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Applications of GIS to the Modeling of NonPoint Source Pollutants in the Vadose Zone: A Conference Overview

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ABSTRACT

Because of their ubiquitous nature and potential chronic health effects, nonpoint source (NPS) pollutants have become a focal point of attention by the general public, particularly regarding pollution of surface and subsurface drinking water sources. The NPS pollutants pose a technical problem because of the areal extent of their contamination that increases the complexity and sheer volume of data far beyond that of point-source pollutants. The spatial nature of the NPS pollution problem necessitates the use of a geographic information system (GIS) to manipulate, retrieve, and display the large volumes of spatial data. This overview provides a brief introduction and review of the modeling of NPS pollutants with GIS and a brief discussion of some of the papers presented at the ASA-CSSA-SSSA 1995 Bouyoucos Conference entitled *Applications of GIS to the Modeling of Nonpoint Source Pollutants in the Vadose Zone.*

POINT-SOURCE POLLUTANTS or rather pollutants that are associated with a point location such as a toxic-waste spill site have received the greatest attention in the past because of the obvious severity of their impact at a localized point. Even though point-source pollution is generally highly toxic, it is relatively easily controlled and identifiable. However, over recent years concern has shifted more to pollutants that are low in concentration, but ubiquitous in nature and referred to as NPS pollutants. The NPS pollutants are contaminants of surface and subsurface soil and water resources (e.g., sediment, fertilizers, pesticides, salts, and trace elements) that are diffuse in nature and cannot be traced to a point location. Often times, NPS pollutants are naturally occurring such as salts and trace elements in soils or are the consequence of direct application by humans (e.g., pesticides and fertilizers), but regardless of their source they are generally the direct consequence of human activities (e.g., agriculture, urban runoff, hydromodification, and resource extraction).

The threat of NPS pollutants varies throughout the world. Yet, NPS pollutants are a problem of global importance (Duda, 1993). The reason is because NPS pollution problems do not recognize the boundaries between nations, nor are they necessarily isolated by the physical barriers between continents.

As the worlds population continues to grow, the foremost nonparochial problem facing humans is meeting the world's food demand with a sustainable agriculture. Sustainable agriculture requires a delicate balance between crop production, natural resource utilization, environmental impacts, and economics. It strives to optimize food production while maintaining economic stability, minimizing the utilization of finite natural resources, and minimizing impacts on the environment. Yet, agriculture remains as the single greatest contributor of NPS pollutants to soil and water resources (Humenik et al., 1987).

Historically, NPS pollutants of surface waters have been of greater environmental concern than NPS pollutants of subsurface soil and water resources. The USEPA (1990) identified agricultural nonpoint runoff of sediment and agricultural chemicals to cause impairment of 55% of surveyed river length and 58% of surveyed lake area that still have water-quality problems. Recently, increased attention has been given to NPS pollution of subsurface soil and water. Throughout the world 30 to 50% of the earth's land is believed affected by NPS pollutants including erosion, fertilizers, pesticides, organic manures, and sewage sludge (Pimental, 1993). Limited surface water resources and continued contamination of surface water supplies, have increased the reliance on groundwater to meet growing water demands in nearly all industrialized nations. Already, groundwater accounts for half of the drinking water and 40% of the irrigation water used in the USA. The degradation of groundwater particularly by NPS pollutants has become a growing public concern primarily because of the concern over long-term health effects. Nonpoint source pollutants pose a tremendous threat to soil and groundwater resources because of the area1 extent of their contamination and the difficulty of effective remediation once soils and groundwater are contaminated. The scope of the contamination by NPS pollutants can be over entire basins, watersheds, and aquifers; and can cross state, national, and even continental boundaries.

CONFERENCE JUSTIFICATION AND GOALS

Assessing the environmental impact of NPS pollutants at a global, regional, and localized scale is a key component to achieving sustainability of agriculture, as well as preserving the environment. Assessment involves the determination of change of some constituent over time.

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Abbreviations: NPS, nonpoint source; GIS, geographical information systems; GPS, global position system.

This change can be measured in real time or predicted with a model. Real-time measurements reflect the activities of the past, whereas model predictions are a glimpse into the future. Both means of assessment are valuable. However, the advantage of prediction, like preventative medicine, is that it can be used to alter the occurrence of detrimental conditions before they manifest. The ability to model environmental contaminants such as NPS pollutants justifiably provides a tool for humans to optimize the use of the environment by sustaining its utility without detrimental consequences, and preserving its esthetic qualities to serve human's need of spirituality.

Because of the volume of data, the spatial heterogeneity of the earth's surface and subsurface, and the complexity of solute transport processes, a multidisciplinary approach is required to assess the impacts of NPS pollutants. The knowledge and information required to address the problem of assessing the impact of NPS pollutants on the environment crosses several subdiscipline lines: spatial statistics, remote sensing, GIS, hydrology, and soil science. Spatial statististics is essential in dealing with the uncertainty and variability of spatial information; remote sensing is needed to measure physical, chemical, and biological properties of soil or to measure real-time environmental impacts over vast areas in a cost effective and timely manner; GIS is needed to manipulate, store, retrieve, and display the tremendous volumes of spatial data; and water flow and solute transport models are needed to simulate future scenarios to assess potential temporal and spatial changes. Integrated methodologies combining spatial statistics, remote-sensing instrumentation, GIS, and solute transport modeling are required to assess the impact of NPS pollutants on soil and water resources from a local to global scale.

It was the need for the 'interaction of these various subdisciplines involving the modeling of NPS pollutants in the vadose zone that led to the organization of the 1995 Bouyoucos Conference *Applications of GIS to the Modeling of Nonpoint Source Pollutants in the Vadose Zone.* The goal of the 1995 Bouyoucos Conference was to stimulate international interaction between the disciplines of spatial statistics, remote sensing, GIS, and solute transport modeling; to enhance the development of techniques for the assessment of NPS pollutants in the vadose zone and in subsurface waters; to evaluate the viability of using a GIS-based multidisciplinary approach as a means of assessing the impact of agriculture on groundwater quality; to promote interest in this newly developing area of applied research; and to explore the positive and negative aspects of the use of a GIS as a tool for NPS pollutant modeling. In addition, current methodologies of coupling GIS to solute transport models were reviewed and case studies were presented.

GENERAL ASPECTS OF GIS-BASED NPS POLLUTION MODELS

Burrough (1996) identified three components or aspects to GIS-based environmental modeling: data, GIS, and model. First and foremost, the solute transport model must be developed. Transport models of NPS pollutants range from the simplest of empirical functional models (e.g., leaching fraction equal to the electrical conductivity of the irrigation water divided by the electrical conductivity of the drainage water) to the most sophisticated 3-D finite-element numerical representations of complex partial differential equations. Secondly, the data for the model must be obtained. This involves the measurement or estimation of the physical, chemical, and biological properties required as input into the model; and the spatial distribution of these transport parameters as defined by their spatial variability and spatial structure. Finally, the solute transport model must be coupled to a GIS containing the spatial input data. Each component will be briefly reviewed to provide general background information.

Data

Currently, the greatest single challenge in cost-effectively modeling NPS pollutants is to obtain sufficient transport parameter data to characterize the spatial distribution of the data with a knowledge of their uncertainty. Maidment (1993) points out that the factor most limiting to hydrologic modeling in general is not the ability to characterize hydrologic processes mathematically, or to solve the resulting equations, but rather the ability to specify the values of the model parameters representing the flow environment accurately. The complex spatial heterogeneity of soil necessitates the collection of tremendous volumes of spatial data. This makes data collection for large areas prohibitively expensive because of labor cost.

Measurement and Estimation of Transport Parameters

A sample of just a few of the commonly measured transport parameters for models of the vadose zone includes hydraulic parameters such as water content-matric potential relations, and matric potential – hydraulic conductivity relations or the capacity model counterparts of field capacity and saturation percentage; bypass flow parameters such *as* mobile-immobile phase fractions; plant parameters including evapotranspiration, root water uptake distribution, plant root maximum depth, and crop history; chemical parameters such as adsorption coefficients; and biological parameters such as degradation rates and microbial population distributions. These parameters along with inital and boundary conditions comprise a small list of the pieces of information needed by most processed-based transport models. Multiply this information by a spatial factor and in some cases by a temporal factor, and the volume of data becomes tremendous.

Because of the volume of data required, it is not difficult to see how a quick and easy means of measuring each model input parameter is crucial to the cost-effective modeling of NPS pollutants. Remote sensing offers a possible solution to the problem. Remote-sensing methods such as electromagnetic induction, ground-penetrating radar, and recently seismic reflectance have been used to reduce the labor intensiveness of directly or indirectly determining some transport parameters. Unfortunately, most of these methods are still in their infancy with regards to applications in solute transport modeling; consequently, they are limited in their current usefulness.

Most transport parameters can only be directly measured from soil samples that makes any attempt to model NPS pollutants beyond a few thousand hectares virtually impossible. As an alternative, the spatial distribution of input parameters has been estimated with the use of soil survey data and pedotransfer functions. The problem with the use of generalized rather than measured data has been that the associated uncertainties are so great that the resulting maps of potential groundwater vulnerability and leaching assessment are actually best used as guides for data collection strategies rather than the purpose of environmental impact assessment for which they were intended (Loague, 1994). In spite of this fact, there has been a proliferation of deterministically derived GIS-based groundwater vulnerability maps at regional scales.

Spatial Variability and Spatial Structure of Transport Parameters

Jury (1986) provides an excellent fundamental discussion of the spatial variability of soil properties and its impact on transport modeling in the vadose zone. As Jury (1986) points out, “any hope of estimating a continuous spatial pattern of chemical emissions at each point in space within a field must be abandoned due to field-scale variability of soils.” The spatial variability of a parameter should generally be represented by its sample mean with its associated sample variance. However, lateral correlations are known to exist for samples taken near to one another; consequently, a knowledge of the spatial structure of each transport parameter is needed to determine the intensiveness or resolution at which a parameter must be measured to characterize its field-scale spatial variability. It is here that spatial statistics is potentially valuable. Spatial correlation can be determined. The maximum sampling spacing of a parameter can be estimated that will capture the parameter’s spatial variability. Various techniques of spatial interpolation can be used to increase resolution while maintaining the integrity of the spatial variability patterns.

Spatial structure of a transport parameter such as dispersion is needed to determine the transition from the local to the field scale as a function of spatial scale. This will allow an estimation of the minimum spatial scale at which the field-scale parameter dominates solute transport behavior. It is for this reason that parameters exhibiting a scale dependency must be measured at the scale for which the application is intended. A dispersion coefficient determined from a laboratory experiment is of no value as input into a model intended for field-scale application.

Actually, there may not always be a need to construct highly accurate representations of the field average of each transport parameter as long as a sensitivity analysis is conducted to determine the effect that a variation in each parameter has on the simulated results. Those parameters with the greatest effect are obviously the parameters to know more accurately. Furthermore, as Jury (1986) points out, an estimate of the variation of each parameter to construct a crude sample frequency diagram may be of greater value than an accurate arithmetic average.

GIS

Over the last two decades significant developments have occurred in the application of GIS to environmental problems. GIS is characterized by its capability to integrate layers of spatially oriented information. The advantages of GIS in its application to general spatial problems include “the ease of data retrieval; ability to discover and display information gained by testing interactions between phenomena; ability to synthesize large amounts of data for spatial examination; ability to make scale and projection changes, remove distortions, and perform coordinate rotation and translation; and the capability to discover and display spatial relationships through the application of empirical and statistical models” (Walsh, 1988). The principle benefit of coupling GIS to environmental models is to enable the models to deal with large volumes of spatial data that geographically anchor many environmental processes. This is especially true of hydrologic processes. GIS applications to hydrologic modeling have been used in the past most widely and effectively by surface hydrologists, and to a lesser extent by groundwater hydrologists for NPS pollutant applications. Only within the last decade have soil scientists begun to use GIS as a tool in data organization and spatial visualization of NPS pollution model simulation.

Coupling of a Solute Transport Model to a GIS

Currently, no GIS has the data representation flexibility for space and time, together with the algorithmic capability to be able to build process-based models internally; consequently, environmental models and GIS must be coupled. Coupling can range from loose to tight coupling. A loose coupling involves a data transfer from one system to another. The GIS is used to preprocess data or to make maps of input data or model results. A majority of the applications found in the literature represent this approach because it requires little software modification. Only the file formats and corresponding input and output routines, usually of the model, must be adapted. In a tight coupling the data management is integrated into the system. Characteristically, a tight coupling will provide a common user interface for both the GIS and model, and the information sharing between the respective components is transparent. An example of a tight coupling of a hydrologic model is RAISON (Lam and Swayne, 1991) that brings together a GIS, hydrologic models, spreadsheet, and expert system. The tightest coupling is an embedded or integrated system where the GIS and model rely on a single data manager. The coupling of software components is within a single application with shared memory rather than sharing files and a common interface. Embedded systems require a substantial amount of time and money to develop, and are usually constraining when changes are needed.

Nyerges (1993) cites four steps in coupling a model to a GIS: (i) description of the data transformations required between the data representation constructs, (ii) specifying software to export and import between the constructs, (iii) determining whether the software can run without intervention, and (iv) setting up the transfer as bidirectional.

Model

Mathematical models integrate existing knowledge into a logical framework of rules, equations, and relationships to quantify how a system behaves (Moore and Gallant, 1991). They range from simple empirical equations such as linear regression equations to sets of complex differential equations. Models incorporate descriptions of the key processes that determine a system's behavior with varying degrees of sophistication. However, a "good model must not only produce accurate results, but must do so for the right reasons" (Klemes, 1986, p. 178S). Hillel (1987) points out four principles that should guide model development: parsimony, modesty, accuracy, and testability. The general reasons for developing subsurface hydrologic models of NPS pollutants are (i) to assist in the understanding of the system that it is intended to represent for the purpose of hypothesis testing, and (ii) to provide a predictive tool for management (Beven, 1989; Grayson et al., 1992).

NPS Pollutants Models with GIS

Historically, three general categories of NPS pollution models have been coupled to GIS: regression models, index models, and transient-state solute transport models. Regression models have generally used multiple linear regression techniques to relate various soil properties or conditions to groundwater vulnerability or to the accumulation of a solute in the soil root zone (Corwin et al., 1988; Corwin and Rhoades, 1988; Corwin et al., 1989). Index models refer to those models generally used to assess potential groundwater pollution hazard with some calculated index generated from either a simple functional model of steady-state solute transport (Merchant et al., 1987; Khan and Liang, 1989; Evans and Myers, 1990; Halliday and Wolfe, 1991; Rundquist et al., 1991) or a steady-state mechanistic model (Wylie et al., 1994). Transient-state solute transport models include both stochastic and deterministic models capable of handling the movement of a pollutant in a nonequilibrium flow system. The most recent progress has occurred in the coupling of transient-state solute transport models to GIS (Bleecker et al., 1990; Petach et al., 1991; Corwin et al., 1993a, b).

Recently numerous hydrologic/water quality models of runoff and soil erosion have been used with a GIS to determine surface sources of nonpoint pollutants from watersheds (Pelletier, 1985; Potter et al., 1986; Oslin et al., 1988; Rudra et al., 1991; Bhaskar et al., 1992; Drayton et al., 1992; Joao and Walsh, 1992; Wolfe, 1992; Heidtke and Auer, 1993; Warwick and Haness, 1994), agricultural areas (Hopkins and Clausen, 1985; Gilliland and Baxter-Potter, 1987; Hession and Shanholtz, 1988; Panuska and Moore, 1991; Hamlett et al., 1992; Lee and White, 1992; Geleta et al., 1994; Tim and Jolly, 1994), and urban areas (Smith and Brilly, 1992; Smith, 1993). Several groundwater models have been coupled to a GIS to simulate water flow and/or NPS pollutants in aquifers (Kernodle and Philip, 1989; Baker and Panciera, 1990; Hinaman, 1993; Roaza et al., 1993; El-Kadi et al., 1994; Darling and Hubbard, 1994). Integrated surface and groundwater hydrologic models have been coupled to a GIS (Powers et al., 1989; Ross and Ross, 1989; Preti and Lubello, 1993). GIS has been coupled to a simple functional model of recharge to map a regional assessment of relative potential recharge to the Floridan aquifer (Boniol et al., 1993).

The first applications of GIS for assessing the impact of NPS pollutants in the vadose zone occurred in the late 1980s. Corwin et al. (1988), Corwin and Rhoades (1988), and Corwin et al. (1989) applied the use of GIS to delineate areas of accumulation of salinity in the vadose zone by coupling a GIS of the Wellton-Mohawk Irrigation District to a phenomenological model of salinity development. GIS has also been used for the assessment of potential groundwater pollution hazard by coupling to a weighted-index site assessment method such as DRASTIC or Seepage or others (Merchant et al., 1987; Evans and Myers, 1990; Regan, 1990; Halliday and Wolfe, 1991; Munnink and Geirnaert, 1991; Rundquist et al., 1991; Hendrix and Buckley, 1992; Richert et al., 1992; Zhang et al., 1993; Hammen and Gerla, 1994; Kellogg et al., 1994); and to simple index-based models such as Rao et al.'s (1985) Attenuation Factor model (Khan and Liang, 1989), Shaffer et al.'s (1991) NLEAP model (Wylie et al., 1994), and Meeks and Dean's (1990) Leaching Pesticide Index model (Pickus et al., 1993). However, all of these approaches assumed steady-state conditions. Subsequently, Bleecker et al. (1990), Petach et al. (1991)) and Corwin et al. (1993a, b) used transient-state solute transport models coupled to a GIS to assess the leaching potential of some common nonpoint source agricultural chemicals under nonequilibrium conditions. However, the work of Bleecker et al. (1990) and Petach et al. (1991) did not use field measurements of input parameters for their model LEACHM. Rather, the input parameters were generalized from sources such as Soil Conservation Service soil survey maps. Hutson (1993), Hutson and Wagenet (1993), and Bleecker et al. (1995) have expanded on the previous work of Petach et al. (1991).

The experimentation and associated spatial data to test the results of these GIS-based NPS pollutants models have been essentially nonexistent. Corwin et al. (1989) provided a traditional nonspatial statistical analysis of measured and predicted results by separating a data set of measured soil root zone salinities into two subsets; using one data set for model development and the other for model validation. The resultant statistical analysis showed a linear regression between measured and predicted values with a slope of 1 .O and y-intercept of zero, but an $R^2 = 0.80$. Typically most models used to simulate NPS pollutants have been validated under similarly less than convincing and rigorous approaches. For example, rating maps of soil nitrate leaching potential have been created using LEACHM-N and NLEAP by Khakural and Robert (1993). Both models were tested but only using data from a lysimeter study (Khakuaral and Robert, 1993). The most significant studies to evaluate the potential reliability of using GIS-based NPS pollutant models with nonmeasured input data (i.e., input data estimated from pedotransfer functions or obtained directly from soil survey data) have come from uncertainty studies conducted by Loague and colleagues (Loague et al., 1989, 1991, 1994; Loague and Green, 1990; Loague et al., 1990). Loague and colleagues ultimately showed that the "best use of the regional scale chemical leaching assessments based upon modeling approaches as simple as index methods is for guiding data collection strategies" (Loague, 1994).

The intended aim of coupling a GIS to a solute transport model is to provide decision makers with a tool for attaining the desired goal of a sustainable agriculture. Economic concerns are as crucial a component in sustainable agriculture as environmental impact. To account for economic concerns, Opaluch and Segerson (1991) have incorporated a microparameter distribution model for capturing economic responses to alternative agricultural management policies into a GIS that enables the development of aggregate farm management policy while maintaining a focus on the site-specific aspect of groundwater contamination. The physical characteristics affecting pollution potential were summarized by a single statistic, a DRASTIC score. However, the relationship between pollution and such factors as soil characteristics and management practices could have been determined with several other models (e.g., LEACHM or others).

CONFERENCE OVERVIEW

Recognizing the importance of the assessment of NPS pollutants in the vadose, the ASA-CSSA-SSSA sponsored the 1995 Bouyoucos Conference *Application of GIS to the Modeling of Nonpoint Source Pollutants in the Vadose Zone* held in Riverside, CA (l-3, May 1995). A total of 17 keynote/invited papers and 38 volunteered papers were presented over a 3-d period. The 17 keynote invited papers concerned assigned topics designed to provide general reference information about the subdisciplines (i.e., spatial statistics, GIS, remote sensing, and solute transport modeling) involved with modeling NPS pollutants in the vadose zone in a GIS context. The volunteered papers provided specific examples of state-of-the-art research that integrated these subdisciplines.

Eight keynote and nine invited presentations were specifically designed to summarize previous research that had brought researchers to the current state of understanding. An overview of GIS as it pertained to environmental impact assessment was adeptly presented by the keynote addresses of Peter Burrough, Michael Goodchild, and Jack Dangermond. Michael Goodchild focused on advanced information technologies useful in assessing environmental impacts including GIS, remote sensing, and the global position system (GPS). Peter Burrough discussed the basic principles, advantages, and problems of (i) linking data and models, and (ii) linking models and GIS with particular attention paid to questions of uncertainty, spatial and temporal variation, scaling, model calibration, model validation and error propagation. Jack Dangermond addressed current commercial applications of GIS to environmental impact analysis.

The remaining keynote presentations dealt with geostatistics, deterministic, and stochastic models of solute transport, the implementation of transport models into GIS , and scale dependency. Andre Joumel expounded on the use of geostatistics as a means of drawing additional information from samples at a limited number of points and identified the biggest challenge as facing up to the uncertainties involved with spatial data that become shrouded in definitive answers generated from maps and statistics that do not include probability maps to assess uncertainty. David Maidment outlined an eight-step program of describing pollutant transport through the vadose zone and implementing it with GIS. Rien van Genuchten surveyed the current state of deterministic modeling of soil water flow and transport with an emphasis on the use of pedotransfer functions that can parameterize the movement of chemicals. William Jury suggested the use of a stochastic-convective formulation (parallel soil columns) as the most compatible means of coupling a stochastic model of solute transport in the vadose zone to a GIS. The challenge of such an approach is the development of a local-scale model whose parameters can be related to identifiable local-scale features. Jeff Wagenet introduced the issue of scale and aggregation level in leaching models and suggested that there should not be on approach to modeling, but many, each linked to an appropriate combination of physical resolution and intent of the investigator. An understanding of the processes, and the spatial and temporal scales at which they operate is important before choosing to work with any given model to solve any given problem.

The invited presentations were designed to be more parochial by reviewing specific issues concerning NPS pollutants in the vadose zone. Topics included the NLEAP/GIS approach for identifying and mitigating regional NO_3–N (M. Shaffer); the spatial structure of solute transport variability in unsaturated field soil (T. Ellsworth); the mapping of the area1 distribution of soil organic C and sorption potential with electromagnetic induction (D. Jaynes); the estimation of soil hydraulic parameters for regional-scale applications of mechanistic models (D. Timlin); the significance of sensitivity analysis in regional-scale solute transport modeling (T. Addiscott); the use of soil survey data for modeling solute transport in the vadose zone (J. Bouma); the application of soil survey attribute data to GIS pollution transport, fate, and other resource assessment models (R. Nielsen and T. Sobecki); the impact of data uncertainty upon regional-scale leaching assessments of NPS polutants (K. Loague); and the current state of subsurface modeling in the simulation of global environmental change (L. Steyaert).

A key issue deserving of further discussion is that focused on in Keith Loague's presentation concerning data uncertainty and its impact on the results of analysis and modeling. Several suggestions were made for dealing with the uncertainty issue and improving the quality of analysis. First, it would be helpful if the locations of field measurements could be shown on maps. This is not standard practice in soil mapping, but its use would add to the value of the data and provide indirect indicators of the spatial variation in quality. Second, methods of interpolation between field measurements should be documented. A wide range of methods of spatial interpolation are available in the current generation of GIS software, and each make a different assumption in producing a wide range of estimates. Documentation of the method would help assess the uncertainties associated with point estimates of interpolated variables. Third, uncertainties should be determined wherever possible, and maintained in digital form as a separate overlay for analysis. Fourth, the impact of sample size on uncertainty should be evaluated and documented where possible, perhaps using Monte Carlo simulation. Finally, the spatial resolution of the data and analysis should be linked as far as possible to explicitly stated assumptions about processes. Lack of such linkages is a common source of problems. To assess the impacts of uncertainty, standardized, objective criteria and metrics are needed that can be used for model validation.

The volunteered papers were dominated by demonstrations of the integration of GIS and deterministic solute transport models, ranging from simple regression models to complex numerical models. Particularly noteworthy was the work presented by M. Soutter and Y. Pannatier that concerned the integration of transport modeling, geostatistics, and stochastic modeling to identify regional-scale groundwater vulnerability to pesticide leaching in Switzerland. The approach used soil and meteorological information, and also used uncertainty analysis. It demonstrated all aspects of GIS-based NPS pollution modeling that served as the theme of the conference. Several case studies were presented that assessed regional-scale groundwater vulnerability to the leaching of pesticides, nitrates, radionuclides, and salts. Other topics included emerging trends and bottlenecks in coupling vadose zone models and GIS, the effect of input parameter and spatial resolution of data sources on solute transport predictions, the problem of identifying spatial and temporal variability of soil factors that influence transport, geostatistical analysis of a soil salinity data set, and baseflow mapping as a means of ranking the relative potential for transmitting contaminants through the vadose zone into an aquifer.

POINTS OF FUTURE STUDY

Three ares of more intensified study are needed to enhance the capability of modeling NPS pollutants in the vadose zone: more cost-effective and efficient methods/instruments of measuring transport parameter data at an increased resolution, a knowledge of the uncertainities associated with the visualized results generated from transport models coupled to a GIS, and continued research into those mechanisms involved in solute transport in the vadose zone that are not clearly understood (e.g., preferential flow).

Reliable and cost-effective approaches for measuring the spatial distribution of transport parameters have not kept pace with developments in solute transport modeling or GIS applications to NPS pollutants. The array of instrumentation needed to measure all the parameters in even the simplest of transport models for the vadose zone is not available and in most cases is not even on the drawing board. Because of this lag, the thirst for data essential to model NPS pollutants has driven researchers to develop transfer functions that use basic soil properties to derive sophisticated transport parameters. This has resulted in a low level of success because of the extreme uncertainty associated with the estimated transport parameters. The need for direct measures of transport parameters with remote instrumentation cannot be stressed enough. The greatest progress needs to be made in the area of instrumentation.

Currently, GIS applications for the modeling of NPS pollutants have burgeoned to a point where generated maps of groundwater pollution vulnerability and of solute accumulation in the vadose zone may be creating a false sense of confidence in the information for nontechnical decision makers. An analogy has been drawn that the sophisticated visualization capabilities of GIS can cloak the limitations of models of NPS pollutants just like fine wrapping paper hides the quality of a cheap present. The nontechnical decision makers who rely on the display maps of NPS pollution are visually seduced into accepting as absolute the boundary lines separating innocuous from toxic zones of contamination, This can lead to misguided decisions that may unfairly discriminate against manufacturers of an acceptable product or practitioners of an acceptable resource management strategy, while potentially overlooking those products and individuals responsible for environmental degradation (Loague, 1994). As suggested by Loague (1994), associated maps of uncertainties need to accompany pollution hazard assessment maps to reduce the risk associated with decisions based on models.

Even though the fate and movement of solutes in the vadose zone has been intensively studied since the 1950s, there are still gaps in our knowledge. These gaps are not just small cracks that need to be filled, but rather of considerable consequence when considering the potential for migration of contaminants to the groundwater. In particular, the inability to model preferential flow poses a challenge to soil physicists. It is well known that preferential flow can be responsible for the rapid movement of usually small volumes of pollutants that are potentially high in concentrations. This can occur for both point or nonpoint sources. Preferential flow can result in nearly a direct movement of the pollutant at its original concentration, though at a much reduced volume, from the soil surface to the groundwater. It is this rapid movement of low volumes of a pollutant at high concentration that poses the greatest threat to groundwater systems.

EPILOGUE

The proliferation of GIS-based deterministic models of NPS pollutants in surface and subsurface soil and water systems is cause for optimism and caution. Developing technologies, like GIS and remote sensing, are catalysts for innovative approaches to heretofore unsolvable problems. If nothing else, new technologies spawn innovation by inspiring unconventional applications of the newly developed technology. The GIS can serve as the catalyst to bring transport modeling, data acquisition, and spatial statistics into a self-contained package to address NPS pollution problems. On a more pessimistic note, GIS can create the illusion of legitimacy by making the package more appealing than the contents warrant. In addition, GIS reduces variation by providing lines of delineation between properties that are fuzzy in reality. Caution must be taken not to fall into the trap of allowing GIS to create black-and-white pictures of the impact of NPS pollutants on the environment. Concomitantly, models, though intrinsic to the scientific method, should not supplant observation, but rather complement observation. Even though the misinterpretation and misuse of models may be an expected consequence of differences in the nature of the ventures of science and professional practice as Philip (1991) pointed out, the application of environmental models should augment and not replace actual observation regardless of the user.

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