Report as of FY2006 for 2006NJ118B: "Integrated Assessment of Economic and Water Quality Impacts of Agricultural Best Management Practices in Upper Cohansey River Watershed"

Publications

- Articles in Refereed Scientific Journals:
    - Qiu, Z., M.T. Walter, and C. Hall. 2007. Managing Variable Source Pollution in Agricultural Watersheds. Journal of Soil and Water Conservation, 62(3): 115-122.
    - Qiu, Z. 2006. An Integrated Framework for Targeting Best Management Practices in an Agricultural Watershed. Journal of Soil and Water Conservation, 61(3):197 (Abstract).
- Conference Proceedings:
    - Qiu, Z. 2006. An Integrated Framework for Targeting Best Management Practices in an Agricultural Watershed. The 61st Annual International Conference of Soil and Water Conservation Society, Keystone, Colorado, July 22-26, 2006. (Oral Presentation)
    - Qiu, Z. 2006. Identifying Critical Source Areas in Watersheds for Riparian Buffer Restoration. The 2006 Conference of the Mid-Atlantic Sections of the American Water Resources Association: Stream Restoration and Protection in the Mid-Atlantic Region, NJ School of Conservation, Montclair State University, Branchville, New Jersey, June 14-16, 2006. (Oral Presentation)

Report Follows

Project Summary:

Problem and Research Objectives

The lack of understanding regarding agricultural best management practices (BMP) effectiveness in improving water quality on a watershed scale is not unique to New Jersey. In the past several decades, many BMPs and land management practices have been developed and implemented to reduce water contamination risk associated with nonpoint sources such as agriculture and urban stormwater runoff. An extensive body of literature exists that describes those conservation practices aimed at protecting water quality; i.e., the chemical, physical, and biological integrity of a water body. Billions of dollars have been spent on implementing land use management and conservation practices for improving water quality. However, water quality degradation from nonpoint sources like agriculture remains a major environmental problem in many parts of the United States. Since much of this work was conducted at the plot- or field-scale, there is little documentation on the effectiveness of these practices in actually restoring water quality. Inferences drawn from plot- and field-scale studies are limited in that they cannot capture the complexities and interactions of conservation practices as applied within various locations throughout a watershed (NRC, 1999; Robertson, et al., 2004).

Research that evaluates the interactions among management practices and their biophysical setting on water quality at the watershed scale is a national priority. As the U.S. shifts heavily toward performance-based environmental policy, federal agencies have put great efforts on assessing the effects of conservation practices at watershed scales. The Conservation Effects Assessment Project (CEAP) began in 2003 as a multi-agency effort to quantify the environmental benefits of conservation practices used by private landowners participating in U.S. Department of Agriculture (USDA) conservation programs. So far the CEAP watersheds are mostly located in the big agricultural states. This research will make contribution to the National CEAP Program by assessing the water quality impacts of conservation practices in suburban settings like New Jersey.

Understanding the economic and water quality impacts of agricultural BMPs is becoming increasingly important for achieving the desired water quality standards in watersheds in suburban settings. It is generally perceived that the water pollutant load reductions from traditional point sources such as industrial and municipal wastewater treatment plants have reached their potential due to stringent regulation and technological innovation in the last three decades. Additional reduction from such point sources will incur much higher abatement costs. On the other hand, the agro-environmental policy has been adopting a “softer carrot” approach through cost-sharing and subsidies for reducing agricultural water pollution. It is also perceived that pollution reduction from agricultural sources has lower abatement costs and the additional pollution reduction that is needed to attain water quality standards in watersheds with mixed land uses in suburban settings should come primarily from agricultural sources. This research will provide essential information to evaluate the potential of achieving water quality improvement through reducing agricultural water pollution and facilitate discussions on water quality trading between point and nonpoint (such as agricultural) sources in suburban settings.

The goal of this research is to provide a science-based information analysis to policy makers who want to maximize the water quality benefits while minimizing economic costs when implementing multiple conservation practices in a watershed. The supporting objectives are (1) to estimate the economic and water quality impacts of various agricultural BMPs being implemented in the Neshanic River watershed. The working hypothesis of this objective is that there is a poor understanding of the costs and water quality benefits of BMPs being implemented; and a detailed information on costs and benefits of BMPs is essential to understand the linkages between BMPs and water quality effects in a watershed scale; and (2) to evaluate the potential of controlling agricultural pollution to achieving locally defined water quality goals through optimal placement of BMPs in the watershed by integrating the results of the estimated costs and water quality benefits in the first objective with an optimization programming model. The working hypothesis of the objective is that spatial variability of natural resource conditions in a watershed has profound impacts on the water quality of conservation practices at the watershed scale.

Methodology

Literature review has been conducted on hydrological theories, agro-environmental policies, effectiveness of agricultural BMPs, and modeling to develop innovative ways of managing agricultural nonpoint source pollution. Empirical evaluation of agricultural BMPs in the Neshanic River watershed went two directions. The first is to identify the critical source areas for the placement of conservation buffers, one of the most popular agricultural BMPs by integrating hydrological modeling with geographic information systems to improve its effectiveness. The second is to apply a watershed-scale water quality simulation model Soil and Water Assessment Tool (SWAT) and economic models to evaluate the placement of conservation buffers and other BMPs in the watershed.

The study area is the 31 square miles of Neshanic River watershed in the Raritan River Basin in Hunterdon County, New Jersey. It is comprised of Walnut Brook, First, Second and Third Neshanic River, and the Neshanic River main branch immediately above the Back Brook entrance into the Neshanic River. The Neshanic River is a tributary to the South Branch of the Raritan River, which drains into the Atlantic Ocean. Based upon numerous monitoring sources, including the New Jersey Department of Environmental Protection (NJDEP) Ambient Biomonitoring Network, the NJDEP/USGS water quality monitoring network, and the Metal Recon Program, the Neshanic River and its branches are impaired for aquatic life, phosphorus, total suspended solids (TSS) and copper, and is listed in Sublist 5 of the New Jersey 2004 Integrated Water Quality Monitoring and Assessment Report. A Total Maximum Daily Load (TMDL) for fecal coliform has been approved and adopted for the Neshanic River. This TMDL requires 87% reductions in fecal coliform loads from medium/high density residential, low density/rural residential, commercial, industrial, mixed urban/other urban, forest, and agricultural lands. A TMDL for the total phosphorus in the Neshanic River is nearly completed. The watershed is also experiencing the increasing occurrences of no/low base water flow in the Neshanic River in the late summer (Reiser, 2004). Compared to other areas, the watershed is one of the worst in terms of the overall water quality in the Raritan River Basin. The Neshanic River had either the highest concentrations of constituents or the highest frequency of not meeting water quality standards for 13 of the 17 constituents. This non-trout river has over 40% of its drainage area in agricultural land use, which is the highest percentage in the entire Raritan River Basin.

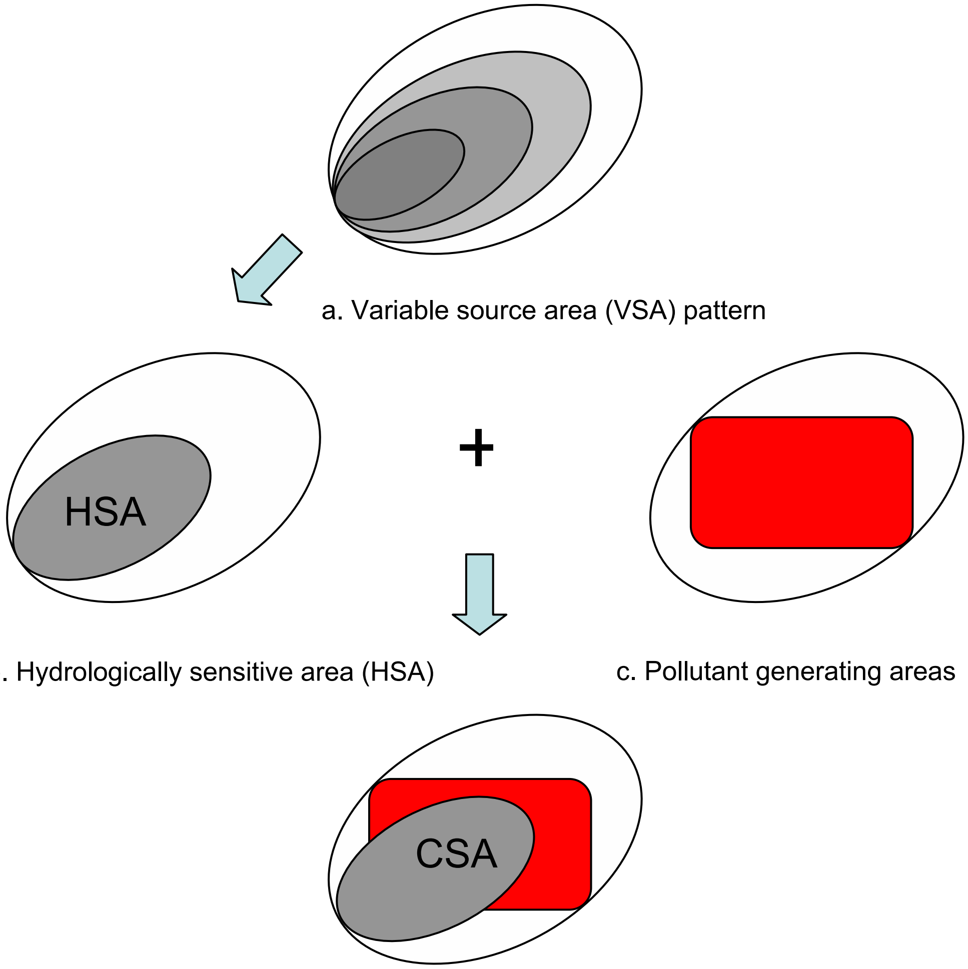
After four years of comprehensive water resource characterization and assessment in the Raritan River Basin, the Watershed Protection Unit at the New Jersey Water Supply Authority developed the Raritan River Basin Management Plan in 2003. According to the Plan, riparian buffer restoration is the number one priority for restoring the water quality in the Basin. The Raritan Watershed Agricultural Committee (RWAC) is a group of proactive agricultural producers and agency personnel in seven counties in the Raritan River Basin that addresses potential water quality impacts of agriculture. Neshanic River watershed was recognized by RWAC as one of the priority watersheds to implement the riparian buffer restoration because of its poor water quality and the high percentage of agricultural lands compared to other watersheds in the Basin. Riparian buffer restoration as a much-needed BMP on agricultural lands can be implemented through the New Jersey Conservation Reserve Enhancement Program (CREP). New Jersey CREP covers 100 percent of the implementation costs of installing riparian buffers and offers land rental payments to landowners who take their lands out of agricultural production and install riparian buffers for 15 years. Clearly identifying the critical source areas for riparian buffer restoration would significantly improve the efficiency of CREP and the water quality in the watershed.

Critical source areas are the intersection of hydrologically sensitive areas and pollutant generating areas in landscapes. Identification of critical source areas is based on the concept of variable source area hydrology. Since the early 1960s, researchers have repeatedly noted saturation excess processes as a more physically realistic runoff process than Hortonian infiltration excess process. The earliest study by the U.S. 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 infiltration excess runoff theory (Betson, 1964; Tennessee Valley Authority, 1965; Amerman, 1965; Ragan, 1967; Hewlett and Nutter, 1970; Dunne, 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. Dunne and Black (1970a, b) are generally credited with the definitive field experiment describing VSA mechanisms, especially for watersheds where shallow, transient interflow is common. According to the VSA hydrology, runoff is generated from saturated areas in landscapes where soil saturation capacity is exceeded and is controlled by the development, expansion and contraction of these saturated areas.

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 converging 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, b; Beven and Kirkby, 1979). Recently, shallow interflow has been shown to be an important control on VSA dynamics, especially in the northeastern U.S. (Moore and Thompson, 1996; Frankenberger et al., 1999; Ogden and Watts, 2000; Srinivasan et al., 2002). Besides the humid northeastern U.S., the VSA hydrological process is acknowledged in Canada (Dickinson et al., 1987 and 1990) and other parts of the U.S., 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).

The pollutant generating areas are the areas in landscapes that have been actively used by people for production and consumption, such as agricultural production, residential development, and industrial and commercial uses. The hydrologically sensitive areas are the areas that actively contribute to generation of runoff and water pollutants in landscapes.

Figure 1: the relationships among VSAs, HSAs and CSAs



a. Variable source area (VSA) pattern

b. Hydrologically sensitive area (HSA)

c. Pollutant generating areas

d. Critical source area (CSA)

Figure 1 presents a procedure that identifies the critical source areas for riparian buffer restoration in a watershed with three steps: (1) identifying the VSA patterns in the watershed using a modeling technique; (2) delineating the hydrologically sensitive areas (HSA) from the identified VSA patterns based on a typical weather condition; and (3) identifying the critical source areas (CSA) of a watershed by overlapping the identified HSA and critical land use layers.

Various models can be used to identify the VSA patterns in a watershed. In this application, a modified topographic index model will be used to identify VSA patterns. As demonstrated by Agnew et al. (2005), the topographic index model can simulate the VSA patterns as the SMR does in the Catskill mountain watersheds. A watershed can be divided into small 10-meter or 30-meter grids. A topographic index can be calculated for each of the grids. The topographic index measures the relative likelihood of being saturated for each grid during a storm. In general, the higher the index, the more likely the grid is saturated in a storm. Specifically, the topographic index is defined as

$$(1) \qquad \lambda = \ln\left(\frac{\alpha}{\tan(\beta) K_s D}\right)$$

where λ is the derived topographic index, α is the upslope contributing area per unit contour length in meters, tan(β) is the local surface topographic slope, *Ks* is the mean saturated hydraulic conductivity of the soil in meters per day, and *D* is the soil depth in meters. α and tan(β) can be derived from a digital elevation model, and *Ks* and *D* can be found in the USDA Natural Resource Conservation Service (NRCS) soil survey data.

Incorporating VSA hydrology into water quality management implies that soil and water conservation efforts should be concentrated on these small but hydrologically sensitive parts of a watershed. Given natural conditions, such as topography, soil, land use/cover and hydrology in landscapes, a series of VSA patterns corresponding to dynamic rainfall events will be identified in the watershed (Qiu, 2003; and Gérard-Marchant et al., 2003). The identified VSA patterns could vary from 1 percent to over 50 percent of the watershed. However, water resource managers usually prefer well-defined, static HSAs for targeting water conservation practices such as conservation buffers. After identifying the VSA patterns in the watershed, a set of criteria can be developed to delineate HSAs from identified VSAs. For example, a typical rainfall event can be used to delineate the HSAs. Since the modified topographic index model is used to simulate the VSA patterns, the calculated topographic index is used to delineate HSAs. For example, a grid is considered to be a part of the HSAs when the topographic index of the grid is greater than a reference number.

Walter et al. (2000) defined CSAs based on HSAs in an agricultural setting. For an agricultural field in the Catskill Mountain region of New York State in which dairy manure is spread, CSAs were defined as the intersection of the HSAs and the manure spread areas in the field. The idea of identifying CSAs can be extended to other settings. In general, CSAs are the intersections of the HSAs and the pollutant generating areas in watersheds. The pollutant generating areas are the areas in landscapes that have been actively used by people for production and consumption, such as agriculture, residential development, and industrial and commercial uses. CSAs can be identified by overlaying the identified HSAs in Step 2 with existing land use and zoning maps. The identified critical areas provide the basis for targeting the conservation buffers.

Three spatial datasets were used to delineate the critical source areas in the watershed: a digital elevation model (DEM), a soil data and a recent land use/cover. The 10-meter resolution DEM was developed by the NJDEP and was downloaded from its website (http://www.state.nj.us/dep/gis/). The Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) soil data was used in this application. Since the study area is entirely located within the Hunterdon County, the digital SSURGO soil databases for Hunterdon County was downloaded from the NRCS Soil Data Mart website (http://soildatamart.nrcs.usda.gov/). The land use/cover data, compiled from the aerial photographs taken in the spring of 2002, were downloaded from NJDEP website.

The DEM and SSURGO soil data are used to derive the topographic index for identifying the VSAs pattern in the watershed. The data are processed using ArcGIS 9.1 in three steps to obtain the VSAs pattern. First, the DEM was processed using an open source ArcGIS extension TauDEM (Torboton, 2005) to obtain a wetness index grid, $\ln(\frac{\alpha}{\tan(\beta)})$, where the variables were defined as above. Second, the soil depth (*D*) and the mean saturated hydraulic conductivity (*Ks*) were extracted for each soil type from the soil data. Their product (*Ks***D*) was calculated and linked to the spatial soil boundary layer. The soil layer was converted into a grid layer based on the value of *KsD*. When extracting the *D* and *Ks*, the physical properties of each soil type in the soil database were evaluated to determine whether there was a restrictive layer or bedrock in the soil. For example, a significant drop in *Ks* could imply the existence of a restrictive layer. If there is a restrictive layer, the soil depth to the restrictive layer was extracted and the mean of the saturated hydraulic conductivities in different soil layers above the restrictive layer was calculated. Third, the Raster Calculator in ArcGIS 9.1 was used to manipulate the two raster layers obtained in the first two steps and to calculate the topographic index based on equation (1). The higher the index, the higher likelihood the grid gets saturated during a storm.

A reference level of the topographic index is selected to classify the HSAs in the watershed from the VSAs pattern. Not all areas within HSAs are subject to conservation buffer restoration. In general, restoration is not a concern for HSAs in forests, already established wetlands, and riparian buffers. Buffer restoration should focus on the parts of the HSAs where land use activities, such as agricultural production and urban development, have the potential to degrade stream water quality. Identified HSAs were overlapped with the 2002 land use/cover to identify the critical source areas for riparian buffer restoration in the watershed. Specifically, HSAs were defined as areas where the topographic index is greater than 10. CSAs are those HSAs for which the land use types are agriculture, barren land and urban. All data were processed and analyzed using ArcGIS 9.1.

Besides the conservation buffers, we are also investigating the other types of BMPs implemented in the watershed such nutrient management, pest management, and tillage management. Due to the restriction in the Privacy Act and Freedom of Information Act, the Natural Resource Conservation Service New Jersey Office did not release any information on BMPs being implemented in the watershed. I have been interviewing farmers, NRCS and the Rutgers Cooperative Extension personnel and conducting field visits and interviews with farmers.

Principal Findings and Significance

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. Our research review challenges this assumption, noting that overland flow associated with agricultural pollutant transport is often physically consistent with the variable source area (VSA) hydrology concept, for which overland flow is generated in parts of the landscape where the soil saturates to the surface. Incorporation of VSA 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, 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.

Following the procedure laid out in Figure 1, the topographic index, hydrologically sensitive areas and critical source areas were derived. The resulting topographic indices in the watershed range from 2 to 25. The higher topographic indices imply a higher likelihood that runoff is generated during a storm event. Table 1 presents the area distribution of the topographic indices in the watershed. The majority of the watershed has topographic indices of 6, 7, 8, 9, and 10. The area corresponding to each index is over 10 percent of the watershed. Only 4.6 percent of the watershed has topographic indices greater than 12. Figure 2 presents the spatial distribution of the topographic index, i.e. the VSA patterns, in the watershed. Several observations can be made based on Figure 2. First, the majority of the grids with the highest topographic indices (above 19 as indicated by the reddish colors) tend to be located along the existing stream network. This is not a surprise because the streams and their riparian areas are VSAs. Second, some of the grids with the highest topographic indices are distributed outside of the existing streams and their riparian areas. Third, a majority of the grids with next highest indices (between 12 and 18 as indicated by the yellowish colors) are outside of the existing streams and riparian areas, in the upland contributing areas. The spatial distribution of topographic indices indicates that conservation buffers for improving water quality should be located beyond the riparian areas of the existing streams.

Table 1: The distribution of area in Neshanic River Watershed according to topographic index

Topographic Index	Number of Grids	Area (hectares)	Distribution (%)
2	106	1.06	0.01
3	1,456	14.56	0.18
4	10,555	105.55	1.32
5	40,025	400.25	5.00
6	86,417	864.17	10.78
7	144,738	1,447.38	18.06
8	161,046	1,610.46	20.10
9	141,879	1,418.79	17.71
10	100,497	1,004.97	12.54
11	52,787	527.87	6.59
12	24,891	248.91	3.11
13	12,476	124.76	1.56
14	7,191	71.91	0.90
15	4,593	45.93	0.57
16	3,196	31.96	0.40
17	2,300	23.00	0.29
18	1,800	18.00	0.22
19	1,771	17.71	0.22
20	1,528	15.28	0.19
21	958	9.58	0.12
22	509	5.09	0.06
23	395	3.95	0.05
24	153	1.53	0.02
25	8	0.08	0.00
Total	801,275	8,013	100

The HSA is determined by evaluating the VSA patterns using different reference numbers in topographic index. It was decided that the grids with topographic indices greater than 10 were considered to be HSAs. A separate GIS layer on HSAs was created by selecting the grids with topographic indices greater than 10 using ArcGIS 9.1. The resulting HSAs cover around 1,146 hectares and make up 14.3 percent of the watershed. CSAs were identified by overlaying the HSAs with topographic indices greater than 10 with the 2002 land use/cover layer for the watershed developed from aerial photographs. There are six broad categories of land uses in the watershed: agriculture; urban; forest; barren; wetlands; and water. The pollutant generating areas are the areas with agriculture, urban and barren land uses.

Figure 2. Derived topographic index map in Neshanic River Watershed

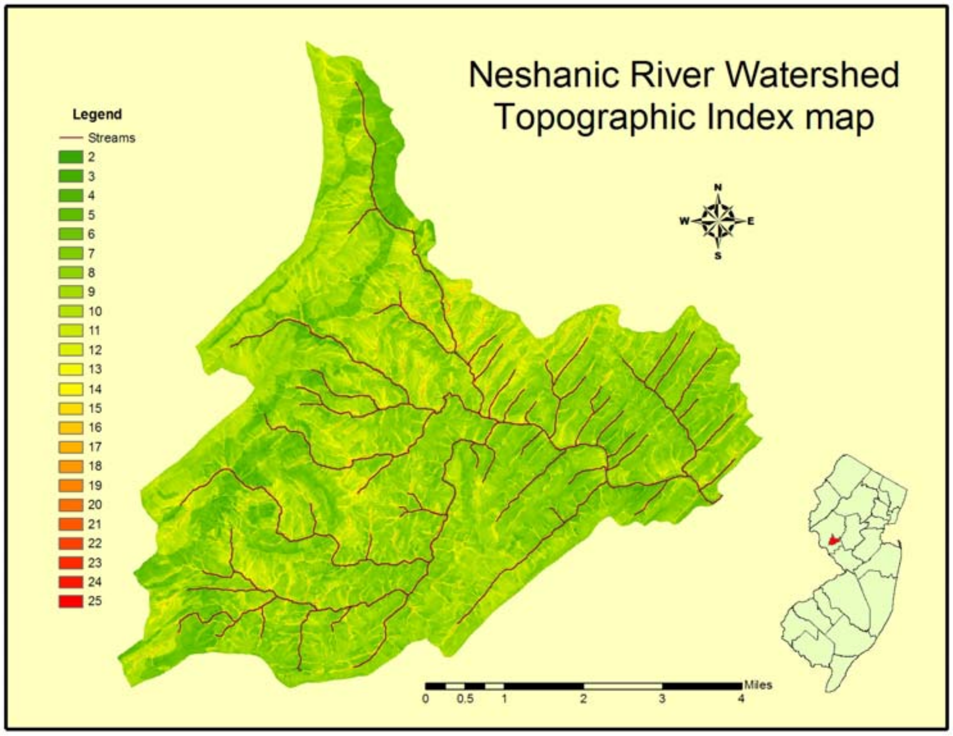


Figure 3. Derived hydrologically sensitive areas and critical source areas in Neshanic River Watershed

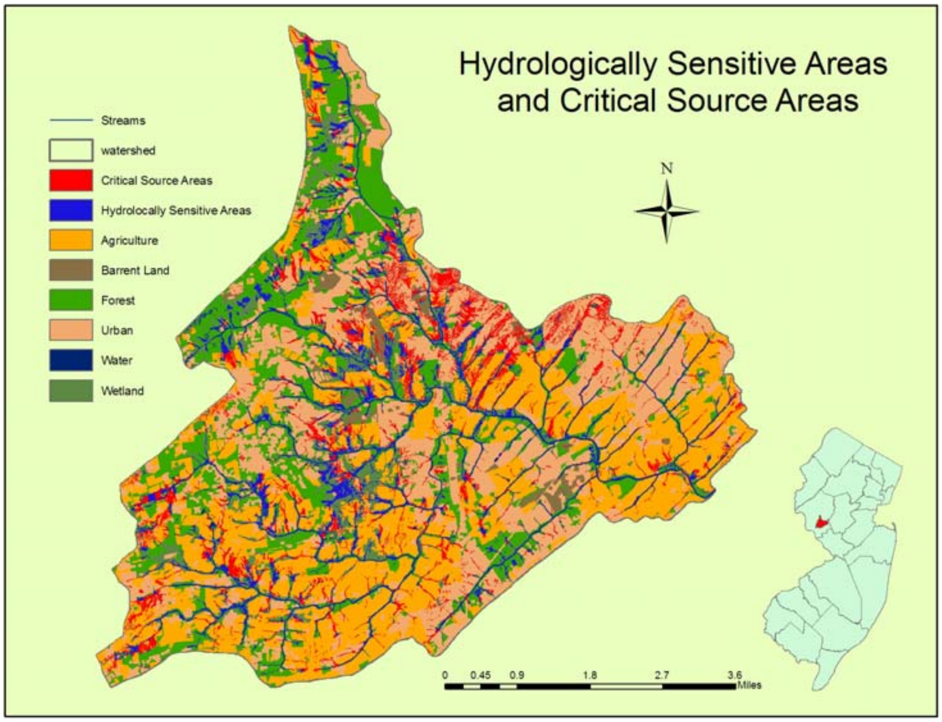


Figure 3 presents the location of the identified CSAs as indicated by the red areas. The total area of the identified CSAs is 654 hectares. As shown in Figure 3, the CSAs are scattered around the watershed. Many of them are located in the upland areas and are not necessarily in close proximity of streams in the watershed. This occurs because many parts of the riparian areas of streams are usually covered by dense forest and wetlands, as shown in Figure 3 and as observed in many other watersheds.

The locations of the CSAs have several implications. First, conservation programs should encourage landowners to install and construct conservation buffers in CSAs. For example, CREP can provide higher incentives to farmers who enroll their lands in CSAs located in agricultural areas. In suburban settings, various land use planning tools and ordinances can be adopted to protect and preserve CSAs from development. For example, conservation easements, which preserve open space, can be targeted to CSAs. Second, conventional riparian preservation as implemented in New Jersey is not efficient and effective in protecting the identified CSAs because many of them are located in upland areas.

The science-based GIS procedure discussed here is a powerful screening tool for identifying potential sites for buffer restoration and construction. Contrary to the conventional wisdom that states buffers should always be in the riparian areas in the existing stream corridors, the CSA map shows that many upland areas should be also targeted for buffer restoration because of their active role in generating runoff. The procedure described here is applicable to both small and large watersheds and can be further extended to rank the identified potential sites based on conservation priorities, data and funding availability.

Although placing conservation buffers within CSAs has the potential to improve the efficiency and effectiveness of the conservation buffer programs, it is challenging to achieve such placement under the existing buffer programs for several reasons. First, the proposed approach is based on a targeting criterion, whereas most existing buffer programs result in conservation buffer placement that reflects the voluntary nature of the program, i.e., buffers are placed where landowners voluntarily agree to place them. Second, since priority is given to placing conservation buffers in CSAs, the approach raises equity concerns among the stakeholders, i.e., priority for buffer placement is given to stakeholders who own land in CSAs. Third, the proposed approach could require constructing conservation buffers in only parts of a field, which can create monitoring and implementation difficulties. In addition, there are limited technical guidelines available for a partial-field buffer approach. Farmers may resist this approach if it adversely affects the economies of scale of farming operations. Fourth, local conservation practices are usually administered by different agencies, which can pose substantial barriers to acquiring the resources and coordinating the efforts needed to implement a CSA-based buffer program.

Empirical evaluation of SWAT modeling in the watershed has been slowed down due to the lack of cooperation from the NRCS New Jersey Office. The SWAT has been compiled and evaluated in the watershed. We are still in the process of finalizing the farming practices and alternative BMPs in watershed by working with farmers, NRCS field offices and agrochemical businesses. By plugging the information into the model, we will calibrate the model and evaluate the placement strategies for BMPs to achieve the watershed management goals.

Cited Literature

Agnew, L.J., M.T. Walter, A. Lembo, P. Gérard-Marchant, T.S. Steenhuis. 2006. Identifying hydrologically sensitive areas: Bridging science and application. *J. Envir. Mgt.* 78: 64-76.

Amerman, C.R. 1965. Use of unit-source watershed data for runoff prediction. *Water Resour. Res.* 1(4): 499-508.

Arnold, J. G., J.R. Williams, R. Srinivasan, K.W. King, R.H. Griggs. *SWAT: Soil and Water Assessment Tool*. Temple, Texas: USDA Agricultural Research Service, 1994.

Arnold, J.G., J.D. Atwood, V.W. Benson, R. Srinivasan and J.R. Williams. 1998. Potential Environmental and Economic Impacts of Implementing National Conservation Buffer Initiative Sedimentation Control Measures. USDA, NRCS, Resource Assessments Division Working Paper, Temple, TX.

Betson, R.P. 1964. What is Watershed Runoff? *Journal of Geophysical Research* 69(8):1541-1552.

Beven K.J. and M.J. Kirkby. 1979. A physically based variable contributing area model of basin hydrology. *Hydrol. Sci. Bull.* 24(1): 43-69.

Boll, J., C.O. Stockle, S.K. Young, E.S. Brooks, J.E. Hammel, C.R. Campbell, and P.A. McDaniel. 1998. Progress toward development of a GIS based water quality management tool for small rural watersheds: modification and application of a distributed model. ASAE presentation paper. ASAE Annual International Meeting. July 12-16, 1998. Disney's Coronado Springs Resort, Orlando FL. Paper 982230. pp.20.

Brooks, E.S., P.A. McDaniel, and J. Boll. 2000. Hydrologic modeling in watersheds of the eastern Palouse: Estimation of subsurface flow contributions. Presented at the 2000 PNW-ASAE Regional Meeting. Water, Energy, and the Environment: Critical Agricultural and Biological Engineering Challenges in the 21st Century sponsored by ASEA and CSAE. Sept 21-23, Richland WA. Paper 2000-10. pp. 11

Dickinson, W.T., R.P. Rudra & G.J. Wall. 1987. Identification of soil erosion and fluvial sediment processes. Hydrological Processes 1: 11-124.

Dickinson, W.T., R.P. Rudra & G.J. Wall. 1990. Targeting remedial measures to control non-point source pollution. Am Wat. Res. Bull. 26(3): 499-507.

Dunne, T. 1970. *Runoff production in humid areas*. U.S. Department of Agriculture Publication ARS-41-160. pp. 108.

Dunne, T. and R.D. Black. 1970a. An Experimental Investigation of Runoff Production in Permeable Soils. Water Resource Research 6(2):179-191.

Dunne, T. and R.D. Black. 1970b. Partial Area Contributions to Storm Runoff in a Small New England Watershed. Water Resource Research 6(5):1296-1311.

Dunne, T., T.R. Moore, and C.H. Taylor. 1975. Recognition and prediction of runoff producing zones in humid regions. *Hydrol. Sci. Bull.* 20(3): 305-327.

Frankenberger, J.R., E.S. Brooks, M.T. Walter, M.F. Walter, T.S. Steenhuis. 1999. A GIS-based Variable Source Area Hydrology Model. Hydrological Processes 13:805-822.

Gérard-Marchant, P., W.D. Hively and T. Steenhuis. 2003. Distributed modeling of total dissolved phosphorus loading on a small farm watershed. In: Pfeffer, M.J., D.J. Van Abs, and K.N. Brooks (Editors), Watershed Management for Water Supply Systems. AWRA's 2003 International Congress. American Water Resources Association, Middleburg, Virginia, TPS-03-2, CD-ROM.

Hewlett, J.D. and Hibbert, A.R. 1967. Factors affecting the response of small watersheds to precipitation in humid regions. *In* W.E. Sopper and H.W. Lull (eds.) *Forest Hydrology*. Pergamon Press, Oxford. pp. 275-290.

Hewlett, J.D. and Troendle, C.A. 1975. Non-point and Diffused Water Sources: A Variable Sources Area Problem. Pages 21-46 in the Proceedings of the Symposium on Watershed Management, American Society of Civil Engineers.

Hewlett, J.D. and W.L. Nutter. 1970. The varying source area of streamflow from upland basins. *Proc. of the Symposium on Interdisciplinary Aspects of Watershed Management*. held in Bozeman, MT. August 3-6, 1970. pp. 65-83. ASCE. New York.

Moore R.D. and J.C. Thompson. 1996. Are water table variations in a shallow forest soil consistent with the TOPMODEL concept*? Water Resour. Res*. 32 (3): 663-669.

National Research Council (NRC). 1999. *New Strategies for America's Watersheds*. Washington, D.C.: National Academy Press.

Ogden F.L. and B.A. Watts BA. 2000. Saturated area formation on nonconvergent hillslope topography with shallow soils: A numerical investigation. *Water Resour. Res*. 36(7): 1795-1804.

Qiu, Z. 2003. A VSA-based strategy for placing conservation buffers in agricultural watersheds. Environmental Management 32(3): 299-311.

Ragan, R.M. 1967. An experimental investigation of partial area contribution. Int. Ass. Sci. Hydrol. Proc. Berne Symposium.

Reiser, R.G. 2004. Evaluation of Streamflow, Water Quality and Permitted and nonpermitted Loads and Yields in the Raritan River Basin, New Jersey, Water Years 1991-98. Water-Resources Investigations Report 03-4207, U.S. Geological Survey, West Trenton, New Jersey.

Robertson, G.P., J.C. Broome, E.A. Chornesky, J.R. Frankenberger, P. Johnson, M. Lippson, J.A. Miranowski, E.D. Ownes, D. Pimentel, and L.A. Thrupp. 2004. Rethinking the vision for environmental research in US agriculture. BioScience. 54(1): 61-65.

Schmitt, S.J. 1999. *Application of a flow source mixing model and remote sensing to the hydrology and water quality of two small watersheds in Northern Missouri*. M.S. Thesis. The School of Natural Resources, University of Missouri, Columbia, MO.

Srinivasan M.S., W.J. Gburek, and J.M. Hamlett. 2002. Dynamics of stormflow generation - A hillslope-scale field study in east-central Pennsylvania, USA. *Hydrol.Proc*. 16(3): 649-665.

Tatiana H., M. Nachabe, M. Ross, and J. Obeysekera. 2003. Modeling runoff from variable source in humid, shallow water table environments. *Journal of the American Water Resources Association* 39(1):75-85.

Tennessee Valley Authority. 1965. Area-stream factor correlation, a pilot study in the Elk River Basin. International Association of Scientific Hydrology Bulletin 10(2):22-37.

Torboton, D.G. 2005. Terrain Analysis Using Digital Elevation Models (TauDEM). Accessible at http://hydrology.neng.usu.edu/taudem/.

U.S. Forest Service. 1961. *Some ideas about storm runoff and baseflow*. Annual Report. Southeastern Forest Experiment Station. pp. 61-66.

Walter, M.T., M.F. Walter, E.S. Brooks, T.S. Steenhuis, J. Boll, and K. 2000. Weiler. Hydrologically sensitive areas: variable source area hydrology implications for water quality risk assessment. Journal of Soil and Water Conservation 55(3):277-284.