PROCEDURE TO QUANTIFY ENVIRONMENTAL RISK OF NUTRIENT LOADINGS TO SURFACE WATERS

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(ABSTRACT)

Agricultural production and human activities in a watershed can expose the watershed to environmental degradation, pollution problems, and a decrease in water quality if resources and activities within a watershed are not managed carefully. In order to best utilize limited resources and maximize the results with respect to time and money spent on nonpoint source (NPS) pollution control and prevention, the environmental risk must be identified so that areas with a higher quantified environmental risk can be targeted. The objectives of the research presented in this master thesis were to develop a procedure to quantify environmental risk of nutrient loadings to surface waters and to demonstrate the procedure on a watershed.

A procedure to quantify environmental risk of nutrient loadings to surface waters was developed. The risk is identified as the probability of occurrence of a nonpoint source (NPS) pollution event caused by a runoff event multiplied by the consequences to a biological or chemical endpoint. The procedure utilizes the NPS pollution model ANSWERS-2000 to generate upland pollutant loadings to receiving waters. The pollutant loading impact on stream water quality is estimated using the stream module of Hydrologic Simulation Program FORTRAN (HSPF). The risk is calculated as the product of probability of occurrence of a NPS event and consequences of that event.

The risk quantification procedure was applied to a watershed in Virginia. Total phosphorus (TP) loadings were evaluated with respect to resultant in-stream dissolved oxygen (DO) concentration. The TP loadings were estimated in ANSWERS-2000 then the consequences were estimated in HSPF. The results indicated that risk was higher for the smaller, more frequent storms indicating that these smaller, more frequent loading events represent a greater risk to the

in-stream water quality and ecosystem than larger events. While the probability of occurrence of lower TP loading was higher because they were caused by smaller, more frequent storms, the consequences were less for the same events.

The developed procedure can provide watershed stakeholders and managers with a useful tool to quantify the environmental risk a watershed is exposed to as a result of different land management and development scenarios. The scenarios can then be compared to identify a risk level that is considered acceptable. The procedure can also be used by policymakers to set a cap on the risk a certain activity can expose a watershed to.

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Tone.

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1.0 Introduction

Agricultural production and human activities in a watershed can expose the watershed to environmental degradation, pollution problems, and a decrease in water quality if resources and activities within a watershed are not managed carefully. The level of risk exposure in a watershed must be quantified by widely accepted and measurable parameters in order to properly manage the environmental risk in the watershed. If this is done successfully, it gives inhabitants of the watershed a tool to control environmental risk to the ecosystem caused by activities in the watershed. Guidelines and regulations can then be made based on acceptable risk levels in the watershed. In order to best utilize limited resources and maximize the results with respect to time and money spent on nonpoint source (NPS) pollution control and prevention, the environmental risk must be identified so that areas with a higher quantified environmental risk can be targeted. The impact of NPS pollution on the environment and the receiving ecosystem must be quantified in order to identify the risk NPS pollution imposes on the environment and the ecosystem.

In the 1970’s, the early days of environmental law enforcement, a zero-risk approach was often taken, with the objective of most regulatory policies and plans to eliminate all environmental degradation and pollution. By the early 1980’s it had become apparent that this zero-risk approach was impractical and far from being economically viable (Barnthouse et al., 1988). With this shift towards reducing risk to a socially and environmentally acceptable level, the need for risk analysis with respect to the environment and the ecosystem became apparent, which led to what today is known as environmental risk assessment, ecological risk assessment, and environmental impact assessment.

The concept of risk assessment is a well-known topic in fields like hazardous materials handling and construction. In calculating risk scenarios for industrial plants and hazardous materials, a worst-case scenario is often assumed to predict the most extreme risk (Paul, 1996). This method does not apply readily to NPS pollution risk assessment because NPS pollution is diffuse and intermittent in nature. In the case of NPS pollution, the continued risk the ecosystem is exposed to, in terms of the many small and medium rainfall events over a year, is of greater importance to the overall health of the waterbody than is the maximum risk that occurs with a 100-year storm.

Hence, it is more appropriate to deal with the issue of risk as a daily-endured risk by the receiving ecosystem, like the average daily risk to the ecosystem as a result of land management practices conducted in the watershed. If a relationship between pollutant loadings to surface waters and environmental risk can be established, it will be possible to quantify impacts of pollutant loadings in terms of economics or possibly other measures which will further aid in the process of choosing the best strategy for managing the watershed for all its inhabitants, human and nonhuman.

1.1 Research Objective

The overall objective of this research was to quantify the environmental risk a waterbody is exposed to as a result of pollutant loadings to surface water. The developed procedure is intended to aid in cost-effective environmental risk management for watersheds.

The specific objectives were to:

1. Develop a procedure to quantify the risk of pollutant loadings to surface waters considering both the probability of loading occurring and loading impact on receiving waters.
2. Apply the developed procedure to a watershed for a specific pollutant.

2.0 Literature Review

2.1 Introduction

As stated in the previous section, the overall objective of this research was to quantify the environmental risk of pollutant loadings to surface waters. The relevant information obtained from the literature review is presented in the following sections. The first section discusses definitions of risk with respect to environmental risk assessment and ecological risk assessment. The second section contains a discussion on various concepts in probability relevant to this research. In the third section, applications of environmental risk assessment to water quality and especially phosphorus are discussed. The application of the risk quantification procedure used in this case study involved the effects of phosphorus loadings on dissolved oxygen concentration in receiving waters, which are discussed in the last section of this literature review.

2.2 Risk and Risk Assessment

Risk is often defined as the uncertainty concerning an undesired event where uncertainty is expressed as the probability of occurrence of the event (ASTM, 1985). Risk assessment dates back to the beginning of the last century when economic risk was the focus. The link to environmental decision making is much newer. Henley and Kumamoto (1991) defined risk according to the following equation:

$$risk\left[\frac{consequence}{time}\right] = frequency\left[\frac{events}{unit\_time}\right] \times magnitude\left[\frac{consequence}{event}\right] \qquad [2.2.1]$$

Whyte and Burton (1980) defined environmental risk as the risk that arises in or is transmitted through the air, water, soil or biological food chains to humankind. From this definition it is clear that environmental risk includes a wide range of areas: public health, economic development, natural resources, introduction of new products and human induced or natural disasters (Whyte and Burton, 1980). The National Research Council defined environmental risk assessment as the characterization of the potential adverse health effects of human exposure to environmental hazards (NRC, 1983). Yet another definition was provided by Wilson and Crouch (1987). They considered environmental risk assessment the use of toxicological and ecological data to estimate the probability that some undesirable environmental event will occur. While the definition by the NRC deals strictly with human health, the Wilson and Crouch definition deals with any undesirable environmental event, which may or may not include human health.

Another closely related field is ecological risk assessment. The two fields are very similar and very often with similar definition. The USEPA (1988) defined ecological risk assessment as any assessment related to actual or potential ecological effects resulting from human activities. Hunsaker et al. (1989) defined regional ecological risk assessment to be concerned with describing and estimating risk to the environmental resources at the regional scale or risk resulting from regional-scale pollution and physical disturbance. A few years later, Suter (1993) defined ecological risk assessment as the process of assigning magnitudes and probabilities to the adverse effects of human activities or natural catastrophes. Suter added that ecological risk assessment is risk assessment for the nonhuman environment. In practice, ecological risk assessment has become the application of the science of ecotoxicology to public policy (Suter, 1993). Ecological risk assessment, though often very similar to environmental risk assessment as stated earlier, tends to focus on the health of the ecosystem and specific species in the ecosystem as a response to a pollutant or human activity, whereas environmental risk assessment often is more concerned with the chemical fate of the pollutants and the pollutant interactions with other chemicals present.

Environmental impact assessment is a term often used in relation to environmental and ecological risk assessment. Environmental impact assessment covers a much broader area; it deals with all aspects and activities involved in the tasks of analyzing and studying the effects of human activities and actions upon the environment (Suter et al., 1987). These effects are not per definition negative changes or implications. While dealing with environmental risk assessment and ecological risk assessment, it is assumed that outcomes of the undesired event are negative.

Risk assessment can be defined as the scientific task of assigning probabilities of adverse effects, while risk management is the task of evaluating the social implications of the risk (Moghissi, 1984). Ruckelshaus (1983) argued the importance of the use of risk analysis, which includes both risk assessment and management, but he distinguished between the two and argued that risk assessment is a scientific task, while risk management should be in the hands of decision and policy makers. Moghissi (1984) reinforced this view, as he argued that separating the two could result in risk assessment policies that are based on arbitrary decisions rather than scientific evidence. Risk assessment can seldom rely on complete information. It is often necessary to make decisions based on incomplete scientific information or based on known scientific basis but lack of necessary data to support the scientific basis. It is very important however that even with incomplete information or lack of necessary data that scientific basis be applied to ensure the best possible and credible outcome (Moghissi, 1984).

Based on this literature review, the following definition was adopted for this work. Environmental risk was defined as the probability of occurrence of an undesirable event (e.g. water pollution) multiplied by the consequence of that specific event (e.g. dissolved oxygen), following the general definition of risk proposed by Henley and Kumamoto (1991). This definition encompasses some of Whyte and Burton's (1980) definition concerning natural resources, while leaving out the human health aspect of environmental risk.

Furthermore, it is important to distinguish between the different components of risk. Natural risk is the risk endured without human interference, such as the risk to a species in the wild that naturally occurs due to the stochastic nature of the environment. Anthropogenic risk is the risk added by human activities and influence. The total risk is then equal to the natural and anthropogenic risks added together (Power et al., 1994). Law and Kelton (1991) argued that only models give the statistical and experimental control necessary to estimate both the natural and anthropogenic risks in a satisfactory way due to the complexity and variability of the system being modeled. The level of statistical and experimental control that Law and Kelton argued is not present in most physical experimental frameworks.

2.3 Probability Concepts

Estimating the probability of occurrence of an undesirable event is a key component of risk quantification. Barnett (1992) distinguished three different interpretations of probability; frequentist, logical and subjective. In a frequentist view, the only information that is regarded relevant for the probability assessment is obtained from observing the outcomes in repeated realizations of the fully described experimental process. Hence, probability of a specific outcome is defined as the total number of times the event occurred in the total number of times the trial was performed. The logical view expresses the rational or credible extent of belief that a person puts on the likely occurrence of an event by the available body of knowledge. The logical view has parallels to the better known 'weight of evidence' approach or the rational argument, which often is used by public interest groups in characterizing environmental risk. Critics of this view argue that it is not possible to obtain a numerical value of risk with this view and that there is a lack of common agreement that makes it hard to use. The third view, the subjective view, is concerned with individual behavior and preferences when confronted with different possible actions and how individuals reach the judgments. The subjective view can be used to quantify expert opinion and is applicable in certain risk quantification situations (e.g. yield risk for farmers). The subjective view is difficult to apply to environmental risk assessment since interpersonal comparison is very difficult.

2.4 Application of Environmental Risk Assessment with Respect to Water Quality

In the field of hydrologic modeling, uncertainty is divided into three types of uncertainty widely recognized and discussed by several authors (Haan, 1989, 1977; Hession et al., 1997; Parson et al., 1998). First is the stochastic nature of the natural environment, the inherent variability in natural processes. An example of characterizing stochastic uncertainty is the work done by Ünlü et al. (1990) in which a stochastic analysis of unsaturated flow was performed. The stochastic behavior of one-dimensional flow was assumed to be a function of soil hydraulic properties, saturated hydraulic conductivity, pore size distribution and specific water capacity. A Monte Carlo Simulation (MCS) approach was used to model the flow system. The second type of uncertainty deals with model uncertainty that arises because it is not possible to know for sure that a hydrologic process is completely or correctly represented in a model. Model uncertainty will greatly influence the confidence in the output from model simulations. Summers et al. (1993) discussed a MCS and a first order error propagation method to quantify prediction uncertainties in water quality models. Chaves and Nearing (1991) applied a modified response surface technique combined with a modified point estimate method to predict uncertainty in the WEPP (Water Erosion Prediction Project) model.

The third type of uncertainty is uncertainty in input parameters to models. Parameter uncertainty represents incomplete information and misrepresentation and misestimation of parameters in a model. Parameter uncertainty increases as the complexity of a model increases, that is, increased knowledge about the processes being modeled leads to a greater number of parameters to estimate, which leads to increased uncertainty about the system. Rowe (1977) used the term "information paradox" to describe this situation. Kuczera and Parent (1998) used a MCS to assess the parameter uncertainty in conceptual catchment models. Hession et al. (1997) considered both the stochastic variability in nature and a combined parameter and model uncertainty into what was termed knowledge uncertainty.

Risk assessment when hydrologic models or other models are involved should ideally consider all three types of uncertainty but this is very often not possible due to the resulting overall complexity of the problem. In this research, the risk assessment was limited to the inherent variability of natural processes, the stochastic uncertainty in the represented system.

In the early 1990's, Orvos and Cairns (1991) examined a risk assessment strategy for the Chesapeake Bay that served as an initial strategy for risk assessment and management in the Chesapeake Bay. The authors argued that for a region as large as the Chesapeake Bay risk assessment and management cannot be carried out in the fragmented fashion that is often done on a more local scale. Orvos and Cairns (1991) stressed that selection of both biological and social endpoints is crucial to the strategy. The biological endpoints must be measurable quantities such as pesticide concentration in surface waters, pollutant concentration, or certain species present in a certain number. The social endpoints must be well defined by the stakeholders in the watershed or region in terms of use and aesthetic value.

Environmental risk assessment is often done based on observed data of a study site where an evaluation of the current state of contamination is necessary. Andersen et al. (1998) studied surface water and sediment in the Copenhagen harbor in Denmark, at the site of a former naval base. They used a simple hydraulic model to assess the release of substances from the sediment to the surface water. In this situation, observed data existed for the current contaminant level of the sediment. Then the potential for the substances accumulated in the sediments to reenter surface waters was assessed. The risk of surface water and sediment contamination was determined based on field data that indicated strongly polluted sediment and sediment porewater in the majority of the study area. Based on this majority finding, the risk of contamination was found to be high. This type of study can be seen as based on a logical probabilistic view, where the weight-of-evidence approach is most predominant.

If quantification is the goal of the environmental risk assessment, the frequentist view is undoubtedly the most appropriate, and combined with a modeling approach it is a promising approach to quantification of environmental risk (Power et al., 1994). One example of a frequentist view applied to a model context is the work of Paul (1996). The author used MCS and fuzzy approaches to perform an environmental risk assessment of nitrogen (N)-leaching from pasture fields in Germany. A MCS approach basically involves a sampling scheme from an input distribution to form an output distribution through a series of runs, very often involving long run times. The fuzzy approach simulates the output function by reducing the exponential complexity of the unknown parameters to a linear system. In this case a vertex method of the fuzzy approach was chosen, which involves selecting a number of sections along the input parameter probability distribution. The total number of computer runs required for this method equals 2*m*n, where n represents the number of uncertain parameters and m equals the number of sections on the membership function. The major difficulty with this method is that it will not necessarily produce a monotonic output, which could make the evaluation process much more difficult than a MCS approach. Paul (1996) found that with both the MCS and the fuzzy approaches the simulations could be significantly improved from the initial trial when additional knowledge and assumed correlations were added to the systems.

Decision-making risk, i.e, risk of making a wrong decision with respect to environmental risk, is another way to approach the concept of environmental risk in terms of modeling and a frequentist probabilistic view. Parson et al. (1998) used the Agricultural Nonpoint Source Pollution Model (AGNPS) to predict the risk to a watershed in south central Michigan with a MCS and a nonparametric resampling technique. The decision risk was defined as the area of overlap between the output distributions of the scenarios being studied. Decision risk relates to environmental risk assessment because by a similar modeling approach the output becomes a probabilistic distribution by the frequentist view. This output distribution can be used both to characterize the decision risk of different options, and to indicate the range of the environmental risk endured by the ecosystem due to different scenarios.

2.5 Phosphorus Loadings Implications on Water Quality

In the application of the risk quantification procedure the focus of the case study was the risk of dissolved oxygen (DO) dropping below a set standard as a result of phosphorus (P) loadings. A search of the literature was conducted for implications of P on in-stream DO concentrations and effects on aquatic ecosystem health.

During the 1970's and beginning of the 1980's, the Organization for Economic Cooperation and Development (OECD) conducted a major study, the OECD Cooperative Program on Eutrophication, in which 18 countries and more than 50 research centers conducted eutrophication studies in over 100 lakes (Vollenweider and Kerekes, 1980). In order to account for geographical variability as well as logistic considerations, the project had four main divisions; Alpine Project, Northern Project, Reservoir and Shallow Lake Project and a lump project for North America. The results of the program showed that P loading into the waterbody represents a key parameter with respect to eutrophication. It was estimated that the uncertainty of the reported annual loading rates was ±25 %. Data from all four project regions were used to link the annual loading rates to classically defined trophic states of water bodies. Based upon these results, the geometric mean for eutrophic lakes was 84.4 mg/m^3 total P. The mean plus and minus one standard deviation was found to be 48 to 189 mg/m^3, while the mesotrophic state showed 7.9 to 90.8 mg/m^3 total P. This indicates a large overlap between the two distributions. A clearer cut was found when the trophic state was decided based upon chlorophyll α content instead of total P. It was concluded that a fixed boundary system between different trophic states was not possible (Vollenweider and Kerekes, 1980).

The work done by Vollenweider and Kerekes in conjunction with the OECD Cooperative Program on Eutrophication was later applied to risk quantification by several authors. Matlock et al. (1994) used an ecological risk assessment paradigm integrated with the SIMPLE (Spatially Integrated Model for Phosphorus Loading and Erosion) model to assess the relationship between NPS P loadings and the trophic state of the receiving aquatic ecosystem. The authors used a 0.5 kg/ha/yr threshold level of total P loading, derived from total P concentrations characteristic of an unimpacted stream converted to threshold loadings based on stream flow. The authors chose an effects-driven retrospective ecological risk assessment paradigm as the method of risk assessment. This method involves the four major steps of hazard definition, hazard measurements and estimation, risk characterization and finally risk management (Suter, 1993). Hazard definition involved a formal statement of the problem and the specific objectives of the study. Then in the hazard measurement and estimation process, the threshold total P level was determined, the P sources in the watershed were identified and quantified, and then the total P loadings to the aquatic system were modeled using SIMPLE. Risk characterization was done by analyzing the exceedance probability. Matlock et al. (1994) did not discuss the final component, risk management. It was found that for this aquatic ecosystem with a threshold of 0.5 kg/ha/yr the current watershed management posed an exceedance probability of total P of approximately 11%, that is one in every nine years the total annual P loading will exceed the threshold of 0.5 kg/ha/yr. This critical loading rate was found from the Vollenweider and Kerekes (1980) method outlined in an OECD report.

Hession et al. (1996) used a watershed-level ecological risk assessment methodology to assess the ecological risk of lentic (lake) ecosystems in response to excess P loadings resulting in eutrophication. A modified EUTROMOD model was used to assess the ecological risk of Wister Lake, Oklahoma. Again the effects-driven retrospective ecological risk assessment paradigm (Suter, 1993) was employed with the trophic state of the lake ecosystem as the assessment endpoint and chlorophyll α as the measured endpoint. EUTROMOD (Reckhow et al., 1992) is a tool for guidance and managing eutrophication in lakes and reservoirs. Hession et al. modified EUTROMOD to include a two-phase MCS procedure so that stochastic variability could be nested with knowledge uncertainty of the system. The result of the model runs was a set of Complementary Cumulative Distribution Functions (CCDF) where the variation in the CCDF's showed the stochastic uncertainty of the system and the distribution of the CCDF's represented the knowledge uncertainty of the system. Two hundred simulations of the two-phase MCS method were performed, with 50 iterations in each simulation, to account for stochastic variability. When the model was applied to the Wister Lake watershed in Oklahoma, the model predicted P loading as the main source of NPS pollution and the main cause of eutrophication of the lake. This was expressed in the presence of chlorophyll α, which was the measured endpoint in the assessment. This is one way to express the resulting risk of P loading to the lake; it could also have been measured in loading rate of P or prescreens of phytoplankton. The assessment endpoint was linked to the measured endpoint using an open and a fixed boundary system approach. The fixed system assumes a fixed boundary between two trophic states, such as 10 μg/L as used in this study, as the breakpoint between mesotrophic and eutrophic systems. The open system presents each trophic state as a probability distribution, hence accounting for the uncertainty in the system. The authors argued for the open system as it preserves the analysis of uncertainty through the whole risk assessment from start to finish, though this open system involves a more subjective boundary between the trophic states. Currently the USEPA uses a fixed boundary system to assess the trophic state of a lake ecosystem based on a National Eutrophication Survey (Hession et al., 1996).

Phosphorus was chosen as the nutrient to use to demonstrate the developed procedure. Phosphorus is a mineral nutrient that is an essential element for all life forms (Correll, 1999). In natural fresh water systems, P is often the limiting nutrient that controls productivity. Increased total P loadings hence result in increased production in the system. The increase in primary production requires more DO consumption, which again results in a reduced DO concentration in the waterbody. This represents a threat to fish populations in the system, at different DO levels depending on the species. In addition, increased production in the waterbody can also result in increased algae blooms that again results in DO depletion, light depletion, loss of submerged aquatic vegetation and possible loss of benthic community (Novotny and Olem, 1994). A loss of benthic community poses a threat to the fish population in the waterbody that feeds on the benthic community. Other possible problems related to eutrophication and increased waterbody production are decreased ecosystem health and biodiversity index. Conceptually as the P-input to a system increases so does the primary productivity while DO and biodiversity decrease gradually to form an oligotrophic to eutrophic system (Correll, 1998).

There are many studies that support P being a limiting nutrient in lakes (Vollenweider and Kerekes, 1980; Evans et al., 1996; Schindler, 1977). In the oceans N is the primary limiting nutrient and estuaries function as a transition zone (Correll, 1998). Other fresh waterbodies such as streams, rivers and reservoirs are not as clearly understood with respect to nutrient limitation. Being fresh water it might be concluded they would behave somewhat like lakes. Streams and rivers have a much shorter residence time of the water and more movement so unless the waterbody is heavily enriched by nutrients, anaerobic conditions will not occur in lakes (Correll, 1998). Newbold et al. (1981) found that bacteria and algae (periphyton) and some vascular plants take up P from the water and some P becomes attached to the bottom sediment. From there it is slowly released back into the water column and transported further downstream before being attached again. This cycle was named “spiraling” of P.

Vollenweider (1980) developed a simple loading model for P loadings to lakes that related algae biomass to total P input, mean water depth and outflow rate per unit lake surface area. A similar model does not exist for streams though work has been done to relate the work done by Vollenweider to apply for streams, like the work done by Hession et al. (1996) described earlier. Smith et al. (1987) conducted a study on water quality in US rivers. From this study it was found that from 1974 to 1981 the average total P concentration was 0.13 mg P/L based on approximately 380 sampling points from two nationwide monitoring networks. As a comparison 0.1 mg P/L is an unacceptably high value and concentrations as low as 0.02 mg P/L can cause water quality problems (Correll, 1998).

Evans et al. (1996) developed a case study from Lake Simcoe in Canada linking human landuse activities, total P loadings, hypolimnetic DO depletion and consequently the loss of cold water fish habitat. From this study it was found that the density of phytoplankton declined as the total P input into the lake declined. This is consistent with what Schindler (1977) documented two decades earlier, that phytoplankton is P limited in most lakes. In Lake Simcoe, natural trout, whitefish and lake herring declined through the 1960’s, 1970’s and 1980’s and in the 1990’s the fish populations were entirely supported by human restocking. During the monitoring period, it was found that the DO in the hypolimnion declined to an average of 2 mg/L at the end of every summer. This suggested that P was being released back into the water from anoxic sediments. Two separate attempts to model the observed system were also performed; one a mechanistic model with Monte Carlo simulations and the second an empirical model using a regression model developed by Vollenweider and Janus (1982). Both modeling attempts produced very similar results for DO concentrations at the end of summer over a wide range of total P loading of 50 to 150 tonne/year. The models were also used to extrapolate back in time prior to human activities in the watershed to give a DO concentration of about 8 mg/L and present day concentrations of 2 to 3 mg/L.

In addition to the biological effects of elevated P concentrations are the economic effects of degraded water quality. The economic effects include cost of restoring water quality and loss of recreational use of the water unless it is restored.

2.6 Summary of Literature Review

Based upon the literature review the following definition of environmental risk was adopted for this thesis; probability of occurrence of undesirable event multiplied by the consequences of that specific event. With the objective of this research involving quantification, a frequentist view of probability was adopted. Previous work done with respect to P loadings and water quality impact over the past three decades has demonstrated that P can be assumed to be a limiting nutrient in a fresh water system. Less research is available on P loadings to streams and rivers than lakes and reservoirs, which makes it more difficult to find the ranges of total phosphorus (TP) to investigate.

Searching the literature revealed that extensive amounts of research have been conducted on the exceedance probability of a pollutant loading event, i.e. Matlock et al. (1994). However, no literature was found directly linking the exceedance probability with a biological endpoint consequence. In this thesis estimated exceedance probability of a NPS loading event is linked to in-stream water quality consequences to determine watershed risk.

3.0 Development of Risk Quantification Procedure

3.1 Introduction

The first step in development of the risk quantification procedure was to develop a conceptual framework. The second step was to implement the conceptual framework. Three criteria were established for the procedure. First, the pollutant loadings as a result of NPS pollution must be estimated. Second, the effects of pollutant loadings entering a water system needed to be modeled to account for in-stream transformations and transport of pollutant loadings. Third, the measured endpoint used to quantify the consequences of the pollutant loading must be a meaningful measure of the risk the watershed is exposed to. Implementation of the conceptual framework included model selection, weather data preparation and risk quantification. Details of the conceptual framework and implementation of the risk quantification procedure are provided in this chapter.

3.2 Conceptual Procedure Development

As previously stated, risk has most often been defined as the probability of an event occurring, with the assumption that this event has negative impact. In this research, the focus was on quantifying this assumed negative impact, if any, and then quantifying risk as:

$$Risk = frequency\left[\frac{\#events}{unit\_time}\right] \times consequence\left[\frac{amount}{event}\right] \qquad [3.2.1]$$

To accomplish this, a method to estimate the probability of occurrence of a pollutant loading event and a method to estimate the consequences of that loading event had to be developed. The stochastic nature of weather determines the frequency and volume of a runoff event as a function of watershed characteristics. The probability of a NPS pollution event occurring is related to the probability of a runoff event occurring. It is possible for a runoff event to occur without NPS loadings but not vice versa. Hence, to calculate the probability of a NPS pollution event occurring a runoff event must have occurred. For a continuous NPS model, weather can be represented as an 'average' year or the weather data can be entered for a longer period of time with the stochastic characteristics included. Between these two approaches, the latter one was selected because the stochastic uncertainty of weather influences the probability of occurrence of NPS pollutant loadings. The length of record needed to represent the stochastic uncertainty is discussed later in the weather data section.

The in-stream impact of NPS pollution on water quality and ecosystem health must be considered in detail to account for consumption and transformations of constituents that occur in a stream system. Modeling of the stream must be done with the same weather data set used to estimate the NPS loadings from land areas.

To quantify the consequences it must first be determined how the pollutant loadings are linked to the possible consequences, e.g., if phosphorus (P) is the pollutant loading considered it must be determined how P loadings are linked to degrading in-stream water quality or reduction in fish populations. The measured endpoint used to quantify the consequences of the pollutant loading must be a meaningful measure of the risk the watershed is exposed to. The definition of meaningful measure will depend on the specific endpoints selected, but must be in units that will tell the user something about the pollutant loading effects on the endpoints. In the case of a chemical water quality endpoint, this will be a measure of impact on the endpoint. For a biologically defined endpoint, it will be a measure of the threat the pollutant loading exposes the endpoint to.

The conceptual development provided a framework for implementation. The steps in the implementation were guided by the criteria and concepts of the conceptual framework.

3.3 Procedure Implementation

3.3.1 Introduction

The risk quantification procedure includes several steps. First, distributions of loadings of NPS pollutants are generated using a NPS simulation model. Second, an in-stream water quality model generates distributions of water quality parameters based on the input NPS pollutant loadings. The distributions of water quality parameters are then related to a selected environmental endpoint such as dissolved oxygen (DO), benthic community health or fish mortality. The final output is the risk imposed on the environmental endpoint by NPS loadings from a particular land area. Each component of the procedure is described in detail in the following sections.

The conceptual framework did not require that two different models be used for NPS pollutant modeling and in-stream modeling. One model that could simulate both phases, NPS pollutant loading and in-stream water quality, and was readily available to potential users would have been preferred. In the domain of readily available models, however, such a model could not be found. A privately owned model like Mike-SHE (Wicks et al., 1992) could possibly satisfy the model criteria but would not be readily available to many potential users of the procedure.

3.3.2 Upland NPS Model Selection

Three criteria were important in selecting the model to estimate the NPS loadings to the stream. First, the model should be physically-based with distributed parameters to capture the spatial variability in the watershed that influences pollutant loadings to the stream. Second, a continuous model was required for long-term simulations to generate an adequate sample size for distribution fitting. Third, it was desirable that the model either directly or through supporting software be able to use ArcView or other geographical information system (GIS) software to create the spatially distributed input.

Considering the stated criteria, ANSWERS-2000 (Bouraoui, 1994) was selected to predict NPS loadings to a stream. ANSWERS-2000 is a distributed parameter, continuous, watershed-scale NPS model that simulates runoff, sediment yield, and nutrient (N and P) loadings as functions of soil, landuse, and topographic conditions. The land area of interest is discretized by overlaying a grid of square cells on the area. Each cell is considered to be homogenous, but adjacent cells can vary in terms of characteristics such as soil type, landuse, and slope. ANSWERS-2000 calculates hydraulic response for each cell by an explicit backward difference solution to the continuity equation combined with Manning's equation, which is used for the stage-discharge relationship. The nutrient loss is then a function of the hydraulic response for each cell. ANSWERS-2000 has a critical shear rill detachment model and also considers interrill erosion and channel scouring (Byne, 2000). ANSWERS-2000 has also been integrated with ArcView through a user interface called QUESTIONS (Veith et al., in preparation), which facilitates manipulation of input and output for viewing and editing in ArcView.

Other possible models included AnnAGNPS (http://www.sedlab.olemiss.edu/AGNPS98.html), SWAT (Arnold et al., 1993), HSPF (Bicknell et al., 1993) and WEPP (http://topsoil.nserl.purdue.edu/nserlweb/weppmain/wepp.html). WEPP only models hydrology and erosion, which made it not a suitable model. AnnAGNPS has a rasterized input format but uses the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991) to predict annual sediment loadings, compared to the critical shear erosion model in ANSWERS-2000. RUSLE is useful in predicting average annual soil loss but lacks the ability to accurately model seasonal variation and variable weather effects on erosion. The critical shear model is process-based while RUSLE is an empirical equation. Process-based erosion simulation better fits the criterion of a physically-based model. SWAT and WEPP do not have the same distributed parameter capabilities as ANSWERS-2000, which was considered to be an important feature. HSPF divides a watershed into pervious and impervious segments and stream reaches. The total number of pervious and impervious segments and stream reaches can not exceed 200. This limitation makes the model less distributed as the area being modeled increases. Comparing HSPF to the grid approach in ANSWERS-2000, the latter was considered a better suited model that allowed for a more detailed NPS pollution estimation.

3.3.3 Stream Model Selection

In choosing the stream quality model, the following criteria were applied. The model had to be able to model water temperature, DO, nutrients and sediment, and run continuously for 50 years. In addition, hydrographs and pollutographs output from ANSWERS-2000 had to be loaded into the stream model as input to the stream. In table 3.3.3.1 are the models that were considered and compared. WASP5 from EPA was not available for download when the model selection was done, hence it could not be evaluated in detail.

From Table 3.3.3.1, QUAL2E, HSPF and the MIKE models were the only ones that met all requirements. The MIKE models were ruled out due to the cost of obtaining the models compared to QUAL2E and HSPF being free of cost. In addition, DHI Water and Environment owns the MIKE models and must approve their use. QUAL2E first appeared to be more appropriate than HSPF because QUAL2E has a more detailed water chemistry routine and is a stream only model. QUAL2E applies a finite-difference solution to the advective-dispersive mass transport and reaction equations and simulates up to 15 water quality constituents in a channel network. Differential equations are applied to calculate P and DO concentrations in the stream network. Because QUAL2E has what is termed a “dynamic” mode, it was thought that hydrographs could be input to the model. Further investigation showed that QUAL2E is a constant flow model with a dynamic weather component. Therefore, hydrographs from ANSWERS-2000 could not be input into the stream via QUAL2E. In addition, the maximum length of simulation for QUAL2E was less than 900 hours, not long enough to generate the required sample size. HSPF can accept variable inflow of both hydrographs and pollutographs and infinite simulation length. Though its methods are less detailed than QUAL2E, HSPF can model a wide variety of water quality constituents, sediment and nutrients, including DO and P balances and concentrations. Thus, HSPF met all criteria for the stream model.

Table 3.3.3.1 Stream model comparison matrix adapted from USGS website (USGS, 2000)

Stream Model	Type	System	Domains	Model DO/Temp	Input flow *	Model N/P	Availability++	Cost***
RMA10	3D	Win/Unix	rivers, lakes, estuaries, reservoirs, costal areas	Temp only	?	No	USACE	Free
WASP5	1,2,3D	DOS	rivers, lakes, estuaries, reservoirs, costal areas	Yes	DYNHYD5	Yes	USEPA	Free
CE-QUAL-RIV1	1D	DOS	rivers, channel networks	Yes	No	Yes	USACE	Free
CE-QUAL-W2	2D	Unix	rivers, reservoirs, estuaries	Yes	No	Yes	USACE	Free
EFDC/HEM3D	1,2,3D	DOS	rivers, lakes, estuaries, reservoirs, costal areas	Yes	No	Yes	VIMS	N/A
HSPF	watershed	DOS	watersheds, channel networks	Yes	V	Yes	USGS	Free
MIKE 11	1D	Win	estuaries, rivers, costal areas	Yes	?	Yes	DHI	$$
MIKE 3	3D	Win	rivers, lakes, estuaries, resevoirs, costal areas	Yes	?	Yes	DHI	$$
MIKE 21	2D	Win	estuaries, costal areas	Yes	?	Yes	DHI	$$
MIKE-SHE	watershed	Win	watersheds, channel networks	Yes	?	Yes	DHI	$$
PRMS	watershed	Unix	watersheds, channel networks	No	?	No	USGS	Free
QUAL2E	1D	Win	rivers, channel networks	Yes	C	Yes	USEPA	Free
SNTEMP	1D	DOS	rivers, channel networks	Temp only	No	No	USGS	Free
SSTEMP	1D	Win	rivers, channel networks	Temp only	No	No	USGS	Free

* V = variable flow, C = constant flow,

** DYNHYD5 dynamic flow model in conjunction to compute flows

*** N/A = not currently available

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USACE = United States Army Corps of Engineers

USEPA = United States Environmental Protection Agency

VIMS = "Virginia Institute of Marine Science at the College of William and Mary

DHI = DHI Water and Environment (formely Danish Hydrologic Institute)

USGS = Unites States Geological Survey

Hydrological Simulation Program FORTRAN (HSPF) is a mathematical model developed in the late 1970's and early 1980's (Singh, 1995) to simulate hydrologic and water quality processes in natural and constructed water systems. It is a somewhat distributed watershed model that simulates precipitation and snowmelt movement through the watershed by modeling overland flow, interflow, and baseflow. Kinematic routing of one-dimensional flow, in the direction of flow, is also included. Receiving channel networks are assumed to be well-mixed systems. The time scale of the model can be user-defined to handle a single event or long-term modeling over a period of 50 to 100 years.

Only the channel network part of HSPF, the module called RCHRES, was used since the overland flow modeling was done in ANSWERS-2000. The RCHRES module simulates water quality processes and flows in a single reach of an open or closed channel or a completely mixed reservoir. The different reaches are joined with a network module. The flow in each reach is unidirectional with a single inlet but possible multiple outlets. Sediment detachment, transport and scouring can be considered in the model, but assumed not to affect the hydraulic properties of the channel. The oxygen subroutine considers longitudinal advection of DO and biochemical oxygen demand (BOD), benthal oxygen demand and release of BOD materials, sinking of BOD material, reaeration and oxygen depletion caused by decay of BOD material. The subroutine has three options for calculating the oxygen reaeration coefficient in the stream. The nutrient subroutine simulates the basic processes that determine the balance of N and P in a water system, and if the plankton subroutine is active, it also accounts for N and P consumed by plankton populations.

3.3.4 Weather Data Preparation

ANSWERS-2000 can use generated or measured weather data. For the risk quantification procedure, statistical weather data generated with CLIGEN was chosen. CLIGEN is a statistical weather data generator originally written for EPIC and later modified for WEPP (Nicks et al., 1995). CLIGEN uses a two-state Markov chain for generating number and distribution of precipitation events. The Markov chain calculates two conditional probabilities, i.e., α, the probability of a wet day given the previous day was dry, and β, the probability of a dry day following a wet day (Nicks et al., 1995):

$$P\ (W \mid D) = \boldsymbol{a} \quad [3.3.4.1]$$

$$P\ (D \mid D) = 1\text{-}\boldsymbol{a} \quad [3.3.4.2]$$

$$P\ (D \mid W) = \boldsymbol{b} \quad [3.3.4.3]$$

$$P\ (W \mid W) = 1\text{-}\boldsymbol{b} \quad [3.3.4.4]$$

Where: P(W|D) = probability of a wet day given a dry day;
P(D|D) = probability of a dry day given a dry day;
P(D|W) = probability of a dry day given a wet day; and
P(W|W) = probability of a wet day given a wet day.

Then CLIGEN uses a skewed normal distribution to estimate the daily precipitation amounts for each month. Based on the Markov chain conditional probabilities and the distribution of daily precipitation amount, the total rainfall for each day is computed.

Using a statistical weather generator has advantages in that any desired length of run can be done without having to consider available historic records. It is also possible to generate as many weather data files as desired for the same period of time with different rainfall. In the developed procedure, stochastic variability in weather was the main factor in risk quantification, hence the length of simulation was very important. A length of record long enough to capture the stochastic variability of weather was considered important to ensure a accurate representation of the stochastic uncertainty. In addition the sequence of the weather record was important, since this could greatly skew the results. ANSWERS-2000 is a continuous model, hence a storm event in days prior to a storm will affect the runoff volume and duration for the storm. The number of days in between rainfall events and number of continuous precipitation days will affect the output of the model. Each storm event is not an independent event in a continuous model like ANSWERS-2000.

To determine the length of simulation required to obtain a sample of adequate size for distribution fitting, two methods were used. For both methods, three 100-year data sets were generated from CLIGEN. The first data set was generated with the first seed in CLIGEN, which is constant, and the two other data sets were generated with random seeds. For the first method, a two-sided t-test assuming unequal variances was performed on each data set comparing annual precipitation amounts. Lengths of 100-years to 50-years, 100-years to 25-years and 100-years to 10-years were compared. The second method involved an iterative process of comparing the monthly means for the three data sets. The total rainfall amounts for each individual month were separated into twelve record sets starting with the first year. As each consecutive year was added to the record set, the mean and standard deviation were calculated and compared to those of the previous iteration. Years were added to the record set until the mean and standard deviation did not change significantly indicating that an adequate length of record was found. The results of both the monthly mean comparison and the annual average comparison were used to determine the length of record that would give an adequate sample size. The results will vary depending upon the weather station data used; hence this evaluation had to be conducted for the specific area being modeled. The longer of the two length of records suggested adequate by the two sided t-test performed on the annual precipitation amounts and the mean monthly comparison was used.

The required weather input to ANSWERS-2000 includes precipitation, soil and air temperature, and total daily solar radiation. The precipitation must be entered in a hyetograph format with a maximum of 11 entries with the units of mm/hr. CLIGEN outputs total precipitation, duration of precipitation and maximum intensity. Based on this information a breakpoint data program, which comes with QUESTIONS, uses a SCS triangular hydrograph approach to make the hyetograph for ANSWERS-2000. The CLIGEN output format limits the number of storms per day to one. Since ANSWERS-2000 only allows for a maximum of 11 entries in the daily hyetograph, longer duration storms are not represented with the same resolution as shorter storms.

The in-stream modeling done with HSPF required different weather inputs and formats than ANSWERS-2000. HSPF reads weather data management files (WDM-files), which are binary data files containing the time series data needed depending on which parts of HSPF are being used. WDMUtil, a free program distributed and maintained by USEPA, was used to create and edit the WDM file for HSPF input. Raw data needed to create the WDM file included daily minimum and maximum temperature (ºF), daily average dew-point temperature (º F), total daily solar radiation (ly/day), daily cloud cover in tenths and total daily wind speed (mi/day). For the in-stream modeling, the precipitation that falls directly into the stream was ignored and no precipitation data were entered into HSPF. All the required inputs for HSPF were included in the CLIGEN output file except cloud cover. The CLIGEN output file was opened in EXCEL and processed so every parameter was saved as a separate time series text file with one column for date (mm/dd/yyyy) and one column with the corresponding parameter value. To read the created text files into WDMUtil, ASCII formatting was used (m2,x,d2,x,y4,f9,v8).

The daily maximum (TMAX-F) and minimum (TMIN-F) temperature data were used to calculate hourly air temperatures (FTEM) using the DISAGGREGATE function in the WDMUtil program. The average daily dew-point temperature (FDEW) was disaggregated with the same function to produce hourly dew-point temperatures (DEWP). Total daily solar radiation (DSOL) and total daily wind speed (DWIND) were read into WDMUtil and then disaggregated with the DISAGREGATE function into hourly values (SOLR) and (WIND), respectively.

In WDMUtil, the following time series were calculated. Daily maximum and minimum temperatures (TMAX and TMIN) were used to calculate daily evapotranspiration (DEVT, in/day) by the Harmon method. Daily evapotranspiration was disaggregated with the DISAGGREGATE function to hourly values (PEVT, in/hr). Daily pan evaporation (DEVP) was calculated from daily maximum (TMAX-F) and minimum (TMIN-F) temperatures, daily dew-point temperature (TDEW-F), daily wind speed (DWIND-F) and daily solar radiation (DSOL). Finally, daily pan evaporation was disaggregated to hourly values (EVAP) with the DISAGGREGATE function for evapotranspiration, as WDMUtil does not have a disaggregate function for evaporation.

Daily cloud cover was not given in the CLIGEN output. A relationship between observed solar radiation and extraterrestrial solar radiation that involved the ratio between actual and possible hours of sunshine, n/N, was used (James, 1988):

$$R_s = (0.25+0.50n/N)R_a \qquad [3.3.4.5]$$

Where: R_s = extraterrestrial solar radiation (mm/day);

R_a = observed solar radiation in evaporation equivalents (mm/day); and

n/N = ratio between actual and possible hours of sunshine.

Cloud cover was estimated as (1-n/N). Daily observed solar radiation, an output from CLIGEN in langleys/day, was converted to mm/day by assuming a heat of vaporization of 585 cal/g. Extraterrestrial solar radiation was calculated from the radius vector of the earth, the declination of the sun, latitude of location and Julian day of the year. The spreadsheet used to calculate cloud cover is included in Appendix A.

The CLIGEN weather dataset used for ANSWERS-2000 ran from 01/01/2000 to 12/31/2049, which are arbitrary values since the data were generated. WDMUtil was written primarily to manipulate historic datasets and does not allow for entries beyond year 2020. This restriction would not allow for an HSPF simulation from 01/01/2000 to 12/31/2049. The initial solution of shifting the HSPF run 100 years back in time to 1900 to 1949 proved difficult since year 2000 is a leap year while year 1900 is not a leap year. The definition of a leap year introduced with the Gregorian calendar by Pope Gregory XIII in 1582 states that every fourth year is a leap year except centuries that are not divisible by 400, thus making the year 2000 a leap year and 1900 not a leap year (The Royal Observatory Greenwich, 2000). Hence the HSPF run was shifted back to a start date of 01/01/1940 and end date of 12/31/1989 to match the leap years. This problem could have easily been avoided if the restriction on WDMUtil had been known prior to completing the ANSWERS-2000 simulations.

3.3.5 ANSWERS-2000 Modeling

ANSWERS-2000 produces best results on smaller watersheds with the majority of flow being overland flow. In addition, ANSWERS-2000 only produces hydrographs and pollutographs at the watershed outlet point. With this in mind, for this procedure a watershed should be divided into subwatersheds, resulting in an individual ANSWERS-2000 simulation for each subwatershed that has an outlet to the main stream. The main stream can be defined based upon visual inspection of topographic maps. By dividing the watershed into subwatersheds, the NPS pollutant loading from each subwatershed can be identified and the resultant environmental risk imposed on the system due to the pollutant loadings can be estimated.

The following steps which are performed for each of the subwatersheds are automated by QUESTIONS. The first step involves filling sinks in the Digital Elevation Model (DEM) of the watershed. Sinks may be natural sinkholes or sinks created as a result of data entry error, but they cannot be present on the map when the watershed boundaries are generated by ArcView. Next, grid layers are generated for each of the following: flow direction, flow accumulation, aspect, slope, stream network, watershed boundary, and drop in direction of stream flow. ANSWERS-2000 requires streams to be grouped according to equal characteristics. QUESTIONS does this by assuming a Strahler (e.g. Chow et al., 1988) ordering scheme. After all the hydrology grids are created, the landuse and soils maps are cut to match the watershed area defined by the hydrologic grids. Subwatersheds located completely downstream of other subwatersheds create a problem in defining the watershed since ArcView automatically defines everything upstream of a point as part of the watershed. To prepare the ANSWERS-2000 input files for such watershed files, QUESTIONS is used to generate the upstream areas. Then the upstream areas are manually removed using the Spatial Analyst extension package to ArcView.

3.3.6. From ANSWERS-2000 Output to HSPF Input

Running two different models in sequence with the output from one as the input to the other most often presents challenges as the input format and requirements are different and seldom does a model output exactly what the next model needs as input. ANSWERS-2000 and HSPF were no exception, though the sequential running proved to be less difficult than first anticipated. Two main differences in ANSWERS-2000 output and HSPF input had to be dealt with. HSPF and ANSWERS-2000 both require sediment particle classes, but ANSWERS-2000 does not output sediment delivery in different particle size classes. Second, ANSWERS-2000 outputs hydrographs and pollutographs in a file separated by a line stating the date of the storm, while HSPF requires a continuous constant time step input. These two problems were solved as follows.

HSPF requires that sediment and sediment-bound nutrients be loaded in terms of sand, silt and clay particle classes. While particle class distribution is an input to ANSWERS-2000, sediment loss is output as a total for all particle sizes. To address this, one array for sediment, one for nitrogen and one for phosphorus were added to the loop in ANSWERS-2000 that sums the sediment particle size classes. These three arrays were then summed by particle class and averaged over the simulation period to provide the required input to HSPF.

ANSWERS-2000 hydrograph and pollutograph output are written to one file for the length of simulation, where hydrographs and pollutographs for each storm are separated with a line stating the date of the storm. HSPF requires a continuous time series input including the intermittent periods between storms in an input file called Multiple Sequential Input of Time Series (MUTSIN). A Visual Basic (VB) program called HplotEnglish was written to handle the conversion of such a large volume of data for each subwatershed from ANSWERS-2000 into HSPF. The code for this program is included in Appendix B. The output of HplotEnglish was a MUTSIN file for each subwatershed that contained flow, sediment, sediment-bound P, dissolved P, sediment-bound NH_4^+, and dissolved NO_3^- time series for the simulation period.

3.3.7 HSPF Modeling

The hydrographs and pollutographs from the subwatersheds run in ANSWERS-2000 were loaded into HSPF. The main input file for HSPF, the Users Control Input (UCI) file, can be written in a text editor. Several programs are available to assist in input file construction, but since only the RCHRES module was used, it was relatively straightforward to write the file in a text editor with aid from the HSPF documentation.

Initially, input data for HSPF were prepared in SI units. However, the model calculations were incorrect; it appeared that HSPF did not read the MUTSIN files properly in SI units. Using English units in HSPF meant converting all outputs from ANSWERS-2000 from SI units.

3.3.8 Risk Quantification

After both ANSWERS-2000 and HSPF simulations are completed, the final steps of combining the results and calculating the watershed risk are performed. A flow chart of the complete procedure is shown in Figure 3.3.8.1.

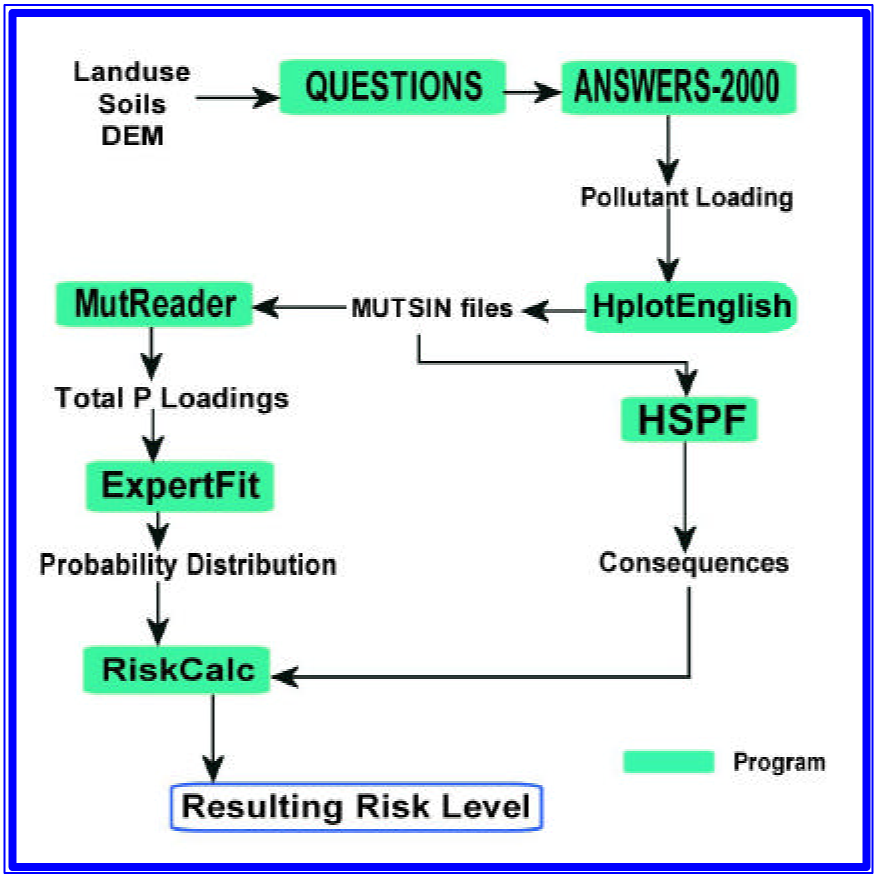

Figure 3.3.8.1: Schematic of risk quantification procedure

To generate the best-fit distribution for the pollutant loadings, the loadings from all subwatersheds are first added together to produce a total pollutant loading for every hour in the watershed. The subwatershed total pollutant loadings were flow-weighted to give total pollutant loadings in mg/L. Due to the large amount of data, a VB program called MutReader was written to automate this process. The code is included in Appendix C. ExpertFit (Averill Law), a statistical software package that fits data to the best fit distributions from a selection of more than twenty of the most common distributions, was used to fit a distribution to the pollutant loading data set output from the MutReader program. ExpertFit can fit an empirical distribution to the data in the event that none of the models included in ExpertFit gives a good fit. The empirical distribution is based on the unique observations in the data set. The unique observations in the data set, Y[1], Y[2], Y[3],….,Y[m] are arranged in increasing order. If all observations in the sample are unique, the sample size n equals the number of different observations, m. The empirical function is then fitted based on the following equation:

$$Y[i] = \frac{\#\, samples \leq Y[i] - 1}{n-1} \qquad [3.3.8.1]$$

Where: Y[i] = value in sample set of interest; and
n = total number of observations in data set.

The final step in the procedure is to calculate the risk as the product of the probability of occurrence of the event of interest and the consequences of that event, where the event of interest is pollutant loading to surface waters. The output from HSPF is read into a third VB program, called RiskCalc, together with the watershed pollutant loadings from the MutReader program. Figure 3.3.8.2 shows how the two data sets were linked together.

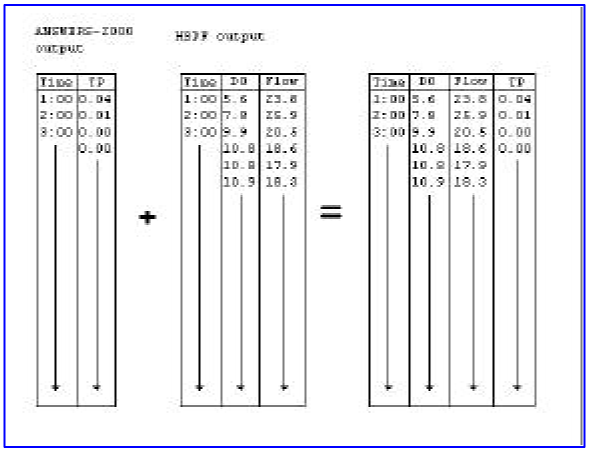

Figure 3.3.8.2: Schematic of linking ANSWERS-2000 output to HSPF output

The RiskCalc program was partly written for the specific endpoint selected for the application of the risk quantification procedure, which has to be specifically defined for each application. The source code for the RiskCalc program is included in Appendix D. RiskCalc reads in the total pollutant loading from the watershed for every hour and the output file from HSPF containing the time, flow, and selected environmental point for every hour. Then the second part of the program takes the following input; criterion for which the case specific endpoint is measured, total pollutant loading for each hour and the probability of exceeding that pollutant loading. The actual risk equation will vary depending on the endpoint selection. To illustrate the procedure, a total phosphorus (TP) loading impact on DO could be written as:

$$Risk = P[TP > x_i] \times \frac{\#hours\_DO < Std.}{\#hours\_TP > x_i} \qquad [3.3.8.2]$$

Where: Risk = risk of DO below standard;

TP = total pollutant loading, expressed as a flow-weighted concentration, from watershed, mg/L;

x_i = the loading of interest, mg/L; and

DO = dissolved oxygen concentration, mg/L.

Resulting from this equation is a risk level expressed in number of hours the DO dropped below standard divided by the total number of hours that the TP loading was in the given range. This results in a dimensionless number between 0-1, where 1 represents a 100% chance of DO dropping below standard when the specified loading is exceeded.

From a watershed management perspective, the total pollutant loading as a loading per hour might be of equal importance as the total pollutant concentration. The concentration has the advantage of being flow-weighted, but from a management point of view, the allowable pollutant loading might be a more useful value in the daily management of the watershed.

3.4 Summary of Procedure Implementation

The risk quantification procedure, as implemented, involves the following steps:

- Identify the pollutant loading and environmental endpoint of interest.
- Formulate the risk quantification equation specific for the pollutant loading and environmental endpoint of interest.
- Obtain necessary data for the watershed, including DEM, landuse and soils data.
- Calculate fertilizer application requirements according to landuse and soils.
- Locate weather station to use and identify the length of record needed for the simulation based on both annual and monthly averages of precipitation.
- Use ANSWERS-2000 to estimate upland pollutant loading.
- Use HSPF to estimate upland pollutant loading impact on receiving water.
- Fit the pollutant loading data to a distribution using ExpertFit.
- Calculate the watershed risk with the RiskCalc program using the output from HSPF and probability distribution from ExpertFit.

At this time ANSWERS-2000 does not model impervious areas adequately, hence the risk quantification procedure, as implemented here, should be applied to mainly agricultural watersheds for the best result.

4.0 Application of Procedure

4.1 Introduction

To illustrate the developed procedure, a watershed with readily available data was needed. The data needed for the procedure includes a DEM covering the watershed area, landuse for the watershed and soils data in Soil Survey Geographic (SSURGO) data from USDA-Natural Resources Conservation Service (NRCS, 2000) compatible format. In addition, a watershed with relatively intense agricultural activity would better demonstrate the use of the procedure since ANSWERS-2000 does not simulate urbanized, impervious areas adequately at this time. Total phosphorus (TP) was selected as the pollutant of interest and dissolved oxygen (DO) was selected as the endpoint of interest. The risk procedure as described in the previous chapter was applied to the watershed and the risk of DO dropping below the state water quality standard for DO at the watershed outlet as a result of TP loading in the watershed was investigated. Although economic consequences and cost were beyond the scope of this project and therefore not considered, economic factors certainly should be considered in performing a risk analysis for a watershed. A management strategy proposed by conducting a risk analysis cannot be implemented without considering economic implications for the inhabitants in the watershed.

In applying the risk quantification procedure to a watershed, SI units were used as far as possible, but some English units also had to be incorporated in running HSPF. In reporting numbers the SI units are given with the English units in parentheses.

4.2 Test Watershed Selection

The Muddy Creek watershed in Rockingham County was selected for demonstrating the application of the risk quantification procedure. The Muddy Creek watershed is located in Virginia’s most agriculturally intensive area with high livestock and poultry production per land area unit. The watershed has been the subject of several previous studies. As a result, the required data were readily available.

Muddy Creek watershed has a total area of about 8184.8 ha (20225 acres). When a grid layer with 30 by 30m cells, which is the resolution of USGS DEMs, was overlaid on the watershed, the number of cells exceeded the maximum of 35000 cells allowed in ANSWERS-2000. As a result, a subwatershed within the Muddy Creek watershed was selected. The stream in the selected subwatershed is not named, therefore, for convenience, it was named Lola Run for the purpose this thesis. Figure 4.2.1 shows the location of the Lola Run subwatershed within the Muddy Creek watershed.

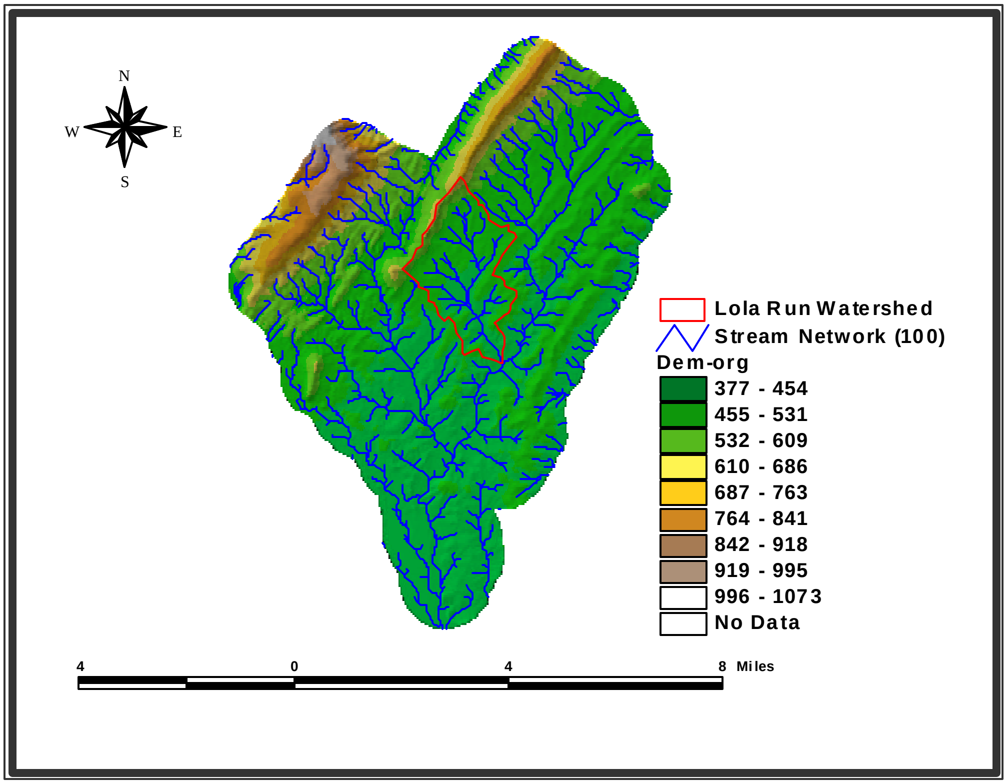

Figure 4.2.1: Location of Lola Run watershed within Muddy Creek watershed

Lola Run enters Muddy Creek at Mount Clinton water quality station. It is marked as a dashed blue line stream on USGS topographic maps, indicating it will go dry in droughts and long periods without rainfall. Photographs taken on December 19, 2000 of Lola Run, the side bank, conditions around the stream and the junction where Lola Run enters Muddy Creek are shown in figures 4.2.2 through 4.2.5.

Figure 4.2.2.Lola Run outlet into Muddy Creek

Figure 4.2.3.Lola Run looking upstream from the outlet

Figure 4.2.4.Lola Run flowing through a field, looking upstream

Figure 4.2.5.Smaller tributary to Lola Run

4.2.1 Endpoint Selection

Dissolved oxygen is a good constituent to choose as it has state regulated limits dependent on the stream classification, e.g. natural trout stream or mountain stream. In addition it is directly related to fish health; different fish species require different minimum DO levels to survive. Muddy Creek is classified as a Mountainous Zones Waters, with a minimum DO standard of 4.0 mg/L (State Water Control Board, 1997).

4.3 Lola Run Landuse

The landuse in the Lola Run watershed (figure 4.3.1) was obtained from the Virginia Department of Conservation and Recreation (VDCR). Field boundaries were determined using 1990 Rockingham County DOQQ orthophotographs, classified landuses from 1989 and 1991 National Aerial Photography Program (NAPP) and 1992 and 1994 Farm Service Agency (FSA) aerial slides (Heatwole, 1999).

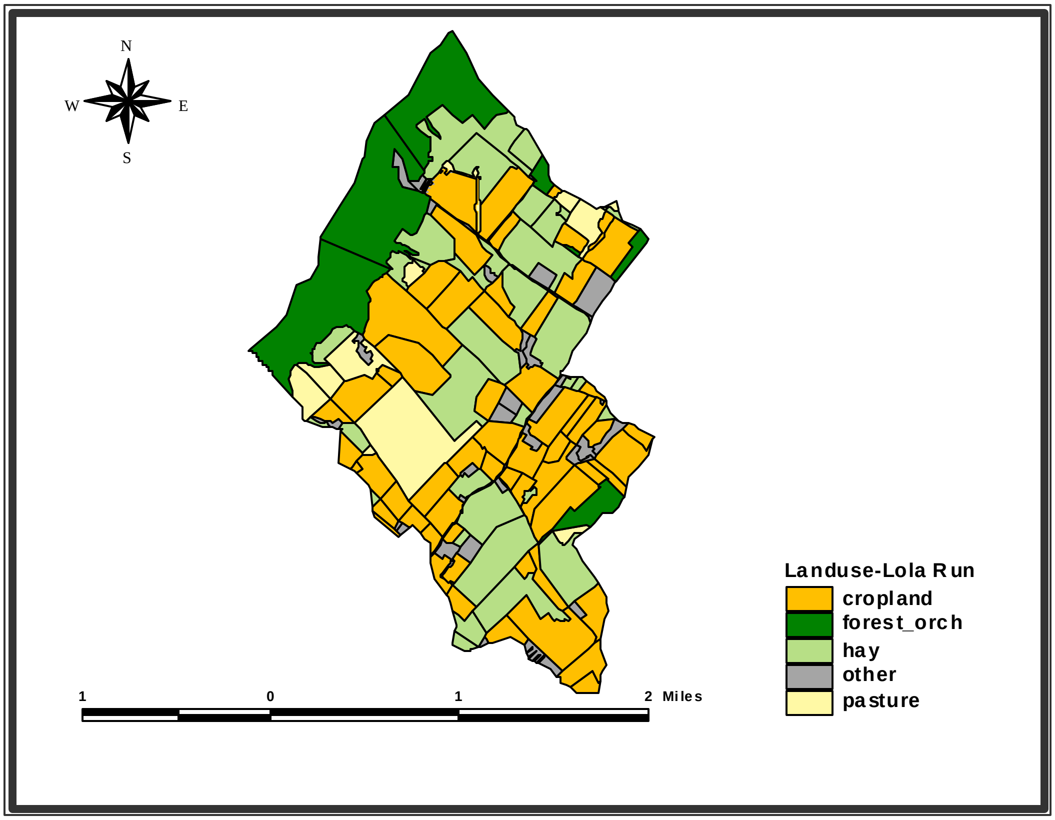

Figure 4.3.1. Landuse in Lola Run watershed

Five landuse categories were identified for Lola Run. The “other” category included farmsteads, loafing lots, poultry houses and rural residential buildings. In table 4.3.1, the landuse categories are listed with the corresponding areas.

Table 4.3.1 Lola Run landuse categories and areas

Landuse Description	# fields in landuse category	Total area ha (acres)	% of total watershed area
cropland	60	394.1 (973.9)	38.9
forest orchard	n/a	188.5 (465.7)	18.6
hay	33	282.6 (698.2)	27.9
pasture	11	94.1 (232.5)	9.3
other	n/a	53.9 (133.3)	5.3

The total watershed area is 1013.2 ha (2503.6 ac), of which 53.9 ha (133.3 ac) is classified as "other". The other category makes up just over 5% of the total watershed area. In running ANSWERS-2000, these areas were merged with the spatially closest field to avoid having impervious areas.

A commonly used crop rotation in the Muddy Creek watershed is corn silage rotated with rye cover or rye silage. Hence this rotation was assumed on all cropland for the modeling. In addition alfalfa hay and pasture are common in the area. Table 4.3.2 shows the detailed outline of the landuse management.

Table 4.3.2 Landuse and management practices for Lola Run used in ANSWERS-2000

Landuse	Management	Fertilizer application
Cropland	Corn silage w/ winter rye grain	Fertilized according to Virginia VALUES* recommendations for soil type
Hay	Alfalfa hay	Fertilized according to Virginia VALUES recommendations for soil type
Pasture	Native permanent pasture	Fertilized according to Virginia VALUES recommendations for soil type
Forest / Orchard	Forest (good standing)	No fertilizer applied

* VALUES refers to the Virginia Agronomic Land Use Evaluation System. It is a database developed at Virginia Polytechnic Institute and State University to base fertilizer application on crop grown, soil type, and expected yield (Simpson et al., 1992).

4.4 Lola Run Soils

The soils data set obtained for Lola Run watershed (Figure 4.4.1) was Soil Survey Geographic (SSURGO) data from USDA-Natural Resources Conservation Service (NRCS, 2000). The SSURGO data are the most detailed soils maps produced by the NRCS. The field mapping methods used in producing the maps follow national standards. The SSURGO maps are available for download by county on the NRCS World Wide Web page (http://www.ftw.nrcs.usda.gov/ssur_data.html). Certain soils in the database were identified on the digitized map but did not have any attributes in the attributes table. In these cases, a neighboring soil, either based on similar soil properties or majority area, was substituted.

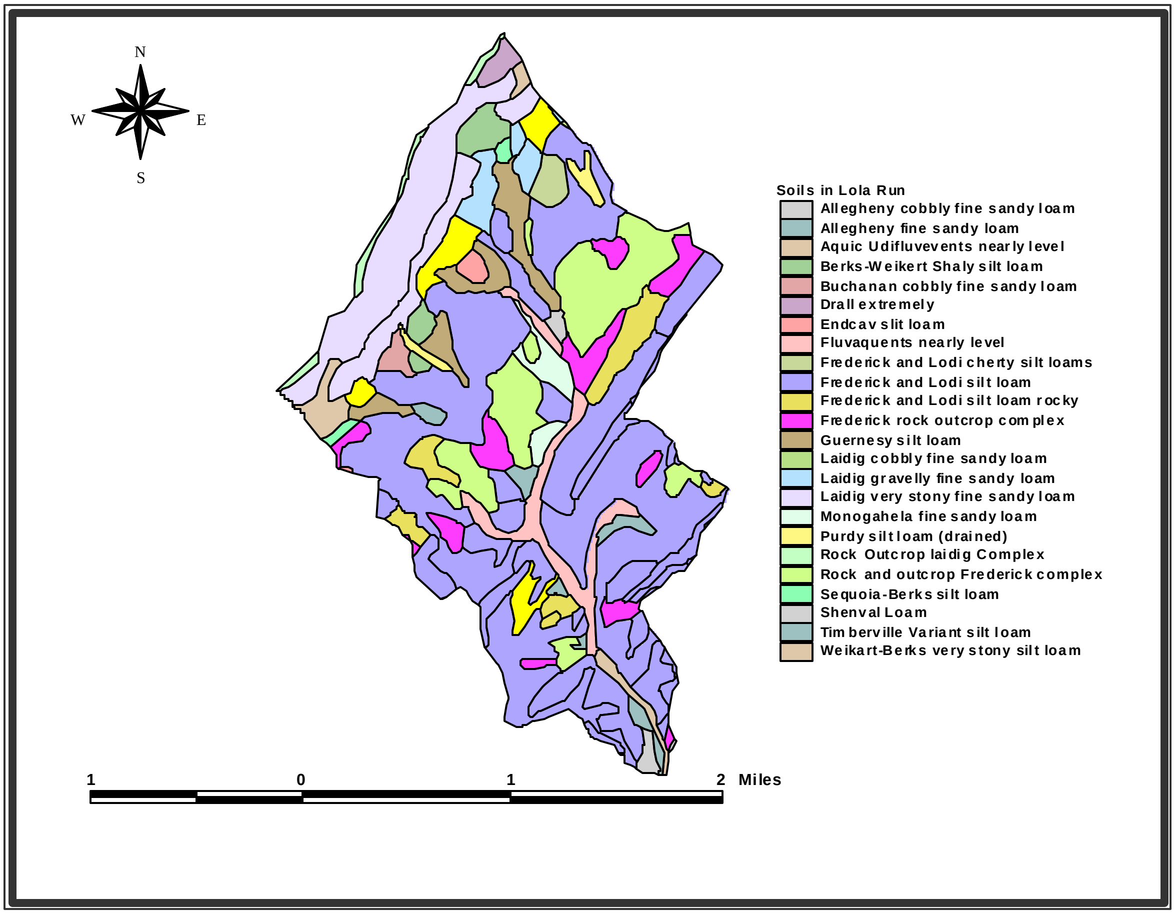

Figure 4.4.1: Lola Run soils map (NRCS, 2000)

4.5 Lola Run Fertilizer Applications

Fertilizer applications were done based upon Virginia VALUES recommendations for the specific soil types. The soil type on each field was determined by using the geoprocessing tool in ArcView to create a union of the soils and fields layers. Then the features in the new layer were dissolved using the geoprocessing tool to produce a field layer with a majority soil type for each field.

ANSWERS-2000 fertilizer inputs are in the form of nitrate (NO_3), ammonium (NH_4^+), and orthophosphate (PO_4^-). ANSWERS-2000 does not distinguish between manure and commercial fertilizer. The Virginia VALUES recommendations are given as N and P_2O_5, which had to be converted to NO_3^-, NH_4^+ and PO_4^-. The N applied was assumed to be 75% NH_4^+ and 25% NO_3^-. The fertilizer applications for each crop and soil are presented in Table 4.4.1.

Table 4.4.1: Fertilizer applications used in ASNWERS-2000 for Lola Run Watershed

Soil	Crop	Fertilizer		
		NH_4^+ (kg/ha)	*NO_3^- (kg/ha)*	*PO_4^+ (kg/ha)*
Frederick and Lodi	Corn silage	151.23	173.59	90.13
	Rye grain	27.01	31.00	90.13
	hay	97.20	32.40	105.16
	pasture	N/A	N/A	N/A
Laidig	Corn silage	118.82	136.39	90.13
	Rye grain	27.01	31.00	90.13
	hay	75.60	25.50	60.09
	pasture	54.00	18.00	60.09
Timberville	Corn silage	162.00	54.00	90.10
	Rye grain	27.01	31.00	90.13
	hay	97.20	32.40	105.16
	pasture	54.00	18.00	112.70
convert from N to NO_3^- multiply by			4.425	
convert from N to NH_4^+ multiply by			1.285	
convert from P_2O_5 to P multiply by			0.437	
convert from P to PO_4^+ multiply by			3.067	
convert lb/ac to kg/ha			1.120847	
Assume 75% NH_4^+ and 25% NO_3^-				

4.5 Weather Data

CLIGEN uses distributions based on historical data to generate a statistical weather file. The user must select a weather station with historical records in CLIGEN. In this case, Big Meadows weather station in Madison County, approximately 56.3 km (35 miles) east of Lola Run, was the closest location. To do a comparison of annual averages in the first seed compared to the following random seeds in CLIGEN, three datasets of 100 years of data were generated from CLIGEN. The first set was generated with the first seed, which is constant, and the second and third sets with random seeds. Total annual rainfall was very similar in the three data sets, about 1240 mm per year (48.8 in/year). To determine the length of simulation needed so that an extreme year in either direction would not significantly change the mean, a two-sided t-test assuming unequal variances was used on the annual total precipitation.

Table 4.5.1: Two sided t-test of annual rainfall at Big Meadows weather station

P-values from two sided t-test on 3 sets of weather data from CLIGEN			
$H_0: \mu = \mu_0$; $H_1: \mu \neq \mu_0$			
Seed selection	**100 years to 50 years**	**100 years to 25 years**	**100 years to 10 years**
1st seed	0.550	0.033	0.099
Random seed 1	0.773	0.632	0.942
Random seed 2	0.662	0.226	0.732

The results (table 4.5.1) suggested that the selection of an appropriate weather data set was not sensitive to the total annual rainfall. The only time the null hypothesis could be rejected for a significance level of 0.05 was for the first seed comparing 100 years to 25 years (p-value=0.033). If the significance level was increased to 0.1 the null hypothesis for the first seed 100 years to 25 years and 100 years to 10 years were both rejected. For two of the three seeds, a 10-year set was not statistically different from a 100-year set.

The monthly mean precipitation amounts were summed in an iterative process, comparing every new iteration to the previous iteration for 50 years of statistical generated data. The results of the mean precipitation comparison for December for the 50 years from three different data sets are shown in Table 4.5.2.

Table 4.5.2: Mean monthly precipitation for December for 50 years of data

Observed mean precipitation for December at Big Meadows = 92.7 mm		
Seed Selection	Mean Precipitation	Standard Deviation
1st seed	90.5 mm (3.56 in)	72.6 mm (2.86 in)
Random seed 1	79.3 mm (3,12 in)	47.1 mm (1.85 in)
Random seed 2	81.2 mm (3.20 in)	59.0 mm (2.32 in)

It was found that a length of record of 50 years was required before an extreme value in either direction would have no significant impact on the monthly means. Hence for the final dataset, the second random seed in CLIGEN was used with a length of simulation of 50 years. Figure 4.5.1 shows the annual rainfall amounts for the weather data set used, and the observed annual average reported at the Harrisonburg NRCS office. The annual rainfall amount for the weather data set used had a mean of 1237 mm (48.7 in) compared to the observed 853.2 mm/year (33.6 in/year) rainfall at Dale Enterprise weather station also located in the Shenandoah Valley just south of Harrisonburg (http://climate.virginia.edu/Climate/normals/442208_30yr_norm.html). This difference was expected since the Big Meadows weather station is on the east side of the Blue Ridge Mountains and Lola Run is on the west side. Big Meadows however is the closest located weather station in CLIGEN and was considered adequate for demonstrating the risk quantification procedure.

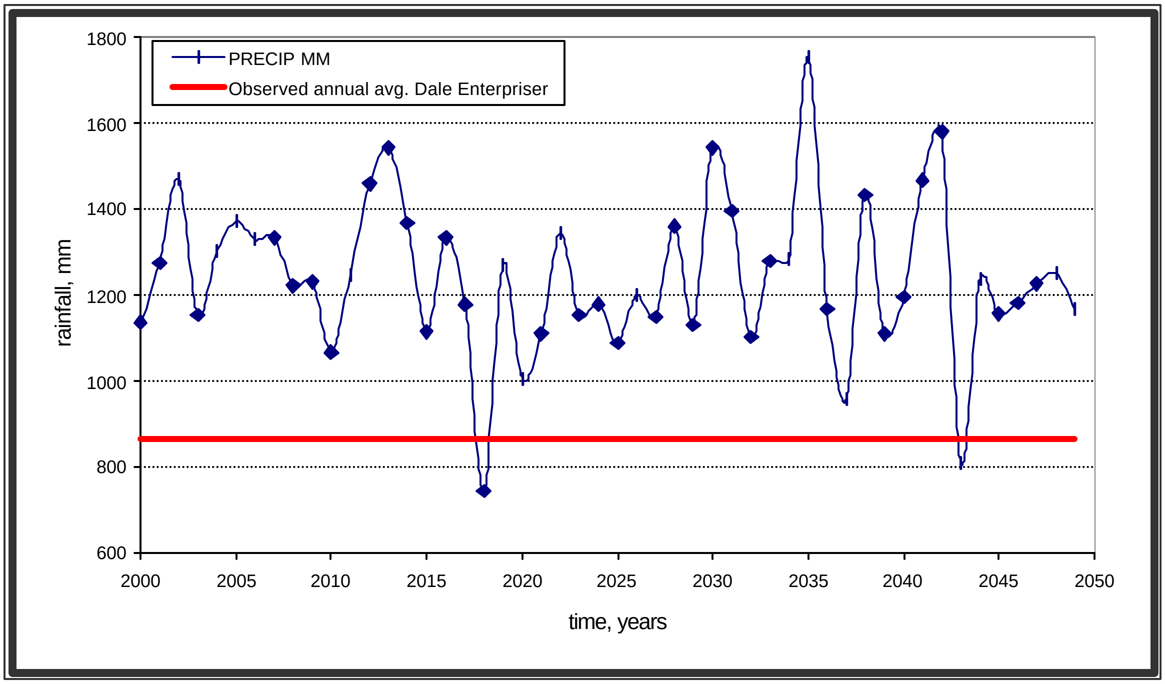

Figure 4.5.1: Generated annual rainfall data set used in ANSWERS-2000 compared to observed annual average

4.6 ANSWERS-2000 Modeling of Lola Run

Lola Run was divided into twelve subwatersheds (Figure 4.6.1) using the watershed calculate function in the Map Calculator in ArcView. The watershed was divided into subwatersheds to create pollutant loading points in the main stream, which could be input points to the stream modeled in HSPF. Due to the output format and options of ANSWERS-2000, the pollutant loading points were best created by modeling several smaller subwatersheds with the outlet point of each subwatershed entering the main stream. The total number of subwatersheds was determined so that every subwatershed discharged into the main stream modeled in HSPF.

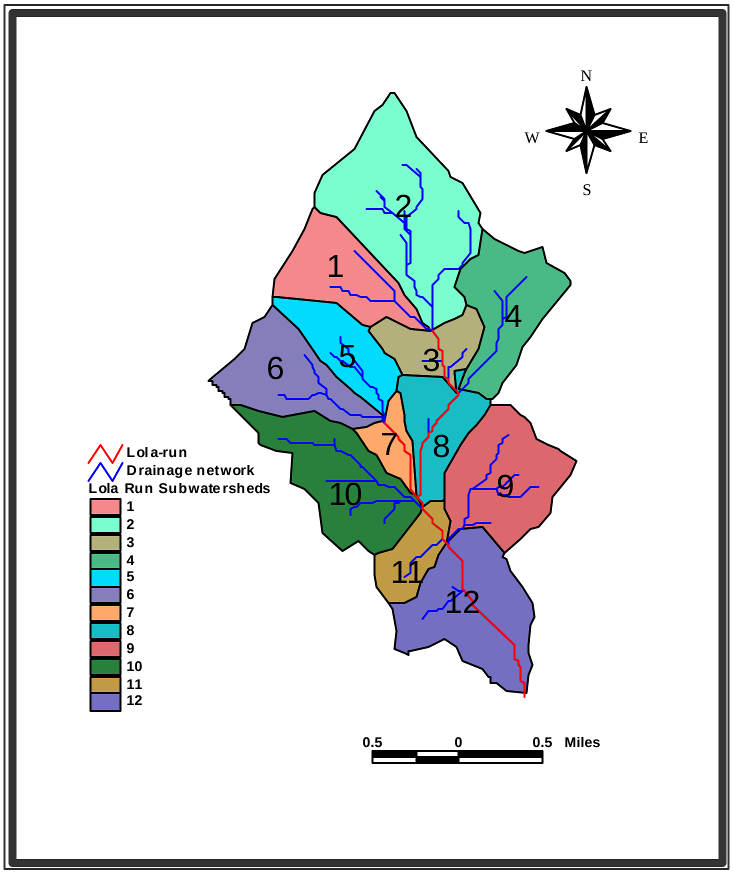

Figure 4.6.1: Subwatershed division of Lola Run watershed

For each of the twelve subwatersheds, QUESTIONS was used to generate the ANSWERS-2000 input files. In addition to the GIS data, the parameters required to characterize the cover, tillage and residues of the different landuses were generated from the database included in QUESTIONS. ANSWERS-2000 was run for each subwatershed separately. ANSWERS-2000 produces an output file with sediment and nutrient losses from each cell. These data were imported into ArcView using QUESTIONS to give a spatial representation of the output. Sediment loss and dissolved PO_4^- output from watershed 2 are displayed in figures 4.6.2 and 4.6.3, respectively. A complete set of results for all subwatersheds is presented in Appendix E.

The ANSWERS-2000 cell by cell output when imported back into ArcView illustrates the location in the watershed with higher sediment and pollutant loadings. From a watershed management standpoint, this output can be used to identify where to implement best management practices (BMPs) to best reduce the overall risk level in the watershed. All twelve subwatersheds followed the same general trends, with a few fields in each watershed producing the majority of the sediment and nutrient loadings. Sediment and nutrient losses were higher on cropland than pasture, which was expected. Sediment loss was higher in watershed areas with cropland on steeper slopes, which was also expected.

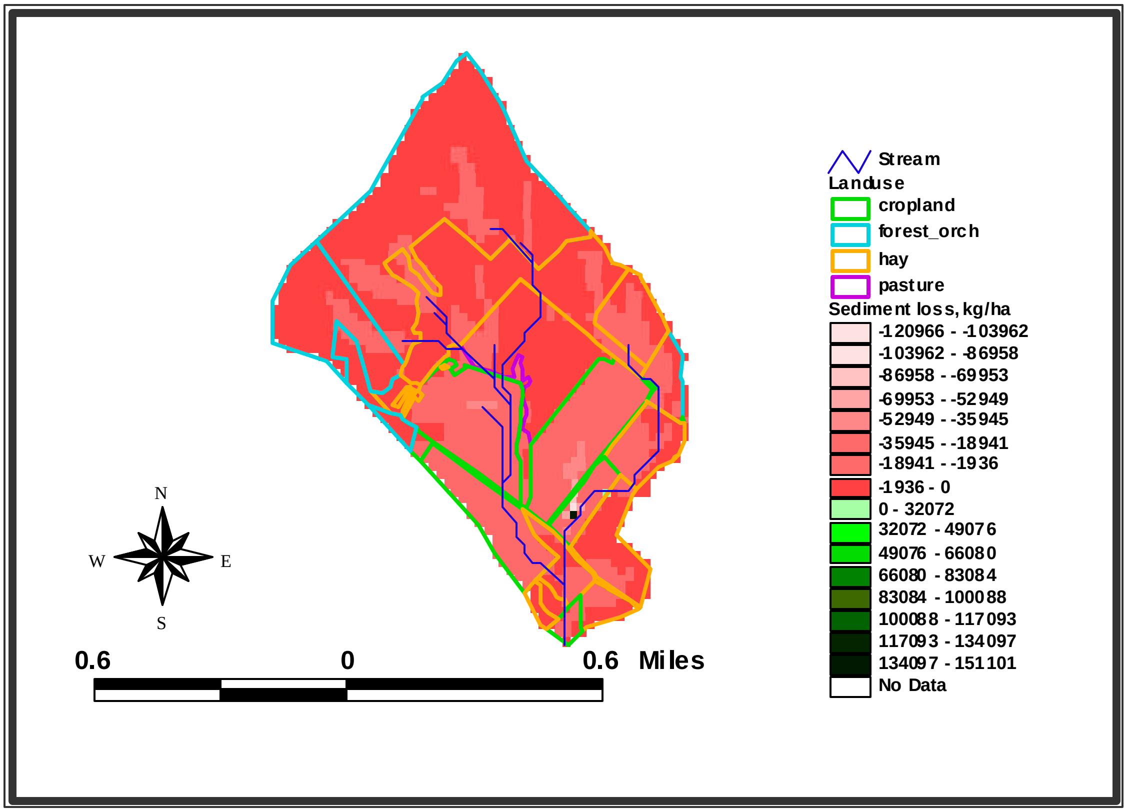

Figure 4.6.2: Average annual sediment loss output from ANSWERS-2000 for Subwatershed 2. A positive number indicates a net sediment deposit and a negative number indicates a net sediment loss from the cell.

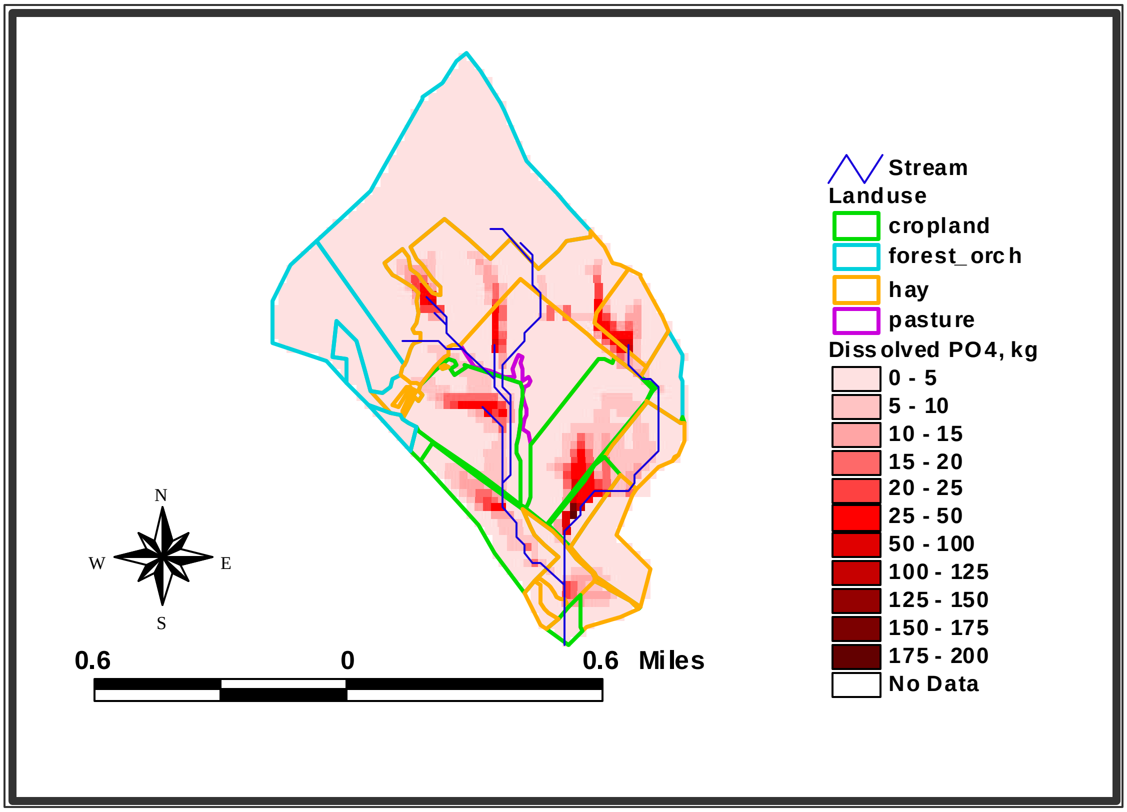

Figure 4.6.3: Dissolved PO4 output from ANSWERS-2000 for Subwatershed 2 in total phosphorus loss in kg/year

4.7 HSPF Modeling

The HSPF model was used only for the stream modeling, which meant that most of the inputs were outputs from ANSWERS-2000 that were transformed using the HplotEnglish program. HSPF requires stage discharge relationships (F-tables) as part of the input. These were developed assuming a trapezoidal channel cross-section with the first meter (3.28 ft) having a side slope of 1:2; beyond 1m the side slopes were assumed to be 1:5. The bottom width of the channel was measured to be about 2.5 m (8.2 ft) to 3 m (9.8 ft) at the outlet point, with gradual narrowing moving upstream. Details of the F-tables calculations are included in Appendix F.

To estimate an appropriate time step for use in HSPF, a travel time calculation was performed for the shortest reach in the reach network. To calculate the velocity in the reach, normal depth was assumed. Normal depth is the depth of uniform flow under constant discharge. The length of the shortest reach was 1410 ft and the maximum flow during a storm was 410 cfs, resulting in a velocity of 5.0 ft/sec and a travel time through the reach of 4.7 min. The 410 cfs storm was the largest runoff event produced in ANSWERS-2000. For travel time calculations see Appendix G. Based on this calculation the time step in HSPF was set to 4 minutes. The printout time step was set at 1-hour and an average of the 4-minute interval values was printed.

HSPF relates P loading to DO concentration through phytoplankton and zooplankton consumption of nutrients in the system. The P uptake increases production in the waterbody which results in increased DO consumption by the planktons. The increased DO consumption lowers the available DO in the waterbody.

A few storms were selected and mass balances of flow and sediment were performed to check the model performance. The storm occurring on February 2, 2000 (year 1940 in HSPF) with a total rainfall of 37.3 mm over a 7 hour period had a total inflow of 39101.4 m^3 (31.7 ac-ft) and an outflow of 38978.0 m^3 (31.6 ac-ft). The sediment balance for the same storm gave a total inflow of 25129 kg (55400 lb) and outflow of 20321 kg (44800 lb). The slight reduction in sediment outflow compared to inflow is due to sediment deposition in the channel. The stream in HSPF was modeled to allow for sediment deposition and detachment of previous deposited sediment. The channel erodibility factor was set to 0.0, meaning no channel scouring was allowed. The output from HSPF was used to calculate consequence in the RiskCalc program. The output from HSPF was in the form of hourly values for 50 years. Plotting the values for such a long simulation was not feasible, but a sample output was plotted, figure 4.7.1, showing the last 10 days of November for the 28th simulation year. The plot shows the DO and TP concentrations over 10 days and covers the largest storm runoff event produced by ANSWERS-2000. The peak runoff rate was 410 cfs and the duration of the storm was 18 hours.

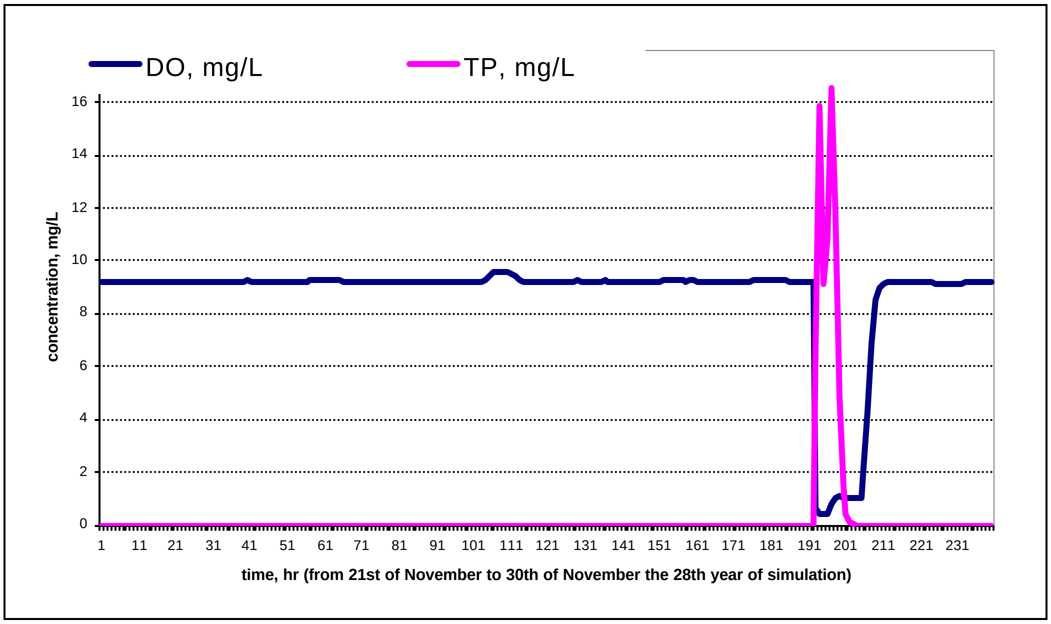

Figure 4.7.1: Sample output from HSPF from the latter half of November during the 28th year simulation showing DO and TP concentrations as a function of time

4.8 Risk Analysis Results

The developed procedure was applied to Lola Run watershed and the risk of TP loadings resulting in DO levels below the given state standard of 4.0 mg/L was analyzed. In this section, the results of the risk analysis are presented and discussed. Since risk is defined as probability of an event occurring multiplied by the consequence of that event, the results section includes presentation and discussions of the probability part and consequence part. Then the combined function that quantified the risk is presented.

The TP loadings output from ANSWERS-2000 for each subwatershed was processed by the MutReader program, producing a text file with TP loadings in mg/L for every hour given that runoff occurred for that hour. Processing the TP loadings file in ExpertFit to fit a distribution to the data resulted in an empirical fit. All goodness of fit tests provided by the program, including the Anderson-Darling and the Kolmogorov-Smirnov tests, strongly rejected that the data fit any of the provided distributions. A statistical summary of the data is provided in table 4.8.1.

Table 4.8.1. Statistical summary of TP loading output from ANSWERS-2000 based on 50 years of simulated weather data

Sample Characteristic	***Value***
Observation type	Real valued
Number of observations	4,069
Minimum observation	0.00000
Maximum observation	1.57248e6 mg/L
Average	11,932.79460 mg/L
Median	48.07890 mg/L
Variance	5.05244e9 $(mg/L)^2$
Coefficient of variation	5.95674
Skewness	13.20423
Kurtosis	216.66873
1st percentile	0.00000 mg/L
5th percentile	0.00000 mg/L
10th percentile	0.00000 mg/L
90th percentile	14,652.07154 mg/L
95th percentile	47,756.33642 mg/L
99th percentile	247,843.29501 mg/L

The high variance of data indicated the large dispersion of the data, which gives less meaning to the mean value of the data set. The mean was 11932.8 mg/L compared to a median of 48.1 mg/L. The data set also had a relatively high positive skewness indicating an asymmetric distribution. The data range spanned from 0.0 to more than 1,500,000 mg/L, which is another indication of the dispersion of the data.

ANSWERS-2000 produced extremely high TP loadings into the stream, including some TP values that clearly exceeded a reasonable value. It was beyond the scope of this project to investigate or correct this problem. As a result of this the TP loadings from ANSWERS-2000 were used only to demonstrate the developed procedure on Lola Run watershed and not in any way to indicate the actual TP loadings in Lola Run. In the case of use for actual risk quantification this problem would have to be rectified.

The endpoint for the risk quantification procedure to Lola Run was DO. The consequence was measured in terms of the number of hours DO dropped below the standard divided by the total number of hours the TP loadings exceeded the loading of interest. The result was the fraction of time (or % if multiplied by 100) that the DO would drop below standard every time a TP loading of interest occurred. This fraction increased as TP loadings increased, which was expected.

The results of the risk analysis (table 4.8.2) are presented in terms of cumulative probability P[TP> x_i]. The probability of occurrence decreased as the TP loadings increased, which was expected. The number of hours DO was less than the standard, 4 mg/L, divided by the total number of hours TP loadings were greater than x_i increased as the TP loadings increased, which was also expected. The risk was higher for the lower TP loadings than the higher TP loadings. Smith et al. (1987) reported that an in-stream TP concentration greater 0.1 mg/L was unacceptably high. The results show that the risk of a TP loading greater than 0.1 mg/L was 0.609 and the average number of hours the DO was less than the standard (4.0 mg/L) was 0.821 for every hour the TP loading exceeded the critical level, meaning that 82.1% of the time a TP loading of 0.1 mg/L occurred the DO dropped below the standard. Smith et al. (1987) reported in-stream concentrations of TP while the risk calculations were done based on a TP concentration input into the stream. Lola Run was a small stream where dilution effects of TP concentrations loaded into the stream can be assumed to be minimal. In watersheds draining a bigger upland area with larger streams this assumption cannot be made, but considering baseflow in the stream the dilution effect of the TP can be estimated. The results indicated that the many small and intermediate size storms had a greater impact on in-stream water quality and ecosystem health than the few large storms that have a very small probability of occurrence. This indicates that the many smaller storms with small TP loadings but with a higher probability of occurrence might be of more concern than the storm that produced the biggest TP loading as this storm has a very small probability of occurring.

Table 4.8.2 Results of risk quantification for Lola Run watershed as a result of TP loadings into the system with a critical DO = 4.0 mg/L

	Probability	Consequence	Risk
TP_critical	P(x>TP_Critical)	# hrs. DO < Std./ # hrs. TP > critical TP	Risk_Level
mg/l			
0.1	0.7417	0.8211	0.6089
0.5	0.7147	0.8298	0.5931
1.0	0.6967	0.8402	0.5853
5.00	0.6385	0.8580	0.5478
10.0	0.6030	0.8732	0.5265
20.0	0.5618	0.8933	0.5018
50.0	0.4974	0.9293	0.4623
100.0	0.4383	0.9568	0.4194
500.0	0.3161	0.9938	0.3142
1000.0	0.2648	0.9991	0.2645
2000.0	0.2149	1.0000	0.2149
10000.0	0.1203	1.0000	0.1203

As a result of the earlier mentioned problem with high TP loadings into the stream, the risk as quantified in table 4.8.2 is not intended to indicate actual risk resulting from TP loadings in Lola Run. The data produced in this demonstration were used solely to demonstrate the developed procedure. In developing the presented procedure only stochastic uncertainty, represented by weather data, was accounted for. In addition to the stochastic uncertainty, the model and parameter uncertainties will have a major effect on the outcome in a computer modeling based procedure as presented here. To obtain more complete and accurate prediction of the environmental risk as a result of TP loadings to surface waters, the model and parameter uncertainty should be incorporated into the procedure. Considering all three types of uncertainty, however, produces an extremely complex and difficult system to analyze.

5.0 Potential Applications of the Risk Quantification Procedure

5.1 Introduction

The risk quantification procedure developed in this research was applied to Lola Run watershed for a single management strategy for landuse and fertilizer application rates to demonstrate the procedure and present a set of results that apply to Lola Run. The risk quantification procedure developed has several more application areas than the one demonstrated. In this chapter the different potential applications are discussed.

5.2 Applicable Uses of the Risk Quantification Procedure

The risk quantification procedure provides watershed management groups and stakeholders with a method to calculate the risk the watershed is exposed to as a result of a particular pollutant loading. For example, risk can be quantified using the described procedure for one or more cropping/management scenarios. The resulting risk values can then be used to determine alternative scenarios that meet an acceptable risk level (acceptable risk levels will vary depending on the situation and will need to be determined by the concerned parties). For example, as illustrated in Figure 5.2.1, risk associated with different fertilizer application strategies can be compared. The fertilizer application strategies could be nitrogen (N) based versus P-based. Each of the fertilizer strategies together with the crop of interest forms a scenario. For example, scenario 1 could be N-based fertilizer application and corn silage while scenario 2 could be P-based fertilizer application and wheat. For a specified risk level, one can determine which, if any, of the evaluated fertilizer strategy/crop combinations would not exceed the predetermined acceptable risk. The manager could then select from those scenario combinations based on criteria such as economics, e.g., maximize net returns on the farm.

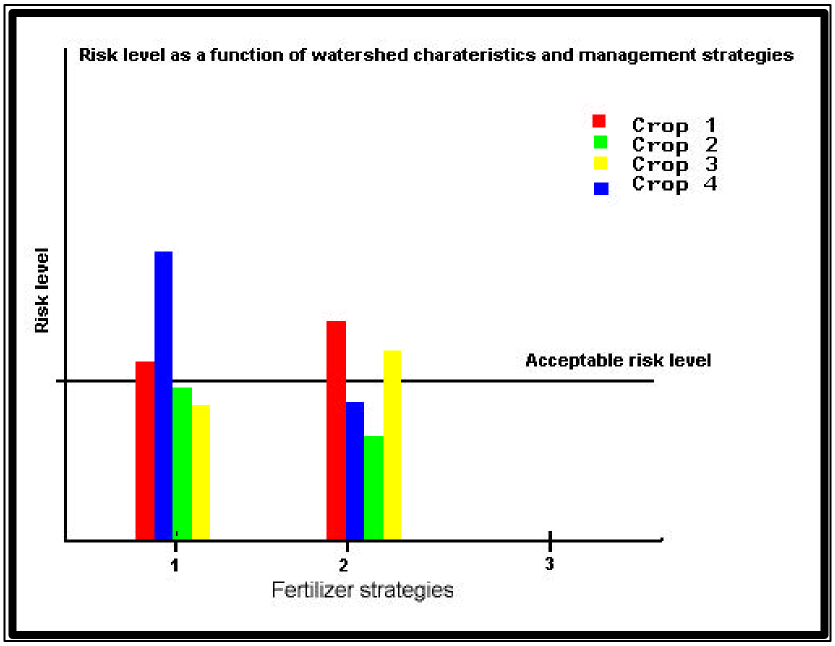

Figure 5.2.1: Illustration of risk procedure to evaluate different management practices

Another application of the procedure is to evaluate the threat to in-stream ecosystems, benthic community or fish. With some additional data/information, such as observed fish kill data with corresponding relevant water quality parameters, the simulated water quality parameter values could be correlated with number of fish kills. In the case of a stream with increased fish kills the risk procedure can be used to identify and quantify risk of fish kills. If the length of time DO must be below the standard to cause fish death was established, the procedure could be used to estimate the number of dead fish per pollutant loading unit. This would provide watershed managers with a tool to quantify the risk of fish kills as a result of pollutant loading.

Regulatory agencies can use the risk quantification procedure to identify acceptable risk levels for watersheds, with respect to the current ecosystem health and water quality. Watersheds could be categorized in terms of environmental sensitivity or current impairment, so that watersheds with a low present impairment might be able to tolerate a higher risk level than watersheds with high present impairment. The watershed stakeholders and managers could then use the risk level set by regulatory agencies as an upper limit for pollutant loadings. How much, if any, reduction in pollutant loading is needed to meet the risk level can be decided based on output from the NPS model. The RiskCalc program written to calculate the risk in the procedure can also be used as a tool to identify the risk level resulting from different pollutant loadings. A screen shot of the program is shown in figure 5.2.2.

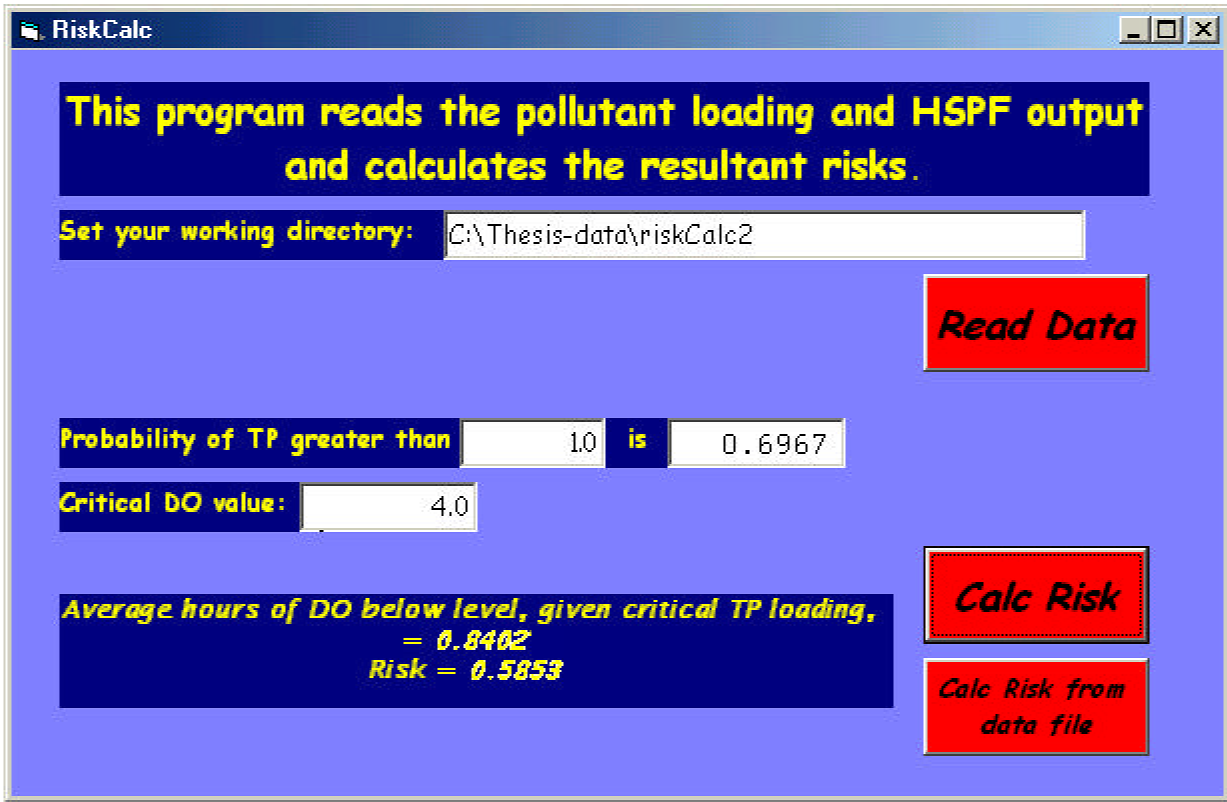

Figure 5.2.2 Screen print of the RiskCalc program

6.0 Summary and Conclusions

The main objective of this research was to develop a procedure to quantify environmental risk of pollutant loadings to surface waters including both the probability of an event occurring and the consequence of that event. The objective was met with the development of the procedure presented in this thesis. The procedure was developed conceptually with emphasis on linking the probability of occurrence of an event with the resulting consequence quantified by NPS model pollutant loading and an in-stream water quality model to simulate instream water chemistry and transport. In implementing the procedure, ANSWERS-2000 was used for NPS modeling and HSPF for in-stream modeling. In addition to the two main models, several VB programs were written to facilitate and automate data processing and conversion from the output of one model to the input of the next. The procedure was demonstrated on a small watershed in Rockingham County, Virginia. The output of this demonstration showed that the many small phosphorus loadings to surface water pose a greater risk to the watershed than the extreme storms, since these storms might have a high consequence but a very small probability of occurring.

Pollutant loadings and consequences are often not directly linked in a way that is easy to model. In order to obtain a better understanding of how the pollutant loadings and consequences are related, more interdisciplinary research is needed. The effect of low DO levels and duration of low DO levels on fish mortality combined with NPS modeling and stream flow modeling might give a better understanding of ways to express the consequences of pollutant loadings in a meaningful way with respect to biological endpoints. The complete picture of watershed risk is very complex. In this research only the stochastic uncertainty was considered; both model uncertainty and parameter uncertainty should be included for a more complete picture.

The risk quantification procedure could be improved in several ways. First making ANSWERS-2000 a better model for urbanized areas would increase the areas in which the risk quantification procedure could be applied. Increasing the hyetograph entries in ANSWERS-2000 to better represent longer storms would decrease the possibility of misrepresentation of the storm and more accurately estimate the NPS loading. A better understanding of the links between pollutant loadings and biological endpoints would improve the risk output in terms of being a more direct link between pollutant loading and impact on biological endpoint. The risk quantification procedure could also benefit from more research into possible ways to express the consequences. Comparing results of the different ways to observed data should give a better understanding of meaningful ways to express the consequence part of the procedure.

Third, using CLIGEN to generate the weather records requires a weather station from the list in CLIGEN be selected. The closest available station might not have a weather pattern similar to that of the watershed.

The above suggested improvements would improve the risk quantification procedure by increasing the confidence in the results and find more useful ways to express the risk for watershed managers and stakeholders. Weather data very much drives the outcome of the procedure, hence the more accurate representation of the weather pattern in the watershed the higher the confidence in the final result.

References

ASTM. 1985. Book of ASTM standards, 11.04. American Society for Testing Materials. Philadelphia.

Andersen, H. V., J. Kjølholt, C. Poll, S. Ø. Dahl, F. Stuer-Lauridsen, F. Pedersen and E. Bjørnstad. 1998. Environmental risk assessment of surface water and sediments in Copenhagen Harbour. Water Science & Technology 37(6-7): 263-272.

Arnold, J. G., P. M. Allen and G. Bernhardt. 1993. A comprehensive surface-groundwater flow model. Journal of Hydrology 142:47-69.

Bicknell, B. R., J. C. Imhoff, J. L. Kittle, A. S. Donigian and R. C. Johanson. 1993. Hydrological simulation program-fortran (HSPF): User's manual for release 10.0. EPA-600/3-84-066. Environmental Research Laboratory, USEPA. Athens, Georgia.

ArcView. Redlands, California: Environmental Systems Research Institute.

Barnthouse, L. W., G. W. Suter II and S. M. Bartell. 1988. Quantifying risk of toxic chemicals to aquatic populations and ecosystems. Chemosphere 17(8): 1487-1492.

Bouraoui, F. 1994. Development of a continuous, physically-based, distributed parameter, nonpoint source model. PhD. dis., Biological Systems Engineering. Virginia Polytechnic Institute and State University, Blacksburg.

Byne, W. 2000. Predicting sediment detachment and channel scouring in the process-based planning model ANSWERS-2000. M.S. Thesis. Biological Systems Engineering, Virginia Polytechnic Institute and State University, Blacksburg.

Chaves, H. M. L. and M. A. Nearing. 1991. Uncertainty analysis of the WEPP soil erosion model. Transactions of the ASAE 34(6): 2437-2443.

Chow, V. T., D. R. Maidment, and L. W. Mays. 1988. Applied Hydrology. Surface Water, ch. 5, 166-170. New York: McGraw-Hill, Inc.

Correll, D. L. 1998. The role of phosphorus in the eutrophication of receiving waters: a review. Journal of Environmental Quality 27: 261-266.

Correll, D. L. 1999. Phosphorus: A rate limiting nutrient in surface waters. Poultry Science 78: 674-682.

Eagleson, P. S. 1970. Dynamic Hydrology. New York: McGraw-Hill Book Company.

Evans, D. O., K. H. Nicholls, Y. C. Allen and M. J. McMurtry. 1996. Historical land use, phosphorus loading, and loss of fish habitat in Lake Simcoe, Canada. Canadian Journal of Fisheries and Aquatic Science 53(Supplement 1): 194-218.

Haan, C. T.1977. Statistical Methods in Hydrology. Ames, IA: The Iowa University Press.

Haan, C. T. 1989. Parametric uncertainty in hydrologic modeling. Transactions of the ASAE 32(1): 137-146.

Heatwole, C. D. November, 11 1999. Muddy Creek Farm Generation Procedure. Available: http://www.isis.vt.edu/watershed/MC/FarmGenerationProcedure.doc. (01/30/01).

Henley, E. J. and H. Kumamoto. 1991. Probabilistic Risk Assessment. New York: The Institute of Electrical and Electronics Engineering Press.

Hession, C. W., D. E. Storm, C. T. Haan, S. L. Burks and M. D. Matlock. 1996. A watershed-level ecological risk assessment methodology. Water Resources Bulletin 32(5):1039-1054.

Hogg, R. V. and J. Ledolter. 1992. Applied Statistics for Engineers and Physical Scientists. New York: Macmillan Publishing Company.

Hunsaker, C. T., R. L. Graham, G. W. Suter II, R. V. O'Neil, B. L. Jackson, and L. W. Barnthouse. 1989. Regional ecological risk assessment: Theory and demonstration. Oak Ridge National Laboratory. Oak Ridge, Tennessee.

James, L. G. 1988. Principles of farm irrigation system design. Irrigation requirements and scheduling, ch. 1, 21-30. New York: John Wiley & Sons, Inc.

Kuczera, G. and E. Parent. 1998. Monte Carlo assessment of parameter uncertainty in conceptual catchment models: the Metropolis algorithm. Journal of Hydrology 211: 69-85.

Law, A. M. and W. D. Kelton. 1991. Simulation Modeling and Analysis. McGraw-Hill. New York.

Lenwood, W. H. Jr., M. C. Scott and W. D. Killen. 1998. Ecological risk assessment of copper and cadmium in the surface waters of Chesapeake Bay watershed. Environmental Toxicology and Chemistry 17(6): 1172-1189.

Matlock, M. D., D. E. Storm, J. G. Sabbagh, C. T. Haan, M. D. Smolen, and S. L. Burks. 1994. An ecological risk assessment paradigm using the Spatially Integrated Model for Phosphorus Loading and Erosion (SIMPLE). Journal of Aquatic Ecosystem Health 3: 287-294.

Microsoft Visual Basic. Redmond, Washington: Microsoft Corporation.

Moghissi, A. A. 1984. Risk assessment risk management – practice and prospects. Mechanical Engineering 103(11):21-23.

Montgomery, R. H., D. V. Lee and K. H. Reckhow. 1983. Predicting variability in Lake Ontario Phosphorus Model. Journal of Great Lakes 9(1):74-82.

Morgan, M. G. and M. Henrion. 1992. Uncertainty. Cambridge, England: Cambridge University Press.

National Research Council. 1983. Risk Assessment in Federal Government: Managing the Process. National Academy Press: Washington D. C.

Newbold, R. J. and J. W. Elwood. 1981. Measuring nutrient spiraling in streams. Canadian Journal of Fisheries and Aquatic Science 38: 860-863.

Nicks, A. D., L. J. Lane and G. A. Gander. 1995. Technical Documentation USDA Water Eosion Prediction Project (WEPP), Ch. 2 Weather Generator. West Lafayette, Indiana.

Novotny, V. and H. Olem. 1994. Water Quality Prevention Identification and Management for Diffuse Pollution. New York: Van Nostrand Reinhold.

NRCS. June, 2000. SSURGO Documentation. Natural Resources Conservation Service Available: http://gis.itc.nrcs.usda.gov/docs/SSURGO_Documentation.html. (January 2001).

Orvos, D. R. and J. Cairns Jr. 1991. Developing a risk assessment strategy for the Chesapeake Bay. Hydrobiologia. 215:189-203.

Parson, S. C., J. M. Hamlett, P. D. Robillard and M. A. Foster. 1998. Determining the decision-making risk from AGNPS simulations. Transactions of the ASAE 41(6): 1679-1688.

Paul, W. 1996. Monte Carlo and fuzzy approaches to environmental risk assessment in plant production. Acta Horticulture no. 406: 425-432.

Power, M. and D. G. Dixon, G. Power. 1994. Perspectives on environmental risk assessment. Journal of Aquatic Ecosystem Health 3: 69-79.

Reckhow, K. H. 1994.Water quality simulation modeling and uncertainty analysis for risk assessment and decision making. Ecological Modeling 72:1-20.

Renard, K. G., G. R. Foster, G. A. Weesies, and J. P Porter. 1991. RUSLE revised universal soil loss equation. Journal of Soil and Water Conservation Society 46: 30-33.

Rowe, W. D. 1977. An Anatomy of Risk. New York: John Wiley & Sons, Inc.

Rubinstein, R. Y. 1981. Simulation and the Monte Carlo Method. New York: John Wiley & Sons, Inc.

Ruckelshaus, W. D. 1983. Science, risk, and public policy. Science 221:1026-1028.

Schindler, D. W. 1977. The evolution of phosphorus limitation in lakes. Science 195:260-262.

Schwab, G. O., D. D. Fangmeier, W. J. Elliot and R. K. Frevert. 1993. Soil and Water Conservation Engineering. New York: John Wiley & Sons, Inc.

Sharpley, A. and H. Tunney. 2000. Phosphorus research strategies to meet agricultural and environmental challenges of the 21st century. Journal of Environmental Quality 29:176-181.

Simpson, T. W., S. J. Donohue, G. W. Hawkins, M. M. Monnett, and J. C. Baker. 1992. The development and implementation of the Virginia Agronomic Land Use Evaluation System (VALUES). Report. Department of Crop and Soil Environmental Sciences, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Smith, R. A., R. B. Alexander and M. G. Wolman. 1987. Water-quality trends in the nation's rivers. Science 235:1607-1615.

Singh, V. P. 1995. Computer models of watershed hydrology. Hydrologic Simulation Program Fortran (HSPF), ed. A. S. Donigian, Jr., ch. 12, 395-442. Highlands, Colorado: Water Resources Publications.

State Water Control Board. 1997. Surface water standards with general, statewide application. Richmond: Commonwealth of Virginia.

Stumm, W. 1992. Water, endangered ecosystem: assessment of chemical pollution. Journal of Environmental Engineering 118(4):466-476.

Summers, K. J., H. T. Wilson and J. Kou. 1993. A method for quantifying the predicted uncertainties associated with water quality models. Ecological Modeling 65:161-176.

Suter, G. W. II. 1993. Ecological Risk Assessment. Ann Arbor, MI: Lewis Publisher.

Suter, G. W. II. 1990. Endpoints for regional ecological risk assessments. Environmental Management 14(1):9-23.

Suter, G. W. II., L. W. Barnthouse, and R. V. O'Neill. 1987. Treatment of risk in environmental impact assessment. Environmental Management 11(3):295-303.

The Royal Observatory Greenwich. August 24, 2000. Leap Years. Available: http://www.rog.nmm.ac.uk/leaflets/leapyear/leapyear.html. (December 20, 2000).

Ünlü, K., D. R. Nielsen and J. W. Biggar. 1990. Stochastic analysis of unsaturated flow: one-dimensional Monte Carlo simulations and comparisons with spectral perturbation analysis and field observations. Water Resources Research 26(9):2207-2218.

USGS. September 27, 2000. Surface Water and Water Quality Models Information Clearinghouse. United States Geological Survey. Available: http://smig.usgs.gov/SMIC/SMIC.html. (March, 2000).

Veith, T. L, T. M. Nordberg, M. L. Wolfe and T. A. Dillaha. QUESTIONS: A user friendly interface to ANSWERS-2000. In preparation, Biological Systems Engineering. Virginia Polytechnic Institute and State University, Blacksburg.

Vollenweider, R. A. and J. Kerekes. 1980. The loading concept as basis for controlling eutrophication philosophy and preliminary results of the OECD programme on eutrophication. Progress in Water Technology 12(2):5-38.

WDMUtil Release 1.2. Washington D.C.: EPA's Office of Science and Technology (OST).

Whyte, A. V. and I. Burton (ed). 1980. Environmental Risk Assessment, SCOPE 15. New York: John Wiley & Sons, Inc.

Wicks, J. M., J. C. Bathurst and C. W. Johnson. 1992. Calibrating SHE-soil erosion model for different land covers. Journal of Irrigation and Drainage Engineering, ASCE 118(5):708-723.

Wilson, R. and E. A. C. Crouch. 1987. Risk assessment and comparisons: an introduction. Science 236:267-270.

APPENDIX A: Percent Cloud Cover Calculations

Equations used to calculate cloud cover (Eagleson, 1970):

$$R_s = \frac{(0.25 + 0.50n)}{N} R_a$$

$$R_a = 1.26714(h_{d0} / r_{ve})\left[h_s \frac{p}{180} Sin(f)Sin(d) + Cos(f)Cos(d)Sin(h_s)\right]$$

$$h_{d0} = 12.126 - 1.85191(10)^{-3} ABS(f) + 7.61048(10)^{-5}(f)^2$$

$$r_{ve} 0.98387 - 1.11403(10^{-4})(J) + 5.2774(10^{-6})(J)^2 - 2.68285(10^{-8})(J)^3 + 3.61634(10^{-11})(J)^4$$

$$h_s = Cos^{-1}(-Tan\, f Tan d)$$

$$d = \frac{180}{p}\begin{pmatrix} 0.006918 - 0.399912 Cos q + 0.070257 Sin q + 0.006758 Cos 2q + 0.000907 Sin 2q \\ -0.002697 Cos 3q - 0.001480 Sin 3q \end{pmatrix}$$

$$q = 0.986(J - 1)$$

Where:
- n/N = ratio between actual and possible hours of sunshine
- R_a = extraterrestrial radiation (mm/day);
- h_{d0} = daytime hours at zero declination, hours;
- r_{ve} = radius vector of the earth;
- h_s = sunrise to sunset hour angle in degrees;
- F = location latitude in degrees (positive for north latitudes and negative for south latitudes)
- d = declination of the sun in degrees;
- q = day of the year expressed in degrees; and
- J = days from January 1st (e.g., J=1 for Jan. 1, J=2 for Jan. 2,…., J=365 for Dec. 31).

Calculation of extraterrestrial solar radiation (Ra)

Latitude	38.5 deg	0.671952 rad	0.795436 tan of latitude
hd0, daytime hours at zero declination, hours		12.16751 hours	

Table A.1: Calculations to estimate cloud cover for use in HSPF weather input

Date	Julian day	day of the year in degrees	day of the year in radians	declination of the sun	hs, sunrise to sunset hour angle	r_{ve}, radius vector of earth	Ra
	day	*degrees*	*radians*	*degrees*	*degrees*		*mm/day*
1-Jan	1	0	0	-23.0586	70.20818	0.983764	6.03409
2-Jan	2	0.986	0.017209	-22.9881	70.27854	0.983668	6.054687
3-Jan	3	1.972	0.034418	-22.91	70.3564	0.983583	6.077278
4-Jan	4	2.958	0.051627	-22.8242	70.44171	0.983507	6.101865
5-Jan	5	3.944	0.068836	-22.7308	70.53442	0.983442	6.128445
6-Jan	6	4.93	0.086045	-22.6298	70.63445	0.983386	6.157016
7-Jan	7	5.916	0.103254	-22.5213	70.74173	0.98334	6.187575
8-Jan	8	6.902	0.120463	-22.4053	70.85619	0.983303	6.220115
9-Jan	9	7.888	0.137672	-22.2817	70.97773	0.983276	6.254632
10-Jan	10	8.874	0.154881	-22.1507	71.10628	0.983257	6.291119
11-Jan	11	9.86	0.172089	-22.0123	71.24173	0.983248	6.329567
12-Jan	12	10.846	0.189298	-21.8666	71.38398	0.983247	6.369966
13-Jan	13	11.832	0.206507	-21.7135	71.53292	0.983256	6.412308
14-Jan	14	12.818	0.223716	-21.5532	71.68846	0.983273	6.456579
15-Jan	15	13.804	0.240925	-21.3857	71.85046	0.983298	6.502766
16-Jan	16	14.79	0.258134	-21.211	72.01882	0.983331	6.550857
17-Jan	17	15.776	0.275343	-21.0292	72.1934	0.983373	6.600835
18-Jan	18	16.762	0.292552	-20.8405	72.37409	0.983422	6.652685
19-Jan	19	17.748	0.309761	-20.6448	72.56075	0.983479	6.706387
20-Jan	20	18.734	0.32697	-20.4422	72.75326	0.983544	6.761924
21-Jan	21	19.72	0.344179	-20.2329	72.95147	0.983616	6.819276
22-Jan	22	20.706	0.361388	-20.0168	73.15525	0.983696	6.878421
23-Jan	23	21.692	0.378597	-19.7941	73.36446	0.983783	6.939336
24-Jan	24	22.678	0.395806	-19.5649	73.57897	0.983877	7.001997
25-Jan	25	23.664	0.413015	-19.3293	73.79863	0.983978	7.066381
26-Jan	26	24.65	0.430224	-19.0873	74.02329	0.984086	7.13246
27-Jan	27	25.636	0.447433	-18.839	74.25281	0.9842	7.200208
28-Jan	28	26.622	0.464642	-18.5846	74.48706	0.984321	7.269595
29-Jan	29	27.608	0.48185	-18.3242	74.72588	0.984449	7.340593
30-Jan	30	28.594	0.499059	-18.0577	74.96913	0.984582	7.413171
31-Jan	31	29.58	0.516268	-17.7855	75.21667	0.984722	7.487296
1-Feb	32	30.566	0.533477	-17.5075	75.46835	0.984868	7.562936
2-Feb	33	31.552	0.550686	-17.2239	75.72403	0.98502	7.640058
3-Feb	34	32.538	0.567895	-16.9348	75.98357	0.985177	7.718625
4-Feb	35	33.524	0.585104	-16.6403	76.24683	0.98534	7.798603
5-Feb	36	34.51	0.602313	-16.3406	76.51366	0.985508	7.879953

Date	Julian day	day of the year in degrees	day of the year in radians	declination of the sun	hs, sunrise to sunset hour angle	r_{ve}, radius vector of earth	Ra
	day	*degrees*	*radians*	*degrees*	*degrees*		*mm/day*
6-Feb	37	35.496	0.619522	-16.0357	76.78393	0.985682	7.962639
7-Feb	38	36.482	0.636731	-15.7258	77.05751	0.985861	8.046622
8-Feb	39	37.468	0.65394	-15.4109	77.33425	0.986044	8.131863
9-Feb	40	38.454	0.671149	-15.0914	77.61402	0.986233	8.21832
10-Feb	41	39.44	0.688358	-14.7671	77.8967	0.986427	8.305953
11-Feb	42	40.426	0.705567	-14.4384	78.18215	0.986625	8.39472
12-Feb	43	41.412	0.722776	-14.1052	78.47024	0.986828	8.484578
13-Feb	44	42.398	0.739985	-13.7678	78.76086	0.987035	8.575485
14-Feb	45	43.384	0.757194	-13.4263	79.05387	0.987247	8.667398
15-Feb	46	44.37	0.774403	-13.0808	79.34916	0.987463	8.760271
16-Feb	47	45.356	0.791612	-12.7315	79.64661	0.987683	8.85406
17-Feb	48	46.342	0.80882	-12.3785	79.94611	0.987907	8.948721
18-Feb	49	47.328	0.826029	-12.0218	80.24754	0.988134	9.044208
19-Feb	50	48.314	0.843238	-11.6618	80.55079	0.988366	9.140475
20-Feb	51	49.3	0.860447	-11.2984	80.85575	0.988601	9.237476
21-Feb	52	50.286	0.877656	-10.9319	81.16233	0.988839	9.335166
22-Feb	53	51.272	0.894865	-10.5623	81.47041	0.989081	9.433498
23-Feb	54	52.258	0.912074	-10.1899	81.77989	0.989326	9.532426
24-Feb	55	53.244	0.929283	-9.81468	82.09069	0.989574	9.631904
25-Feb	56	54.23	0.946492	-9.43688	82.4027	0.989825	9.731885
26-Feb	57	55.216	0.963701	-9.05661	82.71583	0.99008	9.832323
27-Feb	58	56.202	0.98091	-8.67402	83.03	0.990336	9.933172
28-Feb	59	57.188	0.998119	-8.28923	83.34511	0.990596	10.03439
1-Mar	60	58.174	1.015328	-7.90238	83.66108	0.990858	10.13592
2-Mar	61	59.16	1.032537	-7.51361	83.97782	0.991123	10.23773
3-Mar	62	60.146	1.049746	-7.12307	84.29526	0.99139	10.33977
4-Mar	63	61.132	1.066955	-6.73088	84.61332	0.991659	10.44199
5-Mar	64	62.118	1.084164	-6.33717	84.93192	0.99193	10.54435
6-Mar	65	63.104	1.101373	-5.94209	85.25099	0.992204	10.64681
7-Mar	66	64.09	1.118582	-5.54577	85.57046	0.992479	10.74932
8-Mar	67	65.076	1.13579	-5.14834	85.89025	0.992756	10.85185
9-Mar	68	66.062	1.152999	-4.74993	86.2103	0.993035	10.95434
10-Mar	69	67.048	1.170208	-4.35066	86.53054	0.993315	11.05676
11-Mar	70	68.034	1.187417	-3.95068	86.85091	0.993597	11.15907
12-Mar	71	69.02	1.204626	-3.55011	87.17134	0.993881	11.26122
13-Mar	72	70.006	1.221835	-3.14908	87.49179	0.994165	11.36318
14-Mar	73	70.992	1.239044	-2.7477	87.81217	0.994451	11.46491
15-Mar	74	71.978	1.256253	-2.34611	88.13245	0.994738	11.56637
16-Mar	75	72.964	1.273462	-1.94443	88.45255	0.995026	11.66752
17-Mar	76	73.95	1.290671	-1.54277	88.77243	0.995315	11.76834
18-Mar	77	74.936	1.30788	-1.14126	89.09204	0.995605	11.86877
19-Mar	78	75.922	1.325089	-0.74002	89.41132	0.995895	11.96879
20-Mar	79	76.908	1.342298	-0.33917	89.73021	0.996186	12.06837
21-Mar	80	77.894	1.359507	0.061191	90.04867	0.996478	12.16747

Date	Julian day	day of the year in degrees	day of the year in radians	declination of the sun	hs, sunrise to sunset hour angle	r_{ve}, radius vector of earth	Ra
	day	*degrees*	*radians*	*degrees*	*degrees*		*mm/day*
22-Mar	81	78.88	1.376716	0.460938	90.36666	0.99677	12.26606
23-Mar	82	79.866	1.393925	0.85996	90.68411	0.997063	12.36411
24-Mar	83	80.852	1.411134	1.258149	91.00099	0.997356	12.46159
25-Mar	84	81.838	1.428343	1.655394	91.31724	0.997649	12.55848
26-Mar	85	82.824	1.445551	2.051588	91.63283	0.997942	12.65473
27-Mar	86	83.81	1.46276	2.446627	91.94769	0.998235	12.75033
28-Mar	87	84.796	1.479969	2.840405	92.2618	0.998528	12.84525
29-Mar	88	85.782	1.497178	3.232821	92.5751	0.998821	12.93947
30-Mar	89	86.768	1.514387	3.623774	92.88755	0.999113	13.03295
31-Mar	90	87.754	1.531596	4.013165	93.19911	0.999405	13.12568
1-Apr	91	88.74	1.548805	4.400896	93.50973	0.999697	13.21764
2-Apr	92	89.726	1.566014	4.78687	93.81936	0.999989	13.3088
3-Apr	93	90.712	1.583223	5.170994	94.12797	1.000279	13.39914
4-Apr	94	91.698	1.600432	5.553174	94.43551	1.000569	13.48865
5-Apr	95	92.684	1.617641	5.933319	94.74193	1.000859	13.57729
6-Apr	96	93.67	1.63485	6.311338	95.04719	1.001147	13.66507
7-Apr	97	94.656	1.652059	6.687144	95.35126	1.001435	13.75195
8-Apr	98	95.642	1.669268	7.060647	95.65407	1.001721	13.83792
9-Apr	99	96.628	1.686477	7.431764	95.95559	1.002007	13.92297
10-Apr	100	97.614	1.703686	7.800408	96.25577	1.002292	14.00708
11-Apr	101	98.6	1.720895	8.166497	96.55456	1.002575	14.09024
12-Apr	102	99.586	1.738104	8.529948	96.85192	1.002857	14.17243
13-Apr	103	100.572	1.755313	8.890681	97.14781	1.003137	14.25364
14-Apr	104	101.558	1.772521	9.248615	97.44216	1.003417	14.33386
15-Apr	105	102.544	1.78973	9.603673	97.73493	1.003694	14.41308
16-Apr	106	103.53	1.806939	9.955777	98.02608	1.003971	14.49129
17-Apr	107	104.516	1.824148	10.30485	98.31555	1.004245	14.56847
18-Apr	108	105.502	1.841357	10.65082	98.60329	1.004518	14.64462
19-Apr	109	106.488	1.858566	10.9936	98.88925	1.004789	14.71972
20-Apr	110	107.474	1.875775	11.33314	99.17336	1.005058	14.79378
21-Apr	111	108.46	1.892984	11.66934	99.45559	1.005325	14.86678
22-Apr	112	109.446	1.910193	12.00215	99.73586	1.005591	14.93871
23-Apr	113	110.432	1.927402	12.33149	100.0141	1.005854	15.00957
24-Apr	114	111.418	1.944611	12.65729	100.2903	1.006115	15.07935
25-Apr	115	112.404	1.96182	12.97947	100.5644	1.006374	15.14804
26-Apr	116	113.39	1.979029	13.29798	100.8363	1.006631	15.21565
27-Apr	117	114.376	1.996238	13.61275	101.1059	1.006886	15.28215
28-Apr	118	115.362	2.013447	13.9237	101.3733	1.007138	15.34756
29-Apr	119	116.348	2.030656	14.23077	101.6382	1.007388	15.41186
30-Apr	120	117.334	2.047865	14.53389	101.9007	1.007635	15.47505
1-May	121	118.32	2.065074	14.833	102.1606	1.00788	15.53712
2-May	122	119.306	2.082283	15.12803	102.418	1.008123	15.59807
3-May	123	120.292	2.099491	15.41891	102.6727	1.008362	15.65791
4-May	124	121.278	2.1167	15.70559	102.9247	1.008599	15.71661

Date	Julian day	day of the year in degrees	day of the year in radians	declination of the sun	hs, sunrise to sunset hour angle	r_{ve}, radius vector of earth	Ra
	day	*degrees*	*radians*	*degrees*	*degrees*		*mm/day*
5-May	125	122.264	2.133909	15.98799	103.1739	1.008834	15.77419
6-May	126	123.25	2.151118	16.26606	103.4202	1.009065	15.83063
7-May	127	124.236	2.168327	16.53973	103.6635	1.009294	15.88595
8-May	128	125.222	2.185536	16.80893	103.9038	1.009519	15.94012
9-May	129	126.208	2.202745	17.07361	104.1409	1.009742	15.99315
10-May	130	127.194	2.219954	17.3337	104.3748	1.009962	16.04504
11-May	131	128.18	2.237163	17.58915	104.6054	1.010179	16.09579
12-May	132	129.166	2.254372	17.83988	104.8327	1.010393	16.14538
13-May	133	130.152	2.271581	18.08584	105.0565	1.010603	16.19383
14-May	134	131.138	2.28879	18.32696	105.2767	1.010811	16.24113
15-May	135	132.124	2.305999	18.56319	105.4933	1.011015	16.28727
16-May	136	133.11	2.323208	18.79447	105.7061	1.011216	16.33225
17-May	137	134.096	2.340417	19.02073	105.9151	1.011413	16.37608
18-May	138	135.082	2.357626	19.24191	106.1202	1.011607	16.41875
19-May	139	136.068	2.374835	19.45797	106.3212	1.011798	16.46025
20-May	140	137.054	2.392044	19.66883	106.5182	1.011986	16.50059
21-May	141	138.04	2.409252	19.87444	106.7109	1.01217	16.53976
22-May	142	139.026	2.426461	20.07474	106.8993	1.01235	16.57777
23-May	143	140.012	2.44367	20.26968	107.0833	1.012527	16.6146
24-May	144	140.998	2.460879	20.45919	107.2628	1.0127	16.65025
25-May	145	141.984	2.478088	20.64322	107.4378	1.01287	16.68474
26-May	146	142.97	2.495297	20.82172	107.608	1.013036	16.71804
27-May	147	143.956	2.512506	20.99462	107.7734	1.013198	16.75016
28-May	148	144.942	2.529715	21.16189	107.934	1.013357	16.7811
29-May	149	145.928	2.546924	21.32345	108.0895	1.013512	16.81086
30-May	150	146.914	2.564133	21.47926	108.24	1.013663	16.83942
31-May	151	147.9	2.581342	21.62926	108.3853	1.01381	16.8668
1-Jun	152	148.886	2.598551	21.77341	108.5253	1.013953	16.89298
2-Jun	153	149.872	2.61576	21.91165	108.66	1.014093	16.91796
3-Jun	154	150.858	2.632969	22.04393	108.7892	1.014228	16.94175
4-Jun	155	151.844	2.650178	22.1702	108.9128	1.01436	16.96434
5-Jun	156	152.83	2.667387	22.29042	109.0308	1.014487	16.98572
6-Jun	157	153.816	2.684596	22.40454	109.1431	1.014611	17.00589
7-Jun	158	154.802	2.701805	22.51252	109.2496	1.01473	17.02485
8-Jun	159	155.788	2.719014	22.6143	109.3502	1.014846	17.0426
9-Jun	160	156.774	2.736222	22.70985	109.4448	1.014957	17.05913
10-Jun	161	157.76	2.753431	22.79912	109.5334	1.015065	17.07445
11-Jun	162	158.746	2.77064	22.88207	109.6158	1.015168	17.08854
12-Jun	163	159.732	2.787849	22.95867	109.6921	1.015267	17.1014
13-Jun	164	160.718	2.805058	23.02888	109.7621	1.015362	17.11304
14-Jun	165	161.704	2.822267	23.09265	109.8258	1.015453	17.12344
15-Jun	166	162.69	2.839476	23.14996	109.8831	1.01554	17.13262
16-Jun	167	163.676	2.856685	23.20078	109.934	1.015622	17.14055
17-Jun	168	164.662	2.873894	23.24507	109.9784	1.0157	17.14724

Date	Julian day	day of the year in degrees	day of the year in radians	declination of the sun	hs, sunrise to sunset hour angle	r_{ve}, radius vector of earth	Ra
	day	*degrees*	*radians*	*degrees*	*degrees*		*mm/day*
18-Jun	169	165.648	2.891103	23.2828	110.0162	1.015774	17.15269
19-Jun	170	166.634	2.908312	23.31395	110.0475	1.015844	17.15689
20-Jun	171	167.62	2.925521	23.33848	110.0721	1.015909	17.15985
21-Jun	172	168.606	2.94273	23.35639	110.0901	1.015971	17.16155
22-Jun	173	169.592	2.959939	23.36764	110.1014	1.016027	17.16199
23-Jun	174	170.578	2.977148	23.37222	110.106	1.01608	17.16118
24-Jun	175	171.564	2.994357	23.3701	110.1039	1.016128	17.1591
25-Jun	176	172.55	3.011566	23.36128	110.095	1.016172	17.15577
26-Jun	177	173.536	3.028775	23.34574	110.0794	1.016212	17.15117
27-Jun	178	174.522	3.045984	23.32348	110.057	1.016247	17.14529
28-Jun	179	175.508	3.063192	23.29447	110.0279	1.016278	17.13815
29-Jun	180	176.494	3.080401	23.25872	109.992	1.016304	17.12974
30-Jun	181	177.48	3.09761	23.21623	109.9495	1.016326	17.12005
1-Jul	182	178.466	3.114819	23.16699	109.9001	1.016344	17.10909
2-Jul	183	179.452	3.132028	23.111	109.8441	1.016358	17.09684
3-Jul	184	180.438	3.149237	23.04827	109.7815	1.016367	17.08332
4-Jul	185	181.424	3.166446	22.9788	109.7122	1.016371	17.06851
5-Jul	186	182.41	3.183655	22.90261	109.6363	1.016372	17.05242
6-Jul	187	183.396	3.200864	22.8197	109.5538	1.016368	17.03505
7-Jul	188	184.382	3.218073	22.73009	109.4649	1.016359	17.01639
8-Jul	189	185.368	3.235282	22.6338	109.3695	1.016347	16.99644
9-Jul	190	186.354	3.252491	22.53085	109.2677	1.016329	16.97521
10-Jul	191	187.34	3.2697	22.42125	109.1596	1.016308	16.95269
11-Jul	192	188.326	3.286909	22.30504	109.0452	1.016282	16.92888
12-Jul	193	189.312	3.304118	22.18224	108.9246	1.016252	16.90378
13-Jul	194	190.298	3.321327	22.05289	108.7979	1.016217	16.8774
14-Jul	195	191.284	3.338536	21.91701	108.6652	1.016178	16.84973
15-Jul	196	192.27	3.355745	21.77463	108.5265	1.016135	16.82077
16-Jul	197	193.256	3.372953	21.62581	108.3819	1.016087	16.79053
17-Jul	198	194.242	3.390162	21.47058	108.2316	1.016036	16.759
18-Jul	199	195.228	3.407371	21.30899	108.0756	1.015979	16.72619
19-Jul	200	196.214	3.42458	21.14107	107.914	1.015919	16.69209
20-Jul	201	197.2	3.441789	20.96688	107.7468	1.015854	16.65672
21-Jul	202	198.186	3.458998	20.78648	107.5743	1.015785	16.62006
22-Jul	203	199.172	3.476207	20.59991	107.3965	1.015712	16.58214
23-Jul	204	200.158	3.493416	20.40723	107.2136	1.015634	16.54293
24-Jul	205	201.144	3.510625	20.2085	107.0255	1.015552	16.50246
25-Jul	206	202.13	3.527834	20.00379	106.8325	1.015466	16.46073
26-Jul	207	203.116	3.545043	19.79315	106.6346	1.015376	16.41773
27-Jul	208	204.102	3.562252	19.57666	106.432	1.015282	16.37347
28-Jul	209	205.088	3.579461	19.35438	106.2247	1.015184	16.32796
29-Jul	210	206.074	3.59667	19.12638	106.0129	1.015081	16.28119
30-Jul	211	207.06	3.613879	18.89274	105.7968	1.014974	16.23319
31-Jul	212	208.046	3.631088	18.65353	105.5763	1.014863	16.18394

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	day	*degrees*	*radians*	*degrees*	*degrees*		*mm/day*
1-Aug	213	209.032	3.648297	18.40883	105.3516	1.014749	16.13346
2-Aug	214	210.018	3.665506	18.15872	105.1229	1.01463	16.08176
3-Aug	215	211.004	3.682715	17.90328	104.8903	1.014507	16.02883
4-Aug	216	211.99	3.699923	17.64259	104.6538	1.01438	15.97469
5-Aug	217	212.976	3.717132	17.37675	104.4136	1.014249	15.91934
6-Aug	218	213.962	3.734341	17.10583	104.1698	1.014114	15.8628
7-Aug	219	214.948	3.75155	16.82993	103.9225	1.013975	15.80507
8-Aug	220	215.934	3.768759	16.54914	103.6719	1.013833	15.74615
9-Aug	221	216.92	3.785968	16.26355	103.4179	1.013686	15.68606
10-Aug	222	217.906	3.803177	15.97326	103.1609	1.013536	15.62481
11-Aug	223	218.892	3.820386	15.67835	102.9007	1.013382	15.56241
12-Aug	224	219.878	3.837595	15.37893	102.6377	1.013224	15.49887
13-Aug	225	220.864	3.854804	15.0751	102.3718	1.013062	15.43419
14-Aug	226	221.85	3.872013	14.76695	102.1032	1.012897	15.3684
15-Aug	227	222.836	3.889222	14.45458	101.8319	1.012728	15.3015
16-Aug	228	223.822	3.906431	14.1381	101.5581	1.012555	15.2335
17-Aug	229	224.808	3.92364	13.81762	101.2819	1.012379	15.16442
18-Aug	230	225.794	3.940849	13.49323	101.0034	1.012199	15.09427
19-Aug	231	226.78	3.958058	13.16503	100.7227	1.012016	15.02307
20-Aug	232	227.766	3.975267	12.83315	100.4398	1.011829	14.95083
21-Aug	233	228.752	3.992476	12.49767	100.1549	1.011639	14.87756
22-Aug	234	229.738	4.009685	12.15871	99.86803	1.011446	14.80328
23-Aug	235	230.724	4.026893	11.81638	99.5793	1.011249	14.728
24-Aug	236	231.71	4.044102	11.47078	99.2888	1.011049	14.65175
25-Aug	237	232.696	4.061311	11.12203	98.9966	1.010845	14.57454
26-Aug	238	233.682	4.07852	10.77022	98.7028	1.010639	14.49638
27-Aug	239	234.668	4.095729	10.41548	98.40747	1.010429	14.41729
28-Aug	240	235.654	4.112938	10.05792	98.11069	1.010216	14.3373
29-Aug	241	236.64	4.130147	9.69763	97.81254	1.01	14.25642
30-Aug	242	237.626	4.147356	9.334737	97.5131	1.009781	14.17467
31-Aug	243	238.612	4.164565	8.969346	97.21243	1.009559	14.09206
1-Sep	244	239.598	4.181774	8.601569	96.91061	1.009334	14.00863
2-Sep	245	240.584	4.198983	8.231515	96.6077	1.009106	13.92439
3-Sep	246	241.57	4.216192	7.859296	96.30378	1.008875	13.83936
4-Sep	247	242.556	4.233401	7.485021	95.99891	1.008641	13.75356
5-Sep	248	243.542	4.25061	7.1088	95.69315	1.008405	13.66701
6-Sep	249	244.528	4.267819	6.730745	95.38657	1.008166	13.57975
7-Sep	250	245.514	4.285028	6.350964	95.07923	1.007925	13.49178
8-Sep	251	246.5	4.302237	5.969567	94.77118	1.007681	13.40314
9-Sep	252	247.486	4.319446	5.586663	94.46248	1.007434	13.31384
10-Sep	253	248.472	4.336654	5.202361	94.15319	1.007185	13.22392
11-Sep	254	249.458	4.353863	4.81677	93.84337	1.006933	13.13339
12-Sep	255	250.444	4.371072	4.429998	93.53306	1.00668	13.04228
13-Sep	256	251.43	4.388281	4.042153	93.22232	1.006424	12.95062

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14-Sep	257	252.416	4.40549	3.653341	92.9112	1.006165	12.85842
15-Sep	258	253.402	4.422699	3.26367	92.59974	1.005905	12.76572
16-Sep	259	254.388	4.439908	2.873246	92.28801	1.005642	12.67255
17-Sep	260	255.374	4.457117	2.482174	91.97604	1.005378	12.57892
18-Sep	261	256.36	4.474326	2.090561	91.66388	1.005111	12.48487
19-Sep	262	257.346	4.491535	1.698511	91.35158	1.004843	12.39043
20-Sep	263	258.332	4.508744	1.306128	91.03918	1.004573	12.29561
21-Sep	264	259.318	4.525953	0.913516	90.72672	1.004301	12.20045
22-Sep	265	260.304	4.543162	0.520778	90.41426	1.004027	12.10498
23-Sep	266	261.29	4.560371	0.128017	90.10183	1.003752	12.00922
24-Sep	267	262.276	4.57758	-0.26467	89.78947	1.003475	11.9132
25-Sep	268	263.262	4.594789	-0.65717	89.47724	1.003196	11.81696
26-Sep	269	264.248	4.611998	-1.04939	89.16516	1.002917	11.72051
27-Sep	270	265.234	4.629207	-1.44122	88.85328	1.002635	11.62389
28-Sep	271	266.22	4.646416	-1.83258	88.54165	1.002353	11.52713
29-Sep	272	267.206	4.663624	-2.22335	88.2303	1.002069	11.43026
30-Sep	273	268.192	4.680833	-2.61345	87.91927	1.001785	11.33331
1-Oct	274	269.178	4.698042	-3.00276	87.60861	1.001499	11.2363
2-Oct	275	270.164	4.715251	-3.39119	87.29837	1.001212	11.13927
3-Oct	276	271.15	4.73246	-3.77865	86.98857	1.000925	11.04225
4-Oct	277	272.136	4.749669	-4.16504	86.67927	1.000636	10.94527
5-Oct	278	273.122	4.766878	-4.55025	86.37051	1.000347	10.84835
6-Oct	279	274.108	4.784087	-4.9342	86.06233	1.000057	10.75154
7-Oct	280	275.094	4.801296	-5.31679	85.75477	0.999767	10.65485
8-Oct	281	276.08	4.818505	-5.69792	85.44788	0.999476	10.55832
9-Oct	282	277.066	4.835714	-6.07749	85.14171	0.999184	10.46199
10-Oct	283	278.052	4.852923	-6.45542	84.83631	0.998893	10.36588
11-Oct	284	279.038	4.870132	-6.83159	84.53171	0.998601	10.27002
12-Oct	285	280.024	4.887341	-7.20593	84.22797	0.998309	10.17444
13-Oct	286	281.01	4.90455	-7.57834	83.92514	0.998017	10.07919
14-Oct	287	281.996	4.921759	-7.94871	83.62327	0.997724	9.984275
15-Oct	288	282.982	4.938968	-8.31696	83.32242	0.997432	9.889743
16-Oct	289	283.968	4.956177	-8.683	83.02263	0.997141	9.795621
17-Oct	290	284.954	4.973386	-9.04672	82.72397	0.996849	9.701941
18-Oct	291	285.94	4.990594	-9.40804	82.42648	0.996558	9.608734
19-Oct	292	286.926	5.007803	-9.76686	82.13023	0.996267	9.516032
20-Oct	293	287.912	5.025012	-10.1231	81.83528	0.995977	9.423865
21-Oct	294	288.898	5.042221	-10.4766	81.5417	0.995687	9.332267
22-Oct	295	289.884	5.05943	-10.8274	81.24953	0.995399	9.241267
23-Oct	296	290.87	5.076639	-11.1753	80.95886	0.995111	9.150898
24-Oct	297	291.856	5.093848	-11.5202	80.66974	0.994824	9.06119
25-Oct	298	292.842	5.111057	-11.862	80.38225	0.994538	8.972176
26-Oct	299	293.828	5.128266	-12.2007	80.09647	0.994253	8.883887
27-Oct	300	294.814	5.145475	-12.5362	79.81245	0.993969	8.796353

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	day	*degrees*	*radians*	*degrees*	*degrees*		*mm/day*
28-Oct	301	295.8	5.162684	-12.8683	79.53029	0.993687	8.709606
29-Oct	302	296.786	5.179893	-13.1969	79.25006	0.993406	8.623678
30-Oct	303	297.772	5.197102	-13.5221	78.97184	0.993126	8.538598
31-Oct	304	298.758	5.214311	-13.8436	78.69571	0.992849	8.454398
1-Nov	305	299.744	5.23152	-14.1614	78.42177	0.992573	8.371109
2-Nov	306	300.73	5.248729	-14.4754	78.15009	0.992298	8.28876
3-Nov	307	301.716	5.265938	-14.7854	77.88077	0.992026	8.207383
4-Nov	308	302.702	5.283147	-15.0915	77.6139	0.991756	8.127008
5-Nov	309	303.688	5.300355	-15.3935	77.34958	0.991488	8.047665
6-Nov	310	304.674	5.317564	-15.6913	77.0879	0.991222	7.969383
7-Nov	311	305.66	5.334773	-15.9848	76.82897	0.990958	7.892192
8-Nov	312	306.646	5.351982	-16.2739	76.57289	0.990697	7.816122
9-Nov	313	307.632	5.369191	-16.5585	76.31975	0.990439	7.741202
10-Nov	314	308.618	5.3864	-16.8386	76.06968	0.990183	7.66746
11-Nov	315	309.604	5.403609	-17.1141	75.82278	0.98993	7.594926
12-Nov	316	310.59	5.420818	-17.3848	75.57915	0.98968	7.523627
13-Nov	317	311.576	5.438027	-17.6506	75.33892	0.989433	7.453593
14-Nov	318	312.562	5.455236	-17.9115	75.1022	0.989189	7.384849
15-Nov	319	313.548	5.472445	-18.1674	74.86911	0.988949	7.317425
16-Nov	320	314.534	5.489654	-18.4182	74.63977	0.988711	7.251347
17-Nov	321	315.52	5.506863	-18.6638	74.4143	0.988477	7.186641
18-Nov	322	316.506	5.524072	-18.904	74.19281	0.988247	7.123334
19-Nov	323	317.492	5.541281	-19.1389	73.97545	0.988021	7.061452
20-Nov	324	318.478	5.55849	-19.3683	73.76233	0.987798	7.001021
21-Nov	325	319.464	5.575699	-19.5921	73.55358	0.987579	6.942065
22-Nov	326	320.45	5.592908	-19.8103	73.34932	0.987365	6.88461
23-Nov	327	321.436	5.610117	-20.0227	73.1497	0.987154	6.828679
24-Nov	328	322.422	5.627325	-20.2293	72.95483	0.986948	6.774297
25-Nov	329	323.408	5.644534	-20.43	72.76484	0.986747	6.721486
26-Nov	330	324.394	5.661743	-20.6247	72.57987	0.986549	6.67027
27-Nov	331	325.38	5.678952	-20.8133	72.40005	0.986357	6.620671
28-Nov	332	326.366	5.696161	-20.9957	72.22551	0.986169	6.57271
29-Nov	333	327.352	5.71337	-21.1719	72.05637	0.985987	6.52641
30-Nov	334	328.338	5.730579	-21.3418	71.89277	0.985809	6.48179
1-Dec	335	329.324	5.747788	-21.5053	71.73482	0.985637	6.438872
2-Dec	336	330.31	5.764997	-21.6623	71.58267	0.98547	6.397675
3-Dec	337	331.296	5.782206	-21.8127	71.43643	0.985308	6.358218
4-Dec	338	332.282	5.799415	-21.9565	71.29622	0.985152	6.320519
5-Dec	339	333.268	5.816624	-22.0937	71.16217	0.985002	6.284597
6-Dec	340	334.254	5.833833	-22.224	71.0344	0.984858	6.250468
7-Dec	341	335.24	5.851042	-22.3475	70.91301	0.984719	6.218151
8-Dec	342	336.226	5.868251	-22.4642	70.79812	0.984587	6.18766
9-Dec	343	337.212	5.88546	-22.5738	70.68984	0.984461	6.159012
10-Dec	344	338.198	5.902669	-22.6765	70.58828	0.984341	6.132221

Date	Julian day	day of the year in degrees	day of the year in radians	declination of the sun	hs, sunrise to sunset hour angle	r_{ve}, radius vector of earth	Ra
	day	*degrees*	*radians*	*degrees*	*degrees*		*mm/day*
11-Dec	345	339.184	5.919878	-22.772	70.49354	0.984228	6.107301
12-Dec	346	340.17	5.937087	-22.8604	70.4057	0.984122	6.084267
13-Dec	347	341.156	5.954295	-22.9416	70.32487	0.984022	6.063131
14-Dec	348	342.142	5.971504	-23.0156	70.25113	0.983929	6.043904
15-Dec	349	343.128	5.988713	-23.0823	70.18457	0.983844	6.0266
16-Dec	350	344.114	6.005922	-23.1416	70.12525	0.983766	6.011228
17-Dec	351	345.1	6.023131	-23.1936	70.07326	0.983695	5.997798
18-Dec	352	346.086	6.04034	-23.2381	70.02865	0.983631	5.98632
19-Dec	353	347.072	6.057549	-23.2751	69.99149	0.983575	5.976803
20-Dec	354	348.058	6.074758	-23.3047	69.96183	0.983527	5.969254
21-Dec	355	349.044	6.091967	-23.3267	69.93972	0.983487	5.963679
22-Dec	356	350.03	6.109176	-23.3412	69.92519	0.983455	5.960087
23-Dec	357	351.016	6.126385	-23.3481	69.91828	0.983432	5.958481
24-Dec	358	352.002	6.143594	-23.3473	69.91901	0.983416	5.958866
25-Dec	359	352.988	6.160803	-23.339	69.9274	0.98341	5.961247
26-Dec	360	353.974	6.178012	-23.323	69.94347	0.983412	5.965625
27-Dec	361	354.96	6.195221	-23.2993	69.96722	0.983423	5.972002
28-Dec	362	355.946	6.21243	-23.268	69.99864	0.983442	5.98038
29-Dec	363	356.932	6.229639	-23.229	70.03773	0.983471	5.990759
30-Dec	364	357.918	6.246848	-23.1824	70.08447	0.98351	6.003138
31-Dec	365	358.904	6.264056	-23.128	70.13884	0.983557	6.017514

APPENDIX B: HplotEnglish Source Code

HplotEnglish VB Program Code

```
'Name:  HPlotEnglish

'This program converts the hydrograph output from ANSWERS-2000
'to HSPF compatible input format.

'Because of the way this program reads storm markers,
'there needs to be a STORMDATE marker at the end of the file with
'two blanks lines, a line with the first date of the year after
'the final simulation year, and three blank lines.

Const FirstYr = 2000

Private Sub Command1_Click()
  Dim flowIn As Double, Sediment As Double
  Dim SedimentNH4 As Double, DissolvedNH4 As Double
  Dim DissolvedPO4 As Double, SedimentPO4 As Double
  Dim SedimentTKN As Double, DissolvedNO3 As Double
  Dim newfile As String
  Dim intFileNumIN As Integer
  Dim curRec As String, strWord As String, strRow As String
  Dim start As Integer, length As Integer
  Dim j As Integer
  Dim dy As Integer, dylast As Integer, hr As Integer
  Dim juliandate As Long
  Dim daysInYr As Integer, yr As Integer, yrlast As Integer
  Dim hrFlow As Double, hrSed As Double
  Dim hrSedPO4 As Double, hrDisPO4 As Double
  Dim hrSedNH4 As Double, hrDisNH4 As Double
  Dim hrSedTKN As Double, hrDisNO3 As Double
  Dim dblInt As Double, totMin As Double, dblRemainder As Double
  Dim dblTime(101) As Double, flow(101) As Double, sed(101) As Double
  Dim sedPO4(101) As Double, disPO4(101) As Double
  Dim sedNH4(101) As Double, disNH4(101) As Double
  Dim sedTKN(101) As Double, disNO3(101) As Double
  Dim serialdate As Date
  Dim test As String

  'read data from form
  Label2.Caption = "Working Hard....Please Wait"
  Label2.ForeColor = &H80&
  HplotReader.Refresh
  myPath = Text1.Text
  cnt = Int(Text2.Text)

  'open file to write to
  newfile = myPath + "\eng" + Trim(cnt) + ".mut"
  Set fso = CreateObject("Scripting.FileSystemObject")
  Set ts = fso.CreateTextFile(newfile, True)
  ts.Write "------year-mo-da-hr-mn-<flow_(af)><sed_(t/hr)><sedPO4_(lb/hr)>"
  ts.Write "-<disPO4_(lb/hr)><sedNH4(lb/hr)><disNO3_(lb/hr)>" + vbNewLine
  intFileNumIN = FreeFile
  Open myPath + "\watershed" + Trim(cnt) + ".out" _
    For Input As intFileNumIN

  'transfer data
  yr = FirstYr
  hr = 1
  dy = 1
  dylast = dy
  Do Until EOF(intFileNumIN) 'read until end of file
```

```
        Line Input #intFileNumIN, curRec
        strRow = curRec
           start = 1
           length = 4
           strWord = Mid(strRow, start, length)

        'This program uses the STORMDATE line to mark the end of
        'each storm. This means that the first day can not have a storm
        'and that for each day the ELSE part of this if-loop is done,
        'for each line of that hydrograph, first. Then the IF part of
        'the loop is done. The ESLE part reads the hydrograph and puts
        'the data into arrays; the IF part transforms the data into hour
        'sections and writes it to the mutsin file.
        If strWord = "STOR" Then

           'check (for previous storm)to make sure that flow
           'does not temporarily return to zero before storm ends.
           For j = 1 To UBound(dblTime())
              If (flow(j) = Empty And Not (flow(j - 1) = 0)) Then
                 'search down the array for next non-zero
                 For k = j To UBound(flow())
                    If Not (flow(k) = Empty) Then
                       'found a nonzero so back fill from the
                       'zero flow to here with 0.01
                       For l = j To k
                          flow(l) = 0.01 * (35.3146667215) * (3600 / 43560.1742)
                       Next l
                       'quit loop and go back to searching
                       'for next non-zero
                       Exit For
                    End If
                 Next k
              End If
           Next j


If strDate = "17203" Then
   Debug.Print strDate
End If
           'calculate values for the previous stormdate
           dblInt = 0
           dblRemainder = 0
           totMin = 0
           hrFlow = 0
           hrSed = 0
           hrSedPO4 = 0
           hrDisPO4 = 0
           hrSedNH4 = 0
           hrDisNH4 = 0
           hrSedTKN = 0
           hrDisNO3 = 0
           For j = 1 To UBound(dblTime())
              'if hydrograph extent is not reached yet
              If Not ((dblTime(j) = 0) And Not (dblTime(j - 1) = 0)) Then
              dblInt = dblTime(j) - dblTime(j - 1)
              totMin = totMin + dblInt
              If totMin > 60 Then
                 'split interval into remainder of hour
                 dblInt = 60 * hr - dblTime(j - 1)
                 dblRemainder = dblTime(j) - 60 * hr
                 totMin = totMin - dblRemainder
              End If
```

```
    hrFlow = hrFlow + dblInt * flow(j) / 60
    hrSed = hrSed + dblInt * sed(j) / 60
    hrSedPO4 = hrSedPO4 + dblInt * sedPO4(j) / 60
    hrDisPO4 = hrDisPO4 + dblInt * disPO4(j) / 60
    hrSedNH4 = hrSedNH4 + dblInt * sedNH4(j) / 60
    hrDisNH4 = hrDisNH4 + dblInt * disNH4(j) / 60
    hrSedTKN = hrSedTKN + dblInt * sedTKN(j) / 60
    hrDisNO3 = hrDisNO3 + dblInt * disNO3(j) / 60
    End If
    'IF a full hour of data OR if the storm has ended
    'OR if extent of hydrograph is reached
    'THEN write data to file for that hour
    If (totMin = 60) Or _
      (flow(j) = Empty And Not (flow(j - 1) = 0)) Or _
      ((dblTime(j) = 0) And Not (dblTime(j - 1) = 0)) Then
      'write line for this hour
      'get correct date
      strDate = Mid(yr, 3, 2) + Format(dy, "000")
      juliandate = CLng(strDate)
      serialdate = DateSerial(2000 + _
        Int(juliandate / 1000), 1, juliandate Mod 1000)
      ts.Write "      " + Format(yr - 60, "0000") + " " + _
        Format(serialdate, "mm dd") + " "
      ts.Write Format(hr, "00") + " 00 "
      ts.Write Format(hrFlow, "00.000000000") + " "
      ts.Write Format(hrSed, "0000.00000000") + " "
      ts.Write Format(hrSedPO4, "0000.00000000") + " "
      ts.Write Format(hrDisPO4, "0000.00000000") + " "
      ts.Write Format(hrSedNH4, "0000.00000000") + " "
      ts.Write Format(hrDisNO3, "0000.00000000") + vbNewLine

      'clear hourly values
      hrFlow = 0
      hrSed = 0
      hrSedPO4 = 0
      hrDisPO4 = 0
      hrSedNH4 = 0
      hrDisNH4 = 0
      hrSedTKN = 0
      hrDisNO3 = 0
      totMin = 0

      'reset variables with remainder of interval
       If Not (dblRemainder = 0) Then
         hrFlow = dblRemainder * flow(j) / 60
         hrSed = dblRemainder * sed(j) / 60
         hrSedPO4 = dblRemainder * sedPO4(j) / 60
         hrDisPO4 = dblRemainder * disPO4(j) / 60
         hrSedNH4 = dblRemainder * sedNH4(j) / 60
         hrDisNO3 = dblRemainder * disNO3(j) / 60
         totMin = dblRemainder
         dblRemainder = 0
       End If

      'increase hour
      hr = hr + 1
    End If
  Next j

  'fill in blank values for remainder of stormdate
  Do Until hr > 24
    hrFlow = 0
```

```
    hrSed = 0
    hrSedPO4 = 0
    hrDisPO4 = 0
    hrSedNH4 = 0
    hrDisNH4 = 0
    hrSedTKN = 0
    hrDisNO3 = 0

    'get correct date
    strDate = Mid(yr, 3, 2) + Format(dy, "000")
    juliandate = CLng(strDate)
    serialdate = DateSerial(2000 + _
      Int(juliandate / 1000), 1, juliandate Mod 1000)

    'write line for this hour
    ts.Write "      " + Format(yr - 60, "0000") + " " + _
      Format(serialdate, "mm dd") + " "
    ts.Write Format(hr, "00") + " 00 "
    ts.Write Format(hrFlow, "00.000000000") + " "
    ts.Write Format(hrSed, "0000.00000000") + " "
    ts.Write Format(hrSedPO4, "0000.00000000") + " "
    ts.Write Format(hrDisPO4, "0000.00000000") + " "
    ts.Write Format(hrSedNH4, "0000.00000000") + " "
    ts.Write Format(hrDisNO3, "0000.00000000") + vbNewLine
   hr = hr + 1
Loop

'fill in days from lst stormdate to current stormdate
hr = 1
dy = dy + 1
dylast = dy
yrlast = yr
yr = Int(Mid(strRow, 15, 4)) 'read year
dy = Int(Mid(strRow, 19, 3)) 'read day
If (yrlast Mod 4) = 0 Then
  daysInYr = 366
Else
  daysInYr = 365
End If
If yrlast < yr Then
  Do Until dylast > daysInYr
    hr = 1
    Do Until hr > 24
      hrFlow = 0
      hrSed = 0
      hrSedPO4 = 0
      hrDisPO4 = 0
      hrSedNH4 = 0
      hrDisNH4 = 0
      hrSedTKN = 0
      hrDisNO3 = 0

      'get correct date
      strDate = Mid(yrlast, 3, 2) + Format(dylast, "000")
      juliandate = CLng(strDate)
      serialdate = DateSerial(2000 + _
        Int(juliandate / 1000), 1, juliandate Mod 1000)

      'write line for this hour
      ts.Write "      " + Format(yrlast - 60, "0000") + " " + _
        Format(serialdate, "mm dd") + " "
      ts.Write Format(hr, "00") + " 00 "
```

```
                ts.Write Format(hrFlow, "00.000000000") + " "
                ts.Write Format(hrSed, "0000.00000000") + " "
                ts.Write Format(hrSedPO4, "0000.00000000") + " "
                ts.Write Format(hrDisPO4, "0000.00000000") + " "
                ts.Write Format(hrSedNH4, "0000.00000000") + " "
                ts.Write Format(hrDisNO3, "0000.00000000") + vbNewLine
               hr = hr + 1
            Loop
            dylast = dylast + 1
         Loop
         yrlast = yr
         dylast = 1
         hr = 1
      End If
      Do Until (dylast = dy)
         hr = 1
         Do Until hr > 24
            hrFlow = 0
            hrSed = 0
            hrSedPO4 = 0
            hrDisPO4 = 0
            hrSedNH4 = 0
            hrDisNH4 = 0
            hrSedTKN = 0
            hrDisNO3 = 0

            'get correct date
            strDate = Mid(yrlast, 3, 2) + Format(dylast, "000")
            juliandate = CLng(strDate)
            serialdate = DateSerial(2000 + _
            Int(juliandate / 1000), 1, juliandate Mod 1000)

            'write line for this hour
           ts.Write "      " + Format(yrlast - 60, "0000") + " " + _
               Format(serialdate, "mm dd") + " "
            ts.Write Format(hr, "00") + " 00 "
            ts.Write Format(hrFlow, "00.000000000") + " "
            ts.Write Format(hrSed, "0000.00000000") + " "
            ts.Write Format(hrSedPO4, "0000.00000000") + " "
            ts.Write Format(hrDisPO4, "0000.00000000") + " "
            ts.Write Format(hrSedNH4, "0000.00000000") + " "
            ts.Write Format(hrDisNO3, "0000.00000000") + vbNewLine
            hr = hr + 1
         Loop
         dylast = dylast + 1
         hr = 1
      Loop

If curRec = "STORM DATE = 2014236" Then
   Debug.Print strDate
End If
        'skip three lines and read 4th
        Line Input #intFileNumIN, curRec
        Line Input #intFileNumIN, curRec
        Line Input #intFileNumIN, curRec

        'clear arrays and set to fill at beginning
        Erase dblTime
        Erase flow
        Erase sed
        Erase sedPO4
        Erase disPO4
```

```
    Erase sedNH4
    Erase disNH4
    Erase sedTKN
    Erase disNO3
    j = 0
  Else 'not (strWord = "STOR")
     'read the data from the (previous) storm
     strRow = curRec

     'store minutes
        start = 5
        length = 6
        strWord = Mid(strRow, start, length)
     If Not ((strWord = "") Or (strWord = "      ")) Then
        dblTime(j) = CDbl(strWord)
        start = 31
        length = 0
        'store flow
           start = start + length
           length = 10
           strWord = Mid(strRow, start, length)
           If Trim(strWord) = "NaN" Then
            flow(j) = 0
           ElseIf Trim(strWord) = "*********" Then
            flow(j) = 0
           Else
            flowIn = CDbl(strWord)
            'flow(j) = flowIn * (1 / 1000000) * 3600
            flow(j) = flowIn * (35.3146667215) * (3600 / 43560.1742)
            ' converts m^3/s -> ac-ft/hr
           End If
        'store sediment
           start = start + length
           length = 10
           strWord = Mid(strRow, start, length)
           If Trim(strWord) = "NaN" Then
            sed(j) = 0
           ElseIf Trim(strWord) = "*********" Then
            sed(j) = 0
           Else
            Sediment = CDbl(strWord)
            sed(j) = Sediment * (flowIn) * 3.6 * (2.20462 / 2000)
            'sediment input converted from mg/l to ton (2000lb/ton)/hr
           End If
        'store sedPO4
           start = start + length
           length = 10
           strWord = Mid(strRow, start, length)
           If Trim(strWord) = "NaN" Then
            sedPO4(j) = 0
           ElseIf Trim(strWord) = "*********" Then
            sedPO4(j) = 0
           Else
            SedimentPO4 = CDbl(strWord)
            sedPO4(j) = SedimentPO4 * (flowIn * 3.6) * (2.20462)
            ' sediment bound PO4 converted from mg/l to lb/hr
           End If
        'store disPO4
           start = start + length
           length = 10
           strWord = Mid(strRow, start, length)
           If Trim(strWord) = "NaN" Then
```

```
            disPO4(j) = 0
          ElseIf Trim(strWord) = "*********" Then
            disPO4(j) = 0
          Else
            DissolvedPO4 = CDbl(strWord)
            disPO4(j) = DissolvedPO4 * (flowIn * 3.6) * (2.20462)
            'disPO4(j) = DissolvedPO4 * flowIn * (3600 / 1000)
          End If
      'store sedNH4
          start = start + length
          length = 10
          strWord = Mid(strRow, start, length)
          If Trim(strWord) = "NaN" Then
            sedNH4(j) = 0
          ElseIf Trim(strWord) = "*********" Then
            sedNH4(j) = 0
          Else
            SedimentNH4 = CDbl(strWord)
            sedNH4(j) = SedimentNH4 * (flowIn * 3.6) * (2.20462)
            'sedNH4(j) = SedimentNH4 * flowIn * (3600 / 1000)
          End If
       'store disNH4
          start = start + length
          length = 10
          strWord = Mid(strRow, start, length)
          If Trim(strWord) = "NaN" Then
            disNH4(j) = 0
          ElseIf Trim(strWord) = "*********" Then
            disNH4(j) = 0
          Else
            DissolvedNH4 = CDbl(strWord)
            disNH4(j) = DissolvedNH4 * (flowIn * 3.6) * (2.20462)
            'disNH4(j) = DissolvedNH4 * flowIn * (3600 / 1000)
          End If
       'store sedTKN
          start = start + length
          length = 10
          strWord = Mid(strRow, start, length)
          If Trim(strWord) = "NaN" Then
            sedTKN(j) = 0
          ElseIf Trim(strWord) = "*********" Then
            sedTKN(j) = 0
          Else
            SedimentTKN = CDbl(strWord)
            sedTKN(j) = SedimentTKN * (flowIn * 3.6) * (2.20462)
            'sedTKN(j) = SedimentTKN * flowIn * (3600 / 1000)
          End If
        'store disNO3
          start = start + length
          length = 10
          strWord = Mid(strRow, start, length)
          If Trim(strWord) = "NaN" Then
            disNO3(j) = 0
          ElseIf Trim(strWord) = "*********" Then
            disNO3(j) = 0
          Else
            DissolvedNO3 = CDbl(strWord)
            disNO3(j) = DissolvedNO3 * (flowIn * 3.6) * (2.20462)
            'disNO3(j) = DissolvedNO3 * flowIn * (3600 / 1000)
          End If
        'increment array counter
           j = j + 1
```

```
        End If
      End If
   Loop 'end of loop through each row
   Close #intFileNumIN
   ts.Close 'close file being written to

   'refresh form to show finished status
   Label2.BackColor = &HC000&
   Label2.ForeColor = &H4000&
   Label2.Caption = "The program is finished!!"
   HplotReader.Refresh
End Sub
```

APPENDIX C: MutReader Source Code

MutReader Program VB Code

```
' Name: MutReader
'
'This program reads the MUTSIN files from HSPF and flow weighted adds
' the dissolved and sedimentbound Phosphorus to Total Phosphorus,
' The TP values for every hour there was an runoff event is then
' printed in a textfiles called TPprobZS.txt. Inaddition to this file
' a file named TPprob.txt containt only TP runoff event values not
' equal to zero, this file is used for distribution fitting.
' containing all the hourly runoff event TP values

Private arTPmgps() As Double
Private arFlowLPS() As Double
Private arStormFlag() As Boolean
Private Sub Form_Load()
   ReDim arTPmgps(438312)
   ReDim arFlowLPS(438312)
   ReDim arStormFlag(438312)
End Sub
Private Sub Command1_Click()
   Dim fs As FileSystemObject
   Set fs = CreateObject("Scripting.FileSystemObject")
   Dim myPath As String
   Dim myFileNum As Integer

   'read data from file
   Label2.Caption = "reading reading reading reading"
   Label2.ForeColor = &H80&
   MutsinReader.Refresh

   myPath = Text1.Text 'this is working directory
   myFileNum = Int(Text2.Text) 'this is watershed id number
   Call fillTable(myPath, myFileNum)
   Call WriteFile(myPath)

   'indicate finished
   Label2.Caption = "I am done reading in subwatershed."
   Label2.ForeColor = &HF52333

   ' the number 12 hardcoded to fit the number of subwatersheds in the sample
   ' application. It is not necessary to change this number in order to run
   ' the program, but the termination statement will not appear at the right time
   ' To correct this change the cnt=# to the total number of subwatersheds present
   ' in system.
   If cnt = 12 Then
      Label2.Caption = "Program complete!"
      Label2.ForeColor = &HD0174
      Form.BackColor = &H80FFFF
   End If
   MutsinReader.Refresh
End Sub
Sub fillTable(strWrkDir As String, cnt As Integer)
   Const delimiter = " "
   Dim strField As String, strLine As String
   Dim intPos As Integer
   Dim dblFlowAcftphr As Double, dblFlowLPS As Double
   Dim dblSedPlbphr As Double, dblDisPlbphr As Double, dblTPmgpl As Double

   'open file to read
   intFileNumIN = FreeFile
   Open strWrkDir + "\eng" + Trim(cnt) + ".mut" _
```

```
    For Input As intFileNumIN

'skip first line in file
Line Input #intFileNumIN, curRec

i = 0
Do Until EOF(intFileNumIN) 'read until end of file
    'set array counter
        i = i + 1
    'read line
        Line Input #intFileNumIN, curRec
        strLine = curRec
    'discard 1st 23 spaces
        strLine = Right(strLine, Len(strLine) - 23)
    'check flow
        ' Move position to delimiter.
        intPos = InStr(strLine, " ")
        ' Assign field text to strField variable.
        dblFlowAcftphr = CDbl(Left(strLine, intPos - 1))
        'set StormFlag (default is FALSE)
            If dblFlowAcftphr > 0 Then
                arStormFlag(i) = True
            End If
        ' Strip off field value text from text row.
        strLine = Right(strLine, Len(strLine) - intPos)
    'skip sed column of mutsin file.
        ' Move position to delimiter.
        intPos = InStr(strLine, " ")
        'Strip off field value text from text row.
        strLine = Right(strLine, Len(strLine) - intPos)
    'get sedP
        ' Move position to delimiter.
        intPos = InStr(strLine, delimiter)
        ' Assign field text to strField variable.
        dblSedPlbphr = CDbl(Left(strLine, intPos - 1))
        ' Strip off field value text from text row.
        strLine = Right(strLine, Len(strLine) - intPos)
    'get disP
        ' Move position to delimiter.
        intPos = InStr(strLine, delimiter)
        ' Assign field text to strField variable.
        dblDisPlbphr = CDbl(Left(strLine, intPos - 1))
        ' Strip off field value text from text row.
        strLine = Right(strLine, Len(strLine) - intPos)
    'calc TP for this wshed
        If dblFlowAcftphr > 0 Then
            'convert flow from ac-ft/hr to l/s
            dblFlowLPS = dblFlowAcftphr * 1000 * 1233.482 / 3600
            'TP in mg/l for each wshed = sedPO4(lb/hr)+disPO4(lb/hr)
            dblTPmgpl = (dblSedPlbphr + dblDisPlbphr) * 1000 / (2.20462 * 3.6)
            'TP in mg/s for each wshed
            dblTPmgps = dblTPmgpl * dblFlowLPS
        Else
            dblFlowLPS = 0
            dblTPmgpl = 0
            dblTPmgps = 0
        End If

    'Accumulating sum of TP in mg/s for all wsheds
        arTPmgps(i) = arTPmgps(i) + dblTPmgps
    'Accumulating sum of Flow in l/s for all wsheds
        arFlowLPS(i) = arFlowLPS(i) + dblFlowLPS
```

```
'Debug.Print "dblFlowAcftphr = "; dblFlowAcftphr; " dblFlowLPS = "; dblFlowLPS;
'Debug.Print "dblTPmgpl ="; dblTPmgpl; "dblTPmgps = "; dblTPmgps
'Debug.Print "cumul TPmgps = "; arTPmgps(i); "cumul FlowLPS = "; arFlowLPS(i)
  Loop 'until EOF(mutsin)
End Sub
Private Sub WriteFile(strWrkDir As String)
  Const ForWriting = 2
  Const TristateUseDefault = -2
  Dim fs As FileSystemObject
  Dim f As File
  Dim ts As TextStream
  Dim dblFinalTPmgpl As Double

  Set fs = CreateObject("Scripting.FileSystemObject")

  'make file without Zeros
  If Not fs.FileExists(strWrkDir + "\TPprob.txt") Then
    fs.CreateTextFile (strWrkDir + "\TPprob.txt")
  End If
  Set f = fs.GetFile(strWrkDir + "\TPprob.txt")
  Set ts = f.OpenAs TextStream(ForWriting, TristateUseDefault)

  For i = 1 To UBound(arTPmgps())
    'if storm then calc and write TP in mg/l for entire area
    If arStormFlag(i) = True Then
      dblFinalTPmgpl = arTPmgps(i) / arFlowLPS(i)
      ts.WriteLine dblFinalTPmgpl
    End If
  Next i
  ts.Close

  'make file with Zeros
  If Not fs.FileExists(strWrkDir + "\TPprobZS.txt") Then
    fs.CreateTextFile (strWrkDir + "\TPprobZS.txt")
  End If
  Set f = fs.GetFile(strWrkDir + "\TPprobZS.txt")
  Set ts = f.OpenAsTextStream(ForWriting, TristateUseDefault)

  For i = 1 To UBound(arTPmgps())
    If arStormFlag(i) = True Then
      'if storm then calc and write TP in mg/l for entire area
      dblFinalTPmgpl = arTPmgps(i) / arFlowLPS(i)
      ts.WriteLine dblFinalTPmgpl
    Else
      'else no storm and flow = zero so write zero for TP
      dblFinalTPmgpl = 0
      ts.WriteLine dblFinalTPmgpl
    End If
  Next i
  ts.Close
End Sub
```

APPENDIX D: RiskCalc Source Code

RiskCalc Program VB Code

```
'Name RiskCalc

'This program reads calculates the risk reading the input from the
'MutReader program (the TPprobZS.txt). This program can either calculate
'a single risk event using the input boxes or it can calculate a series
'of risk events when provided with a CalcProb.txt files that contains the
'TP value and the corresponding probability of occurrence.

Private arDate() As String
Private arTP() As Double
Private arFlow() As Double
Private arDO() As Double

'for writing file
Dim fs As FileSystemObject
Dim f As File
Dim ts As TextStream

Private Sub Form_Load()
  ReDim arDate(438311)
  ReDim arTP(438311)
  ReDim arFlow(438311)
  ReDim arDO(438311)

  'set form parameters
  Label2.Caption = "Waiting on you!"
  Label2.ForeColor = &HFF&
  RiskCalc.Refresh
End Sub

Private Sub Command1_Click()
  Dim i As Long, j As Integer
  Dim myPath As String, strLine As String, curRec As String
  Dim intPos As Integer, intFileNumIN As Integer

  'set form parameters
  Label2.Caption = "Working Hard....Please Wait"
  Label2.ForeColor = &HFF00FF
  RiskCalc.Refresh

  myPath = Text1.Text 'this is working directory

  'read TP data from file
    'open file to read
    intFileNumIN = FreeFile
    Open myPath + "\TPprobZS.txt" _
      For Input As intFileNumIN
    'set array counter
    i = 0
    'read until end of file
    Do Until EOF(intFileNumIN)
      'read line
      Line Input #intFileNumIN, curRec
      'Assign to TP array.
      arTP(i) = CDbl(curRec)
      'increment array counter
      i = i + 1
    Loop
    Close #intFileNumIN
```

```
    'read Date, Flow, DO data from file
        'open file to read
        intFileNumIN = FreeFile
        Open myPath + "\LOLACFS.out" _
            For Input As intFileNumIN
        'set array counter
         For j = 1 To 26
            'read line
            Line Input #intFileNumIN, curRec
        Next j

        i = 0
        'read until end of file
        Do Until EOF(intFileNumIN)
            'read line
            Line Input #intFileNumIN, curRec
                strLine = curRec
                ' Assign 1st column to Date array.
                arDate(i) = Trim(Mid(strLine, 7, 13))
                ' Assign 2nd column to Flow array.
                'divided by 6 because to get average from HSPF
                arFlow(i) = CDbl(Mid(strLine, 23, 14))
                ' Assign 3rd column to DO array.
                'divided by 6 because to get average from HSPF
                arDO(i) = (CDbl(Mid(strLine, 37, 13)))
            'increment array counter
            i = i + 1
        Loop
        Close #intFileNumIN

    'indicate finished
    Label2.Caption = "I am done reading in files."
    Label2.ForeColor = &HFF&
    RiskCalc.Refresh
End Sub
Private Sub Command2_Click()
    Dim i As Long
    Dim dblTPprob As Double, dblDOValue As Double
    Dim dblLowValue As Double, dblHighValue As Double
    Dim intHourDO As Long, dblAvgDO As Double
    Dim intTPCount As Long
    Dim dblRisk As Double

    'read inputs from form
    dblTPprob = CDbl(Text5.Text)
    dblDOValue = CDbl(Text4.Text)
'   dblLowValue = CDbl(Text2.Text)
    dblHighValue = CDbl(Text3.Text)

    'calculate consequence
    intHourDO = 0
    intTPCount = 0
    For i = 0 To UBound(arTP())
'       If arTP(i) >= dblLowValue And arTP(i) < dblHighValue Then
         If arTP(i) > dblHighValue Then
            intTPCount = intTPCount + 1
            If arDO(i) < dblDOValue Then
                intHourDO = intHourDO + 1
            End If
        End If
    Next i
    dblAvgDO = intHourDO / intTPCount
```

```
    'calc risk
    dblRisk = dblTPprob * dblAvgDO

    'print to form
    Label2.Caption = "Average hours of DO below level, given critical TP loading, = " _
        + Format(dblAvgDO, "#######.######") + vbNewLine _
        + "Risk = " + Format(dblRisk, "######.######")
    RiskCalc.Refresh
    Label2.ForeColor = &HFFFFF&
End Sub

Private Sub Command3_Click()
    Dim i As Long, j As Integer
    Dim myPath As String, strLine As String, curRec As String
    Dim intPos As Integer, intFileNumIN As Integer

    Dim dblTPprob As Double, dblDOValue As Double
'   Dim dblLowValue As Double
    Dim dblHighValue As Double
'   Dim intHourDO As Long,
    Dim intCumHourDO As Long
'   Dim dblAvgDO As Double
    Dim dblCumAvgDO As Double
'   Dim intTPCount As Long
    Dim intCumTPCount As Long
'   Dim dblRisk As Double
    Dim dblCumRisk As Double

    Dim arXvalue(90) As Double
    Dim arProbTPLessX(90) As Double

    myPath = Text1.Text 'this is working directory

    'read cumulative probability data from file
        'open file to read
        intFileNumIN = FreeFile
        Open myPath + "\CalcProb.txt" _
            For Input As intFileNumIN
        'set array counter
        i = 0
        'read until end of file
        Do Until EOF(intFileNumIN)
            'read line
            Line Input #intFileNumIN, curRec
                strLine = curRec
                ' Move position to delimiter.
                intPos = InStr(strLine, vbTab)
                ' Assign 1st column
                arXvalue(i) = CDbl(Left(strLine, intPos - 1))
                ' Assign 2nd column
                arProbTPLessX(i) = CDbl(Right(strLine, Len(strLine) - intPos))
            'increment array counter
            i = i + 1
        Loop
        Close #intFileNumIN

    'open file to write to
    Call OpenWriteFile(myPath, "\risks.out")
    ts.WriteLine "Critical_DO=4.0"
    ts.WriteLine "TP_critical P(x>TP_Critical) Avg_hrs_DO Risk_Level"
```

```
For cnt = 1 To UBound(arXvalue())
   'read inputs from form
   dblDOValue = 4#
'   dblLowValue = arXvalue(cnt - 1)
   dblHighValue = arXvalue(cnt)

   'calculate consequence
   intCumHourDO = 0
   intCumTPCount = 0
   For i = 0 To UBound(arTP())
       If arTP(i) > dblHighValue Then
         intCumTPCount = intCumTPCount + 1
         If arDO(i) < dblDOValue Then
            intCumHourDO = intCumHourDO + 1
         End If
      End If
   Next i

   If intCumTPCount <> 0 Then
      dblCumAvgDO = intCumHourDO / intCumTPCount

   Else
      dblCumAvgDO = 0
   End If

   'calc risk
   dblCumRisk = (1 - arProbTPLessX(cnt)) * dblCumAvgDO
   'write risk
   ts.Write Str(dblHighValue) + " " + Str(1 - arProbTPLessX(cnt)) + " "
   ts.Write Str(dblCumAvgDO) + " " + Str(dblCumRisk) + vbNewLine
Next cnt
ts.Close

   'indicate finished
   Label2.Caption = "Finshed. Output in RISKS.OUT"
   Label2.ForeColor = &HFF&
   RiskCalc.Refresh

End Sub

Private Sub OpenWriteFile(strWrkDir As String, filename As String)
   Const ForWriting = 2
   Const TristateUseDefault = -2

   Set fs = CreateObject("Scripting.FileSystemObject")

   'make file for solution
   If Not fs.FileExists(strWrkDir + filename) Then
      fs.CreateTextFile (strWrkDir + filename)
   End If
   Set f = fs.GetFile(strWrkDir + filename)
   Set ts = f.OpenAsTextStream(ForWriting, TristateUseDefault)
End Sub
```

APPENDIX E: ANSWERS-2000 Output

Subwatershed 1

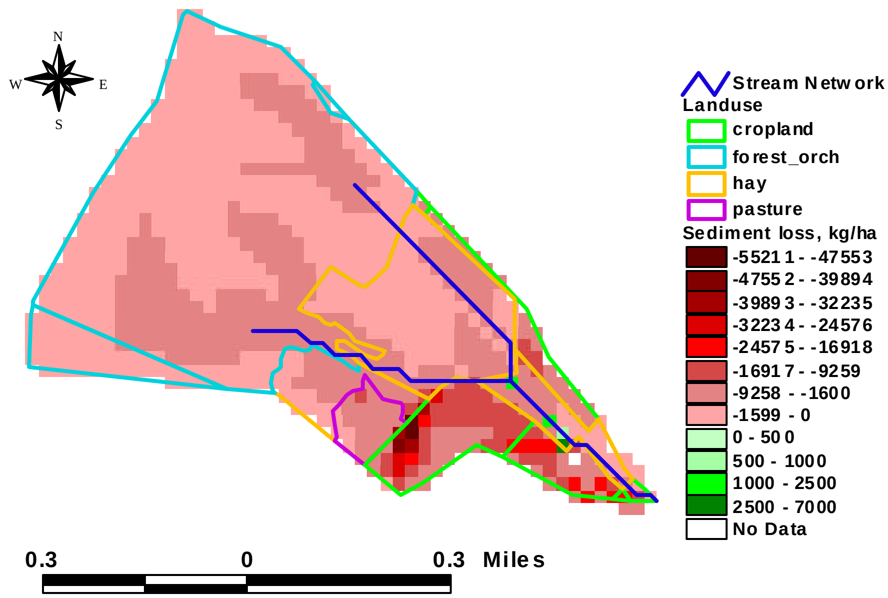

Figure E-1: Average annual sediment loss in subwatershed 1. A positive number indicates a net sediment deposit and a negative number indicates a net sediment loss from the cell.

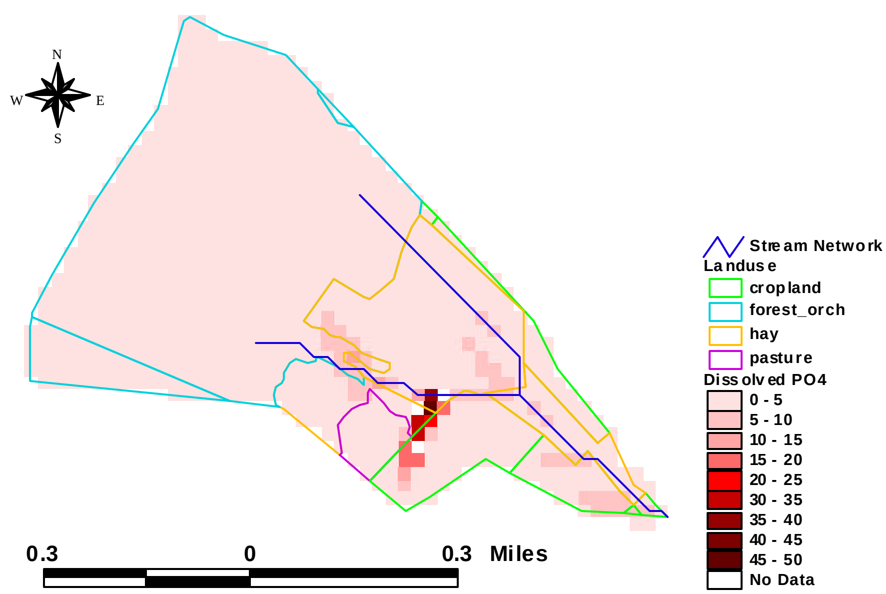

Figure E-2: Average annual dissolved PO_4^- loss, kg in subwatershed 1

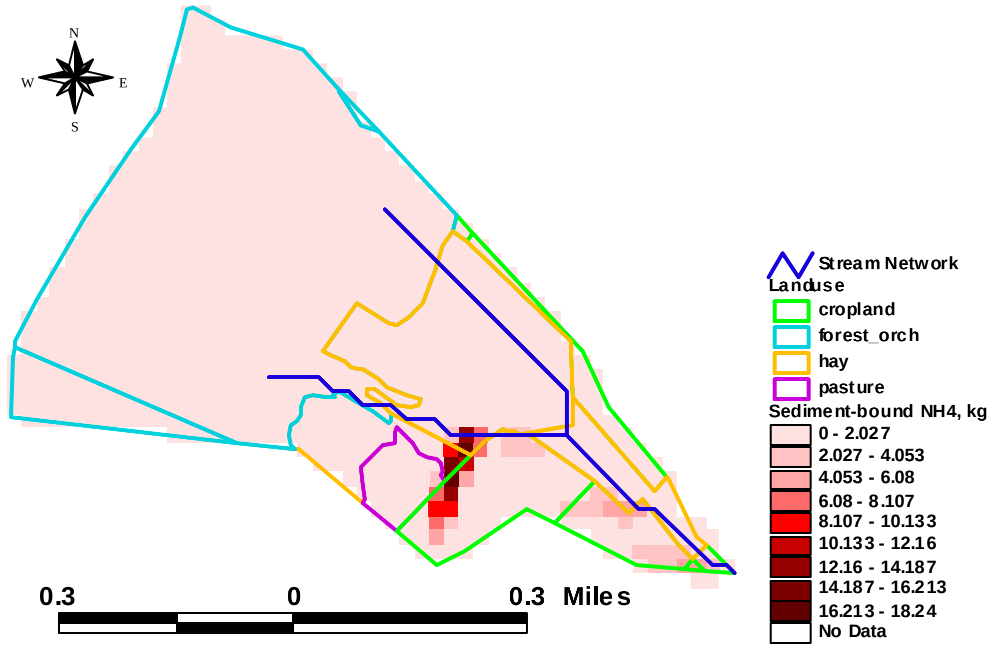

Figure E-3: Average annual sediment-bound NH_4^+ loss in kg, in subwatershed 1

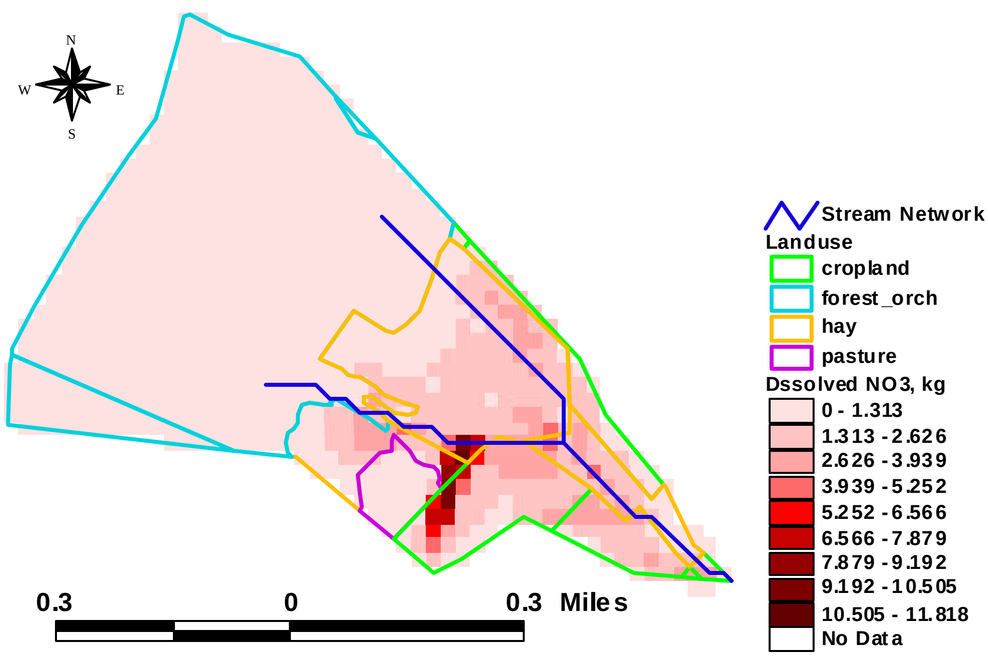

Figure E-4: Average annual dissolved NO_3 loss in kg, in subwatershed 1

Subwatershed 2

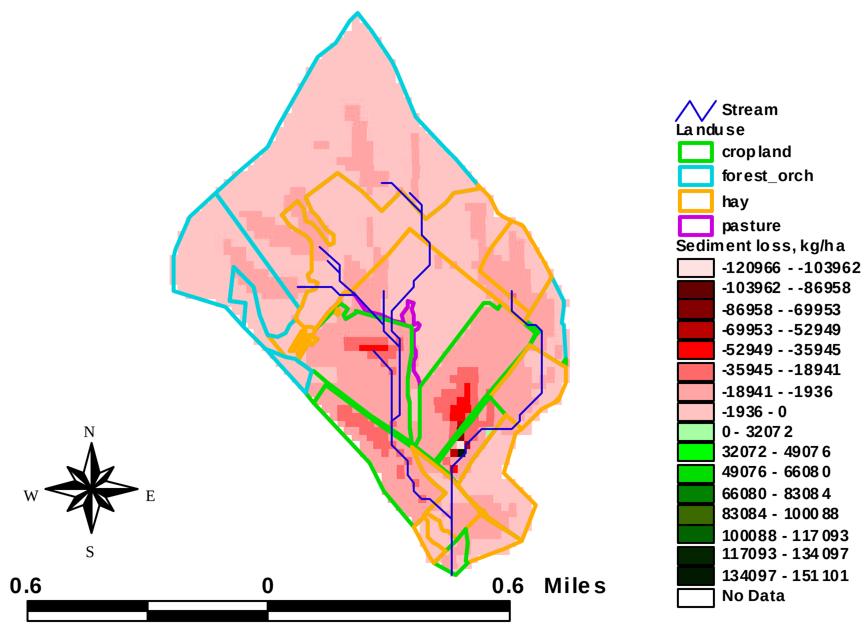

Figure E-5: Average annual sediment loss in subwatershed 2. A positive number indicates a net sediment deposit and a negative number indicates a net sediment loss from the cell.

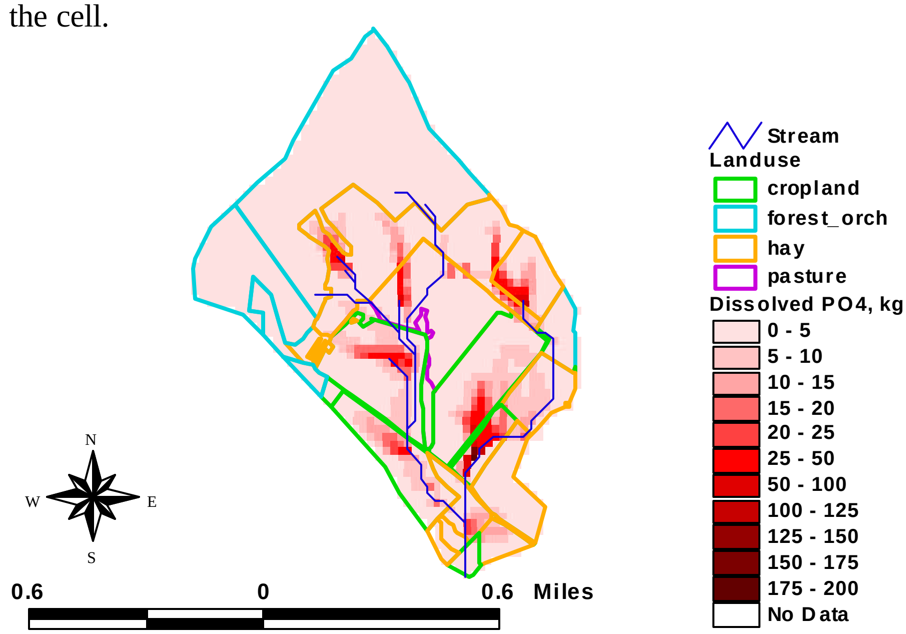

Figure E-6: Average annual dissolved PO_4^- loss in kg, in subwatershed 2

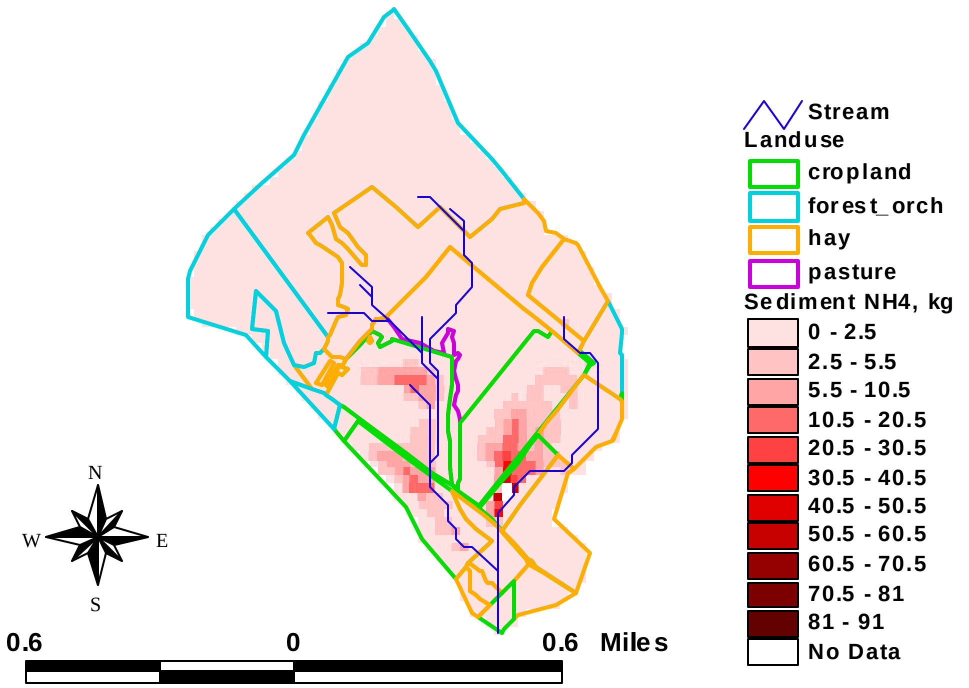

Figure E-7: Average annual sediment-bound NH_4^+ loss in kg, in subwatershed 2

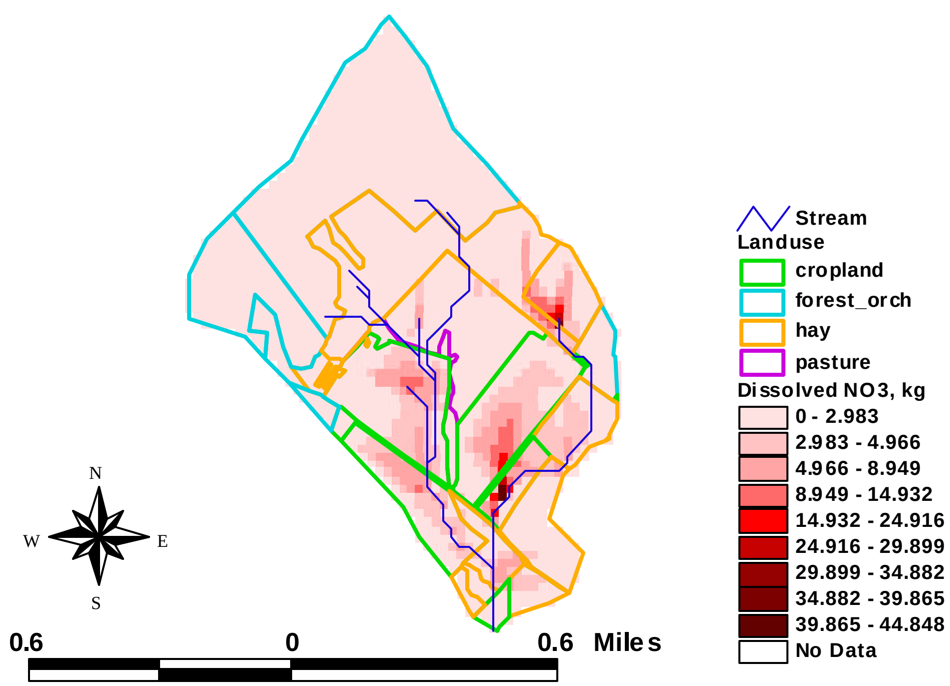

Figure E-8 Average annual dissolved NO_3 loss in kg, in subwatershed 2

Subwatershed 3

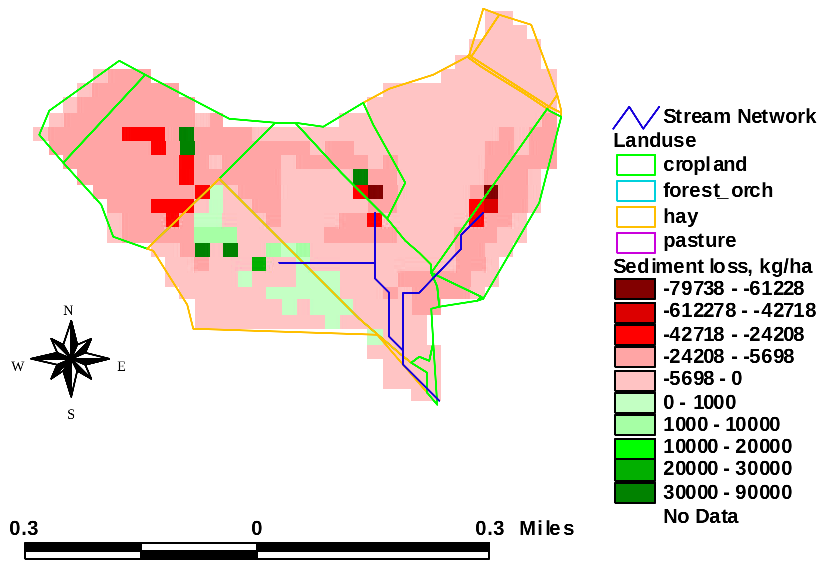

Figure E-9: Average annual sediment loss in subwatershed 3. A positive number indicates a net sediment deposit and a negative number indicates a net sediment loss from the cell.

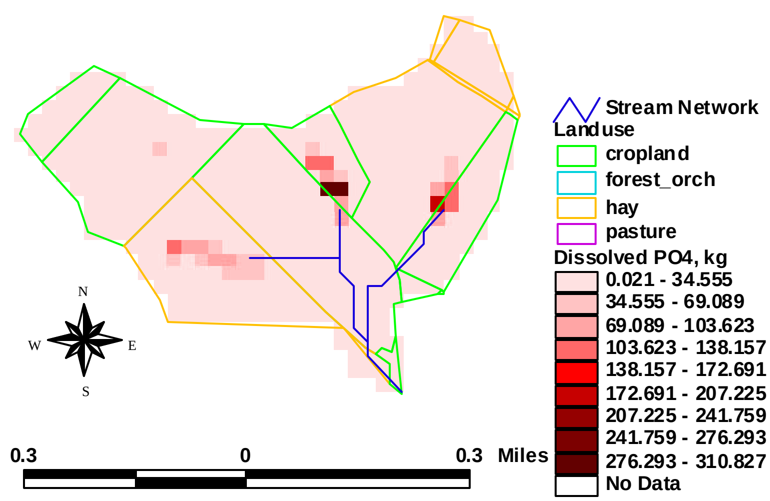

Figure E-10: Average annual dissolved PO_4^- loss in kg, in subwatershed 3

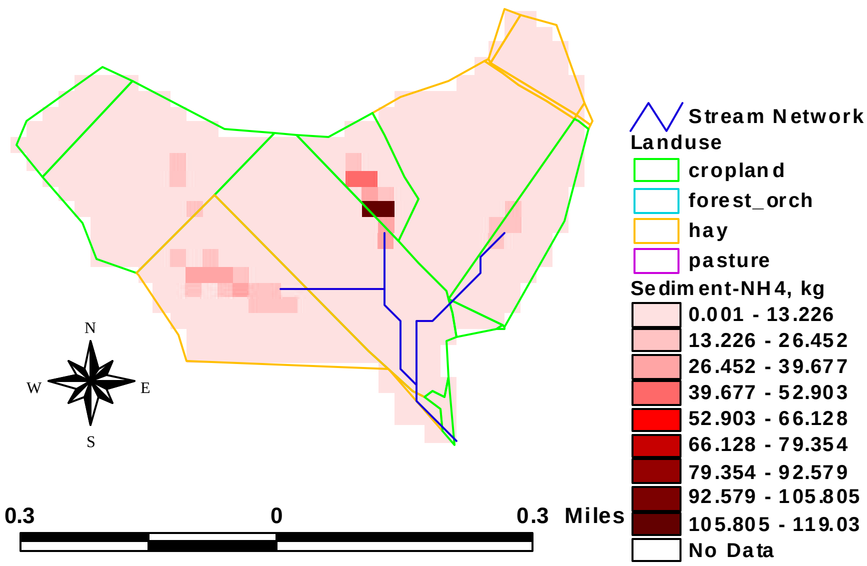

Figure E-11: Average annual sediment-bound NH_4^+ loss in kg, in subwatershed 3

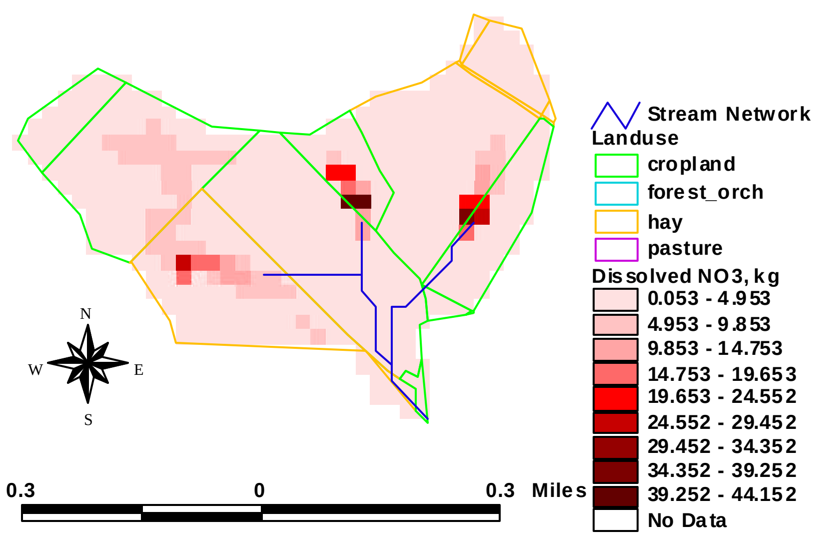

Figure E-12 Average annual dissolved NO_3 loss in kg, in subwatershed 3

Subwatershed 4

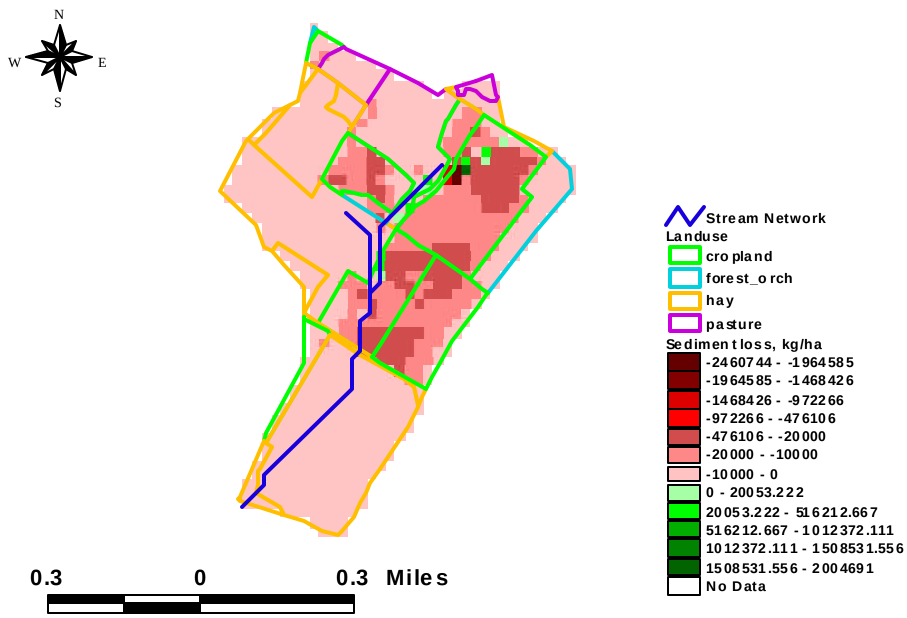

Figure E-13: Average annual sediment loss in subwatershed 4. A positive number indicates a net sediment deposit and a negative number indicates a net sediment loss from the cell.

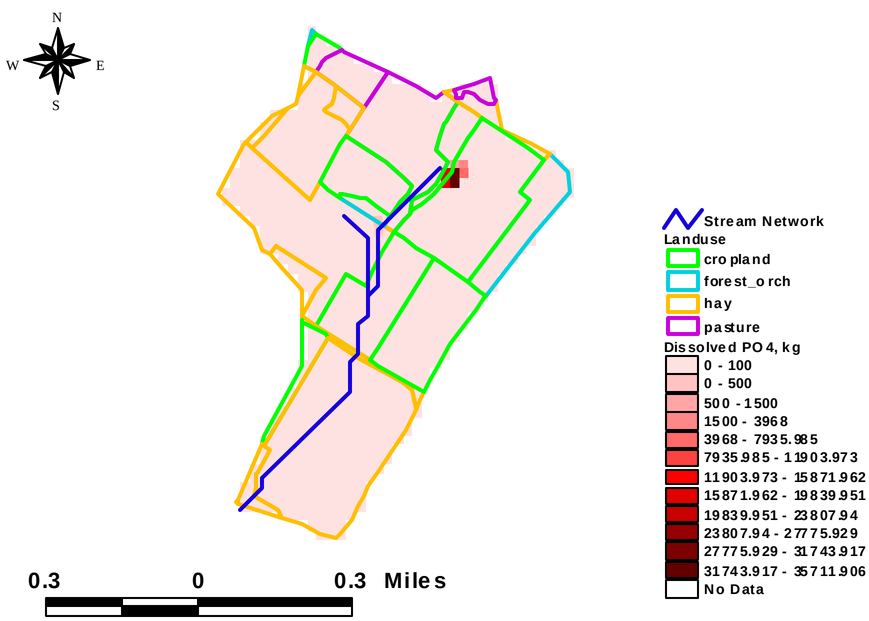

Figure E-14: Average annual dissolved PO_4^- loss in kg, in subwatershed 4

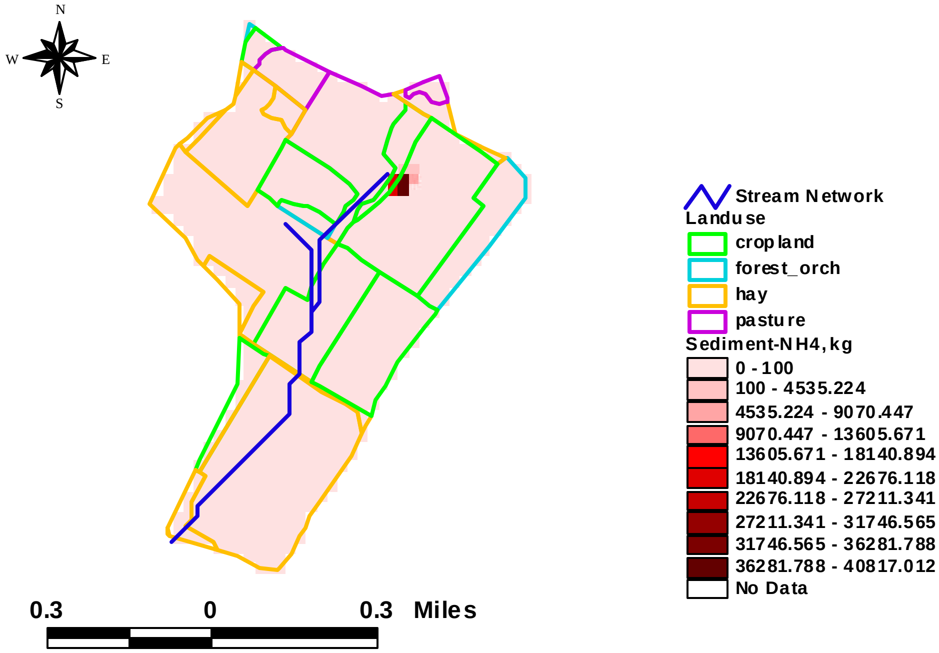

Figure E-15: Average annual sediment-bound NH_4^+ loss in kg, in subwatershed 4

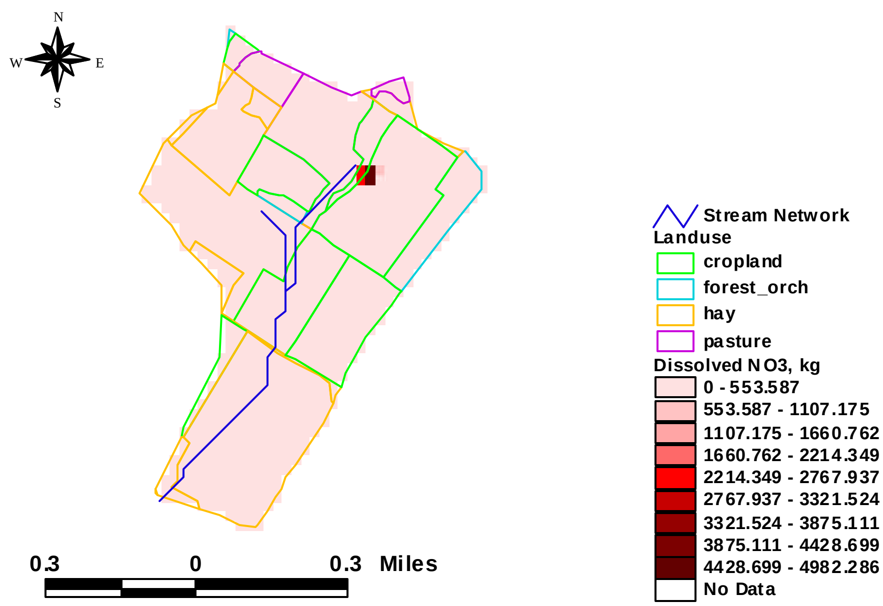

Figure E-16 Average annual dissolved NO_3 loss in subwatershed 4

Subwatershed 5

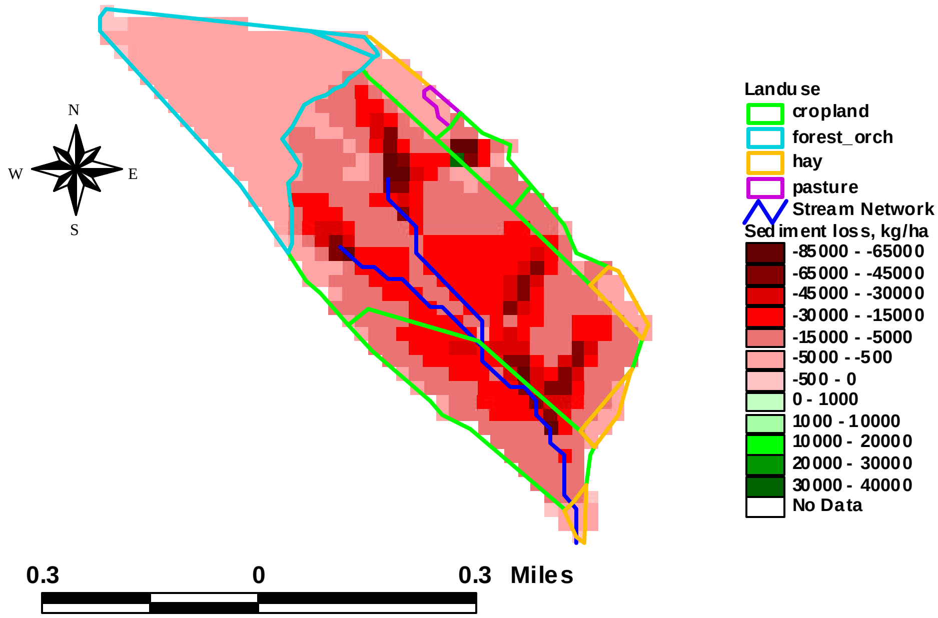

Figure E-17: Average annual sediment loss in subwatershed 5. A positive number indicates a net sediment deposit and a negative number indicates a net sediment loss from the cell.

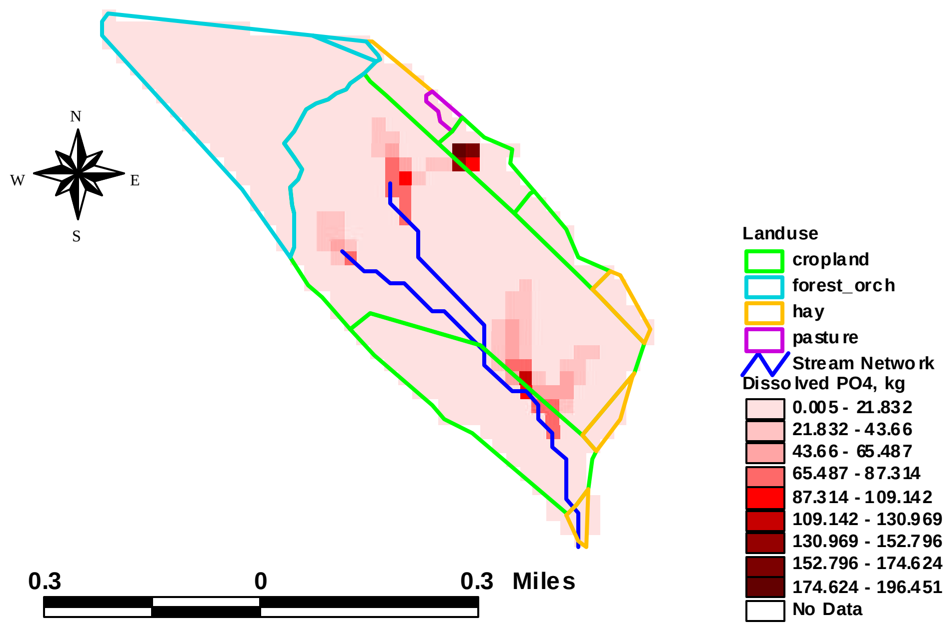

Figure E-18: Average annual dissolved PO_4^- loss in kg, in subwatershed 5

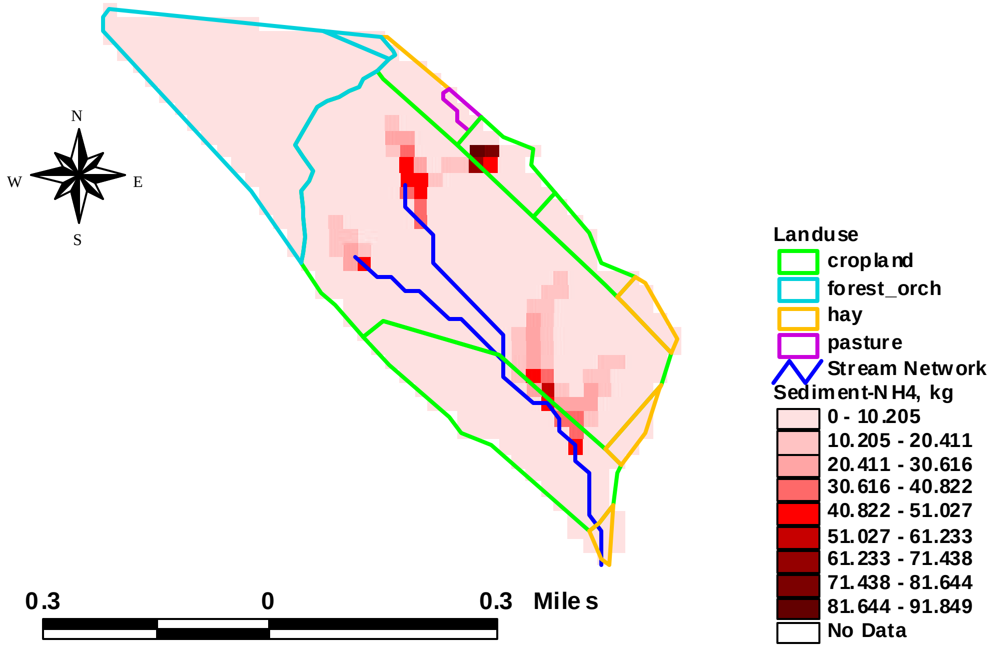

Figure E-19: Average annual sediment-bound NH_4^+ loss in kg, in subwatershed 5

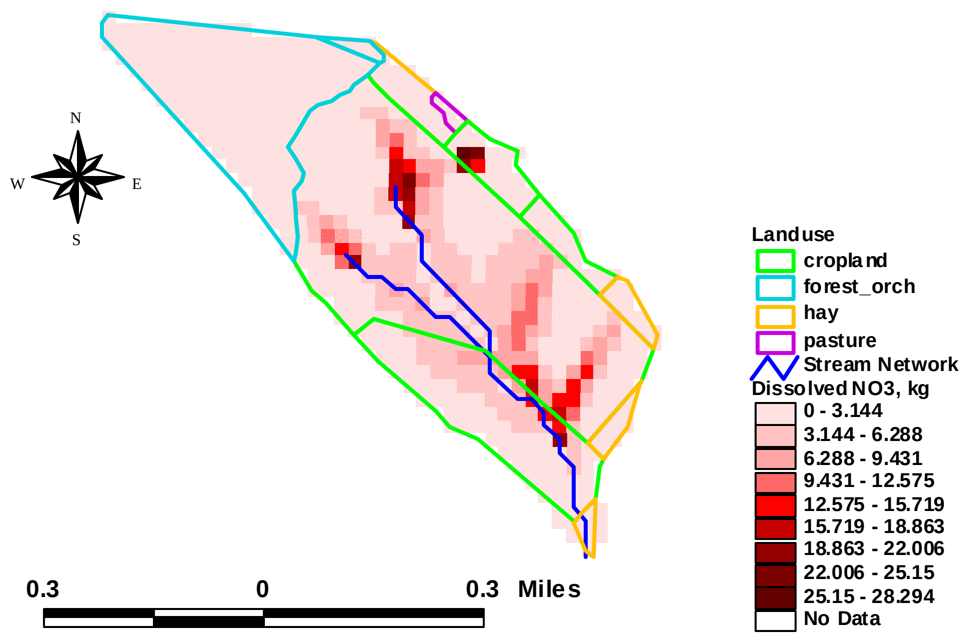

Figure E-20 Average annual dissolved NO_3 loss in kg, in subwatershed 5

Subwatershed 6

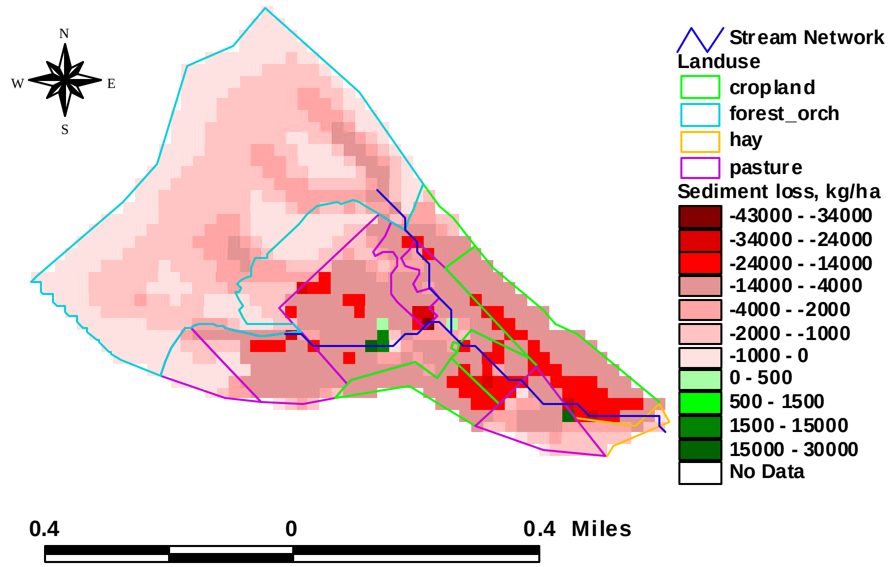

Figure E-21: Average annual sediment loss in subwatershed 6. A positive number indicates a net sediment deposit and a negative number indicates a net sediment loss from the cell.

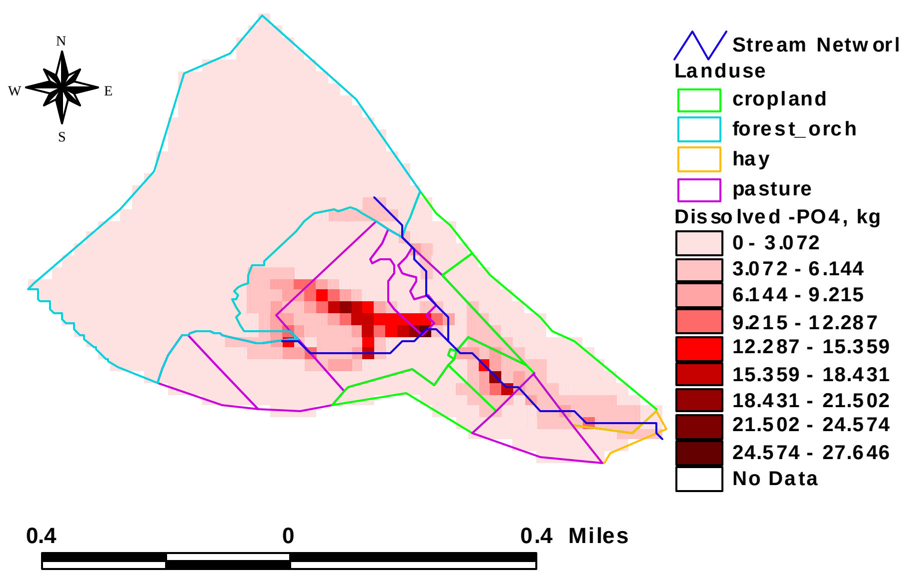

Figure E-22: Average annual dissolved PO_4^- loss in kg, in subwatershed 6

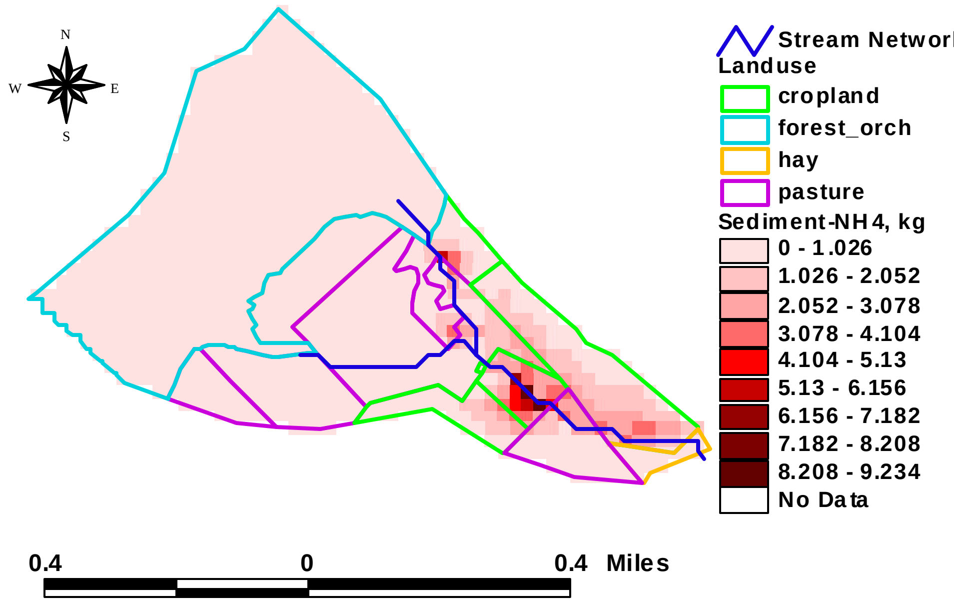

Figure E-23: Average annual sediment-bound NH_4^+ loss in subwatershed 6

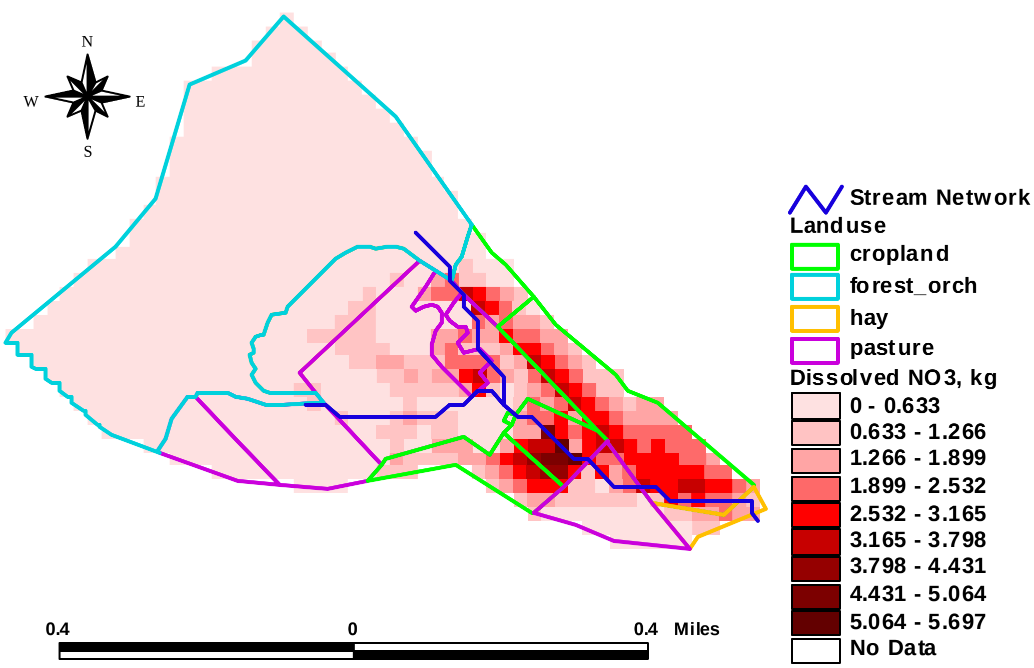

Figure E-24 Average annual dissolved NO_3 loss in subwatershed 6

Subwatershed 7

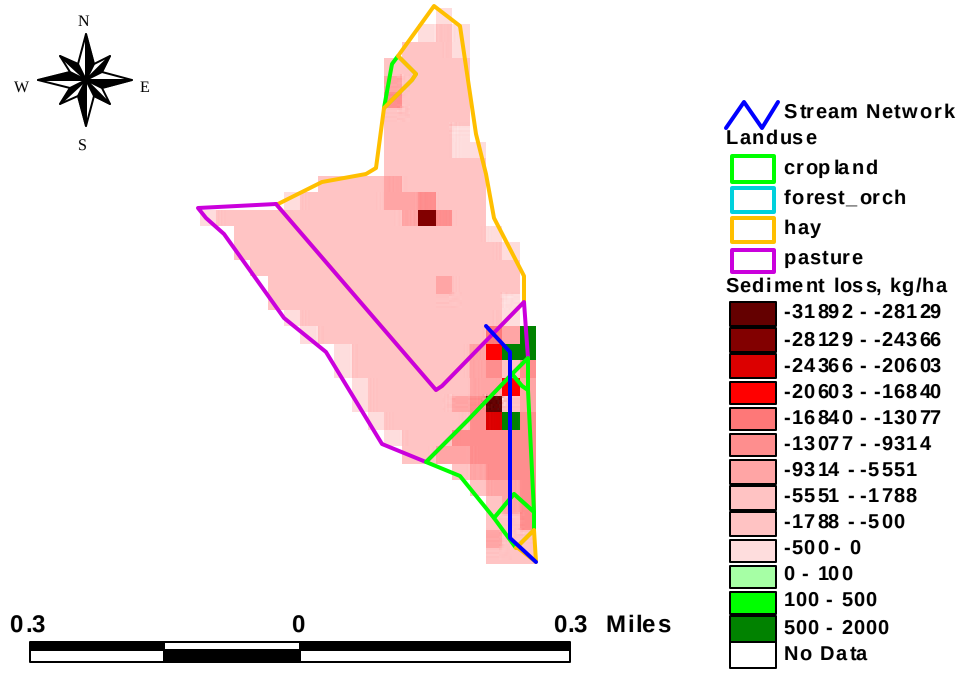

Figure E-25: Average annual sediment loss in subwatershed 7. A positive number indicates a net sediment deposit and a negative number indicates a net sediment loss from the cell.

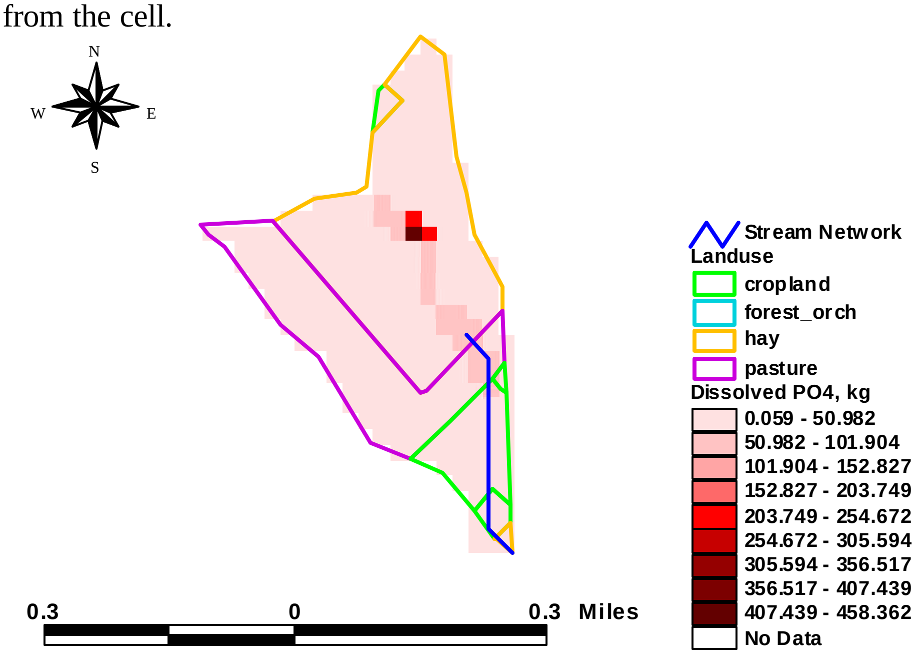

Figure E-26: Average annual dissolved PO_4^- loss in kg, in subwatershed 7

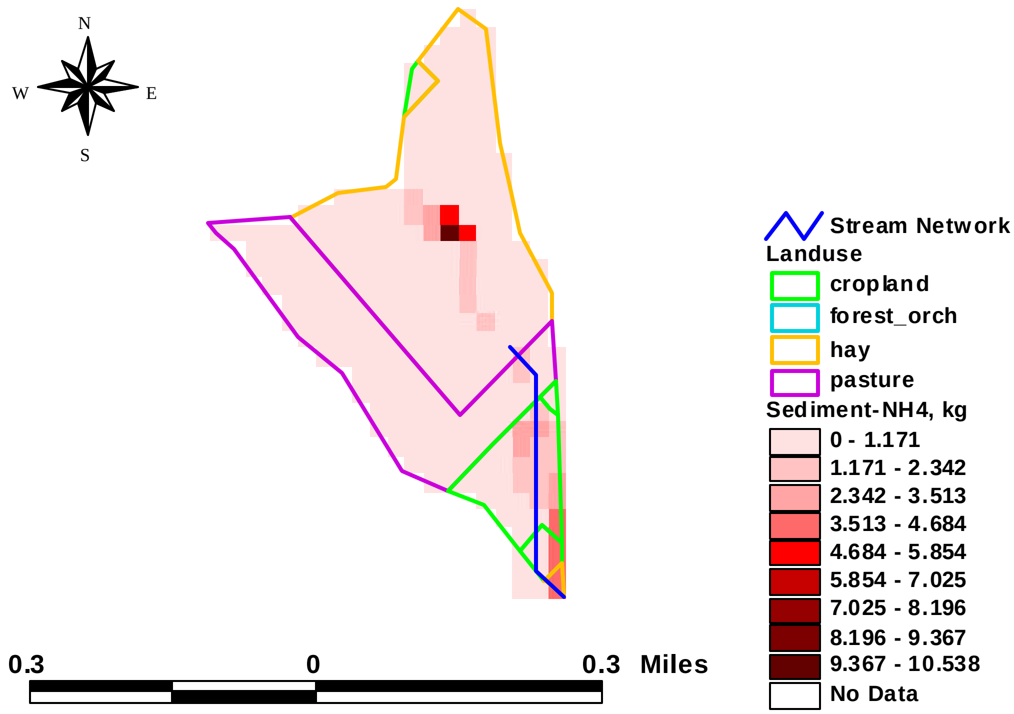

Figure E-27: Average annual sediment-bound NH_4^+ loss in kg, in subwatershed 7

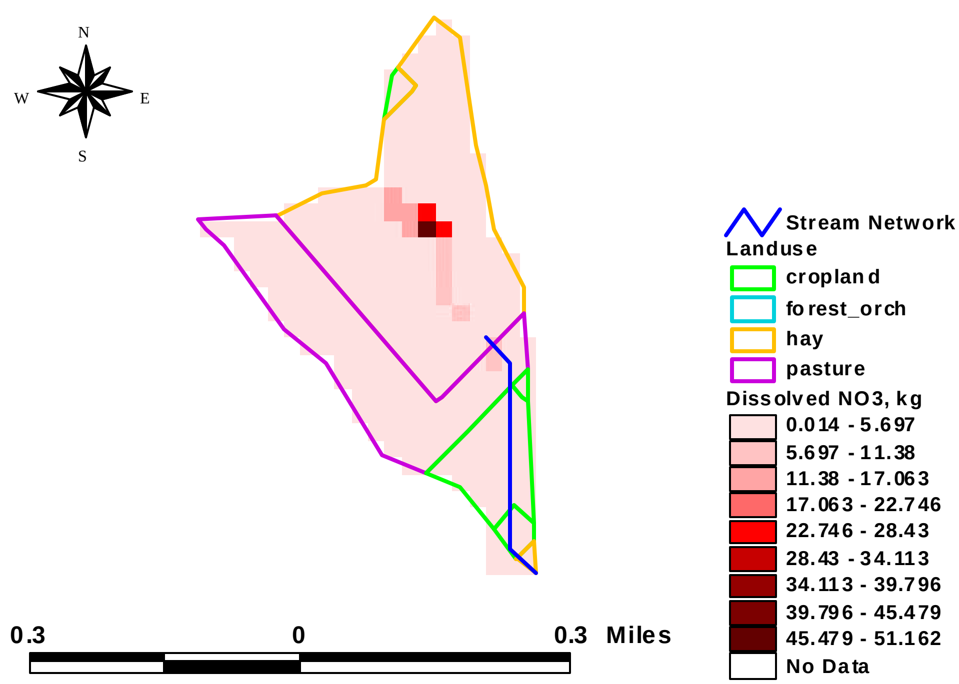

Figure E-28 Average annual dissolved NO_3 loss in kg, in subwatershed 7

Subwatershed 8

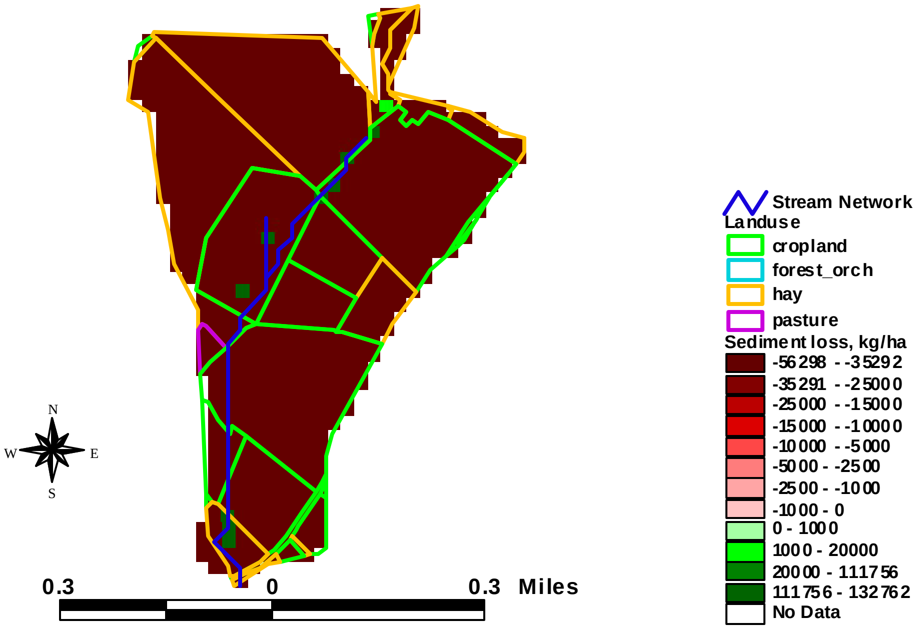

Figure E-29 Average annual sediment loss in subwatershed 8. A positive number indicates a net sediment deposit and a negative number indicates a net sediment loss from the cell.

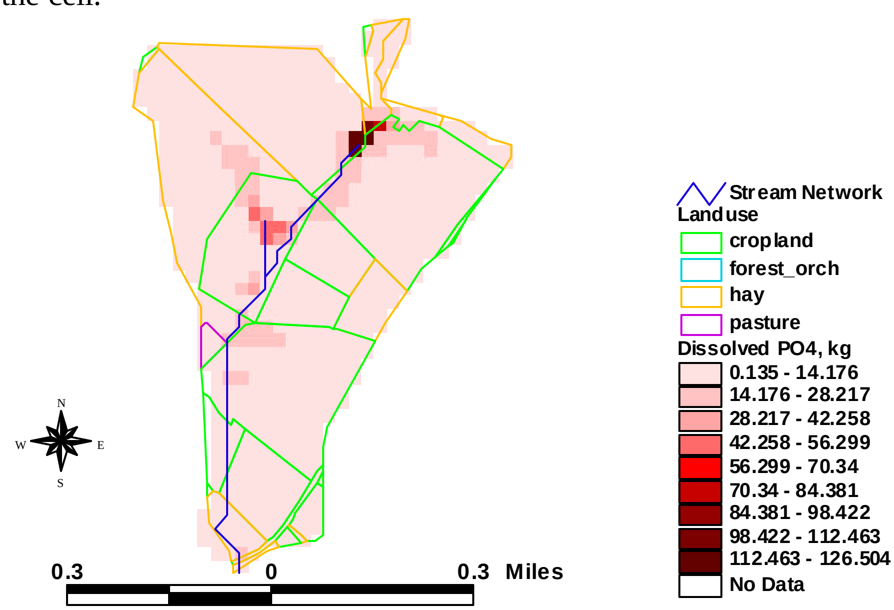

Figure E-30: Average annual dissolved PO_4^- loss in kg, in subwatershed 8

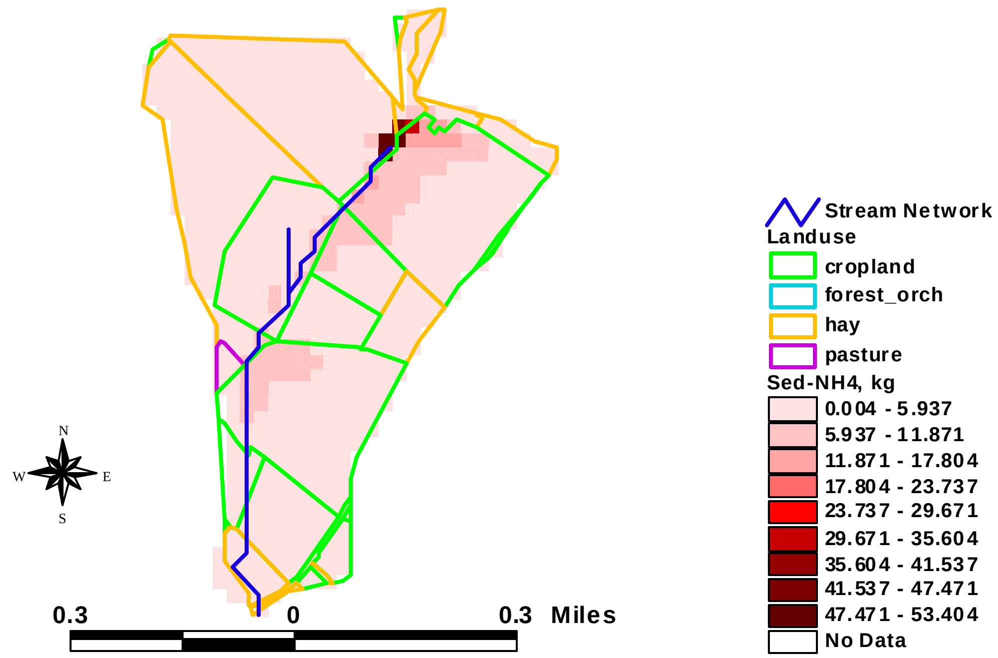

Figure E- 31: Average annual sediment-bound NH_4^+ loss in kg, in subwatershed 8

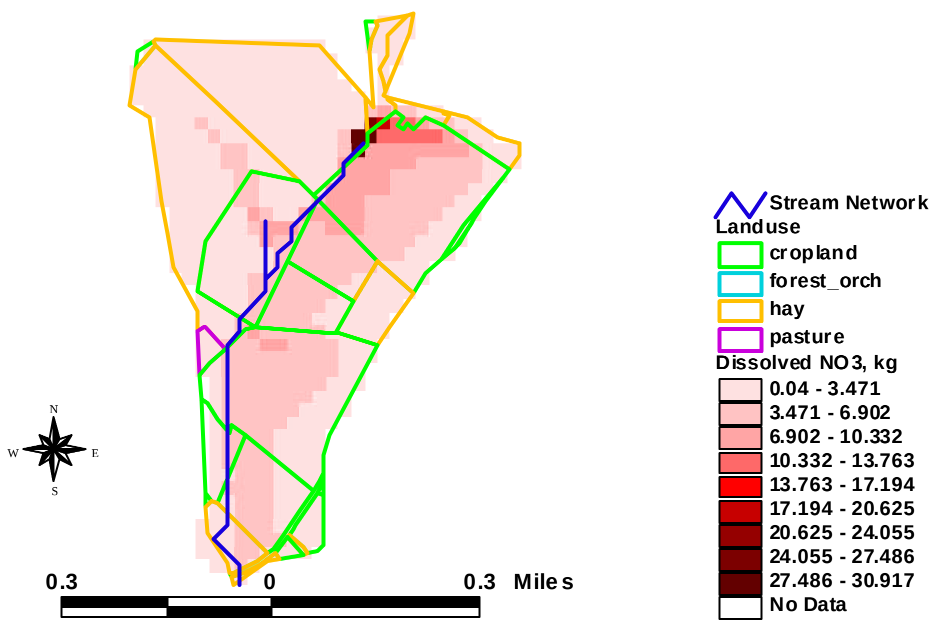

Figure E-32 Average annual dissolved NO_3 loss in kg, in subwatershed 8

Subwatershed 9

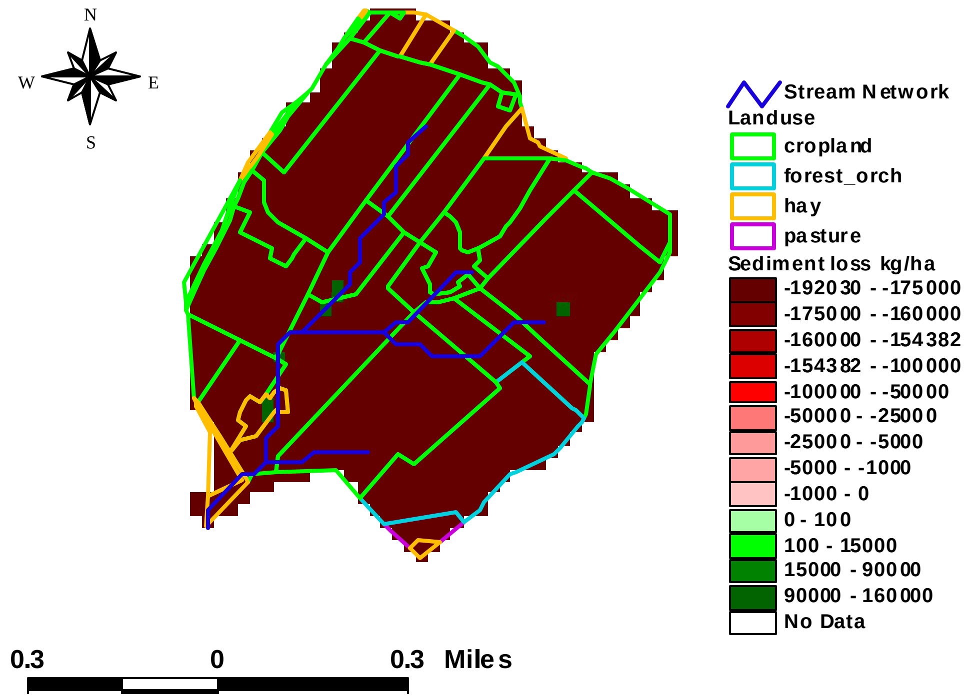

Figure E-33 Average annual sediment loss in subwatershed 9. A positive number indicates a net sediment deposit and a negative number indicates a net sediment loss from the cell.

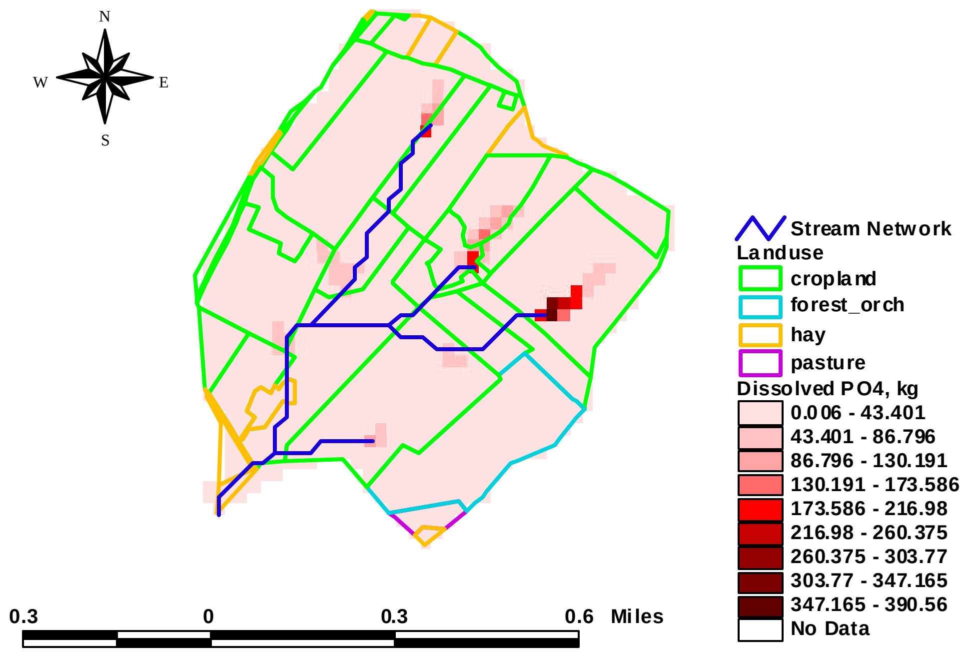

Figure E-34: Average annual dissolved PO_4^- loss in kg, in subwatershed 9

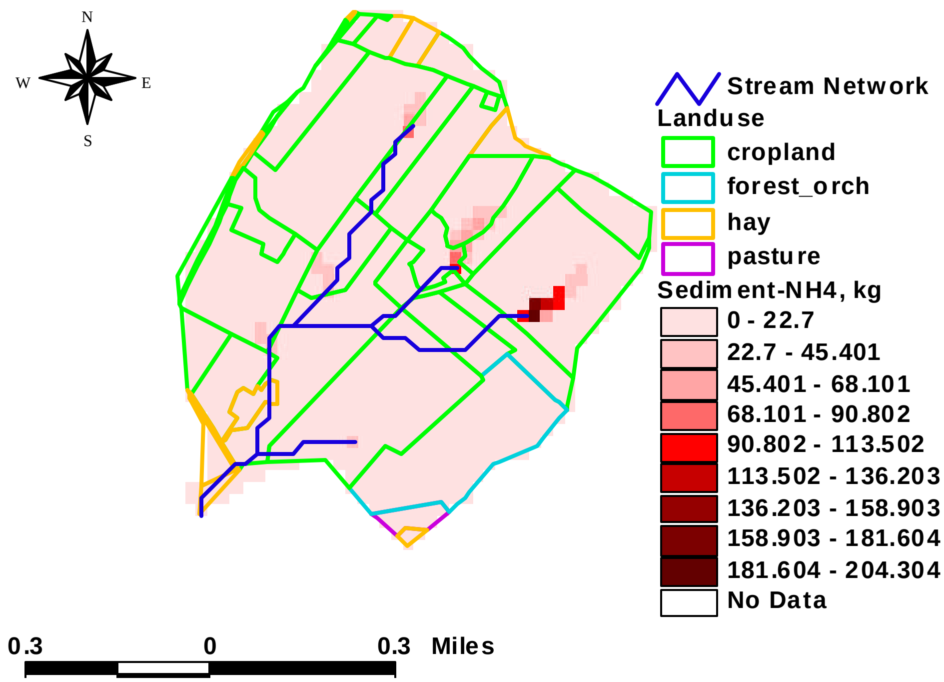

Figure E 35-: Average annual sediment-bound NH_4^+ loss in kg, in subwatershed 9

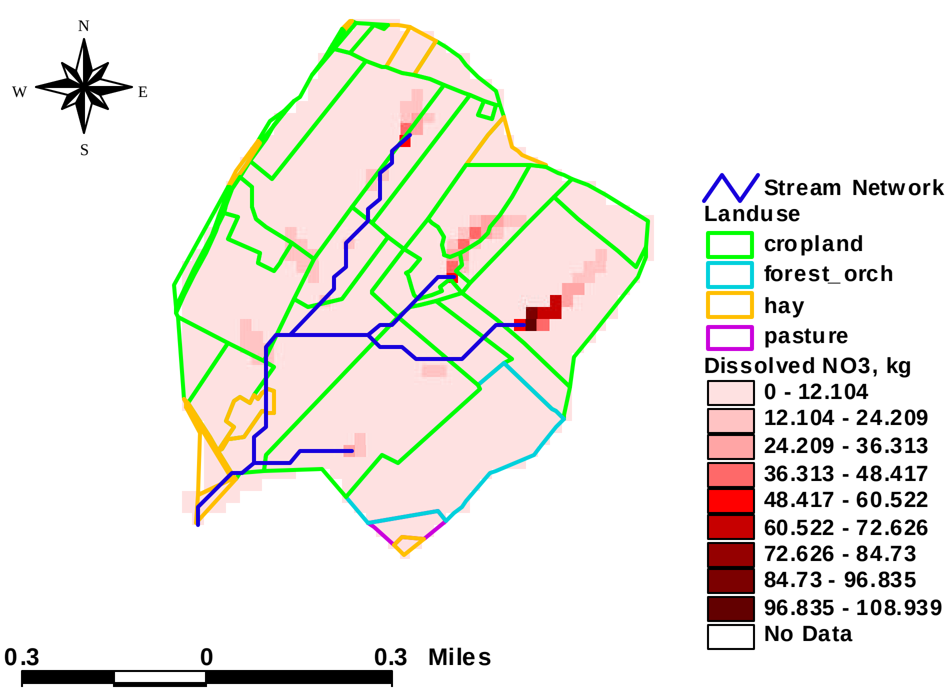

Figure E-36 Average annual dissolved NO_3 loss in kg, in subwatershed 9

Subwatershed 10

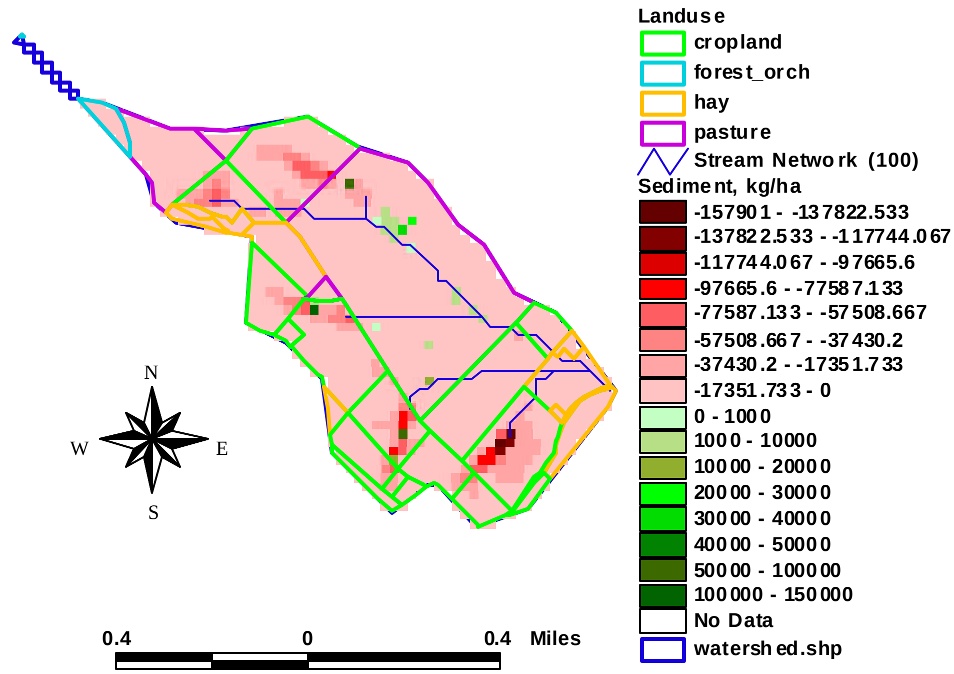

Figure E-37: Average annual sediment loss in subwatershed 10. A positive number indicates a net sediment deposit and a negative number indicates a net sediment loss from the cell.

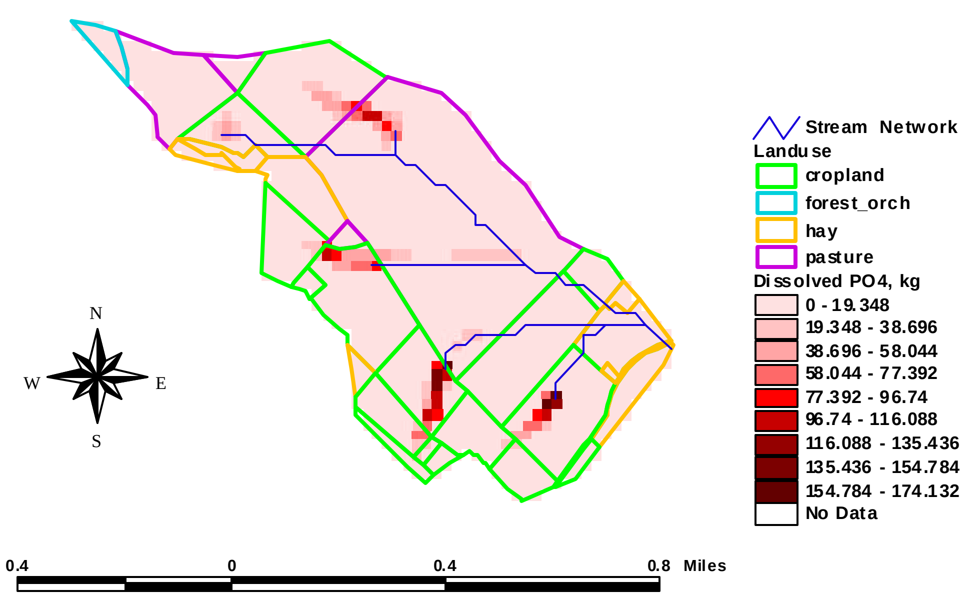

Figure E-38: Average annual dissolved PO_4^- loss in kg, in subwatershed 10

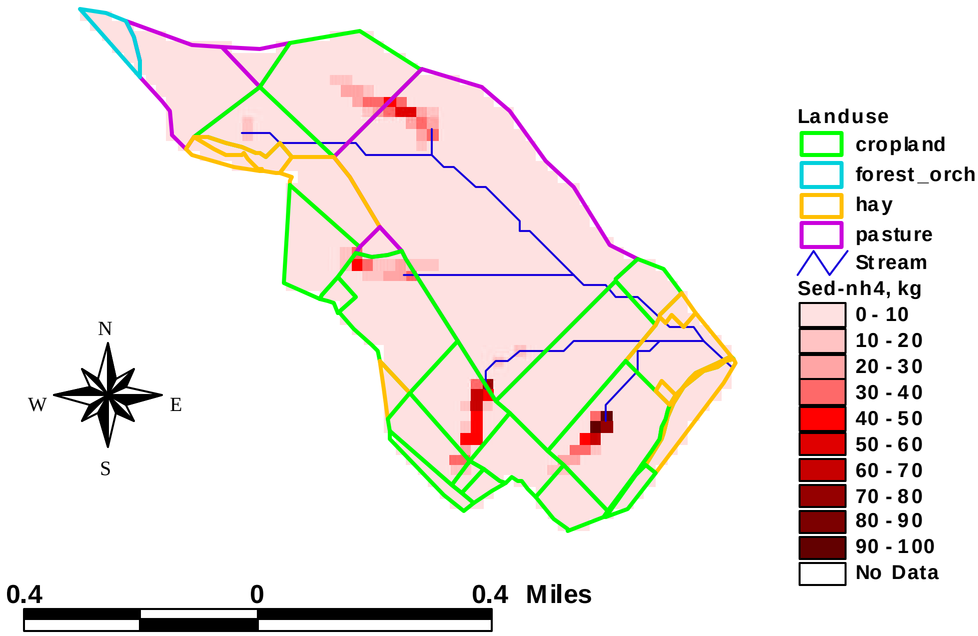

Figure A-39: Average annual sediment-bound NH_4^+ loss in kg, in subwatershed 10

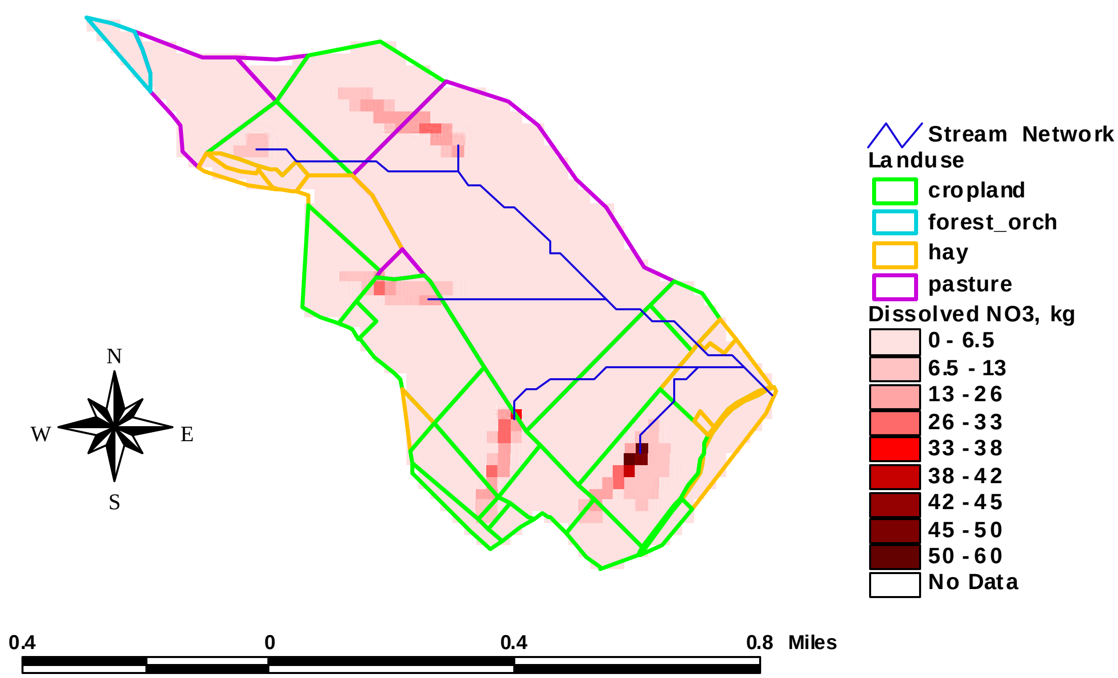

Figure A-40: Average annual dissolved NO_3 loss in kg, in subwatershed 10

Subwatershed 11

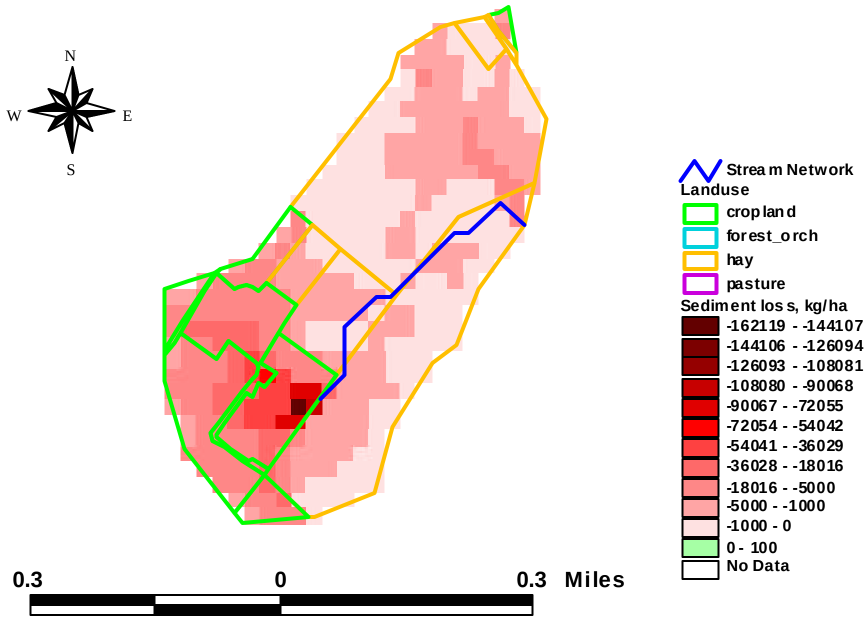

Figure E-41: Average annual sediment loss in subwatershed 11. A positive number indicates a net sediment deposit and a negative number indicates a net sediment loss from the cell.

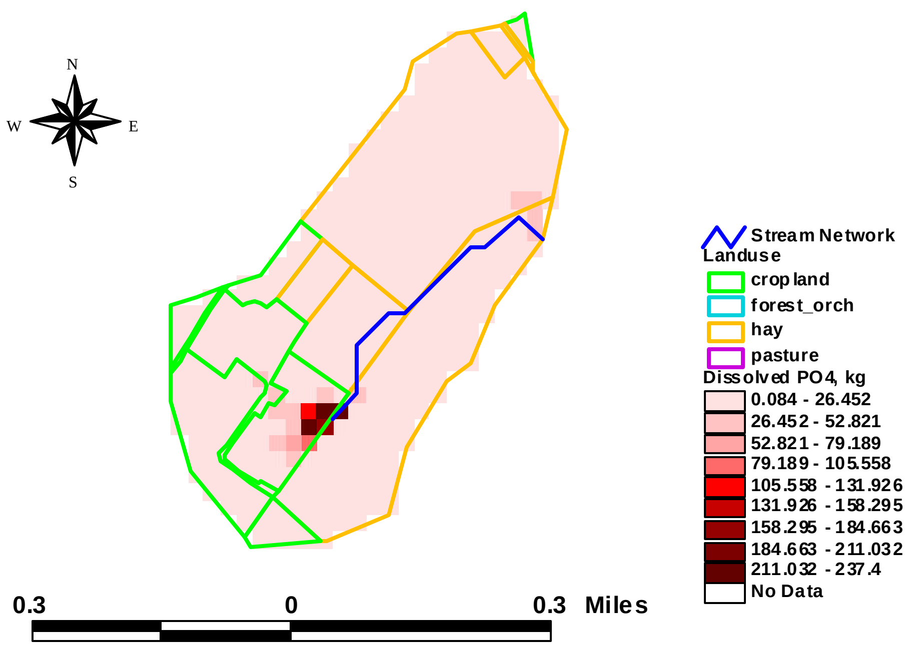

Figure E-42: Average annual dissolved PO_4^- loss in kg, in subwatershed 11

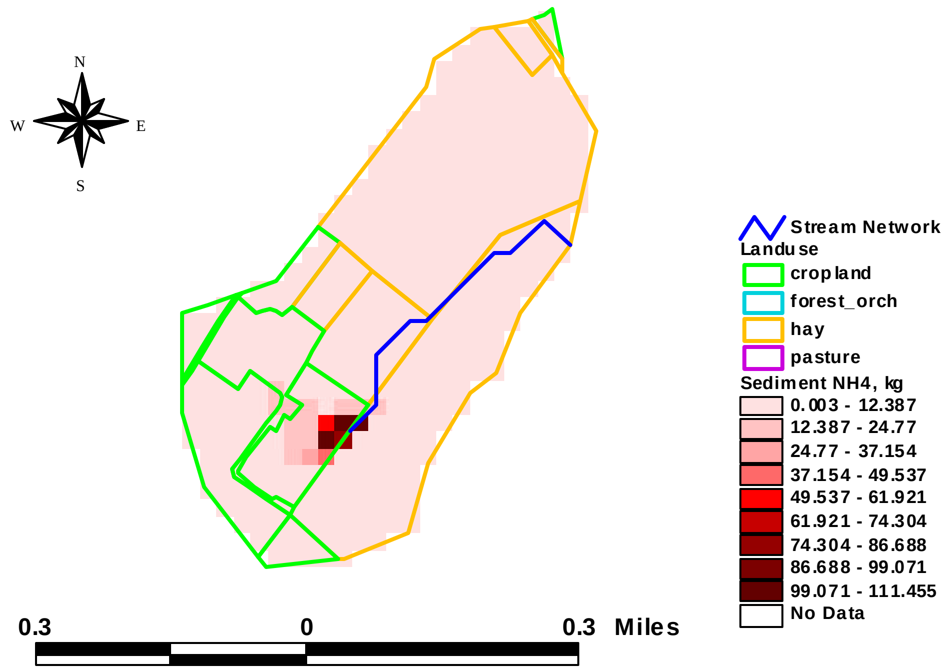

Figure E-43: Average annual sediment-bound NH_4^+ loss in kg, in subwatershed 11

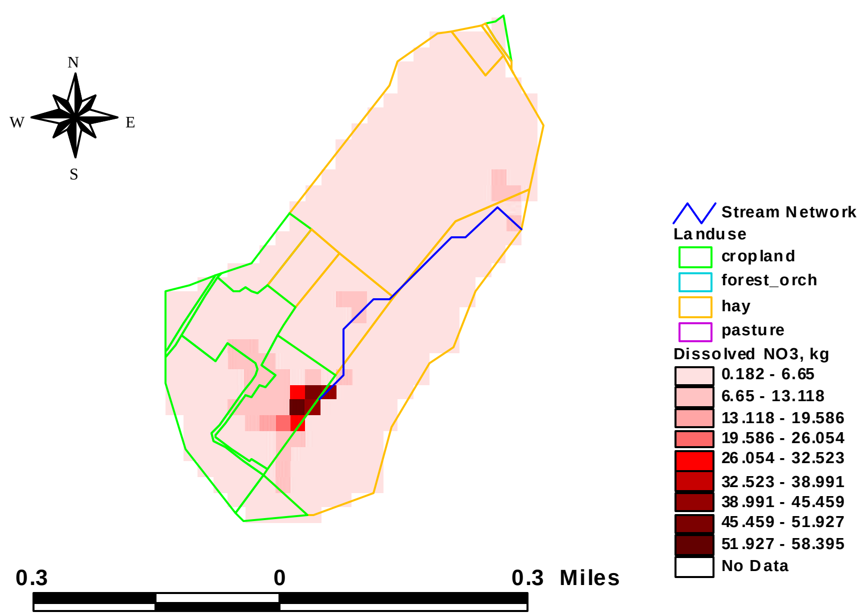

Figure E-44: Average annual dissolved NO_3 loss in kg, in subwatershed 11

Subwatershed 12

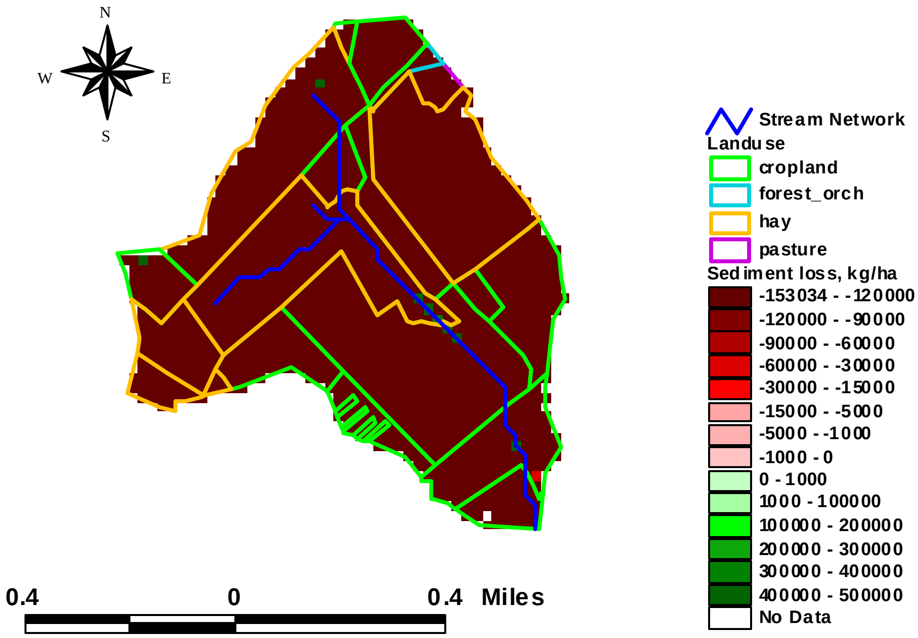

Figure E-45: Average annual sediment loss in subwatershed 12. A positive number indicates a net sediment deposit and a negative number indicates a net sediment loss from the cell.

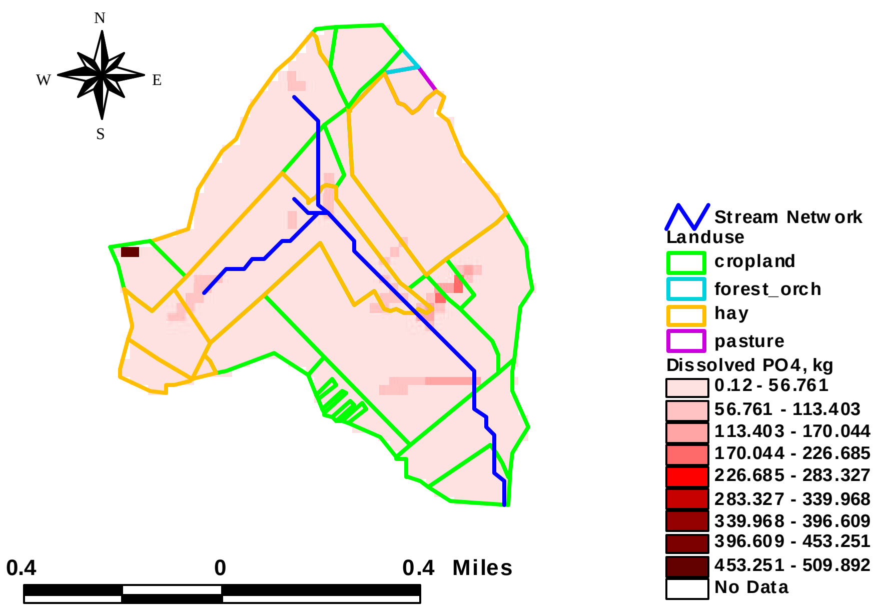

Figure E-46: Average annual dissolved PO_4^- loss in kg,in subwatershed 12

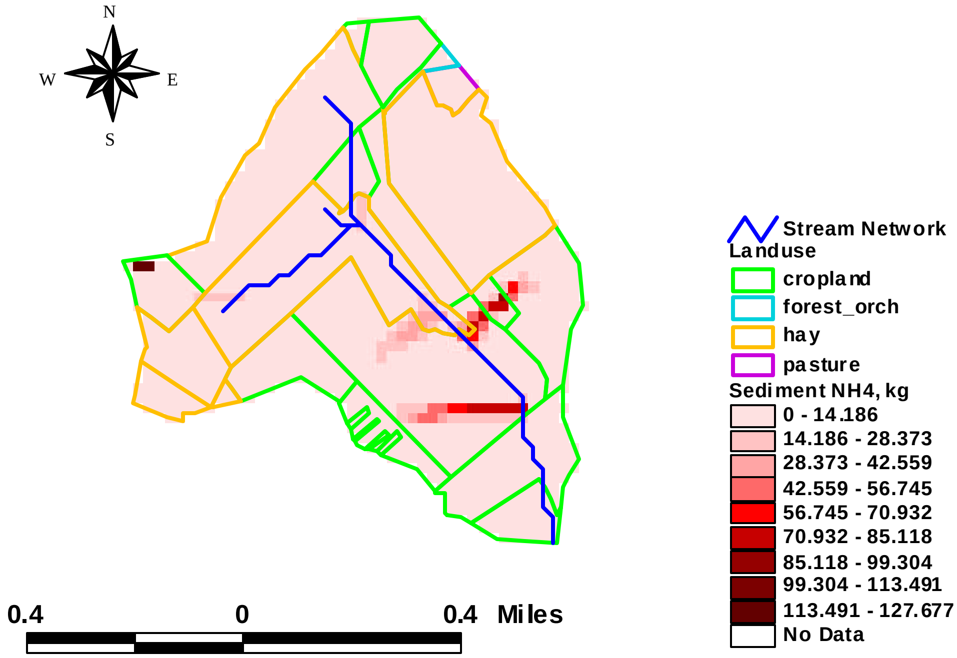

Figure E-47: Average annual sediment-bound NH_4^+ loss in kg, in subwatershed 12

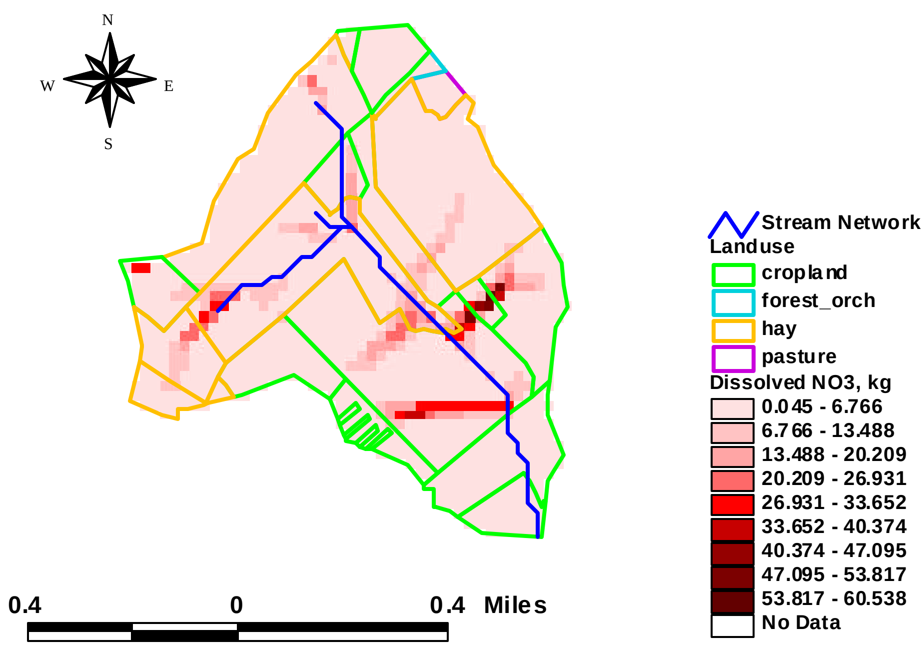

Figure E-48: Average annual dissolved NO_3 loss in kg, in subwatershed 12

APPENDIX F: F-tables calculations

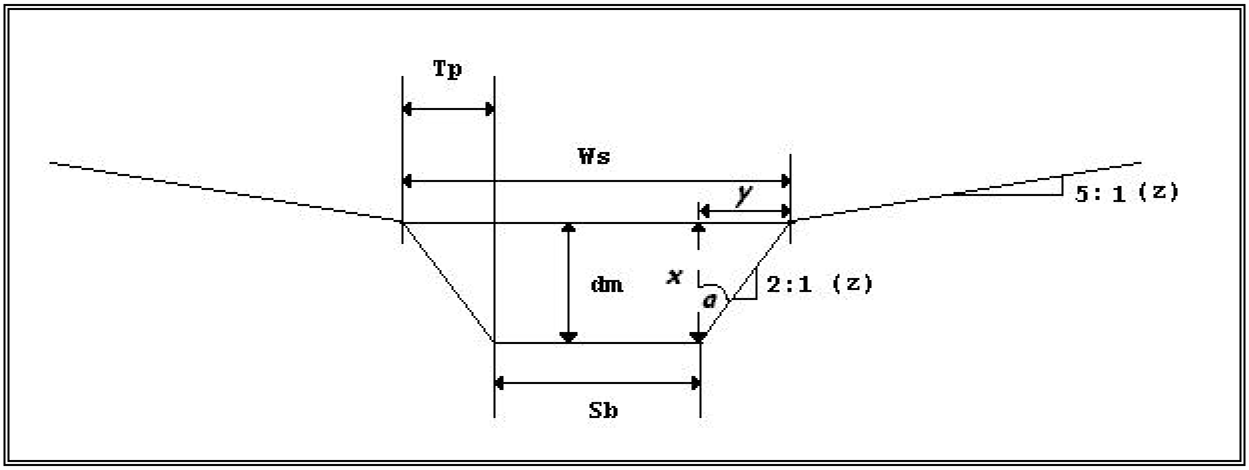

Figure F.1: Cross sectional diagram of stream used for F-tables.

The following equations were used to develop the F-tables for HSPF.

$$Tp = d \times (Tan(a)) \quad \text{[F.1]}$$

Where: Tp = top triangular width (figure F.1) (m); and
a = side slope angle (degrees).

$$Sw = Side\_Wetted = \left[\frac{d}{Cos(a)} \right] \quad \text{[F.2]}$$

Where: Sw =side wetted length (m);
d = depth of water; and
a = side slope angle (degrees).

$$Wp = 2 \times Sw + Sb \quad \text{[F.3]}$$

Where: Wp = wetted perimeter, (m);
Sw = side wetted length (m); and
Sb = stream bottom width (m).

$$Rh = \frac{A}{Wp}$$ [F.4]

Where: Rh = hydraulic radius (m);
A = cross sectional area of stream (m^2); and
Wp = wetted perimeter (m).

$$V = \frac{1}{n} \times (Rh)^{\frac{2}{3}} \times S^{\frac{1}{2}}$$ [F.5]

Where: V = flow velocity (m/s);
n = Manning roughness coefficient; and
S = slope in direction of flow (m/m).

$$Ws = Sb + 2 \times Tp$$ [F.6]

Where: Ws = water surface width (m);
Sb = bottom stream width (m); and
Tp = top triangular width (m).

$$Area = (L \times Ws)/10{,}000$$ [F.7]

Where: Area = surface area of stream, (ha);
L = length of stream (m); and
Ws = water surface width (m).

$$Volume = A \times L$$ [F.8]

Where: Volume = volume of water in stream (m^3);
L = length of stream (m); and
A = cross sectional area (m^2).

$$Outflow = A \times V$$ [F.9]

Where: Outflow = flow rate (m^3/s);
V = flow velocity, (m/s); and
A = cross sectional area (m^2).

Stream-1

drop	7	m	side slopes first 1 m		0.463647609	radians	26.5650512	degrees
length	669.41	m	side slopes beyond 1m		1.373400767	radians	78.6900675	degrees
			slope of channel		0.01045697	m/m		
			mannings n		0.05	(Chow et al. 1988, p-5)		

depth	**stream bottomwidth**	**top-triangle-dis ***	**Cross sec area**	**Side wetted**	**wetted perimeter**	**Hydraulic radius**	**velocity**	**water surface width**	**area**	**volume**	**outflow**
m	*m*	*m*	*m^2*	*m*	*m*		*m/s*	*m*	*ha*	*m^3*	*m^3/s*
0	0.7	0	0.0000	0	0.7	0	0	0.7	0.0468587	0	0
0.2	0.7	0.1	0.1600	0.223606798	1.147213595	0.139468361	0.55002621	0.9	0.0602469	107.1056	0.08800419
0.4	0.7	0.2	0.3600	0.447213595	1.594427191	0.225786415	0.75834144	1.1	0.0736351	240.9876	0.27300292
0.6	0.7	0.3	0.6000	0.670820393	2.041640786	0.293881276	0.90402588	1.3	0.0870233	401.646	0.54241553
0.8	0.7	0.4	0.8800	0.894427191	2.488854382	0.353576331	1.02263748	1.5	0.1004115	589.0808	0.89992099
1	0.7	0.5	1.2000	1.118033989	2.936067977	0.408709883	1.12635773	1.7	0.1137997	803.292	1.35162928
Top trapezoidal											
0	1.7	0	0.0000	0	1.7	0	0	1.7	0.1137997	0	0
0.5	1.7	2.5	2.1000	2.549509757	6.799019514	0.308868065	0.93450491	6.7	0.4485047	1405.761	1.96246032
1	1.7	5	6.7000	5.099019514	11.89803903	0.563118005	1.39465202	11.7	0.7832097	4485.047	9.34416853
1.5	1.7	7.5	13.8000	7.64852927	16.99705854	0.811905187	1.77993084	16.7	1.1179147	9237.858	24.5630456
2	1.7	10	23.4000	10.19803903	22.09607805	1.059011465	2.12487486	21.7	1.4526197	15664.194	49.7220718
3	1.7	15	50.1000	15.29705854	32.29411708	1.551366147	2.74079019	31.7	2.1220297	33537.441	137.313589
5	1.7	25	133.5000	25.49509757	52.69019514	2.533678223	3.80102352	51.7	3.4608497	89366.235	507.43664
17	1.7	85	1473.9000	86.68333173	175.0666635	8.4190786	8.46400596	171.7	11.4937697	986643.4	12475.0984
Bottom and top trapezoid added together											
1	0.7	0.5	1.2000	1.118033989	2.936067977	0.408709883	1.12635773	1.7	0.1137997	803.292	1.35162928
1.5	0.7	3	3.3000	3.667543746	8.035087491	0.410698702	1.13000874	6.7	0.4485047	2209.053	3.72902886
2	0.7	5.5	7.9000	6.217053502	13.134107	0.60148741	1.45730553	11.7	0.7832097	5288.339	11.5127137
2.5	0.7	8	15.0000	8.766563259	18.23312652	0.822678436	1.79564161	16.7	1.1179147	10041.15	26.9346241
3	0.7	10.5	24.6000	11.31607302	23.33214603	1.054339364	2.11862064	21.7	1.4526197	16467.486	52.1180677
4	0.7	15.5	51.3000	16.41509253	33.53018506	1.529964714	2.71552535	31.7	2.1220297	34340.733	139.30645
6	0.7	25.5	134.7000	26.61313156	53.92626311	2.497855261	3.76511082	51.7	3.4608497	90169.527	507.160428
18	0.7	85.5	1475.1000	87.80136572	176.3027314	8.36685846	8.42897047	171.7	11.4937697	987446.69	12433.5743

* in the trapeziodal shape it is the total top width of the trapezoid minus the base width and then divided by 2

Stream-2

drop	7 m	side slopes first 1 m		0.463647609	radians	26.56505118		degrees
length	1151.54 m	side slopes beyond 1m		1.373400767	radians	78.69006753		degrees
		slope of channel		0.006078816	m/m			
		mannings n		0.05	(Chow et al. 1988, p-5)			

depth	stream bottomwidth	top-triangle-dis *	Cross sec area	Side wetted	wetted perimeter	Hydraulic radius	velocity	water surface width	area	volume	outflow
m	*m*	*m*	*m^2*	*m*	*m*		*m/s*	*m*	*ha*	*m^3*	*m^3/s*
0	1	0	0.0000	0	1	0	0	1	0.115154	0	0
0.2	1	0.1	0.2200	0.223606798	1.447213595	0.152016261	0.444153272	1.2	0.1381848	253.3388	0.09771372
0.4	1	0.2	0.4800	0.447213595	1.894427191	0.253374742	0.624379134	1.4	0.1612156	552.7392	0.299701984
0.6	1	0.3	0.7800	0.670820393	2.341640786	0.333099767	0.749299979	1.6	0.1842464	898.2012	0.584453984
0.8	1	0.4	1.1200	0.894427191	2.788854382	0.401598594	0.848791375	1.8	0.2072772	1289.7248	0.95064634
1	1	0.5	1.5000	1.118033989	3.236067977	0.463525492	0.933946324	2	0.230308	1727.31	1.400919486
Top trapezoidal											
0	2	0	0.0000	0	2	0	0	2	0.230308	0	0
0.5	2	2.5	2.2500	2.549509757	7.099019514	0.316945178	0.724873573	7	0.806078	2590.965	1.63096554
1	2	5	7.0000	5.099019514	12.19803903	0.573862732	1.076824304	12	1.381848	8060.78	7.537770131
1.5	2	7.5	14.2500	7.64852927	17.29705854	0.823839497	1.370359687	17	1.957618	16409.445	19.52762555
2	2	10	24.0000	10.19803903	22.39607805	1.071616197	1.632922906	22	2.533388	27636.96	39.19014973
3	2	15	51.0000	15.29705854	32.59411708	1.56469954	2.101648771	32	3.684928	58728.54	107.1840873
5	2	25	135.0000	25.49509757	52.99019514	2.547641118	2.908696007	52	5.988008	155457.9	392.6739609
17	2	85	1479.0000	86.68333173	175.3666635	8.433757995	6.460809335	172	19.806488	1703127.66	9555.537007
Bottom and top trapezoid added together											
1	1	0.5	1.5000	1.118033989	3.236067977	0.463525492	0.933946324	2	0.230308	1727.31	1.400919486
1.5	1	3	3.7500	3.667543746	8.335087491	0.449905295	0.915560199	7	0.806078	4318.275	3.433350746
2	1	5.5	8.5000	6.217053502	13.434107	0.632717902	1.149245777	12	1.381848	9788.09	9.768589104
2.5	1	8	15.7500	8.766563259	18.53312652	0.849829627	1.399031243	17	1.957618	18136.755	22.03474208
3	1	10.5	25.5000	11.31607302	23.63214603	1.079038694	1.640454468	22	2.533388	29364.27	41.83158893
4	1	15.5	52.5000	16.41509253	33.83018506	1.551868543	2.090143585	32	3.684928	60455.85	109.7325382
6	1	25.5	136.5000	26.61313156	54.22626311	2.517230437	2.885502696	52	5.988008	157185.21	393.871118
18	1	85.5	1480.5000	87.80136572	176.6027314	8.383222547	6.434974523	172	19.806488	1704854.97	9526.979781

* in the trapeziodal shape it is the total top width of the trapezoid minus the base width and then divided by 2

Stream 3

drop	6	m	side slopes first 1 m		0.463647609	radians	26.56505118	degrees	
length	814.26	m	side slopes beyond 1m		1.373400767	radians	78.69006753	degrees	
			slope of channel		0.007368654	m/m			
			mannings n		0.05	(Chow et al. 1988, p-5)			

depth	stream bottmwidth	top-triangle-dis *	Cross sec area	Side wetted	wetted perimeter	Hydraulic radius	velocity	water surface width	area	volume	outflow
m	*m*	*m*	*m^2*	*m*	*m*		*m/s*	*m*	*ha*	*m^3*	*m^3/s*
0	0.7	0	0.0000	0	0.7	0	0	0.7	0.0569982	0	0
0.2	0.7	0.1	0.1600	0.2236068	1.147213595	0.139468361	0.461715586	0.9	0.0732834	130.2816	0.073874494
0.4	0.7	0.2	0.3600	0.4472136	1.594427191	0.225786415	0.636584328	1.1	0.0895686	293.1336	0.229170358
0.6	0.7	0.3	0.6000	0.67082039	2.041640786	0.293881276	0.758878092	1.3	0.1058538	488.556	0.455326855
0.8	0.7	0.4	0.8800	0.89442719	2.488854382	0.353576331	0.85844576	1.5	0.122139	716.5488	0.755432269
1	0.7	0.5	1.2000	1.11803399	2.936067977	0.408709883	0.945512984	1.7	0.1384242	977.112	1.13461558
Top trapezoidal											
0	1.7	0	0.0000	0	1.7	0	0	1.7	0.1384242	0	0
0.5	1.7	2.5	2.1000	2.54950976	6.799019514	0.308868065	0.784463501	6.7	0.5455542	1709.946	1.647373352
1	1.7	5	6.7000	5.09901951	11.89803903	0.563118005	1.170730716	11.7	0.9526842	5455.542	7.843895795
1.5	1.7	7.5	13.8000	7.64852927	16.99705854	0.811905187	1.494150282	16.7	1.3598142	11236.788	20.6192739
2	1.7	10	23.4000	10.198039	22.09607805	1.059011465	1.783711087	21.7	1.7669442	19053.684	41.73883944
3	1.7	15	50.1000	15.2970585	32.29411708	1.551366147	2.300736826	31.7	2.5812042	40794.426	115.266915
5	1.7	25	133.5000	25.4950976	52.69019514	2.533678223	3.190742151	51.7	4.2097242	108703.71	425.9640772
17	1.7	85	1473.9000	86.6833317	175.0666635	8.4190786	7.105049585	171.7	13.9808442	1200137.814	10472.13258
Bottom and top trapezoid added together											
1	0.7	0.5	1.2000	1.11803399	2.936067977	0.408709883	0.945512984	1.7	0.1384242	977.112	1.13461558
1.5	0.7	3	3.3000	3.66754375	8.035087491	0.410698702	0.948577801	6.7	0.5455542	2687.058	3.130306744
2	0.7	5.5	7.9000	6.2170535	13.134107	0.60148741	1.223324756	11.7	0.9526842	6432.654	9.664265572
2.5	0.7	8	15.0000	8.76656326	18.23312652	0.822678436	1.507338572	16.7	1.3598142	12213.9	22.61007859
3	0.7	10.5	24.6000	11.316073	23.33214603	1.054339364	1.778461021	21.7	1.7669442	20030.796	43.75014113
4	0.7	15.5	51.3000	16.4150925	33.53018506	1.529964714	2.279528433	31.7	2.5812042	41771.538	116.9398086
6	0.7	25.5	134.7000	26.6131316	53.92626311	2.497855261	3.160595494	51.7	4.2097242	109680.822	425.7322131
18	0.7	85.5	1475.1000	87.8013657	176.3027314	8.36685846	7.075639296	171.7	13.9808442	1201114.926	10437.27553
*	in the trapeziodal shape it is the total top width of the trapezoid minus the base width and then divided by 2										

Stream 4

drop	2	m	side slopes first 1 m		0.46364761	radians	26.56505118	degrees
length	144.85	m	side slopes beyond 1m		1.37340077	radians	78.69006753	degrees
			slope of channel		0.01380739	m/m		
			mannings n		0.05	(Chow et al. 1988, p-5)		

depth	stream bottomwidth	top-triangle-dis *	Cross sec area	Side wetted	wetted perimeter	Hydraulic radius	velocity	water surface width	area	volume	outflow
m	*m*	*m*	*m^2*	*m*	*m*		*m/s*	*m*	*ha*	*m^3*	*m^3/s*
0	1.3	0	0.0000	0	1.3	0	0	1.3	0.0188305	0	0
0.2	1.3	0.1	0.2800	0.223606798	1.7472136	0.16025516	0.69336263	1.5	0.0217275	40.558	0.194141536
0.4	1.3	0.2	0.6000	0.447213595	2.19442719	0.27341987	0.990008963	1.7	0.0246245	86.91	0.594005378
0.6	1.3	0.3	0.9600	0.670820393	2.64164079	0.3634105	1.196788456	1.9	0.0275215	139.056	1.148916918
0.8	1.3	0.4	1.3600	0.894427191	3.08885438	0.44029269	1.360128871	2.1	0.0304185	196.996	1.849775265
1	1.3	0.5	1.8000	1.118033989	3.53606798	0.50903999	1.498259397	2.3	0.0333155	260.73	2.696866915
Top trapezoidal											
0	2.3	0	0.0000	0	2.3	0	0	2.3	0.0333155	0	0
0.5	2.3	2.5	2.4000	2.549509757	7.39901951	0.3243673	1.109456953	7.3	0.1057405	347.64	2.662696688
1	2.3	5	7.3000	5.099019514	12.498039	0.58409163	1.642125705	12.3	0.1781655	1057.405	11.98751765
1.5	2.3	7.5	14.7000	7.64852927	17.5970585	0.83536689	2.084509671	17.3	0.2505905	2129.295	30.64229216
2	2.3	10	24.6000	10.19803903	22.6960781	1.08388771	2.479754027	22.3	0.3230155	3563.31	61.00194906
3	2.3	15	51.9000	15.29705854	32.8941171	1.57778973	3.185066418	32.3	0.4678655	7517.715	165.3049471
5	2.3	25	136.5000	25.49509757	53.2901951	2.5614468	4.399560602	52.3	0.7575655	19772.025	600.5400222
17	2.3	85	1484.1000	86.68333173	175.666663	8.44838725	9.748436163	172.3	2.4957655	214971.885	14467.65411
Bottom and top trapezoid added together											
1	1.3	0.5	1.8000	1.118033989	3.53606798	0.50903999	1.498259397	2.3	0.0333155	260.73	2.696866915
1.5	1.3	3	4.2000	3.667543746	8.63508749	0.48638766	1.453474586	7.3	0.1057405	608.37	6.104593261
2	1.3	5.5	9.1000	6.217053502	13.734107	0.66258403	1.786129955	12.3	0.1781655	1318.135	16.25378259
2.5	1.3	8	16.5000	8.766563259	18.8331265	0.87611582	2.151757988	17.3	0.2505905	2390.025	35.5040068
3	1.3	10.5	26.4000	11.31607302	23.932146	1.10311879	2.508999639	22.3	0.3230155	3824.04	66.23759047
4	1.3	15.5	53.7000	16.41509253	34.1301851	1.57338731	3.179138917	32.3	0.4678655	7778.445	170.7197598
6	1.3	25.5	138.3000	26.61313156	54.5262631	2.53639241	4.370824551	52.3	0.7575655	20032.755	604.4850354
18	1.3	85.5	1485.9000	87.80136572	176.902731	8.39953113	9.710817071	172.3	2.4957655	215232.615	14429.30309

* in the trapeziodal shape it is the total top width of the trapezoid minus the base width and then divided by 2

Stream 5

drop	3	m	side slopes first 1 m		0.463647609	radians	26.56505118	degrees
length	429.41	m	side slopes beyond 1m		1.373400767	radians	78.69006753	degrees
			slope of channel		0.00698633	m/m		
			mannings n		0.05	(Chow et al. 1988, p-5)		

depth	**stream bottomwidth**	**top-triangle-dis ***	**Cross sec area**	**Side wetted**	**wetted perimeter**	**Hydraulic radius**	**velocity**	**water surface width**	**area**	**volume**	**outflow**
m	*m*	*m*	*m^2*	*m*	*m*		*m/s*	*m*	*ha*	*m^3*	*m^3/s*
0	1.5	0	0.0000	0	1.5	0	0	1.5	0.0644115	0	0
0.2	1.5	0.1	0.3200	0.2236068	1.947213595	0.16433739	0.5015476	1.7	0.0729997	137.4112	0.160495224
0.4	1.5	0.2	0.6800	0.4472136	2.394427191	0.283992766	0.7222586	1.9	0.0815879	291.9988	0.491135858
0.6	1.5	0.3	1.0800	0.67082039	2.841640786	0.380062112	0.8771171	2.1	0.0901761	463.7628	0.947286512
0.8	1.5	0.4	1.5200	0.89442719	3.288854382	0.462167011	0.99928	2.3	0.0987643	652.7032	1.518905528
1	1.5	0.5	2.0000	1.11803399	3.736067977	0.535322165	1.1021263	2.5	0.1073525	858.82	2.204252587
Top trapezoidal											
0	2.5	0	0.0000	0	2.5	0	0	2.5	0.1073525	0	0
0.5	2.5	2.5	2.5000	2.54950976	7.599019514	0.328989812	0.7966658	7.5	0.3220575	1073.525	1.991664522
1	2.5	5	7.5000	5.09901951	12.69803903	0.590642381	1.1768044	12.5	0.5367625	3220.575	8.826032995
1.5	2.5	7.5	15.0000	7.64852927	17.79705854	0.842835908	1.4915915	17.5	0.7514675	6441.15	22.37387248
2	2.5	10	25.0000	10.198039	22.89607805	1.091890058	1.7725853	22.5	0.9661725	10735.25	44.31463357
3	2.5	15	52.5000	15.2970585	33.09411708	1.58638467	2.2738416	32.5	1.3955825	22544.025	119.3766862
5	2.5	25	137.5000	25.4950976	53.49019514	2.570564561	3.1369449	52.5	2.2544025	59043.875	431.3299233
17	2.5	85	1487.5000	86.6833317	175.8666635	8.45811236	6.9396385	172.5	7.4073225	638747.375	10322.71223
Bottom and top trapezoid added together											
1	1.5	0.5	2.0000	1.11803399	3.736067977	0.535322165	1.1021263	2.5	0.1073525	858.82	2.204252587
1.5	1.5	3	4.5000	3.66754375	8.835087491	0.509332817	1.0661598	7.5	0.3220575	1932.345	4.797719273
2	1.5	5.5	9.5000	6.2170535	13.934107	0.681780325	1.2949436	12.5	0.5367625	4079.395	12.30196425
2.5	1.5	8	17.0000	8.76656326	19.03312652	0.893179583	1.5504118	17.5	0.7514675	7299.97	26.35700094
3	1.5	10.5	27.0000	11.316073	24.13214603	1.118839575	1.8016334	22.5	0.9661725	11594.07	48.64410193
4	1.5	15.5	54.5000	16.4150925	34.33018506	1.587524212	2.2749304	32.5	1.3955825	23402.845	123.9837078
6	1.5	25.5	139.5000	26.6131316	54.72626311	2.549050347	3.1194174	52.5	2.2544025	59902.695	435.1587254
18	1.5	85.5	1489.5000	87.8013657	177.1027314	8.410372827	6.9135012	172.5	7.4073225	639606.195	10297.66009

* in the trapeziodal shape it is the total top width of the trapezoid minus the base width and then divided by 2

Stream 6

drop	15	m	side slopes first 1 m	0.463647609	radians	26.56505118	degrees
length	1708.23	m	side slopes beyond 1m	1.373400767	radians	78.69006753	degrees
			slope of channel	0.008781019	m/m		
			mannings n	0.05	(Chow et al. 1988, p-5)		

depth	stream bottomwidth	top-triangle-dis *	Cross sec area	Side wetted	wetted perimeter	Hydraulic radius	velocity	water surface width	area	volume	outflow1
m	*m*	*m*	*m^2*	*m*	*m*		*m/s*	*m*	*ha*	*m^3*	*m^3/s*
0	2	0	0.0000	0	2	0	0	2	0.341646	0	0
0.2	2	0.1	0.4200	0.2236068	2.447213595	0.17162376	0.5787896	2.2	0.3758106	717.4566	0.243091637
0.4	2	0.2	0.8800	0.4472136	2.894427191	0.304032522	0.8473883	2.4	0.4099752	1503.2424	0.745701735
0.6	2	0.3	1.3800	0.67082039	3.341640786	0.412970779	1.0393185	2.6	0.4441398	2357.3574	1.434259565
0.8	2	0.4	1.9200	0.89442719	3.788854382	0.506749483	1.1912365	2.8	0.4783044	3279.8016	2.287174101
1	2	0.5	2.5000	1.11803399	4.236067977	0.590169944	1.3186226	3	0.512469	4270.575	3.296556474
Top trapezoidal											
0	3	0	0.0000	0	3	0	0	3	0.512469	0	0
0.5	3	2.5	2.7500	2.54950976	8.099019514	0.339547274	0.9121563	8	1.366584	4697.6325	2.508429959
1	3	5	8.0000	5.09901951	13.19803903	0.606150655	1.3423203	13	2.220699	13665.84	10.73856274
1.5	3	7.5	15.7500	7.64852927	18.29705854	0.860794098	1.6959068	18	3.074814	26904.6225	26.71053159
2	3	10	26.0000	10.198039	23.39607805	1.11129737	2.0107403	23	3.928929	44413.98	52.27924717
3	3	15	54.0000	15.2970585	33.59411708	1.607424296	2.5717148	33	5.637159	92244.42	138.8725995
5	3	25	140.0000	25.4950976	53.99019514	2.593063419	3.5373487	53	9.053619	239152.2	495.2288241
17	3	85	1496.0000	86.6833317	176.3666635	8.482328636	7.7949353	173	29.552379	2555512.08	11661.22324
Bottom and top trapezoid added together											
1	2	0.5	2.5000	1.11803399	4.236067977	0.590169944	1.3186226	3	0.512469	4270.575	3.296556474
1.5	2	3	5.2500	3.66754375	9.335087491	0.562394301	1.2769181	8	1.366584	8968.2075	6.703820287
2	2	5.5	10.5000	6.2170535	14.434107	0.727443686	1.5158936	13	2.220699	17936.415	15.91688228
2.5	2	8	18.2500	8.76656326	19.53312652	0.934310234	1.7911413	18	3.074814	31175.1975	32.68832938
3	2	10.5	28.5000	11.316073	24.63214603	1.157024644	2.0655269	23	3.928929	48684.555	58.86751717
4	2	15.5	56.5000	16.4150925	34.83018506	1.622156182	2.5874039	33	5.637159	96514.995	146.1883209
6	2	25.5	142.5000	26.6131316	55.22626311	2.580294084	3.5257263	53	9.053619	243422.775	502.4159924
18	2	85.5	1498.5000	87.8013657	177.6027314	8.437370236	7.7673676	173	29.552379	2559782.655	11639.4003

* in the trapeziodal shape it is the total top width of the trapezoid minus the base width and then divided by 2

Stream 7

drop	1	m	side slopes first 1 m		0.463647609	radians	26.56505118	degrees
length	34.06	m	side slopes beyond 1m		1.373400767	radians	78.69006753	degrees
			slope of channel		0.029359953	m/m		
			mannings n		0.05	(Chow et al. 1988, p-5)		

depth	**stream bottomwidth**	**top-triangle-dis ***	**Cross sec area**	**Side wetted**	**wetted perimeter**	**Hydraulic radius**	**velocity**	**water surface width**	**area**	**volume**	**outflow**
m	*m*	*m*	*m^2*	*m*	*m*		*m/s*	*m*	*ha*	*m^3*	*m^3/s*
0	2.5	0	0.0000	0	2.5	0	0	2.5	0.008515	0	0
0.2	2.5	0.1	0.5200	0.223606798	2.947213595	0.17643784	1.078041538	2.7	0.0091962	17.7112	0.5605816
0.4	2.5	0.2	1.0800	0.447213595	3.394427191	0.318168557	1.597150515	2.9	0.0098774	36.7848	1.724922556
0.6	2.5	0.3	1.6800	0.670820393	3.841640786	0.437313141	1.974404017	3.1	0.0105586	57.2208	3.316998748
0.8	2.5	0.4	2.3200	0.894427191	4.288854382	0.540936995	2.27512605	3.3	0.0112398	79.0192	5.278292436
1	2.5	0.5	3.0000	1.118033989	4.736067977	0.633436854	2.527608995	3.5	0.011921	102.18	7.582826984
Top trapezoidal											
0	3.5	0	0.0000	0	3.5	0	0	3.5	0.011921	0	0
0.5	3.5	2.5	3.0000	2.549509757	8.599019514	0.348876985	1.698331849	8.5	0.028951	102.18	5.094995546
1	3.5	5	8.5000	5.099019514	13.69803903	0.620526776	2.493147797	13.5	0.045981	289.51	21.19175628
1.5	3.5	7.5	16.5000	7.64852927	18.79705854	0.877796915	3.141740959	18.5	0.063011	561.99	51.83872583
2	3.5	10	27.0000	10.19803903	23.89607805	1.129892526	3.717626579	23.5	0.080041	919.62	100.3759176
3	3.5	15	55.5000	15.29705854	34.09411708	1.627846818	4.742238192	33.5	0.114101	1890.33	263.1942196
5	3.5	25	142.5000	25.49509757	54.49019514	2.61514938	6.504870794	53.5	0.182221	4853.55	926.9440882
17	3.5	85	1504.5000	86.68333173	176.8666635	8.506407994	14.28033777	173.5	0.590941	51243.27	21484.76818
Bottom and top trapezoid added together											
1	2.5	0.5	3.0000	1.118033989	4.736067977	0.633436854	2.527608995	3.5	0.011921	102.18	7.582826984
1.5	2.5	3	6.0000	3.667543746	9.835087491	0.610060663	2.465034616	8.5	0.028951	204.36	14.79020769
2	2.5	5.5	11.5000	6.217053502	14.934107	0.770049391	2.879077761	13.5	0.045981	391.69	33.10939425
2.5	2.5	8	19.5000	8.766563259	20.03312652	0.973387753	3.365877135	18.5	0.063011	664.17	65.63460414
3	2.5	10.5	30.0000	11.31607302	25.13214603	1.193690342	3.856282078	23.5	0.080041	1021.8	115.6884623
4	2.5	15.5	58.5000	16.41509253	35.33018506	1.655807913	4.796388022	33.5	0.114101	1992.51	280.5886993
6	2.5	25.5	145.5000	26.61313156	55.72626311	2.610977156	6.49795035	53.5	0.182221	4955.73	945.4517759
18	2.5	85.5	1507.5000	87.80136572	178.1027314	8.464216061	14.23307816	173.5	0.590941	51345.45	21456.36533

* in the trapeziodal shape it is the total top width of the trapezoid minus the base width and then divided by 2

APPENDIX G: Travel time calculations

Travel time calculation for the shortest reach in Lola Run (reach 5)

Q	410	cfs
n	0.05	
S	0.006982	ft/ft
bottom width	4.9212	ft
side slope angle	63.43495	degrees

AR^(2/3) = Q*n/1.49*S^1/2
AR^(2/3) = 164.6556

depth	**area**	**WP**	**R**	**R 2/3**	**AR 2/3**
ft	*ft^2*	*ft*			
6	101.5272	31.7540	3.1973	2.1703	220.3459
5.5	87.5666	29.5179	2.9666	2.0646	180.7896
5.4	84.8945	29.0707	2.9203	2.0431	173.4450
5.27	81.4805	28.4894	2.8600	2.0149	164.1728
5.2	79.6702	28.1763	2.8276	1.9996	159.3080
5.1	77.1181	27.7291	2.7811	1.9776	152.5119
5	74.6060	27.2819	2.7346	1.9555	145.8949
4.5	62.6454	25.0458	2.5012	1.8426	115.4317
4	51.6848	22.8097	2.2659	1.7252	89.1643
3.5	41.7242	20.5737	2.0280	1.6022	66.8506
3	32.7636	18.3376	1.7867	1.4724	48.2419
2.5	24.8030	16.1015	1.5404	1.3338	33.0823
2	17.8424	13.8655	1.2868	1.1831	21.1089
1	6.9212	9.3933	0.7368	0.8158	5.6462

	R	2.860034	
travel time	v =	5.017124	ft/sec
total time		4.683161	min

Vita

Tone Merete Nordberg was born February 4, 1975, in Trondheim, Norway. After spending her very first years in Trondheim she moved south to Asker outside Oslo. In 1991 after completing nine years of school in Asker she moved another couple of hours south to a little town by the coast called Sandefjord to attend Skagerak International School. In 1995 she graduated from Skagerak International School with an International Baccalaureate (I.B). She set sail for America and a small town in southwest Virginia called Blacksburg to pursue a higher education at Virginia Polytechnic Institute and State University. She completed a Bachelor of Science in Biological Systems Engineering in December, 1998. To further her educational goals she set her eyes upon graduate school and after some initial thoughts of relocating she decided life was good in Blacksburg and began her graduate studies at Virginia Polytechnic Institute and State University in January of 1999. A little more than two years later she received her Master of Science in Biological Systems Engineering in April, 2001. The educational road has come to and end for now and she has decided to try life in the real world for a while.