Efficient Protection of Fisheries Habitat in Great Lakes Tributaries from Agricultural Pollutants

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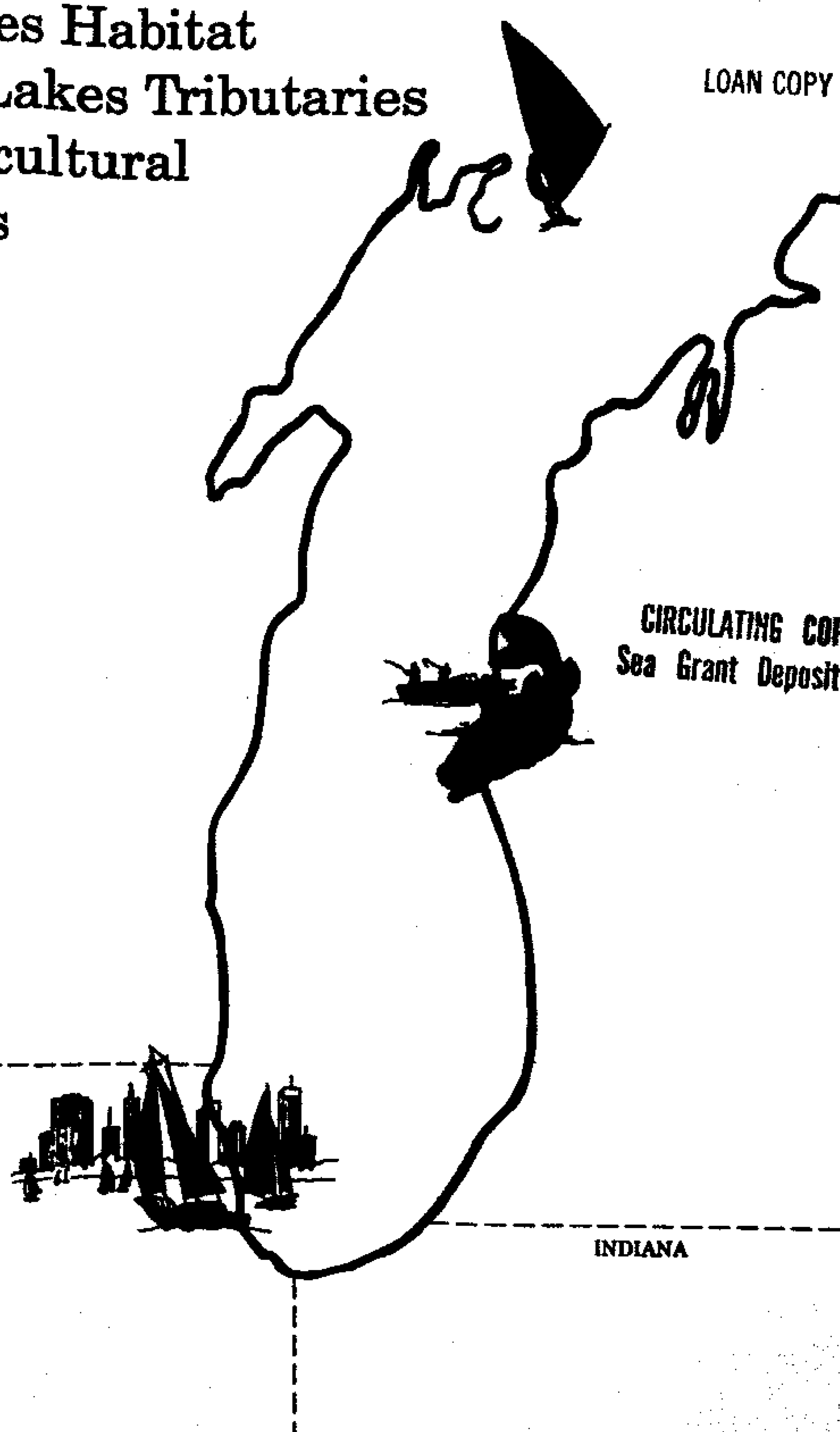

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EFFICIENT PROTECTION OF FISHERIES HABITAT IN GREAT LAKES TRIBUTARIES FROM AGRICULTURAL POLLUTANTS

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ABSTRACT

Achieving greater efficiency in programs to reduce the impacts of agricultural nonpoint pollution is an important interest in the Great Lakes basin, especially with respect to enhancing habitat for sport fish species. One aspect of efficiency is "targeting"—taking abatement actions where they are most cost-effective.

This study develops a pollution-risk management framework that combines farm management models, pollutant transport models, weather event simulations, and fish habitat models. The framework is applied to selected reaches of Lake Michigan tributaries in southwestern Michigan, with particular emphasis on habitat for Salmonids.

The results of the analysis suggest that a "targeted" program can achieve significant improvements in habitat quality and reliability at reasonably low cost. The results also indicate that erosion or sediment control are poor ways to achieve high levels of habitat quality and reliability where soluble pesticides are the limiting pollutants.

KEYWORDS: Economics, Agriculture, Nonpoint Pollution, Targeting, Fish, Great Lakes

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NOTATION

a	area, ha.
c	cost, $.
cn	Soil Conservation Service runoff curve number.
CP	pesticide concentration in soil, g ha^{-1}.
CQ	pesticide concentration in runoff, g ha^{-1}.
d	dissolved phase pesticide available for loss, g ha^{-1}.
EI	storm event rainfall erosivity, MJ-mm/ha/hr/y
g	crop growth phase index
h	saturated hydraulic conductivity, cm/hr.
i	management path index.
IL	infiltration loss during overland flow, cm.
j	transect index.
k	LMU index.
L	hydraulic length, m.
p	pesticide partition coefficient.
PC	probability of exceeding pesticide suitability target.
PS	probability of exceeding sediment suitability target.
PX	minimum acceptable probability of achieving suitability target.
q	daily runoff, cm.
Q^{50}	median daily runoff runoff, m^3day^{-1}.
R	daily rainfall, cm.
S	runoff retention parameter.
SIC	composite pesticide suitability index.
SIP	pesticide suitability index.
SIS	sediment suitability index.
SIT	target suitability value.
sl	slope, m/m.
t	time, day.
tc	overland flow time of concentration, hr.
td	sediment delivery ratio.
UC	USLE cover factor.
UK	USLE soil factor.
UL	USLE topographic factor.
UP	USLE supporting practice factor.
UR	USLE rainfall factor.
x	binary choice variable.
y	sediment loss, tons yr^{-1}.
z	erosion loss, tons yr^{-1}.
α	pesticide decay rate, $days^{-1}$.
θ	soil available water capacity, cm cm^{-1}
μ	soil bulk density, g cm^{-3}
ε	normally distributed random variate

CHAPTER 1: INTRODUCTION

1.1 PROBLEM STATEMENT

Past attention to agricultural nonpoint source pollution has usually focused on erosion rates or levels of agricultural chemical use. Some studies have simulated hydrologic processes that carry these pollutants to surface water. However, there have been few attempts to connect farming practices all the way to instream impacts. Making this connection would allow the "targeting" of management measures so as to reduce ultimate damages at the lowest cost.

The matter of targeting agricultural pollution abatement to instream impacts is important in the Great Lakes basin, where agriculture occupies much of the land. In a review of Great Lakes pollution control efforts, the U.S. General Accounting Office (GAO) concluded:

> Without more attention to nonpoint sources and a coordinated strategy and plan for dealing with them, the Great Lakes Water Quality Objectives [established in the 1978 Great Lakes Water Quality Agreement] may not be achieved even if all other sources of pollution are completely controlled or eliminated (GAO 1982, p. iii).

Past efforts to analyze agricultural nonpoint source pollution have usually focused only on erosion rates or levels of polluting inputs (fertilizers, pesticides, etc.), often disregarding the complex relationships between erosion and the delivery of pollutants to a stream. A task force of the United States-Canada International Joint Commission reported in 1983 that technical knowledge is sufficient to support implementation of nonpoint source pollution control programs, but that a key implementation issue, establishing priorities, has not been adequately addressed:

> Only a small number of nonpoint programs have been targeted to those areas of the landscape which contribute a disproportionately large share of the total pollution load. With continued scarcity of resources, it will be necessary for governments to identify their priority management areas and target their resource expenditures accordingly (Nonpoint Source Task Force 1983, p. 10).

The Task Force recommends "that areas within watersheds which have a higher potential to deliver pollutants be identified and that implementation of measures (to reduce pollution) in these areas receive priority attention."(Nonpoint Source Task Force 1983, p. 14)

The identification of pollution "hot-spots" within watersheds is not an easy task. The runoff of pollutants is a complex process in which both temporal and spatial factors are important. When "hot-spots" are identified, determining the most cost-effective abatement measures may also be difficult if interrelationships in the runoff process exist between different farm fields.

1.2 STUDY OBJECTIVES

This study has several objectives. The first and fundamental goal is to develop an analytical framework for identifying "priority areas" controlling the damage to fisheries habitat in Great Lakes tributaries caused by sediment and sediment-associated pollutants. This is accomplished in a risk management framework. The specific approach involves simulation and optimization models linking farm economics, pollutant runoff, and fisheries habitat within a stochastic (variable) weather system. The models are spatially and temporally defined and together identify both the kind and location of management practices that will achieve a specified level of protection for designated fish species at the lowest cost. Costs are incurred by having farmers employ practices or grow crops that are less than the most profitable options.

The second objective is to use the framework to identify efficient management approaches for protecting sport fish habitat in tributaries to Lake Michigan. This objective involves identifying important fish species and study sites and characterizing the economic, physical, chemical, and biological conditions in the study areas.

The third objective is to investigate the importance of targeting abatement policies to control nonpoint source pollution. This goal is met by identifying and analyzing different policy and management options.

1.3 REPORT OUTLINE

The second and third objectives depend on success with the first—achieving a marriage of diverse model components that reasonably represents the problem of agricultural nonpoint pollution management. Hence, the largest share of this report, chapters 3 and 4, is devoted to model development. Chapter 2 describes the scholarly context of our work. Chapter 5 describes applications of the framework to two subwatersheds along tributaries of southeastern Lake Michigan. Included in the application chapter is an analysis of the importance of targeting. Chapter 6 contains the general conclusions of our study.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

2.1 TARGETING OF AGRICULTURAL POLLUTANT SOURCES

Targeting refers to the abatement of pollution where it is most cost-effective to do so (Nichols 1984). This has both economic and physical dimensions. The economic challenge is to characterize the costs of abatement at different sources and the damages incurred from pollution at different receptors. The physical dimension involves characterizing the pollutant dispersion process that connects sources to receptors. By capturing both dimensions, it is possible to identify an abatement strategy that emphasizes reducing the costs of abatement while mitigating the worst damages.

In the case of agricultural nonpoint source pollution, the physical dimension is particularly challenging. Sediment and agricultural chemicals are entrained in surface runoff which flows downhill, perhaps crossing many farm fields, on its way to a receiving stream. Pollutants are deposited and picked up along the way. Two storms which seem to be similar will result in pollutant runoff loads which are quite different due to timing and the pattern of land uses. Moreover, the management of land near a stream or lake affects the runoff of pollutants from more distant fields.

Not only is the runoff process difficult to characterize, but the prediction of damages is also troublesome. Sediment and agricultural chemicals degrade aquatic ecosystems, accelerate eutrophication, clog stream channels, fill up reservoirs, and so forth (Clark, Haverkamp, and Chapman 1985). The impacts are experienced by water-based recreators, water supply agencies, drainage districts, etc. Thus, the damages are not easy to characterize.

In the present study, we explore two aspects of targeting. First, we investigate selective abatement—abatement that responds to different cost structures and different positions in the pollutant runoff process—to see how much more costly it is to implement unselective policies. This is important to know because selective policies are costly to administer. While the administrative costs are not analyzed here, it is almost certainly true that cost savings due to selective policies would have to be substantial to warrant undertaking the administrative burden. Second, we investigate the management and cost implications of using different damage indicators, specifically, stream-edge pollutant loads versus impacts on the aquatic ecosystems that affect anadromous fish. This analysis will illustrate the consequences of using different indicators and suggest the challenges of using indicators that more closely approximate true damages.

2.2 ECONOMIC ANALYSIS OF AGRICULTURAL POLLUTANT RUNOFF

Past efforts by economists to analyze agricultural nonpoint source pollution problems have focused only on erosion rates or use levels of polluting inputs (fertilizers, pesticides, and so forth). The hydrologic and biological links to water quality conditions are not typically made. As a result, no attention is paid to spatial features that shape the connection between activities on specific land parcels and water quality impacts. Representative of this approach are the studies by Miller and Gill (1976); Heady and Meister (1977); Taylor and Frohberg (1977); Osteen and Seitz (1978); Seitz et al. (1979); Boggess et al. (1980); Walker and Timmons (1980); and Crowder et al. (1984). These studies yield insights about local, regional, or national farm output and income consequences of erosion or input restrictions. However, they are not helpful in designing an economically efficient pattern of land uses for achieving environmental goals.

The few attempts to link economic models of land use practices to water quality impacts, chiefly sedimentation, use a crude pollutant "delivery ratio". The ratio is the proportion of gross erosion that reaches a stream. A watershed-level example of such an approach is Guntermann, Lee, and Swanson (1975). The use of a fixed ratio for a watershed conceals the fact that pollutant delivery may be greatly reduced relative to pollutant emission by appropriate location of abatement measures.

The studies by Park and Shabman (1981, 1982); Carvey and Croley (1984); Lovejoy, Lee, and Beasly (1985); and Milton (1987) link hydrologic simulations of pollutant loads to economic choices (captured in linear programming models). The work of Park and Shabman (1981) is based on detailed hydrologic and spatial descriptions, but the economic portion of the model is aggregated. The optimization is based on only a few cost-water quality extreme points. The solutions are not linked to specific farm fields or locations of management practices and are limited to short-term analyses.

The Watershed Evaluation and Research System (WATERS) (Carvey and Croley 1984) combines the detailed Iowa Institute for Hydrologic Research Distributed Parameter Watershed Model (Jain et al. 1982), financial information on cropping practices from a farm budget generator, and a multiple objective optimization algorithm. The model is designed to search for land management practices that optimize a linear objective function containing arguments for net revenues to farmers and water quality. A trade-off function between these arguments can be traced by changing their relative weights and resolving the model.

WATERS represents progress toward economic targeting, but it has severe limitations. It depends on a storm event hydrologic model that requires substantial computational capabilities. This is reflected in the fact that the only reported application of WATERS simulated only a single storm (Carvey and Croley 1984). Sediment is the only pollutant considered, and WATERS does not link pollutant delivery to water quality impacts.

The Sediment Economics (SEDEC) model developed by Braden, Johnson, and Martin (1985; see also Bouzaher et al. 1988) joins a field-level model of annual net revenues and erosion levels, a sediment delivery model, and a network optimization algorithm. The economic facet of SEDEC uses a model of erosion control economics, SOILEC, developed at the University of Illinois (Eleveld, Johnson, and Dumsday 1983; and Johnson et al. 1989). Erosion rates are computed in SOILEC using the Universal Soil Loss Equation (Wischmeier and Smith 1978). The pollutant transport model in SEDEC is an adaptation of the surface transport model of Clarke and Waldo (1986). This model is used in conjunction with a distributed parameter spatial representation, a network (cascade) model of surface water flow, and an economic optimization algorithm. The model identifies the economic and pollutant load implications of alternative management measures on specific farm fields.

The SEDEC approach has been used on a microcomputer to optimize the control of sediment in Illinois subwatersheds of up to 1,300 acres (Miltz, Braden, and Johnson 1988; Braden, Johnson, Bouzaher, and Miltz 1989; and Wu, Braden, and Johnson 1989). This is about double the reported coverage of the only other economic optimization model (WATERS) that produces detailed results for land uses. But, unlike WATERS, SEDEC reflects a long span of weather events and captures the onsite effects of erosion.

SEDEC has been designed specifically for planning applications. It can reveal changes in farming practices, at particular locations, that will most cheaply reduce sediment loads. It can also reveal the subsidies (or penalties) necessary to compensate (induce) farmers for abating erosion. The potential for using a model such as SEDEC for policy analysis is illustrated in the paper by Miltz, Braden, and Johnson (1988). Based on an application of SEDEC to about 223 acres in the Highland Silver Lake watershed of Madison County, Illinois, the authors show that Illinois' state law limiting erosion to soil loss tolerance levels is nearly twice as costly as the spatially optimal "targeted" policy, identified by SEDEC, for reducing sedimentation.

2.3 AGRICULTURAL POLLUTION EFFECTS ON FISHERIES

The characteristics of ecosystems receiving non-point and agricultural drainage are reasonably well known (Borman and Likens 1979; Gammon et al., 1983; Goodman et al. 1984; Hynes 1974; Karr and Dudley 1978; and Lake and Morrison 1977), and the response of species and communities of organisms has been studied (Herricks and Cairns 1983). An exhaustive review of the research which has been conducted to access the aquatic impacts posed by the multitude of farm chemicals is not attempted here.

Instead, brief explanations are given of the possible modes of impact from agricultural pollutants and the available information pertaining to them. Special emphasis is placed on Salmonids and other game fish species that are of particular interest in tributaries to Lake Michigan. The status of information relating to aquatic impacts from the three agricultural pollutants of greatest concern in midwestern streams, sediment, fertilizers, and pesticides, has been extensively reviewed recently by McCabe and Sandretto (1985).

2.3.1 Sediment

Sediment produce multiple impacts in receiving streams which can be placed into two categories; impacts due to suspended sediments and those caused by deposition of sediments in the stream bed.

Acute toxicity due to suspended particles has been observed in laboratory studies in which extremely high (up to 225,000 mg/l) concentrations were involved. The mechanisms of mortality observed in these studies have included the clogging of gill filaments and opercular cavities, gill abrasion, and starvation (McCabe and Sandretto 1985). In natural aquatic systems, however, avoidance behaviors by fish have been observed and suspended sediments are thought to have little direct impact on fish. Deposition of fine particles in stream beds can affect fish by degrading the quality of spawning habitat and by altering the species composition of the aquatic macroinvertebrate community, a primary food source for Salmonid species. Macroinvertebrate communities can change as a result of decreased intergravel flows of water which reduce dissolved oxygen concentrations and allow metabolic wastes to accumulate in the stream bed. The accumulation of fine sediments in streambeds can also reduce the amount of exposed rocky substrate required by many of the desirable aquatic insect species as surfaces of attachment (Gammon 1970).

The alteration of spawning habitat is generally considered to be the most detrimental effect of sediment to Salmonid species. While specific spawning behavior varies by species, all Salmonids species excavate a pit, called a redd, in gravel substrate. The eggs are deposited in the redd and the embryos incubate for 1 to 2 months. After hatching, the fry spend two to eight weeks in the intergravel environment before emergence.

In addition to reducing the amount of habitat suitable for spawning, fine sediments can reduce the habitat quality for embryos and fry by decreasing intergravel flows. The deposition of fines while the fry are present in the intergravel environment can entrap the fry and prevent them from emerging (Peters 1967; Cooper 1956).

2.3.2 Pesticides

Dangerous levels of organochlorine pesticides such as DDT are still commonly detected in fish tissue samples although their use was banned years ago. Many of the pesticides in current use degrade rapidly in the environment and do not biomagnify. Despite this, chronic and even acutely toxic effects may periodically occur for short durations in tributaries where concentrations are the highest (North Carolina Agricultural Experiment Station 1984).

A voluminous amount of data is available regarding acute toxicological data response of aquatic organisms to pesticides, especially for adult fish. Unfortunately, other important types of data are not as available. These include the chronic toxicity of organisms and the toxicological responses to sediment-bound pesticides.

Salmonids are often found to be among the most sensitive fish species in acute toxicity tests (Mayer and Ellersick 1984). This fact and the high economic value of Salmonids has resulted in the frequent use of the rainbow trout, a salmonid, for toxicity tests. Due to the high costs of chronic toxicity testing, data regarding the chronic toxicity of pesticides to fish are less available than are acute toxicity data. This is unfortunate, as concentrations of pesticides in receiving systems which result in chronic effects are much more likely to occur than acute concentrations.

Although aquatic invertebrates and flora are not used as test organisms as often as fish species, some data are available. Results vary greatly, but tests regarding the acute toxicity of insecticides to aquatic invertebrates suggests that they are more sensitive than fish. This trend suggests that fish food organisms could be affected at levels of insecticide concentrations that are not directly toxic to fish (McCabe and Sadretto 1985).

The acute toxicity of herbicides to fish is generally 1-2 orders of magnitude less than that of insecticides. This is expected, because herbicides are formulated to interfere with the metabolic processes of flora and are only incidentally toxic to fauna. Although some research has been conducted which suggests that the effects of herbicides on aquatic ecosystems are insignificant when compared to insecticides, more research is needed to quantify their effects.

2.3.3 Fertilizers

A considerable amount of research has been conducted concerning the role of nutrient runoff from agricultural sources in the accelerated eutrophication of lakes. The effects of nutrient runoff in streams is rarely seen to be a problem as primary production in stream ecosystems is thought to be controlled by factors other than nutrient concentration. Available sunlight, velocity, substrate, and other physical factors are considered as the controlling influences of primary production in streams. As a result, little attention is given to nutrient pollution in the remainder of this study.

2.3.4 Pollutant Effects Modeling

Very few previous investigations have attempted to link agricultural land use with fisheries impacts. One of the notable exceptions is a model developed by Garbrecht and Theurer (1986). Their simulation model combines a model of runoff and sediment yield with an instream model of sediment intrusion, oxygen depletion in the sediment, and temperature which is used to predict decreases in Salmonid fry emergence. The model is site specific to the 505 square mile watershed of the Tucannon River basin in Washington. The percentage of fry emerging is predicted based on total accumulation of fine sediments in the gravel matrix and daily and seasonal average predictions of temperature and dissolved oxygen in the embryo habitat.

The U.S. Fish and Wildlife Service,USFWS,(1980) developed a series of Habitat Suitability Index (HSI) models as part of their Habitat Evaluation Procedures (HEP). HSI models provide a quantitative means of assessing habitat quality, including parameters for water quality, stream substrate, and sediment variables. Models for over 40 fish species are currently available, including models for seven salmonid and cold water species. HSI models are based on assessments using parameter specific suitability indices. A suitability index value is a unitless number scaled from 0, indicating unsuitable habitat, to 1, indicating optimal habitat. HSI models are flexible and may be adapted to a variety of modeling needs and management requirements.

Herricks and Braga (1986) suggest a general framework for developing suitability curves for water quality parameters, including toxic pollutants. The method relates acute and chronic toxicological responses to different suitability index values.

2.4 RISK ASSESSMENT OF AGRICULTURAL POLLUTION

Field investigations of agricultural nonpoint source pollution have shown both pollutant loads and concentrations to be extremely variable (Wauchope 1978). This has led to the development and use of mathematical models to study the processes involved in pollutant runoff and to evaluate abatement methods and policies. Some of the more commonly used models are ANSWERS (Beasley et al. 1980), CREAMS (Knisel 1980), AGNPS (Young et al. 1989), and HSPF (Donigian et al. 1984). These are all deterministic models—models which produce a single estimate of pollutant runoff without considering the reliability of that estimate. ANSWERS and AGNPS are event models, which consider only a single storm. With CREAMS and HSPF a historical or synthetic record of meteorological inputs is used to generate a time-series of pollutant runoff from which frequency distributions of pollutant loads or concentrations may be developed.

All of these models, however, require a great deal of data and allow only single estimates for the majority of required parameters. Errors in the estimation of key variables can lead to erroneous results. When model predictions are used for decision making, knowledge of the uncertainty of the predictions is useful. As a result of the inherent uncertainty in agricultural pollutant runoff, deterministic models based on steady-state conditions may not provide the necessary information required to manage agricultural pollutant runoff. Risk assessment procedures are available, however, to incorporate uncertainty into model predictions. Instead of making a single prediction of an outcome, the use of risk assessement allows a range of possible outcomes and their probabilities to be characterized.

There are three sources of uncertainty in mathematical models; inherent natural variability, model errors, and parameter uncertainty. Inherent natural variability is produced by the random occurrence of natural events. In the analysis of pollutant runoff from agricultural fields, for example, the stochastic nature of rainfall and temperature fit into this category. The consideration of pesticide runoff also involves several timing related issues. The importance of the time elapsed between pesticide application and a runoff producing rainstorm has been noted by several authors (Wauchope 1978, Leonard et al. 1979). Since pesticides are not likely to be applied simultaneously to all farm fields in a watershed, spatial variation occurs in the amount of pesticides available for runoff. In addition, a particular pesticide may not be used during all years of a crop rotation. When evaluating pesticide runoff from several farm fields, the accurate representation of timing issues also requires that dependence relationships between farm fields in regards to farm management (including crop rotations) be considered.

A common approach to risk assessment with respect to point source pollutants is the use of a deterministic model at an assumed design condition that has a specified probability of occurrence (e.g., the seven day low-flow condition that occurs once in ten years—abbreviated 7Q10). A weakness of this approach is the implication of only one random element, often precipitation or streamflow. Use of this method in the management of agricultural pollutant runoff is limited because of the large number of random elements affecting the outcome. Worst-case scenarios for different management systems may not be the same as well.

The second source of uncertainty is a result of the modeling process itself. All models are approximations of real world situations. In analyzing a complex environmental system, it is impossible to describe accurately all physical, chemical and biological processes while maintaining temporal and spatial integrity. The inevitable compromises lead to prediction errors and thus uncertainty. Uncertainty due to modeling errors is usually evaluated by validation, a comparison of model predictions to actual events. Validation is impossible, or at best limited, when the model is used for evaluating the ramifications of future or hypothetical actions.

Uncertainty is also introduced through errors made in parameter estimation. Models often involve the use of point estimates of variables which vary spatially and/or temporally. Including the variability of a parameter in a model serves to reduce the uncertainty but does not eliminate it. For example, the development of a cumulative probability distribution for stream flow is typically based on a historical record which may not be representative of the variable's true distributional characteristics. Another example of errors in parameter estimation is the use of parameter values obtained from laboratory experiments performed under unrealistic conditions. With deterministic models, this type of uncertainty is dealt with by sensitivity analysis, where each variable is individually adjusted up or down and the model output is examined. Variables which produce the greatest change in model output are identified so that better estimates of their values can be obtained. It is possible, however, to overlook synergistic effects between variables.

Two methods are available in which uncertainty due to both natural variability and parameter estimation can be considered. The first method is popular in science and engineering and is called first-order uncertainty analysis or first-order stochastic dominance (Benjamin and Cornell 1970). First-order analysis requires that the first and second moments (i.e., the mean and variance) of all random elements be known, and requires the assumption that the first two moments of each random element accurately describes the element's distributional characteristics. Dependencies between random elements must also be specified. Taylor's series expansion of the functional relationships is used to develop estimates of the mean and variance for the model output. Clearly, first-order uncertainty analysis requires a greater degree of mathematical sophistication than possessed by most watershed managers.

Uncertainty can also be considered through the use of Monte Carlo simulation, which has become more popular with the availability of powerful desktop computers. Monte Carlo simulation permits solutions to be obtained for complex model formulations which would be too tedious to solve by first-order analysis. The technique requires that cumulative probability distributions be estimated for random elements and that dependencies between random elements be identified. Many sets of random samples are drawn from each probability distribution and are used to evaluate a deterministic model. By solving the model with a large number of random samples the distributional characteristics of the model output can be estimated. Commercially available software has been recently developed which allows sophisticated modeling to be performed by individuals without advanced knowledge of mathematics or computer programming techniques.

2.5 SUMMARY

This study is motivated by interest among policy makers in targeting programs to reduce nonpoint source pollution from agriculture. The study departs from previous work in two ways.

First, it aims to integrate economic, farm management, pollutant transport, and instream (fisheries) impacts in a single model. No previous work achieves such extensive integration. Doing so will make possible the selection of the location and type of farming measures to achieve desired abatement goals, and the assessment of different indicators of those goals.

The second departure is eschewing great technical detail. The framework to be developed here is intended to serve a planning role. Hence, the components should be reasonably transparent, similar in levels of detail, familiar to watershed planners, and amenable to widely available data. The advance from past work is not in developing better components, but in putting together familiar pieces in a way that opens new doors for managers and researchers.

CHAPTER 3: METHODS

3.1 GENERAL OUTLINE OF MODEL

The model presented here consists of four components: a model of farm management, a pesticide runoff and impact simulation, a sediment runoff and impact simulation, and an optimization algorithm (figure 3.1). The simulation models are not designed for exact physical or biological predictions. Doing so would be excessively complex and computationally demanding for active use in management programs. Rather, the aim is a simplified model that is accurate in relative predictions of pollutant loads and effects and that is accessible for use by watershed managers. Accessibility is accomplished by the use, wherever possible, of common algorithms familiar to most watershed managers.

In sections 3.2 and 3.5 the algorithms and procedures used in each component are described in detail. Data requirements of the model and many of the procedures used to incorporate uncertainty in the datasets are discussed in chapter 4. The probability distributions used for many of the variables are discussed in chapter 4 rather than here because the selection of a particular distribution depends on data characteristics.

Before going further, it is useful to describe, once again, the context of the problem. We are concerned with streams that serve as habitat for fish but which drain lands used for farming. Nutrients are not particularly problematic for tributary habitat, but the problem is that these streams are made less hospitable to desired species by agricultural sediment and pesticides. We are interested in discovering farming changes that will efficiently protect the desired species. Protection is defined in terms of probabilities of adverse conditions occurring. Efficiency is defined as reducing farming profits as little as possible.

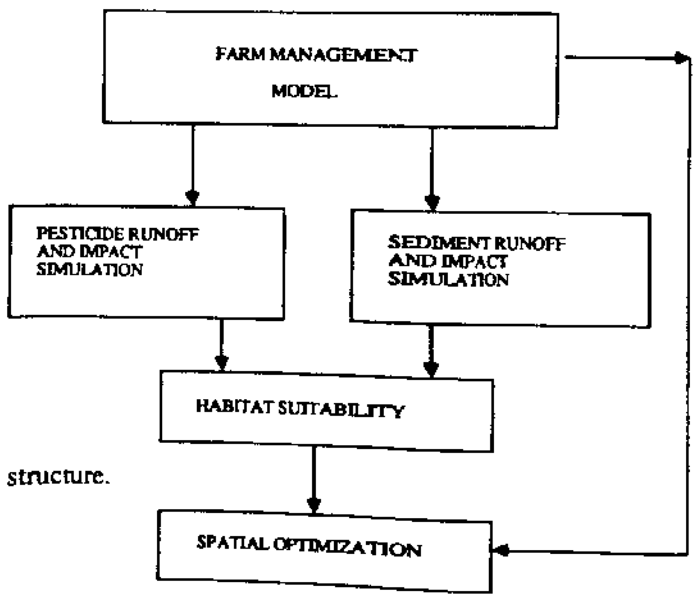


Figure 3.1. Model structure.

3.2 FARM MANAGEMENT

3.2.1 Identification of Decision Units

The procedures used to characterize the watershed landscape and define decision units were developed as part of the SEDEC model (Johnson et al. 1989). The watershed is first subdivided into catchments which are independent in surface drainage. For simplification, a typical runoff path, called a transect, is selected to represent the surface drainage pattern in each catchment.

The next step is the definition of decision units (figure 3.2). Each unit is required to be associated with a single catchment, homogeneous with respect to ownership and management practices, and reasonably uniform in slope. Thus a decision unit, referred to as a Land Management Unit (LMU), is defined as a complete farm field, or a portion of a farm field that has fairly uniform slope and lies inside a single catchment. Slope is included in the definition of LMUs to identify points in the landscape where surface water runoff changes velocity, as this affects the potential for infiltration during overland flow as well as the ability of water to transport sediment. Necessary information associated with each LMU includes topographic data such as area, slope, slope length, and position within a transect; soil types and the proportional area of each; and management associations, i.e., farm and field labels.

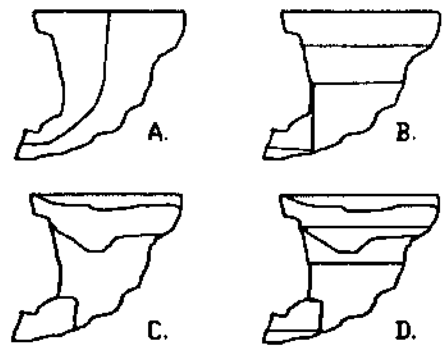


Figure 3.2. Identification of decision units (LMUs).

A. Single catchment, showing transect.
B. Field Boundaries
C. Slope class boundaries.
D. LMUs

3.2.2 Management Alternatives

The decision to be made on each LMU is called a management alternative and consists of a unique combination of tillage practice, crop rotation, and supporting mechanical practice. Each management alternative is characterized by a farm budget, which gives soil dependant crop yields and economic returns, as well as types of pesticides used, and rates and timing of application. Economic returns are soil specific and are computed as a weighted average based on the proportional area of each soil type in an LMU. The economic cost associated with implementing a management alternative on a particular LMU is taken to be the difference between the return associated with that alternative and the highest economic return possible on the LMU.

Information regarding pollution runoff potential is required for each management alternative as well. For each year of a crop rotation unique values are used for pesticide application rates and variables related to runoff and erosion. Variables used in the simulation models which are dependent on soil factors are computed for each LMU as the area weighted average.

3.2.3 Management Paths

Each possible combination of management alternatives for a transect is referred to as a management path. The number of management paths possible for each transect can be very large. For example, if 12 management decisions are possible for each LMU, a transect with 4 independent LMUs would involve 12^4 (20,736) management paths. The number of management paths to be considered will be reduced if two or more LMUs within the same catchment must be managed similarly because they are associated with the same farm or farm field. If associated with the same farm, we assume the same tillage practice will be used on the LMUs. Also, if they are part of the same farm field, we further require the same crop rotation to be used on the LMUs. Management paths which do not meet these requirements are considered infeasible and are eliminated from further consideration.

The assumption concerning management dependencies between LMUs which are part of the same field is important in the simulation models. To illustrate this, consider a hypothetical catchment with three LMUs. The same crop rotation is implemented on all three LMUs and consists of alternating years of corn and wheat. A single pesticide is applied during the corn year, while no pesticides are applied to the wheat. Each LMU has a 0.5 probability of a pesticide application during any given year.

If each LMU is part of a different farm field, they are assumed to be managed independently. The probability of a year in which pesticides are applied to none of the LMUs is 1/8, of a pesticide application to only 1 LMU is 3/8, to two LMUs is 3/8, and to all three LMUs is 1/8.

If, however, the three LMUs are part of the same farm field, our assumptions imply that corn will be planted during the same years on all three LMUs. The probabilities are then 0.5 that a pesticide application will occur on all three LMUs in a given year and 0.5 that no pesticide application takes place. If two of the three LMUs are associated with the same farm field, another set of probabilities exist. Similar differences in variability of runoff and sediment loss result as well. Due to the importance of timing as it relates to pesticide runoff, we further assume that all farm operations (tillage, pesticide applications, etc.) occur on the same day on LMUs which are part of the same farm field.

3.3 PESTICIDE MODEL

The risk of habitat degradation from pesticide runoff is estimated by a model of daily pesticide concentration in runoff coupled with a model of habitat degradation using Habitat Suitability Index (HSI) methods. The effects of pesticides on fish are restricted to those caused by the runoff of soluble pesticides. Insufficient information regarding effects due to sediment bound pesticides preclude their consideration in this model. To keep the model structure simple, several processes have not been considered which may alter runoff volume or the concentration of pesticides in runoff. That part of the pesticide load which infiltrates is assumed to have no effect although it may eventually enter the stream as baseflow. Subsurface drainage is not considered, nor is the absorption of soluble pesticides to organic material during the overland flow process.

Probabilistic estimates of habitat degradation risk are generated by using Monte Carlo simulation techniques. The model considers the variability of rainfall amount, timing, and soil moisture conditions. Uncertainty in the timing of pesticide applications is also considered. With every iteration of the simulation model the following equations are evaluated for several pesticides and for every management path on all catchments. In the following description, subscripts denoting management path, catchment, etc. are dropped where possible. To include all relevant subcripts would obscure the basic simplicity of the model.

3.3.1 Hydrology

The hydrology component uses U.S. Soil Conservation Service's Curve Number (CN) Equation (Mockus 1972) to predict the runoff from each LMU. A simple transport equation estimates infiltration losses during overland flow using estimates of travel time and infiltration rates.

The CN method predicts the runoff from LMU k resulting from a storm on day t by

$$q_{tk} = (r_t - 0.2s_{tk})^2/(r_{tk} + 0.8s_{tk}) \quad (1)$$

where r_t is the rainfall on day t, s_{tk} is a retention parameter (cm) for LMU k on day t, and q_{tk} is the predicted runoff from LMU k. The retention parameter s_{tk} is a function of land use, soil type and antecedent moisture conditions and is related to a curve number cn_{tk} by

$$s_{tk} = 2.54(1000/cn_{tk} - 10). \quad (2)$$

Published tables (e.g., Mockus 1972) are available which provide curve numbers for a variety of land use practices, four hydrologic soil types (A, B, C, and D), and 3 antecedent moisture conditions (AMC I, AMC II, and AMC III). Methods have also been developed which enable the modification of curve numbers to reflect the runoff characteristics of specific agricultural practices. (e.g., Carsel et al. 1984 and Knisel et al. 1980). In this study a crop rotation is characterized by several curve numbers, each of which represents the runoff characteristics of a particular period of time during the crop rotation. Section 4.2.2 describes the methods used to develop the set of curve numbers for each rotation. The methods used to determine the curve number actually used in each iteration of the model are described in section 3.3.4 along with other timing related issues.

Equation (1) gave the field(LMU)-edge runoff from each LMU for a storm on day t but does not reflect the ability of intervening management practices to reduce the amount of direct runoff reaching the stream. This is accomplished by estimating the losses of runoff due to infiltration as the runoff from LMU k flows over LMUs k-1 to LMU 1 en route to the stream. If the total infiltration losses are assumed to be the sum of the losses on each intervening LMU, the direct runoff from LMU k eventually reaching the stream is given by

$$q'_{tk} = q_{tk} - \sum_{k=0}^{k-1} IL_{t} \tag{3}$$

where IL_{tk} (cm) is the portion of q_{tk} infiltrating while passing through LMU k and q'_{tk} (cm) is the part reaching the stream. The infiltration loss IL_{tk-1} is estimated by

$$IL_{k-1} = h_{k-1} \cdot (tc_{(k-1)t}) \cdot (a'_{k-1}/a_k) \tag{4}$$

where a'_{k-1} is the area of LMU k-1 exposed to overland flow from LMU k, a_k is the area of LMU k adjacent to LMU k-1, HC_{k-1} is the saturated hydraulic conductivity of LMU k-1 (cm/hr), and $tc_{(k-1)t}$ is the time of concentration of LMU k-1 on day t which is estimated by the lag method (McCuen 1982):

$$tc_{k-1} = \frac{L_{k-1}^{0.8}\,(s_{k-1,t} + 1)^{0.7}}{1900\; sl_{k-1}^{0.5}} \tag{5}$$

L_{k-1} is the hydraulic length of LMU k-1, $s_{(k-1)t}$ is the runoff retention parameter of LMU k-1 on day t, and sl_{k-1} is the slope of LMU k-1.

3.3.2 SOIL CHEMISTRY

The soil chemistry model is adapted from (Haith 1980) and assumes exponential pesticide decay and partitions the pesticide into dissolved and solid phase components by a single-valued linear isotherm. It considers losses from only the top 1 cm of soil. While the model is capable of evaluating the following equations for multiple pesticides on each LMU in a catchment, the following description will consider only one LMU and a single pesticide. The pesticide content in the top centimeter of soil CP_t (g ha^{-1}) t days after pesticide application is

$$CP_{tk} = CP_{0k} \cdot \exp(-\alpha t) \tag{6}$$

where CP_0 is the application rate (g ha^{-1}) and is the pesticide decay rate (days^{-1}). Dissolved phase pesticide available for loss d_t is given by

$$d_{tk} = [1/(1 + p\mu_k/\theta_k)]CP_{tk} \tag{7}$$

where p is the pesticide partition coefficient, μ is the soil bulk density (g/cm^3) and θ the available water capacity (cm/cm) of LMU k. A rainfall event of depth r_t (cm) producing a runoff depth of q_{tk} (cm) as predicted by equation 1 would result in a field(LMU)-edge pesticide loss of CQ_{tk} ($g\ ha^{-1}$)

$$CQ_{tk} = (q_{tk}/r_t)CP_{tk}. \tag{8}$$

and the amount of pesticide remaining in the top 1 cm of soil after the rainstorm is

$$CP_{tk}^{*} = CP_{tk} \cdot (1 - \theta_k/r_t)\cdot r_t. \tag{9}$$

Haith's (1980) original model also included equations to predict the loss of a sediment-bound pesticide. Although the concentration of pesticide in sediment is much higher when compared to the concentration in runoff, the mass of sediment-bound pesticide is much lower than the mass of pesticide lost in runoff. The error in CP_{tk}^{*} caused by omitting solid-phase pesticide losses from equation (9) is assumed to be negligible.

The reduction in the mass of a pesticide during overland transport to the stream is assumed to be proportional to the reduction of runoff due to infiltration. The mass of pesticide which originates from LMU k and reaches the stream is thus:

$$CQ'_{tk} = CQ_{tk} \cdot q'_{tk}/q_{tk} \tag{10}$$

where CQ'_tk is the mass of pesticide reaching the stream. Reductions in pesticide mass by absorption during transport is not considered. The instream concentration CQ_{tk} (mg/l) from a particular mix of management practices (a management path) of a catchment with K LMUs is computed as the sum of the pesticide mass reaching the stream from each LMU divided by the sum of the runoff reaching the stream from each LMU.

$$CQ_{ti} = \frac{\sum_{k=1}^{K} CQ'_{tk}}{\sum_{k=1}^{K} q'_{tk} \cdot a_k \cdot 100} \tag{11}$$

3.3.3 Suitability

The methods proposed by Herricks and Braga (1986) for developing suitability curves of toxic pollutants provide a basis for incorporating pesticide concentrations into HSI models. For each pesticide, a suitability value of 1.0 is defined by the No Observable Effect Concentration (NOEC) as determined by ecosystem studies using artificial streams. The 96 hour LC50 level defines the 0.2 suitability value and the 24 hour LC50 level defines the 0.0 suitability value. Individual points on the curve are connected by line segments. Additional points on the curve may be defined if sufficient acute or chronic toxicity data is available.

If it is assumed that the five species are managed equally and respond similarly to a given concentration of a pesticide, the number of suitability indices can be reduced using the approach taken by Sale et al. (1982) in which the suitability curve from each specie is combined to form a single curve which represents the most stringent relationships at all levels of a pollutant (figure 3.3). The single suitability curve for each pollutant thus represents a conservative estimate of habitat quality.

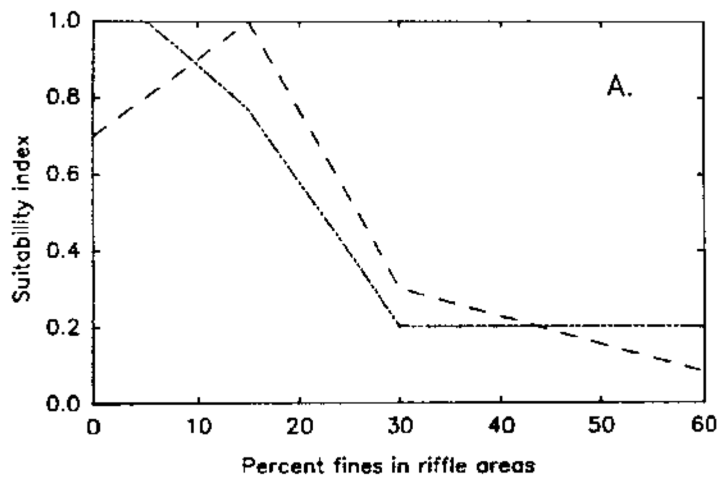
A suitability curve such as that depicted in figure 3.3b is used to convert the predicted pesticide concentrations into daily suitability index values. Letting f(·) represent the suitability curve as a function relating the suitability associated with a particular pesticide to the predicted instream concentration of the pesticide and noting that the subscripts for catchment and time have been dropped:

$$SIP = f(CQ') \tag{12}$$

where CQ' is the instream pesticide concentration resulting from the runoff from a catchment as predicted by equations 1 - 11 and SIP is the associated suitability index. The suitability indices for n pesticides are combined into a single composite habitat variable by taking the nth root of their product:

$$SIC = (SIP_1 \cdot SIP_2 \cdot \ldots \cdot SIP_n)^{1/n} \tag{13}$$

where SIC is the composite suitability index, SIP_n is the suitability index associated with pesticide n, and n is the number of pesticides considered. By computing SIC for each iteration of the pesticide runoff simulation, a probability distribution of SIC is developed for each management path in a catchment.



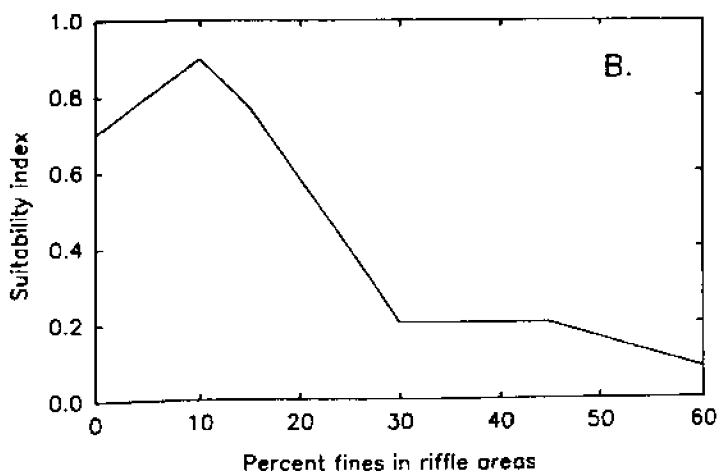


Figure 3.3. Combining suitability curves.
A. Individual species curves.
B. Composite curve.

3.3.4 Simulation Procedure

The pesticide runoff simulation involves the random sampling of several variables. Other variables are sensitive to the timing of specific events and are modified accordingly.

At the beginning of each year two random variables are sampled for each farm field represented in a catchment. The purpose of the two variables is to maintain the dependency relationships between LMUs which are part of the same farm field as explained in section 3.2.4 The first variable randomly samples the crop year for each field from a discrete uniform distribution. In addition to assuring that the appropriate pesticide applications occur on each LMU, this procedure enables the use of curve numbers and pesticide application rates which are appropriate for the current crop year for each LMU. The second variable randomly selects the planting date for each field. The description of each management alternative includes a two week "window" in which planting may occur. We assume the date of planting to be uniformly distributed within this window.

The date, volume, and antecedent moisture condition of the first rainstorm is sampled next. The assumptions made regarding dependencies between the three variables and the methods used to generate their distributions are described in section 4.1.3

Planting dates for each LMU are compared to the storm date for the purpose of curve numbers adjustment. Each crop year is characterized by three curve numbers, one representing conditions prior to planting, the second conditions immediately after planting, and third average conditions during the cropping period. The methods used for deriving the three curve numbers are adapted from Knisel (1980) and are described in section 4.2.2 On LMUs where the planting date is preceded by the storm date, the curve number for pre-planting condition is used. If the storm date falls after the planting date, the approach suggested by Mockus (1972) is used to derive a curve number. This approach assumes that the curve number changes linearly during the cropping season and that the curve number for average conditions during the cropping season is representative of conditions existent midway through the growing season. The condition immediately after planting is dependent on what tillage operations, if any, are performed during planting. If, for example, moldboard plowing accompanies planting, a curve number representing a fallow condition would be used. If a no-till practice is used, the curve number for the day of planting would be the same as that for pre-planting conditions.

The final adjustment to the curve number reflects the effect of soil moisture condition on runoff. If AMC II is randomly sampled no alteration is required.
If, however, AMC I or AMC III is sampled the curve number is adjusted by the relationships given in Chow et al (1988):

$$CN(I) = \{4.2 \,.\, CN(II)\} \,/\, \{10 - 0.058 \,.\, CN(II)\} \tag{14A}$$

$$CN(III) = \{23 \,.\, CN(II)\} \,/\, \{10 + 0.13 \,.\, CN(II)\} \tag{14B}$$

On LMUs where the planting date falls prior to or on the same day as the storm, no pesticide runoff is predicted. For all other LMUs the equations described in Section 3.3.1 are evaluated to predict pesticide losses.

Subsequent iterations begin with the random selection of storm date. If the date is less than thirty days past the last pesticide application, the simulation proceeds as described in the previous paragraph with two exceptions. The value used for the initial pesticide concentration (CP_0) in equation 6 is the pesticide remaining from the previous storm (CP_t^*) and the pesticide is degraded from the date of the previous storm rather than from the date of application. If the storm date is more than thirty days past the last application, new crops and planting dates are randomly selected for each field.

3.4 SEDIMENT MODEL

The sediment simulation model predicts the risk of fish habitat degradation due to sediment runoff and accumulation in the stream bed. The simulation uses Monte Carlo techniques and operates on a seasonal basis to reflect the seasonal differences in crop growth, the rainfall erosivity, and habitat requirements. Four seasons (hereafter called crop-growth (CG) phases) are arbitrarily defined as follows: CG1: April - June, CG2: July - September, CG3: October - December, and CG4: January - March.

Sources of sediment considered in this model are resticted to soil loss by sheet and rill erosion. Gully and streambank erosion is neglected. The Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) is used to predict soil erosion losses from each LMU and sediment delivery to the stream is estimated by a procedure developed by Clarke and Waldo (1986) which uses ratios of USLE parameters between adjacent LMUs and is thus sensitive to the spatial arrangement of topographic features and land management practices. An algorithm differentiates the sediment load into suspended and settleable fractions using site specific particle size distributions and streamflow velocity. Habitat degredation is developed in terms of substrate suitability alteration for all species and lifestages as preducted using HSI model components (see sections 3.4.3, 3.4.4, and 3.4.5).

3.4.1 Erosion

Seasonal erosion losses are estimated as follows by the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978):

$$Y_g = UC_g \cdot UP \cdot UK \cdot UL \cdot UR_g \qquad (15)$$

where Y_g is the erosion during crop-growth stage g in tons/acre*yr, UC_g, UP, UK, UL an UR_g are factors for vegetative cover, supporting practice, soil erodability, topography, and rainfall respectively. In this model the vegetative cover (UC_g) and rainfall (UR_g) factors are randomized and season-specific.

3.4.2 Surface Transport

The sediment transport model developed by Clarke and Waldo (1986) provides a method of estimating the deposition of eroded soil from a particular set of management practices during overland flow. This model identifies potential points of deposition within the watershed and estimates the transport potential of such points using ratios of slope and the USLE cover and supporting practice factors. Note that in the following description the substrate g denoting crop-growth stage has been dropped and in its place the subscript k denoting LMU is used. In this analysis LMU boundaries serve as potential points of deposition and the transport of sediment across the boundary between two LMUs k and k-1 is given by

$$td_k\text{-}1 = UC' \cdot UP' \cdot UL' \qquad (16)$$

where td_{k-1} is the transport efficiency across the boundary, and $UC' = UC_k/UC_{k-1}$ if $UC_k/UC_{k-1} < 1$; and if $UC_k/UC_{k-1} > 1$ then UC' = 1. The truncation of UC' at a value of one prevents the model from predicting more sediment being transported across a boundary than enters it. UP' and UL' are similarly computed ratios of the USLE supporting practice and slope factors. The total amount of sediment reaching a stream from LMU K is the erosion loss from the LMU multiplied by the area of LMU K and the product of the transport function for each LMU between it and the stream

$$Y'_k = Y_k \cdot a_k \cdot td_{k-1} \cdot td_{k-2} \cdot \ldots \cdot td_1 \qquad (17)$$

where Y'_k is the sediment reaching the stream and a_k is the area of LMU k.

3.4.3 Stream Substrate Alterations

Consideration of instream sediment deposition and scour is beyond the scope of the model presented here. Instead, our apporoach is to estimate the instream substrate particle distribution under a variety of sediment loads using field survey data and a lumped parameter runoff model. This is accomplished in the following steps:

1. Determine from field surveys typical stream cross section shapes, slopes and substrate characteristics for riffle and pool habitats, and the relative proportions of riffles and pools.
2. Compute the expected velocity and stream power for the typical cross sections at bank full discharge using Manning's equation.
3. Use figure 4 of Yang and Stall (1976) to compute the maximum suspended sediment concentration of the pool habitat using the measurement of stream power in step 2 above. Assume this concentration will not deposit in the stream.
4. Assume a soil particle size distribution. Determine the sediment loading to the stream using a lumped (spatially) parameter storm event USLE for a storm of a 1 year return period. Initially use local maximum values of the USLE C and P factors.
5. Convert the sediment loading calculated in step 4 to a concentration using the bankflow discharge. Compare this concentration to the maximum suspended sediment concentration for pool areas as determined in step 3 above. The difference is the amount available for deposition. Proportion the amount available to riffle and pool habitats according to the relative areas and calculated stream power of each.
6. Adjust the substrate size distribution for riffle habitats obtained by the field survey to reflect the deposition of sediment particles calculated in step 5.
7. Calculate the annual average erosion rate using the USLE with the C factor used in step 4. Relate the annual average erosion rate to the substrate particle size distribution for riffles. Repeat steps 4-7 over the possible range of the C factor. With each incremental decrease in sediment loading decrease the largest soil particle size classes first.
8. Using the pairs of annual average sediment rates and percentage of fine particles in riffle areas, graph sediment rate vs. percentage fine particles. The resulting piecewise-linear relationship between the percentage of fine particles in riffle substrate and the annual sediment load is used with suitability curves for substrate conditions to produce suitability index values based on sediment loss.

3.4.4 Suitability

Suitability curves for substrate variables are available in the HSI models published by U.S. Fish and Wildlife Service (USFWS). The percentage of fine particles in riffle areas is included in a group of variables dealing with water quality parameters and is a good indicator of macroinvertebrate production, on which Salmonids rely for food (Raleigh et al. 1984). The percentage of fines is also an important indicator of spawning habitat suitability for salmonids. The models for some species include a separate suitability curve for percentage fines in spawning habitat.

By examining the life history of each species, we can identify which life stages of each species are present in tributaries during each of the four crop growth stages used in the sediment runoff model. This information can then be used to develop four suitability curves for each species which reflect each species' particular habitat requirements during each crop growth stage. Absence of a species in a particular crop growth stage would indicate that the species is indifferent to sediment loading during that crop growth stage and optimal habitat is achieved at all possible levels of sediment loading. All curves (one for each species) for a crop growth stage are compared and a single suitability curve is developed by using the most limiting relationship at all levels of the habitat variable. When combined with the sediment runoff simulation, a probability distribution of a percent fines suitability index is generated for each crop-stage stage.

3.4.5 Simulation Procedures

Simulation procedures for sediment runoff are similar to those used in the pesticide runoff model but are not as complex since timing is not as important here. Since each iteration of the sediment simulation represents one year, the crop year for each farm field is randomly generated with each iteration. Because the model considers four crop growth stages, a management alternative consisting of a five year crop rotation, requires twenty values of the USLE vegetative cover factor (UC). Once the crop year is selected for each farm field, the appropriate four UC values are selected. The four values are actually mean values, which are then used to select a random value using a method adapted from Thomas et al. (1988) and described in section 4.2.5.

The only other randomized variables in the sediment model are the USLE rainfall factor. Four values, one for each crop-growth stage, are used. The procedure used to develop statistical parameters of the rainfall factors are decribed in section 4.1.4.

3.5 OPTIMIZATION

The optimization algorithm builds on one used in SEDEC (Bouzaher, Braden, and Johnson, forthcoming). It applies discrete dynamic programming to select a management path from each transect (catchment) such that constraints on suitability index values are met at the lowest cost. An optimal solution is found at discrete levels of the constraint functions. The analyst may select the size of the discrete steps at which optimal solutions are found.

3.5.1 Risk Constraints

Probability distributions such as those described above for suitability are not easily incorporated into constraint functions used in mathematical optimization. Our approach is to select a desired value of the suitability indices, SIT*, and to characterize each management path's effects on fish by the probability of a year occurring in which the target suitability value is exceeded. Both sediment and pesticides must meet the suitability goal, as indicated by the following constraints:

$$\text{Prob}\,(SIC \leq SIT^*) = PC, \tag{18a}$$

$$\text{Prob}\,(SIS \leq SIT^*) = PS. \tag{18b}$$

While the probabilities of habitat degradation due to sediment effects are already expressed as annual probabilities, those related to pesticide effects are expressed as the daily probabilities which are conditional on a runoff-producing rainfall occurring and must first be converted to annual probabilities.

The probability of exceeding the target habitat suitability for the entire watershed is estimated by the weighted averages of the PC and PS values for all catchments. The weighting factors reflect the relative contribution from the management path selected for each catchment. We arbitrarily select as weighting factors the transect (catchment) acreage for sediment suitability and the mean daily runoff volume as predicted by the simulation model for pesticide suitability.

3.5.2 Optimization Model Formulation

The objective function of the optimization model is to minimize the total watershed cost of achieving a stated pollution goal. The total cost is simply the sum of the costs for the management path selected for each catchment. Cost is actually defined by a reduction of profits due to farmer adoption of practices that lower profits in order to achieve abatement benefits for the watershed. The economic cost of each management path is computed by the farm management model and is the difference in profit between it and the most profitable management path for the same catchment.

Our optimization model may be expressed mathematically as:

$$\text{Min} \quad \sum_{j=1}^{J} \sum_{i=1}^{I^j} c_{ij} x_{ij} \tag{19a}$$

s.t.

$$\frac{\sum_{j=1}^{J} \sum_{i=1}^{I^j} PC_{ij}\, Q_{ij}^{50}\, x_{ij}}{\sum_{j=1}^{J} \sum_{i=1}^{I^j} Q_{ij}^{50}\, x_{ij}} \geq PIX \tag{19b}$$

$$\frac{\sum_{j=1}^{J} \sum_{i=1}^{I^j} PS_{ijg}\, a_j\, x_{ij}}{\sum_{j=1}^{J} \sum_{i=1}^{I^j} a_j\, x_{ij}} \geq PIX, \quad g = 1,\ldots,G \tag{19c}$$

$$\sum_{i=1}^{I^j} x_{ij} = 1, \qquad j = 1,\ldots, J \tag{19d}$$

$$x_{ij} = [0,1] \tag{19e}$$

where $j = 1,\ldots,J$ indicates transects; $i = 1,\ldots,I^j$ indicates the I^j management paths on transect j; $x_{ij} = 1$ if path ij is adopted and 0 otherwise; c_{ij} is the cost associated with path ij; PC_{ij} is the probability that the target on pesticide suitability is exceeded by path i on transect j; PS_{ijg} is the probability that the target on sediment suitability during crop-growth phase, $g = 1,\ldots,G$, is exceeded by path i on transect j; a_j is the area of catchment j, used as the weighting factor for PS_{ijg}; Q^{50}_{ij} is the median runoff of path i of transect j, used as the weighting factor for PC_{ij}; and PIX is the minimum acceptable probability of achieving a suitability index value greater than or equal to the target value SIT.

The optimization algorithm identifies the combination of management paths from the catchments that minimizes equation (19a) while meeting the chance constraints on pesticide suitability (19b) and sediment suitability (19c). Constraints (19b) and (19c) are weighted average probabilities of exceeding the target suitability level. Equation (19d) assures that only one management path from each transect is selected. The algorithm determines the optimal solution at each user selected level of PIX.

3.6 MODEL IMPLEMENTATION

The Modeling Task Force of the International Joint Commission recently reviewed the role of mathematical models in the research and management of the Great Lakes (Modeling Task Force 1987) and offered several suggestions regarding the future role of modeling. Foremost among their recommendations is the development of models using more "user-friendly" software on personal computers rather than large mainframe computers.

With the exception of the optimization algorithm, all of the component models described in this chapter were implemented on IBM-AT class computers using the computer spreadsheet program LOTUS 1-2-3 version 2.01 (Lotus Development Co. 1986). The use of a spreadsheet program as a modeling environment has several unique advantages for model users and developers which are not available with higher level programming langauges such as FORTRAN or Pascal. During model development, formulas and parameters can easily be altered or replaced and the new results are made instantaneously available for inspection. The values of intermediate results can be viewed without the neccesity of altering program code or using debugging software. One researcher (Patry 1989) who advocates the use of spreadsheets in scientific modeling considers them to be "very high-level programming languages" based on their integrated graphic and database capabilities, extensive set of mathematical functions, and ease of use.

The use of a spreadsheet program as a modeling environment in this research was aided by two "add-in" software packages which extend or enhance the capabilities of 1-2-3. The add-in package 321 GOSUB (Frontline Systems 1988) allows a series of calculations to be formulated as a subroutine within a spreadsheet. Once created, the subroutines can be used by any number of spreadsheet cells and are accessed similarly to regular spreadsheet mathematical functions. In situations where the same series of computations are used repeatedly, much less computer memory is required since it is not tied up storing the same formulas repeatedly. 321 GOSUB also allows iterative (looping) procedures to be performed efficiently. Subroutine libraries of commonly used algorithms can also be created, freeing the modeler from the burden of coding the algorithm into spreadsheet cells each time it is used.

The other add-in used was @RISK (Palisade Corp. 1988), which permits Monte Carlo simulations to be performed on spreadsheet based models. @RISK adds to the spreadsheet function set over 25 probability distribution functions. Also included are integrated programs which perform the Monte Carlo simulations and summarize the results in graphical as well as tabular form. Any number of model variables can be represented by probability distributions. @RISK is seamlessly integrated with Lotus 1-2-3. Once a model is formulated, a Monte Carlo simulation can be performed by selecting output variables (up to 1000) and the number of iterations (up to 30,000). During execution, @Risk randomly samples each variable represented by a probability distribution, recalculates the model, and stores the results of the output cells. When the desired number of iterations is completed, a separate program is automatically executed which reads in the simulation results and creates tabular summaries as well high resolution graphics for each output variable.

Extending the capabilities of a spreadsheet program with add-ins such as @RISK and 3-2-1 GOSUB creates a powerful and unique modeling environment. During model development emphasis may be placed on the modeling task itself rather than on menial details of programming. Model users also benefit, as the model is delivered in a user-friendly package which is relatively easy to learn and is easily modified for specific purposes.

The entire model package developed consists of several spreadsheets which perform different functions (figure 3.4). In the remainder of this section, the interrelationships between the different spreadsheets will be described. Their ease of use will be demonstrated by a partial description of their use.

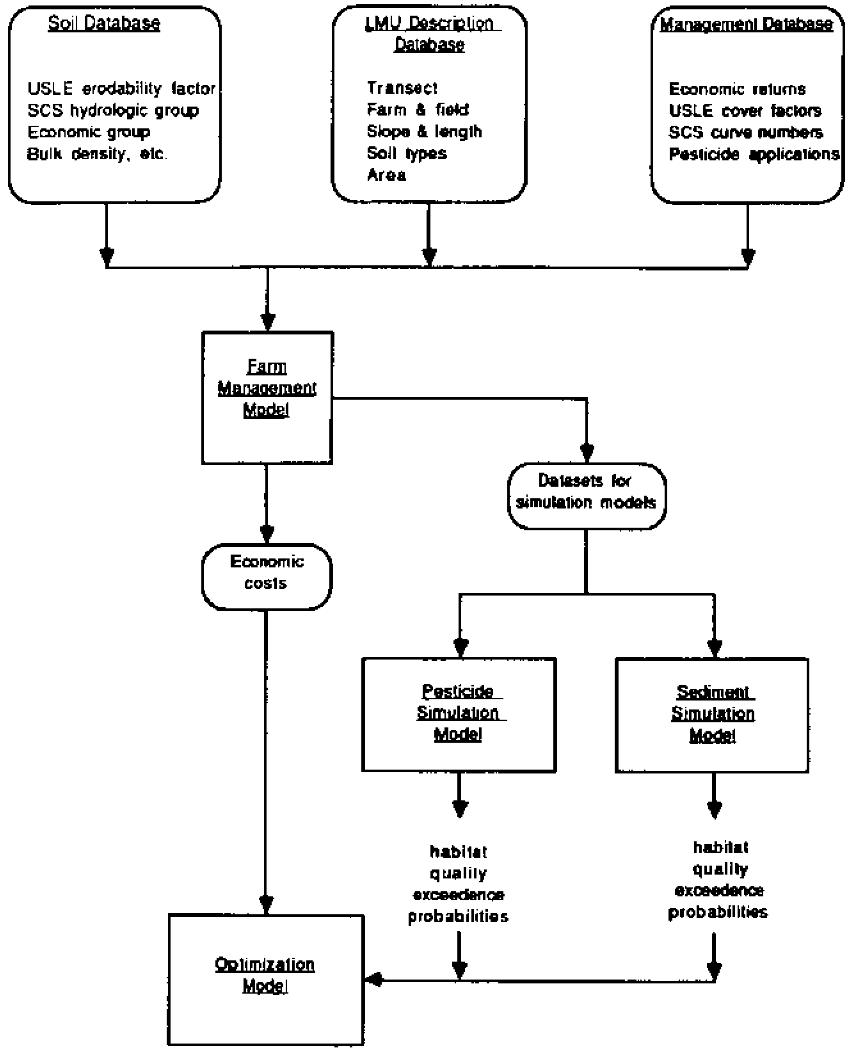


Figure 3.4. Organization of program elements.

Spreadsheet-based datafile:

Spreadsheet-based model:

Three spreadsheets serve as database files which are used to store the data for all soil types, LMUs, and management alternatives. Once these are created, the farm management model accesses all three databases and performs two types of operations. For each catchment it accesses the management and site databases, determines which management paths are feasible, computes the economic cost associated with each, and assigns the management path an identification code which is then used by the other models. It then accesses the soil database, and computes weighted averages of soil specific parameters for each LMU and management alternative combination. Two files for each catchment are created, containing the input data for the pesticide and sediment simulation models.

The simulation models are general templates (spreadsheet models without data) which process each transect individually. The structure of the pesticide simulation model template is shown in figures 3.5 and 3.6 and will be discussed below. The sediment simulation template is similar in organization and use. The spreadsheet is divided into three sections: program, data, and results (figure 3.5). The program section contains subroutines that perform most of the computations as well as macros that aid the model user by automating repetitive tasks which prepare the spreadsheet for the simulation. The data section is divided into blocks which maintain the data in an organized manner. For example, data required for all LMUs (e.g. slope, area, etc.) is kept in one block, with each LMU occupying one row of the block. Another block in the data section contains the meteorological data and generates the random numbers during the simulation. The result section contains two blocks, one containing the pesticide losses from each LMU for all management alternatives, and the second (the catchment block in figure 3.5) contains the instream concentrations and habitat suitability values for each management path. The block is initially 60 rows long, containing space for a maximum of five LMUs, with 12 management alternatives considered on each LMU. To process a catchment with fewer LMUs, the unneeded rows are simply deleted from the block.

The optimization program is coded in Pascal and is presently implemented on an Apollo minicomputer system. This choice of hardware was made out of convenience rather than by necessity. The algorithm could be implemented on IBM-AT type computers given the current maximum problem size, however, a multiobjective version of the SEDEC optimization program was available on the Apollo system and time constraints prevented re-coding the program for another machine.

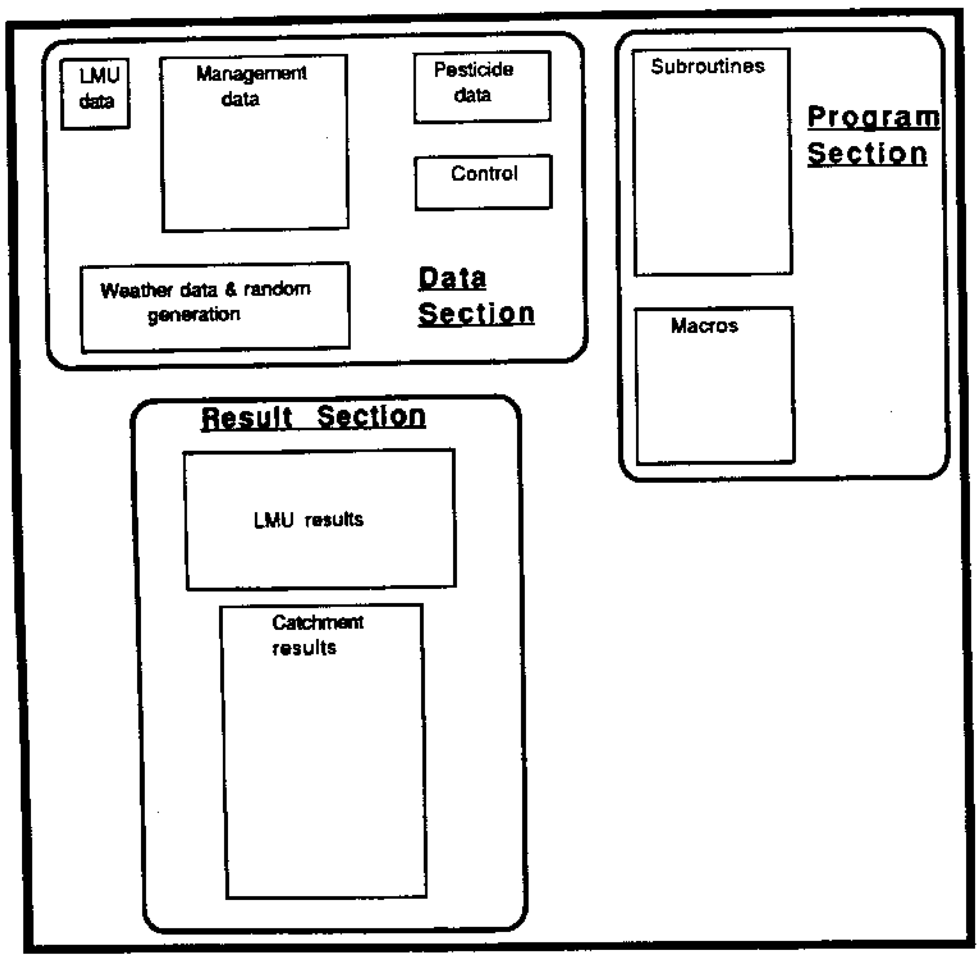


Figure 3.5. Organization of pesticide model template.

3.7 SUMMARY

This chapter has described the components of our analytical framework. That framework is characterized by a roughly uniform level of simplicity across all of its parts, but also by spatial and temporal resolution and connections all the way from farming practices to fish habitat suitabilities. Optimization is performed to identify the least costly farming changes that achieve a specific risk of falling below a designated suitability target. By repeating the optimization within a Monte Carlo simulation, the robustness of watershed management alternatives can be tested across weather events. The outcome is a management prescription that stands the best chance of meeting the environmental goals at the lowest cost.

Although the components are simple, interweaving the parts creates unavoidable complexity. Furthermore, the data needed to use this approach, while readily available in most parts of the United States, must be gathered, prepared, and entered into computerized data sets. Thus, applying the model is a non-trivial exercise. The next section reviews the application to Lake Michigan tributaries and discusses data requirements and the section following that presents results for the Lake Michigan tributaries case studies. The use and usefulness of the framework will become more apparent in these discussions.

CHAPTER 4: APPLICATION TO LAKE MICHIGAN TRIBUTARIES: DATA REQUIREMENTS AND SOURCES

4.1 STUDY SITE CHARACTERIZATION

4.1.1 Game Fish Habitat in Berrien County, Michigan

A major motivation for this study was to learn how agricultural land surrounding Great Lakes tributaries might be managed to protect habitat for important sport fish species. Hence, we applied the framework described in Chapter 3 to two sites in Berrien County, Michigan.

As shown in figure 4.1, Berrien County is located in the southwestern corner of Michigan adjacent to Lake Michigan and contains an extensive network of tributary streams and rivers. Land in Berrien County is predominantly gently sloping moraines and till plains with a wide range of soil textures (U.S. Department of Agriculture 1980). Agricultural is the dominant land use, comprising 52.8% of the county. Corn, grains, and soybeans are the most common crops (table 4.1). A variety of specialty crops such as fruits and vegetables are also grown, but less extensively.

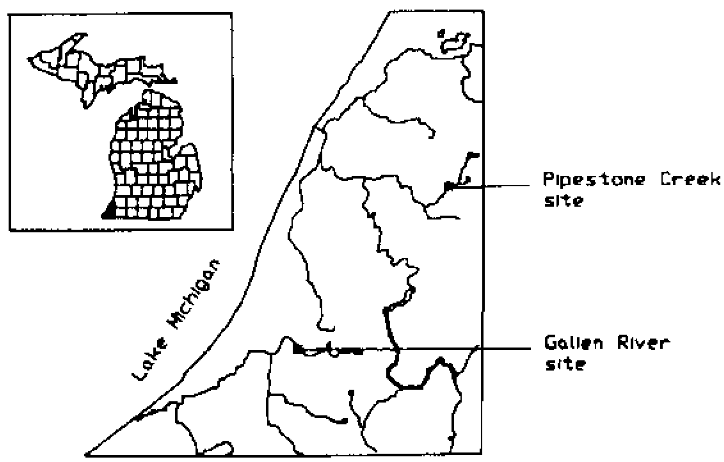


Figure 4.1. Study site locations within Berrien County
Insert: State of Michigan showing location
of Berrien County

Table 4.1. Predominate crops grown in Berrien County, Michigan

Crop	ha (1000)	% of farmed land
Corn	15.5	32.6
Small Grain	6.0	12.7
Soybeans	6.0	12.5
Hay	3.8	7.9
Apples	4.4	9.2
Grapes	2.8	5.8
Cherries	2.3	4.7
Peaches	1.8	3.7
Misc. fruits	1.1	2.4
Vegetables	4.1	8.5

Of the 42 soil types identified in the county, many have potential to erode at severe rates (U.S. Department of Agriculture 1980). In 1982, over 44% (35,000 ha) of farmland in the county was eroding at a rate greater than the tolerable soil loss (T), of which 19% (37,000 ha) was eroding at a rate greater than 2T (U.S. Department of Agriculture 1985).

This area is especially interesting because of the active current interest in enlarging and extending the anadromous fishery in Southwestern Michigan and Northern Indiana. Doing so will provide recreational and aesthetic benefits to this area, which is easily accessible from Chicago and other population centers around southern Lake Michigan. In addition, increased spawning rates in tributaries could reduce the need for stocking of Lake Michigan sport fish species.

The streams and rivers of Berrien County have significant potential as spawning grounds for Salmonids from Lake Michigan, as well as for trout fishing, but spawning is impaired by sediment, pesticide, and fertilizer-laden runoff from cropland (U.S. Department of Agriculture 1985). Michigan and Indiana have launched a joint effort to improve fishery habitat, extend the salmon fishery upriver to Mishawaka, IN, and protect other recreational amenities in the St. Josephs River Basin. Thus, the region is very appropriate for our study.

Study site 1 is drained by Pipestone Creek, a tributary of the St. Josephs River. Site 2 is further to the south and drained by the East branch of the Galien River. Both river systems have received substantial stockings of Salmonids in recent years (table 4.2), and segments of each have been designated as trout streams by the State of Michigan (Michigan Department of Natural Resources 1986, 1987). The study sites were chosen to represent different watershed environments.

At present, the Galien River study site appears to contain better Salmonid habitat than the Pipestone Creek site. A cobble-gravel substrate and a well developed pool-riffle sequence was present through most of the Galien River site. These are ideal circumstances for Salmonid propagation.

Table 4.2. Game fish stocked in Berrien County during 1986.

Species	Stocked in L. Michigan (1,000 fish)	Stocked in Berrien County Tributaries (1,000 fish)
Brook Trout	—	3.9
Brown Trout	30.0	17.6
Chinook Salmon	221.1	—
Lake Trout	109.4	—
Rainbow Trout	9.4	—
Steelhead	78.2	—
Walleye Bay de Noc	—	737.5
Walleye	165.2	—
Walleye Muskegon	—	400.0
County Total:	613.3	1,158.1

The Pipestone Creek study site apparently was channelized in the past, so pool-riffle structures have been largely eliminated. The predominant substrate is silt and clay in the vicinity of the site. These conditions are less ideal for Salmonid propagation. Pipestone reaches located upstream of the site appear to be less disturbed and contain substrates of sand and gravel. This indicates that past channelization may have significantly diminished the Salmonid habitat potential of the Pipestone study site.

The two sites also differ in soils and topography. The predominate soil types at the Pipestone Creek site are of Pella-Kibbie association, which are typically poorly drained silty and loamy soils on level outwash plains, lake plains and deltas. Soils of the Blount-Rimer association dominate the Galien River site. These are loamy and sandy soils on level and gently sloping till plains and moraines (U.S. Department of Agriculture 1980).

4.1.2 Identification of LMUs and Transects

The delineation of catchments and transects within the study watersheds was possible by an examination of U.S. Geological Survey (USGS) 7 1/2 minute series topographic maps. Defining land management units (LMUs), however, requires information from several additional sources. Identifying the location of soil types required the examination of county soil survey maps (U.S. Department of Agriculture 1980), and local plat maps were necessary to identify farm boundaries. Aerial photographs were obtained from the Berrien County Office of the U.S. Agricultural Stabilization and Conservation Service (ASCS) and used to delineate the boundaries of individual farm fields.

The process of defining LMUs includes several steps which require the simultaneous examination of two or more map types. The computer drafting program AUTOCAD (Autodesk, Inc. 1985) was utilized to simplify the process. Computer images of all maps were created by either image scanning technology or manual digitization. The image of each map was then used to create one or more layers in an AUTOCAD file. Each layer was scaled and properly orientated. Multiple layers could be viewed overlaid against each other, and only required layers need be displayed for a particular task. It was also possible to "zoom in" to a particular area of the map so that fine details could be viewed. The use of AUTOCAD also provided an easy means to make length and area measurements using a pointing device such as a mouse.

The Pipestone Creek site consisted of 5 farm fields from 3 farms. The 93 ha watershed was divided into 8 catchments with 19 LMUs (table B.2). The 140 ha Galien River site contained 8 farm fields from 4 farms and was divided into 12 catchments with a total of 33 LMUs (table B.3).

4.1.3 Soil and Topographic Data

Topographic data was extracted from the digitized images of USGS 7 1/2 minute series topographic maps. Area, average slope, and slope length were required for each LMU. The soil types and area of each were similarly extracted from the digitized images of the soil maps.

A database of soil properties and soil-specific parameters required by the simulation models (table B.1) was developed from the tables presented in the Berrien County soil survey book (U.S. Department of Agriculture 1980). For each soil type in the study sites the pesticide model requires the SCS hydrologic soil group, saturated hydraulic conductivity, average water capacity, and soil bulk density. The only soil characteristic required by the sediment model is the USLE soil erodability (K) factor. The proportional areas of each soil type in an LMU were used as weighting factors in computing average values of each soil-specific property for each LMU.

Tables in the soil survey book regarding generalized yield information of specific crops for each soil type were used to characterize each soil type as having low, medium, or high productivity potentials. This classification scheme was used to make the crop budgets soil specific as discussed in Section 4.2.

4.1.4 Rainfall Distributions

The distributional characteristics of daily rainfall were estimated from a 57 year record of rainfall at Eau Claire, MI. Eau Claire is located in Berrien County approximately 3 miles south of the Pipestone Creek site and 12 miles northeast of the Galien River site.

Several probability distributions were developed from the historical record for use in the simulation models. This section considers only those used by the Curve Number runoff equation in the pesticide simulation model. Use of the historical record to estimate the distributional patterns of rainfall erosivity for the USLE is described in the next section.

The pesticide simulation model requires distributional characteristics of three variables related to rainfall: daily rainfall amount, inter-arrival time (the number of days between rainfall events), and antecedent moisture condition (AMC), which is dependent on the total rainfall for the five days prior to a rainfall event.

The SCS Curve Number Equation assumes that all rainfall abstractions (interception, infiltration, etc.) are satisfied before any runoff occurs. As a result of this assumption, it is possible to identify a minimum rainfall amount for which a given curve number will result in a prediction of runoff. For the two sites and management alternatives considered in this study, the maximum curve number is 94 and any storm less than 2.5 cm will result in a prediction of no runoff. The rainfall record, therefore, was first screened to identify rainfall events greater than 2.5 cm. Each event greater than 2.5 cm. was characterized by the rainfall amount, the number of days since the last event greater than 2.5 cm, and the antecedent moisture condition. Standard SCS procedures were used to assign each storm an antecedent moisture condition of AMC I, AMC II or AMC III using the total amount of rainfall (including events less than 2.5 cm) occurring during the previous 5 days. The modified record produced by the screening process was used to develop the distributional characteristics.

An exponential distribution (mean = 1.004 cm) was fitted to the modified record of rainfall amount. The exponential distribution was tested for appropriateness using Pearson's goodness-of-fit test and was acceptable (P = 0.95).

A discrete distribution rather than the commonly used poisson distribution was used to characterize inter-arrival times between storms. This was considered acceptable because the pesticide simulation represents a rather short time span and thus the rare occurrence of very long periods without rainfall (as during a drought) could be neglected. Values for the discrete distribution were created by tabulating the frequencies of inter-arrival times occurring in the historical record (table 4.3). Inter-arrival time was assumed to be independent of rainfall amount.

Table 4.3 Observed frequencies of interarrival times (IAT) (days) for storms greater than .25 cm at Eau Claire, MI.

IAT	freq.	IAT	freq.	IAT	freq.
1	0.320	11	0.020	21	0.00
2	0.169	12	0.014	22	0.002
3	0.109	13	0.011	23	0.001
4	0.097	14	0.012	24	0.00
5	0.050	15	0.010	25	0.001
6	0.045	16	0.008	26	0.00
7	0.042	17	0.008	27	0.00
8	0.029	18	0.004	28	0.00
9	0.021	19	0.003	29	0.0005
10	0.018	20	0.002	30	0.0005

The variability of the antecedent moisture condition was estimated by several discrete simulations. While AMC was assumed to be independent of rainfall amount, it was necessary to make antecedent moisture dependent on inter-arrival times. Considering antecedent moisture to be independent of inter-arrival times would permit random samples to be generated such as an AMC III condition for a storm with an interarrival time of 30 days, which would clearly be in error. To avoid such anomalies, a discrete distribution was developed for each inter-arrival time considered. The probabilities used for inter-arrival time and the three classes of antecedent moisture condition are given in table 4.4.

Table 4.4 Observed frequencies of antecedent moisture condition for storms of different interarrival times (IAT) at Eau Claire, MI.

IAT	AMC I	AMC II	AMCIII
1	0.279	0.478	0.243
2	0.312	0.530	0.158
3	0.438	0.454	0.108
4	0.500	0.398	0.102
5	0.650	0.250	0.100
≥ 6	1.000	0.000	0.000

4.1.5 Annual Erosivity Distributions

No published data concerning seasonal differences in the annual erosivity factor of the USLE nor its variability could be found for Berrien County. If hourly or breakpoint rainfall data are available, the erosivity of qualifying storm events could be computed and summed to create seasonal values. Since only daily rainfall records and the average annual erosivity value were available, an alternate approach was taken.

Richardson et al. (1983) presents a regression equation developed to predict storm event erosivity (EI) from daily rainfall values. The equation includes a normally distributed error term ε and a coefficient c1 used to calibrate the equation to specific locations:

$$EI_t = c1 \cdot r_t^{b} \cdot$$

where EI_t is the rainfall erosivity on day t (MJ-mm/ha-h), c1 is the locally defined correction factor, r_t is the rainfall on day t (mm), b is a regression factor equal to 1.81, and ε is a residual term normally distributed with mean 0 and standard deviation equal to 0.34. Different values of c1 were used for two seasons (Oct. - March and April - Sept.).

To avoid physically unrealistic values of EI_t when ε is very large or very small upper and lower bounds are required and are given by:

$$EI_{min} = (r_t)^2 \cdot (0.00364 \cdot \log_{10}(r_t) - 0.000062) \qquad (20a)$$

$$EI_{max} = (r_t)^2 \cdot (0.291 + 0.1746 \cdot \log_{10}(r_t)) \text{ if } r_t \leq 38 \text{ mm} \qquad (20b)$$

$$EI_{max} = (r_t)^2 \cdot 0.566 \text{ if } r_t > 38 \text{ mm} \qquad (20c)$$

Richardson et al. (1983) tested the equation and presented values for c1 for eleven locations. The nearest location to Berrien County tested was Lansing, Michigan.

For this report approximations of seasonal R distributional characteristics were made using Richardson's equation and the historical daily rainfall record. Records of daily average temperature were also required so that precipitation events occurring as snowfall could be identified. Precipitation was assumed to occur as snowfall whenever the daily average temperature failed to exceed 0 degrees C. Potential erosion losses due to snowmelt were assumed to be negligible.

Daily EI values for each rainfall event were calculated using the historical record of rainfall and randomly generated values of ε. Seasonal and annual totals of R were calculated by summing the EI values of storm events for each year of the historical record.

A sensitivity analysis of the c1 correction factors was conducted in order to find values which resulted in predicted annual average R values closest to the reported value of 2550 MJ-mm/ha/h/y for Berrien

County. The selected values of c1 were then used in a Monte Carlo simulation. The simulation processed the rainfall record 500 times to generate a large synthetic set of R values for each crop-growth period. A lognormal distribution was fitted to the data and found to be suitable by Pearson's goodness-of-fit test. The mean and variance of R for each crop-growth stage are shown in table 4.5

Table 4.5 Seasonal statistical parameters of rainfall erosivity at Eau Claire, MI.

Crop growth season	Rainfall erosivity (MJ-mm/ha/h/yr) mean	s.d.
CG1 (Apr - June)	926	167
CG2 (July - Sept.)	1,038	231
CG3 (Oct. - Dec.)	444	67
CG4 (Jan. - Mar.)	145	45

4.2 MANAGEMENT SYSTEM DATA

Twelve management alternatives were considered in this study. These were combinations of three tillage practices: a conventional tillage method (moldboard plowing), a conservation practice (till-plant), and no-till; two crop rotations: wheat-corn-corn-corn-soybeans (WCCCS) and alfalfa-alfalfa-corn-corn-alfalfa (AACCA); and two mechanical supporting practices: vertical plowing and contour plowing. Table 4.6 shows the assumed dates of important farm operations for each crop rotation.

Table 4.6. Assumed dates of farm operations for crops in Berrien, County, MI.

Event	Corn	Soybeans	Wheat
Plow	Oct 15	Oct 15	——
Chisel	May 1	May 1	——
Disc	May 10	May 15	——
Plant	May 15	May 30	Oct. 1
Harvest	Oct 15	Oct 1	July 1

4.2.1 Crop Yields and Profits

Economic returns for each management alternative were taken from crop budgets developed by Prof. J. Roy Black (1987-1988) of Michigan State University in consultation with the Michigan State Office of the U.S. Soil Conservation Service. Development of the crop budgets required a variety of information including specification of costs associated with fertilizer and pesticides inputs, machinery maintenance and repairs, post-harvest crop drying, and land rental. Yields for all crops other than wheat were differentiated for three soil productivity classes. Crop prices were assumed to be \$60/ton for hay, \$2.25/bu for corn, \$5.40/bu for soybean, and \$2.30/bu for wheat. Economic returns for a management alternative were annualized by averaging the return produced each year within a multi-year rotation. Rotation average returns for each of the three soil productivity classes are given in table 4.7.

Table 4.7 Soil specific average annual economic returns ($/ha/yr.) of management options for soil productivity classes.

Rotation	Till	Soil Productivity Class SP1	SP2	SP3
AACCA	CV	-248.90	-310.50	-468.16
AACCA	CS	-196.62	-258.28	-409.16
AACCA	NT	-208.24	-203.74	-360.35
WWCCS	CV	547.62	250.85	-63.51
WWCCS	CS	459.62	289.19	-12.33
WWCCS	NT	357.18	312.43	-0.37

4.2.2 SCS Curve Numbers

A matrix of sixty curve numbers was developed for each management alternative, representing four hydrologic soil groups and fifteen time periods (five crop years within each rotation, with three crop growth stages in each year). The curve number matrices for the twelve management alternatives are given in table A.5. The consideration of a particular management alternative on an LMU with known soil characteristics allows the matrix to be reduced to a vector of fifteen curve numbers. On LMUs with multiple soil types, the curve number for each time period is computed as the average of the numbers for the four soil groups weighted by the proportional area of each hydrologic soil group in the LMU.

The three time periods for each year of the crop rotation are the pre-planting, immediately after plowing, and the average condition during the cropping season, which is assumed to exist midway through the growing season. Knisel's (1980) method was adapted to develop the curve numbers for the three time periods. The method requires information on crop types, expected crop yields, and tillage and cultural practices. Tables are used which offer recommended curve number reductions for specific crops and practices based on expected crop residue levels.

4.2.3 Pesticide Use, Physical, and Toxicological Data

Data requirements of the soil chemistry segment in the pesticide simulation are rather meager. Application rates are specified in the crop budgets (table 4.8). Since the model assumes pesticide losses occur only from the top 1 cm of soil, the method of application (surface applied or incorporated into the soil) is also an important consideration. We assumed that the conventional and conservation tillage practices involve the incorporation of pesticides to a depth of 8 cm. This was accounted for by reducing the application rate to 1/8 of that specified in the crop budget. Data concerning decay rates and soil-water partitioning were obtained from Rao et al. (1980).

Acute toxicity responses of Salmonid species were obtained from the report by Mayer and Ellersieck (1986), which compiles and interprets the results of more than 4,900 acute toxicity tests conducted at the Columbia National Fisheries Laboratory. The tests included 410 chemicals and 66 species of aquatic animals. Their interpretation involves the development of interspecies correlation models and an assessment of the degree to which several factors have on test results. In regards to interspecies correlations, Mayer and Ellersieck found that confidence limits were highest within families. The results of toxicity tests conducted with rainbow trout were highly correlated ($r \geq .95$) to those of other Salmonid species. Where data was not available for a particular species and chemical, the interspecies correlations were used to estimate the missing data.

Table 4.8 Pesticide application rates, gram/ha. With conventional (Conv) and conservation (Cons) tillage all pesticides are incorporated to a depth of 8 cm.

Pesticide	Rotation	Tillage	Year 1	Year 2	Year 3	Year 4	Year 5
Atrazine	AACCA	all	0	0	1418	1418	0
	WCCCS	all	0	1418	1418	473	0
Furadan	AACCA	Conv	0	0	680	680	0
	AACCA	Cons	0	0	680	680	0
	AACCA	NT	0	0	0	680	0
	WCCCS	Conv	0	680	680	680	0
	WCCCS	Cons	0	680	680	0	0
	WCCCS	NT	0	0	680	0	0
Bladex	AACCA	all	0	0	794	0	0
	WCCCS	all	0	0	454	454	0

Table 4.9 Pesticide physical and toxicological data.

Pesticide	Decay coeff. $(\text{days})^{-1}$	Soil - Water Partition	24 hr. LC_{50} (mg/l)	96 hr. LC_{50} (mg/l)	NOEC (mg/l)
Atrazine	0.0106	0.87	6.8	4.5	0.0179
Furadan	0.0847	0.86	0.68	0.38	0.0622
Bladex	0.0495	0.54	12.0	9.0	0.0196

4.2.4 USLE Cover Factors

The USLE C factors for each crop growth season (table A.4) were determined by Prof. J. Roy Black (1987-1988) and associates in the Department Agricultural Economics at Michigan State University with the assistance of Berrien County SCS personnel.

Several sources of uncertainty are possible in the use of the USLE C factor, even when specific values are selected by local experts. Crop conditions vary from year to year due to differences in the temporal patterns of rainfall, temperature, and sunshine. Published values for specific crops and management practices which are derived from field experiments will contain some degree of experimental error. Some values may also contain errors because they are interpolated from values for other crops or practices. With these factors in mind, uncertainty was incorporated into the C factors using the technique suggested by Thomas et al. (1988).

The normal and log-normal probability distributions commonly used to describe the variability of a wide variety of environmental data are not appropriate for use with C factors. By convention, C factors are bounded by 0 as a lower limit and 1 as an upper limit and therefore can not be described by a distribution with infinite tails.

Thomas et al. (1988) uses a double triangular distribution calibrated against a bounded normal distribution (figure 4.2) to characterize the uncertainty in C factors. The double triangular distribution has a lower limit of 0.9 times the mean value or 0, whichever is less, and an upper limit of 1.1 times the mean value or 1, whichever is greater. The ordinates at the midpoints (points B and D in figure 4.2) between either limit and the mean are set as 0.179 times the ordinate at the mean by calibration against a normal curve. Random numbers fitting the double triangular distribution are generated by pulsing equations given in Thomas et al. (1988) with normally distributed random numbers.

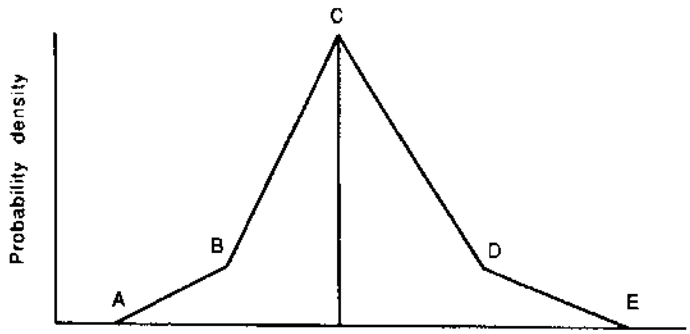


Figure 4.2. Double triangular distribution used to characterize USLE cover factors. Point C is the expected cover factor value, point A and E are the minimum and maximum values, respectively. the abscissa at B and D are midway betweeen C and either extreme value, and the ordinates are 0.179 that of point C.

4.2.6 Other USLE factors

Values of the topographic (LS) factors of the USLE were obtained from Wischmeier and Smith (1978). The long slope lengths and gentle slopes characteristic of most LMUs in the study sites resulted in the USLE predicting that contouring offers no decrease in erosion loss for those LMUs.

The soil erodability (K) factors of the USLE were obtained from the Berrien County soil survey book (U.S. Department of Agriculture 1980). Average values for each LMU were estimated by weighting the value for each soil type present by the proportional area of the soil present in the LMU.

4.3 SUMMARY

This chapter has described the data required by our methodology, sources for those data, and preprocessing steps required to employ them. Specific data for our case studies are also given. These data are the basis of the applications and analyses described in Chapter 5.

CHAPTER 5: APPLICATION TO LAKE MICHIGAN TRIBUTARIES RESULTS AND ANALYSIS

5.1 MANAGEMENT RESULTS

5.1.1 Importance of Targeting

The model used in our analysis "targets" the changes in farming practices according to the economics of individual LMUs and the role that LMUs play in the surface hydrology of the watershed. As a rough rule, an inexpensive change that greatly reduces the quantity of soil and chemicals that reach the stream is favored over more expensive or less effective changes.

"Targeting" involves explicitly searching for low cost approaches to habitat protection. This is important to realize, because abatement policies and programs rarely are "targeted" to the degree that our model allows. Doing so would require extensive information and modelling support, be costly to administer, and be politically difficult to carry out. Thus, the rather advanced "targeting" in our model very likely produces cost estimates that are below costs that might have to be incurred in real-world programs.

5.1.2 Control Costs and Suitability Levels

The model presented here was used to evaluate the costs and effects of farming changes that might protect fish habitat at the Pipestone Creek and Galien River sites. At both sites, the model was evaluated at three target levels of suitability for Salmonids: 0.5, 0.7, and 0.9. These will be referred to as levels of habitat "quality". The relationship between economic cost and the probability of exceeding the habitat suitability targets (to be called "reliability") for the two sites are shown by tradeoff curves in figures 5.1 and 5.2 for the Pipestone Creek and Galien River Sites, respectively.

In the absence of habitat constraints, the most profitable solution vectors for both sites consists of the WCCCS rotation on all fields (table 5.1). The relative proportions of tillage practices are similar for both sites. The Galien River site has a greater proportion of No-till. At the Pipestone Creek site, no-till is restricted to a few LMUs with high proportions of soils in productivity classes SP2 and SP3. LMUs dominated by soils of class SP1, which comprise the majority at both study sites, are cultivated most profitably with conventional or conservation practices.

The probabilities of habitat degradation under the profit maximizing management regime are markedly different for the two sites (table 5.1), and this reflects differences in stream characteristics. For Pipestone, the profit maximizing regime results in pollution levels that leave roughly a 10% probability that any of the selected suitability target levels will be exceeded. That is, the probability of falling below the targets is approximately 90%. The Galien site is generally more suitable with the profit maximizing farming regime, with the probabilities of achieving the designated suitability targets ranging from 54% for a suitability level of 0.5 to 24% for a suitability level of 0.9. As will be discussed in section 5.1.4, the limiting pollutant at high risk (low probability) levels is sediment. Considering the gentler stream gradient and channelization of Pipestone Creek, we would expected Pipestone to have less capacity than Galien to transport sediment downstream as suspended particles. Sediment entering Pipestone Creek is more likely to be deposited (figure 5.0) and accumulate in the stream bed, thereby impairing Salmonid spawning habitat.

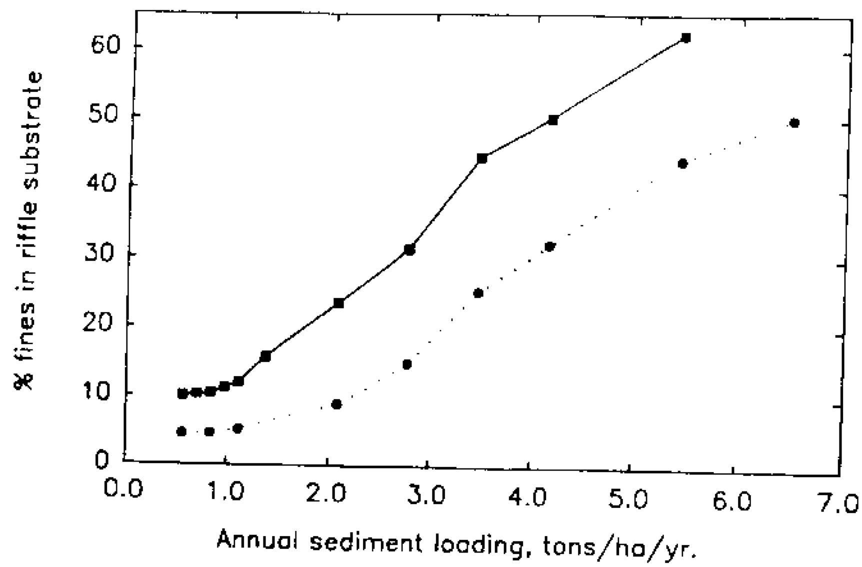


Figure 5.0. Assumed stream substrate alterations due to sediment loading.

Pipestone Creek

Galien River

Table 5.1 Probabilities of exceeding habitat target levels in the absence of habitat constraints.

Site	Habitat suitability 0.5	target 0.7	level 0.9
Pipestone Creek	0.11	0.06	0.02
Galien River	0.54	0.35	0.24

5.1.3 Implications of Different Risk Levels and Suitability Targets

In the fish habitat context, risk translates into a probability of failing to exceed a particular suitability target in the stream channel. Lower risk means a higher probability. We will use the term **"reliability"** for the probability of exceeding a suitability target. A higher suitability target represents conditions that are more favorable for Salmonids. We will refer to the suitability level with the term **"quality"**.

More erosion-prone or pesticide-intensive practices reduce the reliability of a specific suitability target and the level of quality for a particular level of risk. Timing is also a key issue. Practices that involve applying pesticides closer in time to major storm periods or fish life stages are more likely to generate runoff that greatly damages the fishery.

Reducing impairment from agricultural pollution requires farming practices that are less erosive, less pesticide-intensive, timed differently, or all of these. Farmers will give up profits by switching to practices that reduce stream impacts rather than simply maximizing economic returns. The costs of risk reduction or higher suitability standards are the differences in profits realized by the farmers. A policy to improve stream habitat would either force farmers to incur these costs or would compensate the farmers by at least the amount of lost profits. Quite conceivably, greater than the minimum costs or compensation would be realized, and this is another reason to view the cost estimates reported here as conservative.

Movement along individual curves in figures 5.1 and 5.2 shows the changes in total costs needed to increase the probability of ensuring a particular suitability level. As we would expect, the total cost increases only gradually over a considerable range. This suggests that small and inexpensive changes in farming practices can go a long way toward improving the reliability of habitat suitability. However, the costs increase at an increasing rate, implying that more and more costly changes are required to achieve higher and higher reliability.

The nature of the farming changes are suggested by the data in tables 5.2 and 5.3. These data reflect the changes that would be called for at the Pipestone and Galien sites to increase the probability of achieving the 0.5 habitat suitability target from the baseline to 0.6, and on to 0.9, assuming the measures could be targeted.

Table 5.2 Rotation and tillage changes required to exceed the 0.5 suitability target at three levels of reliability at the Pipestone Creek Site. Values given are % of watershed by area.

Management Practice	Reliability:		
	Baseline(11%)	60%	90%
Rotations:			
WCCCS	100%	100%	85%
AACCA	0%	0%	15%
Tillage practices:			
Conventional	67%	35%	24%
Conservation	27%	36%	45%
No-till	6%	29%	31%

Table 5.3 Rotation and tillage changes required to exceed the 0.5 suitability target at three levels of reliability at the Galien River Site. Values given are % of watershed by area.

Management Practice	Reliability:		
	Baseline(54%)	60%	90%
Rotations:			
WCCCS	100%	100%	68%
AACCA	0%	0%	32%
Tillage practices:			
Conventional	42%	34%	22%
Conservation	36%	39%	49%
No-till	22%	27%	29%

Shifting from one curve to another in figures 5.1 and 5.2 represents a change in the quality of Salmonid habitat. Our choice of specific HSI levels is arbitrary. The effect on costs of higher suitability is as expected—higher quality is more costly at every level of reliability. The limited number of index values and study sites prevent conclusions about the rate at which costs rise with higher suitability levels.

Just as greater reliability requires different farming practices, so does higher quality. Tables 5.4 and 5.5 summarize the "targeted" farming changes for 75% reliability and suitability levels of 0.5, 0.7, and 0.9.

Table 5.4 Rotation and tillage changes required to achieve 75% reliability at three levels of habitat quality at the Pipestone Creek Site.Values given are % of watershed by area.

Management Practice	Suitability target:		
	0.5	0.7	0.9
Rotations:			
WCCCS	100%	83%	76%
AACCA	0%	17%	24%
Tillage practices:			
Conventional	35%	30%	21%
Conservation	36%	38%	52%
No-till	30%	32%	27%

Table 5.5 Rotation and tillage changes required to achieve 75% reliability at three levels of habitatquality at the Galien River Site. Values given are % of watershed by area.

Management Practice	Suitability target:		
	0.5	0.7	0.9
Rotations:			
WCCCS	100%	79%	73%
AACCA	0%	21%	27%
Tillage practices:			
Conventional	33%	32%	27%
Conservation	40%	45%	55%
No-til	27%	23%	18%

The results in figures 5.1 and 5.2 show that increasing the suitability target causes a decline in the maximum possible reliability. This suggests that the practices that are best under usual weather circumstances that dominate the suitability determination are not the same as the best practices for the extreme conditions that dominate reliability. Furthermore, conservative farming practices alone cannot achieve high levels of suitability with high reliability. Either land use practices different from those considered here or supplementary stream protection measures would be required.

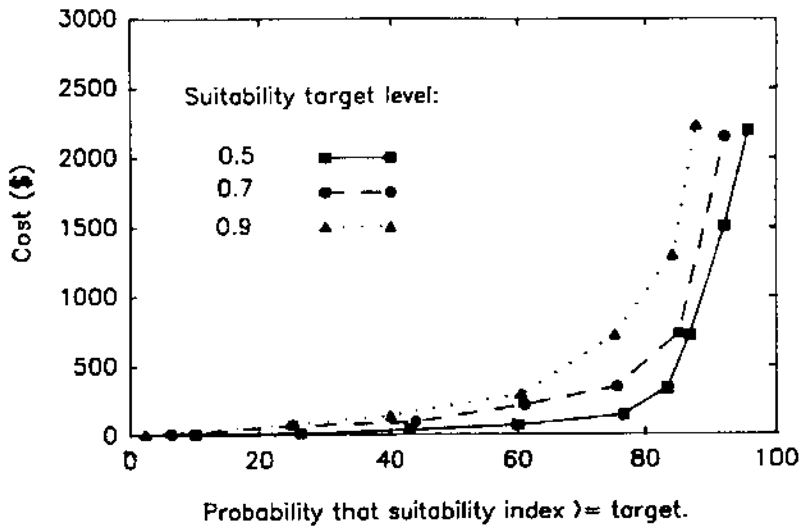


Figure 5.1 Reliability cost frontiers, Pipestone Creek site.

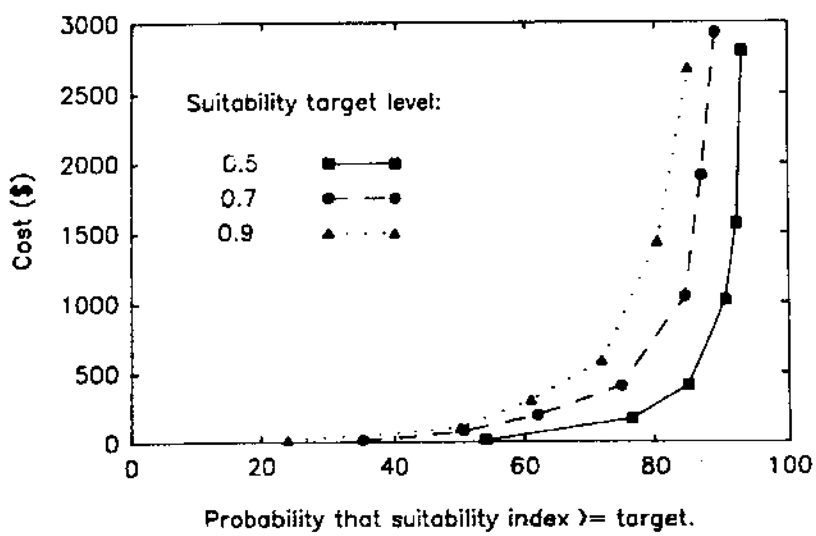


Figure 5.2 Reliability cost frontiers, Galien River site.

5.1.4 Sediment Effects versus Pesticide Effects

Analysis of model results reveals that the constraint on pesticide suitability is non-binding at low levels of reliability. The pesticide constraint does not become binding until rather high probabilities of exceeding the target suitability levels are required, at which point the risk of excessive sediment accumulations is relatively low. This is consistent with the consensus among fisheries biologists that deteriorated substrate conditions are most responsible for the general degradation of fish populations in the Midwest (e.g, Smith 1978).

Tightening the habitat constraint results in a shift towards greater use of the no-till WCCCS managment alternative up to the point at which the pesticide constraint becomes binding. Requiring greater reliability results in a decrease in the use of no-till WCCCS, and the AACCA rotation comes into the least-cost management regime. With the crop rotations considered here, no-till involves the same application rates and frequencies of herbicides (Atrazine and Bladex) as the other tillage practices, and less frequent application of the insecticide Furadan. With no-till, however, the pestcides are not incorporated and consequently are more available for runoff. Widescale adoption of no-till may also result in higher pesticide concentrations since untilled fields have lower runoff rates, which means less dilution of the pesticides.

5.2 COMPARISON WITH EROSION AND SEDIMENT CONTROL POLICIES

The SEDEC model was used to determine the optimal management practices which would be required at the Pipestone Creek site under an abatement policy aimed at sediment. These practices were compared to results of similar costs obtained using the model developed here to detect differences in risk of habitat degradation and precribed farm practices.

Three sediment-based policies were considered: 1) constraining the total sediment load in the watershed; 2) constraining the sediment load from each catchment; and 3) constraining the soil erosion from each LMU. Cost frontiers for each policy are displayed in figure 5.3. The runoff and habitat degradation simulation models were used to predict the risk of habitat degradation for solution vectors at selected points from each cost frontier. The cost and resulting risk of habitat degradation were plotted and compared to results obtained from the model developed here. Results obtained for the three alternative policies at suitability target levels of 0.5 and 0.9 are given in figures 5.4 and 5.5.

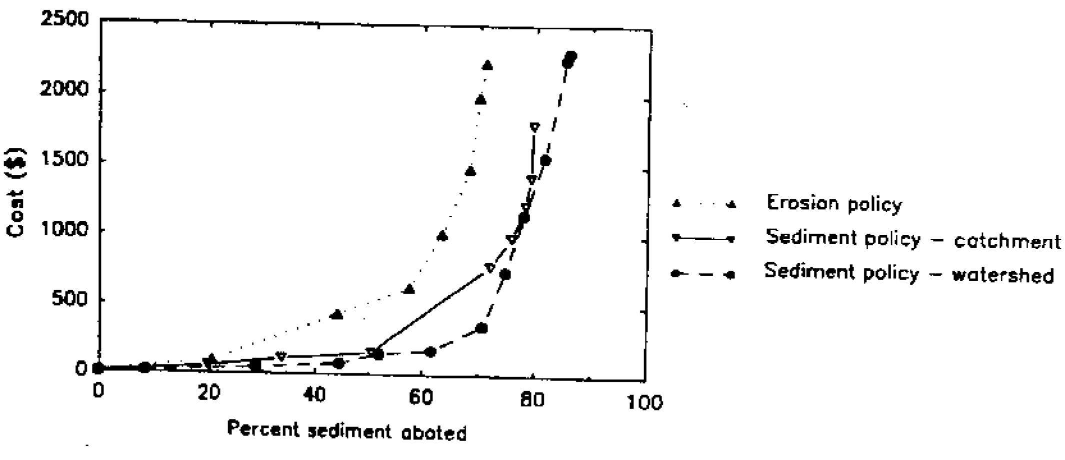


Figure 5.3. Cost frontiers for alternative policies.

These figures show that erosion and sediment target reasonably approximates a habitat suitability target only over a limited range. Both sediment policies provide reasonable approximations of habitat suitability over a wider range than does the erosion policy. The approximations grow worse as pesticides play a greater role in suitability determination, i.e., at higher levels of reliability where the pesticide suitability constraint is controlling. Since the critical pesticides are in solution, and since sediment runoff is not necessarily correlated with runoff volume or concentration, "targeting" sediment is a poor way to deal with pesticide effects. The poor approximations at high suitability levels are due to the greater implementation of the no-till WCCCS management alternative. With all three policies, abatement is achieved mainly by implementation of no-till WCCCS, while the AACCA rotation is not implemented to any significant degree. This is especially true with the erosion policy, which limits the generation of sediment from each LMU. Conversely, the sediment policies achieve abatement by strategic placement of the no-till WCCCS practice to reduce the delivery of sediment. As a result, the sediment policies requires the no-till WCCCS to be installed on fewer fields.

Comparison of the two figures suggests that the range of reasonable approximation shrinks as the suitability target is raised. The explanation is that, with higher suitability targets, the pesticide constraints bind at lower reliability levels.

The rather peculiar nonconvex shapes of the dashed curves in figures 5.4 and 5.5 are due to the fact that controlling sediment will sometimes lower pesticide runoff and sometimes increase it. For example, shifting to no-till can increase pesticide concentrations, thereby reducing the reliability of achieving a suitability objective, while shifting to an alfalfa rotation can reduce both sediment and pesticides. A sedimentation policy takes no account of the pesticide consequences, and the result is higher costs and greater or lesser reliability depending on the precise nature of the sediment control regime.

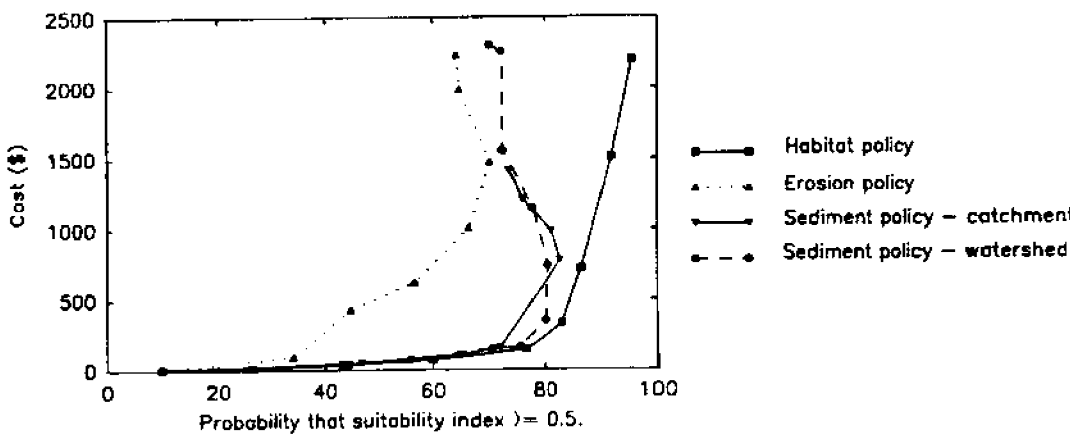


Figure 5.4. Cost and habitat degradation risk of alternative policies, HSI) 0.5.

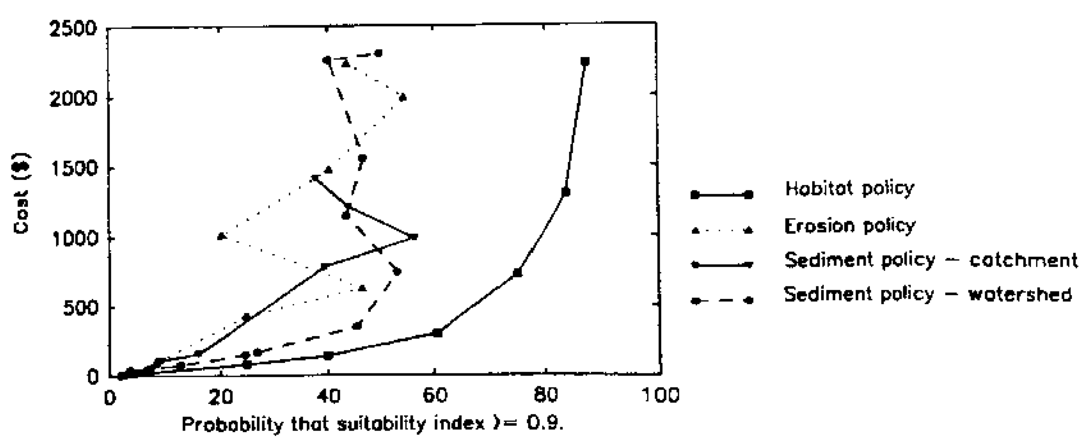


Figure 5.5. Cost and habitat degradation risk of alternative policies, HSI) 0.9.

5.3 IMPLICATION FOR AGRICULTURAL WATERSHED MANAGEMENT AND LAKE MICHIGAN TRIBUTARIES

The preceding analyses suggest several things about farming changes that could improve game fish habitat in Lake Michigan tributaries. They also provide insight into policies for bringing these changes about.

5.3.1 Watershed Management

Most policies to control agricultural nonpoint source pollution have concentrated on the increased use of reduced tillage practices rather than changes in crop rotations. As shown in tables 5.3-5.5, considerable improvements in fish habitat can be achieved through changes in tillage practice only. If high quality salmonid habitat is to be maintained with reliabilty, however, changes in tillage practices alone may be inadequate. As indicated in previous sections, attempts to maintain quality habitat through widescale use of no-till may actually decrease habitat quality if it leads to greater use of pesticide intensive rotations. The two crop rotations considered in this study differed considerably in cost and pesticide use. Achieving a high reliability of habitat quality required that the costly AACCA rotation be implemented at considerable expense. The results obtained here may not have been so dramatic if additional rotations, intermediate in pesticide use and cost, had been considered.

The use of contour plowing has also been encouraged as a conservation practice. Changes in fish habitat due to contour plowing are inconclusive in this analysis. The effect of contouring on soil erosion is predicted through the USLE supporting practice (P) factor. P factors are obtained from tables relating slope and slope length to erosion reduction by contouring. For a given slope, these tables include an upper limit on slope length, beyond which no reduction in erosion is predicted. Slopes on the majority of LMUs at both study sites are mild and rather long, which results in the USLE predicting no reduction in erosion. The SCS curve number equation, used here to predict runoff, has no such upper limit of slope length regarding contouring, and thus predicts reductions in runoff. Clearly, a reduction in runoff should be accompanied by a reduction in sediment transport. In this analysis contouring becomes important only at high levels of habitat quality and reliability. Due to the discrepancy noted, between predicted rates of runoff and sediment delivery, this result may not be accurate. Previous studies using the SEDEC model on sites with greater slopes have found contour plowing to be a cost-efficient practice in regards to sediment delivery.

The analysis in section 5.2 concerning policies which target erosion and sediment suggests that protection of fish habitat is best achieved by using a variety of practices. Watershed management in which only a limited number of management alternatives are encoured based on their ability to reduce one pollutant limits the habitat protection which is possible.

5.3.2 Fish Protection Policies

The results of our analysis suggest that protecting fish habitat can be quite distinct from reducing agricultural pollution, especially a single dimension such as sediment. Policies that address sediment effectively can be much less effective in protecting habitat.

This result is not surprising because fish respond to multiple qualities of the stream channel. Single dimensional policies will be effective only if the dimension chosen is highly correlated with overall suitability. Our analysis indicates that the correlation between sediment and suitability is highest at low suitability and reliability levels but can be quite low at high suitability and reliability levels. Thus, more ambitious fish protection goals should be matched with programs geared to more dimensions of stream quality; in particular, agricultural pesticides.

A specific policy concern raised by this study has to do with no-till farming. No-till has been encouraged by a number of public agencies and private groups. This approach appears to be sound with respect to erosion and sedimentation. But, the consequences for fish, and perhaps other wildlife, may be perverse. This is because no-till sometimes involves greater use of pesticides, which are not as fully incorporated, while it also reduces runoff volume. Non-incorporation means that less water will move more chemicals. These results for no-till point toward a need for modified systems, perhaps like ridge-till, in which there is some incorporation of pesticides.

Another specific policy issue surrounds the apparent desirability of heterogenous cropping systems in a watershed. Growing a variety of crops will cut down on the presence of any one pesticide and the probability of that chemical exerting influence in a particular weather event. This effect is especially important when suitability and reliability goals are high.

Various national agricultural policies, and especially price supports that favor a few crops, are often blamed for promoting monoculture. If these claims are true, our results suggest that they also contribute to reducing fishery quality and diversity by increasing the use of a few pesticides.

5.4 LIMITATIONS

Our findings are subject to a number of limitations, many of which have been mentioned previously in this report. We have studied a very limited number of idealized farming options, a very few agricultural chemicals, in only a two catchments, with respect to habitat suitability indices for only one fish family. Our depiction of watershed landscape and surface drainage systems are elementary. We have not considered subsurface drainage at all, despite its importance in many stream systems. None of our models incorporate the most advanced scientific approaches to the problems at hand. While we have done much to incorporate the effects of weather variability on pollution, we have done almost nothing about the economic and weather vicissitudes confronting farmers. The specific results could be quite different with another set of relative prices (although the general results are likely to follow through). Finally, we have undoubtedly assumed more than a realistic capacity to target policies on economic as well as physical grounds.

Despite all these limitations, the results seem plausible and instructive. Much insight can be gained by tying offsite impacts into models of nonpoint source pollution sources and travels.

5.5 SUMMARY

This chapter presented analyses of two reaches of Lake Michigan tributaries in southwestern Michigan. These tributaries have the potential to support high value Salmonid species, and measures to enhance that potential could contribute materially to programs seeking improved anadramous fisheries in the region.

The results provide insight into management challenges and policy approaches. First, high quality habitat is likely to be more difficult and costly to provide on a reliable basis at the channelized Pipestone site than at the Galien site where the basic conditions are more favorable. Second, much can be achieved at relatively low cost by soil conserving tillage systems. Third, if high levels of quality and reliability are sought, reduced tillage systems may actually be counterproductive. These goals require greater attention to pesticide management, which is served by increasing crop heterogeneity and low-chemical crops (such as alfalfa) in the watershed.

CHAPTER 6: CONCLUSIONS AND DISCUSSION

6.1 STUDY OBJECTIVES

This study began with three objectives. The first and fundamental goal was to develop an analytical framework for identifying "priority areas" controlling the damage to fisheries habitat in Great Lakes tributaries caused by agricultural sediment and sediment-associated pollutants. This was accomplished in a risk management framework. The specific approach involved simulation and optimization models linking farm economics, pollutant runoff, and fisheries habitat within a stochastic (variable) weather system. The models are spatially defined and together identify both the kind and location of management practices that will achieve a specified level of protection for designated fish species at least cost. Costs are incurred by having farmers employ practices or grow crops that are less than the most profitable options.

The second objective was to use the framework to identify efficient management approaches for protecting sport fish habitat in Lake Michigan tributaries. This involved identifying important fish species and study sites and characterizing the economic, physical, chemical, and biological conditions in the study areas. Two stream reaches in Berrien County, Michigan, with different physical characteristics, were analyzed. The Berrien County area, particularly the St. Josephs River system, is the focus of a joint effort by Indiana and Michigan to improve and extend habitat for anadramous species from Lake Michigan.

The third objective was to investigate the importance of targeting abatement policies to control nonpoint source pollution. This goal was met by identifying and analyzing different policy options; specifically, policies based on erosion, sediment load, and habitat suitability targets. All were assessed for their effects on abatement costs and habitat quality (suitability) and reliability (probability of achieving the suitability level). We also compared the cost and management implications of several levels of suitability and reliability.

6.2 RESULTS

The most-profitable farming practices (among those considered here) were quite similar for both study sites, involving Wheat-(3) Corn-Soybean rotations and some diversity of tillage practices. However, similar management regimes did not have similar effects on fish habitat reliability, due to the physical dissimilarities of the stream reaches. At the channelized Pipestone site, with sediment substrate and low gradient, the reliability of achieving suitability targets of 0.5 or more was approximately 10%. The more natural Galien channel, with gravel substrate and somewhat higher gradient, attained a suitability of 0.5 with 54% reliability and an 0.9 suitability with reliability of 24%.

In order to increase the reliability of a specific suitability target or the level of quality for a particular level of risk, less erosion-prone or pesticide-intensive, or differently timed farming practices are required. With respect to reliability, the total cost of improvement increases only gradually over a considerable range. This suggests that small and inexpensive changes in farming practices, if strategically located and timed, can go a long way toward improving reliability. However, the costs increase at an increasing rate, implying that more and more costly changes are required to achieve higher and higher reliability.

The effect on costs of higher suitability is as expected—higher quality is more costly at every level of reliability. The limited number of index values and study sites prevent conclusions about the rate at which costs rise with higher suitability levels.

Increasing the suitability target causes a decline in the maximum possible reliability. This suggests that the practices that are best under usual weather circumstances that dominate the suitability determination are not the same as the best practices for the extreme conditions that dominate reliability. Furthermore, conservative farming practices alone cannot achieve high levels of suitability with high reliability. Either land use practices different from those considered here or supplementary stream protection measures would be required.

Analysis of model results reveals that the constraint on pesticide suitability is not binding at low levels of reliability. The pesticide constraint does not become binding until rather high probabilities of exceeding the target suitability levels are reached, at which point the risk of excessive sediment accumulations is relatively low.

Tightening the habitat constraint results in a shift towards greater use of the no-till managment alternative up to the point at which the pesticide constraint becomes binding. Requiring still higher reliability results in a decrease in the use of no-till and an increase in the AACCA rotation. No-till loses ground because slightly greater pesticide use combined with non-incorporation and lower runoff results in higher pesticide concentrations. The AACCA rotation gains ground because of relatively low use of pesticides and good runoff-interception with alfalfa.

With respect to different policy targets, three sediment-based policies were considered: 1) constraining the total sediment load in the watershed; 2) constraining the sediment load from each catchment; and 3) constraining the soil erosion from each LMU. The runoff and habitat degradation simulation models were used to predict the risk of habitat degradation associated with the most efficient watershed management responses to these policies.

A gross sediment target reasonably approximates a habitat suitability target only over a limited range. The approximation grows worse as pesticides play a greater role in suitability determination. Since the critical pesticides are in solution, and since sediment runoff is not necessarily correlated with runoff volume or concentration, "targeting" sediment is a poor way to deal with pesticide effects. The range of reasonable approximation shrinks as the suitability target is raised. This is because higher suitability targets are subject to binding pesticide constraints bind at lower reliability levels.

The phenomena of higher costs and eratic performance observed in comparing policies "targeted" toward gross sediment to those "targeted" toward suitability are even more pronounced for erosion or catchment sediment targets. The higher costs result from narrowing the scope for spatial optimization, as well as from the failure to account for pesticide impacts.

6.3 IMPLICATIONS

Protecting fish habitat can be quite distinct from reducing agricultural pollution, especially a single pollutant such as sediment. Policies that address sediment effectively can be much less effective in protecting habitat. Single dimensional policies will be effective only if the dimension chosen is highly correlated with overall suitability. Our analysis indicates that the correlation between sediment and suitability is highest at low suitability and reliability levels but can be quite low at high suitability and reliability levels. Thus, more ambitious fish protection goals should be matched with programs geared to more dimensions of stream quality; in particular, agricultural pesticides.

In the Lake Michigan tributaries studied here, important differences were evident in the baseline conditions due to differences in the physical conditions within the stream reaches. The Galien site has fundamentally good characteristics for Salmonid habitat. It appears that reasonably good levels of suitability and reliability can be achieved with little or no changes in farming practices. In comparison, the Pipestone site is not as fundamentally suited to Salmonid propagation. Nevertheless, sediment is the limiting factor in the Pipestone over a significant range of reliabilities and suitabilities, and sediment loads can be reduced at modest cost. It is perhaps unreasonable to push the Pipestone site all the way to Galien-type qualities, but our results suggest that improvements could be achieved at little cost and inconvenience, largely through reducing tillage. Reducing tillage throughout the area could result in a general upgrading of habitat for anadramous fish. However, if extremely high quality and reliability are sought, changes in crop rotations would probably be needed.

In fact, specific concerns are raised by this study about no-till farming. No-till has been encouraged by a number of public agencies and private groups and it may be a sound approach for combatting erosion and sedimentation. But, the consequences for fish, and perhaps other wildlife, may be perverse because pesticide concentrations in runoff may actually increase. The increases can thwart efforts to achieve high levels of suitability and reliability. These results for no-till point toward further development of modified systems, perhaps like ridge-till, in which there is some incorporation of pesticides. Such an approach might offer many of the benefits of reduced tillage while avoiding the risks associated with nonincorporation and reduced runoff, and allow higher levels of suitability and reliability without necessitating different crop rotations.

Another specific policy issue surrounds the apparent desirability of heterogenous cropping systems in a watershed. Growing a variety of crops cuts down on the presence of any one pesticide and the probability of that chemical exerting influence in a particular weather event. This effect is especially important when suitability and reliability goals are high.

Various national agricultural policies, and especially price supports that favor a few crops, are often blamed for reducing diversity. If these claims are true, our results suggest that the policies also contribute to reducing fishery quality and diversity by increasing the use of a few pesticides.

6.4 RESEARCH DIRECTIONS

The research presented here could be pushed in a number of directions. One direction would be to develop a more comprehensive analytical framework—one that accomodates more pollutants, more land area, and more farming possibilities while also simulating near-surface drainage linkages to stream water quality. Additional targets might be considered, including ground water contamination, surface water suitability for contact recreation or water supply use. While these are worthy goals, perhaps of great importance in some applications, they imply expansion of the general framework outlined here rather than a different approach.

A second direction would add to economic considerations on the impact side of the model. To date, only physical impacts have been represented. However, fishing success and quality have economic value. Estimating a value function for the particular species of interest would permit identification of an optimal level of fishery quality and reliability. This type of analysis could be extended to include other types of impacts in a multiple-objective framework.

A third direction would make the model more accessible and useful for watershed management. This would involve simplifying and further clarifying model components, rather than expanding the analytical capabilities, and developing more detailed management information reporting options.

Finally, the model could be used to help discover key physical or locational features that, when used for targeting, improve the efficiency of nonpoint pollution abatement. The approach in the current study supposes that economic information on farming operations is available and can be used as an element of targeting by an omniscient watershed planner. However, this is rarely the case, and there are no instances (aside from auctions of grazing, logging, and oil extraction rights on public lands) where economic conditions are used to target public resource use programs to the extent supposed here. Moving the research a step closer to real policy constraints would provide a more plausible picture of the cost savings from realistic targeting options.

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APPENDIX A: RELATED PAPERS AND PRESENTATIONS

Braden, J., E. Herricks, and R. Larson, *Efficient protection of fisheries habitat in Great Lakes tributaries from agricultural pollutants—progress reports*, Presentations to the Illinois-Indiana Sea Grant National Site Review Teams, West Lafayette, IN, January 1988 and Urbana, IL, January 1989.

Braden, J., E. Herricks, and R. Larson, *Efficient protection of fish habitat in Great Lakes tributaries from agricultural pollution*, Staff Pap. No. 88-E-421, Dept. of Agr. Econ., Univ. of Ill., Urbana, November 1988. (Paper presented at the Symposium on the Great Lakes: living with North America's Inland Waters, American Water Resources Association, Milwaukee, WI, November 1988.)

Braden, J., E. Herricks, and R. Larson, *Combining economic and biological models for managing water quality impacts from agriculture*, Presentation to the Consortion for Agricultural, Resource, and Environmental Policy Research, Washington, D.C., April 12, 1989.

Braden, J., E. Herricks, and R. Larson, *Managing risk to fish habitat subject to agricultural nonpoint pollution*, Presentation at Michigan State University, East Lansing, March 31, 1989.

Braden, J., E. Herricks, and R. Larson, A risk management model for fish habitat subject to agricultural pollution, paper conditionally accepted for *Water Resour. Res.*, April 1989.

Herricks, E., *Efficient protection of fish habitat in Great Lakes tributaries from agricultural pollution*, Presentation at the Water Research Centre - Medmemham, England, May 1989.

Herricks, E. and R. Larson, *Development of fisheries-based aquatic habitat management plans*, Presentation to the Illinois Fisheries Society, La Salle, IL, February 1989.

Larson, R. and J. Braden, *Evaluation of subsidy programs to control sediment loads from cropland*, Presentation at the Second Symposium on Social Science in Resource Management, Urbana, IL, June 1988.

Larson, R. and E. Herricks, *Integration of agricultural runoff and habitat suitability models*, Presentation to the Illinois Fisheries Society, La Salle, IL, February 1989.

APPENDIX B: STUDY SITE DATA

Table B.1 Soil properties for all soil types found at the study sites.

Soil Group	Map Symbol	Saturated Hydraulic Conductivity (cm/hr)	Soil Bulk Density (g/cm^3)	Average Water Capacity (cm/cm)	USLE K-factor (t-ha-hr/ ha-MJ-mm)	SCS Hydrologic Group	Economic Group
Houghton	5A	0.5	0.30	0.40	0.30	A	3
Kibbie	31A	1.5	1.58	0.20	0.28	B	1
Whitaker	61A	1.5	1.38	0.22	0.37	C	1
Pella	32A	1.5	1.25	0.23	0.28	B	1
Spinks	13B	15.2	1.37	0.09	0.17	A	2
Spinks	13C	15.2	1.37	0.09	0.17	A	2
Spinks	13D	15.2	1.37	0.09	0.17	A	3
Thetford	57A	5.1	1.33	0.12	0.17	A	2
Adrian	6A	0.5	0.43	0.40	0.25	A	3
Crosier	16B	1.5	1.48	0.21	0.32	C	1
Selfridge	64A	15.2	1.33	0.11	0.15	C	1
Oakville	10B	15.2	1.42	0.08	0.15	A	3
Oakville	10D	15.2	1.42	0.08	0.15	A	3
Morocco	42A	15.2	1.50	0.11	0.17	B	2
Oshtemo	11B	5.1	1.37	0.13	0.24	B	1
Oshtemo	11C	5.1	1.37	0.13	0.24	B	2
Oshtemo	11D	5.1	1.37	0.13	0.24	B	2
Palms	7A	0.5	0.35	0.40	0.28	A	3
Cohoctah	29A	5.1	1.36	0.18	0.28	B	3
Gilford	20A	5.1	1.60	0.14	0.20	B	1
Granby	37A	15.2	1.26	0.11	0.17	A	2
Edwards	55A	0.5	0.43	0.40	0.31	B	3
Lenawee	25A	1.5	1.23	0.20	0.28	B	1
Elvers	38A	1.5	1.45	0.21	0.28	B	1
Metea	63B	50.8	1.53	0.11	0.17	B	1
Metea	63C	50.8	1.53	0.11	0.17	B	1
Riddles	14B	1.5	1.40	0.22	0.32	B	1
Riddles	14C	1.5	1.40	0.22	0.32	B	1
Rensselaer	17A	0.5	1.38	0.22	0.28	B	1
Rimer	28B	15.2	1.50	0.10	0.17	C	1
Brady	19A	5.1	1.33	0.14	0.20	B	2
Belleville	30A	15.2	1.26	0.11	0.17	B	1

Table B.2 Topographic data for the Pipestone Creek site.

TRANSECT	LMU	AREA ha	FIELD	FARM	LENGTH m	SLOPE %	Soils map symbol (% area)
1	1	1.19	1	1	80	1	64A(100%)
	2	3.73	1	1	210	5	64B(79%) 16B(21%)
	3	2.39	2	2	140	6	16B(81%) 14B(19%)
2	1	9.45	1	1	340	1	64A(100%)
	2	3.50	2	2	195	3	64A(70%) 17A(28%) 32A(2%)
	3	3.50	2	2	190	5	64A(13%) 32A(65%) 57A(21%)
3	1	2.49	1	1	173	2	16B(83%) 63B(17%)
	2	4.62	5	3	400	1	64B(100%)
4	1	6.97	5	3	254	1	57A(38%) 17A(35%) 29A(27%)
5	1	2.61	3	2	260	2	57A(31%) 32A(63%) 17A(6%)
	2	0.58	5	3	55	4	29A(15%) 57A(85%)
6	1	4.49	3	2	447	2	29A(35%) 32A(23%) 31A(35%) 64A(7%)
	2	1.43	5	3	143	4	57A(31%) 31A(69%)
7	1	10.75	3	2	553	2	29A(22%) 64A(20%) 32A(21%)
	2	1.17	2	2	432	5	64A(32%) 32A(68%)
	3	1.66	2	2	124	1	29A(52%) 32A(34%) 64A(4%) 30A(10%)
8	1	11.58	3	2	564	2	63B(100%)
	2	0.91	3	2	116	5	64A(100%)
	3	0.72	2	2	56	8	29A(16%) 55A(23%) 31A(32%) 20A(7%)

Table B.3 Topographic data for the Galien River study site.

TRANSECT	LMU	AREA ha	FIELD	FARM	LENGTH m	SLOPE %	Soils map symbol (% area)
1	1	3.8	1	1	79	1	17A(100%)
	2	5.9	1	1	256	3	17A(37%) 31A(26%) 32A(37%)
2	1	3.2	1	1	159	1	17A(81%) 31A(19%)
	2	7.3	3	1	326	1	17A((9%) 31A(45%) 37A(46%)
	3	6.3	3	1	245	4	10B(100%)
3	1	2.1	1	1	89	2	42A(100%)
	2	1.7	2	2	198	2	42A(71%) 31A(29%)
	3	1.7	2	2	92	6	16B(37%) 14B(63%)
4	1	2.1	2	2	224	1	17A(86%) 29A(14%)
	2	3.5	2	2	118	3	17A(62%) 29A(12%) 57A(26%)
5	1	11.9	3	1	345	1	17A(100%)
	2	7	4	2	301	2	17A(100%)
	3	4.9	4	2	76	5	16B(91%) 13B(9%)
	4	5.6	4	2	281	2	17A(100%)
6	1	1.3	4	2	456	2	57A(47%) 29A(53%)
	2	1.1	4	2	89	4	11B(100%)
	3	2.5	5	3	83	4	11B(100%)
7	1	3.4	5	3	78	1	31A(100%)
	2	4.7	5	3	91	4	11B(90%) 16B(10%)
8	1	13	4	2	235	3	32A(83%) 57A(11%) 29A(6%)
	2	1.2	5	3	68	3	32A(62%) 57A(68%)
	3	4.1	5	3	65	2	32A(27%) 64A(73%)

Table B.3 cont. Topographic data for the Galien River site.

TRANSECT	LMU	AREA ha	FIELD	FARM	LENGTH m	SLOPE %	Soils map symbol (% area)
9	1	6.8	5	3	245	1	31A(100%)
	2	0.7	5	3	178	3	32A(38%) 31A(62%)
	3	3.3	5	3	124	5	13B(59%) 16B(51%)
10	1	2.1	6	3	365	2	17A(24%) 30A(12%) 31A(64%)
	2	4.6	6	3	78	4	13B(15%) 10B(61%) 11B(24%)
11	1	1.3	6	3	278	1	5A(12%) 3A(88%)
	2	5.1	7	4	132	1	17A(55%) 19A(30%) 30A(15%)
12	1	7.3	7	4	125	1	30A(63%) 19A(27%)
	2	3.5	8	4	263	1	37A(42%) 19A(51%) 30A(7%)
	3	4.7	8	4	224	6	14B(100%)
	4	2.3	8	4	78	3	42A(100%)

Table B.4 USLE cover factors for the management alternatives used in this study. CG1 = April - June, CG2 = July - Sept., CG3 = Oct. - Dec., CG4 = Jan. - March.

Time	Year 1	Year 2	Year 3	Year 4	Year 5	Rotation Ave.
			WCCCS - Conventional till			
CG4	0.010	0.029	0.013	0.013	0.008	
CG1	0.056	0.099	0.112	0.112	0.150	
CG2	0.044	0.097	0.099	0.099	0.084	
CG3	0.010	0.164	0.047	0.047	0.029	
Yr. tot.	0.12	0.39	0.27	0.27	0.27	0.264
			WCCCS - Conservation till			
CG4	0.002	0.004	0.004	0.004	0.004	
CG1	0.052	0.060	0.060	0.062	0.062	
CG2	0.040	0.079	0.079	0.081	0.081	
CG3	0.006	0.016	0.016	0.013	0.013	
Yr. tot.	0.1	0.16	0.16	0.16	0.16	0.148
			WCCCS - No-till			
CG4	0.002	0.001	0.001	0.001	0.001	
CG1	0.039	0.016	0.016	0.016	0.023	
CG2	0.040	0.027	0.027	0.027	0.030	
CG3	0.008	0.005	0.005	0.005	0.005	
Yr. tot.	0.09	0.05	0.05	0.05	0.06	0.06
			AACCA - Conventional Till			
CG4	0.004	0.004	0.009	0.016	0.047	
CG1	0.006	0.006	0.079	0.137	0.072	
CG2	0.007	0.007	0.069	0.120	0.056	
CG3	0.003	0.003	0.033	0.057	0.025	
Yr. tot.	0.02	0.02	0.19	0.33	0.2	0.152
			AACCA - Conservation Till			
CG4	0.004	0.004	0.003	0.006	0.028	
CG1	0.006	0.006	0.029	0.054	0.043	
CG2	0.007	0.007	0.026	0.047	0.034	
CG3	0.003	0.003	0.012	0.023	0.015	
Yr. tot.	0.02	0.02	0.07	0.13	0.12	0.072
			AACCA - No-till			
CG4	0.004	0.004	0.000	0.002	0.009	
CG1	0.006	0.006	0.004	0.017	0.014	
CG2	0.007	0.007	0.004	0.015	0.011	
CG2	0.003	0.003	0.002	0.007	0.005	
Yr. tot.	0.02	0.02	0.01	0.04	0.04	0.026

Table B.5 SCS curve numbers for the management alternatives used in this study.

Hydro. Soil Group: A
Rotation: Wheat-Corn-Corn-Corn-Soybean (WCCCS)

Crop	Time period	Tillage -> Mech. Prac. ->	CONV. V	CONV. C	CONS. V	CONS. C	NO-TILL V	NO-TILL C
WHEAT	1		71	69	67	65	65	63
	2		65	63	58	56	57	55
	3		65	63	58	56	57	55
CORN	1		70	69	65	63	63	62
	2		77	76	71	70	69	68
	3		67	65	62	60	60	59
CORN	1		72	71	67	65	65	63
	2		77	76	71	70	69	68
	3		67	65	62	60	60	59
CORN	1		72	71	67	65	65	63
	2		77	76	71	70	69	68
	3		67	65	62	60	60	59
SOYBEAN	1		72	71	67	65	65	63
	2		75	74	71	70	69	68
	3		66	64	62	60	60	69

Hydro. Soil Group: B
Rotation: Wheat-Corn-Corn-Corn-Soybean (WCCCS)

Crop	Time period	Tillage -> Mech. Prac. ->	CONV. V	CONV. C	CONS. V	CONS. C	NO-TILL V	NO-TILL C
WHEAT	1		80	78	76	74	74	72
	2		86	85	80	79	77	77
	3		75	74	69	68	68	67
CORN	1		81	80	74	74	72	72
	2		86	85	80	79	77	77
	3		78	75	72	69	70	68
CORN	1		82	80	76	74	74	72
	2		86	85	80	79	77	77
	3		78	75	72	69	70	68
CORN	1		82	80	76	74	74	72
	2		86	85	80	79	77	77
	3		78	75	72	69	70	68
SOYBEAN	1		82	80	76	74	74	72
	2		84	83	80	79	77	77
	3		76	74	72	69	70	68

Table B.5 cont. SCS curve numbers for the management alternatives used in this study.

Hydro. Soil Group: C
Rotation: Wheat-Corn-Corn-Corn-Soybean (WCCCS)

Crop	Time period	Tillage -> / Mech. Prac. ->	CONV. V	CONV. C	CONS. V	CONS. C	NO-TILL V	NO-TILL C
WHEAT	1		83	80	79	76	77	74
	2		91	89	84	82	82	80
	3		75	74	69	68	68	67
CORN	1		83	81	77	75	75	73
	2		91	89	84	82	82	80
	3		78	75	72	69	70	68
CORN	1		85	82	79	76	77	74
	2		86	85	80	79	77	77
	3		78	75	72	69	70	68
CORN	1		85	82	79	76	77	74
	2		86	85	80	79	77	77
	3		78	75	72	69	70	68
SOYBEAN	1		85	82	79	76	77	74
	2		89	87	84	82	82	80
	3		76	74	72	69	70	68