SYMPOSIUM PAPERS

Advanced Information Technologies for Assessing Nonpoint Source Pollution in the Vadose Zone: Conference Overview

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ABSTRACT

The information age has ushered in an awareness of and concern for global environmental problems such as climatic change, ozone depletion, deforestation, desertification, and nonpoint source (NPS) pollution. Nonpoint source pollution is the single greatest threat to surface and subsurface drinking water resources. Nonpoint source pollutants also pose a threat to sustainable agriculture, which is viewed as the most viable means of meeting the food demands of a world population that is expected to reach 9.4 billion by the middle of the next century. The ability to accurately assess present and future NPS pollution impacts on ecosystems ranging from local to global scales would provide a powerful tool for environmental stewardship and guiding future human activities. Assessing NPS pollutant is a multidisciplinary problem. To address the problem, advanced information technologies and methodologies are needed that draw from all areas of science and are applied in a spatial context. It was from this setting that the 1997 Joint AGU Chapman/SSSA Outreach Conference *Application of GIS, Remote Sensing, Geostatistics, and Solute Transport Modeling for Assessing Nonpoint Source Pollutants in the Vadose Zone* (19–24 Oct. 1997, Riverside, CA) materialized. The objective of the conference was to examine current multidisciplinary technologies and methodologies for assessing NPS pollutants in the vadose zone, and to explore new conceptual approaches. It was the conference's goal to provide a forum to stimulate multidisciplinary interaction to enhance the development of techniques for the real-time measurement and modeling of NPS pollution in the vadose zone and subsurface waters.

THE INFORMATION-TECHNOLOGY AGE of the 1990s is a time of global environmental consciousness where the ramifications of environmental stewardship stretch even into political arenas. Historically, science and technology have taken a back seat to political concerns in the decision-making process. Science and technology are no longer merely tools of national development, but rather they are becoming integral parts of the international political landscape as evidenced by the 1992 Earth Summit Conference in Rio de Janeiro and the 1997 Kyoto Climate Summit. A knowledge and understanding of how resource utilization in individual countries impacts the global environment and associated political ramifications is essential to guide sound national and international policies.

Environmental issues such as climatic change, ozone depletion, erosion, deforestation, desertification, and NPS pollution are of growing concern to industrialized and even nonindustrialized countries of the world. These problems are exacerbated by the trend in world population, which has doubled since 1950 and is expected to reach 9.4 billion by the middle of the next century (World Resources Institute, 1996). The world's industrialized countries now recognize that environmental issues are no longer parochial concerns defined by community, city, state, national, or even continental boundary lines, but rather are global in perspective.

Because of the potential global impact of mankind's activities, it is no longer efficacious to address environmental issues as isolated or compartmentalized problems. Concomitantly, the scientific weaponry necessary to combat these global issues must be technologically sophisticated to deal with the spatial scale and complexity of the problems. Technologies and methodologies are needed that draw from all areas of science and cross over boundaries of scientific disciplines and subdisciplines just as the problems themselves are interdisciplinary. It is against this backdrop that scientists addressing environmental problems find themselves, and from which the 1997 Joint American Geophysical Union (AGU) Chapman/Soil Science Society of America (SSSA) Outreach Conference *Application of GIS, Remote Sensing, Geostatistics, and Solute Transport Modeling for Assessing Nonpoint Source Pollutants in the Vadose Zone* (19–24 Oct., 1997; Riverside, CA) materialized.

It is the objective of this paper to bring the NPS pollution problem, specific to the vadose zone (i.e., the unsaturated region from the soil surface to the groundwater table), into perspective and to discuss the multidisciplinary approach needed in the assessment of NPS pollutants. This paper serves as a preface to integrate the disparate papers presented at the Joint AGU Chapman/SSSA Outreach Conference, some of which are presented in this special symposium section of the *Journal of Environmental Quality* and others (i.e., keynote and

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Abbreviations: NPS, nonpoint source pollution; AGU, American Geophysical Union; GPS, global positioning system; NCGIA, National Center for Geographic Information and Analysis; REV, representative element volume; EM, electromagnetic induction.

invited papers) currently in press (see Corwin et al., 1999b).

EXTENT AND SIGNIFICANCE OF THE NONPOINT SOURCE POLLUTION PROBLEM

Among the foremost global issues is satisfying the ever-growing need for natural resources to meet food and living-standard demands, while minimizing impacts upon an environment that already shows signs of serious levels of biodegradation (Corwin and Wagenet, 1996). There is concern for the future availability of limited natural resources such as water and productive agricultural soil. Not only the availability of finite resources, but the condition of those resources as impacted by domestic, industrial, and agricultural activities is of concern. The condition of soil and water resources is primarily affected by point source and NPS pollutants. Point source and NPS pollutants differ solely in the scale and the areal extent of their source. Nonpoint source pollutants in terrestrial systems refer to "those contaminants in surface and subsurface soil and water resources that are diffuse, or rather, are spread over large areas" (Corwin, 1996). Nonpoint source pollutants of the vadose zone primarily include pesticides, fertilizers, trace elements (such as B, Mo, and As), and salinity.

As pointed out by Duda (1993), the magnitude of NPS pollution is so complex and difficult to characterize that it defies proper evaluation with respect to its global environmental impact. Nonpoint source pollutants are recognized as *the* major contributors to surface and groundwater contamination worldwide (Duda, 1993) and agriculture remains as the single greatest contributor of NPS pollutants (Humenik et al., 1987). Globally, 30 to 50% of the earth's surface is believed to be affected by NPS pollutants (Pimental, 1993). Even within the highly industrialized USA where point source industrial pollutants abound, NPS pollutants impair far more rivers and lakes than point sources (USEPA, 1994). About 80% of the assessed rivers and lakes in the USA are impaired by NPS pollutants, and only 20% by point sources (USEPA, 1994). Most of the reason for this is because developed countries have concentrated their effort on controlling point-source pollutants because of the difficulty in regulating diffuse sources of pollution.

Maintaining a delicate balance between agricultural productivity and minimizing agriculture's impact on the environment is crucial to sustaining a projected global population range of between 7.9 to 11.9 billion by 2050 in lieu of agriculture's prominent role as a contributor of NPS pollutants to soil and water resources (World Resources Institute, 1996). It is self-evident that the ability to assess the environmental impact of NPS pollutants at local, regional, and global scales on a real-time and predictive basis is a key component to achieving sustainability of the environment and agriculture.

Historically, public attention to the NPS pollution of water resources has focused upon the pollution of surface water supplies. Limited surface water supplies and increased demand by agricultural and domestic sectors have placed greater dependency upon groundwater supplies. Currently, half of our drinking water needs and 40% of the irrigation water needs in the USA are met by groundwater supplies. Because of this increased dependency upon groundwater resources, public consciousness has shifted to the protection of groundwater resources and of the overlying soil that serves as a conduit for the movement of pollutants from the soil surface.

The significance of the NPS pollution problem lies in the ramifications to human health. The protection of groundwater resources from NPS pollutants has become a primary concern because of the public's apprehension over long-term health effects of drinking water containing small concentrations of toxic chemicals. A secondary concern is the accumulation of significant levels of inorganic (e.g., salinity and trace elements) and organic chemicals (e.g., pesticides) in soil that detrimentally impact agricultural productivity and crop quality. The extent of the impact of particularly dangerous contaminants is only now becoming apparent to developed countries. Radionuclides, pesticides, solvents, heavy metals, and petroleum compounds are well known, but a new generation of carcinogens, mutagens, and teratogens are found to cycle from one medium or form to another including various classes of PCBs, furans, dioxins, and organochlorines (Duda and Nawar, 1996). Some chemicals (e.g., Cd, Pb, Hg, DDT and degradation products, methoxychlor, triazine herbicides, synthetic pyrethroids, lindane, PCBs, dioxins, and others) are known to disrupt the endrocrine system causing metabolic, neurological, and immune system abnormalities (Duda and Nawar, 1996).

Ostensibly, the point has been reached where the awareness of NPS pollution is less of a concern than the voluntary and regulatory actions that must follow. Before decision makers can formulate effective regulatory actions, the ability to reliably and cost-effectively assess NPS pollutants on a real-time and predictive basis is of paramount importance. It is through real-time assessment that a continued inventory of the NPS pollution problem can be maintained to determine the extent of the problem and evaluate changes, whether for better or worse, that gauge the effect of regulatory and intended ameliorative actions. In addition, predictive assessments set the stage for posing "what if" scenarios that serve a preventative role by suggesting actions that will alter the occurrence of detrimental conditions before they manifest.

MULTIDISCIPLINARY NATURE OF THE PROBLEM

Solutions to complex global environmental problems stand on the shoulders of technological and interdisciplinary scientific achievements. To solve the problems of climatic change, ozone layer depletion, deforestation, desertification, and NPS pollution, it is necessary to examine these issues from a multidisciplinary, systems-based approach, and to look at these problems in a spatial context.

The formidable barriers to the NPS pollution problem are comprised of the complexities of scale and position; the complexities of the physical, chemical, and biological processes of solute transport in porous media; and the spatial complexities of the soil media's heterogeneity. The knowledge, information, and technology required to address each of these complex issues crosses several subdisciplinary lines: classical and spatial statistics, remote sensing, geographic information systems (GIS), surface and subsurface hydrology, soil science and even space science. Spatial statistics 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 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. Neural networks and transfer functions provide a means of deriving complex solute model parameters from easily measured data. Hierarchical theory establishes an organizational hierarchy of pedogenetic modeling approaches and their appropriate scale of application. Fuzzy logic provides a means of handling vague and imprecise data whether as a means to characterize map units or transitional boundaries between map units. Uncertainty analysis serves as a measure of the reliability of simulated model results. Precise geographic location and areal extent are captured with the space science technology of a global positioning system (GPS).

CONFERENCE GOAL AND OVERVIEW

Methodologies integrating all of the aforementioned advanced-information technologies are the linchpin to effectively assessing NPS pollutants. In particular, GIS has burgeoned as a data management and visualization tool for addressing spatially-related environmental problems. In the past 5 yr, the National Center for Geographic Information and Analysis (NCGIA) has presented three conferences focusing on GIS applications to general environmental issues (see the NCGIA Web Site for details http://www.ncgia.ucsb.edu). The 1995 American Society of Agronomy–Crop Science Society of America–Soil Science Society of America (ASA–CSSA–SSSA) Bouyoucos Conference was the first conference to focus on the application of GIS to the modeling of NPS pollutants specifically in the vadose zone (Corwin and Loague, 1996; Corwin and Wagenet, 1996). The Bouyoucos Conference served as the predecessor to the 1997 Joint AGU Chapman/SSSA Outreach Conference. Broadening the focus beyond GIS, the Joint AGU Chapman/SSSA Outreach Conference addressed the full spectrum of the multidisciplinary application of GIS, remote sensing, geostatistics, and solute transport modeling to the assessment of NPS pollutants in the vadose zone. The objective of the jointly-sponsored conference was to explore current multidisciplinary technologies and methodologies for assessing the impact of NPS pollution upon soil and groundwater resources. Assessment, as used in this context, refers to the in-situ quantification of a NPS pollutant and/or the determination of change of some NPS pollutant over time. This change can be either measured in real time or predicted with a model. It was the conference's goal to provide a forum to stimulate interaction between the subdisciplines of spatial statistics, remote sensing, GIS, and solute transport modeling to enhance the development and evaluation of techniques for the measurement, assessment and modeling of NPS pollution in the vadose zone and subsurface waters.

Thirty keynote/invited papers and 51 volunteered papers were presented during the 4 1/2 d conference. The 30 keynote and invited papers concerned assigned topics designed to provide general reference information about the subdisciplines involved with assessing NPS pollution in the vadose zone. See Corwin et al. (1999b) for a compendium of the conference keynote and invited papers. The volunteered papers provided specific examples of state-of-the-art research that either concentrated on a single aspect or component of the NPS pollution problem, or applied an integrated approach to the NPS problem. The papers in this special symposium section of the *Journal of Environmental Quality* are comprised of selected volunteered papers.

Organizationally, the conference consisted of eight technical sessions plus an introductory session. The introductory session focused on (i) politics, technology, and environmental policy-making; (ii) future trends in commercial GIS software specific to environmental assessment; (iii) the societal value of environmental information; and (iv) the extent of the NPS pollution problem. The subsequent eight technical sessions consisted of (i) integrated information technology approaches to NPS pollution problems; (ii) subsurface solute transport modeling; (iii) spatial statistics, geostatistics, and uncertainty analysis; (iv) transfer functions, estimation methods, and parameterization; (v) remote sensing and noninvasive techniques; (vi) problems of scale and scaling; (vii) quantification of spatial variability and soil-landscape models; and (viii) case studies.

The conference opened with an "ivory-tower shattering" keynote address concerning the role of environmental modeling in the decision-making process. John King noted the gradual convergence of policy-makers and environmental modelers, but warned that modelers must be aware that the policy process is necessarily about politics and that models used in that realm are applied as political weapons—not as unbiased tools. The notion that science and technology will mitigate environmental problems on a "truth wins" basis is illusionary. The success of GIS-linked models in policy-making simply depends on the model's ability to serve the analytical needs of the greatest number of policy makers even if they are in political opposition. Furthermore, even though scientific and technological advances are viewed as critical for the successful management of environmental issues, it is unlikely that scientists will play central roles of power and authority in the decision-making process. Subsequent keynote addresses dealt with the advanced information technologies needed to assess NPS pollutants in the vadose zone. John Wilson focused on current and future trends in the development of integrated methodologies for assessing NPS pollution. He suggested that the explosive growth in data capture technologies has caused a data-rich, but information-poor condition that has led to the fragmentation of GIS applications because commercial GIS software cannot keep pace with the growth in niche implementations. Geographic information sytems is in serious need of linkage to software that improves data- and process-modeling capabilities to provide a knowledge-rich system.

The session on subsurface solute transport modeling began by Graham Fogg expounding the virtues of an integrated analysis of both vadose zone and groundwater processes to address aquifer vulnerability. This analysis may be accomplished by applying geomorphological modeling and hydrostratigraphic structure to account for the spatial variability of flow within and below the vadose zone. William Jury noted that stochastic approaches to modeling NPS pollutants in the vadose zone at regional scales are the only viable approach because extensive spatial variability of water flow and solute transport properties make deterministic modeling unfeasible at this scale, necessitating some form of approximate stochastic approach using a local model representation that extrapolates from limited sample data. Donald Myers surveyed the role of spatio-temporal statistical modeling. Remote sensing and noninvasive techniques were addressed both in general and in a specific application (i.e., geophysical measurements of soil electrical conductivity) by Marion Baumgardner and James Rhoades, respectively.

In a pivotal keynote paper concerning scaling spatial predictability, Philippe Baveye served as the conference's "devil's advocate" by questioning whether GIS was the answer to the spatial problems associated with NPS pollution or, indeed, if it was even part of the answer, and by stabbing directly into the heart of distributed modeling as a viable NPS pollution approach. Philippe Baveye's paper tweaked a cerebral nerve that placed it apart from all other conference presentations making it a centerpiece worthy of greater discussion and of pause for thought. Professor Baveye drew an analogy between the present state of knowledge of modeling NPS pollution and development of thermodynamic gas laws from physical theories of particle dynamics. Newton originally derived the fundamental equations describing the motion of a particle about the central potential field resulting from another particle. These equations are uniquely soluble and describe the motion of conic orbits. The introduction of a third particle, however, results in a situation where no solution can be found and as more particles are introduced, the analytical intransigence continues. Despite the inability to predict the individual motions of gas particles in a container from Newton's fundamental equations, an independent line of theory, initially driven by the need to improve the efficiency of the steam engine, led to the formulation of the thermodynamic gas laws. The thermodynamic gas laws are extremely simple statements concerning how properties of an ideal gas system change subject to alterations in applied constants (i.e., how pressure changes when the temperature or volume is altered). Thus, despite the inability to predict larger-scale behavior from smaller-scale conceptual understandings, there are coarser-scale descriptions that allow accurate predictions of the system. Analogously, scientists may be studying NPS pollution at a level of understanding and detail dictated by measurement instruments such as remote sensing and information technology tools such as GIS rather than at a level dictated by the appropriate conceptual framework. Furthermore, the fundamental unit for landscape study is often specified as a catchment or watershed, or even more arbitrarily by survey or geopolitical boundaries (i.e., quarter section lines or water district boundaries), without knowing if these units are meaningful or whether they are the appropriate levels of aggregation for subsurface solute transport. Potentially, scientists are being asked by policy makers to predict at a level of detail something that is inherently unpredictable. This suggests the need for exploration of the scales, or ranges of scales, at which the dynamics of processes are drastically simplified, which falls in line with a quote from Einstein concerning the parsimony of model design, "Models need to be as simple as possible, but not any simpler."

The invited presentations were intended to be more parochial by focusing on specific issues concerning the assessment of NPS pollutants in the vadose zone. From an economics perspective, Richard Bernknopf provided an approach for the estimation of the societal value of information for assessing NPS pollution. A series of subsurface solute transport modeling papers covered applications and philosophical issues. Donald Suarez suggested a reevaluation of the generally accepted notion that sophisticated mechanistic models may be unrealistic for field- or regional-scale applications. This reevaluation is based on advances in remote data collection, geostatistical techniques, and advances in the understanding of soil chemical processes (i.e., the substitution of kinetic models for equilibrium assumptions and representation of adsorption processes with defined surface species rather than site-specific empirical parameters). Jin-Ping Gwo performed a numeric examination of the multiscale effects of mass transfer processes on contaminant transport at a watershed scale and quantified the uncertainties when small-scale processes are upscaled to a watershed. Jetse Stoorvogel and Johan Bouma conducted a risk assessment in space and time for nematicide leaching in a Costa Rican banana plantation using the LEACHP model. John Norman provided a broader perspective by addressing the role of soil-plant-atmosphere models in NPS pollution. Finally, David Mulla tackled the problem of model validation by outlining factors to consider in validating NPS pollution models at moderate to large scales. Invited papers concerning transfer functions and parameterization involved (i) the application of artificial neural networks for developing pedo-transfer functions of soil hydraulic properties by Henk Wösten and S. Tamari; (ii) the accuracy and reliability of pedo-transfer functions for use in regional-scale modeling by Yakov Pachepsky and his colleagues; and (iii) an impressive study by Mark Rockhold using geostatistical methods, similar-media scaling, and conditional simulation with soft data for the parameterization of flow and transport models.

The contingent of invited speakers concerning remote sensing and noninvasive techniques remained true to their professional stature by providing informative reviews of remote sensing to surface and subsurface hydrologic measurements. NASA's Ted Engman provided an overview of remote sensing in hydrology. More specifically, Thomas Schmugge addressed the potential for deriving soil hydraulic properties in the vadose zone with remote sensing. Finally, Wim Bastiaanssen reviewed the current state of spatially delineating actual and relative evapotranspiration from remote sensing.

The entire session for the quantification of spatial variability consisted of invited speakers because the ability to delineate and quantitatively represent spatial variability is a key to the application of GIS to the modeling of NPS pollutants in the vadose zone. Richard Ferguson began with a survey of the sampling and spatial analysis techniques useful in quantifying the composition of soil map units. The timely and practical topic of incorporating spatial variability into existing soil databases was discussed by Russ Yost. Fuzzy logic and inference techniques were used by A.-Xing Zhu to derive more accurate and detailed soil spatial information that allow the realistic characterization of the spatial joint distribution of landscape parameters for distributed modeling at the watershed scale. A particularly scholarly and informative discussion of fractal applications to soil properties and solute transport in porous media was presented by John Crawford. The final conference paper presented by John Letey dealt with the controversial question, "Is modeling supplanting observation rather than complementing it?" Professor Letey indicated that the answer to this question is intuitively obvious from the plethora of unvalidated models, and that modeling should not serve as a substitute for experimentation and observation. Rather, modeling and experimentation should be ongoing processes that reciprocally enhance one another.

The volunteered papers were dominated by integrated information technology approaches and case studies. A particularly noteworthy and encouraging trend, in contrast to earlier GIS-linked NPS pollution modeling papers presented at the Bouyoucos Conference, was the significant increase in the application of uncertainty analysis to augment the modeling studies as a source of reliability information as recommended from the work by Loague and his colleagues (Loague et al., 1996).

PIECING THE NONPOINT SOURCE-POLLUTION ASSESSMENT PUZZLE TOGETHER

Integrated systems for the prediction and real-time measurement of NPS pollutants are more clearly discussed in the context of the individual components that comprise the pieces of the NPS-pollution puzzle (Corwin et al., 1997). These components are dependent upon the advanced information technologies of GPS, GIS, geostatistics, remote sensing, solute transport modeling, neural networks, transfer functions, fuzzy logic, fractals, scale and scaling, hierarchical theory, and uncertainty analysis. Corwin et al. (1997) discussed in detail the role and the interrelationship of these advanced information technologies within an integrated GIS-linked NPS pollution model.

Geographic Information System-Linked Modeling of Nonpoint Source Pollution in the Vadose Zone

Ever since the classic paper by Nielsen et al. (1973) concerning the variability of field-measured soil water properties, scientists have been aware of the spatial complexity of soil, and the complexity of solute transport in soil. Because of the spatial complexity of soil, modeling the fate and movement of NPS pollutants in the vadose zone is a spatial problem well suited for the coupling of a deterministic or stochastic solute transport model with a GIS (Corwin et al., 1997). Corwin et al. (1997) defined GIS-linked NPS pollution models as an integrated system of three basic components: model, GIS, and data. The subcomponents of geostatistics, fuzzy logic, and uncertainty analysis provide enhanced, higher-order information that augments and refines the system.

Primary Components

Solute Transport Model

A model seeks to extract the essence from experimental data through the formulation of mathematical representations of the relevant processes constituting a system (Corwin et al., 1999a). In the case of NPS pollutants, the mathematical formulations describe the appropriate chemical, physical, and biological processes involved in the transport of a solute through the vadose zone within the context of a GIS that contains model input variables and parameters that are spatially referenced (Corwin et al., 1999a). Corwin and Loague (1996) and Corwin et al. (1997, 1999b) provided in-depth discussions of modeling specific to NPS pollutants in the vadose zone.

Model conceptualization is governed by the intended application of the model (Corwin et al., 1999a). The intended application determines the scale; the scale determines the predominant processes, and the level of spatial variability that must be accounted for in the model; the predominant processes determine the type of modeling approach (i.e., functional or mechanistic, qualitative, or quantitative) that should be used (Corwin et al., 1999a). Addiscott and Wagenet (1985) have categorized solute transport models based upon two main conceptual approaches: deterministic and stochastic models. Deterministic models "presume that a system or process operates such that the occurrence of a given set of events leads to a uniquely definable outcome" while stochastic models "presuppose the outcome to be uncertain" (Addiscott and Wagenet, 1985). Arguably, mechanistic-deterministic models are generally better suited as research models that help to understand the interrelationship between the physical, chemical, and biological processes influencing solute transport, while functional-deterministic and stochastic models are more effective as practical applications to real-world problems.

Historically, the inventory of developed deterministic models of solute transport has been far greater than stochastic models. This is no surprise because deterministic models date back over half a century, while stochastic models first made an appearance only 15 yr ago with Jury's introduction of the transfer function model (Jury, 1982). Even though stochastic modeling has gained momentum, the development of deterministic models still has out paced stochastic models over the past 10 and even 5 yr (Corwin et al., 1999a). The greatest barrier to stochastic modeling probably lies in the large amount of data needed to formulate the statistical moments or probability distributions.

Even though the number of developed deterministic models far outweighs the number of stochastic models, there are strong and almost incontrovertible arguments for the use of a stochastic over a deterministic model with respect to the simulation of NPS pollutants. The most compelling argument is that stochastic modeling is "virtually the only viable option to pursue in making large-scale simulations of chemical movement" because "a fully deterministic model would require soil property data for every point in three-dimensional space over which the simulation is to be run" (Jury, 1996). Jury (1996) argued that because no one will ever be able to characterize every point in three-dimensional space, then modeling water flow and solute transport at scales greater than a small plot must use a stochastic approach of one kind or another by necessity.

A review of GIS-linked NPS pollution models of the vadose zone has shown that nearly all are one-dimensional deterministic models coupled to a GIS (Corwin et al., 1997). Corwin et al. (1997) categorized GIS-linked NPS pollution models into three categories: regression models, overlay and index models, and transient-state models. Deterministic GIS-linked models have dealt with spatial complexities by coupling a one-dimensional, deterministic model of solute transport to a GIS consisting of a collection of discrete map units where each map unit represents a contiguous area of homogenous solute transport model parameters (such as, adsorption-desorption coefficients, diffusion-dispersion coefficients, and hydraulic conductivity) and variables (such as, irrigation and precipitation amounts, and evapotranspiration). These "homogeneous transport units" represent noninteracting, spatial domains where the lower limit of measurement scale at which variability between measurements is least. This is analogous to the representative element volume (REV) defined by Bouma (1990) and Mayer et al. (1999), and the "stream-tube" defined by Jury and Roth (1990). Simulations performed on each discrete "homogeneous transport unit" rendered predictions of solute profile distributions and solute loads to the groundwater. However, the assumption of a homogeneous transport unit might be an oversimplification because solute transport properties within each of these units are still spatially variable and should be statistically represented by probability distributions.

Temporal and spatial scale dictate the general type of model. Models of solute transport in the vadose zone exist at all scales with hierarchical theory indicating the appropriate model for the scale of interest (Wagenet and Hutson, 1996). An important consideration in model conceptualization is for the model to account for the predominant processes occurring at the spatial and temporal scales of interest. Qualitatively speaking, as spatial scale increases, the effects of complex local patterns of solute transport are attenuated and become dominated by macroscale characteristics; so, as scale changes, different factors and processes may become dominant. A complete discussion of the application of models at different spatial and temporal scales was given by Wagenet (1993) and Wagenet and Hutson (1996). Fractals provide a potentially useful tool for solute transport modeling because they are mathematical constructs with complex geometries that have no characteristic scale; consequently, they have been used to model processes across a range of scales. As such, fractals can serve as "thought tools" to avoid naive modeling assumptions and as components of predictive models (Crawford et al., 1999).

The magnitude and variability of a soil property often varies with measurement scale. Wagenet and Hutson (1996) discussed this issue of upscaling in greater detail and concluded that sampling and measurement methods for both input parameters and observations to evaluate model performance need to be consistent with the modeling scale. They also noted that models that are developed for a specific spatial scale are often calibrated with data from a much different scale, resulting in model parameters that have little physical significance, and a modeling approach that is questionable.

Geographic Information Systems

Geographic information systems have been succinctly defined by Parker (1988) as "an information technology that stores, analyzes, and displays both spatial and nonspatial data." Since the 1970s, GIS has burgeoned from a computer-based cartographic tool to a sophisticated information technology that can be applied to any georeferenced property or attribute, or even nonspatial information. The GIS has developed into an extremely beneficial tool for the organization, manipulation, and display of information associated with spatial environmental problems such as NPS pollution whether atmospheric, terrestrial, or aquatic.

Even though tremendous advances in GIS have occurred during the short span of 20 yr, commercially-available and public-domain GIS software still do not contain the cadre of statistical routines nor the internal software development flexibility needed to make the modeling of NPS pollutants an easy task. This has prompted a plethora of GIS-linked solute transport models "loosely" coupled to a GIS rather than embedded in the GIS (see the review by Corwin et al., 1997).

The GIS serves as a viable means for representing the complex spatial heterogeneity of the real world through integrated layers of constituent spatial information. To model NPS pollution within the context of a GIS, each parameter or variable of the deterministic transport model is represented by three-dimensional layers of spatial information. The three-dimensional spatial distribution of each transport parameter/variable must be measured or estimated. This creates a tremendous volume of spatial information resulting from the complex spatial heterogeneity exhibited by the numerous physical, chemical, and biological processes involved in solute transport through the vadose zone. The GIS serves as the tool for organizing, manipulating, and visually displaying this information efficiently.

The basis of the application of GIS to NPS pollution is the association of property attributes with spatial location. Global positioning system is an invaluable tool for quick and accurate georeferencing of soil sample sites, thereby providing a cartographic location for soil physical and chemical property data, plant property data, and/or NPS pollutant concentration data.

Wilkinson (1996) noted that as the demand for spatial information grows, there is an ever-increasing complimentarity between remote sensing and GIS. For instance, remote sensing can be used to gather datasets for use in a GIS, and these datasets can be used as ancillary information to improve remotely-sensed imagery, or GIS and remote sensing data can be used in conjunction with each other for environmental modeling and analysis. Artificial neural networks have been particularly useful in extracting geographic information from remote sensing imagery (Yoshida and Omatu, 1994; Chen et al., 1995). The simplest way to use preexisting GIS data in the interpretation of remotely-sensed data is in broadly dividing the landscape into major areas with very different characteristics, that is, topographic, phenological, geological, and climatological areas.

Data

Data is the fuel that drives a model. From this perspective, data are the most fundamental component of a NPS pollution model linked to a GIS. Yet, obtaining data in a useful form to meet the input requirements of current NPS pollution models remains a barrier (Corwin and Wagenet, 1996).

Corwin et al. (1997) pointed out three sources of data for GIS-linked NPS pollutant models: (i) existing data from soils and meteorologic databases, (ii) estimated parameter and input data from transfer functions, and (iii) measured data. Examples of existing soils and meteorological databases include: (i) SOTER—a world soils and terrain digital database compiled by the International Soil Reference and Information Center; (ii) SSURGO, STATSGO, and NATSGO—the county-, state-, and national-level soils databases, respectively, compiled by the USDA National Resource Conservation Service; (iii) UNSODA—the soil hydraulic properties database compiled by the USDA-ARS; (iv) NOAA's weather station database; (v) SNOTEL—USDA/NRCS's daily snow and precipitation database; and (vi) CIMIS—the crop evapotranspiration database for California compiled by the California Department of Water Resources. However, most existing databases, particularly soils databases, do not meet even the minimum requirements for many of the distributed-parameter models used for NPS pollutants in the vadose zone; consequently, modelers' thirst for data has driven them to the development of estimation methods such as transfer functions and artificial neural networks. Transfer functions relate readily-available and easy-to-measure soil properties to complex soil parameters and variables. A table of cited references for transfer functions of various solute transport model parameters has been compiled by Corwin et al. (1997). Artificial neural networks are useful in solving multivariate nonlinear problems such that an output variable is explained by a set of input variables (Hush and Horne, 1993). Neural networks are an alternative to predict soil parameters and variables from other quantitative or qualitative soil variables (Pachepsky et al., 1996; Tamari et al., 1996). Remote sensing and noninvasive techniques offer considerable promise for the measurement of some of the parameters and input variables used in modeling NPS pollutants (Corwin et al., 1997). Corwin et al. (1997) reviewed the current status of remote sensing and its application specifically to modeling NPS pollutants in the vadose zone. Even though remote sensing holds great future promise for fulfilling the input data needs of NPS pollutant models, it has so far fallen short of expectations because of the initial overselling of remote sensing's environmental utility without the fundamental research to backup initial boastful claims. Similarly, the real-time measurement of NPS pollutants in the vadose with remote sensing instrumentation is limited.

Subcomponents

Geostatistics

Corwin et al. (1997) listed the multiple support role of geostatistics in a GIS-linked NPS pollutant model including (i) the determination of the suitability of data as model input, (ii) the estimation of data at locations where no data exist, and (iii) the post-processing of model simulation results. The preprocessing of data with preliminary geostatistical analyses can discover spatial trends, spatial correlation, and erratic data (i.e., specific data values that lie outside the general group). Kriging-type geostatistical techniques are useful as an interpolation tool to estimate data values at unsampled points. Examples of kriging-type techniques and other spatial statistical techniques include kriging, co-kriging, disjunctive kriging, disjunctive co-kriging, sequential indicator simulation, and stochastic simulation. Kriging is also useful as an interpolation techniques for the post-processing of model simulation results. Semivariograms of computed results and initial conditions can be used to indicate changes in spatial variability. From a regulatory standpoint, geostatistics can determine the conditional probability that a particular NPS pollutant concentration value is exceeded.

Fuzzy Set Theory

The variation seen in soil is generally continuous rather than discrete because of geomorphologic processes influencing its genesis and continued alteration. This suggests the need for a continuous rather than a discrete approach to model soil variability. Fuzzy set theory offers a means of modeling the imprecision or vagueness of a soil by quantifying a property according to its membership on a continuous scale rather than on a Boolean binary or an integer scale. Central to fuzzy set theory is the membership function, which is a mathematical relationship that defines the grade of membership with 1 representing full membership, 0 representing nonmembership, and an appropriate function defining intermediate grades between 0 and 1. Aside from representing imprecise or vague data, fuzzy set theory can be applied to transitional boundaries to reflect the gradual changes that actually occur between map unit boundaries on thematic maps. Fuzzy set theory allows for generalization of zones of transition rather than sharp boundaries. Fuzzy sets are a representational and a reasoning device that allow a database to hold information concerning the indistinctness of spatial features (Altman, 1994).

Applications of fuzzy set theory and fuzzy logic in NPS pollutant assessment have included (i) the quantification and classification of map units of soil properties or pollutants, (ii) modeling and simulation of soil processes, (iii) fuzzy soil geostatistics, (iv) soil quality indices, and (v) fuzzy measures of imprecisely defined soil phenomena (see the review of McBratney and Odeh, 1997).

Uncertainty Analysis

The reliability of model predictions is determined by the error associated with its simulated output and intended use of the output. There are three sources of error inherent to all NPS pollutant models: (i) model error, (ii) input error, and (iii) parameter error.

Uncertainty analysis pertaining to risk assessment, risk management, and modeling of NPS pollutants was comprehensively reviewed by Loague and his colleagues (Loague and Corwin, 1996; Loague et al., 1996). In a series of papers by Loague and colleagues, the indispensability of uncertainty analysis as a means of evaluating the reliability of predictions from GIS-linked NPS pollution models was substantiated (Loague et al., 1989; Loague, 1991).

Real-Time Measurement of Nonpoint Source Pollutants

Real-time measurements of NPS pollutants in the vadose zone rely primarily on noninvasive geophysical techniques such as electromagnetic induction (EM). Though generally less desirable because of its disruptive nature and greater labor requirements, soil sampling is considered of greatest value as a means of determining ground truth for the calibration of remote sensing or noninvasive techniques. Electrical resistivity techniques are also quite useful particularly when mobilized (Rhoades, 1999). Electrical resistivity approaches are not particularly invasive, but do require contact with the soil.

Some of the most comprehensive research conducted for the real-time measurement of a NPS pollutant has been for the measurement of soil salinity. Rhoades and his colleagues have made the greatest scientific strides in the development and testing of instrumentation for the real-time measurement and mapping of soil salinity, specifically the measurement of bulk soil electrical conductivity. Rhoades and Corwin first developed empirical, site-specific equations that determined the real-time soil salinity profile from aboveground EM measurements collected at the soil surface in the horizontal and vertical coil configuration (Rhoades and Corwin, 1981; Corwin and Rhoades, 1982, 1990). Lesch et al. (1995) and Hendrickx et al. (1997) have made significant improvements to this early EM work. Real-time mapping of bulk soil electrical conductivity has been demonstrated and used to derive soil salinity management strategies (Rhoades, 1996; Rhoades et al., 1999).

SUMMARY

It is premature to determine whether the 1997 Joint AGU Chapman/SSSA Outreach Conference achieved its goal of stimulating interaction between the attending scientists of the disparate disciplines considered essential to address the problem of assessing NPS pollution of the vadose zone. Rather, the direction of future scientific publications will provide the best indication of the conference's impact. However, the fruit of the labor expended on the conference's predecessor, that is, the 1995 SSSA Bouyoucos Conference, was self-evident at the 1997 Chapman Conference as indicated by the increase in the number of volunteered presentations concerning uncertainty analysis. The association of uncertainties with visualized results generated from transport models coupled to a GIS was cited in the concluding remarks of the Bouyoucos Conference as an area of needed intensified study. Renewed interest in the potential of remote sensing to provide cost-effective and efficient methods of measuring solute transport model input data at an increased resolution was another area cited for intensified study. Evidence of increasing interest in remote sensing was shown by the near capacity attendance at the special sessions on remote sensing held at the 1997 ASA–CSSA–SSSA Annual Meetings (Anaheim, CA; 27–31 Oct. 1997), which followed the Chapman Conference.

Even though there have been tremendous advances in assessing NPS pollution in the vadose zone during the last 10 yr (NRC, 1993; Corwin and Loague, 1996; Corwin and Wagenet, 1996; Corwin et al., 1997), there is much yet to be done. Three obvious limitations to the current use of GIS in regional-scale NPS vulnerability assessments are: (i) the lion's share of GIS-driven modeling applications are only loosely coupled; (ii) in almost all cases data sparsity in space and time over large scales, not computer speed or storage capacity, limits our ability to produce reliable vulnerability assessments; and (iii) most attempts at characterizing model performance have been qualitative in nature.

Not unexpectedly, some of the same research needs cited at the 1995 Bouyoucos Conference still remain because of the short 2-yr time span between the conferences. For example, continued basic and applied research into preferential flow is a high priority because it provides a pathway for the rapid and direct movement of NPS pollutants from the soil surface to groundwater at their original applied concentrations. Intensified development and testing of remote sensing and noninvasive instrumentation and methods are needed to reduce the labor-intensive burden of meeting the data-hungry appetites of NPS pollution models. The continued development of spatial statistical techniques are needed to reduce soil sampling requirements without reducing the characterization of the soil's spatial variability and structure.

Additional research needs became evident at the Joint AGU Chapman/SSSA Outreach Conference including: (i) instrumentation and methodology for the geospatial establishment of spatial domains of statistically homogeneous properties of solute transport and the fuzzy boundaries between these domains; (ii) a clearer understanding of the issues of upscaling of spatial data and its aggregation, as well as downscaling and disaggregation; and (iii) ultimately, the integration of scientific, economic, and political considerations to make NPS pollution assessments with advanced information technologies a decision-maker's, rather than a purely scientific, tool. Economists, information specialists, policy-makers, entrepreneurs and even politicians must become part of the "loop" because these are the individuals who will bring the "ivory tower" technologies to fruition by bridging the sociopolitical and economic barriers that will place them into decision-makers' hands. It is an illusion for scientists to think that their knowledge of technology and pursuit of truth will win out over the practicalities of business and politics, and the public's capricious perceptions. Environmental issues, and especially global environmental issues, are not solely scientific issues nor are they problems that can be solved solely by scientists.

Despite the remaining gaps in knowledge and practical application, positive strides have been made in the short span of 2 yr. The GIS has gained increased legitimacy in the eyes of even the most rigorous of scientists as a tool that, when used knowledgeably, is viable and worthwhile for attacking NPS pollution problems. Similarly, the limitations of GIS have been brought into perspective to the point where it is not misunderstood as a panacea for solving spatial environmental problems, but merely one piece of the puzzle. Rather, an array of advanced information technologies is needed along with the technical expertise and scientific guidance to collectively unravel complicated environmental problems.

Perhaps the forthcoming greatest technological advance for modeling and assessing NPS pollution in the vadose zone will be the ability to perform regional-scale simulations with a system that integrates GIS; solute transport modeling; pedo-transfer functions, neural networks and remote sensing for estimating and/or measuring transport properties; geostatistics for characterizing variability structures and spatial interpolation; fuzzy set theory for handling vague and imprecise data; spatial and temporal analysis; and uncertainty analysis to allow decision-makers to evaluate the reliability of information.

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