DESIGNING VARIABLE-WIDTH FILTER STRIPS USING GIS AND TERRAIN ANALYSIS

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ABSTRACT

Filter strips are a widely-used practice for reducing the load of pollutants that leave agricultural fields in overland runoff. They are typically designed to intercept uniformly-distributed overland runoff with a constant width strip along a field margin. Non-uniform runoff flow, however, can reduce the effectiveness of a constant-width filter strip. In these situations, filter strip effectiveness can be improved by placing more filter area where the runoff load is greater and less where the load is smaller. To do this, quantitative relationships were developed between the pollutant trapping efficiency and the ratio of filter strip area to upslope contributing area, i.e., buffer area ratio, using the Vegetative Filter Strip Model VFSMOD. These relationships can be used to size each portion of a filter strip according to the size of the runoff load to that location. Terrain analysis and GIS are well-suited for automating this approach. Contributing area can be easily calculated for each portion of the field margin and, when coupled with additional information on soil and slope, an appropriate filter area can be determined for that portion. The process is repeated for each segment along the entire field margin and produces a variable-width filter strip that matches the non-uniform pattern of runoff load to that margin. This process is demonstrated on a 36 ha crop field in Shelby Co., Kentucky for which filter strips were designed to retain 95% of the sediment in runoff. Field margins were divided into 4 m segments to match the grid resolution of the Digital Elevation Model. Maps were created that show the field and the associated filter strip design which facilitates field layout. This procedure can greatly improve the fit between filter size and runoff load and achieve greater water quality benefit per hectare of installation.

Keywords: Conservation planning, Digital Elevation Model, Non-point pollution, Precision conservation, Vegetative buffer, Water quality

INTRODUCTION

Filter strips (Code 393, USDA 1997) are installed along margins of crop fields for improving and protecting water quality in agricultural watersheds. Filter strips reduce the load of sediment, nutrients, and other pollutants in overland runoff from fields to waterways by promoting infiltration and sediment deposition. Typically, they are designed to have a constant width (in the direction of water flow) along a field margin and maximum effectiveness is achieved when field runoff is uniformly dispersed across the entire filter strip (USDA, 1997). Several methods have been developed for determining an appropriate width for a filter strip treating spatially-uniform runoff (see review in Dosskey et al., 2008).

In many situations, however, overland runoff converges and moves as concentrated flow across only portions of a field margin (Dillaha et al., 1986, 1989; Fabis et al., 1993; Dosskey et al., 2002). A constant-width filter strip is less effective if overland flow is non-uniform than if the flow is uniform (Dickey and Vanderholm, 1981; Dillaha et al., 1988, 1989; Daniels and Gilliam, 1996; Dosskey et al., 2002). Trapping efficiency is reduced because the strip is too narrow at locations receiving greater runoff loads. Cost-effectiveness is reduced because filter strip has been installed in locations that receive little or no runoff and contribute little to reducing runoff load from the field as a whole. A better design would be a filter strip that is wider where the runoff load is greater and narrower where the runoff load is smaller, thereby forming a variable-width filter strip (Dosskey et al., 2005).

A design method has been developed recently for sizing filter strips in landscapes where overland runoff is non-uniform (Dosskey et al., in press). This method sizes different segments of a filter strip in proportion to the size of the upslope contributing area that drains to each of them. Contributing area is a surrogate for size of the runoff load. By this method, the filter strip is designed to have a constant buffer area ratio rather than a constant width. The basic method is intended for use without the aid of a computer and associated technology, but it can be a laborious task to size a large number of individual segments in a long filter strip. The task could be significantly streamlined by coupling the basic method to computer-aided terrain analysis through a GIS so that contributing areas and filter sizes could be determined quickly and remotely. Such a technology enhancement of the basic method would facilitate the design and implementation of cost-effective filter strips in landscapes where runoff is non-uniform.

The objective of this study was to develop a technique for applying the buffer area ratio model using computer-aided terrain analysis, and to demonstrate its use for designing a filter strip along a field margin where overland runoff is non-uniform.

METHODS

Method for Sizing Filter Strips Using Area Ratio

The basic design model (Dosskey et al., in press) guides the user to select a buffer area ratio that will achieve a desired level of trapping efficiency for a given set of field conditions: slope, soil texture, tillage and residue cover, and the type of pollutant to be controlled. For this study, we focused on sediment. Briefly, the model is a simplification of the process-based Vegetative Filter Strip Model (VFSMOD v.1.04; Muñoz-Carpena and Parsons, 2000, 2005). Repeated simulations were run to quantify the relationship between trapping efficiency (for sediment and for water) and buffer area ratio for a grass filter strip receiving overland runoff from a crop field during a large spring rainfall event (61 mm in 1 hr). The simulations included many different combinations of soil texture, slope, and field cover condition (USLE C factor at seedbed stage), factors which are well-known to significantly affect runoff loads from fields and trapping capabilities of filter strips (Dosskey, 2001; Helmers et al., 2002). The results for each scenario were fit to an equation by non-linear regression. Seven of those regression lines were selected that illustrate the range of possible relationships between trapping efficiency and buffer area ratio (Fig. 1; Table 1). Then rules were developed for estimating which of these seven relationships would be most appropriate for any given combination of soil texture, slope, and field cover condition. For applications to non-sediment pollutants and details of the model development, refer to Dosskey et al. (in press).

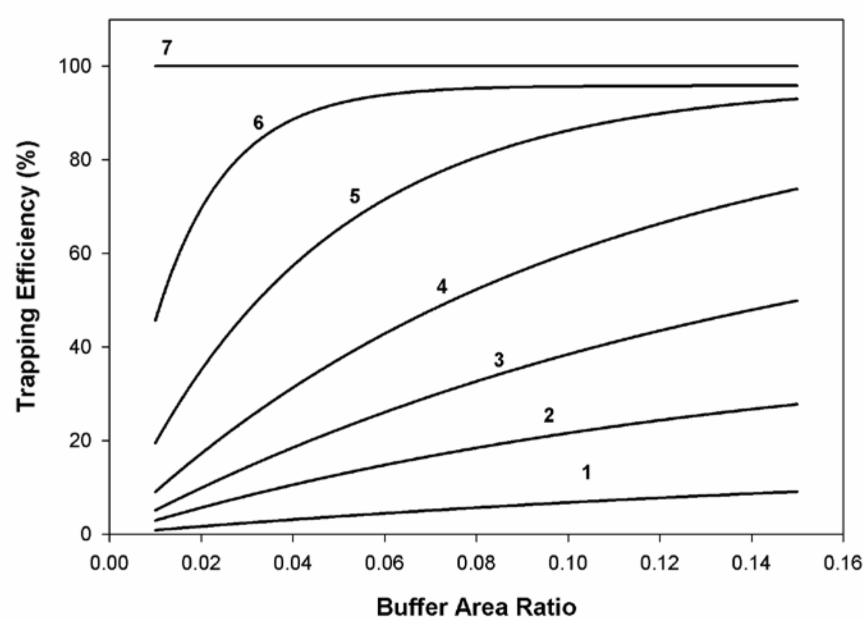

Fig 1. Relationships between pollutant trapping efficiency and buffer area ratio for seven different site conditions. The specific conditions represented by each line are listed in Table 1.

Table 1. Simulation conditions corresponding to each line in Fig. 1. Values for C factor are for the seedbed stage.

Line Number	Pollutant Type	Slope (%)	Soil Texture Class	USLE C Factor
7	Sediment	2	FSL	0.50
6	Sediment	2	SiCL	0.15
5	Sediment	2	SiCL	0.50
4	Water	2	FSL	0.50
3	Water	10	FSL	0.50
2	Sediment	10	SiCL	0.50
1	Water	10	SiCL	0.50

There are two steps for determining which line in Fig. 1 to use for a given segment of field margin. First, select an initial reference line, preferably one for which the conditions shown in Table 1 are most similar to actual site conditions. Then, adjust to a different line depending on differences between the reference line conditions and the actual site conditions according to rules in Table 2. An example of the line selection process is illustrated in Table 3. Using the final selected line, determine the buffer area ratio that will achieve the desired trapping efficiency. Then, multiply that ratio by the size of the contributing area to determine the appropriate size for the filter strip area along that segment of field margin. Contributing area can be determined visually in the field as described by Dosskey et al. (2002). This process is repeated for each segment of field margin where filter strip is to be installed.

Table 2. Rules for sediment for adjusting from an initial reference line in Fig. 1 to a line representing the actual filed site based on how much the actual field site conditions differ from the reference simulation conditions. Three broad soil texture categories are recognized: Coarse (sandy loam, sandy clay loam, fine sandy loam), Medium (very fine sandy loam, loam, and silt loam), and Fine (clay loam, silty clay loam, silt).

Variable	Adjustment Rule
Slope	1 line higher (+1) for each 2.5% lesser slope 1 line lower (-1) for each 2.5% greater slope
Soil Texture	1 line higher (+1) for each category coarser 1 line lower (-1) for each category finer
C Factor	1 line higher (+1) for each 0.35 lower C factor 1 line lower (-1) for each 0.35 higher C factor

Table 3. Example of the two-step line selection process. In this case, line number 5 in Fig. 1 is used as the initial reference line, and after applying the adjustment rules in Table 2, line 4 was selected as the best relationship to use for filter strip design on this site.

Variable	Reference Line Conditions	Actual Site Conditions	Adjustment Rule	Final Selected Line
Slope	2%	7%	-2	
Soil Texture	SiCL	Loam	+1	
C Factor	0.50	0.50	0	
Pollutant Type	Sediment	Sediment	0	
	Line Number 5		Total Adjustments -1	Line Number 4

Coupling the Sizing Model to Terrain Analysis in a GIS

Terrain analysis and GIS can greatly facilitate the design process. A high degree of variation in runoff along a field margin may dictate dividing the field margin into numerous segments. Terrain analysis and GIS using computers and digital data sources can speed the design process as well as provide an objective methodology for acquiring input data to the model.

Terrain analysis is used to divide a field margin into many segments of equal length (i.e., grid cells) and to determine the size, slope, and soil texture of the contributing area to each individual segment. Size and slope is determined using a digital elevation model (DEM) and soil texture is determined using a digital SSURGO soil survey. The C factor at seedbed stage is estimated from general information about crop type and tillage system used in the field (e.g., Wischmeier and Smith, 1978). Soil texture class and C factor are typically constant for a given field, while size and slope of contributing areas can vary substantially. A computer subroutine automates the rules for selecting the appropriate equation (line in Fig. 1, equation in Table 4) for each segment and calculating the filter strip size required that will achieve the target trapping efficiency. Filter strip size is converted to numbers of up-gradient grid cells that must contain filter strip. After this is done, the margin of the entire filter strip can be displayed in the GIS that, when overlaid on an aerial photo, can be used to layout the location of leading edge of the filter strip in the field.

Table 4. Regression equations for the seven design lines shown in Fig. 1, where "y" is trapping efficiency in percent, and "x" is the ratio of filter strip area to contributing area.

Line Number	Equation $y = A(1 - e^{-Bx})$	
	A	B
7	100	∞
6	95.82	64.80
5	96.23	22.66
4	95.01	9.99
3	78.77	6.69
2	41.85	7.25
1	17.52	4.85

Case Study

This study was conducted on a 36 ha field in Shelby County, Kentucky. The field has been in a corn, wheat, and double-crop soybean or corn-soybean rotation for more than 20 yr. In this region, rolling topography is covered by soils that are developed primarily from limestone residuum overlain with pedisediment from limestone-weathered materials and loess (SCS, 1980). Topographic undulations and swales in crop fields are common and result in concentrated runoff flow (Pike et al., 2009).

Surface textures for all soils were silt loams according to the USDA SURGO data. The C factor was estimated to be 0.15 based on seedbed stage of no-till corn after soybean (Wischmeier and Smith, 1978).

To determine the average slope of upslope areas, level-2 10-m USGS digital elevation models (DEMs) were obtained on-line from http://seamless.usgs.gov/ for a 2810 ha area (10.9 mi^2) surrounding the field. The DEMs were smoothed by first creating a 1-m contour with ArcGIS (ESRI, Redlands, CA). Then the contours were reinterpolated to a 4- by 4-m grid with the TopoToRaster command. Next, slope (%) and flow direction (D8 method) were calculated. The Flow Accumulation ArcGIS command was run with the slope grid used as the weight matrix. Then this command was run a second time but no weighting grid was used. The output from the first Flow Accumulation procedure was divided by the output from the second in order to calculate average slope of the upslope grid cells for each 4 by 4-m cell in the DEM. In order for slope adjustments to be made with the rule indicated in Table 2, slope classes were created with the following ranges: $0 \leq SC_{2.0} < 2.25$, $2.25 \leq SC_{4.5} < 5.75$, $5.75 \leq SC_{7.0} < 8.25$, $8.25 \leq SC_{9.5} < 10.75$, $10.75 \leq SC_{12.0} \leq 13.25$, and $13.25 \leq SC_{14.5} < 15.75$. Flow direction (D∞ method), specific catchment area, and stream networks were calculated using TauDEM (Utah State University, Logan, UT; Tarboten, 1997).

Line selection calculations are shown in Table 5 and the different line numbers used for each of six slope classes were indicated. The equation for the curves (Table 4) were rearranged to solve to solve for "x" (i.e., the ratio of filter strip area to contributing area) using an arbitrarily defined trapping efficiency of

95%. To determine the buffer area requirements, the adjusted contributing area values (i.e., specific catchment area calculated with TauDEM) were multiplied by the buffer area ratios for each slope class. Standard grid GIS analysis techniques were used to identify areas on either side of streams. The area along the road on the east side of the field was manually digitized. The buffer area requirements were determined for the areas to the sides of the streams and along the side of the road.

Table 5. Line number selections for the Shelby Co. example site. In this case line number 5 in Fig. 1 was used as the initial reference line. After applying the adjustment rules in Table 2, line numbers 2 through 7 were selected depending on the average slope of the upslope area.

Variable	**Reference Line Conditions**	**Actual Site Conditions**	**Adjustment Rule**	**Final Selected Line**
Slope	2%	2.0, 4.5, 7.0, 9.5, 12.0, and 14.5 %	0, -1, -2, -3, -4, - 5	
Soil Texture	SiCL	SL	+1	
C Factor	0.50	0.15	+1	
Pollutant Type	Sediment	Sediment	0	
	Line Number 5		Total Adjustments +2, +1, 0, -1, -2, and -3	Line Numbers 7, 6, 5, 4, 3, and 2

RESULTS AND DISCUSSION

Filter strip width requirement classes are shown in Fig. 1 for the study site along the margins of the streams and along the side of the road. Conservation professionals could use a map such as this to help determine the appropriate size of filter strip required to reduce sediment delivery by a desired percentage, 95% in this case. For this example, only four filter strip class widths were used (FS1-FS4) because a larger number of classes could be cumbersome for conservation planners to use and interpret in the field. The largest class (i.e., FS4) includes all values > 25 because there will likely be upper limits on the size of filter strips that land owners are willing to use and for which the USDA would provide conservation funds.

Accurate knowledge of the tillage system in practice is essential for determining the correct C factor. Although the study field is in no-till production, some of the surrounding fields are intensively tilled (Fig. 1). We do not know of any existing spatial databases that provide tillage information on a field-by-field basis or a state-wide or nationwide-basis. One way to address this problem would for the planner to first talk to the farmer to determine the tillage practices are that

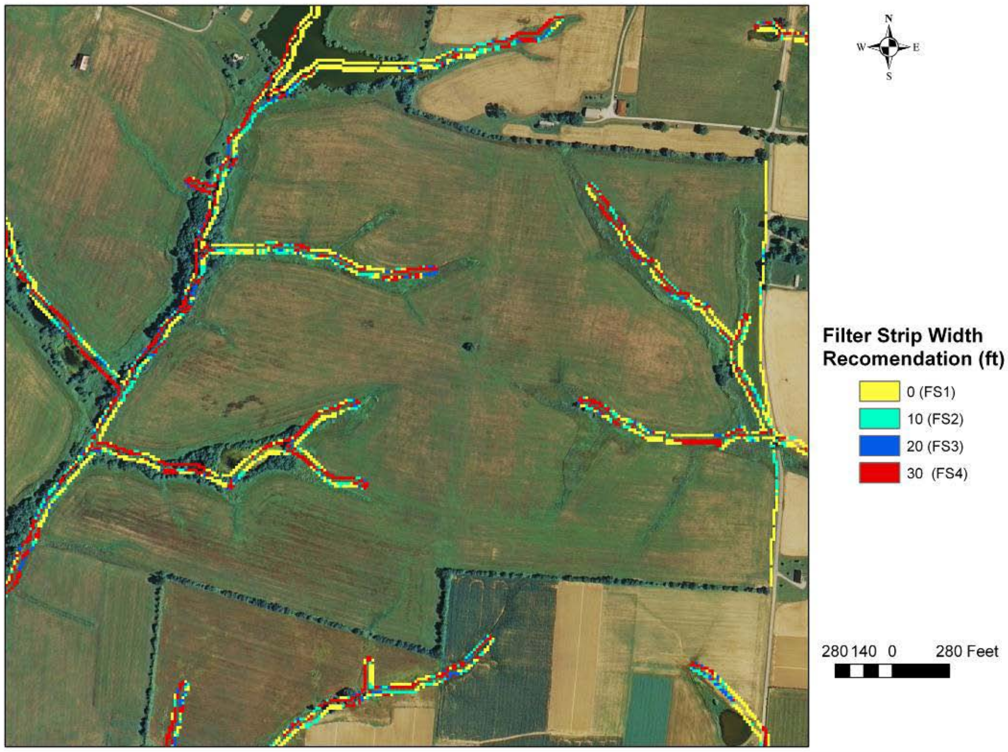

Fig. 1. Filter strips widths required to stop 95% of sediment loading in the northeastern region of the field. The filter strip classes were defined in a way that would make them easy to use by conservation planners in the field. The specific ranges for these categories are given in US feet: $0 \leq FS1 \leq 5$, $5 < FS2 \leq 15$, $15 < FS3 \leq 25$, $FS4 > 25$.

are currently being used. Mapping software could be designed that would allow the planners to enter the tillage information so the appropriate buffers could be calculated and printed.

The zoomed-in image (Fig. 2) provides an example that shows how the filter strip width maps did not exactly match the waterway structures apparent in the image. This occurred partly because the stream delineation parameters require further adjustment. The buffer width maps also appear to be slightly offset likely because of errors in the level-2 10-m DEMs. Specifically, the maximum allowable error for level 2 DEMs is one half the contour width of the USGS topographic map from which they were derived (USGS, 2009). Half the contour width would be equivalent to 152-cm for the field in this paper and for many other Kentucky fields in grain crop production. Slightly offset buffer width maps would not have serious negative consequences for conservation planners who could easily make adjustments in the field. However, the potential impact of DEM errors on the accuracy of the buffer width requirements could have more

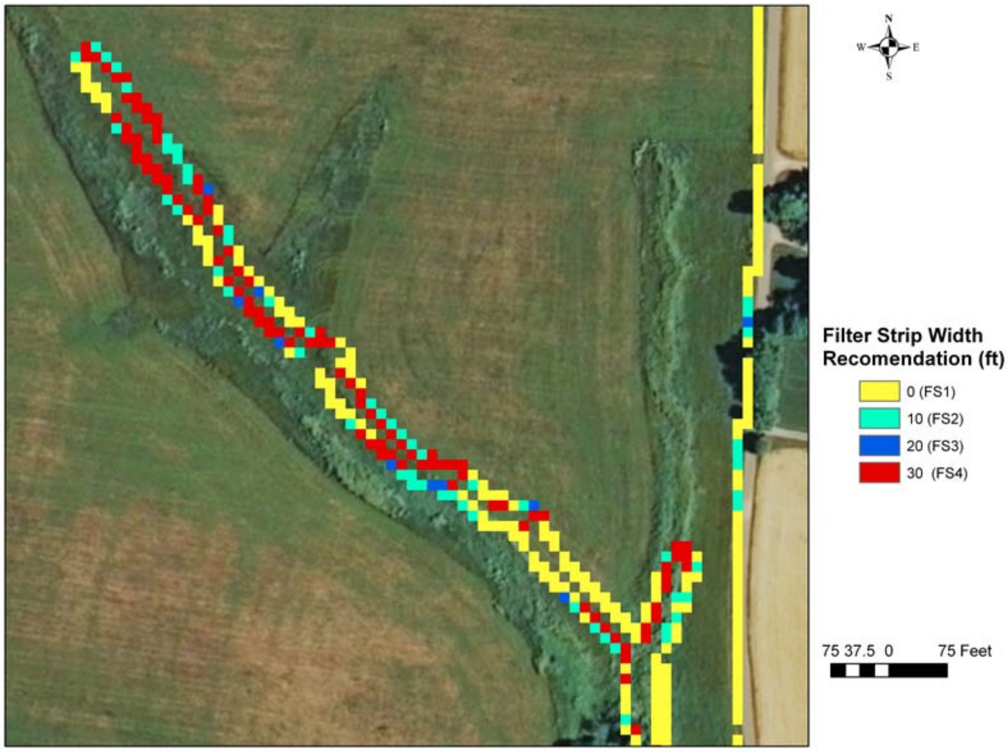

Fig. 2. Map indicating the width of filter strips required to stop 95% of sediment loading for the northeastern region of the field. The class descriptions can be found in the caption of Fig. 1.

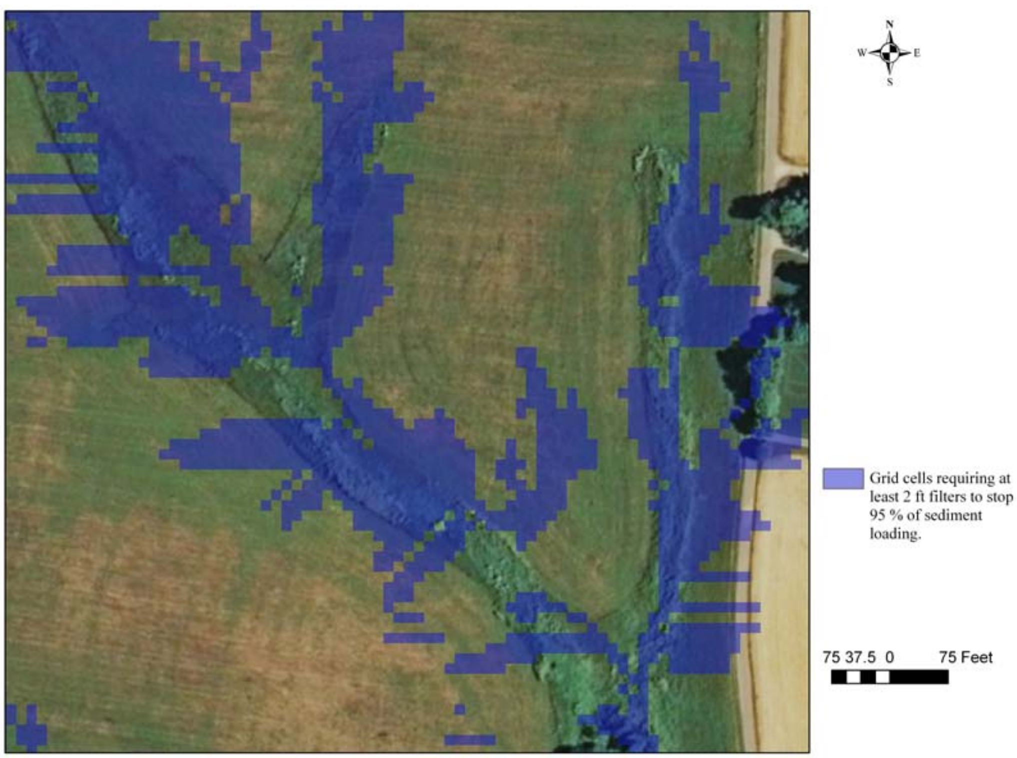

Fig. 3. Map indicating the locations of grid cell requiring at least 2-ft buffers to stop 95% of sediment loading.

serious negative consequences. Therefore, maps created with this approach will require field validation.

This data could also be meaningfully visualized by mapping all the 4 x 4-m grid cells that require some minimum set length of filter strip. For example, all the cells that require at least a 2-ft buffer were shaded in blue (Fig. 3). This kind of map would allow a conservation planner to visualize where the filter strips should be distributed throughout fields. This approach will require field calibration to select the appropriate threshold. Equipping conservation planners with both types of maps previously described (e.g., Fig. 2 and 3) could be helpful for planners in the field.

Advantages of the Variable-Width Procedure

Use of this methodology for designing filter strips has several advantages over traditional constant-width methods. First, the incorporation of the design methods with geospatial technologies enables a more precise fit between filter size and runoff load where runoff from agricultural fields is non-uniform. Second, the geospatial technologies greatly increase the speed of designing a filter strip having a known level of trapping efficiency, especially for large field areas. Third, the result is a variable-width filter strip that achieves greater water quality benefit per hectare of installation.

This procedure can also significantly reduce the cost of achieving a meaningful impact on water quality. Current NRCS standards call for establishing uniform runoff prior to installation of filter strips in areas where runoff flow is not uniform (USDA, 2008). Practices such as land shaping and level spreaders are ways to establish uniform runoff flow, but they add substantial cost to creating effective filter strips. The use of this variable-width procedure may reduce or eliminate the cost of establishing uniform runoff flow by placing more filter area where runoff load is greater and less filter area where runoff load is smaller.

CONCLUSIONS

This method combines a quantitative filter strip design model with geospatial technologies to enable quick and accurate design of efficient and cost-effective filter strips. The fine scale analytical capabilities of terrain analysis and GIS enable a more precise fit between filter size and runoff load where runoff from agricultural fields is non-uniform. The result is variable-width, constant-benefit filter strips that achieve greater water quality benefit per hectare of installation.

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