Managing variable source pollution in agricultural watersheds

Z. Qiu, M.T. Walter, and C. Hall

Abstract: Agricultural runoff is a major contaminant source threatening water quality in streams, lakes, and public drinking water reservoirs. Agricultural pollution control practices and programs are traditionally based on the assumption that overland flow is only generated when rainfall intensities exceed soil infiltration capacity. This paper challenges this assumption, noting that overland flow associated with agricultural pollutant transport is often physically consistent with the variable source area hydrology concept, for which overland flow is generated in parts of the landscape where the soil saturates to the surface. Incorporation of variable source area hydrology into watershed management practices reconceptualizes nonpoint source pollution as "variable source pollution," in which pollution control efforts can be focused on relatively small hydrologically sensitive areas recognizing that the extent of these areas will vary throughout the year. There are substantial technical, economic, social, and institutional barriers to implementing strategies for managing variable source pollution partially because of massive institutional inertia of existing agroenvironmental policies and programs and best management practices. Substantial research is needed to quantify the water quality risks associated with variable source pollution, expand the capacity to identify the critical management areas, and eliminate the institutional barriers for managing variable source pollution in agricultural watersheds.

Key words: nonpoint source pollution—precision conservation—targeting—variable source area hydrology—variable source pollution

Runoff transporting sediments, fertilizers, pesticides, and other pollutants is a major contaminant source that impairs water quality in streams, lakes, and public drinking water reservoirs. Contaminated runoff is often called nonpoint source pollution because of its diffuse nature. A watershed approach has been used to assess and control nonpoint source pollution. Indeed, a watershed approach is approved in the Clean Water Act and the Clean Water Action Plan and has been endorsed by many governmental agencies and professional organizations (Water Environment Federation 1992; Adler et al. 1993; USEPA 1994; NRC 1999). In recent years, many best management practices (BMPs) and watershed management plans (WMPs) have been developed and implemented to reduce water contamination risk associated with agricultural and other nonpoint sources. However, most currently used BMPs, WMPs, and risk assessment models have not been consistently improved to incorporate continuously advanced scientific understanding of how runoff is generated in a watershed (Walter et al. 2000).

Most BMPs, WMPs, and risk assessment models are based on a conventional assumption that runoff is generated only when rainfall intensity exceeds the infiltration capacity of the ground. This process is termed "infiltration excess" runoff, or, more commonly, "Hortonian runoff" in acknowledgement of Robert E. Horton's infiltration theory (Horton 1933 and 1940). Hortonian runoff refers to the quick development of widespread, relatively uniformly distributed overland flow when precipitation intensity exceeds soil infiltration capacities. The Hortonian runoff process is seriously limited in most humid regions, such as in the northeastern United States, because rainfall only rarely exceeds soil infiltration capacity in these areas (Steenhuis and Muck 1988; Merwin et al. 1994; Walter et al. 2003). Runoff in humid regions is primarily generated in relatively small areas on the landscape where water has saturated to the surface (Dunne and Leopold 1978).

Variable Source Area Hydrology

Since the early 1960s, researchers have repeatedly noted saturation excess processes as a more physically realistic runoff process than Hortinan runoff and they started to question the appropriateness of the Hortonian runoff concept to describe runoff at the landscape scale. The earliest study by the US Forest Service (1961) suggested that runoff was generated primarily from discrete saturated areas within forested watersheds. Other early studies refined the saturation excess runoff theory and identified inconsistencies between field observations and the Hortonian runoff theory (Betson 1964; Tennessee Valley Authority 1965; Amerman 1965; Ragan 1967; Dunne 1970; Hewlett and Nutter 1970; Dunne et al. 1975). Hewlett and Hibbert (1967) are generally credited with the term "variable source areas" (VSAs), implying the extent of saturated runoff source areas varies with a watershed's moisture state. Figure 1 shows how the extent of saturated areas changes over the course of a year for a small upstate New York watershed. Note the large extent of saturation for the wet months (March and October) and the greatly contracted extent of saturation during the summer (August). Dunne and Black (1970a, 1970b) are generally credited with the definitive field experiment describing VSA mechanisms, especially for watersheds where shallow, transient interflow is common.

The VSA hydrology concept has evolved over the past 40 years to incorporate the suite of hydrological processes leading to the development and expansion of saturated zones in the landscape. Some of the prominent locations for VSAs are along valley floors and other topographically con-

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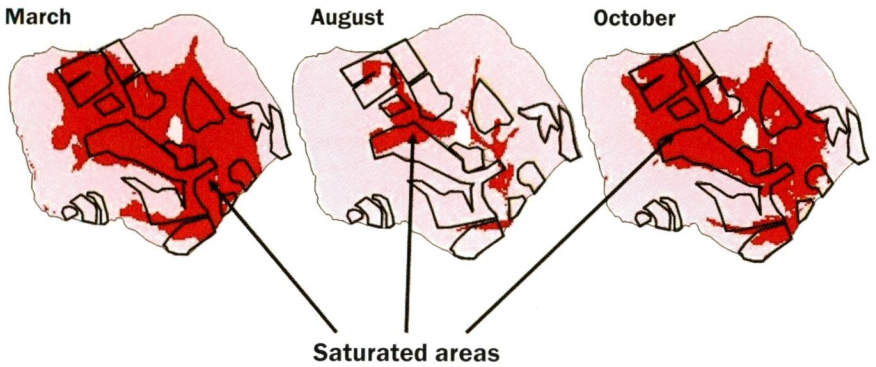
Figure 1
Expansion and contraction of the variable source areas (darker areas) for a small watershed in Delaware County, New York.



Notes: The outlines indicate field boundaries. Modified from Agnew et al. (2006).

verging areas, shallow water table areas, the lower portions of hillsides especially where the topographic slope flattens, and places where a shallow restrictive layer underlies the soil. The source of the water saturating the landscape can be the baseflow, groundwater reservoir or shallow, transient subsurface flow over a near-surface restrictive layer commonly called interflow. Many researchers have shown that the distribution and extent of the saturated areas are often closely related to the pattern of stream channels, i.e., the locations where groundwater re-emerges on the surface (e.g., Dunne and Black 1970a, 1970b; Beven and Kirkby 1979). Recently, shallow interflow has been shown to be an important control on VSA dynamics, especially in the northeastern United States (Moore and Thompson 1996; Frankenberger et al. 1999; Ogden and Watts 2000; Srinivasan et al. 2002). Besides in humid northeastern United States, the VSA hydrological process is acknowledged in other parts of the United States, including the Midwest claypan soil region (Schmitt 1999), the mountainous West (e.g., Idaho [Boll et al. 1998; Brooks et al. 2000]), and the South (e.g., Florida [Tatiana et al. 2003]).

VSA processes are foundational to understanding, modeling, and ultimately controlling nonpoint source pollution. Govindaraju (1996), for example, concluded "modeling studies, which deal with prediction of agricultural chemicals in surface water need to be cognizant of the role of VSA hydrology" (p. 757). Gburek and Sharpley (1998) and Walter et al. (2000, 2001) drew similar conclusions from their respective research.

Management of Variable Source Pollution

There is the ubiquitous acknowledgement of the VSA hydrology concept as a basic principle in hydrological sciences. Indeed, VSA hydrology has appeared in most introductory hydrology textbooks since the 1970s (e.g., Dunne and Leopold 1978; Hornberger et al. 1998). However, it has been virtually ignored in soil and water conservation programs, BMPs, WMPs, and water quality models. There are a very few, but notable, exceptions involving the following recent studies (e.g., the VSA hydrology concept was applied to define critical management zones and manage phosphorus runoff in agricultural watersheds in Pennsylvania and New York; Gburek and Sharpley 1998; Walter et al. 2000, 2001; Gburek et al. 2002). Qiu (2003) evaluated management strategies for placing conservation buffers in agricultural landscapes based on VSA hydrology. The study showed that VSA hydrology provides a theoretical basis for placing conservation buffers, and it was more effective and cost-effective to place conservation buffers within VSAs. Walter et al. (forthcoming) noted that the reason "riparian buffers" are effective is not because they magically "treat" runoff, but because they restrict polluting activities from hydrologically sensitive near-stream areas. Qiu et al. (2002) also applied VSA hydrology to manage hydrologically sensitive areas (HSAs), such as woody draws in agricultural landscapes in Missouri.

Why has VSA hydrology not played a more prominent role in water quality protection? Walter et al. (1979, 2000) argue that current water quality protection practices and assessment tools are largely based on conservation practices that primarily focus on transport of sediment rather than soluble chemicals. Such practices are based upon the belief that keeping sediment out of streams and lakes will generally keep all contaminants out of these water bodies regardless of differences in the transport processes (Walter et al. 1979). However, the transport processes for sediment and dissolved pollutants are distinctly different. A large body of soil erosion research shows that sediment detachment and transport is most substantial during high rain-intensity events, implying that Hortonian runoff is probably appropriate for estimating soil erosion (Ayres 1936; Kirkby and Morgan 1980; Ritesma et al. 1996; Stomph et al. 2002). Dissolved pollutants, on the other hand, are susceptible to transport whenever water flows through or from an area loaded with pollutants, regardless of rainfall intensity. It is interesting that historical soil erosion research was generally performed on small plot studies that were inappropriate for understanding landscape scale processes, such as those giving rise to VSA hydrology (Trimble and Crosson 2000). It has also been suggested that early erosion studies were carried out in parts of the country where VSA hydrology may not be a dominant hydrological process. As demonstrated by Dickinson et al. (1987) in a small watershed in Ontario, Canada, only a small portion of a watershed generates erosion and contributes sediments to the streams.

Another important reason why VSA hydrology is not more widely recognized in national water quality protection strategies is the lack of user-friendly watershed models that simulate VSA hydrological processes. While user-friendly, well-documented simulation models for predicting soil erosion and transport have been under development since 1960, or earlier (Rallison 1980), biophysical models based on VSA hydrology are much younger and less developed, especially outside the arena of basic or pure biogeoscience research (Beven and Kirkby 1979; Wigmosta et al. 1994). It is interesting to note that there appears to be more emphasis among water quality professionals on simply obtaining model results than on refining the underlying biophysical process of the models.

Why is application of VSA hydrology important in water and environmental protection? Understanding where and when overland flow will be generated is the

obvious foundation upon which to build nonpoint source pollution control strategies. One of the primary measures for understanding transport of potential pollutants is the overlap between the distribution of the potential pollutants on the landscape and the distribution of VSAs. Instead of assuming the diffuse nature of contaminated runoff, the VSA hydrology suggests that the sources of contaminated runoff is the small but predictable portion of areas in watersheds, i.e., the overlapped areas between the pollutant generation area and the VSAs. By incorporating VSA hydrology into water quality and environment management, soil and water conservation efforts can be concentrated on those small, sensitive parts of a watershed (Maas 1985; Dickinson et al. 1990), i.e., managing variable source pollution. Managing variable source pollution by combining the scientific principles of VSA hydrology with current agricultural and land management will remove the mystery surrounding pollution sources that is unfortunately implied by the term "nonpoint source pollution."

Managing variable source pollution juxtaposes naturally with recent economists' leanings toward a targeting approach for controlling agricultural nonpoint source pollution (Duda and Johnson 1985; Braden et al. 1989; Prato and Wu 1996; Qiu and Prato 1999). The targeting approach emphasizes targeting conservation efforts on the most critical sources area or "hot spots" in landscapes. Such an approach should significantly reduce costs and improve the cost-effectiveness of controlling agricultural water pollution. However, there are some problems for defining the hot spots in landscape. First, some studies on the targeting approach defined hot spots in terms of smaller size subwatersheds within a large watershed (Qiu and Prato 1999; Westra et al. 2002). Such identified hot spots could have limited applications because the delineated hot spots excludes some critical sources outside the hot spots in watersheds that could make significant contributions to the water pollution. Even within the delineated hot spots, not all areas are equally important in terms of pollutants generation; in another words, these critical source areas were not really identified within the hot spots. Second, defining hot spots at the micro-level (field scale) could be information-extensive and therefore expensive (Pritchard et al. 1993). VSA hydrology provides the theoretical and consistent basis to identify the hot spots from field scale to watershed and regional scales for targeting (Caruso 2001). Following the VSA hydrology, the hot spots should be only small, variable but predictable portions of watersheds or landscapes that regularly and actively contribute to runoff generation. A VSA approach powered by simulation model and information technology could eliminate these problems. Therefore, identifying, monitoring, and managing critical areas in a watershed based on the VSA hydrology are more consistent with the goals of a targeting approach. Accordingly, the cost and risk of contaminating public drinking water supplies and other surface water bodies should be significantly reduced through managing variable source pollution.

Research Needs for Managing Variable Source Pollution

Past soil and water conservation and watershed management efforts have developed a large menu of practices. Neither the importance of such BMPs nor soil and water conservation programs in agricultural watersheds are undermined by managing variable source pollution. However, managing variable source pollution does provide practical guidance for improving the physical effectiveness and cost efficiency of those BMPs and programs. Managing variable source pollution may require changes in the existing BMP manuals to take account of VSA hydrological processes at field and watershed scales. BMPs and other management measures would be targeted toward critical VSAs in watersheds. Given limited budgets and increasing needs for improved water quality in agricultural watersheds, the efficiency and effectiveness of those BMPs and programs become increasingly important in future agro-environmental policy.

Although managing variable source pollution provides a system-based understanding of landscape processes and the solution for controlling agricultural pollution, implementation of such a system-based approach needs additional research. More specifically, scientists need to build on the existing body of basic or pure biogeoscience research associated with VSA hydrology to develop new management applications, to develop better environmental risk measurements, and to integrate fundamental scientific findings with economic and social approaches to deliver efficient and effective management tools and policies in managing variable source pollution. In order to manage variable source pollution in agricultural watersheds, the following additional research is essential.

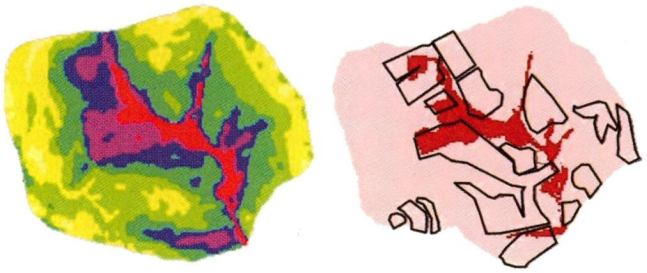
Identifying Variable Source Areas in Agricultural Watersheds. Variable source areas are the portions of a watershed that actively contribute to generating runoff to streams. Identifying VSAs in the landscape is the obvious and necessary precursor to subsequent variable source pollution research needs. Several well-developed watershed models are useful for this purpose. At least three physically based models incorporate VSA hydrology: TOPMODEL (Beven and Kirkby 1979; Ambroise et al. 1996), the Soil Moisture Routing Model (SMR, SMDR) (Zollweg et al. 1996; Frankenberger et al. 1999, Mehta et al. 2004), and the modified curve number (CN) model (Steenhuis et al. 1995; Lyon et al. 2004). Other useful VSA-based models include TOPOG (O'Loughlin 1986) and WET (Moore et al. 1993). TOPMODEL is a semidistributed model that lumps hydrologically similar portions of a watershed based on a topographic index. SMR is fully distributed model using widely available input data. Identifying VSAs with the modified CN model has great potential because it is the basis of most commonly used watershed management models, notably SWAT (Arnold et al. 1998; Fontaine et al. 2002), AGNPS (Young et al. 1987 and 1989), and GWLF (Haith and Shoemaker 1987). It is important to note that physically based models employ different assumptions for different hydrological systems. For example, TOPMODEL predicts VSAs when and where the water table, which it explicitly assumes underlies the entire watershed, intersects the land surface. SMR assumes that shallow, transient subsurface flow primarily controls VSA behavior. This discontinuity in modeling approaches suggests a point for additional research regarding fundamental VSA processes and developing guidelines for determining which processes dominate in a particular watershed and/or developing models that simulate both types of hydrological behavior. Additionally, all models need to adopt user friendly interfaces to increase accessibility by users who are not model developers. Research is also needed to further understand and validate the VSA process in agricultural watersheds where agricultural practices may significantly alter natural hydrological flow paths. This research

Figure 2

Comparison of the concepts of (A) variable source areas and (B) hydrologically sensitive and critical management areas for a hypothetical period of a year.

A
Variable source areas (red to yellow indicates decreasing probability of generating runoff)

B
Hydrologically sensitive areas and critical management areas (outlines indicate field boundaries)



needs to utilize geographical information system (GIS) procedures that identify VSAs in watersheds. Compared to the hydrological models discussed above, a GIS procedure is simpler and easier to implement, and can be easily applied to different scales from fields to large watersheds and regions. For example, Agnew et al. (2006) used a topographic index to identify VSAs in three New York watersheds. Tomer (2003) applied the terrain analysis-based GIS procedure that identifies the critical areas in an Iowa watershed for conservation buffer placement. Such GIS procedures can be modified based on the principles of VSA hydrology to identify the VSAs.

Remote-sensing technology has high potential for identifying VSAs in landscapes. Although using remotely sensed data to directly estimate soil moisture remains physically problematic (Crosson et al. 2002; Yoo 2002), several researchers have shown that remotely sensed data can be used to identify saturated areas (i.e., VSAs). For example, remotely sensed data can be used to delineate wetland areas, usually based on vegetation signatures (e.g., Guntenspergen et al. 2002; Toyra et al. 2002), and presumably wetlands are a type of VSA. Vanderbilt et al. (2002) suggested that saturated surfaces can be directly located using remotely sensed data based on the "glint" or reflective properties of these areas. Thermal imagery has promising potential. For example, using soil water samples as training sets for supervised classifications, Schmitt (1999) delineated VSAs in two small watersheds in Long Branch watershed, Missouri from thermal imagery (2,700 to 4,700 nm). His delineation was based on the normalized difference water index (NDWI) (Gao 1996; McFeeters 1996) and the normalized difference vegetation index (NDVI) (Cialella et al. 1997). Thermal images are generally obtained from a thermal digital camera mounted on a fixed-winged aircraft flying at an elevation of ~1,524 m (5,000 ft) and are probably most readily applicable to small watersheds (<100 ha). Research is needed to identify VSAs in landscapes using commercially available satellites such as Landsat 7, SPOT, and IKONOS at larger scales.

Identifying Hydrologically Sensitive Areas and Critical Management Areas. The spatial and temporal distribution of VSAs can be predicted because they are largely controlled by topography, antecedent moisture conditions, and storm size (Gérard-Marchant et al. 2003; Qiu 2003). The identified VSA patterns could vary from 1% to over 50% of the watershed depending on rainfall. This high degree of variability is difficult to account for in water resource management plans. The term hydrologically sensitive areas (HSAs) was proposed as a water quality management corollary to the hydrologic-science concept of VSAs (Walter et al. 2000 and Agnew et al. 2006). Conceptually, HSAs in a watershed can be defined by a distribution of VSAs that corresponding to a certain probability of generating runoff determined by a storm event (Qiu 2003). Research is needed to develop the criteria that delineate HSAs from identified VSAs in the watershed as discussed. The delineation criteria should incorporate local water quality concerns, preferences of water resource managers, and local natural resource conditions, such as topography and weather. Agnew et al. (2006) delineated HSAs in three New York watersheds based on the modeled probability of saturation; the methodology was simply designed so that it could ultimately be implemented via an Internet mapping system. Superimposing HSAs on land use can be used to identify critical source areas or critical management areas (CMAs) (Walter et al. 2000; Gburek et al. 2002). Currently, CMAs are entirely based on land use (i.e., land use dictates both the pollutant loading distribution over the landscape and hydrological parameters like the curve number). CMAs should be defined so that pollutant loading, which is mirrored in land use patterns, is decoupled from hydrology, which is defined by HSAs. For example, consider an agricultural field in the Catskill Mountain region of New York state in which dairy manure is spread. The corresponding CMA is defined as the intersection of the HSAs and the manure spread areas in the field.

Figure 2 compares VSA to HSA and CMA concepts. In panel A, VSAs are depicted in terms of the probability of generating runoff. Red indicates high probability and yellow indicates low probability. In panel B, HSAs are the darker areas with more than a 30% probability of generating runoff and CMAs are the field areas (open polygons) that intersect the HSAs. Research is needed to evaluate different procedures for defining CMAs under different land use and natural resource conditions to account for the needs of soil and water resource management professionals.

Developing Variable Source Area-based Biophysical Simulation Models. Managing variable source pollution requires well-developed, VSA-based biophysical simulation models that quantify the water quality impacts of land use management practices in watersheds. As discussed previously, these existing widely used water quality simulation models such as SWAT, GWLF, and AGNPS are implicitly based on "infiltration excess" runoff and are at least not appropriate for areas where VSA hydrology controls runoff. However, it is interesting to note that these models have well established and scientifically defensible nutrient transport and fate routines, despite their outdated hydrological components. One way of developing VSA-based biophysical simulation models is to directly incorporate the pollutant transport and fate routines used in the existing water quality models such as SWAT and/or GWLF into one or more of the well-developed VSA

hydrological models, such as TOPMODEL or SMR. The code for these models is available either through open sources, public domain, or personal interactions with the modelers/developers. Alternatively, one can simply change the hydrological basis for these models from infiltration excess, e.g., the curve number's land use-based approach, to a saturation excess, or VSA hydrology. Steenhuis et al. (1995) have developed a curve number model that is consistent with VSA hydrology. In cooperation with the New York City Department of Environmental Protection, they have successfully implemented it in GWLF and are working with the SWAT development team to develop a VSA-based SWAT version (Walter et al. 2006; Schneiderman et al. n.d.; Fuka et al. 2006). Additional research is needed to incorporate the VSA hydrology into other water quality simulation models and to test and validate the developed models under different natural resource conditions.

Understanding Technical, Economic, Social, and Institutional Barriers. There are substantial technical, economic, social, and institutional barriers for adopting measures to manage variable source pollution in agricultural watersheds because of conflicts with existing agro-environmental policies and programs. The existing policies and programs for controlling agricultural nonpoint source pollution fall into the category of a "carrot" approach (i.e., using economic incentives to encourage landowners' voluntary adoption of BMPs and/or land retirement). Those voluntary-based programs are not consistent with the proactive anticipatory approach to managing variable source pollution, which prioritizes the identified CMAs for BMPs and soil and water conservation programs. While many existing BMPs accommodate large-scale, machinery-based agricultural field operations, managing variable source pollution may require BMPs at the subfield scale.

Technical barriers occur due to lack of understanding about the roles of different parts of landscape in runoff generation. Examples of technical barriers are lack of ability to identify VSAs, HSAs, and CMAs in watersheds, and lack of VSA-based BMPs and programs. As discussed above, research is needed to improve resource managers' ability to identify VSAs, HSAs, and CMAs in watersheds, review and modify the existing BMPs and programs, and develop VSA-based BMPs and programs. As discussed above, managing variable source pollution does not undermine the importance of existing BMPs and watershed management programs. However, some BMP manuals and programs could be modified to recognize the differential roles of landscapes in runoff generation in order to improve their effectiveness and efficiency.

Economic barriers occur because conservation needs are greater than the available funding resources. Therefore, economic barriers of managing VSAs are similar to the economic barriers faced by existing programs. However, as discussed above, managing VSAs is consistent with the targeting approach and should be more cost effective. Empirical research is needed to demonstrate the greater cost effectiveness of the VSA-based BMPs and watershed management programs.

Modification of current BMPs and watershed management practices and/or adoption of VSA-based BMPs and programs do not occur easily. Although the measures for managing variable source pollution demonstrate their technical feasibility and cost effectiveness, farmers and resource managers might be not willing to adopt such measures because of social barriers. Social barriers could be simply the unfamiliarity of the new BMPs and programs or perceived environmental and economic risks. Social barriers are not necessarily new with managing variable source pollution but are a lesser understood area in watershed management (NRC 1999). Research is needed to identify such social barriers and to develop the extension and outreach programs that promote BMPs and programs for managing variable source pollution and making long-term decisions for improving water quality in impaired watersheds.

As discussed above, institutions today generally adopt a "carrot" approach for managing nonpoint source pollution in agricultural watersheds. Instead of regulation and/or penalty, the "carrot" approach offers incentives and compensation for farmers to adopt BMPs. In general, the "carrot" approach is voluntary and offers equal opportunities for adoption to all farmers in the watersheds. When the BMPs and conservation efforts are targeted in CMAs to manage variable source pollution in agricultural watersheds, institutions may need to be more accommodating of the targeting approach. In particular, institutions might draw attention to places in the watershed where variable source pollution originates and provide incentives for farmers to adopt BMPs in CMAs.

As an initial step, a focus group method could be used to evaluate the institutional, technical, social, and economic obstacles to preserving/protecting the critical areas in landscapes and implementing the land use-based BMPs that minimize the negative impacts of land use activities in selected critical land management areas. The focus group method has been widely used in many areas, such as marketing, medicine and social sciences (Gibbs 1997). Powell et al. (1996) define a focus group as "a group of individuals selected and assembled by researchers to discuss and comment on, from personal experience, the topic that is the subject of the research" (p. 499). Focus groups are particularly useful here for the following reasons: (1) The idea of VSA-based BMPs and conservation programs is new; (2) affected parties, such as residents, decision-makers, and conservation professionals, exert different political power over adoption of BMPs; and (3) they facilitate examination of the degree of consensus among the participants about preserving/protecting critical areas in agricultural watersheds (Morgan and Kreuger 1993).

Summary and Conclusions

Managing variable source pollution would contribute to the long-term sustainability of the US agriculture, silviculture, and other landscape uses by reducing negative impacts on the environment, such as water pollution due to polluted runoff. For more than two decades, BMPs have been installed across the country and yet nonpoint pollution continues to be an acute national problem, and agriculture has been strongly implicated (e.g., numerous authors in *Science* February 9 and May 25, 2001). In some cases, researchers point directly to the ineffectiveness of current BMPs (Garrison and Asplund 1993; Brannan et al. 2000; Inamdar et al. 2002), particularly the application of sediment control practices to reduce soluble chemical transport by runoff (Walter et al. 1979; Lammers-Helps et al. 1991; Daniels and Gilliam 1996). Effective control of polluted runoff is greatly hampered by (1) incomplete understanding of the fundamental processes affecting the movement of water in the landscape as well as the origin, fate, and transport

of dissolved and suspended solids in rangeland, forestland, and agricultural watersheds at different spatial scales; (2) incomplete understanding of social, economic, and institutional processes for developing management strategies; (3) inadequate technology for assessing environmental and water quality risks; and (4) insufficient resources for implementing BMPs and management plans in all affected land and water bodies.

Managing variable source pollution contributes to the long-term sustainability of the US agriculture and other landscape management activities by addressing deficiencies in current practices for controlling polluted runoff. Specifically, managing variable source pollution provides (1) improved understanding of fundamental hydrological processes, which can be used to assess water quality risks and BMPs for controlling polluted runoff; (2) new technologies for identifying critical source areas that need to be considered in new watershed management strategies; (3) process-based water resource management practices and strategies based on multidisciplinary and cross-institutional cooperation that combines hydrobiophysical science with social and economic sciences; and (4) increased cost-effectiveness of management practices and strategies.

Advances in geospatial technologies, such as global positioning systems, remote sensing, and GIS and information technologies, such as Internet-based decision support systems and telecommunication, make it possible for resource managers to conduct precision conservation in agricultural landscapes for achieving environmental sustainability (Berry et al. 2003). Precision conservation offers the opportunities of applying the existing and new spatial technologies to address macro-scale issues such as watershed and regional water quality and environmental issues through site-specific BMPs at the micro scales such as subfield, field, and/or subwatershed level (Berry et al. 2005; Reschler and Lee 2005; Dosskey et al. 2005). Delgado and Bausch (2005) presented an example in which both economic and water quality objectives could be achieved simultaneously through the precision conservation techniques. Variable source area hydrology potentially provides a scientific basis for applying and developing precision conservation techniques when applicable. Managing variable source pollution emphasizes the interconnections between land and water and the differentiated roles of different landscapes in water resource protection. It is consistent with the trend of precision conservation and provides a good example to examine the interconnected multiple dimensions of precision conservation—i.e., sciences, technologies, applications, and policies.

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Land use change and gully erosion in the Piedmont region of South Carolina

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Abstract: Land use change played an important role in the formation of gullies present today in the Piedmont of the Southeastern United States. Forested areas that were once cleared to cultivate cotton and consequently gullied are now, once again, covered with forest vegetation. Despite this forest cover, gullies are still considered to be important contributors of sediment to streams, and restoration efforts are still ongoing. However, the data available to assess the extent of gully contributions of sediment are limited. This study assessed the present day stability of these gullies relative to the land use conditions from 1939 to 1999. Based on 1939, 1954, 1970, and 1999 aerial photographs, land areas were classified into those found to be open or cultivated in 1939 that had converted to forest by 1999 (cultivated-to-forested) versus areas that were forested throughout this period (continually forested). An analysis was then conducted that quantified the number and morphological characteristics of gullies in these areas. Characteristics assessed during the field surveys that quantified the presence of recent erosion, such as percent bare soil or forest floor displacement, revealed that the majority of the gullies in both areas are stable. Surprisingly, more frequent (4 vs. 2 per transect), deeper (54 vs. 46 cm), and longer (36 vs. 30 m) gullies were found in the continually forested areas. This equated to a higher estimated average total volume eroded in the continually forested areas (299 m^3) compared to the cultivated-to-forested areas (107 m^3). It is believed that the continually forested areas, which had steeper average slopes, were cultivated but abandoned prior to 1939 due to severe gully formation.

Key words: cover change— erosion— gully survey—reforestation

A change in land use from forest to agriculture can cause accelerated erosion. This is especially true if other factors, like slope and rainfall, are conducive to soil erosion. Gully erosion is considered a threshold phenomenon. It arises only when thresholds of flow hydraulics, rainfall, topography, pedology, and land use have been exceeded (Patton and Schumm 1975; Poesen et al. 2003). Patton and Schumm (1975) stated that "for a given drainage area it is possible to define a critical valley slope above which the valley floor is unstable" and susceptible to gullying. However, they have added that this critical slope is difficult to identify due to variation in vegetation, soil erodibility, and land use within the landscape. Land use has, in fact, been consistently investigated as a key driver of gully formation (Gabris et al. 2003; Harvey et al. 1985; Ireland et al. 1939; Poesen et al. 2003; Strunk 2003). For example, in Racaka, Hungary, deforestation and cultivation caused the average length of existing gullies to increase from 21.3 to 38.2 km (13.2 mi to 23.7 mi) (Gabris et al. 2003).

Reforestation is a common approach to controlling erosion in sloping lands. Forests

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