

GIS-based modeling of non-point source pollutants in the vadose zone

Dennis L. Corwin, Keith Loague, and Timothy R. Ellsworth

Interpretive summary

Nonpoint source (NPS) pollution such as salinity, trace elements, pesticides, and fertilizers are characteristically spread over large areas at low concentration. An ability to accurately assess the present and future impact of human activities on large-scale and even global ecosystems would provide a powerful basis for environmental stewardship and help guide future human actions. The purpose of this article is to address the general problems and issues involved in modeling NPS pollutants within a spatial and temporal context. The components and considerations necessary to develop GIS-based NPS models of the vadose zone are examined. Even though the current trend of combining GIS with one-dimensional models of solute transport in the vadose zone offers great potential for simulating NPS pollutants, a cautionary note is presented to warn overzealous modelers that GIS should never disguise the legitimacy of simulated results nor should these results ever supplant field observations.

Key words: geographic information system, groundwater vulnerability, solute transport, stream tube, uncertainty analysis.

ABSTRACT: *The information age of the 1990s is a global consciousness where scientific and technological advances are assumed capable of solving global environmental problems. A significant characteristic of nonpoint source (NPS) pollution problems is the lack of regard for political boundaries and physical barriers between cities, states, nations, and continents. The widespread nature of such environmental problems often results in an analogous diffuse acceptance of responsibility for resolution. Thus, an ability to accurately assess the present and future impact of human activities on the global ecosystem would provide a most powerful basis for environmental stewardship and guiding future human actions. To responsibly respond to impaired ecosystem functioning (i.e., with respect to such issues as climatic change, stratospheric ozone depletion, species diversification, erosion, deforestation, desertification, agricultural sustainability, and non-point source pollution), it is necessary to examine these issues not only from a multidisciplinary systems-based approach, but also with an approach that accounts for spatial and temporal context. The problems and philosophical issues of addressing NPS pollution in the vadose zone within a spatial and temporal context are presented.*

Dennis L. Corwin is a research soil scientist at the USDA-ARS, U.S. Salinity Laboratory, Riverside, Ca; Keith Loague is an associate professor at the Department of Geological and Environmental Sciences; and Timothy R. Ellsworth is a associate professor of Soil Physics at the Department of Natural Resources and Environmental Sciences.

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species diversification, erosion, deforestation, desertification, agricultural sustainability, and non-point source (NPS) pollution), it is necessary to examine these issues not only from a multidisciplinary, systems-based approach, but also with an approach that accounts for spatial and temporal context.

Background in NPS pollutants

The assessment of NPS pollutants is a perfect example of a spatially and temporally complex, multidisciplinary environmental problem that exists over multiple scales. In this case, assessment is taken in its larger context to encompass the description of the current state of pollution through real-time measurements and the ability to predict the future fate and transport of pollutants; thus, providing information to guide current and future decision making. NPS pollutants are defined as those pollutants that are spread over large areas at low concentrations as opposed to point source pollutants that are located at a single site at generally toxic levels. NPS pollutants are ubiquitous in nature, making remediation efforts extremely complex and difficult; have the potential for maintaining a relatively long active presence in the global ecosystem; and may result in long-term, chronic health effects in human and other life forms. NPS pollutants associated with the terrestrial environment are generally the consequence of agricultural activities such as fertilizing; spraying of pesticides; and accumulation of salts and trace elements in irrigated, agricultural soils.

Throughout the world, 30 to 50% of the earth's surface is believed affected by NPS pollutants including erosion, fertilizers, pesticides, organic manures, and sewage sludge (Pimental 1993). Recently, attention has drawn to the assessment of NPS pollutants in the vadose zone (i.e., the zone of soil extending from the soil surface to the ground water table). This attention is due to concern over (1) the protection of ground water resources threatened by the leaching of naturally occurring and man-made contaminants applied to or present within the soil, and (2) the detrimental impact upon agricultural productivity resulting from the accumulation of chemicals (e.g., pesticides, salts, heavy metals, trace elements, etc.) within the root zone. Because ground water accounts for 50% of the nations drinking water and 40% of its irrigation water, the protection of ground water resources is a primary environmental concern to the public. Similarly, the fact that of the 1.2

The information age of the 1990s is a time of global consciousness where scientific and technological advances are assumed to be capable of solving global environmental problems. A significant characteristic of many environmental problems is the lack of regard for political boundaries and physical barriers between cities, states, nations, and continents. The widespread nature of such environmental problems often results in an analogous diffuse acceptance of responsibility for resolution. Thus, an ability to accurately assess the present and future impact of human activities on the global ecosystem would provide a most powerful basis for environmental stewardship and guiding future human actions. To responsibly respond to impaired ecosystem functioning (i.e., with respect to such issues as climatic change, stratospheric ozone depletion,

billion hectares currently suffering moderate to extreme soil degradation throughout the world, approximately 12% is the consequence of NPS pollutants including salinization, acidification, and pollution (Oldeman et al. 1990).

Multidisciplinary nature of the NPS pollutant problem

Like other global environmental issues, the knowledge and information required to address the problem of NPS pollutants crosses several subdisciplinary lines. The capability of predicting the response of a spatially and temporally complex and heterogeneous system, such as the vadose zone, to the large-scale stresses of NPS pollutants is the consequence of the integration of knowledge from a range of subdisciplines, including classical and spatial statistics, time series analysis, remote sensing, geographic information systems (GIS), hydrology, and soil science. Classical statistics are useful for dealing with data uncertainty, model discrimination and model verification; whereas, spatial statistics and time series analysis are of value as a means of characterizing the structure of spatial and temporal variabilities. GIS serves as a means of storing, manipulating, and displaying the tremendous volumes of spatial data associated with NPS pollutants. Remote sensing is the most cost-effective means of measuring the physical, chemical, and biological parameters and input data needed by transient-state solute transport models. The water flow and solute transport models developed by soil scientists and subsurface hydrologists are the essential simulation tools used to assess potential temporal and spatial changes in the fate and transport of NPS pollutants within the vadose zone. Integrated methodologies combining all of these essential components are the key to modeling NPS pollutants.

GIS in particular has burgeoned as a data management and visualization tool for addressing spatial-related environmental problems such as NPS pollutants. In the past five years, the NCGIA has presented three conferences focusing on GIS applications to environmental issues (see the NCGIA web site for details <http://www.ncgia.ucsb.edu>). In 1995 the ASA-CSSA-SSSA Bouyoucos Conference focused on the application of GIS to the modeling of NPS pollutants in the vadose zone (Corwin and Loague 1996). Broadening the focus beyond GIS, the 1997 Joint AGU Chapman/SSSA Outreach Conference (Oct. 19-24, 1997; Riverside,

CA) focused on the application of GIS, remote sensing, geostatistics, and solute transport modeling to the assessment of NPS pollutants in the vadose zone.

Significance of modeling NPS pollutants in the vadose zone

Among the foremost non-parochial problems facing mankind is meeting the world's future food demand with sustainable agriculture. Sustainable agriculture seeks to attain a delicate balance between meeting the world food demand through increased agricultural productivity, the utilization of finite natural resources, and the minimization of detrimental environmental impacts. Assessing the environmental impact of NPS pollutants at local, regional, and global scales is a key component to achieving sustainable agriculture.

Assessment involves the determination of change of some constituent over time. 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 it can be used to alter the occurrence of detrimental conditions before they manifest. The much greater efficiency of preventative, rather than remedial, efforts strongly supports the need for an ability to accurately model environmental contaminants such as NPS pollutants. Such an ability would greatly enable environmental stewardship.

Because the vadose zone serves as the conduit through which NPS pollutants pass from the soil surface to the ground water, the assessment of NPS pollutants in the vadose zone serves as a tool for protecting soil and ground water resources by managing the accumulation of solutes in the soil root zone and the loading of solutes to the ground water. Specifically, GIS-based models of NPS pollutants provide diagnostic and predictive outputs that can be combined with socioeconomic data for assessing local, regional, and global environmental risk; or natural resource management issues (Steyaert 1993). Real-time measures of NPS pollutants provide an inventory and historical record for ascertaining the extent of the impact and its historical trend.

Components of GIS-based NPS pollutant models

In their simplest form, GIS-based environmental models consist of three fundamental components: data; model, and

GIS (Burrough 1996). Within each component, a variety of issues must be addressed and resolved before any realistic approximation of the fate and movement of a NPS pollutant in the vadose zone can be simulated. A comprehensive review of each component and their interrelationship, along with a compilation of all GIS-based NPS pollutant models of the vadose zone has been written by Corwin et al. (1997).

Data. Currently, the collection of spatial data needed to meet the calibration requirements of even the simplest transport model stands as the single greatest challenge to environmental modeling in the vadose zone. Sources of data include (1) measurement using remote sensing or noninvasive techniques, (2) inverse parameter estimation and data assimilation methods, and (3) existing databases.

Remote sensing has the greatest potential for cost-effectively meeting the data intensive needs of environmental models. Measurement methods such as electromagnetic induction, electrical resistivity tomography, aerial photography, x-ray tomography, ground penetrating radar, magnetic resonance imaging, microwaves, multispectral scans (SPOT and Landsat™), thermal infrared, and advanced very high resolution radiometry offer great potential for the measurement of soil properties and parameters useful in solute transport models of the vadose zone, ranging from bulk density to soil water content. A review of these methods, as applied to the measurement of soil properties that are useful in transport modeling within the vadose zone, can be found in Corwin et al. (1997).

The estimation of transport parameters with transfer functions offer a practical means of obtaining data. Transfer functions relate more readily available or easy-to-measure soil properties to more complex, difficult-to-measure transport parameters. The most common of the transfer functions is the pedo-transfer function (PTF), which relates soil particle size distribution, bulk density, and organic carbon content to water retention or unsaturated hydraulic conductivity relations. However, transfer functions are known to be highly inaccurate. For example, it has been shown that greater than 90% of the variability of simulations for a map unit are due to variability in estimating hydraulic parameters with a PTF (Vereecken et al. 1992). Aside from transfer functions, geostatistics can be used to provide an estimate of spatial data and spatial data uncertainties through interpo-

lation and simulation. Another approach to estimate the distribution of environmental properties is data assimilation. This approach extends beyond geostatistics by imposing added constraints to the estimation process that are based on physical laws (McLaughlin 1995).

Temporal changes in parameters, due to the effects of natural and human factors, (e.g., weathering, freeze-thaw cycles, erosion, root growth and decay, biota, tillage, etc.) also add a layer of complexity to the problem of measuring and/or estimating parameters.

Existing databases, such as those developed and maintained by the Natural Resource Conservation Service (formerly Soil Conservation Service), provide the easiest and cheapest means of obtaining input data. Existing soils databases include SSURGO (Soil Survey Geographical Database), STATSGO (State Soil Geographical Database), and NATSGO (National Soil Geographical Database). Each database differs in scale and detail of

data. SSURGO is a county-level database (map scale range 1:12,000 to 1:63,360) and is the most detailed soil property database. STATSGO is the state-level database (map scale 1:250,000) and finally NATSGO is the national soils database (map scale 1:7,500,000). Databases compiled for specific soil properties are also available such as the UNSODA database that provides basic soil properties (particle-size distribution, bulk density, organic matter, etc.) and associated unsaturated hydraulic properties (water retention, hydraulic conductivity, and soil water diffusivity). However, it is generally felt that most soil databases do not meet minimum data requirements for many of the distributed-parameter models of the vadose zone nor do they provide useful statistical information about the uncertainty of the soil property data (Wagenet et al. 1991).

Model. A recent review of GIS-based models of NPS pollutants in the vadose zone has shown that one-dimensional, de-

terministic models have almost exclusively been used in combination with GIS (Corwin et al. 1997). However, stochastic-convective stream-tube modeling seems a potentially compatible stochastic approach. For either vector- or raster-based GIS data storage, the region of interest is discretized into a regular grid. For a given grid cell, it is assumed that the horizontal transport variabilities are much greater than the vertical variations. Thus, a local vertical transport model is assumed, such as a CDE or piston flow process. Then, a distribution of local scale parameter values are somehow estimated for each grid cell. This approach is analogous to the deterministic approach used in the past where piston-flow models used soil survey information. In contrast to the deterministic approach, the resulting stochastic stream-tube model provides not only estimates of the average flow process within each grid cell, but also estimates an associated stochastic component, i.e., the within-grid-cell variability of the flow process.

The establishment of the boundaries of the stream-tube remains as a future challenge that may be met with recently developed mobile geophysical instrumentation. Intensive Wenner array data is capable of delineating areas of similar bulk soil electrical conductivity that, in turn, may define spatial domains of similar flow characteristics resulting from less variation in the physicochemical parameters defining transport. For example, from field data collected by Corwin and his colleagues, the northwest corner of the quarter section in Figure 1 shows an area of low bulk electrical conductivity that corresponds to a spatial domain of higher flow than in the southern half of the quarter section.

The size of the region of interest has profound effects on the spatial and temporal resolution of the soil property data. Considerations of scale and data availability determine the type of model best suited to a given application. For instance, the spatial scale determines the predominant processes that are influential and need to be accounted for in the solute transport model. The leaching of NPS pollutants ranges in scale from molecular to global. Qualitatively speaking, as spatial scale increases, the complex local patterns of solute transport are attenuated and dominated by macroscale characteristics. For this reason, mechanistic models are utilized more frequently at molecular, ped and soil horizon scales; functional models are more often applied to field, watershed, county/state, region, continent

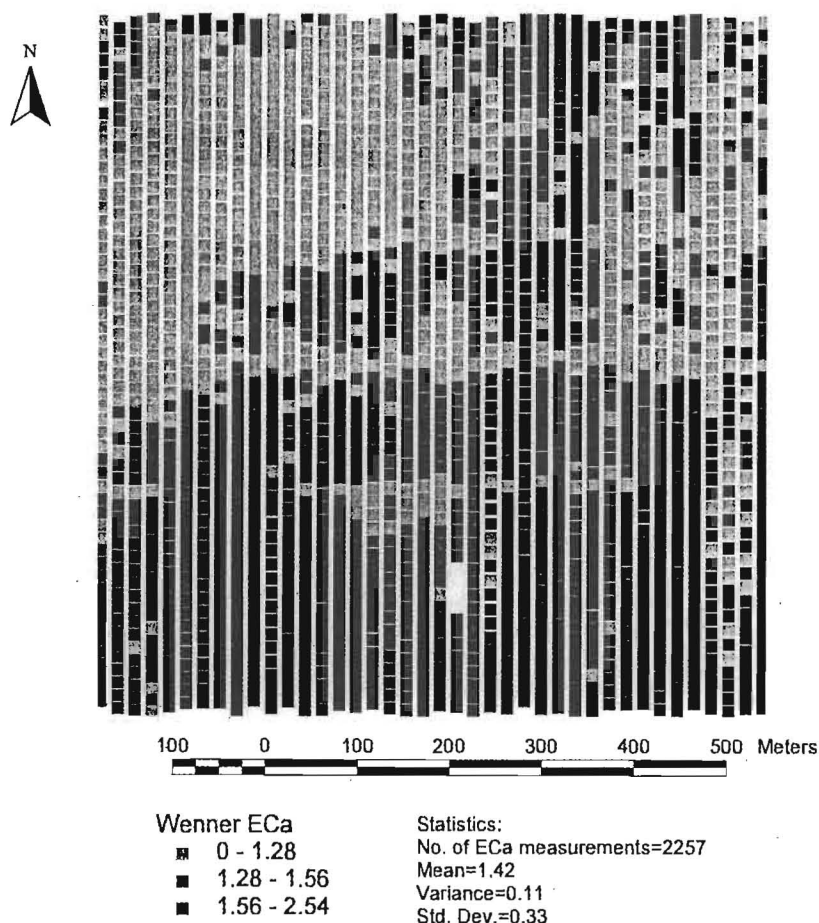


Figure 1. Areal distribution of bulk soil electrical conductivity (ECa) as measured with the Wenner array. Areas of low (ECa = 0 to 1.28 dS/m), medium, (ECa = 1.21 to 1.56 dS/m) and high ECa (ECa = 1.56 to 2.54 dS/m) respectively correspond to spatial domains of high, intermediate, and low salinity transport on a relative basis

and world scales; and statistical models are most often applied at county/state, region, continent and global scales.

GIS. The spatial and temporal complexity of the earth's surface and subsurface make the problem of modeling NPS pollutants in the vadose zone a data intensive task. The volume of information needed to characterize the physical, chemical, and biological parameters and variables needed in a simple functional models is tremendous. The ability to retrieve, manipulate, and display the onerous volume of spatial information is perfectly suited for a GIS. The coupling of GIS to a model of solute transport in the vadose zone is a marriage designed to address the problem of spatially simulating NPS pollutants at field, basin, region, and world scales. GIS provides both the means of or-

ganizing and manipulating the spatial data, and of creating visual displays of georeferenced data.

Considerations of uncertainty

The end products of a GIS-based model of NPS pollutant transport in the vadose zone are maps showing the areal distribution of a solute through the soil profile and solute loading to the ground water. But how reliable are these maps in lieu of the inherent error associated with data and models?

Error is unavoidable and sometimes even undetectable in environmental modeling. Error results in uncertainty and reflects upon the reliability of a model's predictions. Uncertainty has significant practical implications. Uncertainty either affirms or negates the use of predictive

outputs for guidance and action in a decision-making process. A quantification of the uncertainty is necessary to establish to what extent predicted results can be relied upon as a predicted estimate of the truth.

There are several possible sources of uncertainty (see Loague and Corwin 1996). Uncertainty can be due to model errors produced from the simplification of the complexities of processes being described by the model. Uncertainty can result when the model does not capture the natural temporal and spatial variability of a parameter or variable. Uncertainty can also result because of inexactness in the measurement or estimation of a model parameter or variable.

A map generated from a GIS-based model has no real utility without a corresponding map of the associated uncertainties (see Figure 2). Figure 2 clearly illustrates the importance of considering uncertainty in NPS pollutant assessments of regional-scale ground water vulnerability that are to be used in the decision-management arena.

GIS-based models of NPS pollutants in subsurface soil and water systems have proliferated over the past decade. The acknowledged trend in the coupling of GIS with environmental models will continue at an even greater pace due to the introduction of cheaper desktop GIS software that is customizable to the application and to the growing demand for spatial environmental information. Without question, GIS is serving as a catalyst to bring solute transport modeling, data acquisition, and spatial databases into a self-contained package to assess NPS pollutant problems. Yet, a cautionary footnote is needed because the sophisticated visualizations created from GIS should never disguise the legitimacy of the rendered results nor should simulated results ever supplant field observation.

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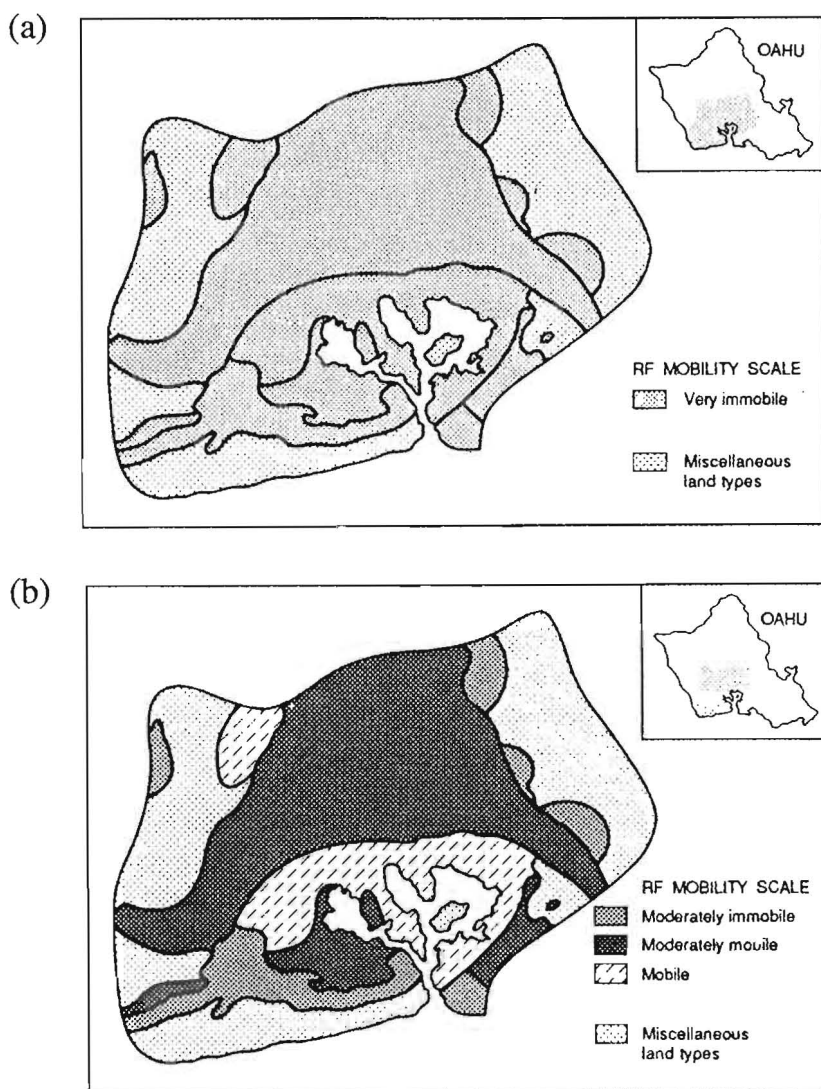


Figure 2. Assessments of ground water vulnerability for the herbicide diuron for the Pearl Harbor Basin (Hawaii)

Note: based upon the retardation factor (RF) index of pesticide leaching (Loague et al. 1990). (a) Vulnerability map based upon RF alone. (b) Vulnerability map based upon RF

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Recreational impacts on erosion and runoff in a central Arizona riparian area

Douglas M. Green

Interpretive summary

The areas bordering lakes and streams are often focal points for recreation. These focal points can be negatively impacted by many forms of recreation. The objective of this study was to assess the impact of recreation on soil compaction, runoff, erosion rates, and vegetation along a stream in central Arizona. The dominate recreational use on the study area was camping and the area is accessible by automobile. A rainfall simulator with an application rate of 5 in (12.7 cm/hr) for 30 minutes was used to produce runoff. Total runoff from heavy use sites was significantly higher when compared to light- and moderate-use areas. Amounts of plant materials were higher in light and moderate use than in the high-use area. A greater degree of soil compacting and large areas of exposed soil surface may have contributed to differences in runoff.

Key words: Arizona, erosion, recreation, riparian, runoff, soil compaction.

ABSTRACT: Riparian areas are often focal points for recreation on western rangelands. The objective of this study was to assess the impact of recreation on soil compaction, runoff, erosion rates, and vegetation in a central Arizona riparian ecosystem. This study was conducted in a *Populus fremontii*-*Fraxinus pennsylvanica* (Fremont Cottonwood-Velvet ash) riparian community type. The dominate recreational use on the study site is camping and the area is accessible by automobile. A rainfall simulator with an application rate of 5 in/hr (12.7 cm/hr) for 30 minutes was used to produce runoff. Initiation of runoff occurred significantly ($P < 0.05$) sooner on high use areas (3 minutes, 18 seconds) than light-use areas (8 minutes, 28 seconds). Total runoff from heavy-use areas was significantly ($P < 0.05$) higher (.12 in; 3.1 mm) when compared to light-use areas (0.008 in; 2 mm). Above ground vegetation ranged from 0 g/m² in the heavy-use plots to 364 g/m² in the light-use plots. Higher bulk densities and large areas of exposed soil surface might have contributed to differences in runoff.

Lakes and streams are important features that attract recreationalists (Lime 1971; Clark and Downing 1985). Riparian systems associated with these areas have a number of functions not found in upland ecosystems. These functions include bank stabilization and woody debris supply to stream ecosystems (Malanson 1993). The ecotonal nature and structural variation give high value to riparian areas as wildlife habitat (Brinson et al. 1981). Riparian areas are also important sinks for nutrients and sediments (Brown 1988; Lowrance et al. 1986). With the increasing popularity of all forms of outdoor recreation has come an increasing use of, and impact on, riparian ecosystems.

Deterioration of recreational sites has negative impacts on the recreational experience.

Douglas M. Green is an assistant professor in the Environmental Resources Program, Arizona State University, Tempe, AZ. This manuscript was submitted in March of 1996 and accepted in May of 1997.

As a site becomes increasingly damaged, recreationalists might be displaced. Recreational displacement is defined as a change in recreational behavior in response to changes in the recreational environment (Schreyer 1979). Displacement of recreation to other less damaged areas might increase the real extent of damage (Becker 1981; Clark and Gibbons 1991). Off-site effects of site deterioration include deposition of sediment in lakes and streams that can reduce the value of these areas to recreationists (Robertson and Colletti 1994). Riparian degradation may also lead to flashier storm hydrographs and changes in aquatic biota (Wissmar and Swanson 1990). Quantitative data about how recreation influences form and function of riparian areas is very limited. Information on the impacts of recreation in riparian areas is important to the management of these ecosystems and their associated watersheds.

Intensive recreation, such as persistent camping, in one area results in a number of negative impacts on the riparian sys-