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An approach for using soil surveys to guide the placement of water quality buffers

M.G. Dosskey, M.J. Helmers, and D.E. Eisenhauer

Abstract: Vegetative buffers may function better for filtering agricultural runoff in some locations than in others because of intrinsic characteristics of the land on which they are placed. The objective of this study was to develop a method based on soil survey attributes that can be used to compare soil map units for how effectively a buffer installed in them could remove pollutants from crop field runoff. Three separate models were developed. The surface runoff models for sediment and for dissolved pollutants were quantitative, based mainly on slope, soil, and rainfall factors of the Revised Universal Soil Loss Equation (RUSLE), and were calibrated using the Vegetative Filter Strip Model (VFSMOD) for a standard buffer design and field management. The groundwater model categorized map units by the presence or absence of suitably-shallow groundwater and hydric conditions for interaction with the root zone of a buffer. The models were applied to a ~65 km² (~25 mi²) agricultural watershed in northwestern Missouri. Data acquisition, calculations, and map production utilized the Soil Survey Geographic Database (SSURGO). For surface runoff, soil survey-based values correlated strongly with corresponding VFSMOD estimates for sediment (R^2 = 0.94) and dissolved pollutant trapping efficiency (R^2 = 0.83) for a wide range of soil, slope, and rainfall conditions. A strong negative correlation between trapping efficiency and field runoff load was indicated. Mapped results revealed large differences in buffer capability for surface runoff across the test watershed (21 to 99 percent for sediment and seven to 47 percent for dissolved pollutants). Trapping efficiency for dissolved pollutants was much smaller than for sediment in every map unit. Lower values of trapping efficiency were associated with map units where runoff loads are higher and where a buffer will trap greater loads of sediment, but smaller loads of dissolved pollutants, than in units with higher values. Comparative rankings can be adjusted somewhat for site conditions that depart from the reference conditions, and recalibration may be desired to better account for them. For groundwater, the confluence of hydric conditions and shallow water table occurred only in the highest reaches of the test watershed, but a buffer can also interact with groundwater in most upland and riparian locations due to the prevalence of a seasonally shallow water table. By this approach, soil surveys may be used as a screening tool to guide planners to locations where buffers are likely to have a greater impact on water quality and away from those where impact is likely to be small.

Keywords: Filter strip, groundwater, models, nonpoint source pollution, riparian buffer, surface runoff, SSURGO

Vegetative filter strips, contour buffers, and riparian buffers (collectively referred to as buffers) are accepted practices for reducing water pollution from agricultural runoff. Buffers are generally regarded as an effective practice in all agricultural regions. However, a buffer may not function equally well in all locations. Soil, slope, and hydrologic conditions that influence pollutant retention by a buffer can differ substantially from one location to another (Lowrance et al., 1997). Consequently, a buffer can be expected to perform better or worse in some locations than in others because of intrinsic characteristics of the land on which they are installed. Such differences may be large enough to justify consideration in how buffers are located and designed, and in expectations for their impact on water quality.

The efficacy of buffer installations could be improved by distinguishing differences in filtering capability of buffers across watersheds and accounting for them in buffer planning. Hydrogeopmorphic settings across a large watershed have been interpreted for the efficacy of riparian buffers (Lowrance et al., 1997). Landscape hydrogeologic characteristics have been linked to groundwater hydrology and nitrate removal efficiency in riparian areas (Vidon and Hill, 2006). Analysis of topography has been used to identify riparian reaches to which greater runoff is likely to flow (Tomer et al., 2003). Topographic and stream-discharge information has been used to identify portions of watersheds where there is relatively greater opportunity for groundwater interception by riparian buffers (Burkart et al., 2004).

Soil surveys may also represent a source of useful information for making comparisons of buffer capability at different locations. Soil surveys contain topographic, soil, and hydrologic characteristics that are important determinants of buffer function. Soil surveys have been published for all farming regions in the United States. The information is standardized, readily available, and is mapped so that location-specific comparisons can be made from uplands to riparian areas and across small and large distances. Good correspondence has been reported between soil survey attributes and other evaluations of water quality function (Rosenblatt et al., 2001; Tomer and James, 2004).

The objective of this study was to develop a method that utilizes soil survey attributes to compare locations for how effectively a buffer could remove pollutants from crop field runoff. Separate models were developed for three buffer functions: trapping sediment in surface runoff, trapping dissolved pollutants in surface runoff, and interacting with pollutants in groundwater runoff.

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Table 1. Values for D_{50} that were used for calculating the sediment factor (from Muñoz-Carpena and Parsons, 2000).

Soil texture class	D_{50} (mm)
Clay	0.023
Silty clay	0.024
Sandy clay	0.066
Silty clay loam	0.025
Clay loam	0.018
Sandy clay loam	0.091
Silt	0.019
Silt Loam	0.027
Loam	0.035
Very fine sandy loam	0.035
Fine sandy loam	0.080
Sandy loam	0.098
Coarse sandy loam	0.160
Loamy very fine sand	0.090
Loamy fine sand	0.120
Loamy sand	0.135
Loamy coarse sand	0.180
Very fine sand	0.140
Fine sand	0.160
Sand	0.170
Coarse sand	0.200

Table 2. Reference conditions for determining the efficiency of a buffer to trap sediment and dissolved pollutants in surface runoff.

Buffer design:	12 m (39.4 ft) width Buffer area ratio = 0.06 Grass vegetation (30 cm tall; 1.65 cm spacing; Manning's n = 0.40)
Field size:	200 m (656 ft) cultivated slope length
Farming practices:	Contour tilled (RUSLE P factor = 1.0) Moderate residue (RUSLE C factor = 0.5)
Rainfall properties:	Type II rainfall pattern for R = 100; Type III for R = 500 2-year return frequency, 24-hour rainfall amount
Assumptions:	Runoff is spatially uniform Crop field has the same soil and slope as the buffer zone Wet antecedent soil moisture condition

Materials and Methods

A model for trapping sediments in surface runoff. A two-step mathematical model was developed for sediment trapping by a buffer. First, an empirical equation was developed to calculate a factor from soil-survey attributes. Then, a calibration equation was developed to convert the empirical factor into an estimate of sediment trapping efficiency of a buffer under standard, or reference, conditions.

The empirical equation was based on soil-survey attributes that describe major variables in sediment trapping by buffers. In general, the capability of a buffer to trap sediment depends on the magnitude of the runoff load from the field and characteristics of the buffer zone that promote deposition. Conditions that produce larger runoff loads, such as higher rainfall, lower soil permeability, greater soil erodibility, and steeper slopes, will decrease trapping efficiency (Helmers et al., 2002). Conditions that favor sediment deposition, such as coarser sediments and flatter slopes, will increase trapping efficiency (Dillaha et al., 1989; Hayes et al., 1984; Robinson et al., 1996). A sediment factor equation was developed that generally relates these major variables in sediment generation and deposition:

$$\text{Sediment factor} = D_{50}/RKLS \quad (1)$$

where,

D_{50} = median particle diameter of the surface soil (mm), and

R = rainfall-runoff erosivity (ft tonf in [ac hr yr $]^{-1}$),

K = soil erodibility (ton [ac EI $]^{-1}$),

L= slope length factor (dimensionless), and

S= slope steepness factor (dimensionless) of the Revised Universal Soil Loss Equation (RUSLE) as defined by Renard et al. (1997).

In Equation 1, values for D_{50} (Table 1) were assigned based on the surface-soil texture classification "surftex" in the SSURGO database. The value for R was estimated from the annualized isoerodent map of the eastern United States (Figure 2-1 in Renard et al., 1997). The value for K was obtained from the soil erodibility factor "kffact" (without rock fragments) for the surface soil layer in the SSURGO database. The value for L was calculated using the equation of McCool et al. (1989) for a 200 m (656 ft) field length and an average slope (%) equal to the arithmetic mean of slope range given by "slopeh" and "slopel" in the SSURGO database. The value for S was calculated using the equation of Wischmeier and Smith (1978) and the arithmetic mean of the slope range.

Reliability of the sediment factor was evaluated by comparing values generated using Equation 1 with corresponding values for sediment trapping efficiency (percent of input load retained in a buffer) under reference conditions (Table 2) obtained using the Vegetative Filter Strip Model (VFSMOD Version 1.06; Muñoz-Carpena and Parsons, 2000). The VFSMOD model is a field scale, mechanistic, single event model that is based on the hydraulics of flow and of sediment transport and deposition (Muñoz-Carpena et al., 1993, 1999). It simulates both field runoff and buffer trapping. The sediment deposition component is based on the University of Kentucky sediment filtration model (Barfield et al., 1979; Hayes et al., 1979, 1984; Tollner et al., 1976, 1977). Good agreement has been determined between modeled and observed trapping efficiencies for conditions in North Carolina (Muñoz-Carpena et al., 1999), Mississippi (Hayes and Hairston, 1983), and Ontario, Canada (Abu-Zreig, 2001). For computing values using VFSMOD, it was assumed that soil and slope conditions were the same for both field and buffer. The model assumes that runoff is uniformly distributed to, and through, the buffer. Longer-term sediment accumulation and re-suspension processes that could affect flow uniformity and deposition are not considered in VFSMOD. The reference conditions in Table 2 were chosen for this particular study to represent an average condition for both upland and riparian buffer situations across the eastern United States.

To evaluate the reliability of the sediment factor, corresponding values were computed for twenty-four combinations of rainfall amount [70 and 127 mm (2.8 and 5.0 in) in 24 hr], slope (two percent and 16 percent), and soil (clay, silt loam, sandy loam, sand, clay loam, and sandy clay loam). These combinations were selected to encompass the wide range of cultivated land conditions found in the eastern United States. A two percent slope was chosen as a conservative lower limit for obtaining uniform runoff flow through buffers. A one percent limit has been recommended for filter strips (Hayes and Dillaha, 1992). Rainfall amounts of 70 mm (2.8 in) and 127 mm (5.0 in) are equivalent to two-year return frequency, 24-hour rainfall events for Marshall, Minnesota and Tallahassee, Florida (Hershfield, 1961) where R = 100 and 500, respectively. Values for additional

Table 3. Values for additional soil variables used in Vegetative Filter Strip Model (VFSMOD) simulations for calculating sediment and water trapping efficiencies of buffers. The values are based on soil texture class. Soil organic matter content was assumed to be two percent.

Soil texture class	K_{sat} (in hr^{-1})	Texture factor	Structure factor	Permeability factor	Hydrologic soil group	Curve number	K factor (ton [ac EI]$^{-1}$)
Clay	0.02	0.01278	0.0650	0.075	D	86	0.2678
Clay loam	0.08	0.02360	0.0650	0.050	D	86	0.3510
Sandy clay loam	0.12	0.02360	0.0650	0.050	D	86	0.3928
Silt Loam	0.27	0.42590	0.0650	0.025	B	75	0.5159
Sandy loam	0.86	0.25490	0.0325	0.000	A	65	0.2874
Sand	9.27	0.01481	0.0325	-0.050	A	65	0.1306

soil variables required to run the VFSMOD simulations are keyed to surface soil texture class according to Table 3.

The relationship between the soil survey-based sediment factor and VFSMOD-based sediment trapping efficiency is plotted in Figure 1. Four of the 24 data points (sandy-soil scenarios) are not shown in the graph because they had extremely high sediment factor values (up to 10 times the range shown in Figure 1) and sediment trapping efficiency values of 100 percent. The graph shows the range that contains the variability and curvature of the relationship. The calibration equation for sediment was derived by non-linear regression on the data in Figure 1 (all 24 points). The equation:

$$\text{Sediment trapping efficiency} = 100 - 85\ e^{-1320\ (\text{Sediment factor})} \qquad (2)$$

was used to convert a value of the sediment factor into an estimate of sediment trapping efficiency (in percent) by a buffer under the reference conditions listed in Table 2.

A model for trapping dissolved pollutants in surface runoff. A modeling approach similar to that used for sediment trapping was used to develop a mathematical model for dissolved-pollutant trapping by a buffer. The empirical equation was developed from soil-survey attributes that describe major variables that influence the retention of dissolved pollutants by buffers. Dissolved pollutants are retained in buffers primarily by infiltration of the runoff water. In general, the capability of a buffer to infiltrate runoff water depends on the amount of runoff from the field and the capability of the buffer zone to infiltrate it (Helmers et al., 2002). Conditions that produce greater runoff volume, such as higher rainfall and steeper slopes, will decrease trapping efficiency. Conditions that favor infiltration, such as higher soil permeability and flatter slopes, will increase trapping efficiency. An infiltration factor equation was developed that generally describes these major variables in runoff generation and infiltration:

$$\text{Infiltration factor} = K_{sat}^2/RLS \qquad (3)$$

where,

K_{sat} = saturated hydraulic conductivity of the surface soil (in hr^{-1}).

Values for R, L, and S were determined by the same procedures used for the sediment factor. The value for K_{sat} was computed as the geometric mean of the lower and upper values of soil permeability for the surface soil layer as indicated by "perml" and "permh", respectively, in the SSURGO database.

Reliability of the infiltration factor was evaluated by comparing values generated using Equation 3 with corresponding values for water trapping efficiency (percent of input volume infiltrated in the buffer) under reference conditions (Table 2) obtained using VFSMOD. Corresponding values were obtained for the same 24 sets of soil, slope, and rainfall conditions used to test the sediment factor. The relationship between the infiltration factor and water trapping efficiency is plotted in Figure 2. The calibration equation for dissolved pollutants was derived by non-linear regression on the data in Figure 2.

Figure 1
Comparison of sediment factor values and corresponding values for sediment trapping efficiency (STE; percent of input load retained in the buffer) calculated using Vegetative Filter Strip Model (Version 1.06; Muñoz-Carpena and Parsons, 2000) for twenty-four combinations of slope (2% and 16%), rainfall (R = 100 and 500), and soil texture class (clay, clay loam, sandy clay loam, silt loam, sandy loam, and sand). Note: Only 20 of the total 24 data pairs are plotted here. Four are well beyond the upper value of sediment factor shown (up to 400) and have trapping efficiency values of 100 percent.

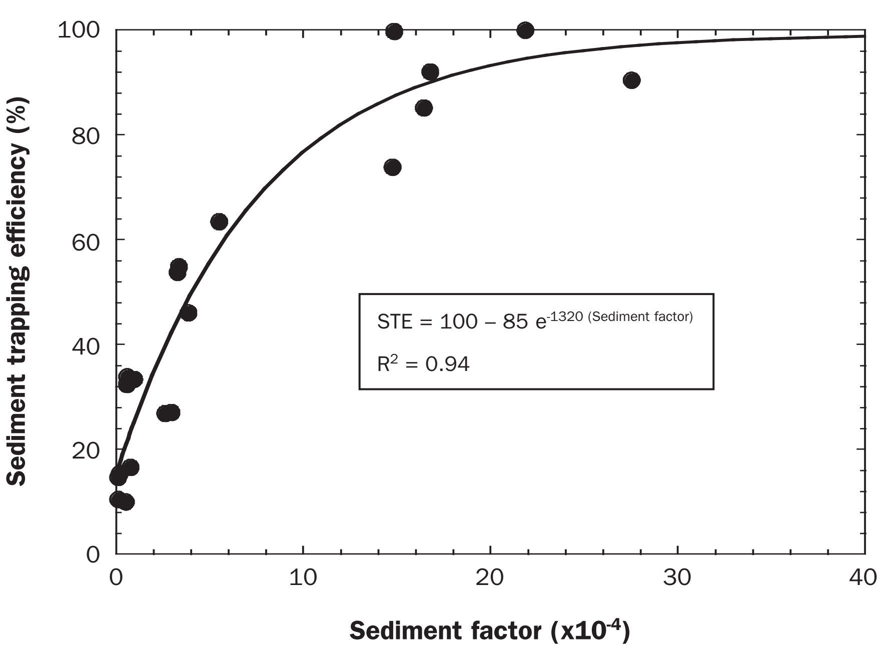


Figure 2
Comparison of infiltration factor values and corresponding values for water trapping efficiency (WTE; percent of input load infiltrated in the buffer) calculated using Vegetative Filter Strip Model (Version 1.06; Muñoz-Carpena and Parsons, 2000) for twenty-four combinations of slope (two percent and 16 percent), rainfall (R = 100 and 500), and soil texture class (clay, clay loam, sandy clay loam, silt loam, sandy loam, and sand).

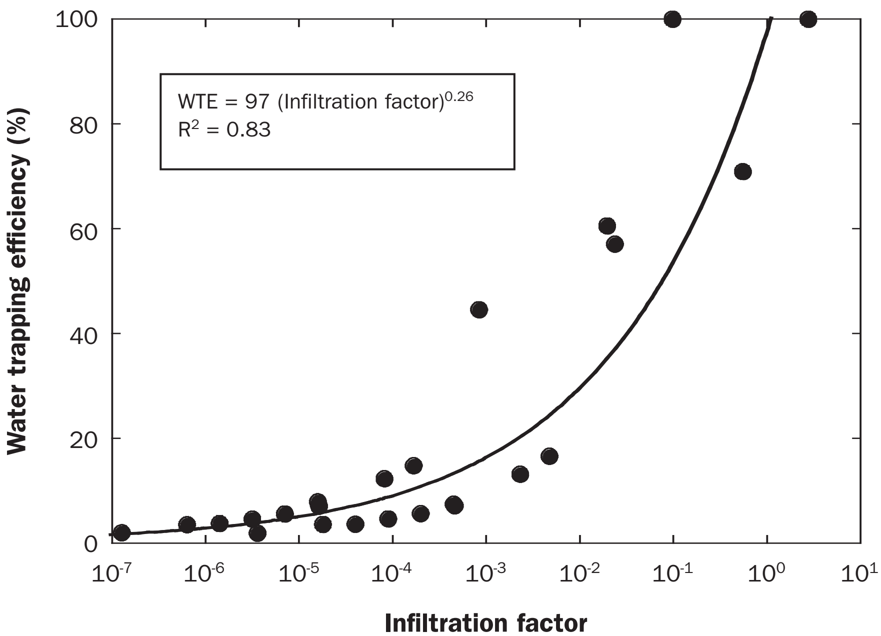
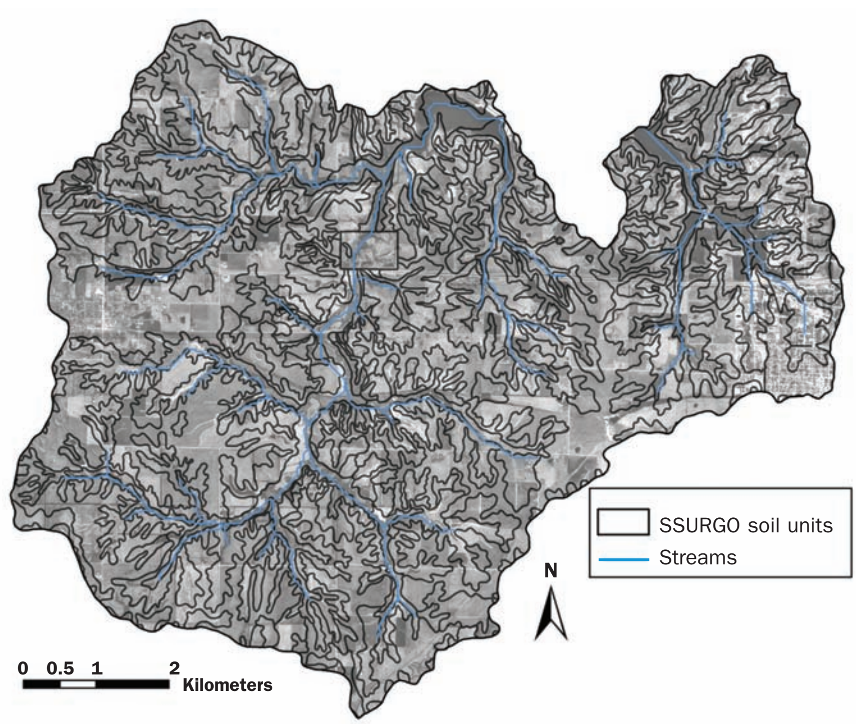


Figure 3
Boundaries of soil map units and location of streams in the Cameron-Grindstone watershed in northwestern Missouri.



The equation:

Water trapping efficiency =
97 (Infiltration factor)$^{0.26}$ (4)

was used to convert a value of the infiltration factor into an estimate of water trapping efficiency (in percent) by a buffer under the reference conditions listed in Table 2.

A model for interaction with pollutants in groundwater. A categorical model was used to identify the presence or absence of conditions that favor buffer interaction with pollutants in groundwater. Pollutants that are dissolved in groundwater are removed by a buffer by plant uptake and by transformations in the soil that occur primarily in the plant root zone (Correll, 1997). The level of effectiveness of a buffer depends on many variables, including the type of pollutant and its concentration in groundwater, the rate of groundwater flow, the fraction of groundwater flow that intersects the root zone, and the rate of root zone interactions with pollutants in groundwater (Correll, 1997; Lowrance et al., 1997; Vidon and Hill, 2004b). Information on most of these variables is not widely available. Soil survey attributes only provide an indication of whether interaction between a buffer and groundwater is possible or not.

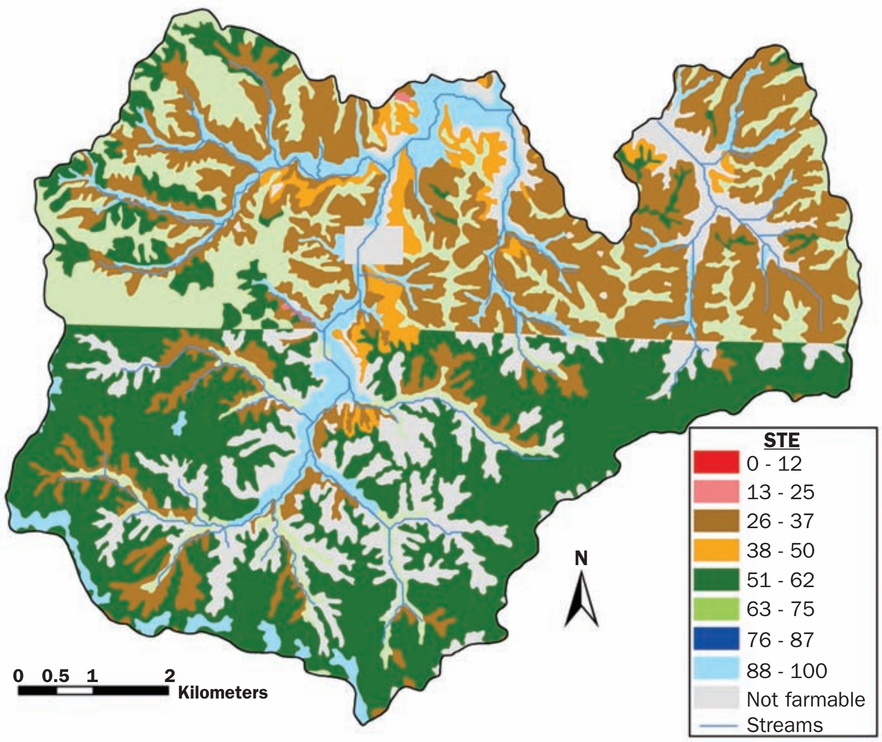
Two soil attributes were used to indicate whether groundwater interaction with a buffer is possible or not: hydric condition and depth to water table. Depth to water table is the predominant attribute that determines if a buffer can interact with pollutants in groundwater. It was assumed that groundwater within six feet (1.8 m) of the soil surface can interact with a buffer root zone. Water table depth was taken as the minimum value in the range of depth to seasonally high water table, "wtdepl" in the SSURGO database.

The hydric classification of a soil indicates the kind of interactions that are possible. A sufficiently low redox potential (or Eh) in the soil can mean that the soil is anaerobic and soil microbes are better able to transform dissolved nitrate in groundwater into nitrogen gas (Gold et al., 2001). The hydric soil classification, "hydric" in the SSURGO database, indicates the existence of sufficiently low redox potential in the root zone for this process to occur (Gold et al., 2001; Rosenblatt et al., 2001; Soil Survey Staff, 1993). Low redox conditions typically occur in soils that are saturated with water for long periods

Table 4. Sediment trapping efficiency (STE), dissolved-pollutant and water trapping efficiency (WTE), and groundwater interaction category for all farmable soil map units in the Cameron-Grindstone watershed in northwestern Missouri.

Name of soil map unit	STE	WTE	Groundwater category
Dekalb County (North half of the watershed)			
Armstrong loam, 5 to 9% slopes	43	22	3
Armstrong clay loam, 5 to 9% slopes	31	12	3
Gara loam, 9 to 14% slopes	29	18	4
Gasconade, 14 to 30% slopes		Not farmable	
Grundy silt loam, 1 to 5% slopes	69	31	3
Grundy silty clay loam, 2 to 5% slopes, eroded	60	29	3
Kennebec silt loam, 0 to 1% slopes	99	47	3
Ladoga silt loam, 2 to 5% slopes	67	29	4
Ladoga silt loam, 5 to 9% slopes, eroded	38	22	4
Lagonda silt loam, 2 to 5% slopes	62	29	3
Lagonda silt loam, 5 to 9% slopes, eroded	35	22	3
Lamoni clay loam, 5 to 9% slopes	29	12	3
Lamoni clay loam, 5 to 9% slopes, eroded	29	12	3
Lamoni, 5 to 9% slopes, severely eroded	34	7	3
Quarries		Not farmable	
Sampsel silty clay loam, 5 to 9% slopes	34	12	2
Sharpsburg silt loam, 2 to 5% slopes	67	29	4
Shelby loam, 9 to 14% slopes	29	18	4
Shelby clay loam, 9 to 14% slopes, severely eroded	21	10	4
Vesser silt loam, 0 to 1% slopes	99	47	3
Water		Not farmable	
Zook silty clay loam, 0 to 1% slopes	98	26	2
Clinton County (South half of the watershed)			
Haig, silt loam, 0 to 2% slopes	96	42	1
Grundy silt loam, 2 to 5% slopes	62	29	3
Grundy silty clay loam, 2 to 5% slopes	60	16	3
Grundy silt loam, 5 to 9% slopes	35	22	3
Grundy silty clay loam, 5 to 9% slopes		Not farmable	
Ladoga silt Loam, 5 to 9% slopes	38	22	4
Bremer silty clay loam, 0 to 2% slopes	97	42	1
Armstrong loam, 5 to 9% slopes	43	22	3
Armstrong clay loam, 9 to 14% slopes	28	10	3
Armstrong clay loam, 5 to 9% slopes, severely eroded	29	12	3
Armstrong clay loam, 9 to 14% slopes, severely eroded		Not farmable	
Gara loam, 9 to 14% slopes	29	18	4
Gara loam, 14 to 20% slopes		Not farmable	
Clarinda silty clay loam, 5 to 9% slopes, eroded	34	12	1
Lamoni silty clay loam, 5 to 9% slopes	34	12	3
Lamoni silty clay loam, 5 to 9% slopes, eroded		Not farmable	
Shelby loam, 9 to 14% slopes	29	18	4
Kennebec silt loam, 0 to 2% slopes	98	42	3
Colo silty clay loam, 2 to 5% slopes	68	29	1
Sharpsburg silty clay loam, 2 to 5% slopes	64	29	4
Sharpsburg silty clay loam, 5 to 9% slopes	36	22	4

Figure 4
Sediment trapping efficiency (STE; in percent) for soil map units in the Cameron-Grindstone watershed in northwestern Missouri. The apparent line of discontinuity in STE values that runs east-west through the middle of the watershed is located on the county line that separates Clinton County in the southern half of the watershed from Dekalb County in the northern half.



during the year. Recent reports, however, suggest denitrification can also be important in non-hydric soils that become saturated periodically (Vidon and Hill, 2004a). Four categories of groundwater condition were recognized:

1. Interaction: Hydric soil and water table less than 6 ft from the soil surface.
2. Interaction: Hydric soil and water table more than 6 ft from the soil surface.
3. Interaction: Non-hydric soil and water table less than 6 ft from the soil surface.
4. No interaction: Non-hydric soil and water table more than 6 ft from the soil surface.

Categories 1, 2, and 3 represent conditions where groundwater interacts with the root zone of buffer vegetation. Categories 1 and 3 indicate a shallow water table. Category 2 occurs where wetness is due to poor drainage of surface horizons rather than a shallow water table. Groundwater is likely to have little or no contact with the root zone of a buffer where category 4 occurs. No attempt was made to assign rates of pollutant removal to categories 1 to 3. They are intended only to identify soils where some removal of pollutants from groundwater by a buffer is possible and to indicate the general processes that may be acting in those locations.

Application of the models to a small watershed. The three models were applied to the ~65 km^2 (~25 mi^2) Cameron-Grindstone watershed in Dekalb and Clinton Counties in northwestern Missouri. The watershed is dominantly under row crop cultivation and pasture. Streams in this watershed drain to drinking water reservoirs where there is concern about elevated levels of sediment, nutrients, and pesticides (Missouri DNR, 2004). In this watershed, upland plains break into shallow valleys (Nigh and Schroeder, 2002). Soils are developed from shallow loess over glacial till in the uplands and from alluvium in the broader valleys. The RUSLE R factor for this area is about 182.

All farmable soil-map units (phase of soil series) in the watershed were assessed. Farmable soil-map units were identified by land capability classes 1, 2, 3, or 4 (USDA, 2003) for either "clirr" or "clnirr" in the SSURGO database. Farmable map units correspond approximately to the range of soil and slope conditions used for developing the calibration equations for surface runoff. A map was produced to display the modeled results for each buffer function. The maps were produced in a geographic information system (ArcInfo Version 9.1, ESRI, Inc., Redlands, California). Shape files for the soil map units were obtained from the SSURGO database (Figure 3). The maps were evaluated for spatial differences in buffer function across the watershed and for how this information could be used to help prioritize locations for buffer installation.

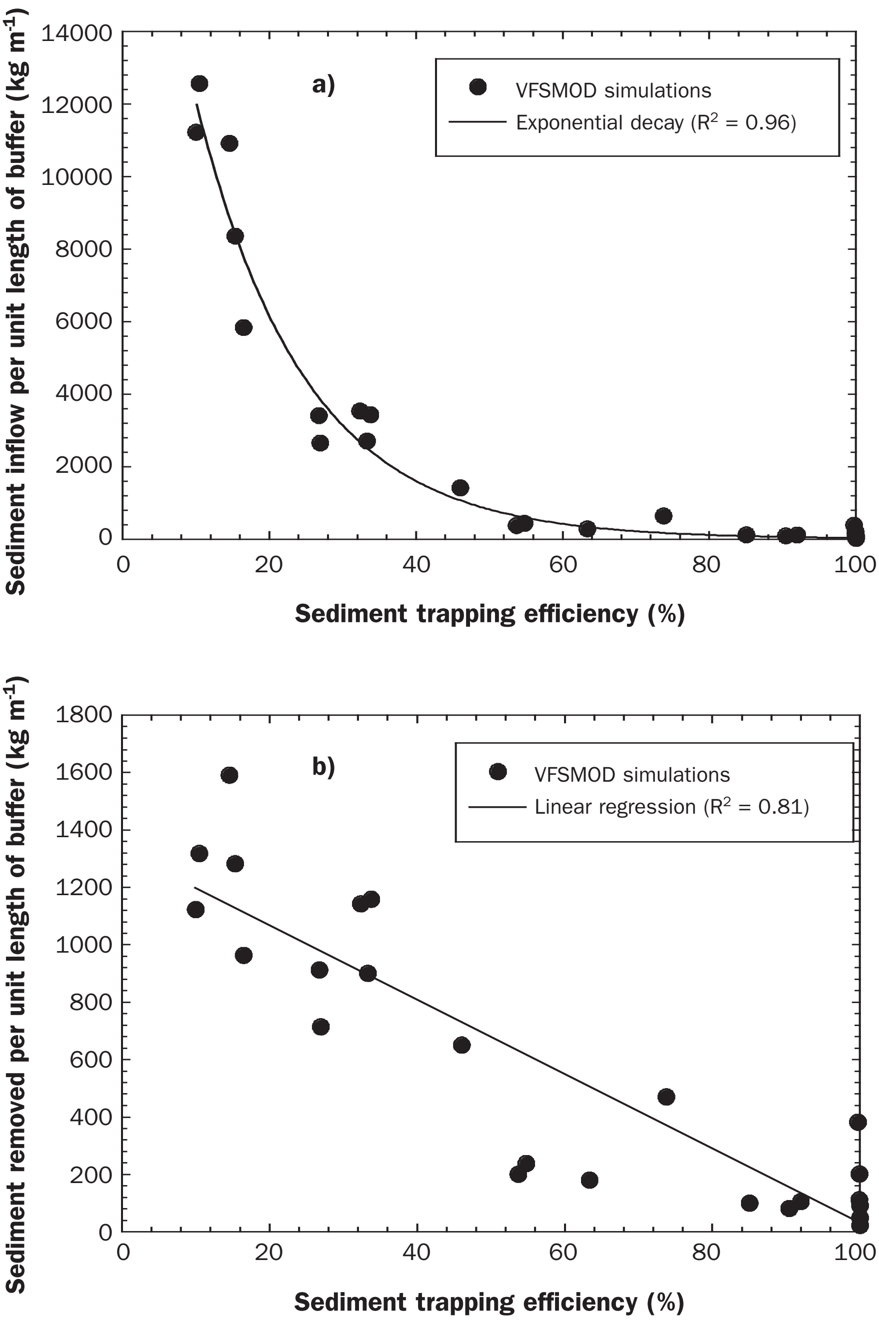
Results and Discussion

Sediment model reliability and interpretation of results. Values for sediment trapping efficiency are generally reliable for comparing the relative capability of buffers to trap sediments from surface runoff over a wide range of soil, slope, and rainfall conditions. The sediment factor, based on soil-survey attributes, strongly correlated with corresponding values for sediment trapping efficiency calculated using VFSMOD for the twenty-four different landscape scenarios (R^2 = 0.94; Figure 1). The regression equation on these data (Equation 2) produced values that were within 15 percent of VFSMOD estimates. Other equation forms and combinations of the current set of variables for the sediment factor were evaluated but Equation 1 had the best fit. Values for sediment trapping efficiency were very sensitive to changes in soil texture, slope, and rainfall characteristics. Over the range of soil, slope, and rainfall conditions that were simulated, sediment trapping efficiency varied from 10 to 100 percent. Based on the strong correlation and high sensitivity, sediment trapping efficiency should provide a reasonable basis for comparing buffer capability among locations.

Application of the sediment trapping efficiency equation to the Cameron-Grindstone watershed in northwestern Missouri revealed a wide range of sediment trapping efficiencies among soil-map units (Table 4). Values for sediment trapping efficiency ranged from 21 to 99 percent. The mapped results indicated that low sediment trapping efficiency values are generally associated with steeper slopes of valley sides, while high values are associated with the gentle topography of upland plateaus and floodplains (Figure 4). The mapped results also revealed an anomalous pattern in the watershed. A distinct line of discontinuity runs east to west through the middle of the watershed (Figure 4). That line

Figure 5

a) Sediment inflow per unit buffer length, and b) Sediment trapped per unit buffer length as functions of sediment trapping efficiency (STE) under reference conditions used in this study.



falls on the county line that separates Clinton County in the southern half of the watershed and Dekalb County in the northern half. The line occurs because soil map units on adjacent sides of the county line were described somewhat differently. For example, large areas associated with steep valley sides are classified as unfarmable (i.e., land capability class >4) in Clinton County while the same landscape position has been described as somewhat less steep and farmable in Dekalb County.

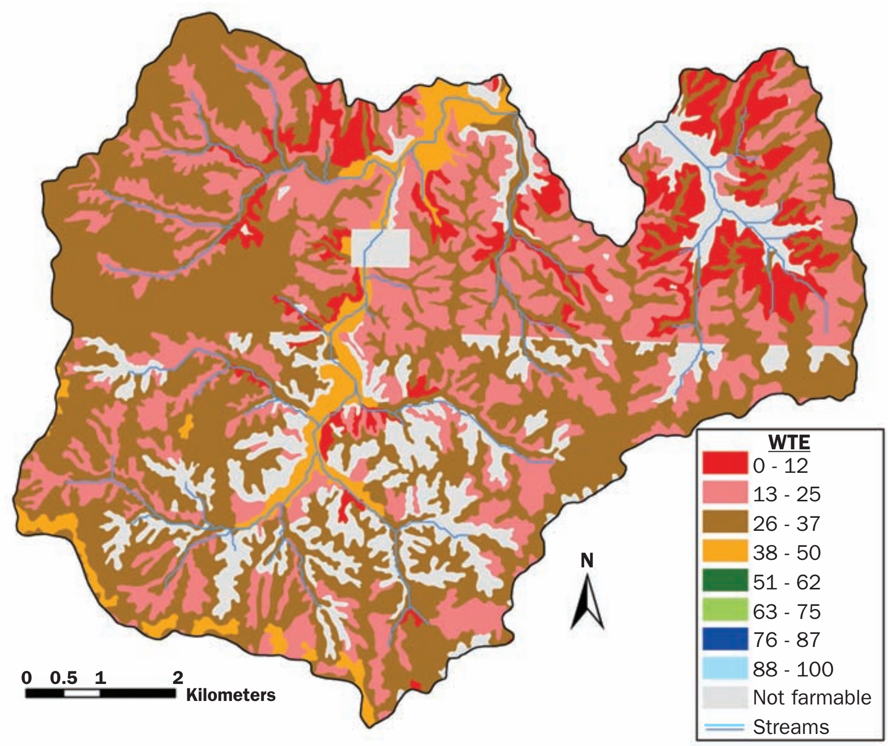
With proper interpretation, the mapped results can be used by watershed planners to help locate and design buffers that will have greater impact on water quality. The simplest interpretation is that map units having higher sediment trapping efficiency values have soil and slope conditions that enable buffers to trap a larger proportion of inflowing sediment. However, closer examination of the model revealed that these locations also correspond to areas where inflowing sediment loads are relatively small. Results of the simulations using VFSMOD, which account for field runoff load, show that higher sediment trapping efficiency values are strongly associated with conditions that generate smaller field runoff loads (Figure 5a). Furthermore, lower sediment trapping efficiency values are associated with greater sediment load being trapped by a buffer (Figure 5b), despite the lower efficiency. The same buffer design located where lower sediment trapping efficiency values occur will trap greater sediment load than in locations having higher sediment trapping efficiency.

These results imply that locations having ***lower*** sediment trapping efficiency values are those where larger runoff loads from cropland may occur and there is opportunity to trap greater pollutant load with a buffer. Furthermore, wider buffers [i.e., than the 12 m (39 ft) wide reference design] may be recommended at these locations in order to improve sediment trapping efficiency and produce even greater load reduction in runoff. In the Cameron-Grindstone watershed, those locations would include Shelby Clay Loam and Armstrong Clay Loam map units among others having relatively lower sediment trapping efficiency values (Table 4). Less opportunity exists to impact stream sediment load with buffers on Vesser and Kennebec soils among others having high sediment trapping efficiency values. Departures from the reference conditions listed in Table 2 should not affect the relative rankings of different map units based on sediment trapping efficiency if the departures are similar for the map units being compared. For example, if two riparian map units are being compared and the slopes of the adjoining fields are steeper than the riparian areas, but in a similar manner, then the relative ranking of the map units based on sediment trapping efficiency would not change.

Comparison of map units that depart from reference conditions in substantially different ways would require some adjustment to rankings based on the reference sediment trapping efficiency. Where actual conditions would produce substantially lower field runoff load (e.g., flatter slope, shorter slope length, and/or coarser soils in the field area) or better trap-

Figure 6

Dissolved pollutant trapping efficiency, as indicated by water trapping efficiency (WTE; in percent), for soil map units in the Cameron-Grindstone watershed in northwestern Missouri. The apparent line of discontinuity in WTE values that runs east-west through the middle of the watershed is located on the county line that separates Clinton County in the southern half of the watershed from Dekalb County in the northern half.



ping conditions for a buffer (e.g. flatter slope, higher soil permeability in the buffer zone) than the reference condition, the reference sediment trapping efficiency would underestimate sediment trapping efficiency and should be adjusted upward. On the other hand, where actual conditions would produce greater field runoff load or diminished sediment trapping conditions, the reference sediment trapping efficiency would overestimate trapping efficiency and should be adjusted downward. After these adjustments, the map units or sites can be re-ranked. In the Cameron-Grindstone watershed, adjustments may improve comparisons between upland and riparian map units. Buffers on the downhill (steeper) side of convex upland units would tend to experience lower trapping efficiency than the reference sediment trapping efficiency, while those on the downhill (flatter) side of concave mid-slope and riparian units would experience higher trapping efficiency than the reference sediment trapping efficiency. An adjusted sediment trapping efficiency value can be roughly approximated for field conditions that depart from the reference by re-estimating the sediment factor (Equation 1) and computing a new sediment trapping efficiency using Equation 2. A technique has been proposed for adjusting the topographic factors (LS) for complex slopes (Foster and Wischmeier, 1974). Rankings based on adjusted values of sediment trapping efficiency may be sufficient for general planning purposes. But, more-accurate estimates would require recalibration of sediment trapping efficiency (Figure 1) and runoff loads (Figures 5a and 5b) for a new set of reference conditions that fit the local situation better. Finally, field site evaluations are critical to ensure that soil map units have been described accurately and to account for site conditions that depart substantially from the reference conditions.

Dissolved-pollutant model reliability and interpretation of results. Values for water trapping efficiency are also generally reliable for comparing the relative capability of buffers to trap water (and dissolved pollutants) from surface runoff over a wide range of soil, slope, and rainfall conditions. The infiltration factor strongly correlated with water trapping efficiency ($R^2 = 0.83$; Figure 2), although not as strongly as for sediment. The regression equation on the data (Equation 4) produced values that were within 30 percent of corresponding values computed using VFSMOD. The greatest disagreement occurred for scenarios having sandy soils where the slope of the relationship is very steep. For scenarios having medium- to fine-textured soils, the regression equation yielded trapping efficiencies that were within 10 percent of the VFSMOD estimates. Furthermore, water trapping efficiency is very sensitive to changes in soil texture, slope, and rainfall characteristics. Over the range of conditions that were simulated, water trapping efficiency varied from two to 100 percent. Based on the strong correlation and high sensitivity, water trapping efficiency should provide a reasonable basis for comparing buffer capability among locations.

Application of the water trapping efficiency equation to the Cameron-Grindstone watershed revealed a wide range of water (and dissolved pollutant) trapping efficiencies among soil map units (Table 4). The values for water trapping efficiency ranged from seven to 47 percent. As with sediment trapping efficiency, the mapped results showed that lower water trapping efficiency values are associated with steeper valley sides, while higher values are associated with the more-gentle topography of upland plateaus and floodplains (Figure 6). The same county-line anomaly that appeared in the sediment trapping efficiency map also appears in the water trapping efficiency map. The results in Table 4 also show that water trapping efficiency is less than sediment trapping efficiency in every map unit in the watershed. On average, water trapping efficiency is about half the value of sediment trapping efficiency (23 versus 51 percent, respectively), which is consistent with reports from experimental studies reviewed by Dosskey (2001). This result indicates that buffer capability for trapping dissolved pollutants is substantially less than for trapping sediment in this watershed. Similar to sediment trapping efficiency, map units having higher water trapping efficiency values have soil and slope conditions that enable buffers to infiltrate a larger proportion of inflowing water and dissolved pollutants. Results of the VFSMOD simulations show that higher water trapping efficiency values are associated with conditions that generate smaller field runoff loads (Figure 7a). But

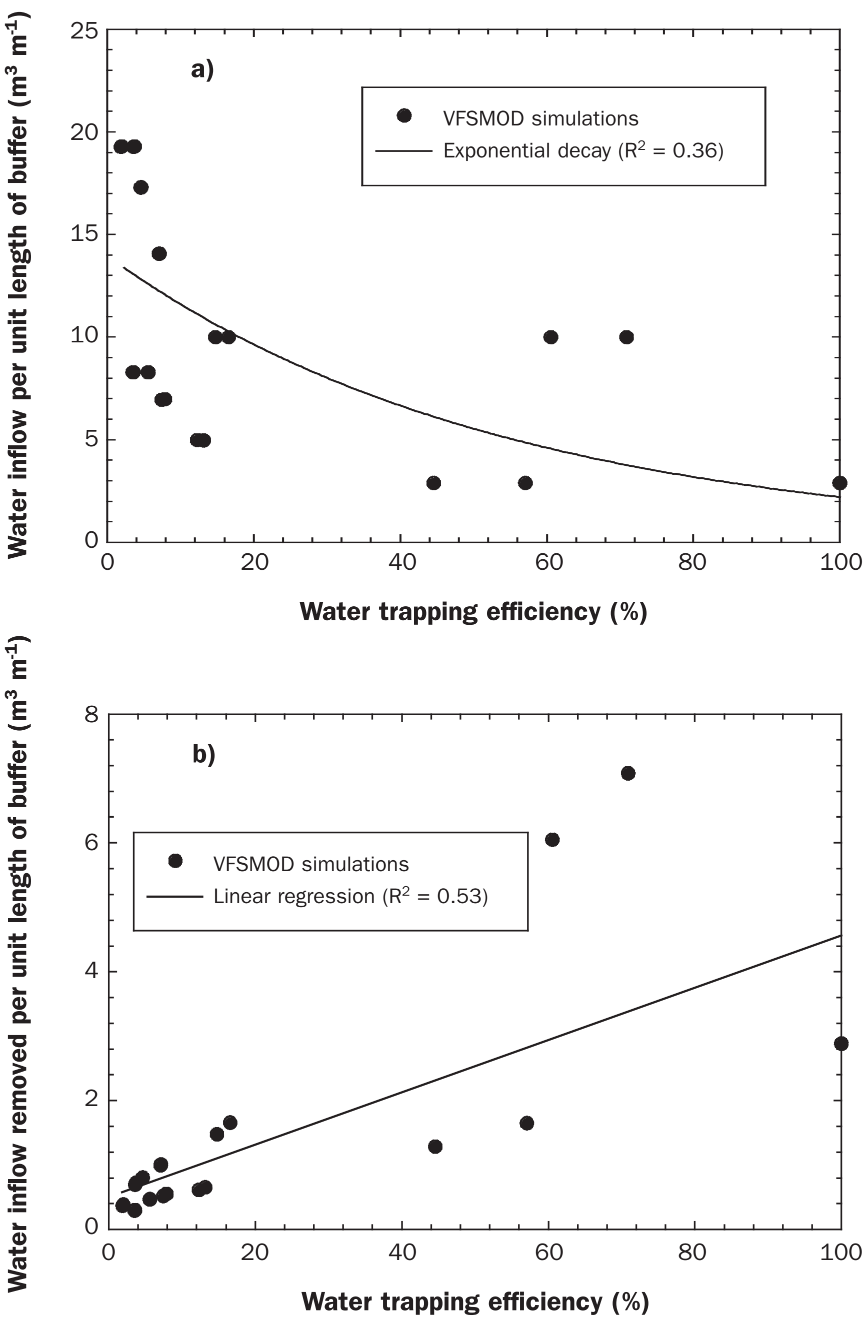


Figure 7
a) Water inflow per unit buffer length, and b) Water trapped per unit buffer length as functions of water trapping efficiency (WTE) under standard conditions used in this study.

unlike sediment trapping efficiency, lower water trapping efficiency values are generally associated with lower infiltrated load (Figure 7b). The same buffer design located where lower water trapping efficiency values occur will trap less dissolved pollutant load than in locations having higher water trapping efficiency, despite a greater load flowing into the buffer. These results imply that locations having ***lower*** water trapping efficiency values are those where larger runoff loads from cropland are likely to occur, but smaller pollutant loads would be trapped by a constant-width buffer. Wider buffers would be needed at these locations in order to improve dissolved pollutant trapping efficiency and yield greater load reduction in runoff. In the Cameron-Grindstone watershed, a buffer in map units having relatively lower water trapping efficiency would have greater opportunity to impact stream pollutant load, but would be realized only if relatively wider buffers were installed.

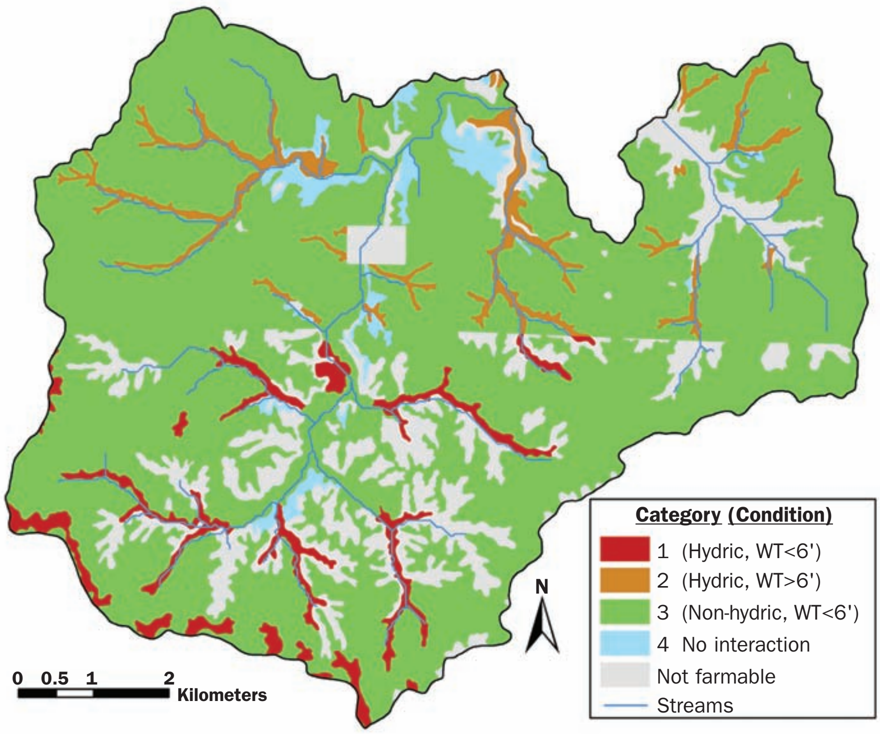
Comparison of map units that depart from reference conditions in substantially different ways would require some adjustment to rankings based on water trapping efficiency. Where actual conditions would produce substantially less field runoff (e.g., flatter slope, shorter slope length, and/or higher soil permeability in the field area) or better infiltration conditions in a buffer (e.g., flatter slope and/or higher soil permeability in the buffer zone) than the reference condition, the reference water trapping efficiency would underestimate dissolved-pollutant trapping efficiency. On the other hand, where actual conditions would produce greater field runoff load or diminished infiltration conditions, the reference water trapping efficiency would overestimate dissolved-pollutant trapping efficiency. An adjusted water trapping efficiency value can be roughly approximated using the same approach as for sediment trapping efficiency and with the same limitations.

Groundwater model reliability and interpretation of results. Interpretations for groundwater are straightforward. A buffer in any soil map unit having conditions described by groundwater categories 1 to 3 will probably interact with pollutants in groundwater. If nitrate attenuation is a specific goal, then map units having hydric conditions (categories 1 and 2) may be more suitable for buffers. This categorical groundwater model is reliable to the extent that pollutant removal by a buffer is limited to groundwater within six feet (1.8 m) of the soil surface. This is an approximate depth limit for most roots of deeper-rooting plant species. Substantial denitrification has been observed at deeper soil depths, particularly in alluvium where organic matter has been buried below the water table (Gold et al., 2001; Hill et al., 2004). In these locations, denitrification probably proceeds regardless of whether a buffer is present or not. The six-foot depth criteria should represent a realistic limit of influence of a buffer on pollutants in groundwater.

In the Cameron-Grindstone watershed, the groundwater model identifies distinct differences among soil map units in water table and hydric conditions (Table 4).

Figure 8

Groundwater interaction categories of soil map units in the Cameron-Grindstone watershed in northwestern Missouri.



Groundwater interaction with buffers is possible in most soil map units in this watershed. All three conditions of interaction (categories 1 to 3) are present. Non-hydric soils having a shallow water table (category 3) is the most common condition. The mapped results revealed that buffer interaction with groundwater is likely in riparian areas, as expected, but not exclusively (Figure 8). Most of the upland map units in the Cameron-Grindstone watershed experience a seasonal shallow water table. In these locations, buffers may be able to address pollutants in groundwater up-gradient from riparian areas. A planning focus on riparian zones for groundwater interaction may miss significant opportunities that exist in upland landscape positions in this watershed. The best opportunity for denitrification, however, is in riparian areas and poorly-drained upland plateaus in the highest reaches of the watershed where shallow water table and hydric conditions converge.

Field evaluations are especially important to ensure that the soil survey data accurately reflect current groundwater conditions. In some locations, farmable area having conditions described by categories 1 to 3 when soil surveys were conducted may have undergone more recent drainage improvements that reduce or eliminate a buffer's capability to interact with groundwater. The potential for this problem is acute in the extensively-drained landscapes of the mid-western U.S. (Wu and Babcock, 1999) and may limit the utility of soil surveys for evaluating groundwater interaction.

Summary and Conclusion

Three models were developed that utilize soil survey attributes to compare locations for how effectively a buffer could remove pollutants from crop field runoff. Reliability of the quantitative models for sediment and for dissolved pollutants in surface runoff is supported by strong correspondence with results using the process-based Vegetative Filter Strip Model (VFSMOD) for a standard buffer design and field management. The categorical model for groundwater is based on reasoning that a buffer interacts only with groundwater that enters the root zone. The three models represent standardized bases for comparing different sites that vary in slope and soil conditions.

The availability of SSURGO digital soil surveys makes the application of these models to watersheds relatively easy and facilitates mapping the results to display spatial patterns. However, SSURGO databases are not yet available for extensive portions of U.S. farmlands. In locations where SSURGO is not available, the tabular data can be still obtained from the STATSGO database (USDA, 1994), but maps must be created by other means.

The models were applied to a ~65 km^2 (~25 mi^2) agricultural watershed in northwestern Missouri. The mapped results revealed large differences in pollutant trapping efficiency for surface runoff across this watershed (21 to 99 percent for sediment and seven to 47 percent for dissolved pollutants). Trapping efficiency for dissolved pollutants was much smaller than for sediment in all map units. Lower values of trapping efficiency were associated with map units where runoff loads are higher and where a buffer will trap greater loads of sediment, but smaller loads of dissolved pollutants. For groundwater, the confluence of hydric conditions and shallow groundwater occurred only at the highest reaches of the test watershed, but a buffer can also interact with groundwater in most upland and riparian locations due to the prevalence of a seasonally-shallow water table. These results substantiate that buffer capability can differ greatly from one location to another in a small watershed, and that those differences can be estimated and mapped using soil surveys.

The reference conditions used in this study to compute trapping efficiencies may not be representative of typical buffer and field conditions in some regions. Changing the reference conditions, however, will not appreciably affect the relative rankings of map units. On the other hand, recalibrating the equations for specific regional conditions will yield sediment trapping efficiency and water trapping efficiency values that better estimate the level of buffer effectiveness. The present set was chosen to illustrate a generalized approach for wide-ranging conditions across the eastern United States. Region-specific references, as well as techniques for handling locally-important adjustments, are important needs for future development.

Because numerous simplifying assumptions were employed, the reference models should be used only as a general guide for the placement of buffers. Rankings based on these models are probably best used as a screening tool to guide planners to locations where buffers are likely to have greater water quality impact and away from those where impacts are likely to be small. The reference values for sediment trapping efficiency and water trapping efficiency, with adjustments as appropriate, can provide a gage for how well a buffer could perform in those locations.

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