Riley, H., T. Børresen, T. Ekeberg, and E. Rydberg. 1994. Trends in reduced tillage research and practice in Scandinavia. Pp. 23-45. *In:* Conservation tillage in temperate agroecosystems. M.R. Carter (ed.) Lewis Publishers, New York, New York.

Ross, C.W. 1986. The effect of subsoiling and irrigation on potato production. Soil Tillage Research 7:315-325.

Round Table on Resource Land Use and Stewardship. 1997. Cultivation island solutions. Queens Printer, Charlottetown, Prince Edward Island.

Sojka, R.E., D.T. Westermann, D.C. Kincaid, I.R. McCann, J.L. Halderson, and M. Thornton. 1993. Zone-subsoiling effects on potato yield and grade. American Potato Journal 70:475-484.

Statistics Canada. 2001. Agriculture 2001 Census. [Online] Available: http://www.statcan.ca/english/freepub/95F0301XIE/tables/pdf/table13Can.pdf (Accessed 8-22-2006)

Taylor, H.M. 1971. Effects of soil strength on seedling emergence, root growth and crop yield. Pp. 292-305. *In:* Compaction of agricultural soils. K.K. Barnes (ed.) American Society of Agricultural Engineers, St. Joseph, Michigan.

Thomas, G.W. 1986. Mineral nutrition and fertilizer placement. Pp. 93-116. *In:* No-tillage and surface tillage agriculture. M.A. Sprague and G.B. Triplett, (eds.) Wiley, New York, New York.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. Water Resources Research 16: 574-582.

Truman, C.C., D.W. Reeves, J.N. Shaw, A.C. Motta, C.H. Burmester, R.L. Raper, and E.B. Schwab. 2003. Tillage impacts on soil property, runoff, and soil loss variations from a Rhodic Paleudult under simulated rainfall. Journal of Soil and Water Conservation 58(4):258-266.

Vrana, V.K. 1991. Crop residue management: What the SWCS study shows in crop residue management for conservation. Proceedings of a National Conference, Soil and Water Conservation Society, Ankeny, Iowa.

Williams, J.L., Jr. and G.A. Wicks. 1978. Weed control problems associated with crop residue systems. Pp. 165-172. *In:* Crop residue management systems, W.R. Oschwald (ed.) Special Publication No. 31. American Society of Agronomy, Madison, Wisconsin.

Young, I.M., A.G. Bengough, C.J. MacKenzie, and J.W. Dickson. 1993. Differences in potato development (*Solanum tuberosum* cv 'Maris Piper') in zero and conventional traffic treatments are related to soil physical conditions and radiation interception. Soil Tillage Research 26:341-359.

Water quality in relation to vegetative buffers around sinkholes in karst terrain

A. Petersen and B. Vondracek

ABSTRACT: There are approximately 8,340 mapped sinkholes in karst terrain of southeast Minnesota. Most sinkholes are adjacent to row crops that likely contribute pollutants to surface waters and aquifers. Vegetated buffers can improve water quality by reducing sediment, fertilizers, pesticides, and other potential contaminants from runoff, and may benefit water quality when placed around sinkholes. We evaluated sediment, nitrogen, phosphorus, and runoff for buffers from 2.5 to 30 m (8.3 to 98 ft) wide with a spreadsheet model. We found buffers 30 m (98 ft) wide may reduce pollution by 80 percent, although buffers 15 m (49 ft) wide may be most cost effective. Buffers could contribute to goals of reducing sediment, nitrogen, and phosphorus loads in Minnesota waters. Buffers 15 m (49 ft) wide around all sinkholes would retire approximately 436 ha (1,077 ac) of land from production and cost approximately $260,000 yr^{-1} based on Conservation Reserve Program payments, while requiring <14 percent of the budget of the program for groundwater protection in southeast Minnesota.

Keywords: Filter strips, nitrogen, phosphorus, pollutants, runoff, sediment

Water pollution is a widespread problem in agricultural settings. Runoff can move sediment, nutrients, pathogens, salts, pesticides, and fertilizers to streams, lakes, and aquifers. Runoff from agricultural lands is implicated in 48 percent of listed U.S. stream water quality impairments in the 2000 National Water Quality Inventory (USEPA, 2000). Streams in agricultural areas are characterized by elevated levels of turbidity, fecal coliform, pesticides, nitrate-nitrogen, and phosphorus (Grow, 1986). Excessive nitrate concentrations threaten drinking water quality, whereas increased phosphorus levels are implicated in eutrophication of surface waters. Sediment is the most widespread agricultural pollutant delivered to streams (United States Environmental Protection Agency, 2000) and can be either suspended load or bed load. High sediment loads in streams have a negative impact on fish and macroinvertebrates (Bruton, 1985; Waters, 1995; Newcombe and Jensen, 1996).

Vegetated riparian buffers are considered a best management practice (BMP) for reducing sediment and pollutant loads and can improve water quality in streams (Correll, 1997; Lee et al., 2000; Blanco-Canqui et al., 2004a; Parkyn, 2004; Lowrance and Sheridan, 2005). By allowing runoff to infiltrate the soil, buffers can recharge groundwater and improve the overall quality of surface water (Welsh, 1991; Spruill, 2004).

Karst terrain covers about one-quarter of the United States (Veni, 2002). Karst areas contain sinkholes, springs, caves, and related features. Water moves through cracks and fissures in carbonate rock and eventually water may emerge as a spring. In southeast Minnesota and other areas of karst terrain, the installation of vegetated buffers around sinkholes would emulate riparian buffers. Approximately 60 percent of southeastern Minnesota is currently used for row-crop agriculture, mostly corn and soybeans, with some additional land used for dairy and grazing (Blann, 2004). The ability of buffers to

Adam Petersen is a grayling technician III for the Montana Fish, Wildlife, and Parks in Bozeman, Montana. **Bruce Vondracek** is a unit leader with the U.S. Geological Survey, Minnesota Cooperative Fish and Wildlife Research Unit at the University of Minnesota in St. Paul, Minnesota.

be overcome by new technology thereby allowing producers to plant into sod and to remove trash during the harvest operation. Despite this, the potential benefits of these conservation tillage systems can outweigh the negative effects.

Acknowledgements

The authors would like to thank David Main, Ambrose Malone, Jason Rayner, Harry Younie, Margaret Sentner, Krista Anderson, Evan Thompson, Matthew Harris, Christina Stewart, Lloyd MacFayden, Donnie Darrach, Sandy Jenkins, Lloyd Kerry, Ryan Drake, and Danny MacIssac for field and technical assistance. Gratitude is expressed to Thomas L. Gallant for assisting with the manuscript compilation and editing.

References cited

Allmaras, R.R., P.W. Unger, and D.W. Wilkins. 1985. Conservation tillage systems and soil productivity in soil erosion and crop productivity. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, Wisconsin.

Anonymous. 1988. USDA color standards for frozen French fried potatoes. 4th edition. Kollmorgen Corporation, Baltimore, Maryland.

Blackshaw, R.E., F.J. Larney, C.W. Lindwall, P.R. Watson, and D.A. Derksen. 2001. Tillage intensity and crop rotation affect weed community dynamics in a winter wheat cropping system. Canadian Journal of Plant Science 81:805-813.

Bouma, J. and van Lanen, H.A.J. 1988. Effects on the crop rotation system on soil physical behavior and relations with potato yield. Pp. 77-88. *In:* Effects of crop rotation on potato production in the temperate zones. J. Vos, C.D. Van Loon, and G.J. Bollen (eds.) Kluwer Academic Publishers, New York, New York.

Buhler, D.D. 1997. Effects of tillage and light environment on emergence of 13 annual weeds. Weed Technology 11:496-501.

Burney, J.R. and L.M. Edwards. 1989. Development of a field rainfall simulator for cool season soil erosion studies. Technical University of Nova Scotia, Halifax, Nova Scotia.

Canada Soil Survey Committee, Subcommittee on Soil Classification. 1978. The Canadian system of soil classification. Canada Department of Agriculture Publication No. 1646. Supply and Services Canada, Ottawa, Ontario.

Carter, M.R. 1990. Relationship of strength properties to bulk density and macroporosity in cultivated loamy sand to loam soils. Soil Tillage Research 15:257-268.

Carter, M.R. and J.B. Sanderson. 2001. Influence of conservation tillage and rotation length on potato productivity, tuber disease and soil quality parameters on a fine sandy loam in eastern Canada. Soil Tillage Research 63:1-13.

Carter, M.R., J.B. Sanderson, J.A. Ivany, and R.P. White. 2002. Influence of rotation and tillage on forage maize productivity, weed species, and soil quality of a fine sandy loam in the cool-humid climate of Atlantic Canada. Soil Tillage Research 67:85-98.

Chow, T.L. and H.W. Rees. 1994. Effects of potato hilling on water runoff and soil erosion under simulated rainfall. Canadian Journal of Soil Science 74: 453-460.

Dumanski, J., L.J. Gregorich, V. Kirkwood, M.A. Cann, J.L.B. Culley, and D.R. Coote. 1994. The status of land management practices on agricultural land in Canada. Technical Bulletin No. 1994-3E CLBRR. Supply and Services Canada, Ottawa, Ontario.

Ekeberg, E. and H.C.F. Riley. 1996. Effects of mouldboard plowing and direct planting on yield and nutrient uptake of potatoes in Norway. Soil Tillage Research 39:131-142.

Ekeberg, E. and H.C.F. Riley. 1997. Tillage intensity effects on soil properties and crop yields in a long-term trial on morainic loam soil in southeast Norway. Soil Tillage Research 42:277-293.

Farnsworth, R.L., R.W. Frazee, E. Giles, and D. Peterson. 1993. The residue dimension: Managing residue for conservation and profit. Land and water: Conserving natural resources in Illinois, No. 9 (Revised). Cooperative Extension Service, University of Illinois, Urbana-Champaign, Illinois.

Fox, M.G. and D.R. Coote. 1985. A preliminary economic assessment of agricultural land degradation in Atlantic and Central Canada and southern British Columbia. Regional Development Branch, Agriculture Canada, Ottawa, Ontario.

Genstat 5 Committee. 1997. Genstat 5 Reference Manual. Oxford University Press, New York, New York.

Griffith, D.R., J.V. Mannering, H.M. Galloway, S.D. Parsons, and C.B. Richey. 1973. Effect of eight tillage-planting systems on soil temperature, percent stand, plant growth, and yield of corn on five Indiana soils. Agronomy Journal 65:321-326.

Griffith, D.R., J.V. Mannering, and J.E. Box. 1986. Soil and moisture management with reduced tillage. Pp. 19-55. *In:* No-tillage and surface tillage agriculture. M.A. Sprague and G.B. Triplett (eds.) Wiley, New York, New York.

Grant, W.J. and E. Epstein. 1973. Minimum tillage for potatoes. American Potato Journal 50:193-203.

Halderson, J.L. 1993. Zoned tillage for potato production. Transactions of the ASAE 36:1377-1380.

Halderson, J.L., I.R. McCann, and J.C. Stark. 1993. Zone tillage for potato production. Transactions of the ASAE 36:1377-1380.

Hatfield, J.L and B.A. Stewart (eds.) 1994. Crops residue management. Advances in Soil Science. Lewis Publishers, Boca Raton, Florida.

Holmstrom, D., R. DeHaan, J.B. Sanderson, and J.A. MacLeod. 1999. Residue management for potato rotation in Prince Edward Island. Journal of Soil and Water Conservation 54(4):445-448.

Ibrahim, B.A. and D.E. Miller. 1989. Effect of subsoiling on yield and quality of corn and potato at two irrigation frequencies. Soil Science Society of America Journal 53:247-251.

Jacobs, P. and Associates, Ltd. 1998. Best management practices: Soil conservation for potato production in Prince Edward Island. PEI Department of Fisheries and Environment, PEI Department of Agriculture and Forestry, and Environment Canada, Charlottetown, Prince Edward Island.

Katsvario, T., W.J. Cox, and H. van Es. 2002. Tillage and rotation effects on soil physical characteristics. Agronomy Journal 94:299-304.

Kladivko, E.J., D.R. Griffith, and J.V. Mannering. 1986. Conservation tillage effects on soil properties and yield of corn and soya bean in Indiana. Soil Tillage Research 8:277-287.

Laflen, J.M., R.E. Highfill, M. Amemiya, and C.K. Mutchler. 1985. Structures and methods for controlling water erosion. Pp. 431-442. *In:* Soil erosion and crop productivity. R.F. Follett and B.A. Stewart (eds.) American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, Wisconsin.

Lanfranconi, L.E., R.R. Bellinder, and R.W. Wallace. 1993. Grain rye residue and weed control strategies in reduced tillage potatoes. Weed Technology 6:1021-1026.

Langdale, G.W., E.E. Alberts, R.R. Bruce, W.M. Edwards, and K.C. McGregor. 1994. Concepts of residue management infiltration, runoff, and erosion. Pp. 109-124. *In:* Crops residue management. J.L. Hatfield and B.A. Stewart (eds.) Lewis Publishers, Boca Raton, Florida.

Langdale, G.W., W.C. Mills, and A.W. Thomas. 1992. Use of conservation tillage to retard erosive effects of large storms. Journal of Soil and Water Conservation 47(6):257-260.

MacDonald, E. 1995. PEI potato production: How big is too big? PEI Soil and Crop Improvement Association, Charlottetown, Prince Edward Island.

MacDougall, J.I., C. Veer, and F. Wilson. 1988. Soils of Prince Edward Island: Prince Edward Island soil survey. Agriculture Canada LRRC Contribution No. 84-54. Supply and Services Canada, Ottawa, Ontario.

Meyer, L.D. 1988. Rainfall simulators for soil conservation research. Pp. 75-96. *In:* Soil erosion research methods. R. Lal (ed.) Soil and Water Conservation Society, Ankeny, Iowa.

Mundy, C., N.G. Creamer, C.R. Crozier, L.G. Wilson, and R.D. Morse. 1999. Soil physical properties and potato yield in no-till, subsurface-till, and conventional-till systems. HortTechnology 9:240-247.

Norton, L.D., N.P. Cogo, and W.C. Moldenhauer. 1985. Effectiveness of mulch in controlling soil erosion. Pp. 598-606. *In:* Soil erosion and conservation. S.A. El-Swaify, W.C. Moldenhauser and A. Lo (eds.) Soil and Water Conservation Society, Ankeny, Iowa.

Phillips, R.E. 1980. Soil moisture. Pp. 112-116. *In:* No-tillage research: Research reports and reviews. R.E. Phillips, G.W. Thomas, and R.L. Blevins (eds.) College of Agriculture and Agricultural Experimental Station, University of Kentucky, Lexington, Kentucky.

Phillips, S.H. 1984. Introduction. Pp. 1-10. *In:* No-tillage agriculture: Principles and practices. R.E. Phillips and S.H. Phillips (eds.) Van Nostrand Reinhold, New York, New York.

Pierce, F.J. and C.G. Burpee. 1995. Zone tillage effects on soil properties and yield of potatoes (*Solanum tuberosum* L.). Soil Tillage and Research 35:135-146.

Pierce, F.J. and R.W. Chase. 1987. Zone tillage for improved quality and yield of Russet Burbank potatoes. American Potato Journal 64:452.

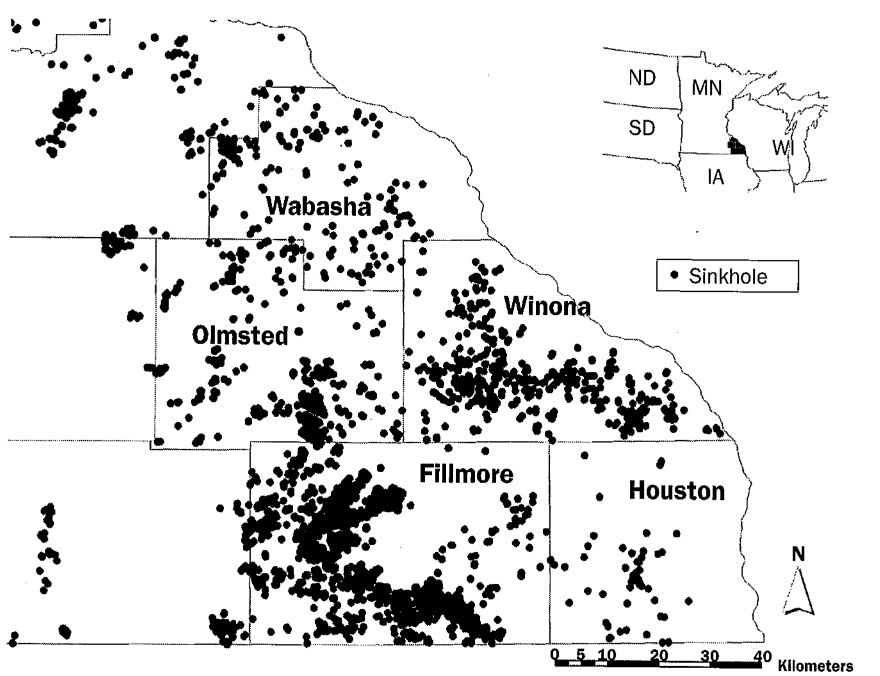
Potato Crop. 1998. Variety, weed and pest control guide. Agdex 257, Publication 1300A. Atlantic Provinces Agriculture Services Co-ordinating Committee. Prince Edward Island Department of Agriculture, Aquaculture and Fisheries, Charlottetown, Prince Edward Island.

Powell, G.E. and K.A. Renner. 1999. Weed control in navy bean in reduced tillage systems. Journal of Production Agriculture 12: 428-433.

Rasmussen, K.J. 1999. Impact of ploughless soil tillage on yield and soil quality: A Scandinavian review. Soil Tillage and Research 53: 3-14.

Riley, H., A. Njos, and E. Ekeberg. 1985. Ploughless cultivation of spring cereals. Research in Norweigian Agriculture 36:53-59.

Figure 1
Sinkhole locations in southeastern Minnesota counties (Gao et al., 2002).



filter pollutants from agricultural runoff (Daniels and Gilliam, 1996; Barfield et al., 1998; Lee et al., 2000; Blanco-Canqui et al., 2004a; Parkyn, 2004; Helmers et al., 2005; Lowrance and Sheridan, 2005) suggests that increasing the amount of vegetation around sinkholes could improve ground and surface water quality in southeast Minnesota.

Our goal was to determine potential water quality benefits of buffers around sinkholes and associated costs of land retirement in southeast Minnesota. Our objectives were to: 1) describe the distribution of sinkholes in relation to land use, soil type, and topography, 2) quantify the current vegetation around sinkholes, 3) determine the potential reduction in runoff, sediment, nitrogen, and phosphorus if vegetative buffers from 2.5 to 30 m (8.3 to 98 ft) wide were installed around sinkholes, and 4) quantify the cost to retire agricultural land in buffers based on Conservation Reserve Program (CRP) payments. We based our estimation of reductions in pollutants on the establishment of permanent herbaceous vegetation consisting of a mix of native grass species that are tall, rigid, perennial, and long-lived. Grass species recommended for establishing filter strips in Minnesota include Western wheatgrass, Canada Wildrye, Big and Little Bluestem, Indiangrass, Sideoats Grama, switchgrass, and Prairie Cordgrass (USDA, 1999). We used land use around sinkholes to calculate pollutant and runoff loads delivered to all sinkholes in 23 watershed-agroecoregions (Hatch et al., 2001) with a spreadsheet model in Microsoft Excel®. We estimated pollutant/runoff reduction using equations developed from the extensive literature on buffers in similar hydrogeologic settings (Wilson, 1967; Neibling and Alberts, 1979; Young et al., 1980; Dillaha et al., 1989; Magette et al., 1989; Parsons et al., 1990; Choi, 1992; Mickelson and Baker, 1993; Coyne et al., 1995; Daniels and Gilliam, 1996; Van Dijk et al., 1996; Patty et al., 1997; Barfield et al., 1998; Boyd et al., 1999; Schmitt et al., 1999).

Materials and Methods

Study area. The study area (Figure 1) is located in the Western Corn Belt Plains and Driftless Area ecoregions (Omernik and Gallant, 1988) in southeast Minnesota and contains 8,339 mapped sinkholes (Gao et al., 2002). Southeast Minnesota receives 748 to 848 mm (30 to 33 in) of precipitation per year, with a mean runoff of 178 to 203 mm (7 to 8 in). Most runoff occurs during late winter and early spring (Minnesota Climatology Working Group, 2006). Sinkholes generally occur on flat hilltops adjacent to or between stream valleys in southeast Minnesota (Dalgleish and Alexander, 1984). Sinkholes are often 3.5 to 13.5 m (12 to 44 ft) in diameter and 1.5 to 13.5 m (5 to 44 ft) deep with circular or elliptical walls ranging from nearly vertical to shallow bowl shapes (Witthuhn and Alexander, 1995). Sinkholes often contain grasses, shrubs, and trees, but adjacent fields are often tilled to the edge of sinkholes. Groundwater discharges to streams primarily from springs draining from sinkholes and provide as much as 80 percent of the baseflow to many streams in the Driftless Area Ecoregion (Troelstrup and Perry, 1989). The majority of the soils in the study area are silt loams in the Fayette, Seaton, Mt. Carroll series. Organic matter typically is from 1.0 to 3.0 percent, cation exchange capacity (CEC) ranges between 8 and 25 cmol kg^{-1}, available water capacity ranges from 0.18 to 0.24 m m^{-1}, bulk density is 1.1 to 1.45 Mg m^{3-1}, and pH is 5.1 to 7.5 (USDA, 2005a).

Sinkhole identification. We used the Karst Feature Database (Gao et al., 2002) to identify and characterize the distribution of sinkholes. Sinkholes were grouped by their location in intersections of major watersheds and agroecoregions. Agroecoregions account for differences in topography, hydrogeology, and cropping practices (Hatch et al., 2001). We delineated major watersheds-agroecoregions using existing GIS data layers available at the Minnesota Department of Natural Resources Data Deli (MN DNR, 2006) (Table 1). Existing data layers containing information on current land use were also used to describe the areas around sinkholes.

Quantification of areas that contribute runoff to sinkholes. Defining areas that drain to each of the 8,339 sinkholes in the 32 watershed-agroecoregions included in this study required the delineation of a contributing drainage basin for each sinkhole, henceforth a 'sinkhole basin'. We used ArcGIS™[3] 8.3 (Environmental Systems Research Institute, 2005) and ArcMap™ to identify and display sinkholes mapped in the Karst Feature Database (Gao et al., 2002). Sinkholes were overlain on a contour map to determine uphill areas that could contribute runoff to sinkholes. We used level two digital elevation models (DEM; 7.5 min) with 30 m^2 grid spacing, cast on Universal Transverse Mercator (UTM) projections, along with the Spatial Analyst tool in ArcMap™ to generate a contour map (contour lines spaced at 2 m intervals). Sinkhole basins were then delineated in accordance with Natural Resources Conservation Service procedures (USDA-NRCS, 2004), and digitized at a 1:200 scale

Table 1. Agroecoregions and associated characteristics in the study area in southeast Minnesota (University of Minnesota, 2004).

Size	Undulating plains	Level plains	Rochester Plateau	Blufflands	Alluvium and outwash	Steeper alluvium
	Agroecoregion					
(ha)	250,014	113,312	337,224	337,346	26,183	34,034
Watersheds	Root, Zumbro, Cedar, Upper Iowa, Cannon, Whitewater, Wapsipinican, and Mississippi-Lake Pepin	Cedar, Zumbro, Root and Cannon River	Cannon, Mississippi and Lake Pepin, Miss. R. - Winona, Miss. R. - Reno, Root, and Zumbro	Zumbro, Root, Whitewater, Cannon, Upper Iowa, Mississippi River-Lake Pepin, and Mississippi River-Reno	Zumbro, Cannon, Root, Cedar, Whitewater, and Upper Iowa River	Root, Zumbro, Cannon, Whitewater, Mississippi River-Reno, Mississippi River-Lake Pepin and Mississippi River-La Crescent
Counties	Dakota, Dodge, Fillmore, Freeborn, Goodhue, Mower, Olmsted, Rice, and Winona	Dodge, Freeborn, Goodhue, Mower, Olmsted, Steele, and Rice	Dakota, Dodge, Fillmore, Goodhue, Houston, Olmsted, Rice, Steele, Wabasha, and Winona	Dakota, Dodge, Fillmore, Goodhue, Houston, Olmsted, Rice, Steele, Wabasha, and Winona	Dakota, Dodge, Fillmore, Goodhue, Mower, Olmsted, Steele, Rice, and Winona	Fillmore, Goodhue, Houston, Olmsted, Wabasha, and Winona
Slope	27% between 0-2%	45% between 0 and 2%	55% between 6 and 45%	40% between 2 and 12%	73% between 0 to 2%	65% between 0 and 2%
	57% between 2-12%	29% between 2 and 6%	40% between 2 and 12%	55% between 6-45%	12% between 6 to 45%	20% between 12-45%
	14% between 6-45%	22% between 2 and 12%				13% between 6-45
Soil drainage	Mostly well drained	Poorly drained to intermediate	Well drained	Well drained	Mostly well drained	Well drained
Soil erosion potential	High (59.4%), to Severe (29.5%)	High (71.7%) to Severe (17.2%)	Extreme (88.6%)	Extreme (87.4%)	Moderate (24.7), High (22.1%), Extreme (31.2%)	Extreme (86.5%)
Soil type and topography	Silty, rolling, (91.1%)	Silty, level or rolling (87.1%)	Silty, gently rolling (85%)	Uplands, steep (71.1%), Silty, rolling (24.4%)	Outwash (80.7%)	Silty, steep or gently rolling (97.2%)

in ArcMap™. We then categorized digitized sinkhole basin polygon layers by their location in watershed-agroecoregions and merged them with existing data layers to generate information on land use, topography, and soil composition.

Characterization of sinkhole buffer areas. We used the Geoprocessing wizard in ArcMap™ to create buffers of 2.5, 5, 7.5, 10, 15, and 30 m (8.2, 16, 25, 33, and 98 ft) around all mapped sinkholes across watershed-agroecoregions. Buffer polygon layers were then used as 'clip layers' in ArcMap™ to sample and quantify land-use data around all sinkholes using International Land Cover/Land Use data sets available at the Minnesota Department of Natural Resource Data Deli website (MN DNR, 2006).

Estimation of runoff and pollutant loads. We developed a database in Microsoft Excel® to model the effect on water quality/quantity for each buffer width in all watershed-agroecoregions. Annual runoff volumes were calculated from 30-year mean annual precipitation records to generate precipitation volume using the land use (Table 2) and area of sinkhole basins for each sinkhole basin and annual runoff coefficients for each land-use type (Table 3). We estimated mean runoff and pollutant loads by multiplying calculated

Table 2. Total land use around all sinkholes for buffer widths from 2.5 to 30 m wide, computed from ArcGIS. Land-use classifications from the Land Management Information Center (2005).

Land use (ha)	Buffer width (m) 2.5	5.0	7.5	10.0	15.0	30.0
Agriculture	13.7	51.0	112.2	197.6	435.6	1530.0
Wooded	5.9	21.5	43.8	83.5	184.5	678.0
Grassland	2.6	6.9	21.1	36.7	81.4	305.9
Rural residence	0.5	1.5	3.9	7.0	15.8	63.4
Shrubland	0.3	0.7	2.2	3.9	8.7	34.3
Wetlands	0.2	0.6	2.1	3.8	10.1	31.2
Urban/industrial	0.4	1.9	4.2	7.5	16.6	54.4
Total	**23.6**	**84.1**	**189.5**	**340.0**	**752.7**	**2697.2**

Table 3. Pollutant concentrations measured in surface runoff and runoff coefficients used to calculate pollutant and runoff volume in sinkhole basins by land use classification with moderate infiltration rates (silt-loam). Values based on Leopold et al. (1964), Baird et al. (1996), Randall and Mulla (2001), Borin et al. (2004), Blanco-Canqui (2004a), and Purdue University (2005). Land-use classifications from the Land Management Information Center (2005).

	Land use					
Pollutant	Rural residence	Wooded	Urban/ industrial	Shrubland	Agricultural	Grassland
Total nitrogen (mg/L)	2.0 - 2.5	1.6 - 2.1	5.8 - 6.6	1.4 - 1.8	8.4 - 10.3	0.6 - 0.8
Total phosphorus (mg/L)	0.5 - 0.6	0.01 - 0.02	0.25 - 0.35	0.3 - 0.4	1.1 - 1.4	0.01 - 0.02
Suspended solids (mg/L)	36 - 44	100 - 200	45 - 60	50 - 70	600 - 750	90 - 110
Runoff coefficient	0.37 - 0.43	0.10 - 0.16	0.75 - 1.0	0.15 - 0.21	0.58 - 0.70	0.17 - 0.23

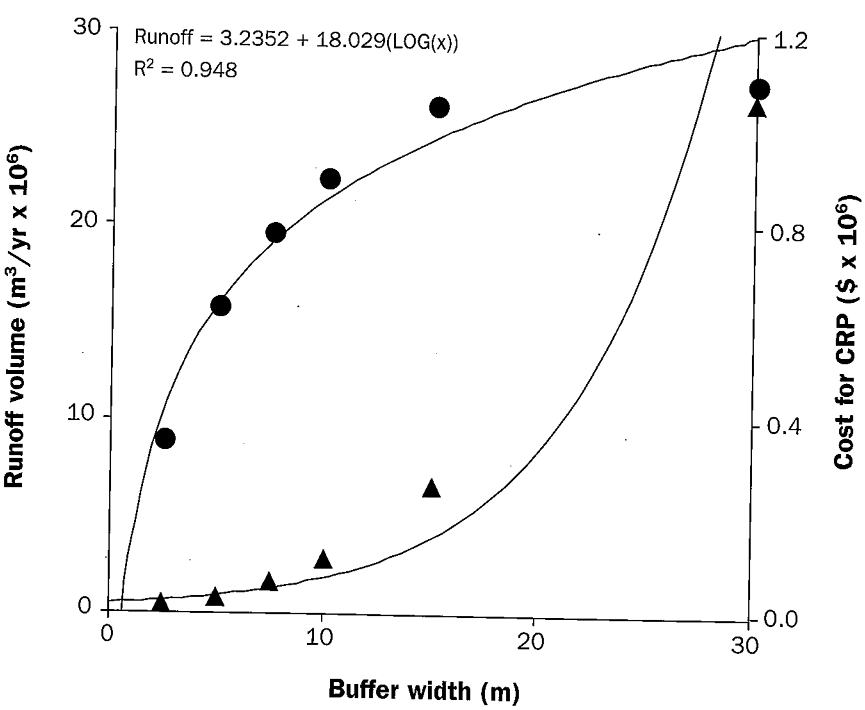
runoff volume with pollutant concentrations specific to each land use by running the model 25 times. During each run of the model, values were randomly chosen from the range of pollutant concentrations and runoff coefficients in Table 3. Annual estimated reductions in runoff and pollutant loads for sinkhole basins in each watershed-agroecoregion were summed to generate an expected response across all sinkholes in southeast Minnesota. We focused the model on sinkholes directly receiving runoff from adjacent agricultural lands: if the area contained vegetation—woods, shrubland, or grassland—then the area was considered effectively buffered and not entered into the model.

We used published values (Table 4) from studies in areas with similar soils, topography, and climate to develop relationships for three slope intervals (Table 5) to describe a mean percent reduction in runoff and pollutants, expressed as a percentage of inflow mass versus outflow mass. Criteria for choosing published studies from which to develop equations were: 1) the study pertained to agricultural runoff in non-riparian areas, 2) silt-loam soils dominated, and 3) climatic conditions were similar to those found in southeast Minnesota. We used a logarithmic equation to describe trapping efficiency as used for sediment (Abu-Zrieg et al., 2004) and sediment-bound pesticides (Harman et al., 2004) as buffer widths increased. Using these logarithmic equations, the expected mean percent reductions in sediment, nitrogen, and phosphorus from runoff were calculated. The reduction of total pollutant/runoff volume from a sinkhole basin was estimated by multiplying the calculated buffer trapping efficiency, ± 10 percent, with the expected pollutant load from a sinkhole basin for each buffer width.

CRP rental rates for agricultural lands around sinkholes. We calculated the cost to retire agricultural land around sinkhole margins by averaging CRP rental rates for agricultural lands in Olmsted, Winona, Fillmore, Wabasha, and Houston counties (USDA, 2002). We calculated a mean rate of \$272.63 US ha^{-1} yr^{-1} for CRP sign-ups. We multiplied the mean annual cost/ha by the cumulative amount of agricultural land around all sinkholes in each watershed-agroecoregion for buffer widths from 2.5 to 30 m (8.2 to 98 ft). We did not include preexisting forest and grasslands around sinkholes in the calculation because we assumed these land uses met the expectations of a vegetated buffer.

Figure 2

Annual runoff intercepted (closed circles) calculated from land use characteristics in sinkhole basins. Cost of buffers (closed triangles) based on Conservation Reserve Program (CRP) rental rates.



Results and Discussion

Sinkholes had a clustered, non-uniform distribution (Figure 1, Table 6). Most sinkholes (75 percent) were located in the Rochester Plateau agroecoregion. Few sinkholes were located in the Level Plains (14 sinkholes) or Steeper Alluvium agroecoregions (8 sinkholes). Land draining to sinkholes comprised <10 percent of the total area of all watershed-agroecoregions, except the Root River-Rochester Plateau [13 percent, or 14,384 ha (35,544 ac)]and Upper Iowa-Rochester Plateau [10 percent, or 1600 ha 3,954 ac)].

Row crops account for about 40 to 70 percent of land use in counties across southeast Minnesota (Minnesota Department of Natural Resources, 2006), but row crops represented 83 percent of the land use in sinkhole basins. Although row-crops were the

Table 4. Studies that examined pollutant reduction as a percentage of inflow versus outflow mass for buffer strips in non-riparian areas on silt-loam soils in agricultural settings used to develop equations in Table 5.

Study	Buffer width (m)	Buffer slope (%)	Total N reduction (%)	Total P reduction (%)	Total sediment reduction (%)	Total runoff reduction (%)
Abu-Zreig, et al., 2003, 2004	2.0	2.3		32	74	36
Abu-Zreig, et al., 2003, 2004	5.0	2.3		54	82	42
Abu-Zreig, et al., 2003, 2004	10.0	2.3		76	92	71
Abu-Zreig, et al., 2003, 2004	15.0	2.3		79	91	57
Abu-Zreig, et al., 2003, 2004	5.0	5.0		68	87	47
Antonious, 1999	3.7	10.0				77
Arora et al., 2003	1.5	4.0			87	38
Barfield et al., 1998	6.0	11.0	47	22	87	43
Barfield et al., 1998	18.0	11.0	100	89	100	100
Barfield et al., 1998	4.6	9.0	95	91	97	91
Barfield et al., 1998	9.1	9.0	98	98	100	97
Barfield et al., 1998	13.7	9.0	97	96	100	94
Bingham et al., 1980	26.0	10.0		80		
Blanco-Canqui, 2004a	8.0	5.0	94	87	91	
Blanco-Canqui, 2004b	8.0	5.0	69	95	98	
Blanco-Canqui, 2004b	4.0	5.0	60	71	93	
Blanco-Canqui, 2004b	0.7	5.0	47	51	87	
Borin, et al., 2004	6.0	1.8		100		
Borin, et al., 2005	6.0	1.8	74	80	94	78
Coyne et al., 1995	9.0	9.0			99	88
Coyne et al., 1998	4.5	9.0			96	76
Coyne et al., 1998	9.0	9.0			98	85
Dillaha et al., 1989	9.1	13.5	77	80	94	62
Dillaha et al., 1989	4.6	13.5	54	59	62	42
Ghaffarzadeh et al, 1992	9.1	7.0			85	
Ghaffarzadeh et al, 1992	9.1	12.0			85	
Magette et al., 1989	4.6	3.0	17	41	72	
Magette et al., 1989	9.2	3.0	72	53	86	
Patty et al., 1997*	6.0	15.0	86	79	91	87
Patty et al., 1997*	12.0	15.0	95	89	97	93
Patty et al., 1997*	18.0	15.0	97	89	98	85
Peterjohn and Correll, 1984	19.0	2.5	89		80	
Robinson et al., 1996	3.0	12.0			70	
Robinson et al., 1996	9.0	12.0			85	
Schmitt et al., 1999	7.5	6.5	57	71	84	36
Schmitt et al., 1999	15.0	6.5	91	96	98	82
Smith, 1989	11.75	2.5	85	63	87	
Wong and McCuen, 1982	30.5	2.0			90	
Wong and McCuen, 1982	61.0	2.0			95	
Young et al., 1980	24.4	2.0			92	
Young et al., 1980	21.3	5.0		67		

* Only Pielo region used because soil types in other regions differed from selection criteria.

dominant land use, forest and grasslands comprised over 50 percent of some sinkhole basins.

Most mapped sinkholes in southeast Minnesota are located on higher elevation plateaus on or in agricultural areas with relatively flat slopes. Soils around a majority of sinkholes were primarily silt-loam with moderate infiltration rates considered highly susceptible to erosion with mean slopes within 30 m (98 ft) of most sinkholes from 7.5 to 10 percent.

The largest quantities of calculated pollutant loads and runoff volume delivered to sinkholes occurred in the Root River Watershed-Rochester Plateau Agroecoregion, where a large amount of runoff volume and agricultural pollutants potentially contribute to underlying aquifers via sinkholes. Buffers 2.5 to 30 m (8.2 to 98 ft) wide around all sinkholes intercepted an increasing amount of runoff, suspended sediment, nitrogen and

Table 5. Equations developed from Table 4 that describe total percent reductions of nitrogen, phosphorus, sediment, and runoff for buffers on silt-loam soils. Equations are categorized by slope for 0 to 5 percent, 5 to 10 percent, and greater than 10 percent. Equations represent the percent reduction of inflow mass versus outflow mass. N = number of studies used for each equation.

		R^2	N
Slope (0 to 5%)			
Nitrogen	Y = 51.3 +15.2 Log(Width)	0.47	9
Phosphorus	Y = 63.0 + 9.0 Log(Width)	0.32	12
Sediment	Y = 87.5 + 3.3 Log(Width)	0.20	14
Runoff	Y = 0.0 +29.7 Log(Width)	0.48	6
Slope (5 to 10%)			
Nitrogen	Y = 24.3 + 25.21 Log(Width)	0.40	8
Phosphorus	Y = 27.0 + 19.6 Log(Width)	0.30	9
Sediment	Y = 77.5 + 3.9 Log(Width)	0.31	13
Runoff	Y = 0 + 36.7 Log(Width)	0.21	12
Slope (>10 %)			
Nitrogen	Y = -24.2 + 41.9 Log(Width)	0.53	5
Phosphorus	Y = 20.5 + 22.5 Log(Width)	0.38	8
Sediment	Y = 48.8 + 18.1 Log(Width)	0.69	10

phosphorus in our modeling exercise (Figures 2 to 5). The interception of pollutant load and runoff volume increased logarithmically as buffer width increased. In general, greater than 90 percent of soluble and insoluble pollutants and runoff were trapped in buffers 30 m (98 ft) wide. Das et al. (2004) determined that buffer strips between 2.3 and 23.2 m (7.6 to 76.1 ft) could reduce sediment by at least 50 percent across South Dakota with the adoption of CRP-type grass buffers.

Buffers 5, 10, and 30 m (16,33,and 98 ft) wide around all sinkholes would remove approximately 50, 200, and 1500 ha (124, 494, and 3,707 ac) of agricultural land from production, respectively. Accordingly, the amount of CRP payments increased exponentially (Figures 2 to 5) as buffer strip widths increased.

$$\text{Cost of CRP} = 0.015(10^{(0.068x)}),\ R^2 = 0.902$$

Annual cost would vary from $10,000 for buffers 2.5 m (8.2 ft) wide to about $1,100,000 for buffers 30 m (98 ft) wide based on recent CRP rates (USDA, 2002). Buffers 15 m (49 ft) wide may be most cost effective in terms of percent reduction of runoff, total nitrogen, and total phosphorus because there is only a small additional reduction for these variables in relation to added cost for CRP (Figure 6). A significant reduction in sediment could be achieved for buffers less than 10 m (33 ft) wide (Figure 6).

Sinkholes provide a direct conduit for pollutants into aquifers, groundwater, or receiving streams through the many fissures and cracks in the karst terrain. The water that moves through sinkholes often bypasses the natural filtering capacity of the soil (Tipping et al., 2001). Mahler et al. (2000) and Dussart-Baptista et al. (2003) have documented bacterial-contaminated particle transport directly from sinkholes through aquifers into receiving streams. The specific loads and pathways for movement of these pollutants are not well known in southeast Minnesota. However, the contribution of pollutant loads to streams could be significant because about 80 percent of the base flow in many streams in the Driftless Area Ecoregion is derived from springs and seeps (Troelstrup and Perry, 1989). In watersheds in nearby northeastern Iowa, approximately 10 percent of the land is drained by sinkholes; however, as much as 25 percent of the aquifer may be water that entered via sinkholes (Rowden et al., 2001).

Currens (2002) monitored groundwater at a spring discharging from a large karst basin before and after implementation of BMPs. A variety of BMPs were used, including grassed buffers along surface flowing reaches and sinkholes. Although groundwater quality only modestly improved, the percentage of row crops in the basin increased during the study period, indicating that some BMPs may have been effective in reducing agricultural

Figure 3

Annual sediment intercepted (closed circles) calculated from land use characteristics in sinkhole basins. Cost of buffers (closed triangles) based on Conservation Reserve Program (CRP) rental rates.

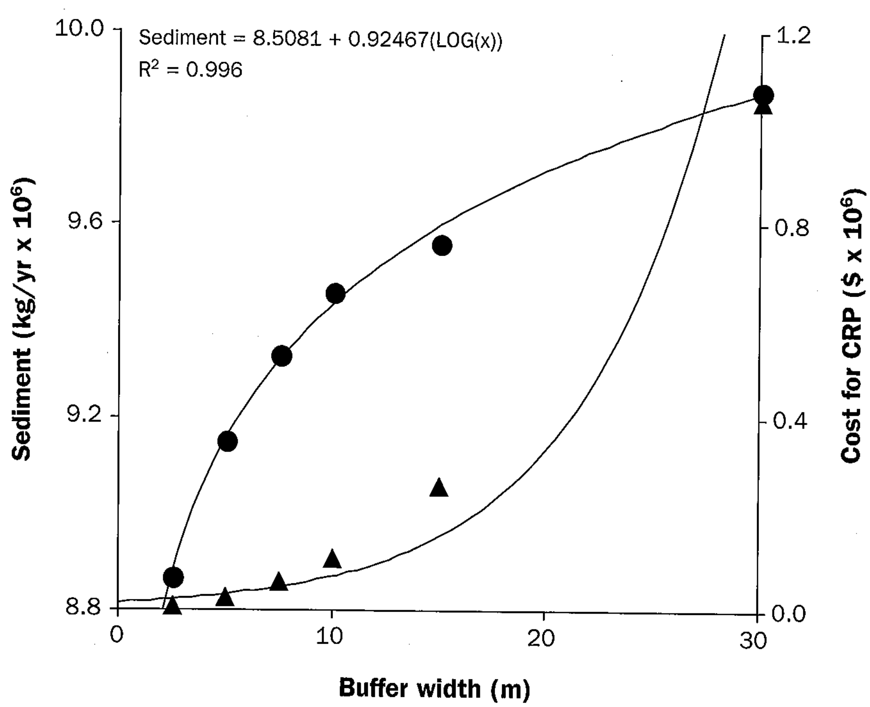


Table 6. Area around sinkholes in watershed-agroecoregions of southeast Minnesota.

Major watershed	Undulating plains	Level plains	Rochester Plateau	Blufflands	Alluvium & outwash	Steeper alluvium	Watershed total
	Agroecoregion						
Mississippi River- Lake Pepin							
- size of region (ha)	N/A	N/A	70712	40433	9850	1937	122932
- sinkholes in region			11	37	1	0	49
- area drained by sinkholes (ha)			141	215	0	0	356
- % of region drained by sinkholes			1.2	0.5	0	0	0.3
Mississippi River - Reno							
- size of region (ha)	N/A	N/A	5387	33365	6031	2352	47135
- sinkholes in region			26	7	0	0	33
- area drained by sinkholes (ha)			42	3	0	0	45
- % of region drained by sinkholes			0.1	0	0	0	0
Mississippi River - La Crescent							
- size of region (ha)	N/A	N/A	N/A	18239	2342	1220	21801
- sinkholes in region				87	0	0	87
- area drained by sinkholes (ha)				65	0	0	65
- % of region drained by sinkholes				0.3	0	0	0.3
Mississippi River - Winona							
- size of region (ha)	61045	N/A	53663	83598	22930	2413	223649
- sinkholes in region	51		133	143	3	1	331
- area drained by sinkholes (ha)	650		1913	980	2	0	3545
- % of region drained by sinkholes	650		4	1	0	0	2
Root River							
- size of region (ha)	90027	6418	109980	194834	14567	13814	429640
- sinkholes in region	419	4	5470	832	5	7	6737
- area drained by sinkholes (ha)	5256	12	14384	1807	2	8	21469
- % of region drained by sinkholes	6	0.2	13	1	0	0	5
Upper Iowa River							
- size of region (ha)	30489	N/A	15416	9265	763	N/A	55933
- sinkholes in region	242		255	31	9		537
- area drained by sinkholes (ha)	401		1600	174	0		2175
- % of region drained by sinkholes	1		10	2	0		4
Zumbro River							
- size of region (ha)	76890	49622	126143	70777	1937	78643	404012
- sinkholes in region	76	10	324	122	33	0	565
- area drained by sinkholes (ha)	231	43	5244	1650	13	0	7181
- % of region drained by sinkholes	0.3	0.1	4	2	0.7	0	2
Agroecoregion total							
- size of region (ha)	258451	56040	381301	450511	58420	100379	1305102
- sinkholes in region	788	14	6219	1259	51	8	8339
- area drained by sinkholes (ha)	6538	55	23324	4894	17	8	34836
- % of region drained by sinkholes	1	0	6	1	0	0	3

pollutant loads (Currens, 2002). The spatiotemporal variability of karst systems to respond to changes in land use coupled with the short duration of the project by Currens (2002) could have masked potential improvements to regional water quality.

Implications. A goal of resource professionals in Minnesota is to reduce sedimentation by about 382,000,000 kg yr^{-1} (USDA, 2005b). Based on our model, buffers 30 m (98 ft) wide around all sinkholes could contribute to that goal and prevent about 10,000,000 kg yr^{-1} of sediment from entering underlying aquifers and eventually reaching surface waters. Preventing most of the sediment in runoff from entering underlying aquifers and receiving streams could benefit water quality because sediment can affect drinking water, aquifer transit pathways, and spring discharge (Tucker, 1982; White, 1988). Sediment that eventually reaches surface waters can have a negative impact on fish and macroinvertebrates by clogging gills, smothering eggs, and reducing water clarity (Bruton, 1985; Waters, 1995; Newcombe and Jensen, 1996). As well, sediment moving through streams in southeast Minnesota has an economic cost in that the Mississippi River must be dredged to maintain navigation.

The national goal to reduce hypoxia in the Gulf of México is a 30 percent reduction of nitrogen in the Mississippi River (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2001). Buffers 30 m wide around sinkholes could prevent 260,000 kg yr^{-1} of nitrogen from entering sinkholes and underlying aquifers from southeast Minnesota. This reduction in nitrogen would account for approximately 19 percent of the goal of reducing nitrogen loads in Minnesota streams and rivers (USDA, 2005b).

The goal for reducing phosphorus loadings in surface waters is 240,000 kg yr^{-1} in Minnesota (USDA, 2005b). Buffers 30 m wide around sinkholes could prevent approximately 12,500 kg yr^{-1} of phosphorus from entering sinkholes or about five percent of the goal. The reductions in sediment, nitrogen, and phosphorus loadings could be achieved by placing a relatively small amount of land, 1,530 ha (3,781 ac) of the more than 1,000,000 ha (2,471,053 ac) in the region, into CRP.

Buffers may be less effective than predicted for soluble constituents, such as nitrogen, since most nitrogen in groundwater enters via soil percolation. Boyer (2005) found that buffers were not effective in retaining nitrogen when installed around sinkholes in West Virginia. Rather, nitrate from runoff that entered buffers entered bedrock fissures and was transported to underlying aquifers. As well, relatively little denitrification should occur in the upland soils around most of the sinkholes in our study area. Denitrification is affected by the amount of soil organic matter and anaerobic conditions in the soil. Riparian areas tend to have more organic matter and anaerobic conditions when compared to upland areas, and, because of this, are able to remove significantly more N from runoff (Correll, 1997). However, the ability of buffers to reduce nitrogen in runoff should not be disregarded. Plant tissues have been shown to retain 28 to 40 percent of the total nitrate-nitrogen and ammonia that enters buffers (Bedard-Haughn et al., 2004). Although buffers installed around sinkholes will not prevent all of the soluble nitrogen from entering aquifers, nutrient retention in buffers is still expected to some degree (Bedard-Haughn et al., 2004).

Buffers around sinkholes may also be an effective way to reduce flashy stream discharge. Increased runoff contributed via sinkholes to aquifers directly results in increased groundwater discharge at springs (Drew, 1967; Hallberg et al., 1985). Reducing the rate of runoff that enters sinkholes will reduce flood intensity in streams that receive a majority of their flow from spring outflow. Modeling by the United States Army Corps of Engineers (1995) has shown that reducing runoff by 10 percent within a watershed may reduce flood peaks with a two- to five-year return period by 25 to 50 percent.

Model considerations. The main assumption of the model we present is that buffers around sinkholes were installed with warm season grasses and that they would be adequately maintained. Periodic clipping

Figure 4
Annual Nitrogen intercepted (closed circles) calculated from land use characteristics in sinkhole basins. Cost of buffers (closed triangles) based on Conservation Reserve Program (CRP) rental rates.

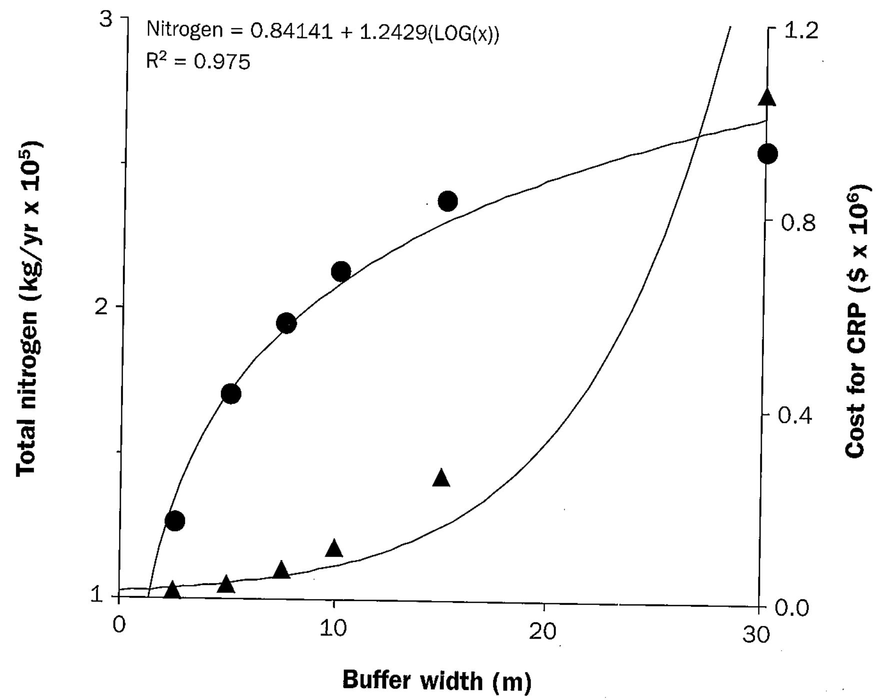


Figure 5
Annual Phosphorus intercepted (closed circles) calculated from land use characteristics in sinkhole basins. Cost of buffers (closed triangles) based on Conservation Reserve Program (CRP) rental rates.

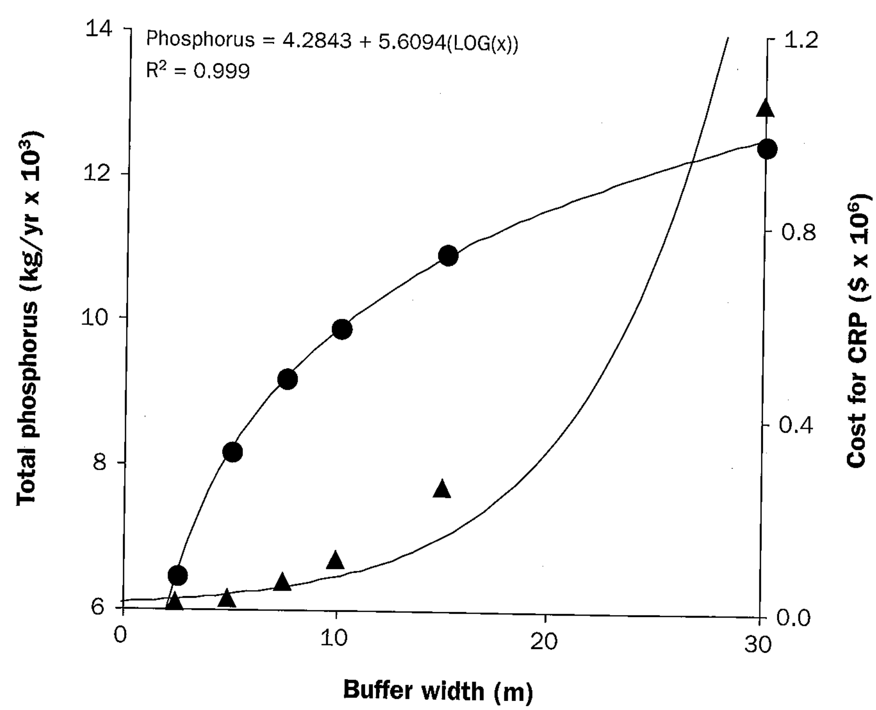
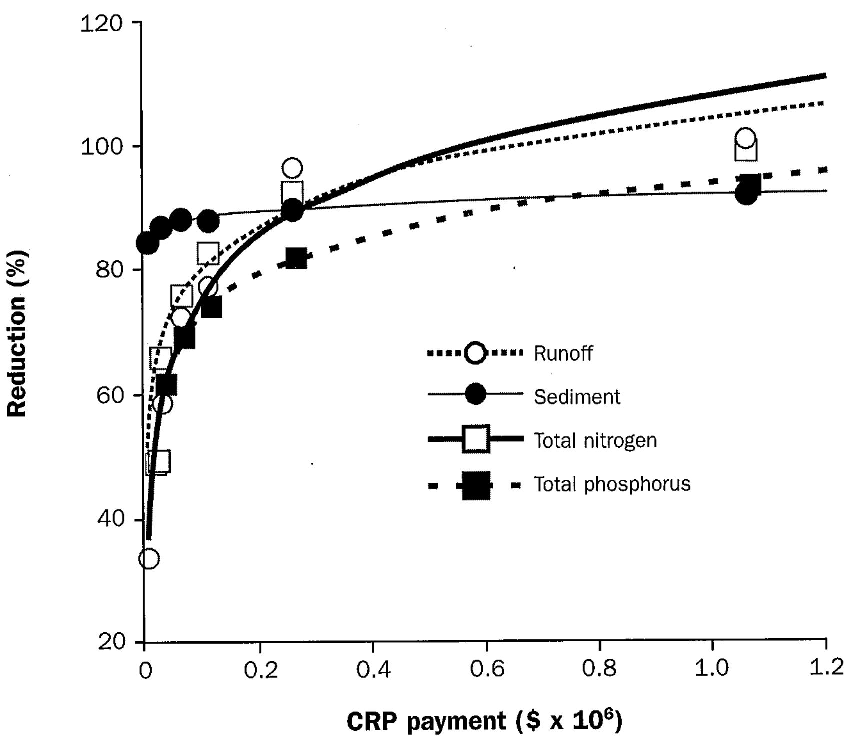


Figure 6

Estimated percent intercepted in runoff, sediment, total nitrogen, and total phosphorus in relation to Conservation Reserve Program (CRP) payments for buffer widths from 2.5 to 30 m wide. The relationship for cost of CRP and buffer width is illustrated in Figures 2 to 5, thus buffer width also increases along the x-axis.



during the first two years of establishment of a buffer will control competition and promote dense sod formation and plant vigor. Thereafter, periodically (every two to three years) removing buffer vegetation is recommended (USDA, 1999). Improper maintenance may impair the ability of buffers to function effectively over the long term. Several years after installation, the ability of buffers to trap pollutant loads can be reduced because buffers often become inundated with sediment (Dillaha et al., 1989). We did not account for the buildup of sediment in our model; however, future efforts could focus on this phenomenon. Equations we developed may overestimate sediment and nutrient removal rates, because the studies we relied upon rarely considered long-term sediment and nutrient accumulation in buffers, nor did they account for channelized flow through buffers.

Accuracy of topographic data will affect most models that estimate pollutant loads (Brothers et al., 2001). Although not available for southeast Minnesota, 10 m (33 ft) digital elevation models would have been preferable to delineate sinkhole basins and estimate runoff volume. We used a 30 m (98 ft) digital elevation model that may have led to overestimation of sinkhole basin size, because 30 m (98 ft)digital elevation models have low topographic resolution, typically 0.5 m (1.6 ft), that produce less detailed contour maps. Overestimating the size of sinkhole basins may have also biased estimates of runoff volume and pollutant loads. Overestimates in pollutant contributions may not be important in our model, given that all sinkholes are not currently mapped in the Karst Feature Database (E. Calvin Alexander, Department of Geology and Geophysics, University of Minnesota, personal communication).

Other considerations. The Minnesota Legislature has approved money to fund a Conservation Reserve Enhancement Program (CREP II). The approved CREP II plan has authorized up to 51,000 ha (126,024 ac) of land to be retired in the Lower Mississippi River watershed in southeast Minnesota (Minnesota Board of Soil and Water Resources, 2005). Within that authorization, 2,500 ha (6,178 ac) of land are eligible for groundwater protection (Minnesota Board of Soil and Water Resources, 2005). Buffers designed for groundwater protection in southeast Minnesota under the CREP II proposal can be up to 60 m (197 ft) wide from the edge of a karst feature. Based on our model, only about 60 percent of the available 2,500 ha (6,178 ac) of CREP II lands specified for groundwater protection would be needed if buffers 30 m (98 ft) wide were installed.

Summary and Conclusion

Our analysis of landscape and soil characteristics around sinkholes suggests that buffers installed around sinkholes could be effective in abating pollutant loads. Runoff/pollutant loads decreased with buffers up to 30 m (98 ft) wide; however, buffers 15 m (49 ft) wide may be most cost effective in terms of percent reduction of runoff, total nitrogen, and total phosphorus in relation to the cost to CRP. Buffers around all or most sinkholes would contribute to the overall goal of reducing sediment, nitrogen, and phosphorus in Minnesota. Preventing agricultural runoff from entering sinkholes could be a BMP with the potential to protect underlying aquifers and receiving streams from the effects of agricultural pollutants and excessive runoff. Although agricultural land was the dominant land use in the immediate vicinity of sinkholes, establishing buffers around sinkholes would require a small amount of agricultural land to be retired relative to the areas they drain. Although the model we present evaluated common agricultural pollutants, future efforts could focus on pesticides, fecal coliform, and other pollutants that can have observable impacts on macroinvertebrates, fish (Favari et al., 2002), and humans (Blair and Zahm, 1993).

Acknowledgements

Funding was provided by the U.S. Geological Survey and the Minnesota Cooperative Fish and Wildlife Research Unit. We thank E. Calvin Alexander, Jr. for providing insight and information for the study. Angela Bedard-Haughn, James Currens, and two anonymous reviewers provided thoughtful comments on an earlier draft. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use by the U.S. Government.

References Cited

Abu-Zrieg, M., R.P. Rudra, H.R. Whiteley, M.N. Lalonde, and N.K. Kaushik. 2003. Phosphorus removal in vegetated filter strips. Journal of Environmental Quality 32:613-619.

Abu-Zrieg, M., R.P. Rudra, H.R. Whiteley, M.N. Lalonde, and N.K. Kaushik. 2004. Experimental investigation of runoff reduction and sediment removal by vegetated filter strips. Hydrological Processes 18:2029-2037.

Antonius, G.F. 1999. Efficiency of grass buffer strips and cropping system to off-site dacthal movement. Bulletin of Environmental Contamination and Toxicology 63:25-32.

Arora, K., S.K. Mickelson, and J.L. Baker. 2003. Effectiveness of vegetated buffer strips in reducing pesticide transport in simulated runoff. Transactions of the ASAE 46:635-644.

Baird, C.F., T.J. Dybala, M.E. Jennings, and D.J. Ockerman. 1996. Characterization of nonpoint sources and loadings to the Corpus Christi Bay National Estuary Program study area: Corpus Christi Bay National Estuary Program, Publication No. 5. 226 pp.

Barfield, B.J., R.L. Blevins, and V.P. Evangelou. 1998. Water quality impacts of natural filter strips in karst areas. Transactions of the ASAE 41:371-381.

Bedard-Haughn, A., K.W. Tate, and C. Van Kessel. 2004. Using nitrogen-15 to quantify vegetative buffer effectiveness for sequestering nitrogen in runoff. Journal of Environmental Quality 33:2252-2262.

Bingham, S.C., P.W. Westerman, and M.R. Overcash. 1980. Effect of grass buffer zone length in reducing the pollution from land application areas. Transactions of the ASAE 23:330-335.

Blair, A. and S.H. Zahm. 1993. Patterns of pesticide use among farmers: implications for epidemiologic research. Epidemiology 4:55-62.

Blanco-Canqui, H., C.J. Gantzer, S.H. Anderson, and E.E. Alberts. 2004a. Grass barriers for reduced concentrated flow induced soil and nutrient loss. Soil Science Society of America Journal 68:1963-1972.

Blanco-Canqui, H., C.J. Gantzer, S.H. Anderson, E.E. Alberts, and A.L. Thompson. 2004b. Grass barrier and vegetative filter strip effectiveness in reducing runoff, sediment, nitrogen, and phosphorus loss. Soil Science Society of America Journal 68:1670-1678.

Blann, K. 2004. Landscape-scale analysis of stream fish communities and habitats: lessons from southeastern Minnesota. Ph.D. Dissertation, University of Minnesota, St. Paul, Minnesota.

Borin, M., E. Bigon, G. Zanin, and L. Fava. 2004. Performance of a narrow buffer strip in abating agricultural pollutants in the shallow subsurface water flux. Environmental Pollution 131:313-321.

Borin, M., M. Vianello, F. Morari, G. Zanin. 2005. Effectiveness of buffer strips in removing pollutants in runoff from a cultivated field in North-East Italy. Agriculture, Ecosystems, and Environment 105:101-115.

Boyd, P.M., L.W. Wulf, J.L. Baker, and S.K. Mickelson. 1999. Pesticide transport over and through the soil profile of a vegetative filter strip. American Society of Agricultural Engineers Paper No. 992077. St. Joseph, Michigan.

Boyer, D. 2005. Assesment of a sinkhole filter for removing agricultural contaminants. Soil and Water Conservation Society. Poster Presentation. Annual International Meeting of the Soil and Water Conservation Society. Rochester, New York. http://www.ars.usda.gov/research/publications/publications.htm?SEQ_NO_115=176832 (Accessed August 22, 2006)

Brothers, J.M., D.E. Eisenhauer, M.J. Helmers, M.G. Dosskey, and T.G. Franti. 2001. Modeling vegetative buffer performance considering topographic data accuracy. American Society of Agricultural Engineers Paper Presentation No. 01-2125. July 30-August 1. Sacramento, California.

Bruton, M.N. 1985. The effects of suspenoids on fish. Hydrobiologia 125:221-241.

Choi, J. 1992. Impact of intervening land use on runoff quality. Thesis (PhD), University of Maryland, College Park, Maryland.

Correll, D.L. 1997. Buffer zones and water quality protection: General principles. Pp. 7-20. *In:* Buffer zones: Their processes and potential in water protection. N.E. Haycock (ed.) Quest Environmental, Harpenden, Hertfordshire, United Kingdom.

Coyne, M.S., R.A. Gilfillen, R. Rhodes, and R.L. Blevins. 1995. Soil and fecal coliform trapping by grass filter strips during simulated rain. Journal of Soil and Water Conservation 50(4):405-408.

Coyne, M.S., R.A. Gilfillen, A. Vallalba, Z. Zhang, R. Rhodes, L. Dunn, and R.L. Blevins. 1998. Fecal bacteria trapping by grass filter strips during simulated rain. Journal of Soil and Water Conservation 53(2):140-145.

Currens, J.C. 2002. Changes in groundwater quality in a conduit-flow dominated karst aquifer, following BMP implementation. Environmental Geology 42:525-531.

Dalgleish, J. and E.C. Alexander, Jr. 1984. Sinkhole distribution in Winona County, Minnesota. Geologic Atlas of Winona County: Minnesota Geological Survey. St. Paul, Minnesota. 2 pp.

Daniels, R.B. and J.W. Gilliam. 1996. Sediment and chemical load reduction by grass and riparian filters. Soil Science Society of America Journal 60:246-251.

Das, C., W.J. Capehart, H.V. Mott, P.R. Zimmerman, and T.E. Schumacher. 2004. Assessing regional impacts of Conservation Reserve Program-type grass buffer strips on sediment load reduction from cultivated lands. Journal of Soil and Water Conservation 59(2):134-141.

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, and D. Lee. 1989. Vegetative filter strips for agriculture nonpoint source pollution control. Transactions of the ASAE 32:513-519.

Drew, D.P. 1967. Aspects of the hydrology of the Mendip Hills, Somerset, United Kingdom. Thesis (PhD), University of Bristol, United Kingdom.

Dussart-Baptista, L., N. Massei, and T. Jouenne. 2003. Transfer of bacteria-contaminated particles in a karst aquifer: Evolution of contaminated materials from a sinkhole to a spring. Journal of Hydrology 284:285-295.

Environmental Systems Research Institute. 2005. ArcGIS 8.3 Build 800, and ArcMap for Windows. Copyright, 1999 - 2003. Redlands, California 92373-8100.

Favari, L., E. Lopez, L. Martinez-Tabche, and E. Diaz-Pardo. 2002. Effect of insecticides on plankton and fish of Ignacio Ramirez reservoir (Mexico): A biochemical and biomagnification study. Ecotoxicology and Environmental Safety 51:177-186.

Gao, Y., E.C. Alexander, Jr., and R.G. Tipping. 2002. Development of a karst feature database for southeastern Minnesota. Journal of Cave and Karst Studies 64:51-57.

Ghaffarzadeh, M., C.A. Robinson, and R.M. Cruse. 1992. Vegetative filter strip effects on sediment deposition from overland flow. Agronomy Abstracts. Madison, Wisconsin. 324 pp.

Grow, S.R. 1986. Water quality in the Forestville Creek karst basin of southeastern Minnesota. Thesis (MS), University of Minnesota, Minneapolis, Minnesota. 219 pp.

Hallberg, G.R., R.D. Libra, and B.E. Hoyer. 1985. Nonpoint source contamination of groundwater in karst-carbonate aquifers in Iowa. Pp. 109-114. *In:* Perspectives on nonpoint source pollution proceedings. U.S. Environmental Protection Agency, Office of Water Regulations and Standards, Publication No. 42UJ/5-85-001. Washington, D.C.

Harman, W.L., E. Wang, and J.R. Williams. 2004. Reducing atrazine losses: Water quality implications of alternative runoff control practices. Journal of Environmental Quality 33:7-12.

Hatch, L.K., A. Mallawatantri, D. Wheeler, A. Gleason, D. Mulla, J. Perry, K.W. Easter, R. Smith, L. Gerlach, and P. Brezonik. 2001. Land management at the major watershed-agroecoregion intersection. Journal of Soil and Water Conservation 56(1):44-51.

Helmers, M.J., D.E. Eisenhauer, M.G. Dosskey, T.G. Franti, J.M. Brothers, and M.C. McCullough. 2005. Flow pathways and sediment trapping in a field-scale vegetative filter. Transactions of the ASAE 48:955-968.

Land Management Information Center. 2005. Land-use definitions. Minnesota Department of Administration. URL http://www.lmic.state.mn.us/projects/about-landuse.html (Accessed August 22, 2006)

Lee, K.H., T.M. Isenhart, R.C. Schultz, and S.K. Mickelson. 2000. Multi-species riparian buffers trap sediment and nutrients during rainfall simulations. Journal of Environmental Quality 29:1200-1205.

Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. Fluvial processes in Geomorphology. W.H. Freeman and Company, San Francisco, California. 521 pp.

Lowrance, R. and J.M. Sheridan. 2005. Surface runoff water quality in a managed three zone riparian buffer. Journal of Environmental Quality 34:1851-1859.

Magette, W., R. Brinsfield, R. Palmer, and J. Wood. 1989. Nutrient and sediment removal by vegetated filter strips. Transactions of the ASAE 32:663-667.

Mahler, B.J., J.C. Personné, G.F. Lods, and C. Drogue. 2000. Transport of free and particulate-associated bacteria in karst. Journal of Hydrology 238:179-193.

Mickelson, S.K. and J.L. Baker. 1993. Buffer strips for controlling herbicide runoff losses. American Society of Agricultural Engineers Paper No. 93-2084. St Joseph, Michigan.

Minnesota Board of Water and Soil Resources. 2005. Minnesota's CREP II Proposal. http://www.bwsr.state.mn.us/CREP2/CREPagreement.pdf (Accessed August 22, 2006)

Minnesota Climatology Working Group. 2006. Annual summaries of monthly precipitation data by county in Minnesota. http://climate.umn.edu/HIDENannual/ (Accessed August 22, 2006)

Minnesota Department of Natural Resources (MN DNR). 2006. Minnesota Department of Natural Resources Data Deli homepage. http://deli.dnr.state.mn.us/data_catalog.html (Accessed August 22, 2006)

Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. 2001. Action plan for reducing, mitigating, and controlling hypoxia in the northern Gulf of Mexico. Washington, D.C.

Niebling, W. H. and E.E Alberts. 1979. Composition and yield of soil particles transported through sod strips. American Society of Agricultural Engineers. Paper No. 79-2065. St. Joseph, Michigan.

Newcombe, C.P. and J.O.T. Jensen. 1996. Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact. North American Journal of Fisheries Management 16:693-727.

Omernik, J.M. and A.L. Gallant. 1988. Ecoregions of the upper Midwest states. U.S. Environmental Protection Agency, Environmental Research Laboratory Publication No. EPA-1600/3-88-037. Corvallis, Oregon. 56 pp.

Parkyn, S. 2004. Review of riparian buffer zone effectiveness. Ministry of Agriculture and Forestry. MAF technical paper, 1171-4662; No. 2004/05, Wellington, New Zealand.

Parsons , J.E., R.D. Daniels, J.W. Gilliam and T.A. Dillaha. 1990. Water quality impacts of vegetative filter strips in riparian areas. American Society of Agricultural Engineers Paper No. 90-2501. St. Joseph, Michigan.

Patty, L., B. Real, and J.J. Gril. 1997. The use of grassed buffer strips to remove pesticides, nitrate and soluble phosphorous compounds from runoff water. Pesticide Science 49:243-251.

Peterjohn, W.T. and D.L. Correll. 1984. Nutrient dynamics in an agricultural watershed: observation of a riparian forest. Ecology 65:1466-1475.

Purdue University. 2005. Runoff coefficients for rational equation table. Purdue University Extension Service. http://pasture.ecn.purdue.edu/~abe526/resources1/Runoff/C_table.html (Accessed August 22, 2006)

Randall, G.W. and D.J. Mulla 2001. Nitrate nitrogen in surface waters as influenced by climatic conditions and agricultural practices. Journal of Environmental Quality 30:337-334.

Robinson, C.A., M. Ghaffarzadeh, and R.M. Cruse. 1996. Vegetative filter strip effects on sediment concentration on cropland runoff. Journal of Soil and Water Conservation 50:227-230.

Rowden, R.D., H. Liu, and R.D Libra. 2001. Results from the Big Spring Basin water quality monitoring and demonstration projects. Journal of Hydrology 9:487-497.

Schmitt. T.J., M.G. Dosskey, and K.D. Hoagland. 1999. Filter strip performance and processes for different vegetation widths, and contaminants. Journal of Environmental Quality 28:1479-1489.

Smith, C.M. 1989. Riparian pasture retirement effects on sediment, phosphorus and nitrogen in channelised surface run-off from pastures. New Zealand Journal of Marine and Freshwater Research 23:139-146.

Spruill, T.B. 2004. Effectiveness of riparian buffers in controlling groundwater discharge of nitrate to streams in selected hydrogeologic settings of the North Carolina Coastal Plain. Water Science and Technology 49:63-70.

Tipping, R.G., J.A. Green, and E.C. Alexander, Jr. 2001. Karst features, County Altlas Series, Atlas C-14, Part A, Minnesota Department of Natural Resources, St. Paul, Minnesota.

Troelstrup, N.H. and J.A. Perry. 1989. Water quality in southeastern Minnesota streams: observations along a gradient of land use and geology. Journal of the Minnesota Academy of Science 55:6-13.

Tucker. N.L. 1982. Nonpoint agricultural pollution in a karst aquifer: Lost River groundwater drainage basin, Warren County, Kentucky. Thesis (MS), Western Kentucky University, Bowling Green, Kentucky.

University of Minnesota. 2004. Agroecoregions of southeast Minnesota. University of Minnesota Department of Soil, Water and Climate. http://www.soils.umn.edu/research/seminn/doc/agecoregionnew.html (Accessed August 22, 2006)

U.S. Army Corps of Engineers. 1995. Floodplain management assessment of the Upper Mississippi River and Lower Missouri Rivers and tributaries, volume 6. Washington, D.C.

U.S. Department of Agriculture (USDA). 1999. Grass filter. Conservation practice standard, Code No. 393, USDA Natural Resources Conservation Service, Des Moines, Iowa.

U.S. Department of Agriculture (USDA). 2002. 2002 Census of Agriculture, Minnesota State and County data Volume 1, Geographical Area Series Part 23. National Agricultural Statistics Service AC-02-A-23.

U.S. Department of Agriculture (USDA). 2005a. Natural Resources Conservation Service http://soils.usda.gov/survey/printed_surveys/state.asp?state=Minnesota&abbr=MN (Accessed August 22, 2006)

U.S. Department of Agriculture (USDA). 2005b. Conservation Reserve Enhancement Program - Minnesota II Fact Sheet. Farm Service Agency. Washington, D.C. 3 pp. http://www.fsa.usda.gov/pas/publications/facts/crepmn05.pdf (Accessed August 22, 2006)

U.S. Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS). 2004. How to read a topographic map and delineate a watershed. http://www.nh.nrcs.usda.gov/technical/Publications/Topowatershed.pdf (Accessed August 22, 2006)

U.S. Environmental Protection Agency (USEPA). 2000. National Water Quality Inventory: 2000 report. US Environmental Protection Agency, Office of Water. EPA-841-R-02-001. Washington, D.C.

Van Dijk, P.M., F.M. Kwaad, and M. Klapwijk. 1996. Retention of water and sediment by grass strips. Hydrological Processes 10:1069-1080.

Veni, G. 2002. Revising the karst map of the United States. Journal of Cave and Karst Studies. 64:45-50.

Waters, T.F. 1995. Sediment in streams: sources, biological effects and control. American Fisheries Society Monograph No. 7. Bethesda, Maryland. 251 pp.

Welsh, D. 1991. Riparian forest buffers: Function and design for protection and enhancement of water resources. U.S. Department of Agriculture, Forest Service Publication No. NA-PR-07-91. Radnor, Pennsylvania. 22 pp.

White, W.B. 1988. Geomorphology and hydrology of karst terrains. Oxford University Press, New York, New York. 464 pp.

Wilson, L.G. 1967. Sediment removal from floodwater by grass filtration. Transactions of the ASAE 10:35-37.

Witthuhn, K.M. and E.C. Alexander, Jr. 1995. Sinkholes and sinkhole probability in Fillmore County. Minnesota Department of Natural Resources, Division of Waters County Atlas Series C-8, Part B. St. Paul, Minnesota. 2 pp.

Wong, S.L. and R.H. McCuen 1982. The design of vegetative buffer strips for runoff and sediment control. Appendix J in Stormwater Management in Coastal Areas Technical Paper. Maryland Coastal Zone Management Program. New York, New York.

Young, R.A., T. Huntrods, and W. Anderson. 1980. Effectiveness of vegetative buffer strips in controlling pollution from feedlot runoff. Journal of Environmental Quality 9:483-487.