertilizer application and incorporation.

The level of detail used in the fault tree also became an issue with the runoff and erosion events. In both instances, there are many factors which contribute to the occurrence of the event. Details concerning causal factors were excluded from the tree because there exist other alternatives to quantify the events in question which are simpler and fully-justifiable. This issue is discussed further in the following section.

4.4.2 Threshold Values

The term threshold values refers to setting a quantifiable upper or lower limit to determine the occurrence of an event. For example, suppose a researcher was developing a fault tree for nitrate in drinking water. The top event of the tree might be stated merely as "nitrate is present in the aquifer" or as "excessive nitrate levels present in the aquifer". If the researcher were to use a threshold value, the top event might be "nitrate levels in the aquifer exceed drinking water standards (>10 mg NO_3-N per liter)". In the present research, the events for which threshold values seemed most appropriate were "runoff occurs" and "erosion occurs".

The issue of threshold values was first explored for the event "runoff occurs" using the SCS Curve Number Method (Schwab et al., 1993, p. 79). First, a minimum depth of rainfall causing runoff, 6.35 millimeters (0.25 inch), was derived from precipitation and runoff data (Mostaghimi et al., 1989; Mostaghimi, 1995-1996) for the Owl Run watershed. Utilizing the SCS equations, a minimum curve number (CN), 89, was determined which would result in runoff for the predetermined storm event (6.35 mm). The rainfall depth and the minimum curve number thresholds were then used in the fault tree as causal events for the occurrence of runoff. Upon further analysis, the logic of this procedure was found to be faulty. There are a number of threshold value combinations for rainfall depth and minimum curve number which would result in runoff. There is no way to represent them all on the fault tree. For example, a rainfall depth of greater than 6.35 millimeters would also result in runoff with a CN of greater than or equal to 89. However, for a storm depth of 10 millimeters, a CN as low as 84 would result in runoff as well. The probability of a CN being between 84 and 89 is not included in the tree using this technique.

An alternative method for handling the occurrence of runoff was chosen. There are generally accepted quantitative methods for determining the occurrence and magnitude of runoff, e.g., SCS Curve Number Method. By not developing the event "runoff occurs" further and accepting it as a basic event, a quantitative method for computing runoff can be used. A single runoff volume can be chosen as a threshold value for the occurrence of runoff. By taking this approach, determining the infinite combinations of threshold values for the causal factors of runoff (e.g., precipitation and soil or cover conditions) was avoided. Details of the calculations for a minimum runoff event are described in section 4.6 Probability Assignment.

A similar situation was discovered upon evaluation of the event "erosion occurs". Here, too, there are several causal factors (e.g., soil condition, cover, rainfall intensity, slope) which would require threshold values. Again, the issue of multiple combinations of events resulting in the same outcome arises. By accepting "erosion occurs" as a basic event other options could be explored. As for runoff, there are generally accepted methods for quantifying erosion (e.g., the Universal Soil Loss Equation (USLE) (Schwab et al., 1993, p. 98)). As with the runoff procedure, one threshold for erosion could be set. However, a simpler logic was chosen. By assuming that any runoff will move some soil particles toward the waterway, the probability for the occurrence of erosion can be based entirely on the occurrence of runoff. This assumption is valid for the Owl Run watershed based on runoff and sediment yield data (Mostaghimi et al., 1989). This method serves to eliminate confusing detail from the tree itself.

Other events, like the presence of clay or organic matter, were assigned threshold values. The threshold values for clay and organic matter content are minimum values which remain independent of each other. The two thresholds are not combined through the use of a function to establish the occurrence of an upper level event as with the causal factors of the erosion and runoff events. The probabilities of the clay and organic matter events can also be determined independently.

4.5 Analysis of the Qualitative Application of the Fault Tree Technique

The basic events, or causes of failure, found for the Owl Run watershed using fault tree analysis can be categorized. The discharge of nitrogen is the result of a combination of factors involving management decisions, topography, soil characteristics, and climate. Soil characteristics and climatic conditions usually do not fall under the direct control of producers. Therefore, to reduce the probability of nitrogen discharge within the watershed, attention should be focused on those factors which can be controlled: the management decisions.

Three management areas emphasized in the fault tree include soil cover, nutrient management, and animal facility control. Cover is extremely important in controlling erosion and providing for the uptake of nutrients. Nutrient management ensures that plant nutrients are supplied to crops when needed and in the right amounts. The management of nutrients involves careful use of inorganic fertilizers as well as the responsible application of animal manure. Proper control of animal facilities prevents the direct deposition of nitrogen into streams by denying animals access to waterways. Other facility controls include waste storage and runoff routing. Adequate waste storage provides alternatives to spreading manure during periods of unfavorable soil and climatic conditions. Runoff routing keeps clean runoff water from crossing areas where animals have been confined and which may have high nutrient concentrations.

Producers in the Owl Run watershed can decrease their likelihood of discharging nitrogen by maintaining plant or residue cover whenever possible; by carefully managing the nutrients on their farms, including manure and inorganic fertilizers; and by strictly controlling the activities associated with their animal operations. The extent to which producers can decrease their risk of nitrogen discharge cannot be determined from a qualitative assessment; a quantitative assessment provides that information.

The issues of cover, nutrient management, and good animal management practices have been understood by soil and water conservationists for several decades. For years, workers in these fields have encouraged producers to implement those practices that would both benefit the productivity of the farm and protect the quality of the land and water around them. Although the fault tree does not reveal anything revolutionary pertaining to agricultural science, it does present the facts in a new format. This format is visually-oriented with connections between cause and effect clearly outlined. This technique might be a useful tool in communicating to producers the effects of their actions.

4.6 Probability Assignment

The quantitative assessment of the probability of nitrogen discharge to Owl Run began with assigning probabilities to each basic or undeveloped event. Each basic or undeveloped event was evaluated for both the pre- and post-BMP years of 1987 and 1993, respectively, for the dairy subwatershed, QOD, and the entire watershed, QOA. As mentioned previously, land use data were used extensively in the calculation of event probabilities. Table 4.1 is a list of the land use abbreviations used throughout this section. An abridged version of the land use records for the Owl Run watershed is presented in Tables 4.2 through 4.5. Table 4.6 is a listing of important sums or combinations of land uses utilized in determining the probabilities for each event.

The following paragraphs detail the procedures used to determine each basic event probability shown on the fault tree. Following the procedural explanation, the probabilities calculated for subwatershed QOD and QOA are summarized in Tables 4.9 and 4.10, respectively.

Table 4.1: Land use abbreviations

Abbreviation	Description	Abbreviation	Description
ALF	Alfalfa	**NTC**	No-till corn
CH	Church	**PA**	Pasture
CLO	Clover	**PLW**	Plowed
CM	Commercial	**PO**	Pond
CO	Conventional corn	**RDR**	Road/railroad
COR	Conventional corn residue	**RES**	Residential
FA	Farmstead	**SBR**	Soybean residue
FBR	Full season bean residue	**SCO**	Strip conventional corn
FSB	Full season beans	**SCR**	Strip conventional corn residue
GR	Grass	**SG**	Small grain
HA	Hay	**SGR**	Small grain residue
ID	Idle	**SNC**	Strip no-till corn residue
LI	Light industry	**SNTC**	Strip no-till corn
LO	Loafing lot	**SPL**	Strip corn, plowed
MCO	Minimum till corn	**SUA**	Summer annual
MCR	Minimum till corn residue	**WET**	Wetland
MSG	Minimum till small grain	**WH**	Wheat
NCR	No-till corn residue	**WO**	Woodland
NR	No record	**WW**	Waterway
NSA	No-till summer annual		

Table 4.2: Summer land use for subwatershed QOD (Pane, unpublished land use data, 1996)

Summer Land Use	**1987 (ha)**	**1993 (ha)**
ALF	9.98	9.98
CH	0.58	0.58
CO	51.90	20.71
FA	5.24	5.88
HA	46.02	28.39
LO	12.76	12.76
MCO	0	12.33
NR	7.27	0
NSA	0	8.61
NTC	25.43	13.59
PA	62.17	69.60
PLW	0	3.74
PO	1.17	1.17
RES	19.09	19.47
SNTC	0	26.66
SUA	0	6.94
WET	2.55	0.72
WO	86.93	86.67
WW	0	3.29
Total area:	331.09	331.09

Table 4.3: Winter land use for subwatershed QOD (Pane, unpublished land use data, 1996)

Winter Land Use	1987 (ha)	1993 (ha)
ALF	9.98	9.98
CH	0.58	0.58
COR	23.64	11.08
FA	5.24	5.88
GR	0	8.61
HA	46.02	28.39
LO	12.76	12.76
NR	7.27	0
NTC	13.93	0
PA	62.17	69.60
PO	1.17	1.17
RES	19.09	19.47
SG	39.76	46.23
SNC	0	26.66
WET	2.55	0.72
WO	86.93	86.67
WW	0	3.29
Total area:	331.09	331.09

Table 4.4: Summer land use for the Owl Run watershed (QOA) (Pane, unpublished land use data, 1996)

Summer Land Use	1987 (ha)	1993 (ha)	Summer Land Use	1987 (ha)	1993 (ha)
ALF	9.98	9.98	**NTC**	52.64	47.54
CH	1.35	1.35	**PA**	171.16	232.30
CLO	0	3.44	**PLW**	0	3.74
CM	3.71	3.71	**PO**	4.39	4.49
CO	128.63	79.56	**RDR**	22.36	22.36
FA	26.19	21.12	**RES**	86.04	82.28
FSB	0	18.61	**SCO**	0	8.16
GR	2.42	8.63	**SG**	9.09	11.44
HA	143.60	137.95	**SNTC**	0	26.66
ID	58.42	9.83	**SUA**	13.06	14.09
LI	4.75	4.75	**WET**	2.55	0.72
LO	26.10	23.03	**WO**	304.92	302.15
MCO	32.56	67.35	**WW**	0	3.29
NR	53.22	0			
NSA	0	8.61	**Total area:**	1157.14	1157.14

Table 4.5: Winter land use for the Owl Run watershed (QOA) (Pane, unpublished land use data, 1996)

Winter Land Use	1987 (ha)	1993 (ha)	Winter Land Use	1987 (ha)	1993 (ha)
ALF	9.98	9.98	**PA**	169.82	253.90
CH	1.35	1.35	**PLW**	0	2.94
CM	3.71	3.71	**PO**	4.39	4.13
CO	48.53	0	**RDR**	22.36	22.36
COR	6.67	120.40	**RES**	86.04	82.28
FA	26.19	21.12	**SBR**	0	17.84
GR	2.42	11.85	**SCR**	0	21.31
HA	143.60	127.72	**SG**	135.35	71.61
ID	58.42	10.54	**SGR**	9.09	0
LI	4.75	7.01	**SNC**	0	5.35
LO	26.10	23.03	**SPL**	0	8.16
MCR	0	3.05	**WET**	2.55	0.72
MSG	0	7.92	**WH**	16.31	0
NCR	0	13.06	**WO**	304.92	302.51
NR	60.66	0	**WW**	0	3.29
NTC	13.93	0	**Total area:**	1157.14	1157.14

Table 4.6: Land use sums used in probability development

Land Type	QOD 1987	QOD 1993	QOA 1987	QOA 1993
Length of stream accessed by PA[1] or LO[1] (km)	n/a[2]	n/a	6.0	4.2
Total length of stream bordering PA or LO (km)	n/a	n/a	6.0	6.0
Non-legume cropland (ha)	77.33	88.84	235.98	232.45
Fertilized hayland (ha)	24.60	20.33	27.15	34.18
Total land under production (ha) (includes PA and HA[1]) (winter)	208.26	213.31	589.24 (581.80)	666.30 (698.12)
Improved cover on LO (ha)	0	5.82	0	5.82
Total land eligible for tillage (ha) (excludes PA and HA)	87.31	102.56	245.96	295.74
Total land eligible for cover (ha) (includes HA, excludes PA)	133.33	130.95	385.88	421.19
Land without erosion control (ha)	64.66	14.78	141.77	72.91

[1] PA = pasture; LO = loafing lots; HA = hayland

[2] n/a = not applicable

Cattle have access to the stream

The probability that livestock have direct access to the streams was determined on a length basis. In the case of subwatershed QOD, no definitive documentation was found to indicate the presence of stream bank fencing in either the pre- or post-BMP period. Therefore, because both pastures and loafing lots in QOD border streams, the probability that animals have access to the waterway for both years is 1.0.

For QOA, the available data do not offer definite proof of stream bank fencing for the pre-BMP year, 1987. Again, the probability for this event in 1987 is 1.0. By the beginning of the post-BMP year, 1993, approximately 1.8 kilometers of fencing had been installed (Wang, 1991). The total length of waterway exposed to pastures or loafing lots was measured to be 6.0 kilometers

(Table 4.6). Therefore, the percentage of waterway still accessible to livestock is 70percent and, likewise, the probability that the waterway is exposed to livestock is 0.70. In October 1993, 1.78 kilometers of additional fencing was installed (Pane, 1996). It was, however, neglected in this analysis because it was not functional for the entire year.

There are other possible methods for calculating this probability. One alternative that was considered was based on the area of the pastures allowing access to the stream. This method was ultimately rejected because a large area with a small length of stream access, and vice versa, would skew the probabilities. An ideal method of analysis for this probability would incorporate the number of cattle that actually have access to the stream. However, as these data were not available on a field by field basis for Owl Run, the next best method was chosen.

No off-stream shade sources

The probability that pastures contained no off-stream shade was estimated to be approximately 0.50 (Pane, 1997). The shade conditions within the watershed did not change from the pre-BMP period to the post-BMP period. Therefore, for the Owl Run watershed (QOA), the probability of 0.50 was used for both 1987 and 1993. It is assumed that QOD was representative of the whole watershed. Therefore, this estimated probability was also used for QOD in 1987 and 1993.

No off-stream water sources

It is estimated that in the pre-BMP year 80 percent of the pasture bordering Owl Run had no other convenient source of water for the cattle (Pane, 1997). During BMP implementation, upland water troughs were installed to provide an alternative source of water. Some stream bank fencing was also built at that time. By 1993, the percent of pasture with the stream as its sole source of water was decreased to 50 (Pane, 1997). Again, QOD was assumed to be representative of the entire watershed. Therefore, the probabilities used for this event for both QOD and QOA are 0.80 and 0.50 for 1987 and 1993, respectively.

Runoff occurs

To calculate the probability that runoff occurs on any given day, the amount of rainfall necessary to produce runoff was first calculated. The Soil Conservation Service (SCS) Curve Number Method for calculating runoff depth was utilized (Schwab et al., 1993, p. 79). The land use data were evaluated to determine that land use which corresponds to the highest curve number (CN) within the watershed. The high CN indicates impermeability or a tendency to contribute to runoff. The agricultural land use in QOA which yields the highest CN, 85, is straight row crops in good condition on soils in hydrologic group C (Schwab, et al., 1993, p. 74). Straight row crops, namely corn, are a significant portion of the land use in QOA, and 68.5 percent of the soils are in group C. In general, land uses on soils classified as hydrologic group D yield higher CNs than those in group C. However, in QOA the 11.2 percent of the watershed classified as group D is used mainly for pasture, hayland, or woodland. These land uses for group D soils yield CNs lower than the 85 determined for group C soils used for straight row crops.

The selected CN was then used to calculate S, the maximum potential difference between rainfall and runoff, as specified by the SCS Curve Number Method (Schwab, 1993, p. 80):

$$S = \frac{25400}{CN} - 254 \tag{3}$$

Using the CN of 85, S was calculated to be 44.82 millimeters. The SCS equation was then used to determine the depth of rainfall, I, necessary to produce runoff (i.e., Q > 0) (Schwab et al., 1993, p. 79):

$$Q = \frac{(I - 0.2S)^2}{I + 0.8S} \tag{4}$$

where: *Q* = direct surface runoff depth in mm

I = storm rainfall in mm

S = maximum potential difference between rainfall and runoff in mm.

The storm rainfall necessary to produce some runoff, I, was calculated to be nine millimeters. Therefore, any rainfall event of nine millimeters or more would result in some surface runoff within the Owl Run watershed.

Rainfall records were then analyzed to determine the frequency of occurrence of rainfall events with a magnitude greater than or equal to nine millimeters. Climatological data from the U.S. Weather Bureau were gathered for the weather station closest to The Owl Run watershed in Warrenton, Virginia. Currently, the U.S. Weather Bureau uses the years of 1961 to 1990 to calculate average or normal values of temperature and precipitation (NOAA, 1996). Following the example of the bureau, the data available from Warrenton for 1961 through 1990 were utilized for this analysis.

Intervals, or classes, were established for the purpose of consolidating the rainfall record of 10,835 days based on procedures outlined by Haan (1977, p. 17-20). The first class was determined by the bureau records. The smallest rainfall event that can be recorded is 0.25 millimeter (0.01 inch). Any event smaller than 0.25 millimeter is recorded as a trace amount of rainfall. Therefore, no rainfall and trace amounts of rainfall were recorded together in the 0 to 0.25 millimeter class. It is suggested that no more than 20 intervals be used when analyzing data and that the intervals not be too large (Haan, 1977, p. 17-20). Therefore, it was decided that intervals of 2.5 millimeters were a reasonable compromise between covering the broad range of rainfall depths and keeping the interval small enough to show trends and lend significance to the compiled data. For simplicity, the second interval was chosen to span 0.25 to 2.5 millimeters so that the following intervals might begin and end on the whole or half millimeter.

The number of rainfall events occurring in the established classes over the 30 year period were recorded. The results of this data collection are depicted as a histogram in Figure 4.3. The cumulative frequency of occurrence for the interval boundaries was then determined. The results of these calculations are shown in Table 4.7. Because the cumulative probability of occurrence is known for 7.5 and 10.0 millimeters, linear interpolation was used to calculate the probability for nine millimeters. The probability of occurrence for all rainfalls equal to or greater than nine millimeters was calculated to be 0.11. This probability is reported in Tables 4.9 and 4.10.

It might be argued that by simply counting the number of rainfall occurrences exceeding nine millimeters within the thirty years of record that a more accurate probability for this event could have been obtained. However, the rainfall event of interest might change if land uses within the watershed were to change substantially. In this case, the rainfall depth was nine millimeters because the highest CN was 85. Were the farmers to change farming practices, the highest CN might change, yielding a different rainfall depth necessary to cause runoff. The process of counting the historical rainfall data would have to be repeated each time a change in farming practices and curve number were made. The technique used in this analysis provides a reusable, broader, more complete analysis of the history of rainfall events. It also prevents the repetition of analysis necessary with the alternative method.

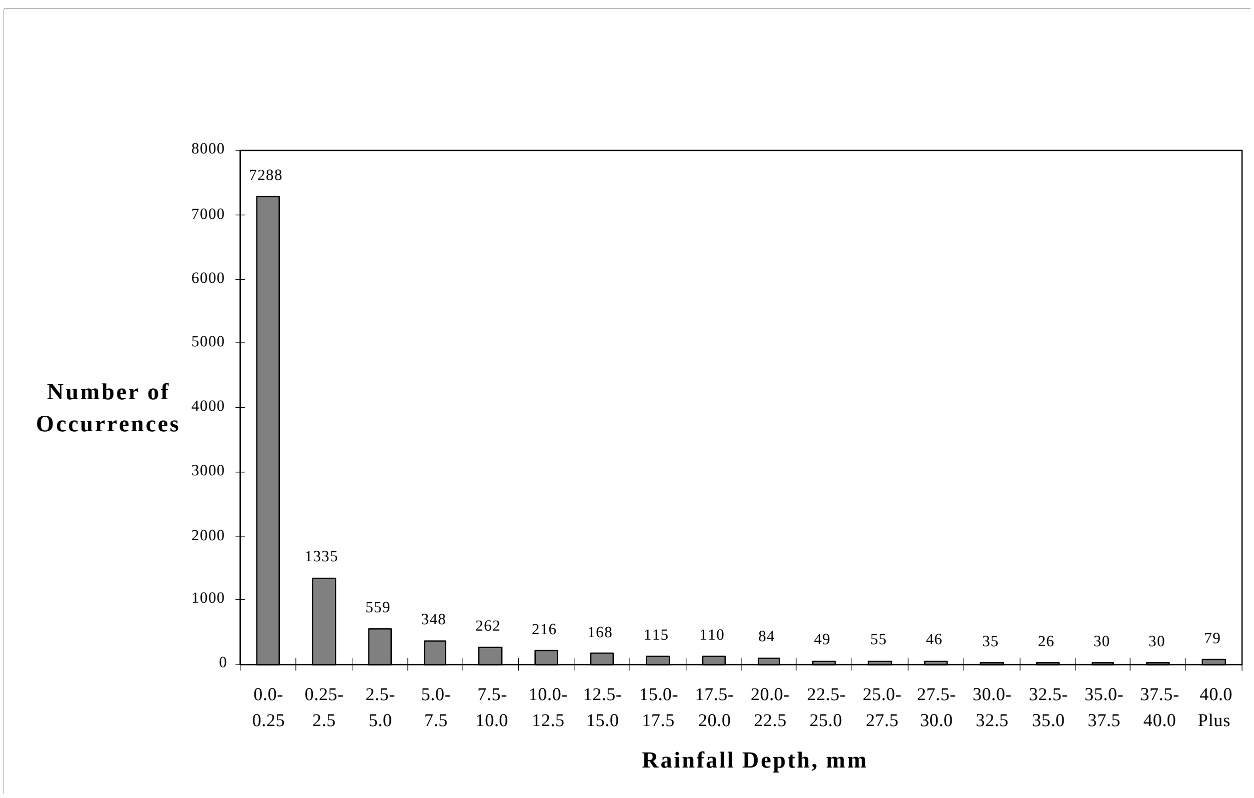


Figure 4.3: Histogram of rainfall occurrence, 1961-1990

N fertilizer is applied to surface layer

The probability that nitrogen fertilizer is applied to the surface layer was determined using land use and fertilization records. It was assumed that any land utilized for the production of non-legume crops was fertilized (Table 4.6). This includes all land used for corn, grain, and summer annual production. Twenty percent of the land designated as pasture was also fertilized (Pane, 1996). Loafing lots were also considered fertilized for the purpose of this research because they received manure on a consistent basis. Fertilization records also indicated those hay fields which received manure or inorganic fertilizer during the years in question (Table 4.6). The total land area fertilized was divided by the total area under agricultural production (Table 4.6). As seen in Table 4.9, the probabilities for QOD are 0.61 and 0.64 for 1987 and 1993, respectively. Similarly, the probabilities calculated for the entire watershed were 0.54 for 1987 and 0.50 for 1993.

Table 4.7: Results of weather data analysis

Rainfall Depth R_i (mm)	Number of Occurrences (R_i to R_{i-1})	Cumulative Occurrences	Cumulative Probability $P(x>R_i)$
> 40.0	79	79	0.007
37.5	30	109	0.010
35.0	30	139	0.013
32.5	26	165	0.015
30.0	35	200	0.018
27.5	46	246	0.023
25.0	55	301	0.028
22.5	49	350	0.032
20.0	84	434	0.040
17.5	110	544	0.050
15.0	115	659	0.061
12.5	168	827	0.076
10.0	216	1043	0.096
7.5	262	1305	0.120
5.0	348	1653	0.153
2.5	559	2212	0.204
0.25	1335	3547	0.327
0	7288	10835	1.000

Fertilizer is applied in fall/winter

The fertilization records for QOD did not indicate that any land received fall or winter applications of fertilizer in 1987. Only the loafing lots received applications/deposits of manure. This initially seems to be in error because the two dairies located within the subwatershed were daily-scrape-and-haul operations at the time. However, both dairies used fields located outside the boundaries of the Owl Run watershed as spreading areas during this year. Therefore, the probability that fertilizer was applied in QOD in the fall/winter of 1987 was 0.10 (i.e., the area of the loafing lots divided by the area of land receiving fertilizer during the year).

By 1993, one dairy within QOD had installed a waste storage facility and was not obliged to apply manure during the winter. In 1993, fertilization records indicated that one field, with an area of 3.60 hectares, received one load of manure per day during the winter from the dairy without a storage facility. The loafing lots also received manure during the winter of 1993. In addition, inorganic fertilizer was applied to 40.25 hectares of small grains. The probability that fertilizer/manure was applied during the winter of 1993 was calculated to be 0.42 by dividing the area receiving fertilizer/manure by the total area of land receiving fertilizer during the 1993 year.

For QOA, the probabilities for 1987 and 1993 were calculated to be 0.11 and 0.22, respectively. In 1987, three fields planted to small grain, totaling 10.75 hectares, received applications of both manure and chemical nitrogen fertilizer. The loafing lots also received manure. As with QOD, the probability of 0.11 was calculated by dividing this total by the total area of land fertilized during that year.

By 1993, all but one dairy had installed a waste storage facility. The remaining dairy continued to scrape and haul daily. In 1993, one field of 12.10 hectares received the manure applications from this dairy. In addition, chemical fertilizer was applied to 40.25 hectares of small grains and 23.03 hectares of loafing lots received manure. The total receiving fertilizer/manure in the winter was divided by the total land area receiving fertilizer that year for a probability of 0.22.

No winter cover crop established

The probability that no winter cover crop was established was determined by summing the area of cultivated land without a growing crop during the winter and dividing the total by the area of land eligible for cover. All cultivated land was considered eligible for cover (Table 4.6). The area of the loafing lots was included in the total unless significant improvement in cover conditions in the post-BMP year were identified by an Owl Run expert (Pane, 1996). In addition, any pasture in poor condition (i.e., pasture with less than 50 percent cover) was included in the total. Based on expert opinion, 20 percent of all pasture was designated as having poor condition. As seen in Tables 4.9 and 4.10, the probabilities calculated for 1987 and 1993, respectively, are 0.31 and 0.28 for QOD and 0.24 and 0.36 for QOA.

Application rate exceeds crop nutrient requirements

In the pre-BMP years, approximately 15 percent of the agricultural land received excess nutrients (Mostaghimi, 1995-1996; Pane, 1996-1997). Therefore, the probability that the application rate exceeded crop nutrient requirements for both QOD and QOA in 1987 is 0.15. Unpublished nutrient application records indicated that within QOD in 1993 there was no instance in which farmers applied more fertilizer than was recommended by soil tests. The corresponding probability for QOD in 1993 is 0.

For QOA, the same unpublished data records indicated that one dairy farmer over-applied nitrogen to his corn fields. The corn fields in close proximity to the loafing lot of this dairy (i.e., bordering or one field over) were considered to be over-fertilized. The total area considered over-fertilized was 16.38 hectares. This total divided by the number of hectares fertilized that year yields the probability of 0.05 shown in Table 4.10.

Fertilizer not incorporated into the soil

Approximately 85 percent of the fertilizer applied within the watershed is not incorporated within a reasonable period of time (e.g., a week) after spreading (Mostaghimi, 1995-1996; Pane, 1996-1997). This practice has not altered in the post-BMP years. Therefore, the probability used in this analysis was 0.85 for both QOD and QOA for 1987 and 1993.

Runoff occurs within seven days of application

Rainfall and runoff data for 1987 and 1993 (Mostaghimi et al., 1989; AGEN, 1993) were used to calculate the probability that a runoff event would occur within seven days of a fertilizer application. The number of days during each year that were followed by seven runoff-free days were counted. By subtracting this number of days from the number of days in the year and dividing by the total number of days in the year, the probability that runoff occurs within seven days of fertilizer application was determined. For 1987, the probability determined was 0.60. In 1993, the probability was 0.56. These probabilities were utilized for both the subwatershed and whole watershed (Tables 4.9 and 4.10).

The probabilities for this event were based on site-specific data that are not commonly available. These probabilities are also not based on a record of sufficient length to be predictive. The technique used here was considered the most accurate method of calculating these probabilities for the years in question. However, the type of data used here would only be available for closely monitored watersheds. A method of calculating these probabilities that was based on a longer record of readily available data would be preferable. By utilizing the same Weather Bureau records used for the runoff event and establishing a threshold rainfall depth sufficient to cause runoff, the number of dry and wet days could be determined. However, as was mentioned previously, the depth of rainfall necessary to cause runoff would change as land uses change. A repetition of the analysis of the rainfall data would be necessary each time the curve number and, therefore, the rainfall depth necessary to cause runoff changed.

Confined animals present

The probability that confined animals were present in the watershed was determined on a time basis. The percent of total time spent in a loafing lot was sought. Based on expert opinion, dairy cattle in the Owl Run watershed spend, on average throughout the year, approximately 15 percent of their day in loafing lots. This percentage was converted to a probability of 0.15. The amount of time spent in loafing lots did not change from the pre- to post-BMP period (Pane, 1996).

No vegetative BMPs between confinement and stream

The presence of BMPs between loafing lots and the stream was considered as an alternative to runoff diversions and completely confining the lot runoff. In 1987, neither QOD dairy had such BMPs, making the probability 1.0. By 1993, however, both dairies had installed vegetative filter strips, making the probability zero. For QOA, two dairies were located some distance from the stream and had some form of established vegetation between the loafing lots and the stream. In each case, the vegetation was not a planned filter strip. However, these two dairies were regarded as though the vegetation were an established BMP because the same purpose was served. The remaining three dairies were considered in developing the probability for no vegetative BMPs. The probability for 1987 was calculated by dividing the number of dairies without such intervention by the total number of dairies (i.e., 3/5 or 0.60). By 1993 all dairies had installed some form of vegetated filter strip, therefore, the probability for QOA that year was zero as seen in Table 4.10.

No runoff diversions

The probability that no structures exist to divert clean runoff from flowing over loafing lots is 1.0. There are no indications of such structures in the watershed for either the pre- or post-BMP years (Mostaghimi, 1996).

Runoff from confinement not contained

As with runoff diversions, no precautions have been taken within the watershed to contain runoff from loafing lots. The volume of water that would require containment is considered to be excessive for storage in waste handling facilities (Mostaghimi, 1996). Therefore, the probability for this event is 1.0 in all cases.

Erosion occurs

The probabilities for the occurrence of erosion were taken directly from the probabilities for the occurrence of runoff (Tables 4.9 and 4.10). It was assumed that some erosion would always occur in the presence of runoff. This assumption is valid for the Owl Run watershed based on an examination of the rainfall, runoff, and sediment yield data from the monitoring stations

(Mostaghimi et al., 1989). The possibility of sediment removal from runoff is considered below in the event "no BMPs installed to remove sediment from runoff".

Clay present >10%

The event probabilities related to soil properties were determined using the soil survey, land use data, and scientific judgment. The soils in the Owl Run watershed are silt loams with slopes varying from 0 to 25 percent. The major soil types are listed in Table 4.8. The alternative soil series names, in parentheses in the table, are the new designations being assigned to these series. As yet, these names are unpublished but will be used in the next soil survey for Fauquier County (Stewart, 1996). The information available from the present soil survey of Fauquier County is limited. In addition, the condition of soils is highly site-specific. Therefore, the determination of the probabilities for the presence of clay and organic matter relied heavily on scientific judgment and experience.

The threshold for the presence of clay was set at 10 percent. It is possible for silt loams to have less than 10 percent clay (Brady, 1990, p.99). However, experience reveals that the soils of the Owl Run watershed are heavy, an indicator of clay content (Pane, 1996). Therefore, the probability that the clay content of soils in the watershed is over 10 percent was assumed to be 1.0 for both study years.

Organic matter present >0.5%

The probability of the soil having an organic matter content over 0.5 percent was determined in a similar manner. The soil survey indicates that the soils of Owl Run have varying organic matter levels ranging from low to high, however, no specific numbers are given. The organic matter content of mineral soils, in general, ranges from one to six percent (Brady, 1990, p. 10). Therefore, an organic matter content of 0.5 percent would be considered extremely low. Because the soil survey does not indicate abnormally low organic matter levels and because much of the Owl Run watershed, in both the pre- and post-BMP years, had some type of residue or plant biomass left in or on the soil, a probability of 1.0 was deemed acceptable. The probabilities established for both clay and organic matter presence were utilized for both QOD and QOA for both years.

NH_4^+ fertilizer applied to the surface layer

The probabilities assigned to this event were taken from the probability previously calculated for nitrogen fertilizer application to the surface layer. Experience indicates that essentially all of the fertilizer forms utilized in the watershed, organic and inorganic, contain ammonium or ammonium salts (Pane, 1996). Therefore, the probabilities calculated for nitrogen fertilizer application can also be utilized here.

Table 4.8: Owl Run watershed soil characteristics (Mostaghimi et al., 1989)

Soil Series (Alternative name)	**Percent Slope**	**Percent of Watershed Area**
Bowmansville silt loam	0-2	1.2
Bucks silt loam (Panorama silt loam)	2-7	16.3
Calverton silt loam (Dulles silt loam)	2-7	8.2
Croton silt loam (Albano silt loam)	0-5	8.8
Kelly silt loam	2-7	2.4
Montalto silt loam (Legore-Oak Hill complex)	2-7	14.4
Montalto stony silt loam (Oak Hill rock outcrop complex)	7-14	2
Penn silt loam (Brentsville silt loam)	2-7	35.7
Penn silt loam (Brentsville silt loam)	7-14	4.1
Rowland silt loam	0-2	2.9
Wadesboro silt loam (Sudley silt loam)	2-7	1.4
Other	0-25	2.6

Tillage leaves <30% of soil surface covered

The probability that tillage leaves <30% of the soil surface covered was developed by dividing the total number of hectares under conventional tillage by the number of hectares eligible for tillage. The amount of land eligible for tillage includes all land under production except pastures and hayland. For QOD, probabilities of 0.59 and 0.31 were calculated for 1987 and 1993, respectively (Table 4.9). The probabilities for QOA were found to be 0.58 and 0.41 for the same years (Table 4.10).

Pasture has <50% cover

As previously stated, twenty percent of the pastures in any given year were estimated to be in poor condition (i.e., having less than 50 percent cover) (Pane, 1996). This total and the area of loafing lots in poor condition were summed and divided by the total number of hectares used as pasture and loafing lots to determine the probability for this event. Probabilities of 0.34 and 0.25 were calculated for QOD in 1987 and 1993, respectively. The corresponding values for QOA are 0.31 and 0.25.

No cover or residue on surface

Only the total land eligible for cover was considered for this event. Pasture was excluded from consideration because it was handled separately in the event described above. The probability for the presence of cover was based on the winter land use data. The total land area not having either a cover crop or residue remaining on the surface was divided by the total land eligible for cover (Table 4.6). For QOD, the probabilities were calculated to be 0.10 and 0 for 1987 and 1993. During the same years, the probabilities for QOA were calculated to be 0.16 and 0.04.

No BMPs installed to remove sediment from runoff

Land uses that did not include some type of erosion control practice were considered for this event. Loafing lots without filters of some type and conventionally tilled cropland are included in the totals found in Table 4.6 for 1987. As stated previously, two of the dairies had substantial amounts of vegetation between the loafing lots and the stream. These lots, covering an area of 12.96 hectares, were not included in the total shown in Table 4.6 for QOA. The 1987 totals in the table were divided by the amount of land under production to calculate the probabilities for 1987. The values calculated were 0.31 and 0.24 for QOD and QOA, respectively.

By 1993, several BMPs had been established to control sediment transport to the stream. All of the loafing lots discharged into some type of vegetated filter strip (VFS) or buffer. Therefore, their acreage was not included in the total area without sediment removal BMPs for 1993. In addition, records showed that 29 hectares of cropland now drained into VFSs (Wang, 1991). Based on a visual inspection of maps produced by Wang (1991), it was estimated that approximately one-third of these VFSs were located in QOD. Therefore, one-third of the 29 hectares (9.67 ha) was subtracted from the area of conventionally tilled land for QOD. This total (14.78 ha) was divided by the total land under production for QOD in 1993 (213.31 ha) to yield a probability of 0.07. For QOA, the entire 29 hectares now discharging to BMPs was subtracted from the conventionally tilled acreage for QOA to yield 72.91 hectares without erosion control. This total was divided by the total land under production (666.30 ha) to calculate a probability of 0.11 for QOA in 1993.

Table 4.9: Probabilities assigned for the QOD subwatershed for 1987 and 1993

	Event	QOD 1987	QOD 1993	Source
A	Cattle have access to the stream	1	1	(1)
B	No off-stream shade source	0.50	0.50	(4) 2/97
C	No off-stream water source	0.80	0.50	(4) 2/97
D	Runoff occurs	0.11	0.11	(1)(2)
E	N fertilizer is applied to surface layer	0.61	0.64	(3)
F	Fertilizer is applied in fall/winter	0.10	0.42	(3)
G	No winter cover crop established	0.31	0.28	(1)
H	Application rate exceeds nutrient requirements	0.15	0	(4)(5) 12/96
I	Fertilizer not incorporated into the soil	0.85	0.85	(5) 10/95
J	Runoff occurs within 7 days of application	0.60	0.56	(6)
K	Confined animals present	0.15	0.15	(4) 12/96
L	No vegetative BMPs between confinement and stream	1	0	(4) 12/96
M	No runoff diversions	1	1	(5) 12/96
N	Runoff from confinement not contained	1	1	(5) 12/96
O	Erosion occurs	0.11	0.11	(1)(2)
P	Clay present >10%	1	1	(7)(4) 12/96
Q	Organic matter present >0.5%	1	1	(7)(1)
R	NH_4^+ fertilizer applied to the surface layer	0.61	0.64	(3)(4) 11/96
S	Tillage leaves <30% of soil surface covered	0.59	0.31	(1)
T	Pasture has <50% cover	0.34	0.25	(1)(4) 11/96
U	No cover or residue on surface	0.10	0	(1)
V	No BMPs installed to remove sediment from runoff	0.31	0.07	(1)(8)

(1) Pane, unpublished land use data, 1996
(2) NOAA, 1961-1990
(3) McClellan, unpublished fertilization data, 1996
(4) Pane, personal communication
(5) Mostaghimi, personal communication
(6) AGEN, 1993 and Mostaghimi et al., 1989
(7) Petro, soil survey, 1956
(8) Wang, 1991

Table 4.10: Probabilities assigned for the Owl Run watershed (QOA) for 1987 and 1993

	Event	1987	1993	Source
A	Cattle have access to the stream	1	0.70	(1)
B	No off-stream shade source	0.50	0.50	(4) 2/97
C	No off-stream water source	0.80	0.50	(4) 2/97
D	Runoff occurs	0.11	0.11	(2)
E	N fertilizer is applied to surface layer	0.54	0.50	(3)
F	Fertilizer is applied in fall/winter	0.11	0.22	(3)
G	No winter cover crop established	0.24	0.36	(1)
H	Application rate exceeds nutrient recommendation	0.15	0.05	(4)(5) 12/96
I	Fertilizer not incorporated into the soil	0.85	0.85	(5) 10/95
J	Runoff occurs within 7 days of application	0.60	0.56	(6)
K	Confined animals present	0.15	0.15	(4) 12/96
L	No vegetative BMPs between confinement and stream	0.60	0	(4) 12/96
M	No runoff diversions	1	1	(5) 12/96
N	Runoff from confinement not contained	1	1	(5) 12/96
O	Erosion occurs	0.11	0.11	(2)
P	Clay present >10%	1	1	(7)(4) 12/96
Q	Organic matter present >0.5%	1	1	(7)(1)
R	NH_4^+ fertilizer applied to the surface layer	0.54	0.50	(3)(4) 11/96
S	Tillage leaves <30% of soil surface covered	0.58	0.41	(1)
T	Pasture has <50% cover	0.31	0.25	(1)(4) 11/96
U	No cover or residue on surface	0.16	0.04	(1)
V	No BMPs installed to remove sediment from runoff	0.24	0.11	(1)(8)

(1) Pane, unpublished land use data, 1996
(2) NOAA, 1961-1990
(3) McClellan, unpublished fertilization data, 1996
(4) Pane, personal communication
(5) Mostaghimi, personal communication
(6) AGEN, 1993 and Mostaghimi et al., 1989
(7) Petro, soil survey, 1956
(8) Wang, 1991

4.7 The Probability of Nitrogen Discharge to Owl Run

Once the basic event probabilities had been assigned, the calculations to obtain the top event probability were performed. By assigning letters to each basic event, as indicated in Tables 4.9 and 4.10, and following the procedures for Boolean algebra outlined in section 3.3, the following equation for calculating the probability of nitrogen discharge to Owl Run was developed:

$$P(discharge) = [ABC] + [DE(FG + H + IJ) + DK(L + M + N)] + [ORV(P + Q)(S + T + U)] \quad (5)$$

The first term, ABC, was derived from the "cattle are in the stream and contribute N directly" branch of the fault tree. The second and third terms were the result of the dissolved nitrogen and adsorbed nitrogen branches, respectively. By substituting the values listed in Tables 4.9 and 4.10, the probabilities of discharge for each scenario were calculated. The results are displayed in Table 4.11.

Table 4.11: Probability of nitrogen discharge to Owl Run on any day as a result of cattle in the stream on any day, soluble nitrogen contributions on any day, and adsorbed nitrogen contributions on any day

	Cattle in the stream	+	Soluble N	+	Adsorbed N	=	P(discharge)
QOD							
1987	0.40	+	0.06	+	0.02	=	0.48
1993	0.25	+	0.06	+	0.003	=	0.31
QOA							
1987	0.40	+	0.06	+	0.01	=	0.47
1993	0.18	+	0.05	+	0.004	=	0.23

4.8 Discussion of the Probability or Nitrogen Discharge to Owl Run

4.8.1 Unexpected Results

In most instances, the quantitative fault tree analysis yielded expected results. In general, the data indicated that improvements made from 1987 to 1993 (e.g., BMPs) had a positive impact on the watershed by decreasing the probability of nitrogen discharge to Owl Run. In a few cases, however, this generalization did not hold true. In the analysis of subwatershed QOD, two event probabilities increased from 1987 to 1993. The nitrogen fertilizer application events, E and R, increased by 0.04 over the study period. This small increase represents an increase in the area of land fertilized from 1987 to 1993. As indicated in Table 4.6, there was a slight increase in the number of hectares fertilized during that period. It should also be noted that the data records are more complete for 1993 than for 1987. Therefore, this analysis is correct for the data available, but it may not represent the watershed systems fully due to the lack of records in 1987 (see NR in Tables 4.4 and 4.5).

The fall or winter application event probability, F, also increased for QOD, by 0.32. An increase of 0.11 in the probability for this event was also observed in the analysis of QOA. There are several possible explanations for these increases. The most obvious is that increases in winter fertilizer application actually occurred over the six year interval. An increase in the fertilization of winter cover crops would produce such a result. However, it is also known that fewer dairies were applying manure daily in 1993 than in 1987 because of the construction of waste storage facilities. Another possible explanation is that the lack of data from 1987 extends to the fertilization records as well. A more likely explanation, however, is that the dairies used land outside of the Owl Run watershed boundaries as spreading areas for their daily manure loads in 1987. There was some allusion to this possibility in the fertilization records.

Another unexpected increase in probabilities was seen for the lack of winter cover crop event, G. An increase of 0.12 was seen for QOA. One would expect a decrease in this value due to an emphasis in cover crop BMPs between the years of 1987 and 1993. As shown in Table 4.6, there was an increase of 116.32 hectares of land under cultivation in the winter from 1987 to 1993. An increase in cover crop usage of 112.34 hectares did not keep pace with the increase in land under cultivation and resulted in a higher probability for the event "no cover crop established".

4.8.2 Discussion of Direct Cattle Contributions of Nitrogen

The fault tree branch with the greatest influence on the total probability of discharge was the probability that livestock are in the stream (i.e., the first term of Equation 5). This result indicates that allowing animals open access to Owl Run with no alternative sources of water or shade was the most significant factor contributing to nitrogen discharge on a daily basis. As the other factors associated with nitrogen release on the fault tree (i.e., runoff and erosion) are related to rainfall, an intermittent event, it may be true that on a daily basis, eliminating livestock waste deposits to the stream is the most crucial action to take. Over time, however, it appears that the relatively small contribution of cropland sources to the overall probability would result in an underestimation of the total nitrogen contribution of these sources and cause the neglect of needed management BMPs.

It may be argued that animal deposition of manure is not truly nonpoint source pollution, and the event could be trimmed from the tree. If this course of action were chosen, the emphasis of the fault tree would be directed entirely at cropland practices and the management of confined areas. As can be seen from Table 4.11, the ultimate probability of discharge would be lowered dramatically if the first term were eliminated. However, as the determination of what probability constitutes a high level of risk is entirely subjective, the small probabilities would not inevitably represent a problem with the analysis.

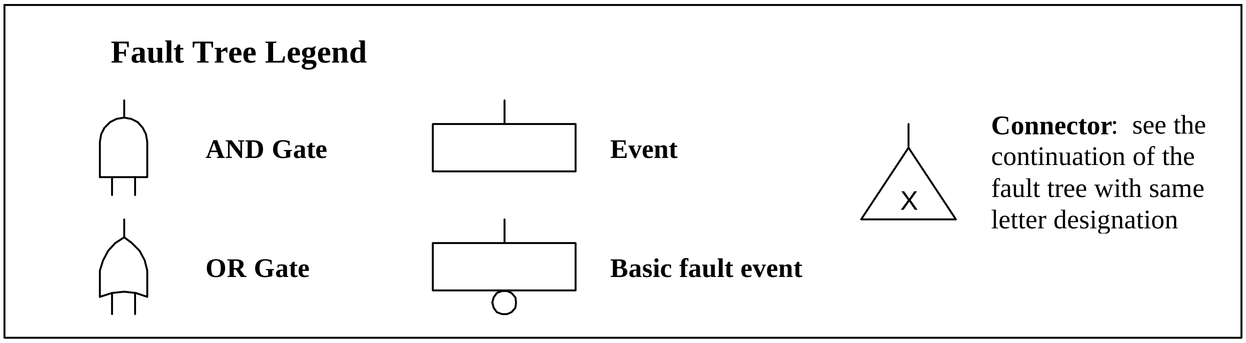
One of the disadvantages to this particular fault tree, and the equation derived from it, is that the BMPs embedded in the lower levels of the fault tree do not substantially affect the overall probability. For example, probabilities of 1.0 were developed for the lack of runoff diversions and lack of facilities to contain animal confinement runoff. Looking at the data for QOA for 1993, three dairies would have to install both BMPs (i.e., runoff diversions and collection of loafing lot runoff) for the sum of L, M, and N to be less than 1.0 (e.g., L + M + N = 0 + 0.40 + 0.40 = 0.80). With this sum equal to 0.80, the overall probability of discharge is still 0.23. Again, this example serves to illustrate the controlling influence of the animal deposition event. Disregarding this event would substantially increase the influence of the embedded BMPs, and, consequently, place the focus of the analysis on cropland practices. While the control of pastured animals is important from a managerial perspective, it may be more appropriate to exclude these events from the fault tree for the purpose of evaluating the probability of NPS pollution.

4.9 Probability of Nitrogen Discharge to Owl Run During a Runoff Event

An alternate way to approach the fault tree would be to assume the occurrence of rainfall, runoff, and erosion. This approach would more accurately depict NPS pollution processes because rainfall and runoff are the driving forces behind NPS pollution. Figure 4.4 depicts a fault tree for the discharge of excessive nitrogen to Owl Run during a runoff event. This tree differs from the original fault tree because it does not include the runoff and erosion events. They are assumed to be occurring at the time that the fault tree is evaluated. The deposition of cattle excreta is also not included as per the discussion in section 4.8.2 and because the deposition event is not dependent on the occurrence of runoff. The following equation was derived from the new fault tree (Figure 4.4) with event labels as given in Tables 4.9 and 4.10:

$$P(discharge) = \left[E(FG + H + IJ) + K(L + M + N)\right] + \left[RV(P + Q)(S + T + U)\right] \tag{6}$$

Using Equation 6, the probability of nitrogen discharge in the dissolved and adsorbed phases during a runoff event (Table 4.12) are an order of magnitude greater than on any given day (Table 4.11). Again, the size of the probability is not necessarily indicative of the level of risk because risk depends on both the frequency and the consequences of an event. In this instance, no consideration was given to the specific consequences of the event. However, this fault tree takes a more realistic look at the true concerns of nonpoint source pollution (i.e., discharge of pollutants during runoff events) and better illustrates the impact of BMPs. By redefining the top event of the fault tree to assume the occurrence of runoff, the quantitative analysis of the tree is more responsive to management and land use changes within the watershed. The following examples make it clear that the choice of the top event for a fault tree significantly affects the usefulness of the tree.



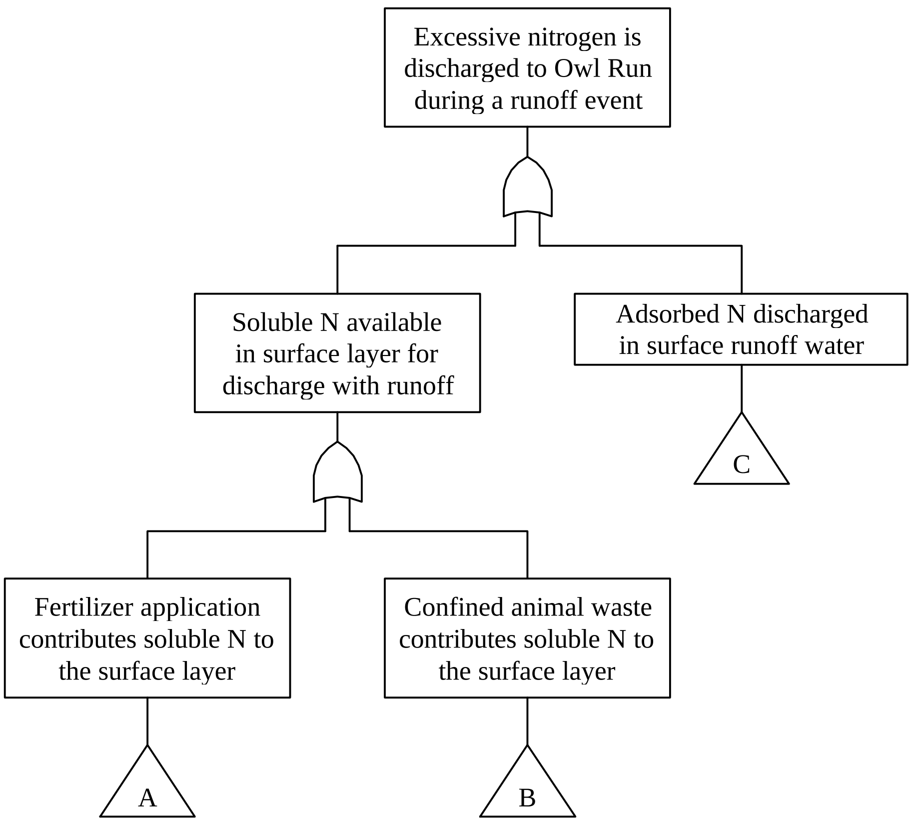


Figure 4.4: Fault tree for the discharge of nitrogen to Owl Run during a runoff event

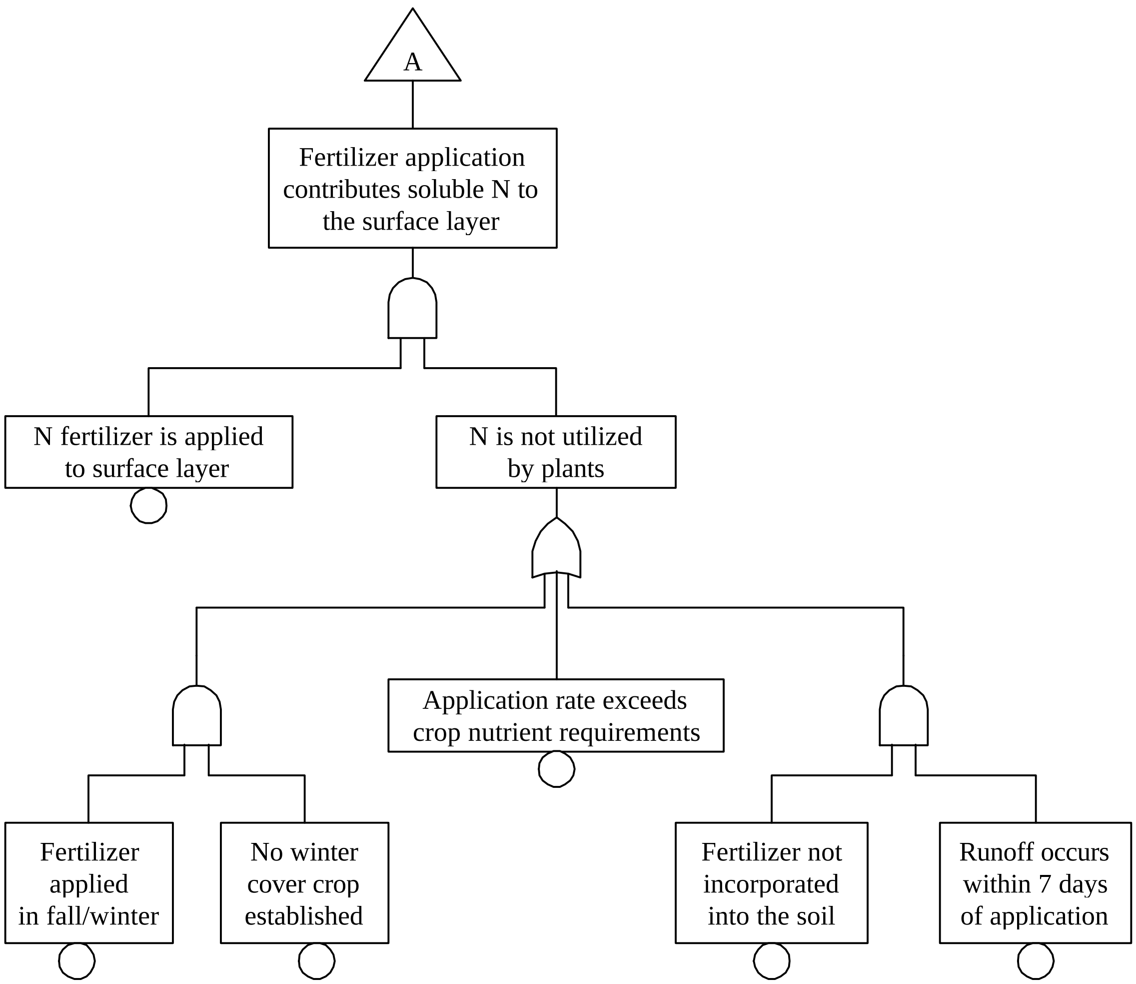


Figure 4.4: Fault tree for the discharge of nitrogen to Owl Run during a runoff event (continued)

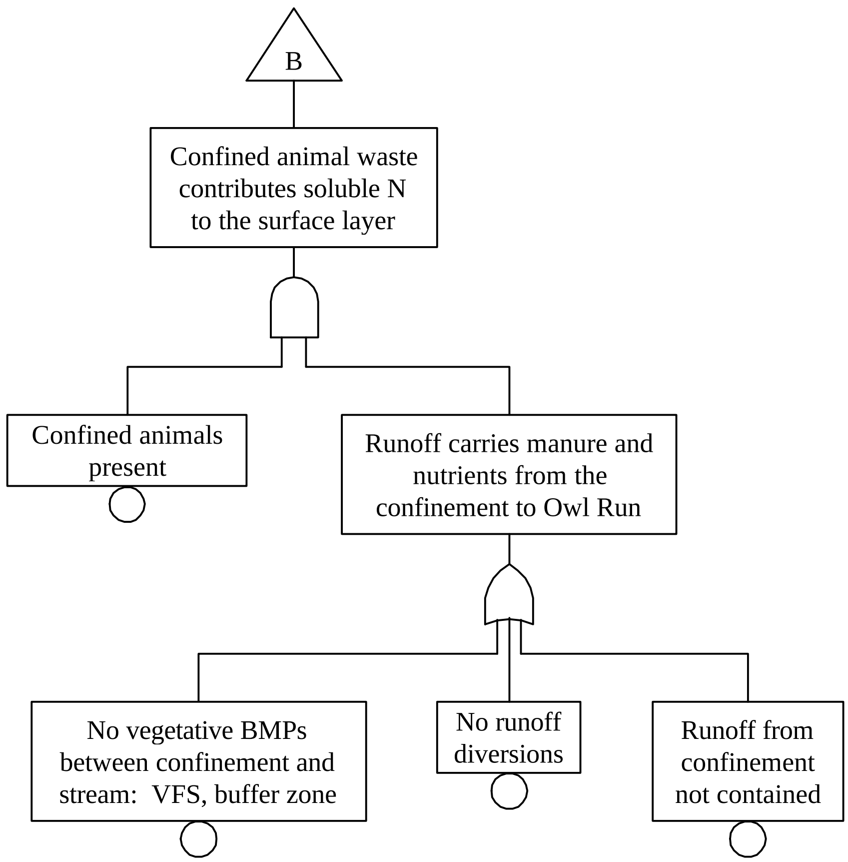


Figure 4.4: Fault tree for the discharge of nitrogen to Owl Run during a runoff event (continued)

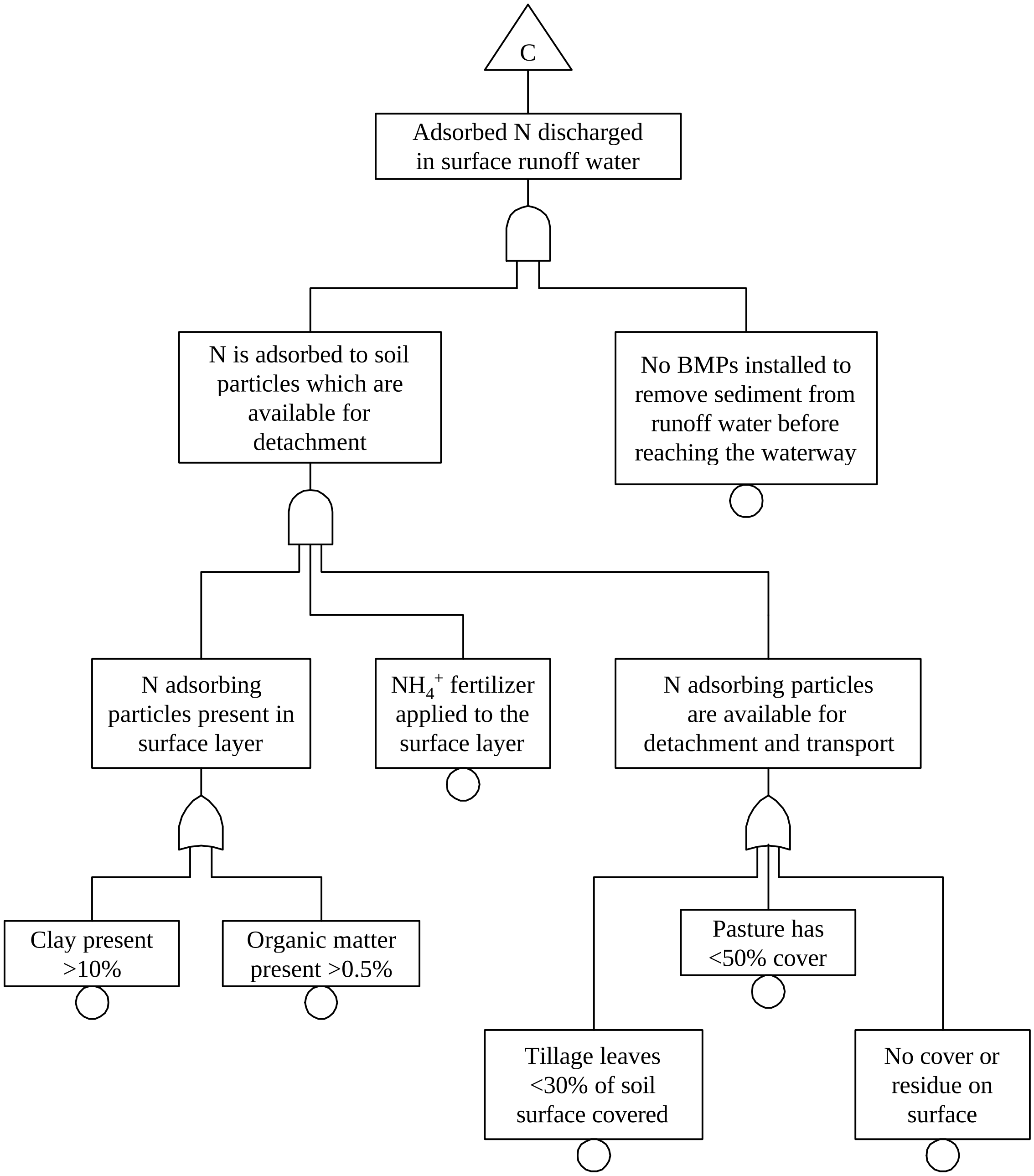


Figure 4.4: Fault tree for the discharge of nitrogen to Owl Run during a runoff event (continued)

Table 4.12: Probability of nitrogen discharge to Owl Run during a runoff event

	Soluble N	+	Adsorbed N	=	P(discharge)
QOD					
1987	0.57	+	0.19	=	0.76
1993	0.53	+	0.03	=	0.56
QOA					
1987	0.52	+	0.13	=	0.65
1993	0.46	+	0.04	=	0.50

For example, assume that the farmers in the watershed have decided to maintain cover on all land during the winter months. This action would make the probability for the event no winter cover crop established equal to zero for both watersheds rather than 0.28 for QOD and 0.36 for QOA. Using Equation 6 and the other probabilities calculated for 1993, the probability of discharge for QOD would be reduced from 0.55 to 0.48. Using the same methodology for QOA, the probability is reduced from 0.49 to 0.45. The beneficial effect of installing cover crop BMPs within the watershed is reflected in the probability of nitrogen discharge.

One practice which could be improved within the watershed is the incorporation of fertilizer or manure. As stated previously, 85 percent of all fertilizer is surface applied with no incorporation in the watershed. If this percentage were reduced to 50 percent, the probability for event I could be reduced to 0.50. Consequently, the probability of nitrogen discharge to Owl Run in 1993 would be reduced to 0.43 for QOD and 0.39 for QOA. These new values represent a 0.13 and 0.11 decrease in the overall probabilities for QOD and QOA, respectively. Again, the beneficial nature of incorporating fertilizer is readily illustrated by the fault tree through a substantial decrease in the probability of nitrogen discharge. The ability to clearly show the effects of practice changes increases the usefulness of this technique.

4.10 Analysis of the Quantitative Application of the Fault Tree Technique

The quantitative application of the fault tree technique to nitrogen discharge was a data, time, and thought intensive process. In short, the amount of data required to perform a PRA, using the methodology of this research, limits its use to all but the most intensively monitored situations. However, because extensive data were available for this watershed, the final results were much as expected. The fault tree calculations adequately reflected the activities within the watershed. Changes in cultural practices were illustrated by a subsequent increase or decrease in the overall probability of nitrogen discharge to Owl Run. Therefore, where there has been extensive monitoring and recordkeeping, the quantitative application of the fault tree would appear to be a useful technique for comparing management options. The following paragraphs discuss some of the factors limiting the applicability of this methodology to less rigorously monitored regions.

Large amounts of site-specific land use data were used in developing the probabilties necessary for this analysis, as well as comparable fertilizer records. Sources for these data types would be available for most areas for which a fault tree analysis might be desired. However, the accuracy and completeness of the data must be sufficient for the analysis to have meaning. Historical rainfall data were also used. An original analysis of the weather data, as was performed here, is very time intensive. If the type of data consolidation outlined in this research were necessary for every new fault tree analysis, the usefulness of this technique would be limited strictly to research.

The last data type used was site-specific rainfall-runoff records. These data were used only once to determine the probability that a runoff event occurs within seven days of a fertilizer application. An alternative method for calculating this probability would be to use long-term weather records in conjunction with the rainfall depth necessary to produce runoff. This value could be derived from long-term runoff monitoring or land use and soil information. Analysis of the weather data would have to be performed every time the rainfall depth was changed (e.g., for different watersheds) or each time practices within the watershed changed significantly. These methods of probability determination limit the usefulness of this technique, because long-term runoff records are not commonly available for watersheds or farms. In addition, the repeated analysis of the weather data would be impractical and time consuming.

Several of the events were difficult to quantify for varying reasons. The event that runoff occurs within seven days of a fertilizer application was one such event. As discussed above, there was no good way to calculate the probability of this event because of the specific nature of the data needed to do so. The method selected was the most accurate method given that the site-specific data on runoff were available. However, this method would be impossible for other watersheds unless they were monitored.

The runoff and erosion events were also hard to quantify because there were multiple techniques from which to select. As has already been discussed, there exist generally accepted methods for quantifying the erosion and runoff events. A choice had to be made as to whether to utilize these conventional methods or to use the fault tree structure to break the events down further. It was decided that the level of detail necessary to break down the erosion and runoff events was excessive when compared to the rest of the fault tree. The erosion and runoff events were eventually eliminated from the tree, however, the initial choice of which method to use was difficult. Once the conventional methods had been selected over fault tree methodology, the decision of how to use the conventional methods to calculate a probability was also a difficult one.

It may be argued that events involving the implementation of BMPs were approached too simplistically because only the presence or absence of the BMP was considered. No allowance was made for how well a BMP performs its task (i.e., whether or not it is operating properly). That no such allowance was made can be traced back to the very nature of the fault tree itself. The events on a fault tree are binary events: they either happen or do not happen. Therefore, the only probability that could be evaluated for BMPs was their presence or absence. It might be possible to show the gray areas of BMP operation using the fault tree, but the number of events would increase dramatically, as would the detail of the events and the amount of data necessary to calculate the probabilities.

4.11 The Risk of Nitrogen Discharge to Owl Run During a Runoff Event: an example

This section presents one example of how the results of a fault tree analysis might be used to develop values for risk. The risk examined here is the average amount of nitrogen that the stream is exposed to through the actions of producers in the Owl Run watershed each time a runoff event occurs. Recall from the literature review that risk is the product of the frequency of occurrence for an event and the consequences of that event. In this example, the frequency of interest is the probability for nitrogen discharge during a runoff event (Table 4.12). The consequence is the average nitrogen release during a storm event for the year in question. The average consequence was determined by multiplying the average concentration of nitrogen release during a storm by the average volume of a runoff event (Mostaghimi et al., 1989; AGEN, 1993). The results of the risk calculations are displayed in Table 4.13.

Table 4.13: Risk of nitrogen release to Owl Run

	Frequency[1]	*	**Consequence**[2]			=	**Risk**
	P(discharge)	*	(mg/L)	*	($L*10^6$/ roe)[3]	=	(Mg N/roe)[3]
QOD							
1987	0.76	*	8.56	*	32.10	=	0.21
1993	0.56	*	6.59	*	35.04	=	0.13
QOA							
1987	0.65	*	9.02	*	105.52	=	0.62
1993	0.50	*	4.80	*	127.79	=	0.31

[1] from Table 4.12
[2] calculated from Mostaghimi et al. (1989); AGEN (1993)
[3]roe = runoff event(s)

For the subwatershed, QOD, the cultural practices during 1987 posed a risk of 0.21 megagrams of nitrogen per runoff event to the stream. By 1993, the risk level had been reduced by 38 percent to 0.13 megagrams per runoff event through the implementation of various BMPs. Similarly, for the QOA watershed, the 1987 risk was calculated to be 0.62 megagrams of nitrogen per runoff event. This risk had been reduce by half in 1993 to 0.31 megagrams of nitrogen per runoff event. If these levels of discharge were deemed a threat to water quality, watershed managers could consult the fault tree to see which events contribute the most to the probability of discharge. By implementing BMPs in those areas, the probability of discharge can be lowered, thereby decreasing the risk of nitrogen discharge.

This example is only one possible method that might be used to develop a risk value for NPS pollution. Another method might be to express risk on an annual basis. Multiplying the risk values from Table 4.13 by an assumed 32 runoff events per year yields annual risk values. The calculations yield values of 6.72 and 4.16 megagrams of nitrogen per year in 1987 and 1993, respectively, for subwatershed QOD. The corresponding values for QOA are 19.84 and 9.92 megagrams of nitrogen per year. These calculations show that there have been many changes made in the Owl Run watershed which have contributed to a reduction in the amount of nitrogen released to the stream. As research continues on BMPs and the ecological impacts of NPS pollution, other methods of calculating risk will certainly be explored.

4.12 PRA vs. Modeling

In determining the applicability of PRA, and specifically fault tree analysis, to agricultural NPS pollution, the question of "How does this technique compare to computer modeling?" must be addressed. Proponents of NPS pollution models will point out that models can be used to approximate a concentration of nitrogen released during a runoff event. By running the model repeatedly for random climatic conditions, probabilities could also be obtained. Some models can even generate maps showing what areas or land uses pose a threat to water quality. It is not proposed that PRA should replace NPS pollution modeling. The two techniques have very different goals and could not substitute for each other. However, they might be used in a complimentary fashion.

Models tend to be very conceptual: requiring a basic understanding of the underlying principles and equations in the code for effective application. While model output is very specific (e.g., liters of runoff, milligrams of nitrate per liter of runoff) and easily interpreted, such output necessitates extensive data inputs. Fault trees, however, are very visual; they can be understood by laypersons with minimal instruction. The tree structure clearly shows which events contribute to nitrogen release problems within the watershed. In addition, the calculations involved in tree analysis are simple. While a quantitative tree analysis also requires substantial amounts of data, models are even more data intensive. It may also be possible to reduce the data requirement for fault tree analysis with further research. While output from tree analysis is much less specific than model output, both techniques yield numbers that can be used for comparing management options.

The visual nature of the fault tree gives it an advantage over modeling when working with laypersons. The simplicity of the tree structure makes it possible for them to be used in the qualitative sense as communication and education tools. The complexity of NPS pollution models limits them to the realms of research and analysis. Quantitative analysis of fault trees can also be applied to research and analysis objectives. However, as models are more familiar to researchers, and because models yield more specific results, models will probably remain the preferred method of quantitative analysis.

4.13 Overall Assessment

This research has shown that PRA can be effectively applied to the NPS pollution field. The qualitative development and analysis of fault trees was shown to be a useful tool for encouraging a detailed understanding of the system in question. In this respect, fault tree development might prove useful in an educational or training setting. In addition, due to the visual nature of the fault tree, it may also serve as a valuable communication tool in technical assistance field work. The fault tree developed for this research clearly displays the cause and effect relationships between farming practices and NPS pollution discharge. Therefore, the tree could be used in practice to educate producers on the effects of their actions.

The quantitative analysis of the fault tree was successful for the highly monitored situation utilized for this research. The most difficult aspect of the quantitative analysis was developing the methodology for calculating the basic probabilities. Once the methodology was established, however, the calculations involved were very basic. Additional research would help to standardize the methodology for risk assessment in the NPS pollution field and alleviate this problem. The most limiting factor for applying PRA quantitatively to NPS pollution is the data requirements. However, for situations in which the necessary data are available, or can be estimated, PRA can be a valuable management tool. Again, continued research in this area could result in better methodologies and a decreased need for specific data.

4.14 Summary

The qualitative assessment was accomplished with the presentation of an event tree for the occurrence of precipitation and a fault tree for the discharge of excessive nitrogen to the stream on any day. The event tree showed the basic hydrologic processes at work in a watershed, but its usefulness in a PRA for NPS pollution is extremely limited. The fault tree was effective in illustrating those farming practices which contribute to the loss of nitrogen from the watershed.

A quantitative assessment was achieved by assigning probabilities of occurrence to all of the basic events on the fault tree for the discharge of nitrogen to Owl Run on any day. The results of the quantitative analysis showed that the probability of direct deposition of nitrogen by cattle essentially controlled the overall probability of nitrogen discharge. The probabilities of nitrogen discharge from cropland sources and fertilizer applications were small in comparison to the cattle contributions. It was decided that such results might ultimately cause an underestimation of the risk posed by nitrogen discharge due to cropland practices.

In order to better represent the NPS pollution process, a second fault tree was developed for the discharge of nitrogen during a runoff event. This tree asssumed that rainfall, runoff, and erosion were occurring on the day for which the tree was evaluated. It also did not include the events related to nitrogen contributions due to animal defecation. The second tree was evaluated quantitatively using many of the probabilities developed for the first tree. Although the time and data required to determine these probabilities could be considered excessive for most applications or situations, the results of the calculations were ultimately responsive to changes within the watershed (i.e., BMPs).

An example was given for converting the probability of nitrogen discharge to Owl Run to a value for risk. Fault tree analysis was compared with NPS pollution modeling to determine the advantages and disadvantages of each. It was concluded that PRA could be effectively applied to NPS pollution.

Chapter 5: Conclusions

A Probabilistic Risk Assessment (PRA) was performed for agricultrual nonpoint source (NPS) pollution using nitrogen as a representative pollutant. A qualitative PRA was conducted through the development of an event tree and a fault tree. The event tree was initited with a precipitation event because rainfall is the driving force behind NPS pollution. The event tree illustrated the basic hydrologic processes occurring within the watershed. It showed that the ultimate fates of precipitation are uptake by plants, ground water recharge, runoff or interflow to surface water, or evaporation. The event tree can be useful in showing the logical sequences of events within the NPS pollution process. However, as developed here, the event tree cannot incorporate sufficient detail to be useful in a full risk assessment for NPS pollution.

A fault tree was developed for the discharge of excessive nitrogen to the stream on any day to complete the qualitative PRA. The fault tree clearly showed that the proper management of cover, nutrients, and livestock are essential to controlling the probability of nitrogen release to the stream. While this fact is nothing new to agriculturists, the fault tree presents the information in a new format. The visual nature of the fault tree clearly illustrates the cause and effect nature of events, plainly outlining which activities present a threat to water quality.

The author found that the process of developing the fault tree encouraged true understanding of the system being analyzed. For example, the author assisted in introducing fault tree methodology to a NPS pollution control course in an educational study not connected with this research. The students indicated in exit surveys that the exercise of developing a fault tree for NPS pollution discharge to a stream helped them to think through the NPS pollution process. The methodology forced the students to discover the root causes of NPS pollution and enhanced their understanding of ways to prevent pollution discharge. This aspect of the fault tree technique, in conjunction with its visual nature, suggests that the qualitative analysis of fault trees may be effective in an educational or training environment. They might also be useful in educating producers as to which activities contribute to water quality problems. If the technique were used in this fashion, some instruction on the meaning of logic gates would be necessary but should not be a limiting factor.

The quantitative PRA was accomplished by assigning probabilities to each basic or undeveloped event on the fault tree. From these probabilities, the probability that excessive nitrogen is discharged to Owl Run on any day was calculated using Boolean algebra. The process of assigning individual probabilities was data, time, and thought intensive. Some of the data types utilized in this research would not be commonly available for other watersheds. Also, some of the methods used for determining probabilities would be time limiting for nonresearch applications. Despite these limitations, most of the probabilities were developed from land use and fertilizer application information which is available in some form for most regions.

Some difficulties were encountered in the probability assignment phase. A straight percentage was clearly the method to use in most cases. However, in several cases no such percentage could be obtained and other, more complex techniques were employed. These techniques could limit the general usefulness of the fault tree methodology in nonresearch applications. In still other instances, the data necessary to accurately define a probability were not available. In such cases, a probability was estimated using the data that were available or an expert opinion was sought.

Basic limitations of the fault tree technique also limit its usefulness with respect to NPS pollution control. One such limitation is that degrees of events cannot be expressed. For example, a BMP is either present or not present on a fault tree. There can be no indication of how effective the BMP is in preventing NPS pollution unless the level of detail expressed in the tree is substantially expanded. Such an expansion can create additional problems. Another limitation is that the ultimate result of the fault tree calculations is a probability of occurrence. The interpretation of this value is not as easily accomplished as with the output of NPS pollution computer models, for example, where the output has specific meaning and units (e.g., milligrams of nitrogen per liter of runoff).

The results of the quantitative assessment were disappointing in that BMP implementation had very little effect on the overall probability of discharge. This realization prompted an alteration of the fault tree to assume the occurrence of a runoff event. The changes to the tree made the probability of discharge more responsive to changes within the watershed (i.e., BMP implementation). As runoff is the driving force behind NPS pollution, the new fault tree also represented the true concerns of NPS pollution control more accurately.

Although the quantitative analysis of the second tree clearly illustrated the effects of BMP installation, the time required to gather, organize, and clarify the data needed to complete the analysis is still considered excessive for general use. Much of the data used in this research had been gathered for other purposes. It would be unrealistic to expect that such data could be easily gathered for other small watersheds. A plausible alternative, however, would be to apply this methodology to individual farms using only the farmers' records and expert opinion regarding conditions on the farm. However, the necessity for doing so should be examined. Using a fault tree in its qualitative capacity should be sufficient to alert farmers and technical assistance personnel to areas of concern for NPS pollution discharge on the farm. As the meaning attached to the actual probabilities derived from the fault tree is subjective, the value in determining the probabilities explicitly is arguable.

The example presented in section 4.11 showed how this reserach might be used to determine a value of risk for nitrogen release. Specific monitoring data from Owl Run were used to estimate a value for the consequences of nitrogen discharge in runoff. This value was paired with the results of this research to calculate an approximation of the total amount of nitrogen released in megagrams per year. These numbers could then be used to determine if the present agricultural proactices are allowing too much nitrogen to enter the stream (i.e., the practices present a significant risk to water quality), and appropriate actions could be taken. At the present time, a method for determining consequences and risk in the absence of specific monitoring data is not known. Additional research in these areas is needed.

Therefore, it is concluded that PRA, especially fault tree analysis, may best be used as a visual communication tool. The fault tree method may also be useful in a teaching or extension setting for encouraging the understanding of the NPS pollution process and the appropriate preventative measures. Quantitative analysis of fault trees and calculations of risk will continue to be limited to highly monitored situations unless more research can be conducted that will provide data on the general effects of BMPs and the consequences (e.g., environmental and economic) of NPS pollution.

Chapter 6: Recommendations

The need for some type of assessment tool for NPS pollution was outlined in the literature review of this document. This need will only increase as the public becomes more concerned with the welfare of the environment. While fault tree analysis seems to be a suitable qualitative assessment tool, it is not a feasible method of quantifying risk from agricultural NPS pollution. Other methods of assessment (e.g., Delphi technique, risk indices) should be investigated to determine their suitability for use in the field of NPS pollution.

The qualitative fault tree shows promise as an educational tool. This aspect of its use should be investigated further, especially in a technical assistance or training situation.

The quantitative usefulness of the fault tree could be improved through an overall simplification of the quantitative techniques. At the present time, the amount of data necessary to complete an assessment limits the usefulness of this technique. Alternative methods of calculating probabilities should be sought to reduce the amount of data necessary to complete a quantitative fault tree assessment. It is also suggested that research into the economic and environmental effects of NPS pollution be continued. A more complete understanding of the consequences involved will be helpful to future NPS pollution risk research.

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Sharon Perkins Buck

Sharon Perkins Buck was born Sharon Renee Perkins on January 14, 1973 to Melford and June Perkins of Goochland County, Virginia. She was married to W. David Buck on July 30, 1994. Mrs. Buck received a Bachelor of Science in Agricultural Engineering from the Department of Biological Systems Engineering, Virginia Polytechnic Institute and State University (VPI&SU) in 1995. She immediately began working toward a Master of Science in Biological Systems Engineering at VPI&SU. She served as both a research and teaching assistant during her tenure there. Mrs. Buck has co-authored one paper: ASAE Paper 96-2029 *Applying Probabilistic Risk Assessment (PRA) to Agricultural Nonpoint Source Pollution*. The paper was presented at the 1996 Annual International Meeting of the ASAE -- the society for engineering in agricultural, food, and biological systems in Phoenix, Arizona on July 15, 1996. Mrs. Buck will pursue employment following completion of her Master of Science degree.