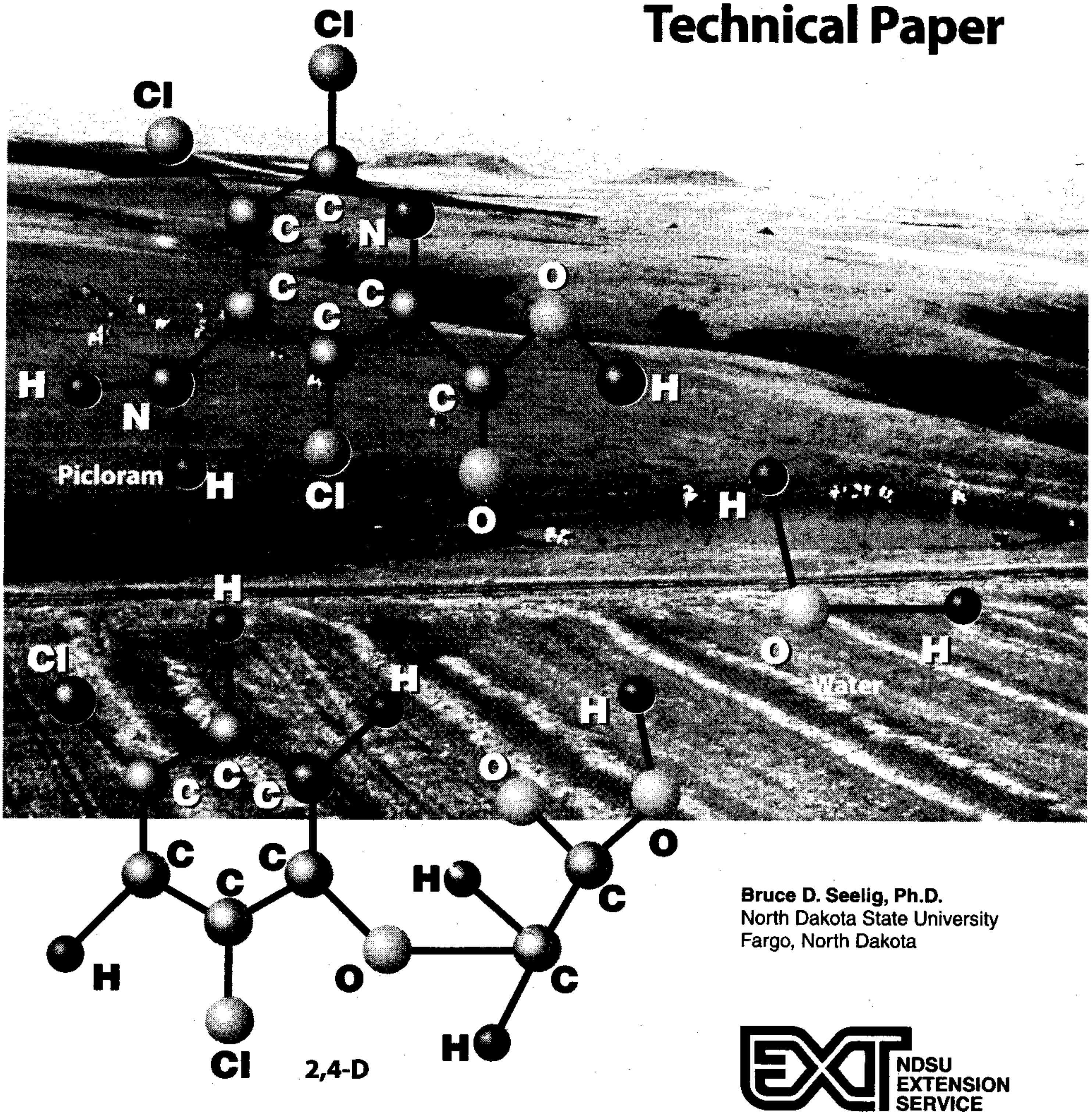
Extension Report No. 25

Best Management Practices for Groundwater Protection from Agricultural Pesticides: Technical Paper



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Introduction

Groundwater is an essential resource to the people of North Dakota. Over 60 percent of the state's population depends on groundwater for domestic purposes (Garklavs and Nelson, 1986). Nearly all the rural population in North Dakota depend on groundwater. Consequently, maintenance of quality and quantity of this resource is a public mandate for several state and federal organizations.

The North Dakota Department of Agriculture is responsible for development of the "Water Protection Strategy for Pesticides." Implementation of that strategy includes the preparation of a **Generic State Management Plan (GSMP)**. Voluntary and mandatory measures for groundwater protection are [illegible] of the GSMP under **Section VII - Prevention Actions**. With funding assistance from the U.S. Environmental Protection Agency (EPA), the North Dakota Department of Agriculture and NDSU Extension Service have entered into a memorandum of agreement to develop a system of **best management practices (BMP)** under the **Voluntary Management Measures (Step 1) of Section VII**.

This document was prepared as a guide for individuals in occupations and organizations that are required to provide technical advice regarding management of natural resources. The recommendations are intended to provide a systematic approach for stepwise development and implementation of management practices from the regional to the local level. The information presented will assist technical advisors with recommendations and lend credibility to their advice. This document is predicated on the following concept. **The extent to which BMPs will be adopted is directly related to the quality of information presented and the ability of technical advisors to deliver the information to producers.**

The BMP selection process and recommendations outlined in this document were derived within the context of present scientific knowledge. An extensive review of scientific literature related to groundwater, pesticides, and agricultural management was done. Results of this review helped to define important relationships between groundwater and agricultural management and also helped to identify methods to address situations of conflict. Pertinent information from the literature review is presented as the technical justification for the groundwater protection BMP recommendations. It is also used as support for the procedure recommended to attain adoption of BMPs in North Dakota.

Pesticides and groundwater are topics of considerable public interest and misunderstanding. The public and its representatives can make effective and fair policy decisions regarding groundwater protection if they have access to accurate, unbiased information. There are many sources and types of information, but only information gathered through strict adherence to scientific principles meets the criteria for accuracy and objectivity.

Definition of water quality problems and solutions requires flexibility. As scientific inquiry proceeds, new information will require changes in plans and strategies to meet the needs and demands of society. The BMP strategy proposed in this document was designed for adaptability to change.

Technical Notes:
Effects of Pesticides in the Environment

Since the late 1940s, the use of synthetic organic pesticides has become a major component of modern agriculture (Cheng, 1990). When pesticides are applied as recommended under the appropriate prescribed conditions, they are effective and have little impact on the environment. However, trace amounts of pesticides have been detected in land, atmosphere, and water far from sites of application. The U.S. Environmental Protection Agency has estimated that approximately 50 of the more than 1,000 registered pesticides have chemical characteristics that are conducive to movement to groundwater (CAST Groundwater Task Force, 1985).

Public concern and sensitivity over pesticides in the environment developed in the 1960s (Leonard, 1990). The adverse impacts of chlorinated hydrocarbon insecticides (ie. DDT, dieldrin, chlordane) on avian and aquatic populations is well documented. These types of insecticides, which are no longer used in the U.S., were particularly pernicious because of their persistence and bio-magnification characteristics. Pesticides developed since the 1960s are generally less persistent, less toxic to mammals and aquatic organisms, and do not concentrate in the food-chain (Leonard, 1990).

Although the chemical composition of newer pesticides is designed to reduce environmental impacts, incidents of pesticide damage still occur. These incidents of environmental impact can usually be traced to non-recommended handling and application practices that are often the result of a lack of knowledge (Cheng, 1990). The harmful effects of pesticides are related to a combination of toxicity, concentration, time-length of exposure, and type of exposure.

Human health effects of pesticides in water resources are related to long-term exposure to small quantities of pesticide (CAST Health Issues Task Force, 1987). Generally, pesticide concentrations in groundwater are too low to cause human health problems (U.S. EPA Staff, 1990a). No specific cases of human illness have been documented from ingestion of low concentrations of pesticides in drinking water (CAST Health Issues Task Force, 1987). Instead, long-term health effects (chronic) are estimated statistically on the human population as a whole.

Estimation of the chronic effects of long-term exposure to low concentrations of pesticides is controversial due to the different approaches of risk assessment. The best estimate of true risk permitted by available scientific information is "scientific risk" (Black, 1987). "Regulatory risk" uses scientific information and methods, but the purpose is to assure safety. Procedures and assumptions are used to assess "regulatory risk" that collectively overestimates the risk for safety assurance. "Scientific risk" is a more realistic assessment and considerably lower than "regulatory risk" (Black, 1987).

The determination of the probability of human illness is based on extrapolation of results from the exposure of laboratory animals to large doses of pesticides (CAST Health Issues Task Force, 1987). Their potential as carcinogens, teratogens, and mutagens are measured. Chemicals are classified into three categories: human carcinogens (I); possible human carcinogens (II); and no evidence for carcinogenicity (III).

For human carcinogens (category I) the Environmental Protection Agency (EPA) recognizes no tolerable concentrations in water. EPA interprets acceptable risk for possible human carcinogens (category II) as one additional death per million persons exposed daily for a lifetime to a specific pesticide dose. EPA's calculation of risk for category III chemicals includes a safety margin that overestimates the true risk by 10 to 1000 times (CAST Health Issues Task Force, 1987). Determinations of the highest acceptable concentration of each pesticide are used by EPA to set maximum contaminant level (MCL) standards for water.

Due to public concern regarding the effects of water contamination on human health and the environment, the U.S. Congress has passed several laws that give the federal government regulatory power over those materials and activities that pollute our water resources. Pesticide manufacture and use are regulated under Federal law. The Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) administered by EPA controls the registration, manufacture, transportation, and use of pesticides. This law provides for strict labeling requirements for pesticide containers and classification of all pesticides into the use categories of "restricted" or "general." Pesticides that could cause human injury or environmental damage are classified as "restricted use" and must be applied by only individuals that have been certified.

The Federal Water Pollution Control Act and Rural Clean Water Act give EPA further power to regulate sources (point and non-point) of water pollution to achieve national water quality goals. Pesticides are one of the many contaminants that fall under the jurisdiction of these laws.

The Safe Drinking Water Act (SDWA) gives EPA additional authority to ensure that public water systems deliver uncontaminated water to their customers. Primary and secondary drinking water standards have been established under this law. EPA has been given the authority to establish enforceable maximum contaminant levels (MCL) for all public water systems. Contaminant levels for specific pesticides are established under the rules of the SDWA.

Technical Notes: *Pesticide Use in North Dakota*

Pesticide use in North Dakota follows the national trend of herbicides composing the largest percentage of total pesticide applied (Leonard, 1990). For example, in 1993 over 90 percent of the wheat acreage in North Dakota received herbicide applications, but less than 1 percent received insecticide applications (ND Agricultural Statistics Service Staff, 1994). However, some crops do not follow the general trend. For example, in 1993 only 53 percent of the potato acreage in North Dakota received herbicide applications and over 90 percent received insecticide and fungicide applications.

Since 1978 herbicide use in North Dakota has grown steadily from 16,947,000 acres treated to 28,777,000 acres in 1992 (Zollinger et al., 1993). In 1978 the herbicides used on the largest acreage (in descending order) were 2,4-D, trifluralin, MCPA, and triallate. In 1992 the order of herbicide use was 2,4-D, dicamba, MCPA, and trifluralin.

Insecticide use in North Dakota increased from approximately 365,000 treated acres in 1978 to 2,234,000 acres in 1989 and declined to 1,170,000 acres in 1992 (Zollinger et al., 1993). In 1978 the insecticides used on the largest acreage (in descending order) were azinphos-methyl, toxaphene, aldicarb, and phorate. In 1992 the order of insecticide use was carbofuran, esfenvalerate, ethyl parathion, and terbufos.

Fungicide use in North Dakota has steadily increased from approximately 104,000 acres treated in 1978 to 929,000 acres in 1992 (Zollinger et al., 1993). In 1978 the fungicides used on the largest acreage (in descending order) were mancozeb, thiabendazole, and maneb. In 1992 the order of fungicide use was mancozeb, propiconazole, and triphinyltin hydroxide.

Reviewing the pattern of pesticide use in North Dakota since 1978 (Table 1) reveals a number of trends that have implications with respect to groundwater contamination. Herbicide use has changed the least with respect to total acres treated and types of chemicals used. The acreage treated has increased two-fold and dicamba has replaced triallate as one of the most used herbicides. The leaching potential is high for 2,4-D, dicamba, and some forms of MCPA (Seelig, 1994).

Insecticide use in North Dakota appears to have peaked in 1989 with a six-fold increase in acres treated compared to 1978. The group of most commonly used pesticides in 1992 is completely different than those used in 1978. In 1978 only aldicarb had a high leaching potential (Seelig, 1994), and it was the third most frequently used insecticide. In 1992 only carbofuran had a high leaching potential (Seelig, 1994), but it was the most frequently used insecticide in North Dakota.

Table 1. Most commonly used pesticides in North Dakota 1978 and 1992 (Zollinger et al., 1993)

Chemical	Acres Treated	Leaching Potential	Chemical	Acres Treated	Leaching Potential
	(x 1000)	(Seelig, 1994)		(x 1000)	(Seelig, 1994)
Herbicides 1978			***Herbicides 1992***		
2,4-D	9339	high	2,4-D	8187	high
trifluralin	2052	intermediate	dicamba	3803	high
MCPA	1744	high/intermediate	MCPA	3049	high/intermediate
triallate	1046	intermediate	trifluralin	2862	intermediate
Insecticides 1978			***Insecticides 1992***		
azinphos-methyl	73	intermediate	carbofuran	247	high
toxaphene	65	low	esfenvalerate	161	intermediate
aldicarb	31	high	ethyl parathion	128	low
phorate	31	intermediate	terbufos	127	intermediate
Fungicides 1978			***Fungicides 1992***		
mancozeb	46	intermediate	mancozeb	361	intermediate
thiabendazole	26	intermediate	propiconazole	226	intermediate
maneb	15	intermediate	triphenyltin hydroxide	134	low

Fungicide use in North Dakota has increased nine-fold in acres treated since 1978. Only Mancozeb continues to be frequently used. None of the commonly used fungicides in 1978 or 1992 have high leaching potentials (Seelig, 1994).

BMP Definition

The best management practices (BMP) definition that will be used in this document was proposed by Baker and Johnson (1983) and is stated "**Practices that can be used to control nonpoint source pollution and that are socially and economically acceptable are termed Best Management Practices.**"

Technical Notes: *Regulatory Definition of BMPs*

Definitions of best management practice may differ slightly. In section 33-16-02 of the North Dakota Administrative Code, *Standards of Water Quality for State of North Dakota*, BMPs are defined as "**methods, measures, or procedures selected by the department (NDSDH) to control nonpoint source pollution. Best management practices include, but are not limited to, structural and nonstructural measures and operation and maintenance procedures**".

Daniel et al. (1991) note that the term BMP was defined in Public Law 92-500, the Federal Water Pollution Act of 1972. Rigorous criteria outlined in 92-500 must be met before a practice is considered a BMP. **Implementation of the BMP must result in water quality improvement, be cost effective, and acceptable to the producer.**

In 1978 EPA proposed legislation that indicated how BMPs would be imposed in National Pollutant Discharge Elimination System (NPDES) permits under Section 304(e) of the Clean Water Act. This proposal never became effective; however, it remains as a guideline for NPDES permit writers.

Recently, "**management measures**" have been defined in section 6217(g)(5) of the Coastal Zone Act Reauthorization Amendments of 1990 as "**economically achievable measures for the control of the addition of pollutants from existing and new categories and classes of nonpoint sources of pollution, which reflect the greatest degree of pollutant reduction achievable through the application of the best available nonpoint pollution control practices, technologies, processes, siting criteria, operating methods, or other alternatives**".

Total Resource Management and Pesticides

A broad perspective is needed for productive management of natural resources. The focus of the BMPs recommended in this document is relatively narrow. Pesticide BMPs for groundwater protection will have to be integrated into a total management plan for the farm. Integration will require knowledge regarding interaction between management practices used to reduce environmental impacts from pesticides and those practices used for different purposes (Refer to Appendix B). Control of different contaminants (pesticides, nutrients, sediments) in different water resources (groundwater, lakes, rivers) must be considered. Economic and social impacts from implementing groundwater protection practices must be assessed.

The concept of total resource management should always be addressed; however, the complexity can be challenging. For example, the relationship between integrated pest management (IPM) practices that promote healthy crops and reduce use of pesticides is recognized (Maas et al., 1984; Schweizer, 1988; Van Es, 1990). However, managing an optimal growth environment for healthy crops also requires good plant nutrition and practices that reduce weed competition. Improved plant nutrition often requires greater input of nutrients; the potential for both surface and groundwater contamination may be increased. Mechanical disturbance of the soil is an alternative to pesticide use for weed and disease control, but it also increases the potential for soil erosion and contamination of surface water.

Interrelationships between insecticide and herbicide use should be considered. Fawcett (1987) points out that in some situations improved weed control with herbicides can result in reduced insecticide applications due to loss of insect habitat. Total resource management must balance different forms of environmental impact; this is much easier said than done.

The primary objective of the following recommendations for BMP selection and implementation is groundwater protection from pesticides. Although the importance of the interrelationships between the factors that affect total farm management is recognized, detailed discussion regarding integrated management and pesticide/groundwater BMPs is beyond the scope of this document. The proposed process for BMP selection will allow integration of pesticide/groundwater BMPs into a total farm management plan at the site-specific level.

Technical Notes: *Practical Perspective on BMPs*

An analysis of past and ongoing water improvement projects will help to guide the development of effective BMP strategies. It should be noted that only a few of these projects have had groundwater components and most have been focused on nutrient abatement. Experience and knowledge regarding cause and effect relationships between management and water quality is much further advanced in the area of surface water compared to groundwater (Daniel et al., 1991). Different contaminant sources, concentrations, modes of transport, and chemical fate make direct analogies between surface water and groundwater BMPs impossible. General conclusions regarding implementation strategies, program delivery, project evaluation, and producer response are useful for the design of any type of BMP strategy.

Many investigators have demonstrated practices that reduce the potential for water contamination while maintaining yields at levels comparable to conventional farming (Schweizer, 1988; Montgomery et al., 1990; Ayars and Phene, 1993; Martin et al., 1993; Nokes et al., 1993; Watts et al., 1993a). Reduced tillage appears to enhance yields due to additional moisture storage compared to conventional tillage (Unger, 1986). However, the assumed economic benefits do not always materialize. Deibert et al. (1986) and Tanaka (1989) found that no yield enhancement of wheat from additional stored soil moisture under reduced tillage occurred in the northern Great Plains. Other investigations show that certain management practices can reduce leaching losses but not eliminate them (Randall et al., 1993), and in some cases leaching cannot even be reduced to acceptable levels without reductions in yield (Melvin et al., 1993). Thus, practices that reduce contamination potential do not always deliver yields that are comparable to conventional management.

After 10 years of BMP implementation on Rural Clean Water Projects (RCWP), substantial change in the target water resources was not demonstrated in many cases (Clausen et al., 1992; German, 1992; Koerkle, 1992; McCoy and Summers, 1992; Meals, 1992a,b; Schlagel, 1992). It is often difficult to show direct relationships between management and water quality because of the vast amount of natural variability (Baker and Johnson, 1983). Improvements were noted in some projects but were difficult to link to specific management practices (Chandler and Maret, 1992). In other studies water quality improvements appear to be related to the application of BMPs, but additional improvement is needed (Gunsalus et al., 1992; Moore et al., 1992). In many cases logic and experience are legitimately used to predict relative effects of BMPs (Baker and Johnson, 1983).

The lack of immediate response to BMPs and variable response appears to be typical for water quality projects (Baker, 1987b; Hallberg et al., 1993; Hocking et al., 1993; Sutton, 1993). Wall et al. (1992) determined that the effects of nitrogen BMP implementation in Minnesota would not be seen until the year 2000 due to the 15 to 60 year lag between infiltration and groundwater recharge. On the other hand, in Pennsylvania significant reductions in nitrate in groundwater were observed within four to 19 months after implementation of nutrient management plans (Hall and Risser, 1992).

Technical Notes: *Economics of BMP Adoption*

The definition of BMPs implies that in addition to meeting environmental criteria these practices must be economical. Attempts to model economic results of BMP adoption reveal a variety of answers depending on the assumptions used to estimate factors such as producer behavior (Miranowski and Alt, 1983) or agricultural markets (Taylor, 1983). The results of BMP policies adopted over large regional areas may affect market prices unpredictably, because producers will change practices and acreages (Taylor, 1983). The final result may be either higher or lower farm income irrespective of the initial impact on farm income (before price changes).

Miranowski and Alt (1983) noted that producers often choose less risky management systems which are not necessarily the alternatives that provide the greatest farm income. Other external factors, such as rising energy costs, may lead to both less farm income and greater environmental protection. Conflicting results from different economic models indicate the importance of factor selection and accurate assumptions (Taylor, 1983). Probably more important, conflicting results show the complexity of predicting economic impacts of BMP adoption.

Economic evaluation of adopting different management practices or systems should be an integral part of the BMP selection process, particularly at the site specific stage (Hickman et al., 1994). However, economic impacts can be expected to vary between regions and farms within those regions. Expectations of predicting precise economic impacts due to BMP adoption are not likely to be fulfilled in the near future.

Field Management for Groundwater Protection from Pesticides

Practices for groundwater protection that are incorporated into a producer's crop management system are defined as field BMPs, if they meet the criteria for effectiveness and acceptance. Strong correlations between crop management practices and groundwater quality have not been demonstrated in North Dakota. Consequently, field BMPs will generally have lower priority compared to farmstead BMPs. This does not diminish the importance of field BMPs; however, it should help organize BMP selection with a logical progression of effort. The process will address groundwater and pesticide problems by first emphasizing implementation of farmstead BMPs and then progress to the implementation of field BMPs, if required.

Review of groundwater and pesticide projects indicate that an effective system of field BMPs must account for natural variability of groundwater sensitivity. Pesticide fate and potential for groundwater contamination have been demonstrated to be variable and related to a combination of factors, such as soil type and depth to the aquifer. Identifying and delineating the natural variability of these factors serves to focus BMP implementation efforts on those areas with the greatest potential for contamination. The groundwater sensitivity categories (high, high-intermediate, low-intermediate, and low) defined by Seelig (1994) will be the basic units used to organize the field BMPs.

The groundwater sensitivity categories assign relative potential for pesticide contamination to occur in a qualitative sense. For instance, the high sensitivity category has greater potential for pesticide contamination than the high-intermediate category. Quantification of how much greater the contamination potential of the high category is compared to the high-intermediate category would require a significant research effort. Also, the sensitivity categories are not intended to predict the level of probability that contamination will occur. The use of groundwater sensitivity categories helps provide a method to systematically group BMPs with some basis of logic. At this time they will not help us solve cause and effect relationships to any degree of accuracy.

Utilizing groundwater sensitivity categories will help determine amount of emphasis placed on the two BMP strategies (farmstead and field). As previously discussed, farmstead BMPs should generally receive greater emphasis; however, as groundwater sensitivity increases, so should the emphasis on field BMPs. Areas assessed as having high or high-intermediate sensitivity to groundwater contamination have at least one identified factor that will provide little attenuation of pesticides. The focus for field BMPs should be placed on that factor or factors. Areas assessed as low or low-intermediate sensitivity have no identified factors that clearly contribute to pesticide movement to groundwater. As a result, recommendations for field BMPs in areas of low and low-intermediate sensitivity will lack specificity.

It should be noted the groundwater assessment system (Seelig, 1994) does not directly account for preferential flow(Refer to Appendix A). Review of many studies indicates that this process occurs frequently under certain conditions, and North Dakota is probably no exception. These studies indicate that although preferential flow can occur in many environments, its spatial and temporal variability cannot be accurately characterized. At this time, preferential flow through macropores does not appear to a be a factor that delivers substantial quantities of pesticides to groundwater in North Dakota. Considering our present state of knowledge regarding the preferential flow mechanism, it is probably best accounted for by identifying the vadose zone thickness (depth to aquifer).

Technical Notes: *Importance of Factor Variability to BMP Selection*

Many factors affect water quality in a given watershed and some may negate improvements from management efforts (Magette et al., 1988; Goodman et al., 1992; Anderson et al., 1993; Ward et al., 1993; Logan et al., 1994). Thus, effectiveness and practicality of BMPs will depend on local conditions, including soil type and slope, climate, hydrology, resources available, and management ability (Fawcett et al., 1993). For instance, Kanwar et al. (1993) found that a combination of crop rotation, tillage, and pesticide chemistry influenced the leaching potential of applied pesticides. However, the solutions to non-point source problems in one area do not necessarily transfer to other areas, because environmental conditions change (Christensen, 1983).

Soil type has been demonstrated by several investigators as a key to the success or failure of management systems. Conservation tillage has been shown to be more effective in controlling runoff and soil loss on soil types with good drainage (Edwards and Amerman, 1984; Schepers, 1987). Logan et al. (1994) found little difference in runoff and soil loss between conservation and conventional tillage on heavy textured soil types. Differences in bulk density, aggregate stability, and surficial soil chemistry between no-till and conventional till were found to be significantly greater on certain types of soils (Rhoton et al., 1993). Pesticides were transported deeper in lowland soils compared to upland soils in a Missouri field (Delin and Landon, 1993). Conservation tillage significantly increased biomass accumulation in a Kentucky soil but did not cause a significant change in biomass in a Canadian soil with lower soil temperature(Smith and Blevins, 1987). In some studies differences in potential for preferential flow have been related to soil type (Quisenberry et al., 1993; Flury et al., 1994).

Although some studies have shown general relationships between soil type and pesticide movement, Moorman et al. (1993) found the variability within to be nearly as great as the variability among soil mapping units. Ghodrati and Jury (1992) observed significant differences in preferential flow within a field plot on sandy soils. Staver and Brinsfield (1991) suggested that soil variability affecting pesticide movement is so great that accurate mass balance cannot be economically determined. Certain soil properties have been found to have greater spatial correlation under conventional tillage than conservation tillage (Cressie and Horton, 1987; Mohanty and Kanwar, 1994). The prevailing level of temporal and spatial variability makes accurate prediction of pesticide movement with the computer models GLEAMS, PRZM, CMIS, LEACHEM, MOUSE, and USBR extremely difficult at most locations (Steenhuis et al., 1990).

BMP Selection Procedure

Occasional detection of low concentrations of pesticides in North Dakota groundwater obliges agencies mandated to manage groundwater to fully understand the ramifications of the monitoring results. Effective management and protection of groundwater requires knowledge of the processes that affect groundwater. Ineffective management policies will result if perceptions of groundwater processes are substituted for adequate understanding (Beaver et al., 1990).

The present state of knowledge regarding management impacts on pesticide contamination of groundwater does not support specific answers to many questions that arise from the occasional detection of low pesticide concentrations. Continued research that relates management to pesticide use and groundwater contamination is needed. The BMP recommendations presently based on available scientific information will eventually need modification to conform to knowledge gained from on-going and future research.

After review of various projects and studies that have utilized BMPs, one may conclude that the process of BMP selection is probably just as important if not more important than the actual BMPs. Successful BMP selection and implementation depends on a process that combines problem identification, focused efforts, technical guidance, and producer input (Figure 1).

An iterative process is proposed for BMP selection. A simple definition of "iterate" is "to repeat." A more specific definition of "iterate" relates to science and mathematics. A step-wise series of repetitive calculations lead to a more accurate answer at the end of each step or iteration.

The BMP selection procedure proposed is not exactly iterative in the sense of the science and mathematics usage, but the process is similar. Each step or iteration of the BMP selection process begins with BMPs that are subsequently modified to fit more specific conditions (Figure 2). **Each step of the selection process will include the four operations mentioned earlier as essential to successful BMP implementation: 1) identification of groundwater problems;**

2) focused effort in areas assessed as highly sensitive to groundwater contamination; 3) solicitation of technical guidance that is scientifically based; and 4) solicitation of producer input regarding management practice feasibility.

Technical Notes: *Stepwise Selection Procedure for BMPs*

Studies have shown that BMPs are not adopted for a variety of non-technical reasons, such as perception of risk, lack of information, different priorities, disruption to effective management systems, and lack of financial incentive (Nowak and Korsching, 1983; Jordan and Elnagheeb, 1993; McCallister et al., 1993; Rikoon et al., 1993). It has been suggested that the traditional linear method of inducing change (voluntary through education -> financial incentive -> regulatory) has not and will not produce significant water quality improvement (Nowak and Korsching, 1983; Logan, 1990; Napier, 1993). Nowak and Korsching (1983) suggested that interdisciplinary effort is required to solve the institutional and social problems that hinder full implementation of BMPs.

Logan (1990) concluded that results from the RCWP and similar programs indicate the BMP approach has failed, and the primary reasons are inadequate funding and lack of grassroots support. Even when accurate predictions of cause and effect between management and water quality are possible, it does not guarantee BMP adoption (Christensen, 1983; Logan, 1990). Producers are often not concerned with water quality problems and see them as their neighbors' problems (Napier, 1993; O'Keefe et al., 1993). Contant (1990) concluded that an effective approach to influencing producer attitudes and activities occurs in three steps: 1) stimulate interest; 2) individual contact; 3) collaboration with producers in the transition to new practices.

Observation of the results from RCWP and similar projects provides several guidelines for future BMP strategies. The most important points of consideration are the following: 1) clear identification of water quality problems and improvements; 2) targeting BMP activities to identified problem areas; 3) one-to-one technical/educational contact with producers; and 4) grassroots ownership of the problem and solution (Christensen, 1983; Logan, 1990; U.S. EPA Staff, 1990b; NCSU Water Quality Group, 1993; Watson et al., 1994). Hickman et al. (1994) recommend a four step process for producers to use for BMP selection: 1) prioritize resources; 2) identify resource protection strategies; 3) link BMPs with strategies; 4) economic analysis of strategy implementation.

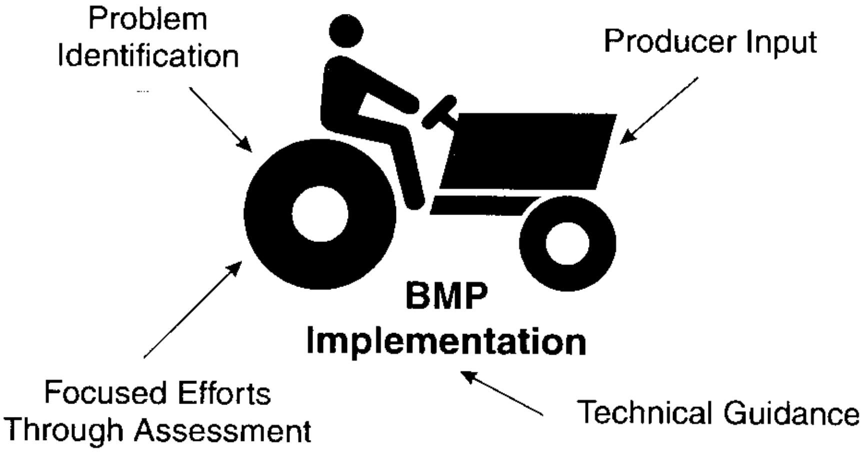


Figure 1. Essential ingredients for successful BMP implementation.

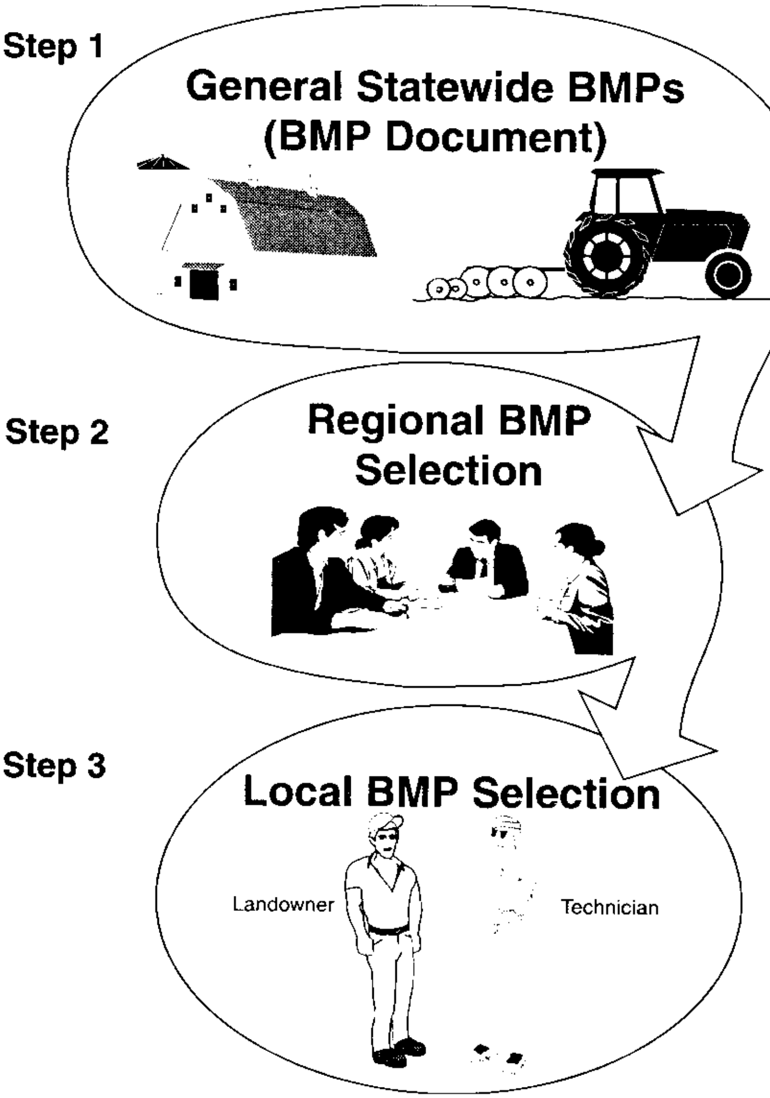


Figure 2. Stepwise procedure for BMP selection.

An important part of successful BMP implementation appears to be a BMP selection process that flows from general concepts to site specific practices. U.S. EPA Staff (1993b) have recognized the need for two levels of BMPs, general and site-specific. Several investigators conclude that successful BMP implementation can only occur when site variability is recognized and accounted for within the design of site-specific BMPs (Christensen, 1983; Baker et al., 1987; Walter et al., 1987; Daniel et al., 1991).

The First Step

The preparation of this document is the first step. Study results have been reviewed to generally characterize groundwater problems and sensitivity in North Dakota. Management practices have been reviewed to assess their general application to North Dakota conditions.

The Second Step

The second step is a process that uses expertise from appropriate organizations to help producers within a specific region of the state select BMPs. The process will organize producers according to natural boundaries and common resources. Producers with similar soils, landscapes, and climate are most likely to have similar management systems and problems.

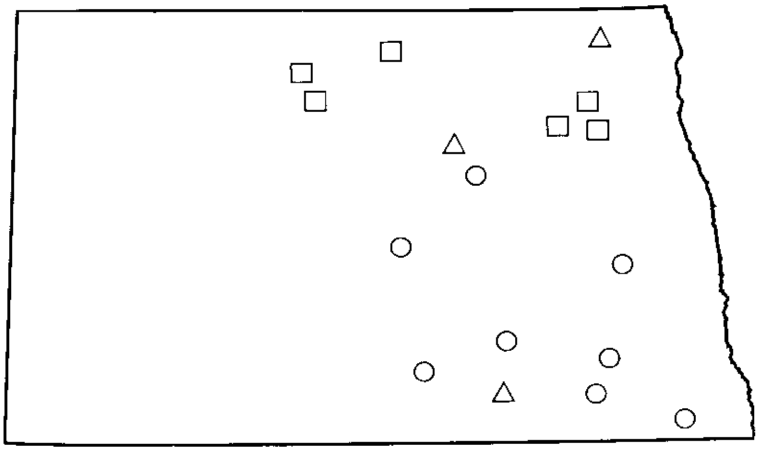
It is suggested the expertise of the Advisory Committee for the State Strategic Plan for Groundwater/Pesticides Protection be utilized during the second step. Determining the geographical extent of BMP-regions would be the responsibility of this group.

The concept of producer selection of BMPs for groundwater protection is related to the results and recommendations from other BMP projects. The model for grassroots involvement in the BMP selection process has proven to be quite successful in Colorado (Waskom and Walker, 1994). Producer involvement in designing recommendations that will affect their operations appears to be critical to the success of most BMP programs.

NDSU Extension Service will facilitate producer selection of regional BMPs with the expert advice of other organizations. Local ownership of BMP programs can be accomplished by not only soliciting local input, but also allowing local decision-making. Participants in this process must understand, however, that local selection of BMPs is an experimental program. By state and federal law, authority for BMP selection and implementation to protect water quality rests with several regulatory agencies. If voluntary selection and implementation of BMPs are unsuccessful in protecting groundwater quality, these agencies reserve the right to select and implement management practices as they find necessary.

NDSU Extension Service will facilitate the process of finding appropriate representatives for the regional BMP selection committees. Extension staff will receive training related to the BMP selection procedure and the objectives of groundwater protection. Emphasis on BMP recommendations that are acceptable and reasonable to local producers will be clearly communicated.

An important component of the regional BMP selection process will be demonstration of need for groundwater protection from pesticide contamination. Pesticide detections in local groundwater supplies will be identified and located by reviewing results of groundwater studies, such as the NDSDH Groundwater Monitoring Program (Figure 3).



Legend for NDSDH Groundwater Monitoring Program

	○ 1992	□ 1993	△ 1994
Aquifers	Icelandic Oakes Warwick	Denbigh Elk Valley Fordville Inkster Lake Souris Shell	Galesburg - Page Hankinson Marstonmoor Plain Milnor Channel Sand Prairie Sheyenne Delta

Figure 3. Approximate location of aquifers monitored for pesticide contamination by NDSDH (Radig and Bartelson, 1993; 1995; 1995b).

Groundwater impacts from both present and past pesticide use patterns in the region must be considered. This information should be presented within the context of a regional groundwater sensitivity assessment (Figure 4).

NDSU Extension Bulletin No. 63, "An Assessment System for Potential Groundwater Contamination from Agricultural Pesticide Use in North Dakota," will be used to categorize areas ofgroundwater sensitivity (Table 2). The extension state coordinator for the Groundwater/ Pesticide BMP program will coordinate data acquisition and assessment. The advisory committee will assist each regional BMP committee with interpretation of the relationship between groundwater data and the sensitivity assessment.

After the committee has reached a consensus regarding interpretation of the groundwater information, BMPs recommended in the first step of the BMP selection process will be reviewed. The advisory committee will provide technical guidance regarding these BMPs and their supporting documentation. With the assistance of the advisory committee, the regional BMP selection committees will determine which BMPs are appropriate for their region and the types of modifications needed. The BMP committee will also make recommendations that relate to additional information needs, preparation of BMP materials for local producers, and a BMP implementation plan.

Based on the regional BMP committee's recommendations, the NDSU Extension Service Coordinator will be responsible for developing a regional document that will be subject to the review and approval of the advisory committee and regional BMP committee. This document will serve as the source for technical guidance regarding the development of site specific BMP plans.

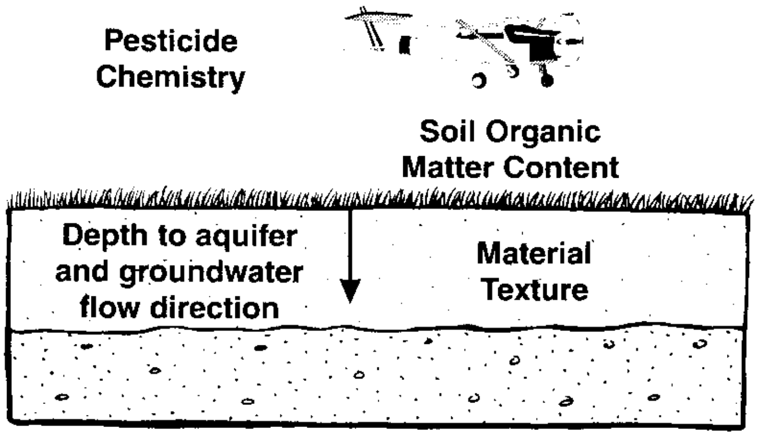


Figure 4. Factors used to determine groundwater sensitivity (Seelig, 1994).

The Third Step

The third step of the BMP selection process involves the final modification of information prior to actual site specific implementation of BMPs. It is the bridge between theoretical activities and actual land management practices. The BMP planning process will be analogous to other farm planning processes in that site variation will be recognized and used to tailor the final BMP plan for each producer. Allowing the producer to make final decisions regarding BMPs used in the management plan should create local support for the process.

A site-specific comparison of groundwater data with a sensitivity assessment will be necessary. Groundwater data compiled during the regional selection process can be utilized. NDSU Extension Bulletin EB-63, "An Assessment System for Potential Groundwater Contamination from Agricultural Pesticide Use in North Dakota," should be used to guide a site-specific assessment that can be compared to the groundwater data. This analysis will help determine which regional BMPs may be most appropriate for an individual producer.

The third step in the BMP selection process is dependent on technical assistance. Individuals from local organizations or industry that provide technical information to producers will be educated to provide assistance with this process. Development of a training manual with

Table 2. Aquifer sensitivity categories defined (Seelig, 1994).

	Filtration Potential (F.P.)*			
Sensitivity Category	**▲ O.M.**	**■ Chem**	**✧ Text**	**♣ Aqui.**
High	Low	Low	Low	Low
High/Intermediate	*(at least 1 factor has low F.P.)*			
Low/Intermediate	*(no factors have low F.P.)*			
Low	High	High	High	High

* Filtration Potential (F.P.) – a relative indication of the influence that a factor has on the amount of pesticide that will be retained or filtered by the materials overlaying an aquifer.

▲ O.M.	Soil organic matter
■ Chem.	Pesticide chemistry
✧ Text	Material texture (relates to permeability)
♣ Aqui.	Depth to aquifer and direction of groundwater flow

supporting materials will be coordinated by the extension state groundwater/pesticide BMP coordinator. Training workshops will be interdisciplinary with participation of the organizations that compose the BMP advisory committee.

BMP Recommendations

Farmstead BMPs

1) **Prevent spillage and back-siphoning from spray equipment into the well by preventing overflow and maintaining an air gap between the filling hose and the water level in the tank.** Use anti-backflow devices on filler hoses.

2) **Maintain as much distance as possible from the well and the pesticide mixing and loading site.** Distance recommendations range from 25 to 150 feet.

3) **Mix, load, and rinse pesticides over an impermeable surface that is designed to drain to a sealed catchment, whenever possible.**

4) **Rinse chemical containers thoroughly using the triple rinse method or a pressure rinser.** Rinsate can be used as part of the make-up water in the sprayer tank.

5) **Recycle pesticide containers and avoid the need to locate an acceptable landfill site.** Use of dissolvable packaging, reusable containers, or returnable containers also avoids the problems associated with finding a suitable disposal site for empty containers. If these options are not practical, dispose of pesticide containers in an acceptable manner. Stockpiles of empty containers should be avoided through timely disposal.

6) **Dispose of unused pesticides that have been banned or are no longer wanted to reduce the overall contamination potential from the farmstead.** These chemicals are a particular problem because of possible leakage from containers that have lost their integrity through time. Often the labels are gone, so if there is leakage, the proper method of clean-up is a guess. Until recently, disposal of these types of old chemicals has been problematic due to questions of legal responsibility. New programs have been developed to assist producers with disposal. These chemicals should be stored in a secure location where clean-up of spills or leakage can be accomplished with a minimum of difficulty.

7) **Store pesticides in a secure, properly ventilated location where product usefulness can be maintained with minimal risk to people, animals, and the environment.** Moisture and temperature need to be controlled to maintain the life of the product and integrity of its container. This location should have an impermeable surface where spills can easily be contained and cleaned up. All drains must be self-contained or plugged, so that spilled pesticides have no direct connection with surface water or groundwater. The building should be located down-slope and as far away from the well as possible. It should not be located in areas that flood or that have standing water for any length of time. Each pesticide container should have its label plainly visible with the date of storage clearly marked. Containers should be inspected regularly for leakage, and the proper equipment and materials to rapidly respond to a spill should be easily accessible in the storage area.

8) **Attend to all pesticide spills immediately.** After human medical attention has been secured, the proper response includes containment of the spill, if possible, and then contacting the appropriate authorities, if necessary. After the spill has been contained, the area of spillage should be covered with an absorbent and/or neutralizer recommended by the manufacturer of the chemical. Do not hose down the spill; this merely spreads the problem. Shovel or sweep the clean-up material and affected soil into a leak-proof drum and dispose of according to local regulations for contaminated materials.

9) **Attend to all back-siphoning incidents immediately.** If pesticides are back-siphoned into a well or hydrant, the incident should be reported to the North Dakota State Department of Health (NDSDH). Pumping the well as soon as possible after the incident will help to minimize pesticide movement into the aquifer. Recommendations from the NDSDH should be followed regarding the proper disposal of pumped water. Contaminated soil around the hydrant may have to be removed for effective remediation. NDSDH recommendations should be followed regarding the extent of excavation and proper disposal of contaminated soil.

10) **Clean the pesticide sprayer properly. In the farmyard, clean over an impermeable surface.** Rinse water can be recovered from a sealed

catchment and used as part of the makeup-water the next time that chemical is applied. Sometimes, haul-back tank mixes are unavoidable. When this occurs, the haul-back should not be dumped but should be stored and used in a similar fashion as rinse water. **In the field:** To avoid the need for a rinsing pad and storage of rinse water, clean water can be taken to the field in a separate tank. The system can be cleaned by applying the rinse water to an acceptable field.

11) **Use closed-handling systems for mixing pesticides where practical.** Closed-handling systems consist of a pump and series of pressure-hoses that allow the user to siphon concentrated pesticide and mix with water without direct contact with the chemical. These systems reduce the safety risk of handling pesticides and also the environmental risk of spills.

12) **Locate and construct new wells according to codes that are intended to avoid contamination.** The well contractor cannot avoid sites such as old dumping pits and pesticide mixing areas unless advised about them. Prior to well construction, a plan for farmstead expansion should also be considered, so that future pesticide handling and storage on the farmstead do not jeopardize the integrity of the water source.

13) **Decommission or plug old wells, if not intended for future use.** Many farmsteads have several abandoned wells. Abandoned wells should never be used to dispose of any form of garbage or hazardous material, because they are a direct conduit to the groundwater. In many cases abandoned wells are located in the same aquifer as active farmstead wells. All abandoned wells should be plugged with materials and methods that will not allow settling in the future.

Farmstead BMPS Summarized

Pesticide detections in North Dakota groundwater are sporadic and do not present a general public health hazard (Nelson, 1988). **The results of monitoring and research studies to date have not demonstrated a significant "cause and effect" relationship between labeled application rates of pesticides and pesticide detections in North Dakota aquifers. When pesticides have been detected in North Dakota groundwater, they have usually been related to the condition of the well and activities around the well. Concentrations of detected pesticides have not exceeded health standards established by EPA.**

Interpretation of existing evidence suggests that in North Dakota, farmstead BMPs should be considered first when dealing with pesticides in groundwater. Appropriate pesticide handling practices that help protect the well should always be used, whether pesticide contamination is documented or not. Detailed discussion of farmstead BMP implementation is found in the references listed in Appendix C. Each reference title includes the source of information and the related BMP numbers.

Technical Notes: *Pesticides in Groundwater*

Evidence from groundwater studies and monitoring projects shows that pesticides are or have been present in groundwater at some locations (Frank et al., 1987a,b; Barrett and Williams, 1989; Louis and Vowinkel, 1989; Ritter, 1990; U.S. EPA Staff, 1990a; German et al., 1991; Rudolph and Goss, 1993; Wallrabenstein and Baker, 1992; Barnett and Howard, 1993; Burkart and Kolpin, 1993a,b; Spalding et al., 1993). Advances in analysis have made possible detection of extremely small quantities of pesticides previously undetectable (CAST Groundwater Task Force, 1985). Intensive sampling efforts and lower detection limits have increased the frequency of pesticide detections in groundwater (Moody, 1990). As technology advances, even smaller quantities of pesticides will be detectable in water.

Results of a national survey of drinking water wells indicate that 10 percent of community and 4 percent of rural wells have detectable levels of at least one pesticide (U.S. EPA Staff, 1990a). None of the pesticide detections in community wells occurred at concentrations that exceeded EPA health standards (Health Advisory Levels or Maximum Contaminant Levels), but a small number of rural private wells (less than 1 percent) did exceed health standard concentrations. Of 126 pesticides analyzed, atrazine and a degradate of dacthal were the most commonly found pesticides in well water. Four North Dakota community water wells (Berlin, Minot, Ray, and Underwood) were included in this study. Pesticides were not detected in any of these wells.

The documented results of monitoring and research studies characterize the incidence of pesticides in North Dakota groundwater as sporadic events of low concentrations (Table 3). Barrett and Williams (1989) suggested that pesticide detections in the lower parts per billion range are likely due to spillage, back siphoning, etc., while detections in the range of sub-parts per billion are more likely due to normal applications. Cases of contamination have not been found to have any predictable cause and effect relationship with normal pesticide applications in North Dakota. However, documentation does exist in several cases to suggest the source of water well contamination is from poor handling practices or sub-standard well construction. Management practices that address these problems are applicable for all farmsteads or locations of drinking water wells in North Dakota.

Technical Notes: *Pesticides in Groundwater Related to Contamination Sources*

Determination of the source of pesticide contamination in groundwater is important. Both specifically identified sources (point) and unidentified sources (non-point) contribute to pesticide contamination of groundwater. Discerning between point and non-point sources of pesticides found in groundwater is often difficult (Barrett and Williams, 1989). In a study of pesticide contamination in Ontario groundwater, little evidence was found to link normal field applications to contaminated wells (Frank et al., 1987a,b). **The most likely**

Table 3. Results of groundwater/pesticide studies in North Dakota.

Date(s) of Sampling	Source	No. and Type of Water Sources and Sample Location	No. Water Sources Analyzed	No. Pesticides Analyzed For	Samples with Pesticides	Pesticides Detected >HAL or MCL	No. of and Most Common Pesticides Detected
1994	Radig and Bartelson, 1995a	Six SE aquifers	149	49	26	None	(11) Picloram
1993	Radig and Bartelson, 1995b	Six NE aquifers	117	50	21	None	(10) Picloram
1992	Radig and Bartelson, 1993	Four Eastern aquifers	137	44	3	Non	(3) Picloram
1988-90	Abel, 1988	Statewide public water systems	346+	20	<1%	None	(2) Picloram Alachlor
1985-86	Lym and Messersmith, 1988	Ten counties with leafy spurge infestations	144	1	5	None	(1) Picloram
1985-87	Montgomery, Prunty, Mathison, Stegman, and Albus, 1988	Oakes aquifer	229	4	6	None	(1) Alachlor
1988	Meyer and Ulmer, 1989	Foster County	8	1	2	None	(1) Picloram
1985	Glatt, 1986	Statewide municipal systems	92	7	10	None	(4) Picloram
1985	Glatt, 1985	Rolette County	126	1	11	None	(1) Picloram

route of pesticide contamination was from surface water entering poorly located or poorly constructed wells. Analysis of the National Drinking Water Well Survey database indicates that more frequent pesticide detections occur in shallow and poorly constructed wells (U.S. EPA Staff, 1992). Wallrabenstein and Baker (1992) concluded, after testing over 35,000 private wells in Ohio, that most contaminated wells either tap shallow aquifers or are improperly constructed and maintained. Rudolph and Goss (1993) reached similar conclusions from a study of over 1,300 wells in Ontario. The results of a study of Midwestern surficial aquifers show that the frequency of herbicide detections increase as the depth to the aquifer decreases (Burkart and Kolpin, 1993a,b).

La Fleur et al. (1973) were among the first investigators to demonstrate that over-application of pesticides in the field could result in contamination of shallow groundwater. Subsequent studies have found that labeled rates of pesticide applications were linked to groundwater contamination incidents in many states (Ritter, 1990). It is postulated, if pesticide detections are related to labeled application rates, increased detections should be significantly related to increased pesticide use. The results from the National Drinking Water Well Survey (U.S. EPA staff, 1992) showed a significant relationship between the value of the crop grown and frequency of pesticide detections. However, Burkart and Kolpin (1993a,b) found that atrazine use and frequency of groundwater detections were significantly correlated in only parts of the Midwest. Frequency of herbicide detection was positively correlated with proximity to irrigated areas, urban areas, and rivers. Rudolph and Goss (1993) found no correlation between specific land-use practices and frequency of groundwater contamination in Ontario. Analysis of 8,000 well water samples from 54 of Indiana's 92 counties revealed patterns of pesticide con-tamination that related to soil conditions and proximity to streams (Barnett and Howard, 1993). U.S. EPA Staff (1992) concluded from the National Drinking Water Well Survey that a variety of environmental conditions and human activities affect the occurrence of pesticides in groundwater and no single factor can be used to adequately predict pesticide contamination.

Monitoring results of North Dakota groundwater show similar general trends as those studies presented from other states and regions. Although neither Abel (1992) or Glatt (1986) were able to determine the source of pesticides in the municipal systems tested, other studies on rural wells in North Dakota indicate that point source contamination was most likely responsible for the observed pesticide detections (Glatt, 1985; Lym and Messersmith, 1988; Montgomery et al., 1988; Radig and Bartelson, 1993; 1995a; 1995b).

Field BMPs for High Sensitivity Areas

Improved Pesticide Application BMPs

1) **Use pesticides with low mobility and persistence.** Often there are no substitutes that provide the desired pest control offered by certain highly mobile pesticides. The best alternative in this situation is utilization of management practices that reduce pesticide applications while still maintaining the desired pest control. Product labels indicate where and under what conditions mobile pesticides should not be used.

2) **Use pesticide formulations that reduce drift losses.** Generally granules and pellets reduce drift compared to dusts, wettable powders, and fine liquid sprays.

3) **Adjust spray equipment to give the range in droplet size for optimum coverage of the target.** The optimum range in droplet size will reduce drift to a minimum and provide maximum dispersion and target coverage.

4) **Release pesticide spray as close to the target as possible.**

5) **Never apply pesticides during weather conditions that may cause significant drift of small droplets away from the spray target.** Windy conditions or stable air conditions created by a temperature inversion (cold air trapped between the soil surface and warm air above) generally contribute to pesticide drift. Vertical movement of small droplets is reduced under these conditions and lateral drift is increased. Many pesticide labels recommend spraying only when wind speeds are 10 mph or less.

6) **Calibrate application equipment regularly to ensure that the proper amount of pesticide is applied.** This simple activity is required by law and avoids over-application of pesticides and under-applications that result in the need for additional applications because pests were not adequately controlled with the first application. Sprayer calibration and nozzle maintenance have large effects on application efficiency.

7) **Add petroleum or modified vegetable oil adjuvants to herbicide mixes, when recommended.** Adjuvants have been shown to increase the effectiveness of many herbicides. Increasing herbicide effectiveness means the total active product can be reduced without loss of pest control.

8) **Utilize banded applications of pesticides when possible.** This will reduce the amount of pesticide used compared to broadcast applications. However, under some circumstances, such as coincidence of ammonia injection furrows and pesticide bands, this practice may increase movement of the pesticide through the soil. Also in some areas additional cultivations required for weed control due to banding has not been acceptable to producers.

9) **Utilize methods of pesticide application that target individual pests or improve uniformity of application if possible.** Some of these techniques, such as wick applicators, have been around for years, and others, such as injection sprayers, make use of the latest innovations in computer technology and geographical referencing.

10) **Use pesticides that can be incorporated into the soil, if possible.** This will help to reduce losses due to volatilization and surface runoff, thus improving pest control and reducing the need for greater amounts of active ingredient or additional applications. However, this practice may increase the amount of pesticide that leaches through the soil.

11) **Avoid pesticide applications prior to intense rainfall events.** The largest losses of pesticide occur during the first runoff event after application. The amount of loss decreases with each additional day between application and intense rainfall.

Improved Pesticide Application BMPs Summarized

Areas that are assigned to the high sensitivity category will exhibit only minimal attenuation of pesticides. Highly mobile or persistent pesticides are used in these areas, where groundwater recharge (Refer to Appendix A) occurs through coarse textured soils overlaying a shallow aquifer. Such soils have low amounts of organic matter to retain pesticides that infiltrate the soil surface. Under these circumstances the most effective management methods will be those that eliminate or reduce the total amount of pesticide used.

If it is not feasible to substitute highly mobile or persistent pesticides with other products or methods for pest control, improved application or target efficiency becomes extremely important. Detailed discussion of BMP implementation for improved pesticide application is found in the references listed in Appendix C. Each reference title includes the source of information and the related BMP numbers.

Technical Notes: *Improved Pesticide Application*

Improvements in application efficiency have the potential to produce greater reductions in pesticide losses, when compared to either IPM practices or soil and water conservation practices (Maas et al., 1984). Himel et al. (1990) estimate that 60 to 80 percent of most pesticide spray is lost to the soil or peripheral foliage. Timing of chemical applications, application rates, and chemical placement may have greater influence on groundwater contamination than natural factors such as the presence of macropores (Baker et al., 1987).

Pesticide drift is a large component of pesticides' movement off-site (Maas et al., 1984; Management Work Group, 1989). Himel et al. (1990) estimated that drift losses typically account for 3 to 5 percent of applied pesticides. The typical range of pesticide losses in runoff is 1 to 2 percent of the applied pesticide (Leonard et al., 1990). Convective movement of pesticides and volatilization combine to cause pesticide losses to the atmosphere that have been detected in rainfall (Hatfield et al., 1993b; Nations et al., 1993). Dusts, wettable powders, and fine liquid sprays exhibit the greatest losses due to drift (Maas et al., 1984). Aqueous solutions, liquids, and liquid concentrates have the greatest potential for volatilization losses.

Himel et al. (1990) discussed the conflict between the two general theories regarding pesticide spray transport and impingement. The sedimentation theory predicts that smaller droplets are transported farther from the target area and pesticide drift will increase with wind speed. The turbulence theory predicts that as air turbulence increases the probability of small droplet impact on the crop canopy also increases, thus reducing drift losses. Turbulence generally increases with windspeed.

Avoiding spraying in excessively windy conditions, optimizing droplet size, using certain formulations (granules, pellets, and emulsions), and incorporating pesticides into the soil have been demonstrated to reduce drift and volatilization losses (Maas et al., 1984; Management Work Group, 1989). Pesticide incorporation into the soil has been suggested by some to increase the potential loss of pesticides to groundwater (McBride, 1988; Burgess, 1989).

Banded application of pesticides combined with cultivation and interseeding can substantially reduce pesticide applications on row crops (Lamey et al., 1994; Van Es, 1990). Kanwar and Baker (1993) reported reduced concentrations of atrazine under banded application compared to broadcast application. However, Clay et al. (1993) found when the anhydrous ammonia slot coincided with the atrazine band, deeper movement of atrazine into the soil occurred. Despite the economic and environmental advantages of pesticide banding, it may not always be adopted by producers due to constraints of time and labor (Rikoon et al., 1993) or because of solid seeded crops. Banded application of certain pesticides has been adopted by a majority of the producers in North Dakota who grow dry beans and sugar beets (Lamey et al., 1994; Dexter et al., 1995).

Timing of pesticide applications with respect to intense rainfall has a major influence on the amount of pesticide transported off-site or leached (Maas et al., 1984; Baker, 1987a; Baker et al., 1987; Sander et al., 1989; Gish et al., 1991; Sigua et al., 1993; Wagger et al., 1993; Hall and Mumma, 1994). As the time between pesticide application and intense rainfall increases, off-site movement of pesticide decreases. Some studies show that a small rainfall event prior to a larger rainfall event also decreases the amount of pesticide that moves off-site (Sigua et al., 1993).

Advanced technology in chemical application equipment allows for site-specific applications that improve efficiency and reduce the total amount of chemicals applied (Peterson et al., 1993; Searcy and Rudolph, 1994). By combining global positioning satellite (GPS) and geographical information system technologies, specific chemical needs for small areas can be assessed and delivered quickly and accurately as opposed to uniform field applications of chemicals (He et al., 1992). Hanso et al. (1994) demonstrated the effectiveness of mapping wild oats infestations with digital imagery for site-specific applications of herbicide. Peterson et al. (1989) used GPS-GIS technology for yield mapping of winter wheat that improved crop production efficiency. Reduced runoff and leaching losses of agrichemicals have been attributed to adoption of site-specific farming techniques (Mulla et al., 1992).

Integrated Pest Management (IPM) BMPs

12) **Plant pest-resistant cultivars if available.** Many plant diseases can be avoided by growing tolerant or resistant cultivars. For example, wheat cultivars with improved resistance to some leaf diseases are available in North Dakota. The need for fungicide applications is reduced on these cultivars.

13) **Maintain competitive plant growth through the regular use of good agronomic practices.** Some of the more important practices include: planting into a soil environment conducive to germination and seedling growth, good planting technique, using high quality seed, seeding at optimum rates; timing planting and harvesting for optimum conditions, and maintaining soil fertility based on regular soil testing.

14) **Use crop rotation to break pest life-cycles.** Take-all, tan spot, Septoria, common root rot, Hessian fly, certain wireworms, wheat stem sawfly, and wheat stem maggots are all problems common to wheat that are best controlled through crop rotation.

15) **Control volunteer plants that can serve as hosts for certain diseases and insects.** For example, volunteer small grain should be destroyed two to three weeks before planting the new wheat crop. Volunteer small grain that hosts disease or insects has the greatest potential to affect the new crop within a distance of 1 mile.

16) **Use tillage to control pests where appropriate.** The effects of tillage on soil erosion and surface water quality should be considered when making the decision to use this management practice for pest control.

17) **Use biological control of pests when available and when effectiveness has been demonstrated.** This option is more likely to be viable on rangeland as opposed to cropland. For example, picloram usage is of particular concern on sandy soils with shallow water tables due to its high mobility and persistence. On rangeland, leafy spurge can be controlled with goats or sheep in some areas. However, the most promising biological control agents are several species of flea beetles.

18) **Use preemptive techniques for pest management.** Pest control should not be limited to only responsive methods. Preemptive management measures are implemented in advance of the actual observation of pests. This type of management may be the most effective means of dealing with certain pest problems. Responsive management options can be quite limited if pests are allowed to reach outbreak levels. By implementing management strategies that maintain pests below threshold levels, the use of expensive or less effective methods of pest control can be avoided. Where available, pest-crop models should be utilized to accurately predict pest problems and help guide management decisions. Pest-crop models are of greatest value when accurate and continuous weather observations are available. The North Dakota Agricultural Weather Network (NDAWN) at NDSU provides continuous weather information from over 30 locations across North Dakota.

19) **Optimize timing of pesticide applications according to pest life cycles and economic thresholds of damage.** This can only be accomplished by regular scouting of fields to assess pest levels and crop damage.

20) **Rotate pesticides to prevent development of pest resistance.** Chemical compounds with different modes of action should be selected or rotated for use on the target pest.

Integrated Pest Management (IPM) BMPs Summarized

Integrated pest management (IPM) combines various management strategies to deal with pest problems. Advocates of IPM recognize that reliance on any single form of pest management does not provide optimal results. Adoption of multiple pest management methods and judicious use of pesticides often results in overall reduction in the total amount of pesticide applied.
In some cases, increased pesticide applications may be attributed to increased awareness of pest problems identified through IPM monitoring and scouting techniques. In these cases, IPM methods benefit groundwater protection through improved timing, efficiency, and appropriateness of the pesticide applications. Detailed discussion of BMP implementation for integrated pest management is found in the references listed in Appendix C. Each reference title includes the source of information and the related BMP numbers.

Technical Notes:
Integrated Pest Management (IPM)

It is generally recognized that integration of cultural, mechanical, biological, ecological, and chemical methods is required for optimal pest control (Schweizer, 1988). In many cases adopting other pest control options may result in pesticide use reductions, especially if pesticides have been the only method of pest control.

Scouting and monitoring of pests are vital tools to a successful IPM program, because pest control is highly site-specific (Maas et al., 1984). A survey of North Dakota farmers showed 69 percent monitored their fields (Zollinger et al., 1993). Pesticide usage is lower on small grains compared to row crops due to economic constraints. The mainstay for pest management in small grains continues to be cultural practices and plant resistance (Peters, 1970). The most popular non-pesticide IPM practices in North Dakota are planting clean seed, crop rotation, and summer fallow (McMullen and Dexter, 1985; Zollinger et al., 1993).

Biological control of pests is expected to have less success on cropland as compared to forest land or orchards (Peters, 1970). Biological control is the least used IPM option on cropland (McMullen and Dexter, 1985; Schweizer, 1988; Zollinger et al., 1993); however, it has increasing potential on rangeland for the control of leafy spurge (Bovey, 1987). Although pesticides such as dicamba and glyphosate have been used to control leafy spurge, the most effective pesticide is highly mobile and persistent picloram (Messersmith and Lym, 1990). The grazing of sheep and goats has only limited potential to control leafy spurge. European and Asian flea beetles have potential to be a major part of leafy spurge control in the future. Lym and Zollinger (1995) have recommended a strategy of combining all the methods available for the most effective control of leafy spurge. Reductions in pesticide use via IPM are assumed to significantly reduce the potential for water resource contamination. The accuracy of this assumption has rarely been evaluated in the field (Maas et al., 1984). Even the assumption of pesticide-use reductions through the application of IPM does not always hold true (Baldwin and Santelmann, 1980). Greater awareness of pests through an IPM scouting program may result in increased use of pesticides (McMullen and Dexter, 1985). However, when compared to soil and water conservation practices (SWCP) Maas et al. (1984) considered IPM practices to have greater potential in reducing pesticide impacts to water resources.

Soil and Water Conservation BMPs

21) **Utilize animal wastes, if available, as a source of organic matter and as a portion of nutrient inputs.** When added to the soil, animal wastes are a source of organic matter. The nutrient content of the animal waste must be properly credited according to standard methods, and applications should be made according to fertilizer recommendations based on a reasonable yield goal and soil testing results. Animal wastes are a potential source of nutrient pollution to groundwater and surface water. This must be taken into consideration when utilizing animal waste applications to reduce potential pesticide contamination to groundwater.

22) **Rotate low residue crops with green manure or with high residue crops that return larger portions of organic material to the soil.** This practice will help to offset organic matter losses that occur during periods of inadequate protection from erosion.

23) **Utilize reduced tillage methods wherever possible.** Reduced tillage practices help to maintain or improve soil organic matter content through improved protection from erosion and decreased mineralization of organic matter.

24) **Use tillage to disrupt macropores if preferential movement of pesticides is a source of groundwater problems.** Although reduced tillage is beneficial with respect to soil erosion and the maintenance of organic matter, it may promote movement of pesticides through soil macropores. In cases where preferential flow is demonstrated as a major factor in water movement, the practice of no-till or zero-till should be modified to include some method of surface disruption. Research results indicate that tillage disrupts macropore connections with the surface and often significantly reduces preferential flow (Refer to Appendices A and B). Excessive tillage to reduce preferential flow, however, would be an overreaction that would probably result in greater soil erosion.

25) **Use soil conservation practices that reduce the force of the wind.** In addition to reduced tillage, other practices include a combination of field wind barriers and strip cropping. Wind erosion is most likely to be a problem on soils included in the high sensitivity groundwater category due to their coarse texture and long, flat slopes.

26) **Use soil conservation practices that reduce the force of runoff water.** In addition to reduced tillage other practices are a combination of grassed waterways and farming on the contour. Water erosion is not likely to be a critical problem on the soils included in the high sensitivity groundwater category due to their coarse texture and relatively low relief.

Soil and Water Conservation BMPs Summarized

The maintenance of soil organic matter through soil conservation practices plays an important role in providing a healthy environment for crop growth. Soil organic matter influences soil nutrient levels and physical conditions that control the exchange of water and gasses between plant and soil. Healthy plants are less likely to develop pest problems, reducing the need for pesticide applications. Soil organic matter also is the primary substance that adsorbs or attenuates the movement of pesticides through the soil profile.

As organic matter decreases so does the soil's ability to adsorb pesticides that move through it. Organic matter also plays an important role in the maintenance of stable soil structure which affects soil permeability and water infiltration. Increased water infiltration may result in greater potential for pesticide leaching and groundwater contamination.

Management of organic matter is important to groundwater protection but is also extremely challenging due to the opposing effects on pesticide movement. **The balance between increased adsorption and infiltration will have to be weighed for each management recommendation under many different environments.**

Soils in the high sensitivity groundwater category characteristically have high infiltration rates, because they are coarse textured. Increasing the organic matter percentage in these soils is not likely to result in significant changes in water infiltration. There does appear to be an advantage to increasing the adsorptive capacity of these soils by increasing the organic matter content.

This can be accomplished by adding organic materials and by protecting the soil organic matter through reduced tillage and soil conservation practices.

Low organic matter content for many of the soils in the high sensitivity groundwater category is due to the droughty nature of coarse textured materials. An additional reason for low organic matter content may be from losses due to a combination of higher mineralization rates under tillage and high soil erosion rates.

Irrigation BMPs

27) **Schedule irrigations appropriately by accounting for the soil moisture and crop water use.** Regular measurement of soil moisture is an accurate way of determining when to irrigate. An indirect method used to estimate soil-water balance, commonly called the "checkbook method," is based on knowledge of the soil moisture holding capacity, daily crop water use, and daily rainfall measurements. Soil water content determined using the checkbook method should be verified occasionally with field measurements. It is critical that the determination of the water budget is done systematically and accurately so that applications of water meet the needs of the crop, without over application.

28) **Time water applications to avoid water movement beyond the rooting zone.** Weather patterns should be assessed prior to each irrigation. Irrigation should not fill the soil to field capacity. Deficit irrigation techniques that leave room in the rooting zone for additional moisture from rainfall have been demonstrated to protect groundwater without yield reductions. The soil profile should never be used to store irrigation water through the winter. To the contrary, irrigation water should be managed so that stored soil water is at a minimum in the fall.

29) **Adjust water application amounts to meet varying crop demands at different growth stages.** Irrigation has the potential to meet these variable demands more readily than dryland agriculture, thus maintaining a stable environment for plant growth. Large amounts of unused residual chemicals left in the soil are not likely to occur if management results in vigorous plant growth throughout the year. The potential for chemical leaching and groundwater contamination is diminished.

30) **Irrigation water must be applied uniformly and accurately.** A functional flow meter and accurate pressure gauge, either at the pump or on the pipeline near the point of discharge, is essential for accurate application of irrigation water and chemicals.

31) **When chemicals are injected into an irrigation system, chemigation equipment which protects the water supply must be used.** State regulations regarding the proper chemigation equipment required to protect the water source from back-siphonage must be followed. In addition, the pesticide used for chemigation **must** have the crop and irrigation system specified on its label. Chemigation can provide excellent control of pesticide application timing and coverage which can result in an overall reduction in the total amount of applied pesticides.

32) **The chemigation unit must be calibrated with each use to ensure accurate application of chemicals.** An accurate way of measuring the amount of chemical being injected into the irrigation system is essential to good irrigation management. Accurate measurement of the amount of applied chemical not only optimizes chemical usage but also ensures a uniform application over the entire irrigated field.

33) **Provide secondary containment where pesticides are stored near the irrigation well when chemigation is practiced.** Secondary containment made of impermeable material reduces the risk of contamination in the case of a leak or spill.

Irrigation BMPs Summarized

Irrigated acreages are most likely to be included in the high sensitivity category. The management practices recommended for groundwater protection on dryland acreages also apply to irrigated fields. However, irrigation presents management opportunities and needs that are unique and require additional management recommendations with respect to crop production and groundwater protection. Detailed discussion of BMP implementation for irrigation is found in the references listed in Appendix C. Each reference title includes the source of information and the related BMP numbers.

Technical Notes: *Irrigation Management and Pesticides*

In some areas irrigation has been demonstrated to have greater potential for groundwater contamination compared to dryland agriculture. Irrigation may increase the potential for groundwater contamination for several reasons. If not managed correctly, over-application of water can result in substantial leaching through the root zone. Prevention of leaching and maintenance of adequate soil moisture levels requires a high level of management, particularly with shallow rooted crops on soils with low water-holding capacities (coarse textures).

Greater inputs of nutrients are generally required for irrigated crops to meet their yield potential. Irrigation improves the opportunity for crops to meet their genetic yield potential compared to dryland farming. Montgomery et al. (1988) found that three times as much nitrogen was applied over the Oakes aquifer on irrigated fields compared to dryland fields and approximately three times as much nitrate was found in the tile drainage beneath the irrigated fields compared to the dryland fields.

Irrigation management studies in North Dakota and other states demonstrate that managed inputs reduce the potential for groundwater contamination. Several studies indicate that water and nitrogen inputs can be reduced compared to conventional irrigation management without impact on yields (Montgomery et al., 1990; Ayars and Phene, 1993; Watts et al., 1993a; Derby et al., 1994; Knighton and Albus, 1992). The timing of water and nutrient inputs has been shown to be critical with respect to both yields and contaminant movement (Montgomery et al., 1990; Eisenhauer et al., 1993; Martin et al., 1993; Watts et al., 1993a,b).

The amount of pesticide applied to control pests for a given crop is probably very similar for both dryland and irrigated farming. However, on coarse-textured soils, irrigated management often allows higher value crops that require greater pest control to be included in the rotation. Aldicarb contamination of groundwater in New York and Wisconsin was related to its use on irrigated potatoes (Ritter, 1990). Pesticides in groundwater have been observed to be much less responsive to different irrigation management schemes, because they are detected so rarely compared to nitrates (Montgomery et al., 1988; Kolberg et al., 1989).

Theoretically, small quantities of several pesticides could leach to shallow groundwater under irrigated management in North Dakota (Knighton, 1990). Phorate and aldicarb were predicted as the most likely to leach. Predicted as least likely to leach were 2,4-D, EPTC, and propachlor.

Another potential source of groundwater contamination under irrigated management is backflow or spillage due to the practice of chemigation. A national survey of irrigators indicated that chemigation was used on 42 percent, 62 percent, and 3 percent of sprinkler, trickle, and furrow irrigated acreages, respectively (Lundstrom, 1988). Eighty percent of the chemigation was for application of fertilizers. Irrigators who chemigate in North Dakota must comply with state and federal regulations that require installation of a functional check-valve in the water-line, a low pressure sensor, an inspection port, a low-pressure drain, an interlock between the water pump and chemical pump, a proper chemical injection pump, and a pressure operated check-valve in the chemical-injection-line.

Field BMPs for High-Intermediate Sensitivity Areas

The high-intermediate sensitivity category includes a broader range of situations than the high sensitivity category. There are many combinations of factors that fit this category, and they cannot be expected to be treated in the same way. The assessment process helps determine which factor or factors are most likely to increase the potential for pesticide contamination.

The strategy for BMP selection is to determine the most likely cause of pesticide contamination of groundwater in a given area and then bring to bear the best management practices that deal specifically with the cause. In the case of the high sensitivity category, there were many potential causes resulting in many recommendations for a single sensitivity category. For the high-intermediate category the same BMP recommendations are applicable; however, they can be directed to the various subcategories.

Each subcategory of the high-intermediate sensitivity category is determined by a factor or factors that increase the potential for pesticide contamination compared to other areas. For example, an area of coarse textured soils with organic matter contents greater than 2 percent that overlays an aquifer deeper than 50 feet where pesticides with intermediate leaching potential are used would be categorized as high-intermediate, due to the coarse textured soils with high permeability. If groundwater analyses in this area indicate a problem from field applications of pesticide, field BMPs should focus on the texture factor. If irrigated, the BMPs discussed in the section above are also appropriate to areas categorized as high-intermediate.

Field BMPs for Low-Intermediate Sensitivity Areas

Areas categorized as low-intermediate sensitivity do not have obvious factors on which to focus field BMPs. Unless groundwater monitoring data indicate otherwise, pesticide contamination of groundwater of these areas is most likely from farmstead activities around the well. Farmstead BMPs should receive most if not all of the emphasis in these areas. If pesticides in groundwater are directly linked to field applications in a low-intermediate area, field BMPs should be recommended based on the factor or factors that are least likely to contribute to pesticide attenuation. Also, in irrigated areas or areas where preferential flow may be an important factor, the BMPs recommended for these situations are applicable.

Field BMPs for Low Sensitivity Areas

As stated in the groundwater assessment document, the assessment categories group areas according to the potential or probability of groundwater contamination. There is no guarantee that contamination will or will not occur in any specific area. Just because an area is categorized as low sensitivity does not mean contamination from field applications will never happen. It does mean that it is less likely to happen compared to the other categories.

In areas of low sensitivity, farmstead sources of groundwater contamination are the most probable compared to field sources. Farmstead BMPs should receive most emphasis. If monitoring data indicate that field activities cause groundwater contamination in an area of low sensitivity, field BMPs should be based on the factors that are least likely to attenuate pesticides.

BMPs for Land Outside of Groundwater Sensitivity Areas

Part of the groundwater assessment process is to separate locations that overlay valuable aquifers from those that don't. This is an essential step to delivering effective management to those areas that have the highest priority needs. As this process of deliberate segregation is implemented, large areas of the state will lay outside of the groundwater sensitivity areas. It is recognized that groundwater contamination may occur in aquifers that cannot be discretely delineated in the county groundwater study reports. Many private water supplies occur in these types of materials, and it is not the intent of either the assessment or BMP selection procedure to ignore these situations. Despite the difficulties faced when attempting to make recommendations regarding undelineated aquifers, there are a few suggestions that may be useful. The intermittent or extremely deep nature of these aquifers reduce the potential for contamination by field application of pesticides. Programs and plans designed to protect these groundwater resources should be focused on farmstead BMPs.

In those instances where field applications are suspected as contributing to groundwater pesticide contamination in undelineated aquifers, the assessment process should proceed as recommended in NDSU Extension Bulletin EB-63, "An Assessment System for Potential Groundwater Contamination from Agricultural Pesticide Use in North Dakota." However, information about the hydrology and geological materials may be quite difficult to find. A few educated assumptions will have to be made before the site can be placed into one of the four sensitivity categories. Subsequently, field BMPs can be selected and modified based on the BMPs selected by the appropriate regional selection committee.

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Appendix A: Mechanics of Groundwater Contamination

Water Potential and Movement, Hydrology

Water moves continuously through a hydrologic cycle (Freeze and Cherry, 1979; Heath, 1984). The hydrologic cycle is analogous to an engine that receives a constant supply of solar energy which drives water through a continuous loop of different phases (solid, liquid, and vapor) at different rates. It follows that differences in the energy status or potential of water molecules control the form and movement of water.

Water potential may be expressed as the following: 1) energy per unit mass (joules per kilogram); 2) energy per unit volume (joules per meter^3, bars, or atmospheres); or 3) energy per unit weight (joules per newton).

The third expression of water potential can be simplified, because a joule is equal to a newton meter; therefore newtons can be canceled out, leaving only the unit of length (meter), which is referred to as hydraulic head or the potential of an equivalent column of water. Because of its convenience, hydraulic head is often used to express soil water potential. Water of high energy or potential moves to areas of lower energy or potential (Hillel, 1980). Total water potential is the sum of pressure, gravitational, osmotic, and pneumatic potentials.

Hydrology is the study of liquid water movement either within the earth or on its surface. The discipline of hydrology is divided into two distinct areas, groundwater and surface water. The difference between these two sub-disciplines can be very distinct; however, the common origin of all waters and many connections throughout the hydrologic cycle require knowledge of both and their interface.

Infiltration and Water Movement

Water infiltration into the soil is the initial process that influences both surface water and groundwater. When wetted, every soil surface reaches a rate of water absorption which cannot be exceeded. This limit is defined as the infiltration capacity (Satterlund, 1972). When the rate of applied water (rainfall or irrigation) exceeds the infiltration capacity, surface runoff occurs. Important soil factors that affect infiltration capacity include texture, structure, colloids, moisture content, frost, and organic matter content. Landuse and vegetation exert substantial effects on infiltration indirectly through their influence on soil properties. Soil variability and local precipitation patterns control surface water hydrology and groundwater recharge.

The flow of water through a saturated soil matrix is often described as adhering to Darcy's Law of flow (Hillel, 1980). Darcy's Law predicts the average transport of water through a saturated material. Darcy's Law can be expressed by the simple equation $q = K \Delta H/L$, where q = the volume of water flowing through a unit cross-sectional area per unit time; K = saturated hydraulic conductivity; ΔH = change in hydraulic head (potential); L = distance between the hydraulic head change. Darcy's Law assumes that the conditions of laminar flow prevail and average potential gradient accurately represent the energy state of water throughout the soil. These assumptions are valid for most saturated soils and predictions of mass movement of water are accurate (Hillel, 1980).

Over the years, soil physicists have extended Darcy's Law so that unsaturated flow of water and solutes can be more accurately predicted. These extensions recognize that soils are typically unsaturated and heterogenous. The principles of Darcy's Law can be adapted to unsaturated flow of water, but K is no longer aconstant. The unsaturated hydraulic conductivity (k) is a function of the soil moisture content and decreases exponentially as the pressure potential declines at lower soil moisture contents (Hillel, 1980). The practical implication of this relationship is that saturated flow of water, through an aquifer for instance, can be orders of magnitude greater than flow through the overlying unsaturated materials.

The Vadose Zone

A zone usually exists between the soil and groundwater surfaces. This zone is often referred to as the vadose zone (Driscoll, 1987). The groundwater surface is referred to as the water table (Figure 1A). The water table describes a subsurface where all pores below it are filled with water (saturated) and the pressure potential of the water along that surface is equal to the atmospheric

Figure 2A

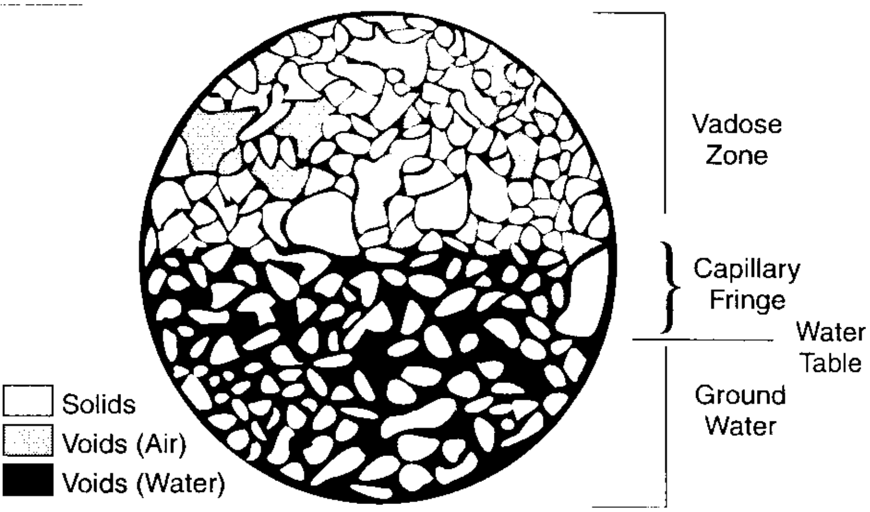

Figure 1A. Schematic representation of air and water filled voids near the water table.

pressure or a gauge pressure of zero (Thomas, 1955; Freeze and Cherry, 1979). Above the water table, in the vadose zone, the pores are not fully saturated with water and the pressure potential is negative.

The vadose zone may vary in thickness from a few inches to many feet in both space and time. The lower portion of the vadose zone is the capillary fringe where all voids are filled with water but under a slight negative pressure potential. The capillary fringe thickness varies with texture and is greatest in fine grained materials.

Water movement through the vadose zone generally occurs under unsaturated conditions (Freeze and Cherry, 1979). **The vadose zone is a dynamic zone of water flow that plays a significant role in determining the fate of pesticides and quality of groundwater.** Water movement from the surface downward into the vadose zone is defined as infiltration. Some water that infiltrates into the vadose zone may reach the water table and is defined as groundwater recharge.

Evapotranspiration at the soil surface lowers the water potential and causes water at greater depths with higher potential to move upward through the vadose zone (Thomas, 1955). If the water table is close enough to the soil surface, usually within 6 feet, groundwater will discharge through the vadose zone often resulting in saline soils (U.S. Salinity Laboratory Staff, 1954; Szabolcs, 1965).

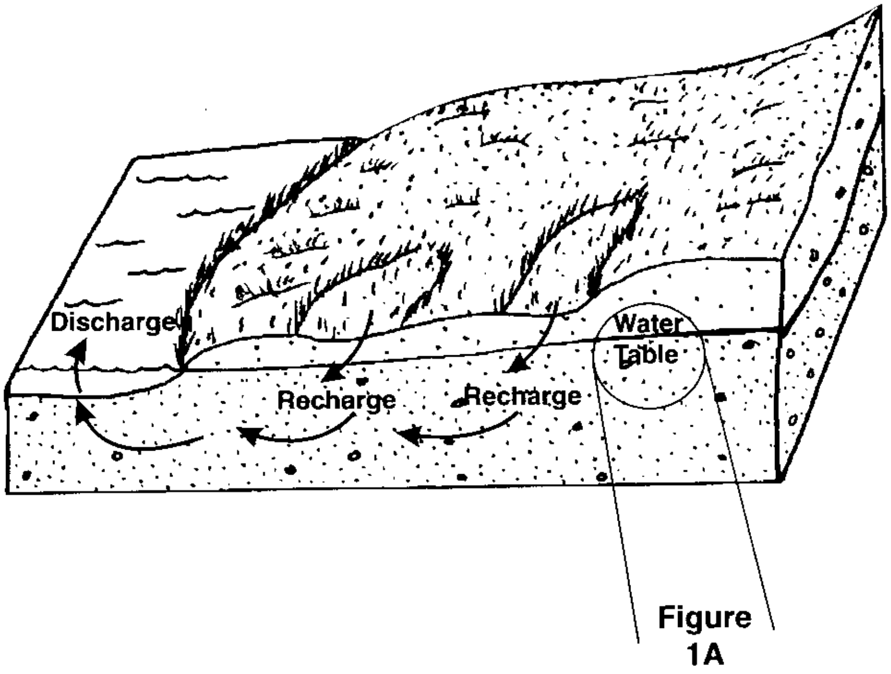

Figure 2A. Groundwater recharge and discharge on a typical North Dakota landscape.

Groundwater Recharge and Discharge

Groundwater recharge is defined as water entry into the saturated zone at the water table. Groundwater discharge, the opposite of recharge, is defined as removal of water from the saturated zone at the water table (Freeze and Cherry, 1979). The counterpart to recharge and discharge in the saturated zone is infiltration and evapotranspiration in the unsaturated zone, respectively.

Freeze and Cherry (1979) recognized that not all geographic areas are equal with respect to groundwater recharge and discharge. Landscape positions that consistently contribute water to the groundwater are defined as groundwater recharge areas and those that consistently lose water are defined as discharge areas (Figure 2A). Site factors that determine the location of groundwater recharge are soil texture, surface cover, topographic position, and local climate (Satterlund, 1972). Isotopic analysis of a North Dakota aquifer revealed that most groundwater recharge occurred rapidly during intense events and had a component of preferential flow (Komor and Emerson, 1994).

Groundwater recharge in the northern Great Plains is often described as depression focused (Lissey, 1971; Knuteson et al.,1989). Low annual precipitation coupled with high potential evapotranspiration allow only limited groundwater recharge from large portions of the landscape.

Depressional topographic positions that accumulate runoff water (focused) are most likely to receive enough water in excess of evapotranspiration to allow movement beyond the rooting zone to the groundwater. These areas may be extremely small and difficult to identify (Seelig et al., 1991; Schuh et al., 1993).

Recharge areas may be controlled by micro-topographic lows (Schuh et al., 1993) or stratigraphy (Seelig and Richardson, 1994), and can be identified by detailed observation of soils. Soil survey information is an integral component of most groundwater vulnerability assessment systems (Volk, 1990; Cates and Madison, 1991; Luther, 1992; Seelig, 1994). Quisenberry et al. (1993) and Flury et al. (1994) have proposed that soil morphologic information will be the key to identifying areas prone to preferential flow.

Pesticide Movement to Groundwater

Convective transport of substances dissolved in water (solutes) is related to the mass flow of water through soils as described by Darcy's Law (Hillel, 1980). The flux of solutes carried convectively with water is also related to other processes. **Solutes interact chemically and physically with both the soil matrix and solution as water moves through the pores (Hillel, 1980). Factors that affect these interactions are pH, temperature, oxidation-reduction potential, composition of the soil matrix, and concentration of the solutes.**

Pesticide concentrations in soil water are affected by many interactions of which adsorption, volatilization, and microbial degradation are considered most important (Cheng, 1990).

Different theories and equations have been developed that predict pesticide adsorption as it passes through the soil matrix. For example, King and McCarty (1968) demonstrated that the movement of several organic phosphorus insecticides could be predicted using the concepts of the chromatographic movement theory. The Langmuir and Freundlich equations have also been used by many investigators to model pesticide movement (Bohn et al., 1985).

Some specific properties of pesticides that determine their mobility in the environment are water solubility, vapor pressure, and polarity (Cheng, 1990). Although solubility has been recognized as an important pesticide property, Wauchope et al. (1992) demonstrated that two pesticide properties, the organic carbon adsorption coefficient (K_{oc}) and pesticide half-life ($T_{1/2}$), can be used to compare different pesticides' potential to leach through the soil matrix. In two different systems, pesticides have been ranked according to their potential to leach based on Wauhcope et al. (1992) observations (Goss, 1992; Hornsby, 1992). Most studies indicate that the large mass of water and solute flow can be accounted for as matrix flow and can be predicted using Darcian assumptions and pesticide retention relationships (Singh and Kanwar, 1993; Springer et al., 1993; Ward et al., 1993; Czapar et al., 1994).

Some simulation models based on Darcian flow have been successful in predicting the movement of the major portion of applied pesticide (Sauer et al., 1990; Ma et al., 1993; Singh and Kanwar, 1993; Krzyszowska et al., 1994). Knighton (1990) used the process-based Leaching Estimation and Chemistry Model (LEACHM) to predict pesticide movement in a sandy soil under irrigation in North Dakota. **The results of this simulation indicated that from 0 to 2.5 percent of the applied pesticide may be expected to leach through the soil profile to shallow groundwater (less than 10 feet).** The lack of pesticide detections in the groundwater is in general agreement with the model predictions (Knighton and Albus, 1993).

Two main problems arise from simulation of pesticide movement. Natural variability of soil and geologic materials makes accurate determination of the pesticide fate cost prohibitive (Staver and Brinsfield, 1991). Accounting for pesticides that move preferentially through soil macropores has not been accomplished (Wagenet, 1987; Pickus, 1993; Wu et al., 1993).

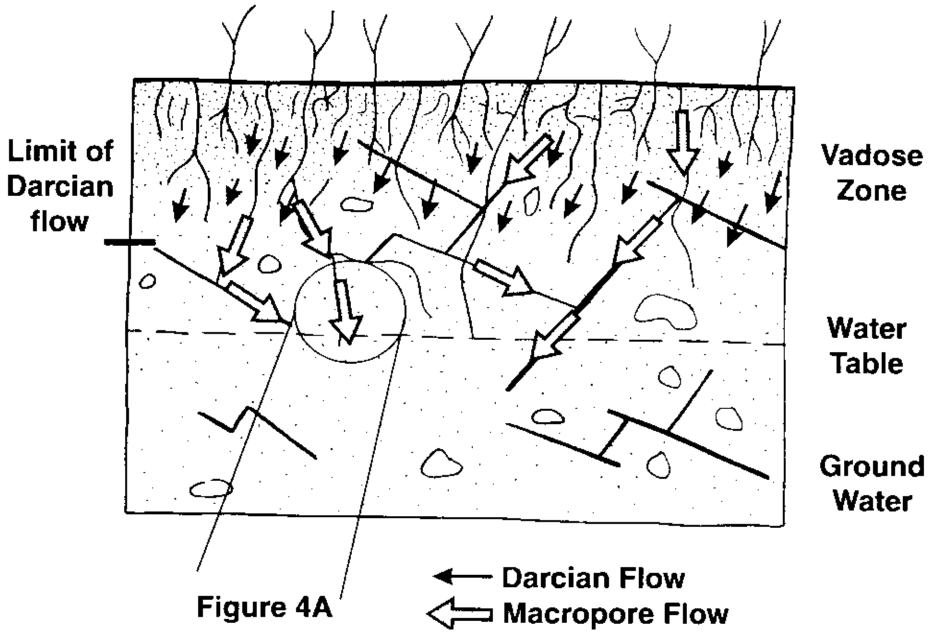

Figure 3A. A schematic diagram of Darcian flow compared to preferential.

Pesticides and Preferential Flow Through Soil Macropores

Research has demonstrated that under some circumstances flow of water and pesticides through soil macropores can cause pesticides and water to quickly percolate to greater depths than predicted by Darcy's Law (Figure 3A) (Beven and Germann, 1982; Edwards et al., 1988; Bischoff et al., 1990; Gish et al., 1991; Shipitalo et al., 1990; Delin and Landon, 1993; Kanwar et al., 1993; Tindall and Vencill, 1993). High-velocity flow through macropores may cause large differences in hydraulic gradients within a few centimeters that cannot be adequately represented by an average figure, a required assumption for Darcy's Law (Beven and Germann, 1982). Further, high-velocity flow may result in turbulence, a violation of the laminar flow assumption required by Darcy's Law (Hillel, 1980).

Figure 3A

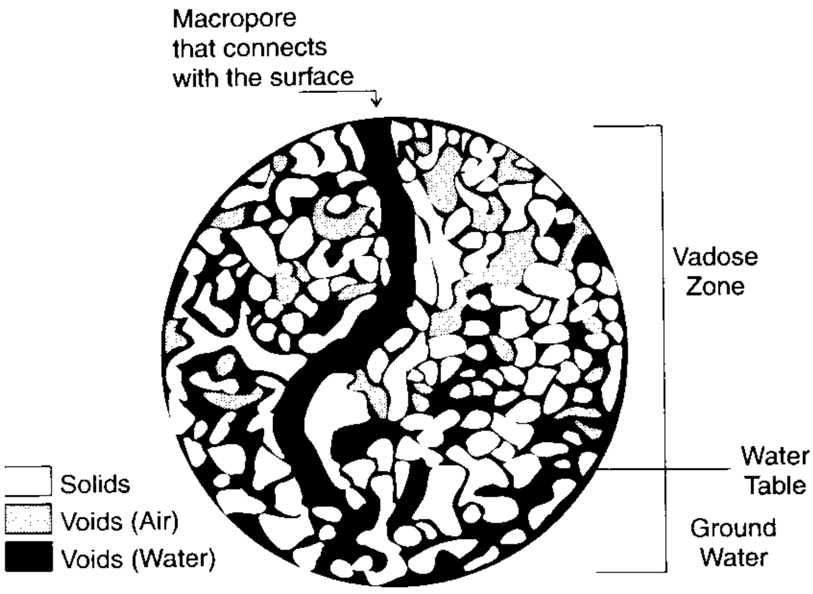

Figure 4A. A schematic diagram of preferential flow through a macropore.

Water flow through macropores that circumvents large portions of the soil matrix is often defined as preferential flow (Figure 4A). In one field study, less than 1 percent of the total soil volume was involved in the transport process due to preferential flow (Gish et al., 1991). Francis et al. (1988) found that preferential flow accounted for 7 to 13 percent of the volumetric soil moisture depending on soil treatment. Schuh and Klinkebiel (1994) observed preferential flow during spring recharge in North Dakota, but the bulk movement of water and bromide tracer occurred as flow through the smaller pores in the matrix.

Beven and Germann (1982) concluded that macropores are probably best defined according to their function rather than absolute size (Table 1A) or type (Table 2A) . Macropores conduct water that does not readily exchange with water in the smaller pores of the soil matrix (Skopp, 1981). Several types of preferential flow paths were identified at four sites investigated in North Dakota (Goebel et al., 1994).

Table 1A. Macropore dimensions recognized in different studies.

Diameter	Investigator(s)
>1000 μ	German et al., 1991
> 400 μ	Edwards et al., 1988
> 30 μ	Francis et al., 1988

Sudden presence of a pesticide in groundwater shortly after application and often accompanied by rapid disappearance is characteristic of preferential flow (Kanwar et al., 1993; Gish et al., 1991). Tindall and Vencill (1993) found high concentrations of atrazine at depths of 60 to 135 cm one month after application. Olson and Kanwar (1993) observed water movement to a depth of 180 cm within three hours of a simulated rainfall of 12.7 cm. Foran et al. (1993) noted impact to tile line water 6 to 20 hours after manure applications at eight of 12 sites. Czapar et al. (1994) found that peak concentrations of applied chemicals occurred in tile water 130 minutes after the onset of a simulated rain of 5.3 cm. Gish et al. (1991) observed from 2 to 9 percent of applied triazines in the groundwater immediately after a 48-hour rainfall of 4.8 cm. About 0.047 percent of the total tracer (fluorescent dye) applied was observed to have moved to a depth of 6 ft within three hours after the application of 3 in of irrigation water in a South Dakota soil (German et al., 1991). Rapid movement of water and a bromide tracer was observed shortly after spring runoff in North Dakota (Schuh and Klinkebiel, 1994).

The extent of preferential flow through macropores is influenced by a combination of factors (Ghodrati and Jury, 1992). Determination of a predictable pattern of preferential flow is difficult because of the variety of factors that influence it. Several studies indicate that macropore flow

Table 2A. Observations of preferential flow paths in different studies.

Macropore Type	Investigator(s)
Seasonal cracks or fissures	Baer et al., 1993 Tindall and Vencill, 1993
Permanent fractures	McKay et al., 1993 Pachepsky et al., 1993 Timlin et al., 1993
Interpedal voids	Bicki and Guo, 1989 Quisenberry et al., 1993 Flury et al., 1994
Intergranualr voids in sandy soils	Selker et al., 1989 Ghodrati and Jury,1992
Worm channels	Steenhuis et al., 1990 Stehouwer et al., 1994
Relict plant root channels	Edwards et al., 1988 Bicki and Guo, 1989
Compound packing voids from tillage	Francis et al., 1988

is most likely to occur during and shortly after intense rainfall (Edwards et al., 1988; German et al., 1991; Sigua et al., 1993). Beven and Germann (1982) suggest that rainfall intensities in the range of 1 to 10 mm per hour may be sufficient to initiate macropore flow, depending on the prior precipitation.

Amounts of pesticides moved during these events increases as the amount of time between application and onset of the rainfall event decreases (Gish et al., 1991; Lowery et al., 1993; Sigua et al., 1993; Hall and Mumma, 1994). It has been observed that a minor rainfall event, that allows water to distribute evenly among the pores in the soil matrix, substantially reduces pesticide movement during a subsequent major rainfall event (Shipitalo et al., 1990; Sigua et al., 1993).

Some studies have measured increased amounts of preferential flow with increased antecedent soil moisture (Francis et al., 1988; Bischoff et al., 1990; Flury et al., 1994), but **other studies show that preferential flow is more likely to occur under dry soil conditions** (Shipitalo et al., 1990). Andreini and Steenhuis (1988) noted that preferential flow paths were highly variable with respect to location and time. Selker et al. (1989) found similar inconsistent patterns of preferential flow with respect to time in a sandy soil. Shipitalo et al. (1990) observed that macropore flow consistently occurred from the same area, but did not correlate well with measurements of density or size of macropores. They also found the area contributing to macropore flow to increase as flow continued over time; however, the overall importance of preferential flow to total flow decreased with time. Ghodrati and Jury (1992) noted that preferential flow occurred in some plots but did not occur in others even though the soils and management were similar.

Some of the variation in preferential flow may be explained by the type of soil (Beven and Germann, 1982). Preferential flow of pesticide may occur through sandy soils under irrigated management (Ghodrati and Jury, 1992; Knighton and Albus, 1993).

Different soils in the same field have been observed to exhibit substantially different amounts of preferential flow. Soils on the lower topographic positions were observed to have greater potential for preferential flow compared to soils on higher landscape positions in Missouri (Baer et al., 1993; Delin and Landon, 1993). Schuh and Klinkebiel (1994) made a similar observation in North Dakota.

Soils characterized as "highly structured" have also been identified as locations of preferential flow (Flury et al.,1994). Quisenberry et al. (1993) proposed that potential for preferential flow can be systematically determined by relating it to soil type.

The properties of the contaminants themselves also have an impact on their translocation through preferential flow. The movement of halide tracers and nitrate due to preferential flow has been found to be greater than pesticides and organic dyes in some studies (Andreini and Steenhuis, 1988; Czapar et al., 1994). Differences in preferential movement of different pesticides also have been noted (Gish et al., 1991; Ghodrati and Jury, 1992; Czapar et al., 1994; Stehouwer et al., 1994). These differences were related to the pesticide adsorption coefficient (Ghodrati and Jury, 1992; Stehouwer et al., 1994). Twenty-five to 87 percent of the pesticide in solution was eventually adsorbed to the lining material of earthworm burrows in one study (Stehouwer et al., 1994).

The form of the pesticide also has been found to affect pesticide movement through preferential pathways. Wettable powder and liquid formulations applied as broadcast spray to the soil surface were observed to move more readily with preferential flow than encapsulated formulations or pesticide that was incorporated into the soil (Gish et al., 1991). Ghodrati and Jury (1992) observed that pesticides in wettable powder formulations did not migrate below 30 cm in tilled fields.

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Appendix B: Management Effects on Pesticide Movement

Tillage

Soil tillage has a substantial effect on water and solute movement through its influence on water infiltration and subsequent flow through and over the soil (Mielke et al., 1986; Fausey et al., 1993; Hatfield et al., 1993a; Hatfield and Prueger, 1993). Conservation tillage is defined as any tillage and planting system that maintains at least 30 percent of the soil surface covered by residue after planting or maintains at least 1,000 pounds per acre of flat small grain residue equivalent on the surface during the critical erosion period (Mannering et al., 1987). Conventional tillage is defined as a combination of primary and secondary tillage that is normally used to prepare a seedbed for a given crop in a given geographical area.

It has been observed in many studies that conservation tillage practices, particularly no-till, increase water infiltration compared to conventional tillage (Edwards and Amerman, 1984; Dick et al., 1986; Mielke et al., 1986; Baker, 1987a; Donigian and Carsel, 1987; Edwards et al., 1988; Francis et al., 1988; Hatfield and Prueger, 1993; Hall and Mumma, 1994). These same studies show that increased infiltration decreased runoff and protected surface water quality but increased pesticide and nitrate leaching. In fact, many soil and water conservation practices (SWCP) probably have, at best, no effect on pesticide impacts to groundwater and in some cases negative effects (Hickman et al., 1994). In some areas, leached water is short circuited by tile drainage that outlets in surface streams, thus protecting groundwater at the expense of surface water (Baker, 1987b; Logan, 1987; Keim et al., 1989; Keeney and Deluca, 1993; Czapar et al., 1994).

Many investigators have attributed increased infiltration and leaching under no-till to preferential flow through macropores (Dick et al., 1986; Wagenet, 1987; Andreini and Steenhuis, 1988; Francis et al., 1988; Bischoff et al., 1990; Kanwar et al., 1993; Gish et al., 1991; Levanon et al., 1993; Hall and Mumma, 1994). During the first few years after changing management from conventional tillage to no-till, investigators have observed increased bulk density in the surface soil layer. This phenomenon has been attributed to greater macroporosity in freshly tilled soils compared to soils under no-till management (Voorhees and Lindstrom, 1983; Glotfelty, 1987; Francis et al.,1988; Rhoton et al., 1993; Addiscott and Dexter, 1994). Greater macropore continuity and stability and less tortuosity in no-till compared to conventional tillage are suggested in some cases as the reason for greater preferential flow (Edwards et al., 1988; Francis et al., 1988; Steenhuis et al., 1990).

Although there is general concurrence that conservation tillage reduces runoff and increases infiltration, results vary regarding the effects on groundwater contamination (Baker, 1987a; Berryhill et al., 1989). It was concluded from a modeling exercise comparing conservation tillage to conventional tillage in the Lake Erie Basin that reduced tillage will contribute to higher concentrations of pesticides in groundwater (Donigian and Carsel, 1987). However, Brinsfield et al. (1987) and Bischoff et al. (1990) found no significant difference in pesticide detections in groundwater beneath different tillage treatments. Magette et al. (1988) reported no difference in groundwater recharge between watersheds with different tillage. Levanon et al. (1993) found preferential flow of solutes to be substantial under both no-till and conventional tillage. Preferential flow through macropores could actually reduce groundwater contamination if the contaminants are located within the smaller pores of the soil matrix (Baker, 1987a).

Effects of tillage on soil environmental factors other than infiltration also influence pesticide fate. Pesticide degradation generally appears to be slightly faster in no-till compared to conventional till systems due to a more favorable environment for microorganisms (Glotfelty, 1987; Helling, 1987). Some studies show decreased potential for pesticide leaching in no-till due to the increased adsorption on greater amounts of organic matter (Wagger et al., 1993). When compared to conventional tillage, conservation tillage is most likely to reduce the movement of pesticides to surface water, if they are strongly bound to the soil or are highly soluble (Maas et al., 1984; Baker et al., 1987).

There may be greater volatilization losses of pesticides from no-till due to the lack of incorporation and higher soil moisture (Glotfelty, 1987; Prueger et al., 1993). Dao (1987) found that no-till compared to conventional till posed less risk to groundwater due to increased volatilization. However, Glotfelty (1987) suggested that conservation tillage may reduce volatilization losses due to lower soil temperatures.

Interception of applied pesticides by crop residues affects subsequent pesticide movement (Baker, 1987a). Release of adsorbed pesticide from crop residue to runoff water is thought to be one of the mechanisms that causes higher pesticide concentrations in runoff from fields where conservation tillage was practiced compared to conventionally tilled fields (Foy and Hiranpradit, 1989; Sander et al., 1989; Christensen et al., 1993; Wagger et al., 1993). Brown et al. (1985) noted that despite herbicide interception by plant residue on no-till wheat sites, the largest runoff losses of pesticides occurred from conventionally tilled sites.

Conservation Tillage and Pesticide Use

It has been estimated that conservation tillage would require an increase in use of herbicides from 10 to 60 percent (Wauchope, 1987). Increased rates theoretically could pose a greater risk to water resources. Fawcett (1987) concluded from several surveys that conservation tillage on corn will not result in much greater use of herbicides, but it may result in increased use on small grains. Johnson et al. (1989) observed no reduction in weed control by several pre-emergence pesticides applied to different tillage treatments despite distinct differences in amounts of pesticide adsorbed to corn residue. In North Dakota, expanded use of chisel plows has increased the infestation pressure of small-seeded annuals such as foxtail and kochia and increased the need for their control (Koskinen and McWhorter, 1989).

Fawcett (1987) suggested that potential for plant diseases will increase in fields where conservation tillage is used. However, the increased disease potential can be managed using treated seed, resistant varieties, and crop rotations rather than increased fungicide applications. Baker et al. (1987) and Logan (1987) concluded that conservation tillage generally will not result in substantial increased use of pesticides in the northern cornbelt.

Pesticide Use Reduction

Source Reductions

Logan (1990) suggested that source reductions of pesticides have been the most effective management option to protect water resources. Source reductions are related to regulatory activities external to producer decisions. The effectiveness of source control is illustrated by reduced levels of DDT and other chloro-organic pesticides after regulations required discontinuation of their use. Concentrations of DDT and lindane peaked in the Red River and its tributaries prior to their use restrictions in 1972 and the mid-80s, respectively, and have since declined significantly (Tornes and Brigham, 1994). Some source reductions in pesticides such as the "atrazine rule" in Wisconsin have successfully reduced pesticide use with little effect on farm economics (Wolf et al., 1993). Decreased frequency of aldicarb detections in groundwater followed use-restrictions on potatoes in New York (Ritter, 1990).

Banning pesticide or restricting pesticide use has far reaching consequences. In 1980 it was estimated that elimination of herbicides would reduce annual farm revenues by 31 percent and result in economic losses of $13 billion (Abernathy, 1980). In addition, there would be significant costs to society arising from the environmental impact from the 46 percent increase in acreage that would be required to make up for the loss in production. Kopp (1994) documents the fact that benefits of pesticide use do not reside only in the agricultural sector. Society as a whole receives major benefits from pesticide use through improved nutrition, living conditions, and disease control.

Site Reductions

Voluntary methods that reduce site application of pesticides have been promoted by a variety of state and federal organizations (Maas et al., 1984; Management Work Group, 1989; Swader, 1993; U.S. EPA Staff, 1993a). The two main categories of voluntary activities that accomplish site reductions are integrated pest management (IPM) and improved pesticide application techniques.

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Appendix C: References for Practical BMP Implementation

Protect Your Water Supply From Agricultural Chemical Backflow
Michigan State University Extension Bulletin E-2349
FARM1

SAFE Storage, Handling and Disposal of Pesticides and Containers
NDSU Extension Bulletin AE-977
FARM3

Designing Facilities for Pesticide and Fertilizer Containment
Midwest Plan Service Bulletin MWPS-37
FARM3 FARM7 FARM10 FARM11

Pesticide Container Rinsing and Water Quality
NDSU Extension Bulletin AE-1052
FARM4

SAFE Storage, Handling, and Disposal of Pesticides and Containers
NDSU Extension Bulletin AE-977
FARM5 FARM7 FARM10

Pesticide Act Chapter 4-35 NDCC
N.D. Department of Agriculture
FARM5

Chemical Container Disposal Sites in North Dakota
N.D. Department of Agriculture
FARM5

Assessing Your Hazardous Waste Management Practices
NDSU Extension Bulletin AE-1076
FARM6

PROJECT SAFE SEND
N.D. Department of Agriculture
FARM6

Applying Pesticides Correctly – A Guide for Private and Commercial Applicators
USDA/EPA
FARM8 FIELD3 FIELD6

Hazardous Substances Used in North Dakota Agriculture
NDSU Extension Circular No. 947
FARM8

Sprayer Field Wash System
NDSU Extension Circular AE-1041
FARM10

Closed Systems for Handling Liquid Pesticides
Cornell University Extension Bulletin
FARM11

Water Well Construction and Water Well Pump Installation Article 33-18 NDAC
N.D. State Department of Health
FARM12

Assessing the Condition of Your Well and Its Location
NDSU Extension Bulletin AE-1074
FARM12

A Guide to Plugging Abandoned Wells
NDSU Extension Bulletin AE-996
FARM13

An Assessment System for Potential Groundwater Contamination from Agricultural Pesticide Use in North Dakota
NDSU Extension Bulletin No. 63
FIELD1

Spray Equipment and Calibration
NDSU Extension Bulletin AE-73
FIELD3 FIELD6

Calibrating Granular Pesticide Applicators
NDSU Extension Circular AE-888
FIELD6

Chemical Applications in Agriculture – Methods and Equipment for Field Sprayers
North Central Region Extension Publication No. 520
FIELD9

North Dakota Agricultural Weather Network NDAWN
Department of Soil Science, NDSU
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Livestock Waste Facilities
Midwest Plan Service Handbook 18
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Animal Waste Management
NDSU Extension Circular AS-956
FIELD21

North Dakota Fertilizer Recommendation Tables and Equations Based on Soil Test Levels and Yield Goals
NDSU Extension Bulletin SF-882
FIELD21

Soil Sampling for Fertilizer Recommendations
NDSU Extension Bulletin SF-990
FIELD21

Managing Nitrogen Fertilizer to Prevent Groundwater Contamination
NDSU Extension Bulletin EB-64
FIELD21

Crop Rotations for North Dakota
NDSU Extension Bulletin EB-48
FIELD22

Crop Rotations for Profit in North Dakota
NDSU Extension Bulletin A-1059
FIELD22

Conservation Tillage Systems and Management
Midwest Plan Service Handbook No. 45
FIELD23 FIELD25

Zero Tillage Production Manual
The Manitoba-North Dakota Zero Tillage Farmers Association
FIELD23 FIELD26

Conservation Tillage Calendar for Spring Wheat and Durum
NDSU Extension Circular SC-982
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Water Quality: The Tillage Component
NDSU Extension Bulletin AE-1072
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Reduced Tillage Seeding Equipment
NDSU Extension Bulletin AE-826
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Soil Erosion Control – Clean Water Through Crop Management Programs
NDSU Extension Bulletin SC-710
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Soil a Threatened Resource
NDSU Extension Service Circular SC-983
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Soil and Water Characteristics Important in Irrigation
NDSU Extension Bulletin S&F-573
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Soil, Water, and Plant Relationships
NDSU Extension Bulletin AE-87
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Tensiometers – Their Use, Installation, and Maintenance
NDSU Extension Bulletin AE-100
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Irrigation Scheduling by the Checkbook Method
NDSU Extension Bulletin AE-792
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Irrigation of Small Grains
NDSU Extension Bulletin S&F-101
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Irrigated Corn Production
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Growing Irrigated Potatoes
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Chemigation – Calibrating Systems for Center Pivot Irrigation
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Best Management Practices Manual for the Oakes Irrigation Test Area
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