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Improved indexes for targeting placement of buffers of Hortonian runoff

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Abstract: Targeting specific locations within agricultural watersheds for installing vegetative buffers has been advocated as a way to enhance the impact of buffers and buffer programs on stream water quality. Existing models for targeting buffers of Hortonian, or infiltration-excess, runoff are not well developed. The objective was to improve on an existing soil survey–based approach that would provide finer scale resolution, account for variable size of runoff source area to different locations, and compare locations directly on the basis of pollutant load that could be retained by a buffer. The method couples the Soil Survey Geographic database with topographic information provided by a grid digital elevation model in a geographic information system. Simple empirical equations were developed from soil and topographic variables to generate two indexes, one for deposition of sediment and one for infiltration of dissolved pollutants, and the equations were calibrated to the load of sediment and water, respectively, retained by a buffer under reference conditions using the process-based Vegetative Filter Strip Model. The resulting index equations and analytical procedures were demonstrated on a 67 km^2 (25.9 mi^2) agricultural watershed in northwestern Missouri, where overland runoff contributes to degraded stream water quality. For both indexes, mapped results clearly mimic spatial patterns of water flow convergence into subdrainages, substantiating the importance of size of source area to a given location on capability to intercept pollutants from surface runoff. A method is described for estimating a range of index values that is appropriate for targeting vegetative buffers. The index for sediment retention is robust. However, the index for water (and dissolved pollutant) retention is much less robust because infiltration is very small, compared to inflow volumes, and is relatively insensitive to the magnitude of inflow from source areas. Consequently, an index of inflow volume may be more useful for planning alternative practices for reducing dissolved pollutant loads to streams. The improved indexes provide a better method than previous indexes for targeting vegetative buffers in watersheds where Hortonian runoff causes significant nonpoint pollution.

Key words: conservation planning—nonpoint pollution—precision conservation—surface runoff—terrain analysis—watershed

Targeting specific locations within agricultural watersheds to install vegetative buffers has been proposed as a way to increase the impact of individual installations on the quality of water derived from agricultural watersheds and the cost effectiveness of improvement programs (Qiu 2009; Tomer et al. 2003; Walter et al. 2007). A vegetative buffer, such as a filter strip or forested riparian buffer, can improve water quality in two general ways. First, installation of a buffer reduces the size of the source by converting some of the source area (e.g., cropland, pasture) to a buffer that contributes substantially less sediment, nutrients, and other pollutants to runoff flow. Second, the buffer area further functions to retain pollutants in runoff from adjacent source areas. Retention processes include deposition, infiltration, and various abiotic and biotic transformations in the soil and vegetation (Dosskey et al. 2010).

Spatially distributed models have been developed to assist planners with identifying sites where buffers can produce relatively greater impact on water quality in streams (Dosskey et al. 2006; Tomer et al. 2003; Walter 2000). These models produce numerical indexes for gauging relative level of impact that buffer installation could produce at different sites. These indexes associate magnitude of impact with how much runoff water would flow to a given site and on the capability of a buffer at that site to retain pollutants from the runoff water. Conceptually, a site through which greater runoff load passes and where conditions create greater capability to retain pollutants from the runoff is a site where buffer installation would reduce pollutant loading to a greater degree. However, there are important differences among these models that determine the appropriate circumstances for their use (Dosskey and Qiu 2011; Tomer et al. 2009).

Existing models follow two general approaches. The first approach emphasizes the capability of sites to retain pollutants from overland runoff, with minor emphasis on size of the input load (Dosskey et al. 2006). Two indexes include the Sediment Trapping Efficiency Index (STE) for the deposition of sediment and sediment-bound pollutants and the Water Trapping Efficiency Index (WTE) for infiltration of water and dissolved pollutants. These indexes gauge the inherent capability of sites to function for retention (i.e., trapping) of pollutants in infiltration-excess, or Hortonian, overland runoff from crop land. The indexes are based on slope and soil properties (e.g., texture, hydraulic conductivity) determined from county-level (Soil Survey Geographic [SSURGO]) soil surveys and describe buffer capability in each soil map unit, much like the soil suitability ratings for particular land uses. The entire soil map unit receives the same index value based on average slope and other map unit–averaged soil attributes.

A recent study, however, highlighted significant weaknesses in this approach that may hinder its utility for targeting (Dosskey and Qiu 2011), including the following:

- Lack of accounting for variation in size of upslope runoff area as a factor con-

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tributing to runoff load and potential for pollutant retention at different locations. The current approach assumes that runoff to different locations is generated from a unit source area and that variation in runoff load derives only from slope and soil properties. In many agricultural landscapes, however, runoff diverges from hills and converges into swales as it moves through fields toward a field margin and results in substantial variation in the size of runoff source area and associated runoff load to different locations (Dosskey et al. 2002).

- Spatial resolution is too low for effective targeting of buffers. Slope can vary greatly from one site to another within a soil map unit (Tomer and James 2004), and sediment generation and buffer trapping capabilities are sensitive to slope (Dillaha et al. 1989; Wischmeier and Smith 1978). Employing an average slope condition for a large soil map unit may lack adequate spatial resolution for indexing the capabilities of individual sites where buffers might be applied.
- Interpretation of the index values is not straightforward and can confuse a planner. The index gauges efficiency of pollutant retention (load retained as a percent of input load) which, for sediment, is inversely related to the load of pollutants trapped. For example, a lower value for sediment trapping efficiency is associated with a larger input load of sediment and a greater amount of sediment retained by a buffer, despite the lower trapping efficiency (Dosskey et al. 2006). An index that is more directly linked to pollutant load and retention would be less confusing and more helpful for planners, particularly those who are trying to achieve loading targets, such as total maximum daily load and credits for water quality trading.

A second modeling approach focuses on locations where relatively greater amounts of runoff water pass on the way toward a stream, with minor emphasis on capability of the site to retain pollutants from the runoff water. This approach analyzes spatial patterns of topography and soil hydrologic properties to predict spatial patterns of runoff flow. The Wetness Index analyzes only topography for identifying locations that receive runoff from relatively larger source areas and that also have a relatively flatter slope, which is conducive to infiltration and deposition of surface runoff and for accumulation of subsurface flow (Burkart et al. 2004; Moore et al. 1991; Tomer et al. 2003). An extension of the Wetness Index, the Topographic Index, couples the Wetness Index with a factor for gauging the capacity of soil to transport and store infiltrated water (Walter et al. 2002). The Topographic Index was developed specifically for watersheds that exhibit variable source area hydrology, where it is interpreted as gauging the propensity for exfiltration (Walter et al. 2005), or saturation-excess overland flow, to occur (Walter et al. 2002). In exfiltration- and saturation-prone locations, agricultural practices, such as tillage, fertilization, and manure application can become large sources of sediment, nutrients, and/or pathogens to overland flow. Installation of vegetative buffer in these locations will improve water quality, primarily by eliminating source area. The Wetness Index and Topographic Index are facilitated by the use of a grid digital elevation model (DEM) in a geographic information system (GIS) that can depict topography at horizontal spatial resolutions of 30 × 30 m (100 × 100 ft) or finer.

We hypothesize that the major weaknesses of the soil survey–based trapping efficiency indexes could be solved by incorporating major aspects of the topographic approach. The result would produce improved indexes for targeting buffers among sites exhibiting Hortonian runoff hydrology. By employing a DEM, slope could be determined at a finer spatial resolution than the soil map unit, and source area could be determined and used as a variable for comparing sites. The utility of the indexes also could be enhanced by calibrating them directly to load of pollutants that would be retained by a buffer, rather than to percentage of load. The objective of this study was to improve the soil survey–based indexes for targeting buffers of Hortonian runoff by (1) accounting for variation in source area size, (2) improving the spatial resolution, and (3) linking the index values to impact on pollutant load.

Table 1

Reference conditions used in all Vegetative Filter Strip Model simulations for developing and calibrating the empirical equations.

Model component	Modeled conditions
Buffer design	12 m width Grass vegetation (30 cm tall; 1.65 cm spacing; Manning's n = 0.40)
Field size	200 m cultivated slope length
Farming practices	Contour tilled (USLE P factor = 1.0)* Seedbed stage with moderate residue (USLE C factor = 0.5)*
Rainfall properties	Type II rainfall pattern for R = 100; Type III for R = 500† Two-year return frequency, 24 h rainfall amount
Other	Crop field has the same soil and slope as the buffer zone Wet antecedent soil moisture condition Runoff is spatially uniform within field and buffer areas

* Support practice factor (P) and cover and management factor (C) of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978).

† Rainfall-runoff erosivity factor (R) of the Revised Universal Soil Loss Equation (Renard et al. 1997).

Materials and Methods

Original Soil Survey-Based Indexes. Two index models were developed by Dosskey et al. (2006), one to enumerate propensity for deposition of sediments and sediment-bound pollutants and another for infiltration of water and dissolved pollutants. For both models, the same basic approach was used. First, an empirical factor equation was developed from a few easily determined soil and site attributes that are functionally related to runoff generation in fields and to sediment deposition and water infiltration in a filter strip. Then, a calibration equation was developed to convert the empirical factor into an estimate of trapping efficiency by a filter strip (percent of input load retained in the buffer) under reference conditions. Reference conditions included a 12 m (39.4 ft) wide grass buffer intercepting infiltration-excess runoff from a clean-cultivated field extending 200 m (656 ft) upslope from the buffer during a 24-hour rainfall event, representing a two-year return frequency at the location of the planning area (table 1). Slope and soil characteristics were assumed to be the same for both the filter strip and upslope field.

For sediment, the original empirical equation is

Table 2

Values for soil variables used in the empirical equations and in model simulations that are keyed to surface soil texture class. Soil organic matter content was assumed to be 2% for all texture classes.

Soil texture class	Ksat* (in hr^{-1})	Ksat* (μm s^{-1})	Wetting front suction* (m)	Saturated water content* (m^3 m^{-3})	Hydrologic soil group	Runoff curve number	USLE K factor† (ton [ac EI]$^{-1}$)	USLE K factor† (tonne [ha EI]$^{-1}$)	D_{50} (mm)
Clay loam	0.08	0.556	0.2088	0.464	D	86	0.3510	0.0462	0.018
Silt loam	0.27	1.890	0.1668	0.501	B	75	0.5159	0.0679	0.027
Sandy loam	0.86	6.060	0.1101	0.453	A	65	0.2874	0.0379	0.098

* Values of saturated hydraulic conductivity from Rawls and Brakensiek 1983.

† USLE *K* factor is the soil erodibility factor in the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978).

$$\text{Sediment Factor} = D_{50}/(RKLS), \qquad (1)$$

which is calibrated to sediment trapping efficiency under reference conditions by

$$\text{STE} = 100 - 85e^{-1,320\ (\text{Sediment Factor})}, \qquad (2)$$

where STE is sediment trapping efficiency (percent of input mass retained in a buffer), D_{50} is the median particle diameter of the surface soil (mm), and R, K, L, and S are the rainfall-runoff erosivity factor (ft tf in [ac hr yr]$^{-1}$), soil erodibility factor (t [ac EI]$^{-1}$), slope length factor (dimensionless), and slope steepness factor (dimensionless) of the Revised Universal Soil Loss Equation (RUSLE) as defined by Renard et al. (1997). The value for D_{50} is assigned to the surface soil texture class identified in the SSURGO database according to Rawls and Brakensiek (1983). The value for R is estimated from the annualized isoerodent map of the eastern United States (Renard et al. 1997). The value for K is obtained from the soil erodibility factor in the SSURGO database. The value for L is 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 in the SSURGO database. The value for S is calculated using the equation of Wischmeier and Smith (1978) and the arithmetic mean of the slope range.

Calibration of the Sediment Factor to STE was performed using the Vegetative Filter Strip Model (VFSMOD ver. 1.06, University of Florida) (Muñoz-Carpena and Parsons 2000). For the calibration, corresponding values were computed for 24 combinations of rainfall amount (71 mm [2.8 in] in 24 h for R = 100 and 127 mm [5.0 in] in 24 h for R = 500), slope (2% and 16%), and soil texture class (clay, silt loam, sandy loam, sand, clay loam, and sandy clay loam). The two rainfall amounts are equivalent to a two-year return frequency, 24 h rainfall event for Marshall, Minnesota (71 mm), and Tallahassee, Florida (127 mm) (Hershfield 1961), where R = 100 and 500, respectively. Values for additional soil variables required to run the VFSMOD simulations that are keyed to surface soil texture class are shown in table 2.

For water, the original empirical equation is

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

which is calibrated to water trapping efficiency under reference conditions by

$$\text{WTE} = 97(\text{infiltration factor})^{0.26}, \qquad (4)$$

where WTE is water trapping efficiency (percent of input volume retained in a buffer), and K_{sat} is the saturated hydraulic conductivity of the surface soil layer (in hr^{-1}). Values for R, L, and S are determined by the same procedures used for the Sediment Factor. The value for K_{sat} is computed as the geometric mean of the lower and upper values of soil permeability for the surface soil layer in the SSURGO database. Trapping efficiency for dissolved pollutants is assumed to be similar to water.

For planning using these original soil survey–based methods, a single index value for sediment trapping efficiency and another for water trapping efficiency is calculated for each county-level map unit in a planning area. Then the SSURGO soil map units are mapped in a GIS to display spatial patterns of the indexes and identify priority locations for placement of buffers.

Improved Soil Survey/Digital Elevation Model–Based Indexes. The original indexes, STE and WTE, were modified by building upon the original methods with the following changes. The SSURGO soil survey was overlain with a 10 × 10 m (33 × 33 ft) grid DEM in a GIS (ArcInfo ver. 9.3.1, 2009, ESRI, Redmond, California). Soil texture, erodibility, and hydraulic conductivity were determined for each 100 m^2 (1,076 ft^2) grid cell in the DEM based on the soil map unit that occupies the center point of each grid cell. The slope of each grid cell was determined from the DEM using the Slope command in ArcInfo. The size of area that drains runoff into each grid cell (i.e., runoff source area) was determined using the Flow Accumulation command in ArcInfo.

For sediment, the original empirical equation was changed by multiplying the soil loss rate per acre ($RKLS$) for a given cell by the size of runoff source area (A [in acres]) to each grid cell and by inverting the equation. The revised empirical equation is

$$\text{Sediment Retention Factor} = ARKLS/D_{50}. \qquad (5)$$

Also, calculation of L and S was simplified by using the single equation of Moore and Wilson (1992),

$$(LS) = (A_s/22.13)^{0.4}\ (\sin \beta/0.0896)^{1.3}, \qquad (6)$$

where A_s is the specific catchment area (m^2 m^{-1}), which is the source area (m^2) per m length of contour of a grid cell (assumed to be 10 m (33 ft) when using a 10 × 10 m DEM), and β is the slope of the grid cell in degrees. The calibration equation converts a value of the Sediment Retention Factor into sediment load retained in a buffer under the original reference conditions by

$$\text{SRI} = 18.6\ (\text{Sediment Retention Factor})^{0.4333}, \qquad (7)$$

where SRI is the Sediment Retention Index (kg m^{-1} of buffer contour). The load of sediment-bound pollutants retained in a buffer is assumed to be proportional to the load of sediment retained.

The Sediment Retention Factor was calibrated directly to the load of sediment retained using the Vegetative Filter Strip

Model (VFSMOD-W Version 5) (Muñoz-Carpena and Parsons 2010). Corresponding values of the Sediment Retention Factor and the sediment retained by 1 m (3.3 ft) of buffer contour were computed for 36 combinations of rainfall amount (71 mm [2.8 in] in 24 h for R = 100 and 127 mm [5.0 in] in 24 h for R = 500), slope (2% and 12%), soil texture class (clay loam, silt loam, and sandy loam), and source area size (200, 1,000, and 2,000 m^2 [0.048, 0.24, and 0.48 ac]). All three source area scenarios had the same slope length (200 m [656 ft]) but varied in width along the contour (1, 5, and 10 m [3.3, 16.4, and 33 ft]). This approach to modeling converging flow using the VFSMOD has been successfully used by others (Helmers et al. 2005). Values for additional soil variables that are required to run the VFSMOD simulations and are keyed to the surface soil texture class were assigned according to table 2. The corresponding values were plotted and fitted with an equation (figure 1a). Several other equation forms and combinations of the current set of variables for the Sediment Retention Factor were evaluated by comparison to VFSMOD results. Equation 5 was selected because it makes sense from a conceptual standpoint, it is relatively simple to calculate, and it produced an excellent fit (r^2 = 0.99).

For water, the empirical equation conceptually describes the supply of water to a buffer and the propensity for water to infiltrate the soil. Using similar procedures as those for sediment, the empirical equation,

$$\text{Water Retention Factor} = AR^{0.5} K_{sat}, \qquad (8)$$

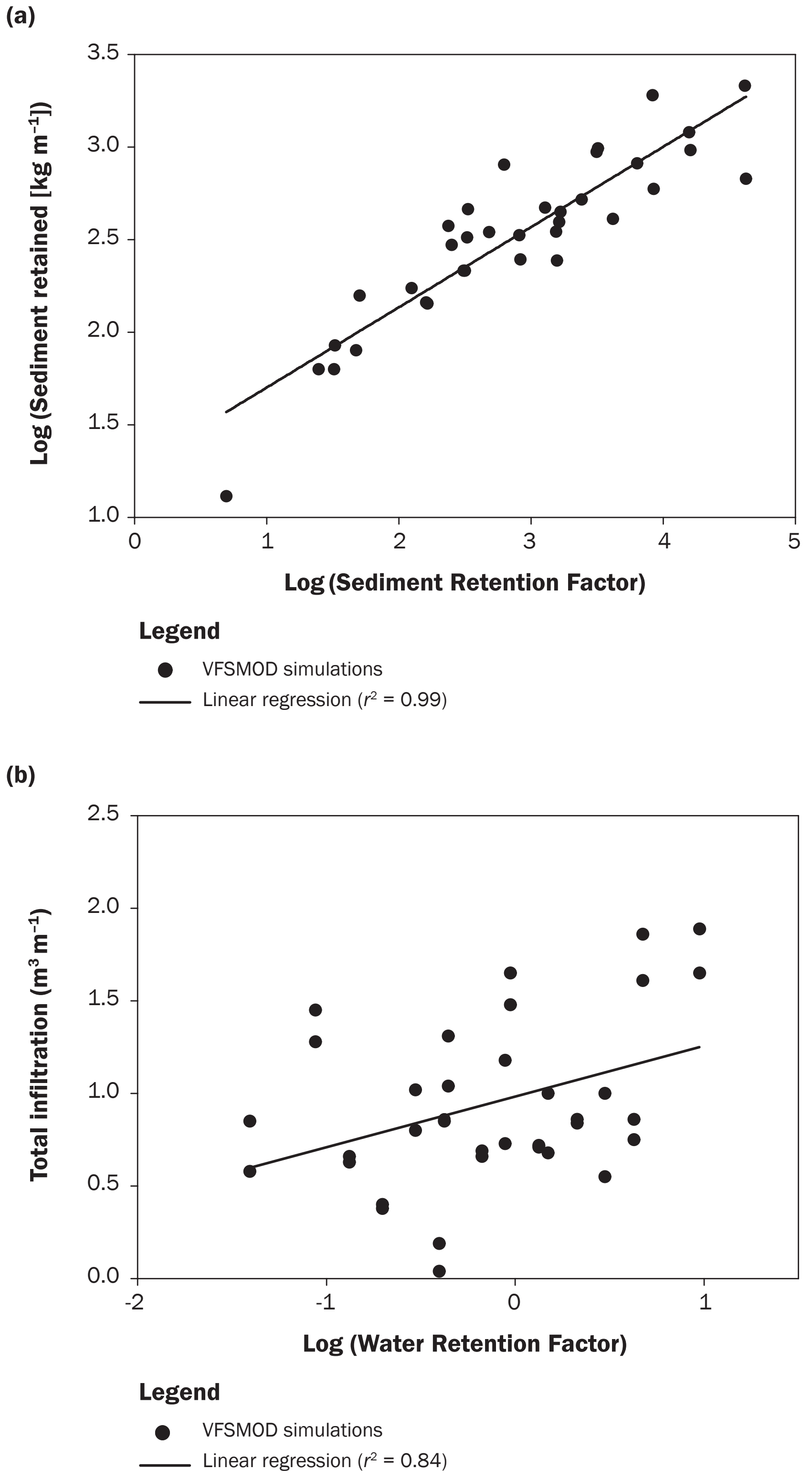
was calibrated to water volume infiltrated under the original reference conditions by

$$\text{WRI} = 0.2805\log(\text{Water Retention Factor}) + 0.9766, \qquad (9)$$

where WRI is Water Retention Index (m^3 infiltrated per m of buffer contour) (figure 1b). The load of dissolved pollutants retained by a buffer is assumed to be proportional to the volume of water infiltrated. Correlation between the empirical equation and VFSMOD results was not as strong for water retention (r^2 = 0.84) as it was for sediment retention (r^2 = 0.99). One reason for a lower correlation is that total infiltration in the buffer was very small (range = 0.04 to 1.89 m^3 m^{-1}), compared to input volume

Figure 1

Scatterplot and fitted regression line for (a) empirical Sediment Retention Factor versus Vegetative Filter Strip Model (VFSMOD)–determined sediment retained and (b) empirical Water Retention Factor versus VFSMOD–determined total infiltration, in a reference buffer under reference conditions.



(range = 2.10 to 180 $m^3\ m^{-1}$) and was fairly insensitive to magnitude of input volume.

For planning using the SRI and WRI, a single value of each index is calculated for each grid cell (100 m^2 [1,076 ft^2] when using a 10 × 10 m [33 × 33 ft] DEM). A buffer located in a cell having a higher index value would be expected to trap a greater load of a given pollutant than a cell with a lower value. Cells having higher values would be better locations to place buffers for reducing the load of pollutants in runoff to a water body. A map can be produced in the GIS to show spatial patterns of SRI and WRI and used for prioritizing locations to place buffers in a watershed.

Case Study Application of the Improved Indexes. The original and improved models were applied to the 67 km^2 (25.9 mi^2) Cameron-Grindstone watershed in Dekalb and Clinton counties in northwestern Missouri, 70 km (43 mi) north of Kansas City. The watershed is predominantly 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 (MDNR 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 (Renard et al. 1997).

Data for the SSURGO soil survey of the watershed was obtained from the USDA NRCS Soil Data Mart (USDA NRCS 2010b). A 10 × 10 m [33 × 33 ft] DEM for the watershed was obtained from the USDA NRCS Geospatial Data Gateway (USDA NRCS 2010a). Analysis of these data was performed using only the ArcInfo software. The watershed boundary was determined from the 10 × 10 m DEM using the Watershed command in ArcInfo.

All farmable soil map units in the watershed and grid cells occupying farmable map units were assessed. Farmable soil map units were identified by land capability classes 1, 2, 3, or 4 (USDA NRCS 2003) in the SSURGO database. Farmable map units correspond approximately to the range of soil and slope conditions used for developing the calibration equations. Maps were produced using the original and the improved indexes. Important aspects of spatial patterns, resolution, and utility of original and improved indexes were compared and contrasted.

Results and Discussion

Original Sediment Trapping Efficiency Index. The Cameron-Grindstone watershed contains 32 different farmable soil types (SSURGO map unit symbols). The mapped areas (polygons) containing these soil types average 18 ha (45 ac) in size with a range of 0.0002 to 630 ha (0.0004 to 1,558 ac) and a median of 6.5 ha (16 ac). Polygons that were smaller than a few hectares were produced when larger soil map polygons were truncated by the watershed boundary and do not represent the resolution of soil mapping polygons in this watershed. Of the 32 soil types in this watershed, only 20 were unique with respect to the combination of surface soil texture, average slope, and RUSLE K factor, thereby producing 20 different values of the STE Index in this watershed. The areal extent associated with each STE value shows a very uneven distribution (figure 2b). When mapped (figure 2a), the patterns identify the steep midslopes between flatter upland plateaus and alluvial valleys as having lower STE values and, according to the model, potential for a buffer to retain greater amounts of sediment. This method assumes that all locations have the same size of source area. By not accounting for differences in size of runoff source area among different locations, interpretive difficulties can occur. For example, a site at the top of a ridge or along the watershed boundary has little or no runoff source area, but it may have the same index rating as a site within the same map unit that is located lower on the slope and, consequently, would intercept substantially more runoff.

The present STE map (figure 2a) contains some differences compared to the STE map of this same watershed that appears in Dosskey et al. (2006). Those differences reflect revision of the SSURGO database between 2005 and 2010 that mainly affect land capability classification and slope range attributes for some soil map units.

Sediment Retention Index. The SRI accounts for varying sizes of runoff source areas among different locations and is directly linked to the load of sediment that could be retained by a buffer. The mapped units (figure 3a) are all 100 m^2 (1,076 ft^2), which is considerably smaller than mapped areas using the original STE Index (figure 2a). The areal extent associated with each value of SRI shows a much smoother distribution (figure 3b) than the original STE Index (figure 2b). The general spatial pattern in the map shows higher index values nearer streams where runoff water converges, and this pattern is fairly consistent across the watershed. This result illustrates the critical importance of spatial patterns of runoff flow in determining the capability of buffers to intercept pollutants and reduce pollutant loading to streams. For simplicity, we used a 10 × 10 m (33 × 33 ft) DEM and the built-in ArcInfo flow algorithms Watershed and Flow Accumulation for this analysis. These methods may provide sufficient resolution for many planning purposes, but other DEM resolutions and more sophisticated flow algorithms (Tarboton 1997) could also be used.

Index values in the study watershed range from near 0 to over 210,000. In general, higher values of SRI correspond to higher potential to trap sediment from runoff. However, vegetative buffers are appropriate only within a narrower range of SRI values. Very high values of SRI indicate very large source areas that would often produce amounts of runoff that can overtop or erode a vegetative buffer. For example, an overlay of the SRI map on an aerial photo of the watershed (figure 4) (photo downloaded from USDA NRCS 2010a) shows that very large values of SRI are associated with the locations of stream channels. Closer examination by overlaying the SRI map on a 1:24,000 stream map (USGS 2010) indicates that stream channels correspond to SRI values larger than about 3,000. Using the aerial photo, smaller channels correspond to SRI values of about 1,000 to 3,000, and grassed waterways that drain nonterraced crop fields tend to occur in locations corresponding to SRI values of 400 to 1,000. Grassed waterways indicate locations where field runoff often concentrates to the point where gully erosion would likely occur in the absence of dense grass groundcover and where a vegetative buffer may not be as effective. Based on these general empirical observations, the upper limit for the effective application of buffers appears to be at an SRI value of about 400 in this watershed (figure 3b). More rigorous and objective GIS procedures, such as sequential classification coupled with field observations, could also be used if more accurate threshold identification is desired. The SRI calibration covered the range of SRI values 37 to 1,880.

Figure 2

(a) Map showing spatial pattern of the original Sediment Trapping Efficiency Index (STE) in the 67 km^2 Cameron-Grindstone watershed in northwestern Missouri and (b) areal distribution of values of STE in the watershed.

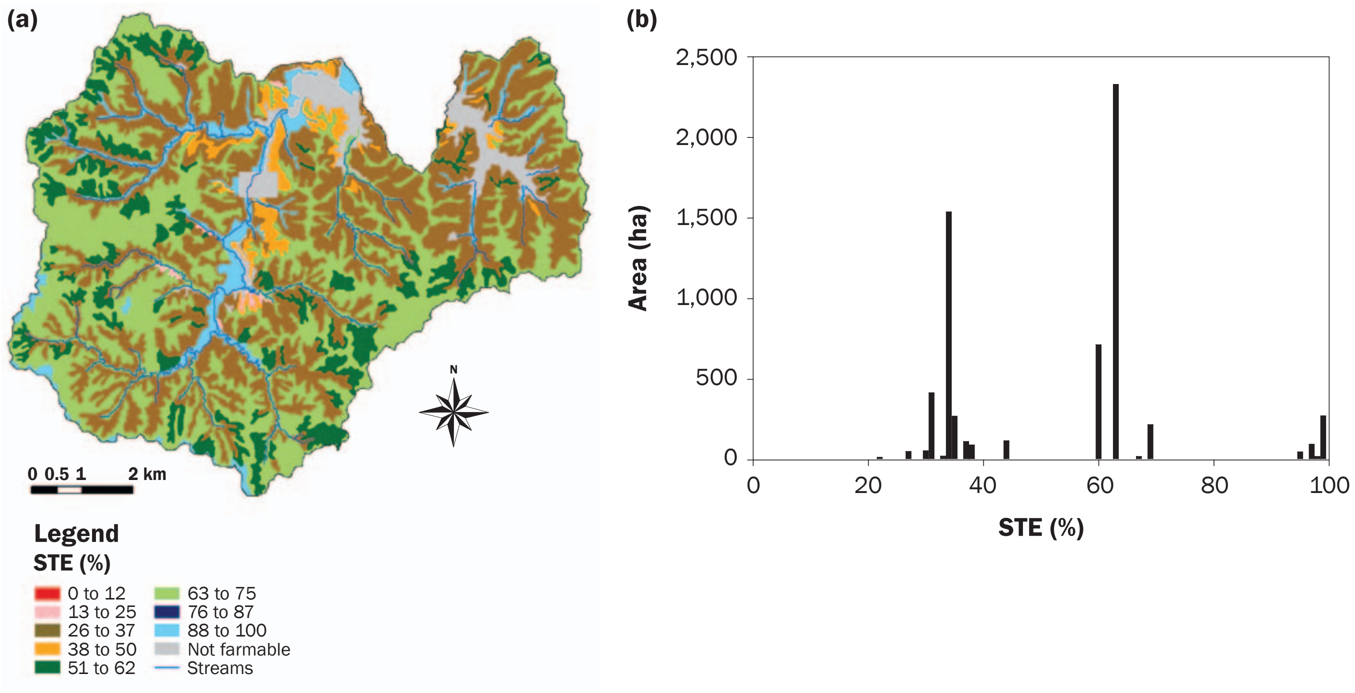


Figure 3

(a) Map showing spatial pattern of the improved Sediment Retention Index (*SRI*) in the 67 km^2 Cameron-Grindstone watershed in northwestern Missouri and (b) areal distribution of *SRI* values between 1 and 1,000. Each bar represents the number of 100 m^2 grid cells within *SRI* increments of 40. The complete *SRI* range was 0 to 210,772 in this watershed. The dashed line indicates the estimated maximum *SRI* value for sites where a vegetative buffer would be appropriate in this watershed.

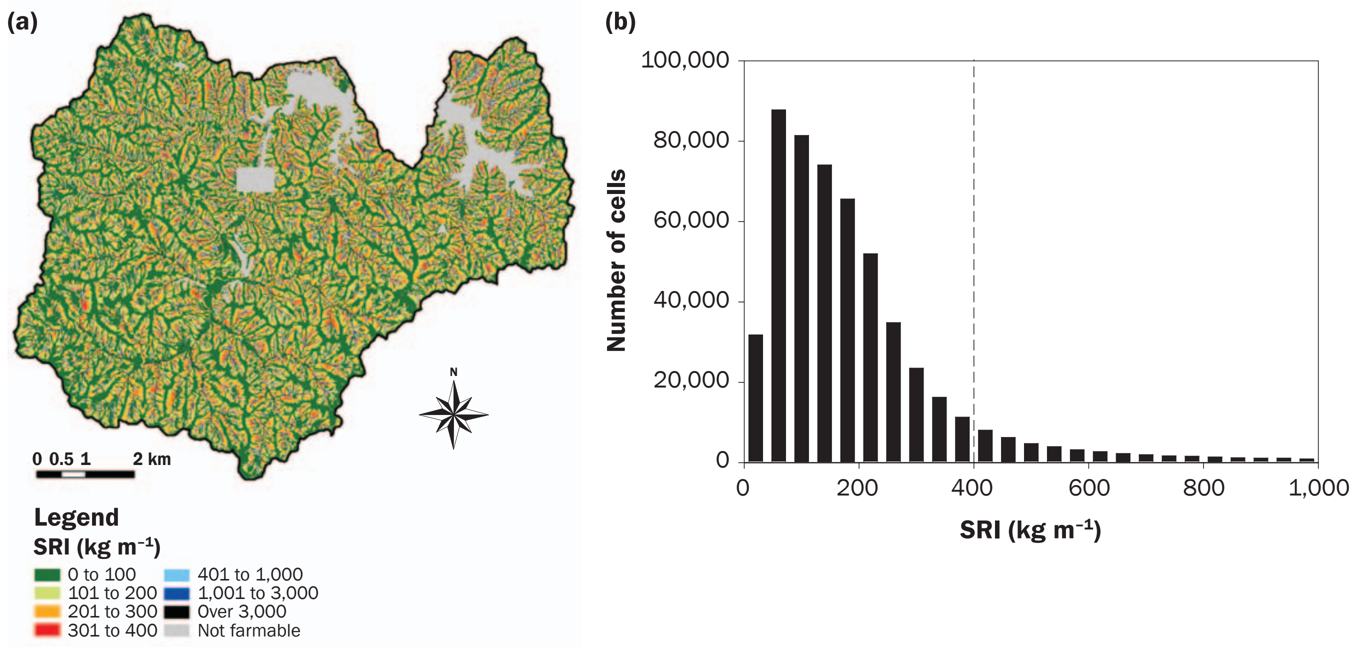
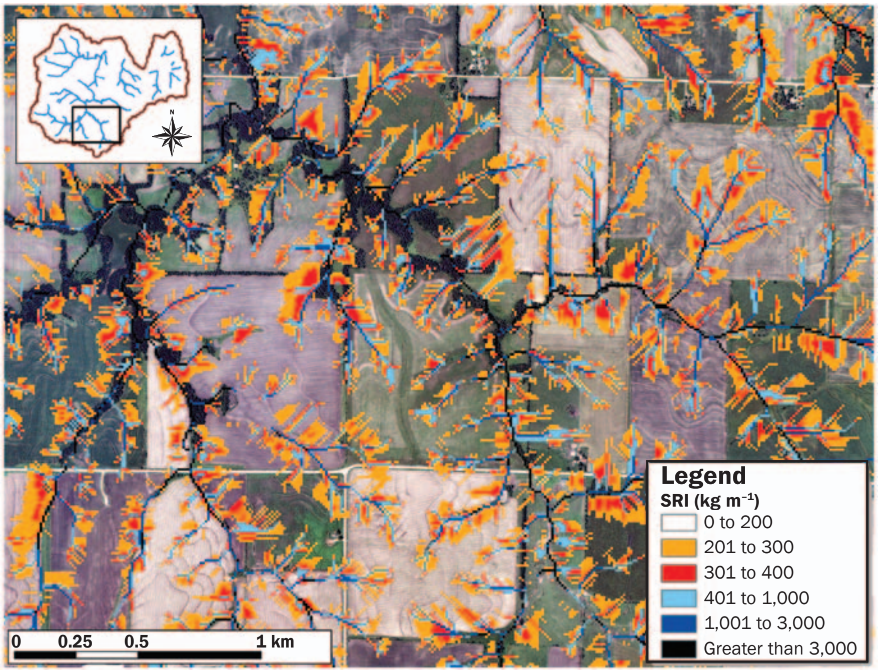


Figure 4

The Sediment Retention Index (SRI) map overlain on a 2009 aerial photo of a 6 km² (2.4 mi²) portion of the Cameron-Grindstone watershed in northwestern Missouri. Only those grid cells having SRI values greater than 200 are color coded.



For buffer planning in this watershed, sites can be prioritized for buffer installation using the SRI, beginning with cells having values of 400 and then proceeding to lower values of SRI as resources allow. For example, 6% of the farmable area in this watershed has SRI values within the range of 300 to 400. If resources allow installation of buffers on 6% of farmable land, then buffers placed in these cells would potentially prevent the greatest amount of sediment and sediment-bound pollutants from entering stream channels. If some of these cells already have vegetative buffer in them or if their up-gradient source areas are in a condition that does not generate a significant sediment load (e.g., hay, pasture, terraced fields, farmsteads), then priority should be assigned to sites having the next lower value of SRI and which have high sediment-generating source areas. This stepwise assignment of priority would be necessary in the study watershed because field terracing is a common erosion and sediment control practice. Since SRI was calibrated for contour-tilled crop fields (without other erosion control practices), prioritization using SRI will work best among sites having up-gradient land in this condition. The SRI–based prioritization can also be used as a relative comparison among sites having other, but similar, source area conditions. However, for comparing sites having contrasting land uses, the SRI will not be very useful as it is. Some adjustment of SRI could be made, perhaps through adjustments in the soil loss portion (numerator) of the Sediment Retention Factor equation (equation 5) for which the calibration step assumed the USLE C and P factors to be 0.5 and 1.0, respectively. However, the reliability of such an adjustment is uncertain since different land uses produce different relationships between runoff volume and sediment generation that would also affect deposition in a buffer. Finally, the upper SRI threshold for prioritization may need to be determined separately for each watershed planning area.

Prioritization based on SRI may require additional adjustment, depending on how accurately the DEM can describe true spatial patterns of surface runoff. Terraces, berms, drainage ditches, and other kinds of land-shaping can alter runoff patterns and source area sizes from those indicated from DEM data. In general, accuracy will decline for coarser-resolution DEMs and for those based on older topographic data. Site visits and/or analysis of recent aerial photos should be used to determine how well a given DEM represents the actual land surface. Because of limitations in the accuracy of DEM and SSURGO data combined with simplifying assumptions employed in the index models, the SRI is best used as a general scoping tool to guide planners to locations within watersheds that are likely to yield greater sediment retention using vegetative buffers. The planner would then use a field-scale tool to determine appropriate designs for vegetative buffers at those locations.

Original Water Trapping Efficiency Index. The study watershed contains 10 soil types that are unique with respect to the combination of surface soil texture, average slope, and soil hydraulic conductivity, thereby producing 10 different values of the WTE Index in this watershed. Similar to the STE Index, the areal extent associated with each WTE value shows a very uneven distribution (figure 5b). When mapped (figure 5a), the spatial patterns identify alluvial valleys and upland plateaus having higher WTE values and, according to the model, potential for a buffer to retain water and dissolved pollutants with greater efficiency (percent of input load retained). The WTE Index does not account for variation in size of runoff source area, which poses the same interpretive difficulties as described for the STE Index. A site at the top of a ridge or along the watershed boundary has little or no runoff source area, but it will have the same index rating as a site within the same map unit that is located lower on the slope, which would have a larger source area and, consequently, would intercept substantially more runoff. Also like STE, the present WTE map (figure 5a) contains some differences compared to the map published in Dosskey et al. (2006) due to revision of the SSURGO database between 2005 and 2010.

Water Retention Index. The WRI accounts for varying sizes of runoff source areas among different locations, is directly linked to the volume of water that could be retained by a buffer, and is mapped at a spatial resolution of 100 m² (1,076 ft²), which is considerably smaller than mapped areas using the original WTE Index (figure 6a). The areal extent associated with each value of WRI shows a much smoother distribution (figure 6b) than the original WTE Index. Threshold estimation for the WRI using the same procedures as for the SRI indicated that the upper limit for application of vegetative

Figure 5

(a) Map showing spatial pattern of the original Water Trapping Efficiency Index (WTE) in the 67 km² Cameron-Grindstone watershed in northwestern Missouri and (b) areal distribution of values of WTE in the watershed.

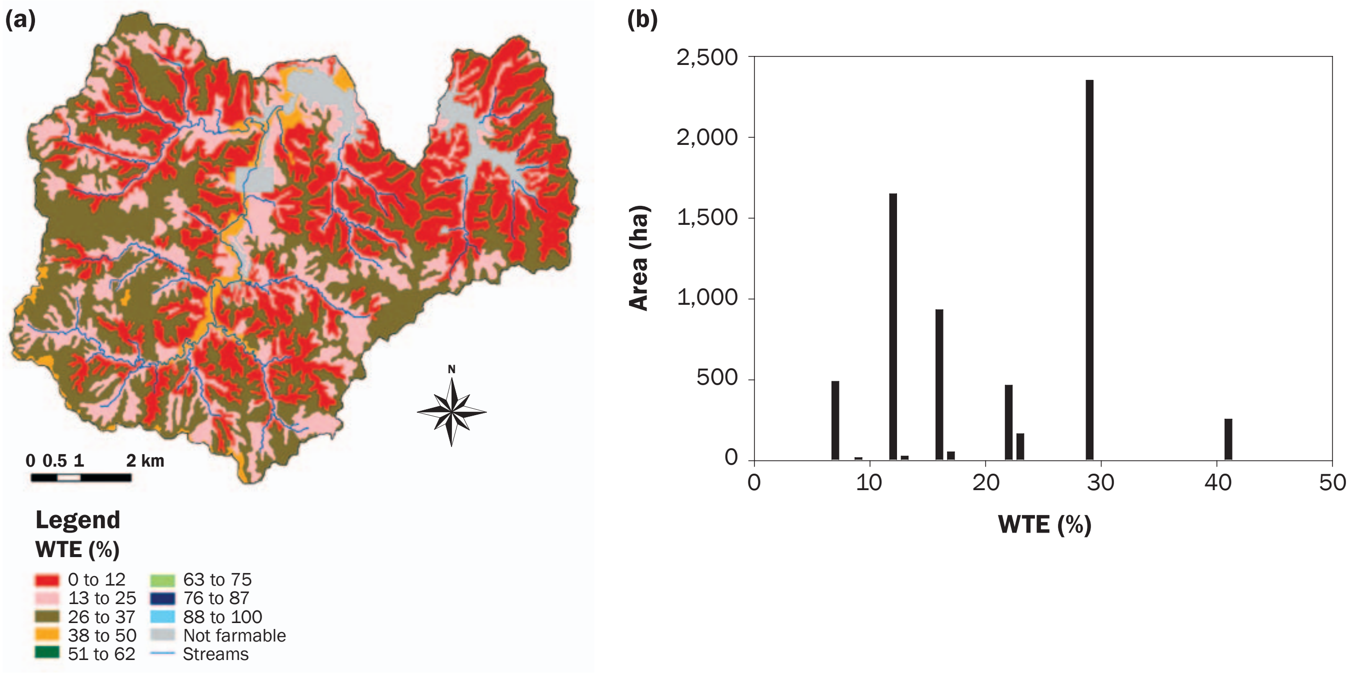


Figure 6

(a) Map showing spatial pattern of the Water Retention Index (WRI) in the 67 km² Cameron-Grindstone watershed in northwestern Missouri and (b) areal distribution of values of WRI between 0.5 and 2.4 in the watershed. Each bar represents the number of 100 m² grid cells within WRI increments of one-tenth. The dashed line indicates the estimated maximum value for sites where a vegetative buffer would be appropriate in this watershed.

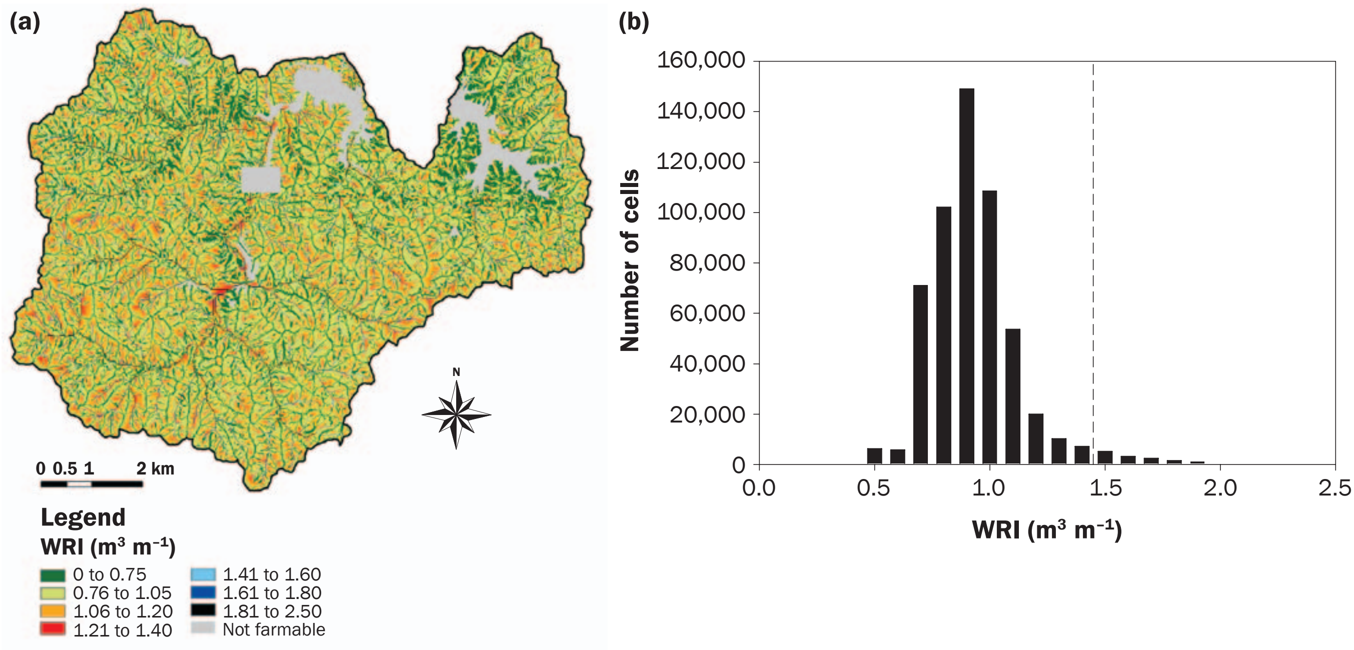
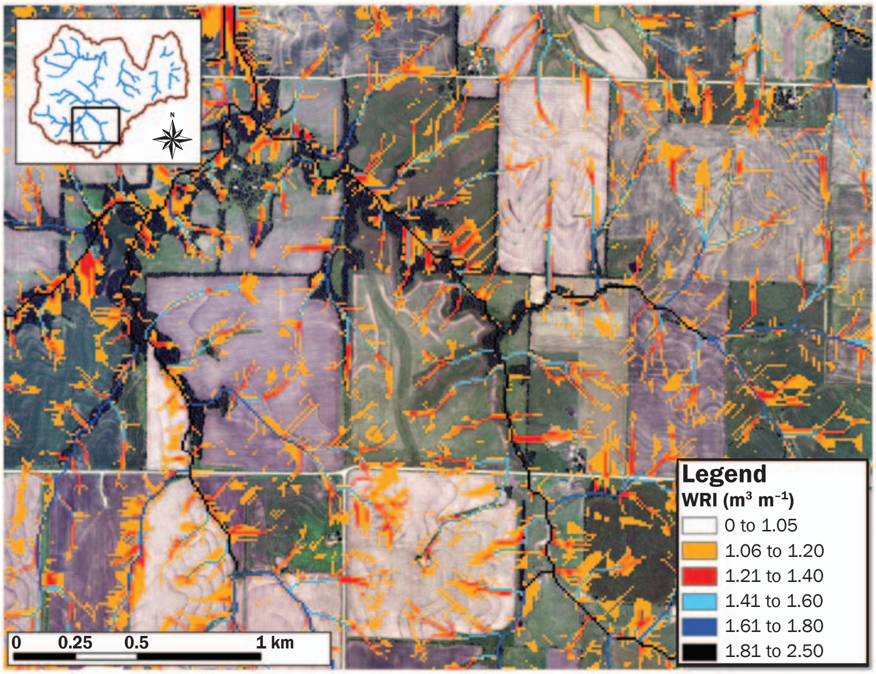


Figure 7

The WRI map overlain on a 2009 aerial photo of a 6 km² portion of the Cameron-Grindstone watershed in northwestern Missouri. Only those grid cells having WRI values greater than 1.05 are color coded.



buffers in this watershed is about 1.4 (figures 6b and 7). The watershed map (figure 6a) indicates that more cells in the range of 1.1 to 1.4 occur in the southern half of the watershed. A WRI range of 1.2 to 1.4 encompasses 5% of the farmable land in the watershed. Values of WRI that are larger than about 1.4 correlate visually with locations of stream channels and grassed waterways.

The utility of the WRI, however, is questionable. Modeled water retention by the reference buffer was consistently much lower than, and was not correlated with, the modeled water input volume. Water infiltration ranged from 0.04 to 1.89 $m^3\ m^{-1}$ (0.4 to 20.3 $ft^3\ ft^{-1}$), while input volume ranged from 2.95 to 181 $m^3\ m^{-1}$ (31.7 to 1,948 $ft^3\ ft^{-1}$), and their correlation was almost nonexistent (linear regression $r^2 = 0.01$). For comparison, rainfall onto the reference buffer was 0.85 $m^3\ m^{-1}$ (9.2 $ft^3\ ft^{-1}$) (for 71 mm [2.8 in] rainfall) or 1.52 $m^3\ m^{-1}$ (16.4 $ft^3\ ft^{-1}$) (for 127 mm [5.0 in] rainfall). These results indicate that there is very limited capacity for a buffer to infiltrate additional water from source area runoff under the reference rainfall conditions. Consequently, infiltration was insensitive to the size of runoff source area (linear regression $r^2 = 0.02$). Additional runoff from larger source areas simply passes through the buffer. As a result, the WRI may show areas of larger or smaller values (figure 7), but the reliability of those differences are questionable, and the differences may be too small to be of practical significance for discriminating sites on the basis of retaining dissolved pollutants in surface runoff.

Water Inflow Index. An alternative approach for dissolved pollutants would be to identify locations based on high runoff volume from source areas (i.e., water inflow to a buffer) rather than on infiltration within a buffer. This information could be used to locate other conservation measures, like treatment wetlands to intercept dissolved pollutants and field management practices that reduce the dissolved pollutant load generated in runoff.

An index was developed to gauge runoff volume using the same methods used for SRI and WRI. The empirical equation,

$$\text{Water Inflow Factor} = AR/K_{sat}^{0.5}, \qquad (10)$$

was calibrated to water inflow volume under the original reference conditions by

$$\text{WII} = 0.81\ (\text{Water Inflow Factor})^{0.8076}, \qquad (11)$$

where WII is the Water Inflow Index ($m^3\ m^{-1}$ of contour). The WII correlates strongly with the modeled volume of water ($r^2 = 0.997$) (figure 8). This index should provide a more robust spatially explicit tool for mapping variation in surface runoff than using source area alone (e.g., the Flow Accumulation function in ArcInfo) because the WII also accounts for how soil type modifies the volume of runoff from source areas, and the index is calibrated directly into volume of water. Threshold values of the WII could be used to help identify effective locations for various conservation treatments for controlling dissolved pollutants whose applications and designs are dependent of the amount of overland flow. For example, threshold WII values for the study watershed were estimated using the same empirical methods as were used for SRI and WRI. Streams were associated with values greater than 1,500, and grassed waterways were associated with values between 400 and 1,500 (figure 9). Treatment wetlands might be appropriate in locations having WII values over 400, where significant but not excessive flow convergence occurs, while field management options may be more appropriate in the runoff source areas of cells having values smaller than 400 in this watershed.

Summary and Conclusions

Two index models, SRI and WRI, were developed that utilize soil surveys and DEMs to compare different locations on the basis of how much pollutant load could be retained by a vegetative buffer from Hortonian- or infiltration-excess–driven agricultural runoff. The indexes can be used as scoping tools to guide planners to locations within watersheds where installation of vegetative buffers would yield greater reduction in pollutant loading to streams.

The indexes represent an improvement over earlier versions, STE and WTE, by accounting for variable size in runoff source area, by providing finer spatial resolution, and by directly gauging the load of pollutants that would be retained in a buffer. Reliability of the SRI is supported by a strong correlation with results using the process-based VFSMOD ($r^2 = 0.99$) for a wide range of soil, site, and climate conditions. Reliability of the WRI for gauging infiltration of dissolved pollutants is not as strong as for the SRI ($r^2 = 0.84$), and infiltration is very small

Figure 8

Scatterplot and fitted regression line of the empirical Water Inflow Factor versus the Vegetative Filter Strip Model (VFSMOD)–determined total water input to a reference buffer under reference conditions.

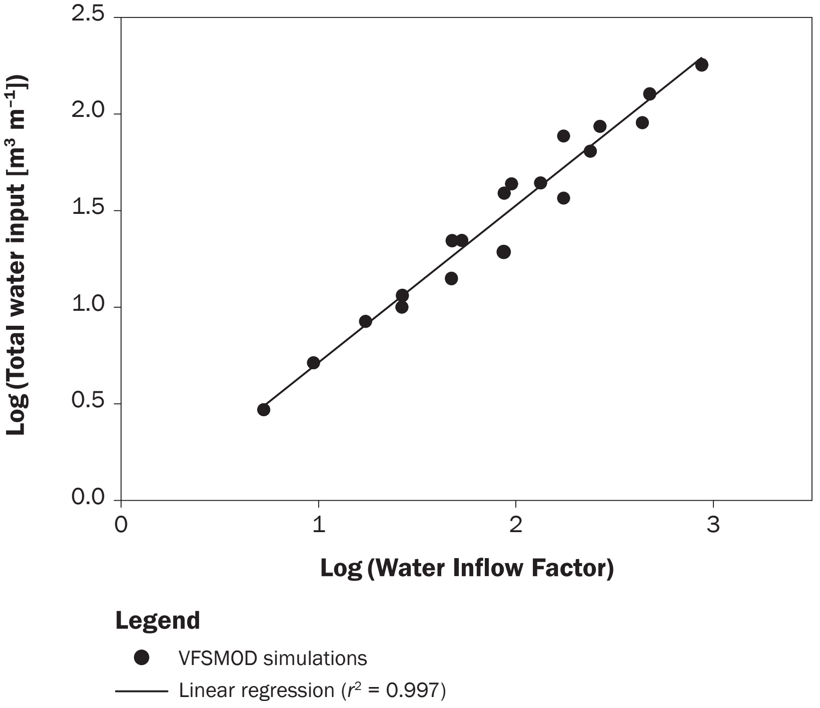
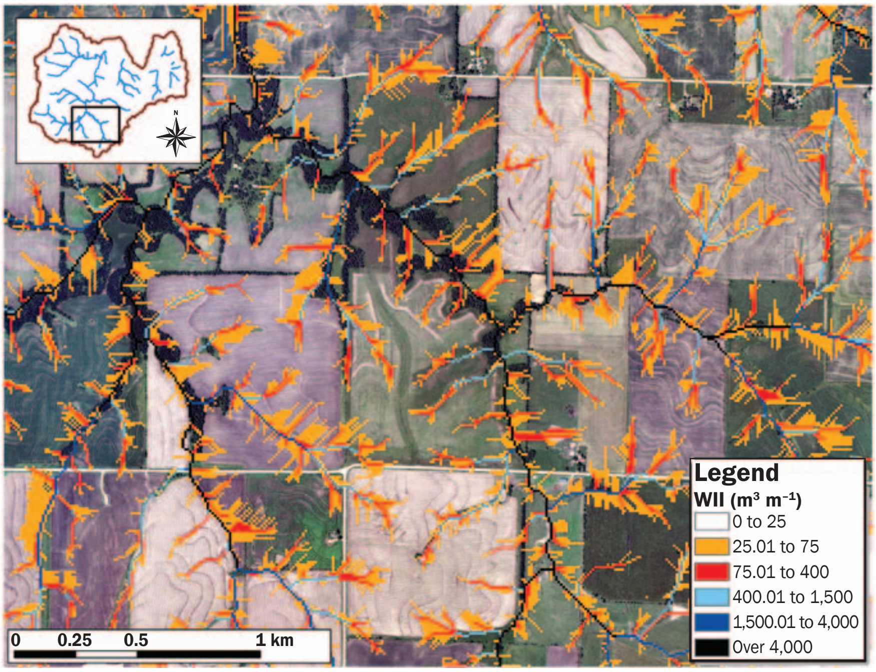


Figure 9

The Water Inflow Index (WII) map overlain on a 2009 aerial photo of a 6 km² portion of the Cameron-Grindstone watershed in northwestern Missouri. Only those grid cells having WII values greater than 25 are color coded.



compared to total runoff volume from large source areas and a large storm event. The simpler WII, which gauges only the volume of runoff water generated by source areas (r^2 = 0.997), may be more useful than the WRI for planning to reduce load of dissolved pollutants by identifying source areas where practices could be employed to reduce the generation of dissolved pollutants in runoff.

These improved indexes represent standardized bases for comparing different sites that vary in slope, soil conditions, and source area size. The indexes are easy to use because the variables are easily determined from soil surveys and DEMs, they are simple to calculate, they make sense from a functional standpoint, and the assessment process utilizes publically available data and common GIS software.

A demonstration of the models and analysis on a 67 km² (25.9 mi²) agricultural watershed in northwestern Missouri showed that buffer capability can differ substantially from one location to another in a watershed. The size of runoff source areas, determined by topography, is a critical variable in identifying better locations for installing vegetative buffers. Differences in buffering capability can be estimated and mapped using soil surveys and DEMs in a GIS. The index values, with field checking and adjustments as recommended, can provide a gauge for comparing how well a buffer could perform in different locations. It remains to be determined, however, how much the use of these targeting indexes can improve watershed water quality and the cost-effectiveness of buffer programs.

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