



<b>Title</b>	Managing Ground Water Quality in Relation to Agricultural Activities
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<b>Publication date</b>	1989-06
<b>Publication information</b>	Magette, W. L., Adel Shirmohammadi, Billy V. Lessley, and et al. "Managing Ground Water Quality in Relation to Agricultural Activities." Wiley Blackwell (Blackwell Publishing), June 1989. <a href="https://doi.org/10.1111/j.1752-1688.1989.tb03097.x">https://doi.org/10.1111/j.1752-1688.1989.tb03097.x</a> .
<b>Publisher</b>	Wiley Blackwell (Blackwell Publishing)
<b>Item record/more information</b>	<a href="http://hdl.handle.net/10197/4851">http://hdl.handle.net/10197/4851</a>
<b>Publisher's statement</b>	This is the author's version of the following article: William L. Magette, Adel Shirmohammadi, Billy V. Lessley, & Richard A. Weismiller (1989) "MANAGING GROUND WATER QUALITY IN RELATION TO AGRICULTURAL ACTIVITIES" Journal of the American Water Resources Association, 25 : 599-606 which has been published in final form at <a href="http://dx.doi.org/10.1111/j.1752-1688.1989.tb03097.x">http://dx.doi.org/10.1111/j.1752-1688.1989.tb03097.x</a> .
<b>Publisher's version (DOI)</b>	<a href="https://doi.org/10.1111/j.1752-1688.1989.tb03097.x">10.1111/j.1752-1688.1989.tb03097.x</a>

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# MANAGING GROUND WATER QUALITY IN RELATION TO AGRICULTURAL ACTIVITIES<sup>1</sup>

*William L. Magette, Adel Shirmohammadi, Billy V. Lessley, and Richard A. Weismiller*

**ABSTRACT:** Ground water quality is an environmental issue of national concern. Agricultural activities, because they involve large land areas, often are cited as a major contributor of ground water contamination. It appears that some degree of ground water contamination from agricultural land use is inevitable, especially where precipitation exceeds evapotranspiration. For this reason, and because agriculture differs significantly from point sources of pollution, farmers, policymakers, and scientists need alternative management strategies by which to protect ground water. Mathematical models coupled to geographic information systems to form expert systems can be important management tools for both policymakers and agricultural producers. An expert system can provide farmers, researchers, and environmental managers with information by which to better manage agricultural production systems to minimize ground water contamination. Significant research is necessary to perfect such a system, necessitating interim ground water management strategies that include not only a strong research program, but educational and public policy components as well.

(**KEY TERMS:** Ground water; agrochemicals; environmental policy; modeling; expert systems; pollution.)

## INTRODUCTION

Ground water quality is an issue of great public concern in the United States; 95 percent of rural households depend solely upon ground water to meet water needs (ESCOP, 1985). Only a few years ago, most reports of ground water contamination concerned localized problems caused by loss of a hazardous chemical into the environment at a specific location. Since 1985, attention has become focused on rural ground water quality. Scientific conferences that address land use impacts on ground water are becoming commonplace (e.g. NWWA, 1986).

Recently, research has shown that ground water contamination in rural areas dominated by agricultural land use may be more pervasive than originally perceived. Problems on New York's Long Island (e.g. Baker, 1986) related to the pesticide aldicarb focused national attention on the potential environmental hazards associated with agricultural chemicals. Recent studies in Big Spring Basin (Iowa) watershed show an even more alarming trend that correlates increased fertilizer usage with increased nitrate nitrogen concentrations in ground water (Hallberg, 1986a; 1986b). Bachman (1984) found nitrate in unconfined groundwater to be correlated with agricultural and residential land use. Similar findings elsewhere are encouraging the passage of discussion of legislative solutions to ground water contamination problems.

A ground water management program directed toward agriculture can ameliorate conflicts that may occur between agricultural production and ground water quality. However, the agricultural component of such a program should be an integral part of a comprehensive ground water management strategy. Fundamentally, management of

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<sup>1</sup> Paper No. 88108 of the *Water Resources Bulletin*.

a natural system for water quality and quantity protection involves describing the response of the system to various inputs. Understanding the system and inputs to it, and predicting responses given a variety of alternative stimuli, should be the goal of any management strategy for ground water.

Geographic information systems (GIS) offer a convenient means by which to organize data about variables that affect ground water systems. Likewise, mathematical models can be designed to describe the system response to those variables. Together, the two can be the basis for an “expert system”, which is a valuable tool by which both policymakers and agricultural producers can manage agricultural impacts on ground water. This paper discusses the concepts and developmental needs for assembling an expert system for ground water management in relation to agricultural activities. Such an approach is shown to be necessary because of the difficulties in managing losses of pollutants from agricultural systems operated in an uncontrolled environment. Other considerations that policymakers should incorporate while developing a ground water management strategy that addresses agricultural activities are discussed also.

## **PRACTICAL CONSIDERATIONS**

Agricultural production systems differ in many ways from most pollutant sources, which poses special problems for pollution control. First, agriculture involves vast land areas. Approximately 1,250 million acres (506 million hectares) are devoted to agricultural activities in the United States. Various agrochemicals are added to these lands. A portion of these inputs has the potential to contaminate both ground and surface water. Second, farmers are strongly independent and operate without formal “industry standards”. The selection of farming methods, and decisions about what crops to plant and in what quantities are largely individual decisions. While cropping-choices are market-driven, farming techniques often are deeply rooted in tradition, due in part to the fact that most farming operations have been passed from generation to generation within families. Third, because of intense competition and low profit margins, farmers cannot pass the cost of pollution control to consumers (Farrell, 1988). Finally, but most importantly, agricultural production takes place in the open environment where farmers have no control over climatic events, the major driving force that causes losses of pollutants.

From a pollution control perspective, these differences pose special challenges to agricultural producers, resource management agencies, and policymakers. For example, the best managerial efforts of an agricultural producer to control pollutant losses can be overshadowed by unusual weather patterns. Research is documenting that nitrate concentrations in surficial aquifers may exceed the recommended level of 10mg/L for public drinking water primarily because of climatic trends during a growing season rather than unsound production practices (Staver, Magette, and Brinsfield, 1987; Brinsfield, Staver, and Magette, 1988).

In addition, the relationship between agricultural activities and ground water contamination is not necessarily direct, as opposed to point sources of contamination. At a given fertilization rate, increased crop yields can be obtained by better management of the production system (Tisdale and Nelson, 1975). All other things being equal, increased crop yields imply increased nutrient uptake, leaving less nutrients available to be lost by leaching or runoff. Thus, a one-to-one relationship

between agrochemical usage and losses does not exist, and reducing the amounts of agrochemicals used need not be the only means of reducing losses of agrochemicals to ground water. Indeed the philosophy of best management practices (BMPs) is that managerial techniques are effective in controlling agricultural nonpoint source pollution (Weismiller, 1984).

Finally, there are currently no practical and reliable meters by which to sense impending ground water contamination from agricultural activities. It is not feasible to measure "effluent quality" from agricultural land use that encompasses thousands of hectares, as can be done when pollutants are released through a defined discharge point. Water leaching through the root zone undergoes numerous biological, chemical, and physical transformations both in the root zone and underlying vadose zone before reaching the water table. Unfortunately, the extent to which these changes occur is highly variable. Water also flows through the profile by various pathways, not all necessarily uniformly distributed. This makes the selection of a representative monitoring point(s) within the soil profile impossible. Even if it were possible to select appropriate monitoring points, the agrochemicals that are potential pollutants are already in the production system (i.e. the land). If not bound by the soil matrix, dissipated by physical, biological, or chemical processes, or taken up by growing plants, these agrochemicals are available for transport to ground water when hydrologic conditions dictate.

Consequently, traditional pollution control techniques (i.e. waste collection and treatment) employed in point source managements programs do not work for nonpoint source pollution management. Instead, nonpoint source programs emphasize the use of managerial techniques to control losses of pollutants. With the exceptions of integrated pest management (IPM) and guidelines for the application of agrochemicals, many agricultural management practices are designed for surface water rather than ground water protection. Thus, contamination of ground water sometimes can occur from agricultural activities even when agricultural best management practices are employed (Brinsfield, Staver, and Magette, 1988). This suggests the need for better management practices. However, it also implies the need for a better understanding of how managerial decisions affect ground water quality and how incentives can be used more effectively to prevent the loss of pollutants. The need for a more complete understanding can be addressed simultaneously in an expert system.

## **COMPONENTS OF AN EXPERT SYSTEM FOR GROUND WATER QUALITY PROTECTION**

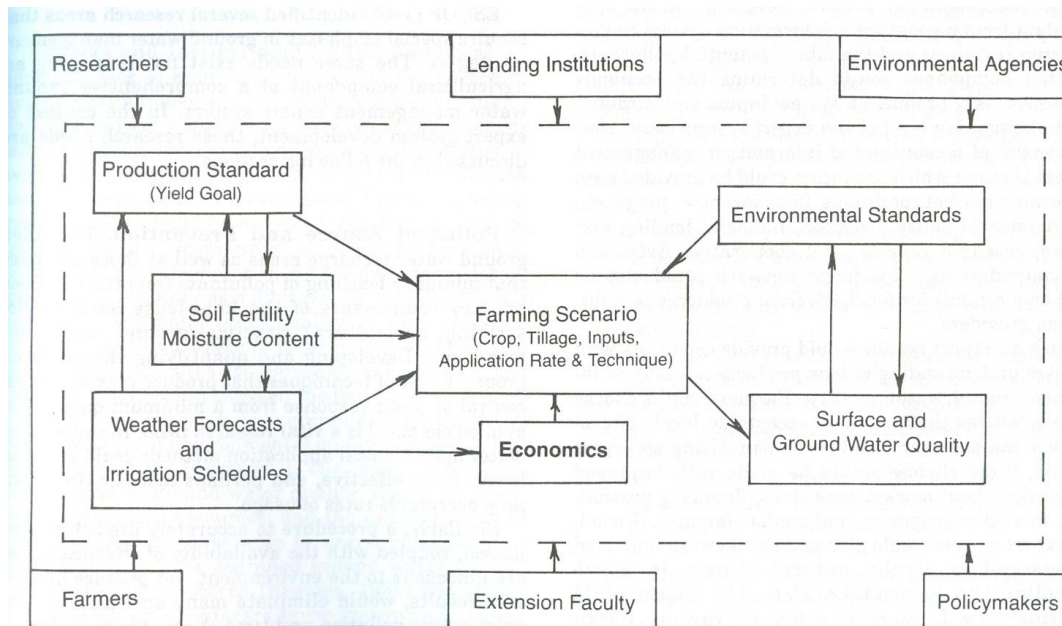
In simple terms, an expert system is a collection of known facts and/or relationships that are used to predict the outcome of a variety of stimuli or inputs, and from which potential action decisions can be made. The value of an expert system is its versatility in rapidly evaluating different scenarios. In terms of ground water protection, an expert system would describe the impacts of various land-based activities and climactic variables on ground water quality and quantity. However, agricultural activities and their influence on ground water would be one component of such an expert system. Other components would be necessary to complete a comprehensive expert system.

As shown in Figure 1, the agricultural component of a ground water management expert system would closely mimic the natural world in which agricultural production proceeds. In reality, production occurs in the midst of considerable uncertainty about the interaction between soil resources, water, crops, climate, landowner and/or farmer manager skills and resources, policies, market conditions, environmental standards or concerns, and the development of new knowledge. This world is represented schematically by the inner box in Figure 1 and denoted by broken lines. An individual production system (farming scenario) consists of a land base managed by a producer that decides what crops to produce and how to produce them, i.e. what production techniques to use. However, these decisions are strongly influenced by soil characteristics that include fertility and moisture-holding capacity, which partially dictate what production level is possible, and which are themselves influenced by managerial decisions and weather conditions. Economic considerations are central to all decisions affecting the production system. Likewise, environmental standards for surface and ground water quality protection influence the components of the production system, just as the production system can impact water quality.

In addition to the natural environment, various individuals and institutions influence these interactions: farmers, lending institutions, government agencies, marketing agencies, researchers and Extension faculty, and policymakers. These are represented in the outer box in Figure 1. Producers (farmers) are the ultimate decision-makers controlling the production system. Researchers – as developers of new knowledge about production techniques, crop varieties, agrochemicals, natural resource protection, etc. – and cooperative Extension faculty – as members of land grant university systems most responsible for delivering the new knowledge to producers – influence the producer and producer decisions about the production system. Lending institutions also influence the nature of production systems since they base financial support both on a producer's financial health and the likelihood that a given production system will be successful. Policymakers determine what incentive/disincentive programs will apply to given production systems. Likewise, environmental agencies determine the environmental standards to be maintained by a given production system.

Within this framework of uncertainty, agricultural producers individually try to achieve an optimum level of production that will yield the greatest economic return. An expert system that explains *a priori* the interaction among the variables described above would help reduce some of the uncertainties associated with agricultural production and facilitate decision-making that protects ground water. The system would have two layers corresponding to the intrinsic and extrinsic factors described above. At the production system level, a key component would consist of a model to predict production system response to environmental stimuli and managerial decisions. Modules in this component would include crop growth models and pollutant transport models that would use weather forecasts and site specific data from a geographic information system to predict crop responses and the fate of potential pollutants. Another component would determine the economic consequences of production system inputs and outputs.

The remaining level of the expert system could simply consist of a coordinated information management system through which producers could be provided data concerning market conditions, farm incentive programs, environmental policy decisions, financial lending programs, research reports, and cooperative Extension recommendations. This latter network could also be used as a conduit for feedback from producers to information providers.



**Figure 1. Conceptual Diagram of an Expert System for Managing Ground Water Quality in Relation to Agricultural Activities.**

Such an expert system would provide producers with a better understanding of how production practices influence ground water quality. Farmers could choose those practices that result in acceptable levels of production and environmental protection. Using an expert system, these choices would be made with improved knowledge about market conditions, financing possibilities, incentive programs, and similar impacts. Second, the expert system would give policymakers an improved understanding of the natural system in which agricultural production takes place. The system would describe how farmers respond to various incentive/disincentive programs. Policymakers subsequently could choose among those policy instruments that promote desired results among producers in the most effective manner.

## DEVELOPMENTAL NEEDS

Some of the necessary parts for an agricultural component of a ground water management expert system already exist. Information networks are in place to provide farmers a variety of production related information ranging from local weather forecasts to future market reports (American Farm Bureau, 1987). Geographic information systems are readily available (e.g. ERDAS, 1987). Some knowledge is available about farmer response to pollution control policies (Kramer, 1985). Mathematical models such as CREAMS (Knisel, 1980) offer the basis for describing the effect of field-scale managerial decisions on the movement of agricultural pollutants. These have been used successfully to suggest both the environmental and economic impacts of various cropping systems (Magette, *et al.*, 1988). However, Shoemaker and Magette (1987) concluded that a model is not currently available that can adequately evaluate the impact of agricultural management of nutrients and pesticides on both surface and ground water.

ESCOP (1985) identifies several research areas that require specific emphases in ground water management strategies. The same need exists for developing an agricultural component of a comprehensive ground water management expert system. In the context of expert system development, these research needs are discussed in the following sections.

**Pollutant Source and Prevention.** Identified ground water recharge areas as well as those practices that minimize leaching of pollutants from the root zone are key components of the knowledge base for describing agricultural practices/ground water interactions. Developing and quantifying the effect on ground water of techniques that produce maximum pest control or plant response from a minimum quantity of applied chemical is a vital research need. In some cases, better agrochemical application methods could result in lower, more effective, and perhaps more environmentally acceptable rates of usage.

Similarly, a procedure to accurately predict precipitation, coupled with the availability of chemicals that are innocuous to the environment, yet produce desired crop results, would eliminate many agricultural nonpoint source pollution problems. A reliable procedure to determine and/or predict nitrogen availability would do much to promote better control of nitrogen fertilizers and animal wastes.

**Pollutant Fate.** Whereas managers of surface water quality have long relied upon mathematical models for allocating permissible pollutant loadings among various surface water users, such a technique is only in its infancy relative to ground water management. Much research into the interaction effects will be required to describe the vast number of variables that change in space and time (soil physical and chemical characteristics, topography, land use, ambient and soil temperature, soil moisture, precipitation, and agrochemical characteristics) and dramatically influence the movement of pollutants to ground water.

**Remediation Techniques.** Because agricultural production occurs in the uncontrolled environment, climatic conditions will occur that result in pollutant losses even from well managed systems. Techniques are needed to allow decontamination of ground water once polluted. A description of the costs and technical limitations of such methods would also permit managerial decisions regarding the cost effectiveness of levels of pollution prevention versus cleanup.

**Impacts and Institutional Issues.** There is a fundamental lack of knowledge concerning the long-term human health impacts of low dosage chemical contamination of ground water. Consequently, an environmentally acceptable level of ground water contamination is evasive. Primary drinking water standards set by EPA can, of course, be used as one level of purity to which ground water should be managed, but this list fails to include many commonly used agrochemicals. (Similarly, a nondegradation policy accepting existing ground water as a limit can be used.) Without a given level of ground water quality that is considered desirable, it is impossible to determine acceptable surface application rates for agrochemicals, even if one knew the relationship between the two.

Much more research is required to determine the worth and cost of environmental quality, and what motivates individuals to protect it. The costs of attaining a given degree of ground water quality; the costs of renovating degraded resources; and the costs in terms of health effects, inconvenience to users, and other impacts resulting

from degraded ground water are not clearly defined. Research (Kramer, 1985) has shown that agricultural producers favour government incentives as a means to encourage the use of pollution control practices. However, critics of voluntary programs based on monetary incentives to control pollution suggest that such programs are less effective than they could be (Padgitt, 1986). More research is necessary into the institutional aspects of ground water protection to define an optimum strategy for implementation.

## INTERIM MANAGEMENT TECHNIQUES

Although preliminary expert systems for ground water management can be formulated at present, considerable time will be required to perfect these tools. In the interim, more traditional methods will be required with which to manage ground water. Many of these would continue as integral parts of a comprehensive management strategy, and include as a minimum education, public policy instruments (regulations, ordinances, etc.), and monitoring.

**Education.** Education should be linked to research programs in a comprehensive ground water management strategy (Magette and Shirmohammadi, 1988). Ground water is shared by a variety of users, therefore educational programs must be directed to a variety of audiences. Technology transfer regarding ground water management can be successfully accomplished through existing agencies such as Cooperative Extension Services, U.S. Geological Survey, USDA Soil Conservation Service, and local water quality agencies (ECOP, 1986). An educational programme should evoke a change in practice by the target audiences.

As regards agriculture, indicating a change in agricultural production practices can be difficult for several reasons:

1. Producers may lack understanding about impacts of agricultural practices on the environment;
2. Producers may lack understanding about the mechanisms by which agrochemicals act in the environment;
3. Because of the costs of agrochemical inputs versus the return gained from the crops produced, producers realize that, economically, it is better to err by using too much rather than too little agrochemical; and
4. Producers have large investments in, and other costs associated with, equipment that may not be adaptable to new production techniques.

The nature of issues that must be targeted by any ground water management educational program that addresses other audiences is no less complex. Water is generally a "free good" that has little economic value to individuals except where quantity or quality problems exist. Not surprisingly, an educational program must be conducted as an interdisciplinary effort involving agricultural and sociological disciplines and utilizing a variety of motivators. Such a program that addressed both agricultural and non-agricultural audiences concerning nonpoint source pollution control in the Chesapeake Bay basin has been developed in Maryland (Magette, Weismiller, and Gugulis, 1985) and is serving as a prototype for a ground water protection educational campaign.

Additionally, targeting specific water quality issues with an educational campaign, such as is being fostered by the U.S. Department of Agriculture (Johnsrud, 1988) can focus limited resources on critical issues. However, a diverse audience represented by agricultural and non-agricultural interests is motivated to change by various circumstances. This requires that an assessment of educational programs be conducted to identify characteristics of targeted audiences if effective educational programs are to be developed. Smith *et al.*, (1989) used “if then” techniques to evaluate audiences that included agricultural producers, urban residents, state policymakers, local government officials, and teen and pre-teen youth for an educational program on water quality. Afterward, educational models were developed that outlined program content and delivery strategies. Although each model had common education elements, significant differences were needed in the mode of program of delivery.

**Public Policy Decisions.** A variety of techniques are available to regulate environmental matters including zoning, outright bans on use of certain materials or practices, taxes, direct subsidies and setting environmental standards. Many of these are discussed elsewhere in relation to agricultural pollutants (e.g. Massey, 1987; Contant, 1986). In considering any of these alternatives, serious attention must be given to the potential economic impacts the decisions might have on farmers, the protection afforded to ground water, and the “manageability” of the program.

Because farmers have such narrow profit margins (Farrell, 1988), economic incentives would likely produce a fast change in practices that potentially affect ground water. Kramer (1985) reports that 80% of farmers surveyed about pollution control felt government assistance was necessary. A majority of the respondents felt monetary incentives were the most viable method for enhancing the implementation of best management practices. These incentives could include tax credits, low interest loans, and cost sharing programs.

Regulatory programs were least favored by farmers as a means to promote best management practice adoption (Kramer, 1985). However, Padgitt (1986) points out that strictly voluntary adoption of soil conservation practices has generally not solved soil erosion problems in the United States, despite the fact that organized promotions of the practices have been ongoing for 50 years. Though tremendous improvements in soil management have been made, many problems remain, prompting the discussion of regulatory approaches to solve the problem. Direct regulation of pollution, especially that from nonpoint sources, is fraught with obstacles, however. As Leftwich and Sharp (1978) point out, direct controls require the regulatory authority to be capable of (1) determining what the economically desirable levels of pollution are, (2) efficiently allocating permissible pollution among different polluters, and (3) enforcing the standards of emissions. Although direct regulation of surface water pollution from point sources has been accomplished via the National Pollutant Discharge Elimination System (NPDES) of permits, such a system is based on the self-reporting of pollutant discharge by permit holders. As pointed out previously, monitoring the loss of pollutants to ground water from agricultural systems is not technically feasible.

In lieu of regulatory controls as a means to manage agricultural impacts on ground water, several different economic approaches could be taken to induce a reduction in agrochemical usage. An environmental tax on agrochemicals might be one solution. The state of Wisconsin (Massey, 1986) has invoked such a tax on fertilizers, as well as fees for the production of pesticides and a variety of other

activities that potentially impact ground water. A tax of this sort would be expected to produce a reduction in agrochemical use as long as producers (farmers) felt the total cost (including the tax) of each incremental chemical input was higher than the value of incremental crop yield produced by the chemical. An additional advantage of such a tax on inputs is that it discourages overproduction. Depending on the chemical and crop, however, such a tax may need to be severe to induce changes in usage (Holik *et al.*, 1984). Alternatively, incentives could be utilized by which income or business taxes might be reduced using “environmental credits” to reward those producers that adopt and follow best management practices.

Still another economic approach might involve subsidy payments to hold the use of absolute amounts (not just rates) of agrochemicals to some predetermined level. For example, most farmers maintain at least crude records of farm expenditures. These could be used to determine for a given period an average consumption figure for agrochemicals on individual farms. Farmers then could be paid to use less than this X-year average amount of chemicals each year. Such a policy would relate somewhat to principles used in allocating ground water among users, and could help eliminate the trends identified by Hallberg (1986a) that correlate decreased water quality with increased agrochemical usage.

**Monitoring.** In any managed natural system, some methodology is desirable by which to assess the effects of management. The procedure might also provide “baseline” information by which problem areas could be defined and from which future changes could be measured. Other objectives can be satisfied also (Kazmann, 1981). For a comprehensive ground water management strategy some monitoring system is essential.

Ground water monitoring can be conducted for quality assurance of potable water supplies, for compliance with quality standards, in response to emergencies, or for statistical analyses (Miller, 1981). Guidelines for establishing monitoring programs are widely available (Miller, 1981; Scalf *et al.*, 1981; Morrison, 1983; Barcelona *et al.*, 1985; Barcelona *et al.*, 1987). The objectives of the monitoring program must be clearly defined before the program is initiated and appropriate resources committed. The need for adequate financial resources to support a comprehensive ground water monitoring strategy cannot be overstated. A system to monitor field-by-field ground water impacts may be prohibitively expensive (Magette, 1988). Alternatively, larger scale monitoring systems give less information about localized impacts. Likely, a regionalized monitoring network such as being employed in the National Water Quality Assessment program (Hirsch, Alley, and Wilber, 1988) will be necessary to determine regional ground water quality, coupled with more intensive monitoring where problems or potential problems are identified.

## SUMMARY

Most of the techniques suggested for a ground water management strategy are surrounded by a degree of uncertainty. As mentioned earlier, there are many gaps in the scientific understanding of interactions between land-based activities and ground water quality. Common to all management strategies, however, is the question, “How much is the environment worth?” This is no trivial question, since some researchers (Leftwich and Sharp, 1978) maintain that the absence of well-defined, individual

property rights in the environment (one measure of worth) is a key reason why individuals pollute.

The uncertainties faced in managing ground water resources demand that a multi-faceted approach be employed. An integral part of such a program should be an expert system to clarify various mechanisms ranging from individual management alternatives to effective public policy tools, to effect changes of land impacts on ground water. As a minimum, a strategy for ground water management must have vigorous monitoring, research, and educational components – mixed with judicious use of public policy instruments until more is known in detail about how land activities impact ground water. And, as indicated by years of experience with surface water pollution abatement, emphasis in any strategy should be placed on preventing ground water problems rather than on reacting to them.

### **ACKNOWLEDGEMENTS**

Scientific Article No. A-4818, Contribution No. 7844 of the Maryland Agricultural Experiment Station.

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