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A design aid for determining width of filter strips

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

Abstract: Watershed planners need a tool for determining width of filter strips that is accurate enough for developing cost-effective site designs and easy enough to use for making quick determinations on a large number and variety of sites. This study employed the process-based Vegetative Filter Strip Model to evaluate the relationship between filter strip width and trapping efficiency for sediment and water and to produce a design aid for use where specific water quality targets must be met. Model simulations illustrate that relatively narrow filter strips can have high impact in some situations, while in others even a modest impact cannot be achieved at any practical width. A graphical design aid was developed for estimating the width needed to achieve target trapping efficiencies for different pollutants under a broad range of agricultural site conditions. Using the model simulations for sediment and water, a graph was produced containing a family of seven lines that divide the full range of possible relationships between width and trapping efficiency into fairly even increments. Simple rules guide the selection of one line that best describes a given field situation by considering field length and cover management, slope, and soil texture. Relationships for sediment-bound and dissolved pollutants are interpreted from the modeled relationships for sediment and water. Interpolation between lines can refine the results and account for additional variables, if needed. The design aid is easy to use, accounts for several major variables that determine filter strip performance, and is based on a validated, process-based, mathematical model. This design aid strikes a balance between accuracy and utility that fills a wide gap between existing design guides and mathematical models.

Key words: models—nonpoint source pollution—surface runoff—vegetative buffers—water quality—watershed planning

Strategies for water quality improvement in agricultural watersheds often include filter strips. Filter strips are installed to reduce the load of sediment, nutrients, and other pollutants in surface runoff from fields that may otherwise reach waterways. Proper design can help ensure that a filter strip will achieve a desired level of impact.

The width of a filter strip is an important design variable for determining both the level of impact and the cost of installation. Wider filter strips generally work better (Dillaha et al. 1989; Magette et al. 1989; Robinson et al. 1996; Schmitt et al. 1999), but widening beyond what is necessary can add to costs and create resistance to adoption. Watershed planners often express desired levels of impact in terms of a percentage reduction of runoff load that is required to meet some regulatory limit (e.g., total maximum daily load). An effective design process, then, would identify the width of filter strip that achieves that percentage.

The relationship between filter strip width and level of impact, however, is not a simple one. For a given width, the percentage of pollutant load that is retained (i.e., trapping efficiency) varies with site conditions and pollutant type (Dosskey 2001). For example, conditions that produce larger runoff

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loads from fields and/or reduce infiltration in filter strips will decrease the trapping efficiency for a given width (e.g., Dillaha et al. 1988, 1989; Hayes et al. 1984; Helmers et al. 2002; Lee et al. 2000; Muñoz-Carpena et al. 1993; Verchot et al. 1997), and coarse sediments are more easily retained than fine sediments and dissolved pollutants (Hayes et al. 1984; Lee et al. 2000). The relationship is also non-linear, especially for sediments, as the percentage of pollutants that are retained increases more slowly as width is increased (Dillaha et al. 1989; Magette et al. 1989; Robinson et al. 1996; Schmitt et al. 1999).

The existing body of experimental results is inadequate for distilling directly into an effective design guide. The collection of experimental studies on filter strips have been conducted under an unsystematic assortment of conditions such that a calculated average relationship developed from these results (e.g., Mayer et al. 2005, 2007; National Council for Air and Stream Improvement Inc. 2000) could contain large error for describing a hypothetical average site and any actual specific site. In many of these experimental studies, filter strips were relatively large and/or were challenged by relatively small runoff loads that yielded very high pollutant retentions (Dosskey et al. 2002). Design loads, however, should be large since most pollutants are transported during larger rainfall events (Larson et al. 1997). Consequently, the collective experimental literature reports impact levels that are too high or too unstructured for guiding effective site design.

Complex mathematical models provide an alternative approach for determining the relationship between filter strip width and level of impact. These models are process-based and account for the full range of known variables and interactions that affect both runoff delivery from fields and pollutant retention by filter strips. The Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Knisel 1980), Water Erosion Prediction Project model (Nearing et al. 1989), and the University of Kentucky sediment filtration model (Barfield et al. 1979; Hayes et al. 1979, 1984; Tollner et al. 1976, 1977) have been used in various combinations for estimating delivery and retention (Dillaha and Hayes 1991; Stettler 1994; Williams and Nicks 1988, 1993). The Vegetative Filter Strip Model (VFSMOD) (Muñoz-Carpena and Parsons 2005), an extension of the University of Kentucky sediment filtration model and the Riparian Ecosystems Management Model (Lowrance et al. 2000), are stand-alone models that have been developed and used more recently (Lowrance et al. 2001; Muñoz-Carpena and Parsons 2004; Suwandono et al. 1999). All of these modeling approaches have been structured to assess the level of impact that a given filter strip design would produce at a given site. They could be used for design purposes by repeatedly inputting a different value for width until the model predicts an impact that meets a desired level. They are broadly applicable to many geographical settings and are potentially quite accurate, but they require large amounts of detailed input data on specific site conditions, computers to perform the calculations, and a high level of skill to properly parameterize, run, and interpret results from them. Because of their high complexity, these models are not used for site planning.

Simpler mathematical models have been produced for the purpose of aiding assessments and design. Flanagan (1989) developed a mathematical abstraction from the CREAMS model for assessing impact of filter strips. The Riparian Buffer Delineation Equation models (Phillips 1989b) were developed for assessing sediment and nitrate retention based on theoretical equations that account for slope, surface roughness, and soil hydraulic characteristics relative to those of a reference filter strip. The Soil and Water Assessment Tool model (Neitsch et al. 2002) contains a filter strip assessment model of unspecified derivation where trapping efficiency is solely a function of filter strip width. In the Soil and Water Assessment Tool model, one equation is used for all site conditions and all pollutants, except for microbial pollutants which are described by a different, but equally simple, equation. The Riparian Buffer Delineation Equation models and Soil and Water Assessment Tool model equations can be easily transformed into design models by rearranging them to solve for width instead of level of impact (e.g., Xiang 1996). Wong and McCuen (1982) produced a design model for sediment trapping efficiency based on sediment particle size and the slope and surface roughness of a filter strip. Theoretical deposition equations were simplified into easy-to-use nomographs, but they are unable to discern target trapping efficiencies less than 75% or width determinations of less than 30 m (100 ft). The main drawback of simple models is that they contain only a small subset of variables which, in turn, limit their geographic applicability and/or create potential for large error when applied to a specific site. Of these simpler mathematical models, only the CREAMS-based abstraction has been validated (Flanagan 1989).

Other design models and guides have been developed where level of impact is not a variable for determining appropriate width for filter strips. In these models and guides, the level of impact is simply implied to be adequate. Trimble and Sartz (1957) developed a simple equation for sediment control where width is a function of land slope. Nieswand et al. (1990) reduced the sediment equations of Wong and McCuen (1982) to a simple function of slope. Several non-mathematical guides have also been developed. The Natural Resources Conservation Service identifies some minimum design widths whose selection depends on pollutant type and field drainage area (USDA 1997). Ranges of minimum design width have been produced that are loosely based on reviews of published experimental results (Castelle et al. 1994; Dosskey et al. 1997a; Palone and Todd 1997; Wenger 1999). Even simpler guides specify a single width that would be adequate under many circumstances for filtering pollutants from surface runoff in addition to providing other desired conservation benefits (Dosskey et al. 1997b; Schultz et al. 1995; Welsch 1991). Width guides that do not specify a level of impact would be unsuitable for planning cost-effective filter strips where specific runoff water quality targets must be met.

Watershed planners need a design aid for determining filter strip width that strikes a balance between being accurate enough for developing cost-effective site designs and being easy enough to use for making quick determinations on a large number and wide variety of sites. There currently exists a wide gap between the complex assessment models and the simple but imprecise design guides. The objectives of this study were to evaluate relationships between pollutant retention and width of a filter strip, and from those results, to produce a design aid that strikes a balance between accuracy and utility that is intermediate to those that are currently available and that can be applied widely across the United States.

Materials and Methods

Approach. The process-based VFSMOD version 1.04 (Muñoz-Carpena and Parsons 2005) was used to estimate the level of sediment and water retention by several different widths of grass filter strip in a cropland setting. Sediment and water retentions reflect the main processes, deposition and infiltration, by which pollutants are retained by filter strips. Retention was defined as trapping efficiency or the difference between input and output loads as a percentage of input load. The simulation was repeated for different combinations of slopes, soil types, drainage area sizes, and cropping practices—major site variables that determine runoff load from fields and retention by filter strips (Dosskey 2001; Helmers et al. 2002). The results were displayed graphically to visually gage how much each of these variables affects the relationship between width and trapping efficiency. From them, a single graph was synthesized that shows a family of lines spanning the full range of simulation results. Then, rules were developed for selecting one line that is most appropriate for determining width of filter strip for any given agricultural site.

The idea of using a complex mathematical assessment model to create a graphical design aid was suggested by Flanagan (1989). McKague et al. (1996) created such a graph for a narrow range of site conditions, but used it for assessing impact rather than for design. By using a validated, process-based model, reasonable accuracy is assured. For design purposes, graphical representations are easier to understand and apply than are mathematical equations (Flanagan 1989; McKague et al. 1996; Wong and McCuen 1982) and are useful where an approximate answer is appropriate. This approach was extended in this study by adding a line selection process that can account for a larger set of variables that would broaden the geographic applicability of the graph to most cropland settings in the United States.

Model Simulations. The VFSMOD is a field-scale, single-event model that is based on the hydraulics of flow and processes of sediment transport and deposition (Muñoz-Carpena et al. 1993, 1999). It simulates both field runoff delivery and filter strip retention of sediments and water. Good agreement between VFSMOD-modeled and observed trapping efficiencies has been determined for conditions in North Carolina (Muñoz-Carpena et al. 1999), Mississippi (Hayes and Hairston 1983), and Ontario, Canada (Abu-Zreig et al. 2001).

For all simulations, it was assumed that runoff was generated by a rainfall event of 61 mm (2.4 in) in 1 hour onto a wet, cultivated field (table 1). This size of rainfall event has a 10 year return frequency across the Central Plains (e.g., Garden City, Kansas), Corn Belt (e.g., Ames, Iowa), and northern

Table 1
Design conditions used for conducting all model simulations.

Category	Design condition
Filter strip	Well-established grass (25 mm tall, 1.6 mm spacing, Manning's n = 0.40)
	Slope and soil texture same as the contributing field area
	Runoff uniformly distributed
Field	Seedbed stage (USLE P factor = 1.0)
	Wet antecedent soil moisture
Rainfall	Single event
	61 mm in 1 hour

Table 2
Values for the four site variables used to evaluate relationships between filter strip width and trapping efficiency of sediment and water in cultivated agricultural landscapes.

Variable	Values
Field slope length	200 m, 400 m
Slope	2%, 10%
Soil texture class	Fine sandy loam, silty clay loam
USLE C factor	0.15, 0.50

Figure 1
Contrast between sediment and water for the relationship between trapping efficiency and filter strip width under two different site conditions: site A (fine sandy loam, C factor = 0.50, field length = 200 m, slope = 2%) and site B (silty clay loam, C factor = 0.15, field length = 200 m, slope = 2%).

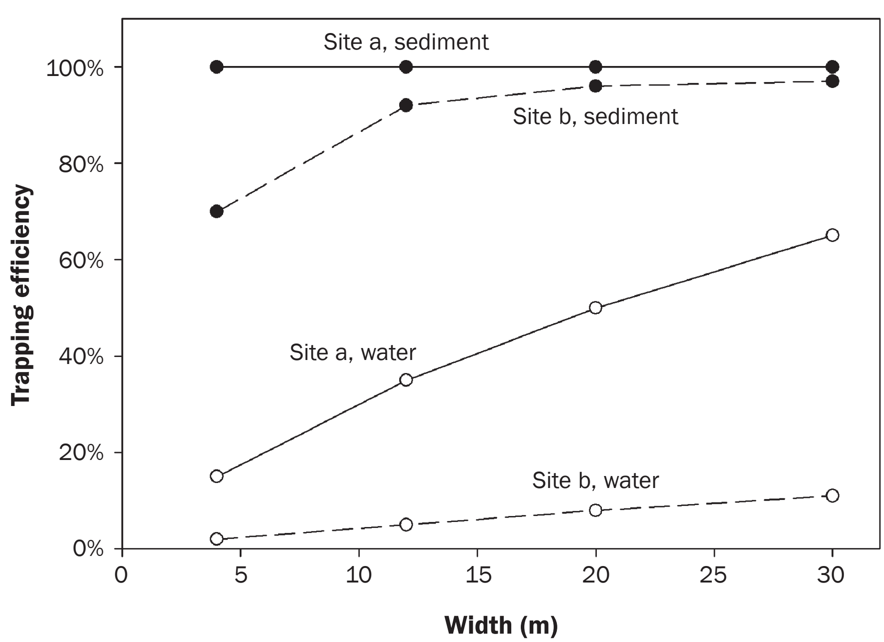
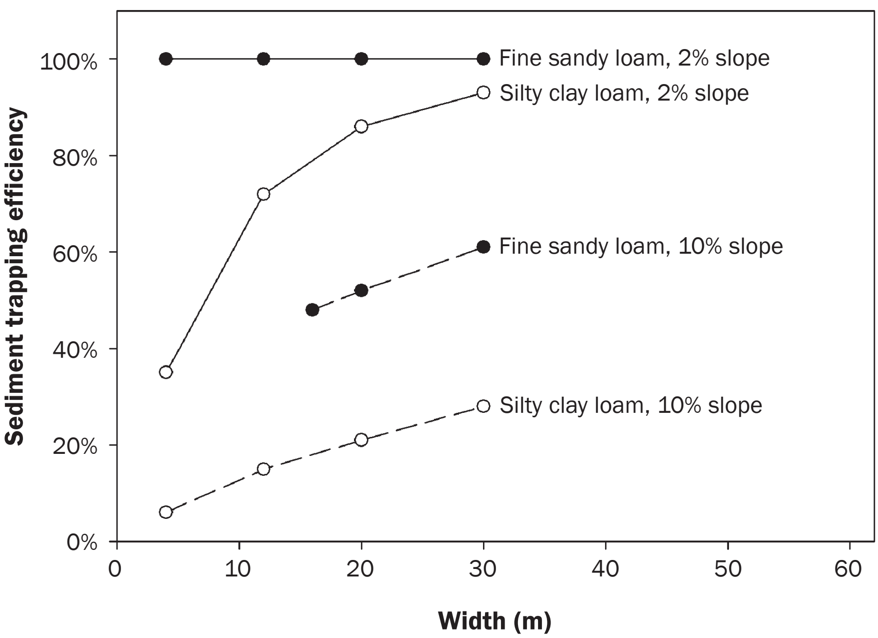


Table 3
Values for soil parameters used in model simulations that key to soil texture class (soil hydraulic properties taken from Rawls et al. 1993).

Soil texture class	K_{sat} (cm h^{-1})	Porosity (m^3 m^{-3})	Initial water content (m^3 m^{-3})	Curve number	USLE K factor (tn [ac EI]$^{-1}$)
Silty clay loam	0.20	0.471	0.169	90	0.37
Fine sandy loam	2.18	0.453	0.064	75	0.20

Figure 2
Contrast between sites having different soils (fine sandy loam and silty clay loam) and slopes (2% and 10%) for sediment trapping efficiency as a function of filter strip width.



Notes: All four of these simulations were at field slope length of 200 m and a C factor of 0.50. Lack of data points for narrower widths for the simulation of fine sandy loam on 10% slope is due to sediment deposition filling the narrow filter strip to capacity before the runoff event ended.

Piedmont (e.g., Durham, North Carolina) regions (Hershfield 1961). A 10-year return-period design storm was chosen for the simulations as suggested by Larson et al. (1997). Runoff was delivered in uniformly distributed flow to a well-established grass filter strip having the same slope and soil texture as the cultivated field.

Four site variables were evaluated: (1) slope, (2) soil texture, (3) field slope length, and (4) field cover management practices (i.e., Universal Soil Loss Equation [USLE] C factor) (Wischmeier and Smith 1978). Slope and soil texture affect trapping capability of a filter strip, and when coupled with field length and cover management, largely determine the input load of runoff water and sediment to the filter strip (e.g., Philips 1989a; Helmers et al. 2002). These four variables are also relatively easy for a planner to estimate for any given site. For the simulations, two values were selected for each variable that bracket a wide range of agricultural site conditions (table 2). The high value for C factor (0.50) generally describes the seedbed stage of corn after corn or grain sorghum using disk plow tillage or corn after beans using chisel tillage (Wischmeier and Smith 1978). The low value for C factor (0.15) generally describes corn after corn with chisel or no-till that leaves good residue cover. Values for parameters used in VFSMOD that are keyed to each soil texture class are listed in table 3.

Trapping efficiencies for sediment and water were calculated for ten different combinations of values for the four site variables. For each combination, simulations were repeated for several filter strip widths: 4, 12, 20, and 30 m (13.1, 39.4, 65.6, and 98.4 ft) when field length was selected to be 200 m (656 ft), and 8, 24, 40, and 60 m (26.2, 78.7, 131, and 197 ft) when field length was 400 m (1,312 ft) providing filter to field area ratios of 0.02, 0.06, 0.10, and 0.15. For some conditions, a shorter or longer filter width was added to extend the simulation range.

Selected results were plotted to illustrate the range of possible relationships between filter strip width and trapping efficiency among different agricultural sites and runoff materials (sediment and water) and to visually gage how much the relationship is affected by a substantial change in one or more site variables.

Results and Discussion

Simulation Results. The simulation results clearly show that the width of filter strip required to achieve a given level of trapping efficiency is extremely variable (figure 1). Filter strips as narrow as 4 m (13.1 ft) were estimated to trap nearly 100% of the incoming material in some cases, while 30-m (98.4-ft) strips trapped only 10% of the load in other cases. The trapping efficiency of a given width of filter strip depends very strongly on the kind of material being trapped. High trapping efficiencies were estimated for sediment and much lower trapping efficiencies were estimated for water under the same site conditions. The low trapping efficiencies for water illustrate that rainfall plus field runoff often greatly exceeds the infiltration capacity of filter strips. Site conditions also influence the relationship between width and trapping efficiency. For example, a filter strip on coarse-textured soil below a disk plowed corn field (C factor = 0.50) yielded substantially higher trapping efficiencies for sediment and water than an otherwise similar strip on fine-textured soil below a chisel-tilled corn field (C factor = 0.15; figure 1). Overall, these results illustrate that relatively narrow filter strips can have a high impact in some situations, while in others even a modest impact cannot be achieved at any practical width.

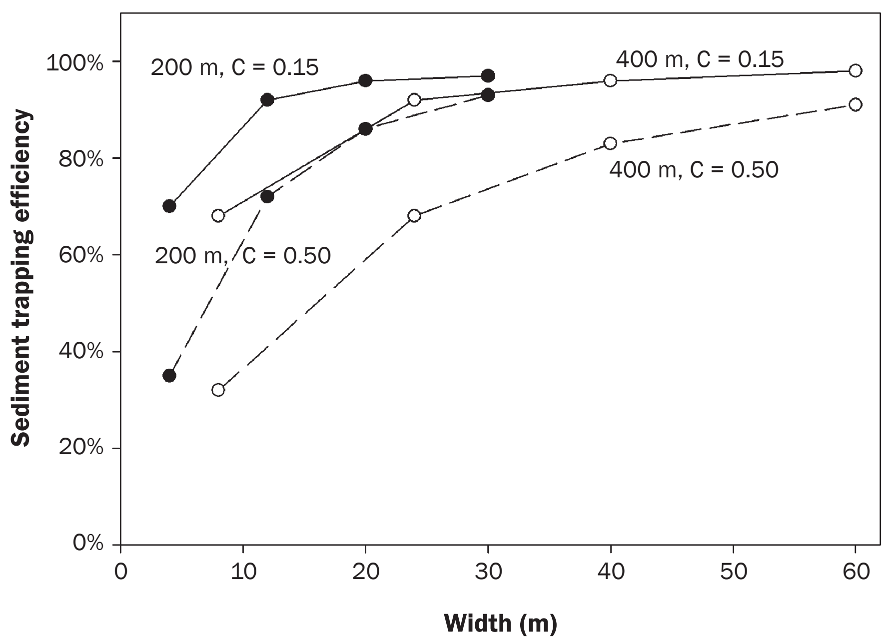
Each of the four site variables (soil texture, slope, field slope length, field C factor) had a substantial effect on the relationship between trapping efficiency and width of filter strip.

Table 4
Simulation conditions corresponding to each line in figure 4.

Line number	Field length (m)	USLE C factor	Slope	Soil texture class	Material type
7	200	0.50	2%	FSL	Sediment
6	200	0.15	2%	SiCL	Sediment
5	200	0.50	2%	SiCL	Sediment
4	400	0.50	2%	SiCL	Sediment
3	400	0.50	2%	FSL	Water
2	200	0.50	10%	SiCL	Sediment
1	400	0.50	2%	SiCL	Water

Greater slopes yielded lower sediment trapping efficiencies for a given filter strip width, as did finer-textured soils (figure 2). For example, a 20-m (65.6-ft) wide filter strip would trap 100% of incoming sediment on a 2% slope having fine sandy loam soil while the same filter strip would trap only 21% of incoming sediment on a 10% slope having silty clay loam soil. Each of these site characteristics can have large individual effects. For example, a 4-m (13.1-ft) wide strip on a 2% slope having fine sandy loam soil would trap nearly 100% of sediment in runoff but only 35% of runoff sediment if the soil was silty clay loam. The finer-textured soil experiences less infiltration in the field and in the filter strip and produces more fine particles that are less easily deposited in a filter strip. The slope effect is also large. For example, a 20-m wide strip on a silty clay loam having a 2% slope would trap 85% of incoming sediment, but only 20% of incoming sediment if the slope was 10%. Greater slope and finer-textured soil act to both increase field runoff load and reduce the trapping capability of a filter strip, which explains the large effect that each of these variables has on trapping efficiency.

Figure 3
Contrast between sites having different field slope lengths (200 and 400 m) and C factors (0.15 and 0.50) for sediment trapping efficiency as a function of filter strip width.



Note: All four of these simulations were at 2% slope on silty clay loam soil.

Site characteristics that affect only the field runoff load also had an affect on trapping efficiency of a filter strip. Longer field length and poorer cover management (higher C factor), both of which create greater runoff loads, yielded lower sediment trapping efficiency for a given width than a shorter field with better cover management (figure 3). Each of these site characteristics, individually, had a marked impact on sediment trapping efficiency but not as large as the individual effects of slope and soil texture displayed in figure 2. Overall, the simulation results illustrate the importance of both runoff loading and filter capability in determining the relationship between trapping efficiency and width of filter strips.

Design Aid Development. From the collection of simulation results, seven relationships were selected that span the range of results in fairly equal increments. Nonlinear regression of the equation form

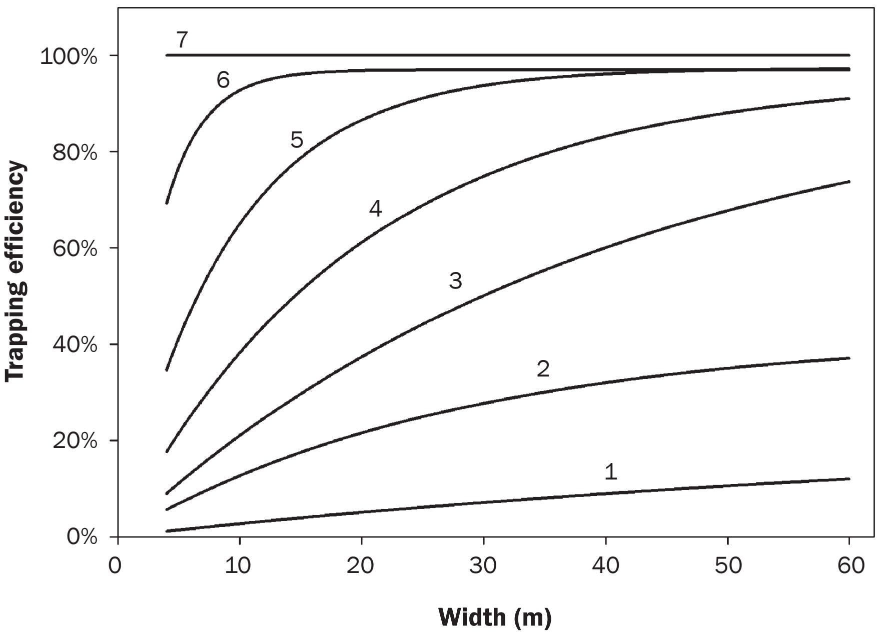
$$y = a\,(1 - e^{-bx}) \qquad (1)$$

was conducted on the data points from each of the seven sets of simulation conditions (table 4) and the regressed relationships were plotted (figure 4). Other equation forms were evaluated, but this one produced a near-perfect fit for all seven relationships (table 5).

The relationships illustrated in figure 4 can be used as a design aid for determining appropriate width for filter strips. The first step would be to identify the desired level of trapping efficiency. Then, identify one line in the graph that represents the closest match between simulation conditions (table 4) and actual conditions at a site, and read the corresponding width that will achieve that level of trapping efficiency.

The line selection process is key to obtaining a reasonable estimate for width of a filter strip. It is straightforward for a site that has similar conditions to one of those which were plotted in figure 4. In most cases, however, actual site conditions will differ from these simulations in one or more of the four variables. In such cases, selecting the best line will require two steps. First, pick a reference line to start from, such as one for which simulation conditions are more similar to the

Figure 4
Relationships for seven different site conditions from among the full set of simulations.



Note: The site conditions represented by each line are listed in table 4.

Table 5
Regression equations and fit statistics for the seven reference lines shown in figure 4.

	Equation $y = a\ (1 - e^{-bx})$		
Line number	***a***	***b***	**Adjusted r^2**
7	100	+inf	1.0000
6	97.0041	0.3133	0.9993
5	97.3184	0.1103	0.9999
4	95.5259	0.0511	0.9999
3	95.0098	0.0250	0.9997
2	41.8543	0.0362	0.9992
1	22.9239	0.0124	0.9997

Note that +inf refers to an infinitely large number.

actual site. Then, adjust to a different line based on how much the conditions at the actual site differ from those that represent the reference line. In general, adjust to a line above the reference line for conditions that would yield a smaller runoff load or greater filter capability than the reference conditions and to a line below the reference line for conditions that would yield greater runoff load or lesser filter capability than the reference conditions.

Rules of thumb were developed for determining how many lines above or below the initial reference line would be most appropriate (table 6). Adjustments for site conditions are based on visual comparisons of graphed simulation results such as those shown in figures 2 and 3. The rules of thumb include selecting one line above or below a reference line for each halving or doubling of field length, respectively; for each 2.5% lesser or steeper slope, respectively; for each 0.35 decrease or increase in C factor, respectively; and for each soil texture category coarser or finer, respectively. Three broad soil texture categories (coarse, medium, and fine) are recognized based on our judgment of the balance between particle-size distribution, erodiblity, and water permeability. Estimates of C factor values for various cultivation systems can be obtained from a look-up table in Wischmeier and Smith (1978), the USDA Natural Resources Conservation Service state office or university extension publications (e.g., Nebraska Cooperative Extension Service 1988), or by calculation using USDA web-based software (USDA 2007).

Rules were also developed for adjusting the reference lines based on sediment and water for different pollutant types (table 6). Since infiltration of runoff water is the main process by which its solute content is also retained, retention of dissolved pollutants such as nitrate, atrazine, and dissolved phosphorus may be approximated by the line for water. Field studies show that water infiltration in filter strips can underestimate dissolved pollutant retention by up to 16% for a single, independent runoff event (Schmitt et al. 1999). However, this underestimate can be offset, and even produce an overestimate, where previously-trapped pollutants are remobilized during subsequent runoff events (Dillaha et al. 1989; Lee et al. 2000). Since some remobilization offset will probably occur in typical applications over the long run, retention of dissolved pollutants is probably similar enough to water for the purposes of this design aid. A three-line adjustment is indicated for starting with a sediment relationship and adjusting to a line that describes water (figure 1), and visa versa. This adjustment can also apply to dissolved pollutants. However, since the magnitude of remobilization is likely to vary from one situation to another, there will be greater uncertainty surrounding an adjustment for dissolved pollutants than for water.

Retention of sediment-bound pollutants is somewhat less than for sediment as a whole since sediment-bound pollutants tend to be associated more with finer particles, such as clays and fine silts, which do not deposit as readily in filter strips as sands and coarse silts (Lee et al. 2000; Schmitt et al. 1999). Phosphorus in runoff from tilled fields is mainly sediment-bound but also includes a small fraction that is dissolved which would further reduce its retention compared to sediment (Dillaha et al. 1989; Schmitt et al. 1999). Field studies show that total P retention is about 10% less than for sediment (Dillaha et al. 1989; Schmitt et al. 1999), so a conservative adjustment rule for total P is to select one line lower than for sediment (table 6).

An example of the process for selecting an appropriate line from figure 4 is illustrated in the worksheet in table 7. For the field site conditions shown in the table, line number 5 was initially selected as the initial reference, and adjustment was necessary for substantial departures in field length, slope, and soil texture. Using the rules of thumb listed in table 6, a net adjustment of one line below the reference line was indicated, so line number 4 was determined to be most appropriate for use under the conditions at that field site. If the worksheet produces a final line number higher than seven or lower than one, then line seven or line one, respectively, should be used as the design line.

Accuracy of the adjustment rules was evaluated by determining how accurately they identified the proper line for a given simulation condition by starting from a different simulation condition and making adjustments according to table 6. A matrix of those results on the conditions for the lines in figure 4 (table 4) produced only two cases out of 42 where the final selected line did not match the actual line for those conditions (table 8). In those two cases, one resulted in selection of one line above and the other resulted in selection of one line below, the simulation line for that set of conditions, so there was no apparent bias in the adjustment rules.

Accuracy of the design aid was also tested on the thirteen simulation results not displayed in figure 4 plus independent simulation results for a study of three field sites in southeastern Nebraska. For this test, design aid-selected lines were compared to corresponding lines that were generated specifically for each of those site conditions using VFSMOD. Average conditions among the three field sites ranged from silty clay loam to silt loam, 2% to 4% slope, and 74- to 350-m (243- to 1,148-ft) field length (Dosskey et al. 2002). Adjustments for field site conditions were interpolated to the nearest 1/2 line for differences in conditions that were between the increments specified in table 6. For the eight sediment simulations, the design aid-selected lines were within one line of site-specific VFSMOD simulations (figure 5). Accuracy of the design aid for water trapping was lower, within two lines of the site-specific simulations. The design aid showed no bias for either sediment or water. These results indicate that the design aid is, as expected, less precise than the full VFSMOD model and that the simplifications made in developing the design aid reduced its precision for describing water more than

Table 6
Rules for adjusting from an initial reference line in figure 4 to a final selected line based on how much the actual field site conditions differ from the reference simulation conditions.

Variable	Adjustment rule
Pollutant type	3 lines higher (+3) from dissolved pollutant to sediment
	2 lines higher (+2) from dissolved pollutant to total P
	1 line lower (–1) from sediment to total P
	3 lines lower (–3) from sediment to dissolved pollutant
Field length	1 line higher (+1) for each halving of the field length
	1 line lower (–1) for each doubling of the field length
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

Notes: For soil texture, three broad 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). For pollutant type, dissolved pollutants are interpreted as being retained similarly to water.

Table 7
Example of the two-step line selection process.

Variable	Initial reference line	Field site condition	Adjustment rule	Final selected line
Field length	200 m	350 m	–1	
Slope	2%	4.5%	–1	
Soil texture	Silty clay loam	Loam	+1	
C factor	0.50	0.50	0	
Pollutant type	Sediment	Sediment	0	
	Line number		Total adjustments	Line number
	5		–1	4

In this case, line number 5 in figure 4 was identified as the initial reference line, and after applying the adjustment rules in table 6, line 4 was selected as the most appropriate relationship to use for filter strip design on this site.

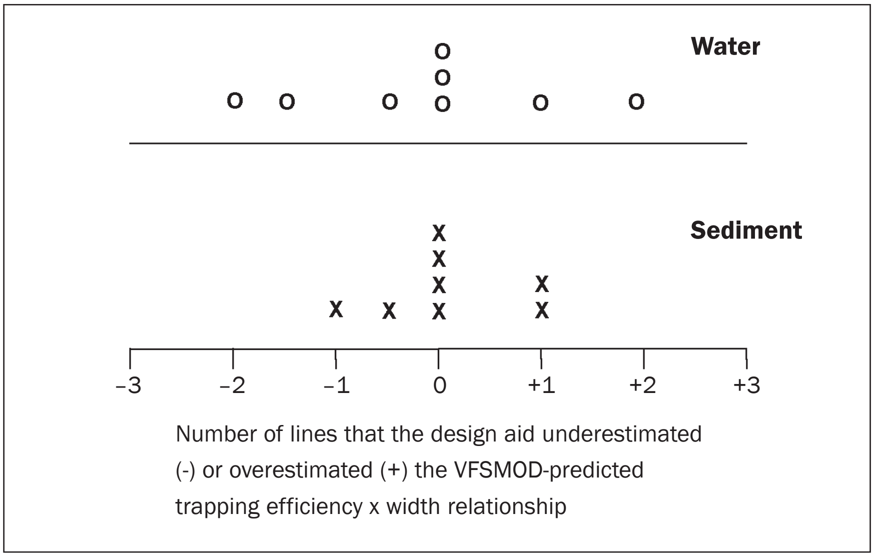
Table 8
A test of accuracy of the adjustment rules.

	Reference line number						
Conditions line number	7	6	5	4	3	2	1
7	—	7	7	7	7	7	7
6	6	—	6	**5**	6	6	6
5	5	5	—	5	5	5	5
4	4	4	4	—	4	4	4
3	3	3	3	3	—	3	3
2	**3**	2	2	2	2	—	2
1	1	1	1	1	1	1	—

Notes: Each line in figure 4 was selected as the initial reference line and then the adjustment rules (table 6) were applied for conditions representing every other line (table 4) to determine how closely the final line selection (body of the table) matched the correct line number for those conditions (left-hand column). Numbers in bold represent the only two cases out of 42 where the final selected line did not match the predicted line for those conditions.

Figure 5

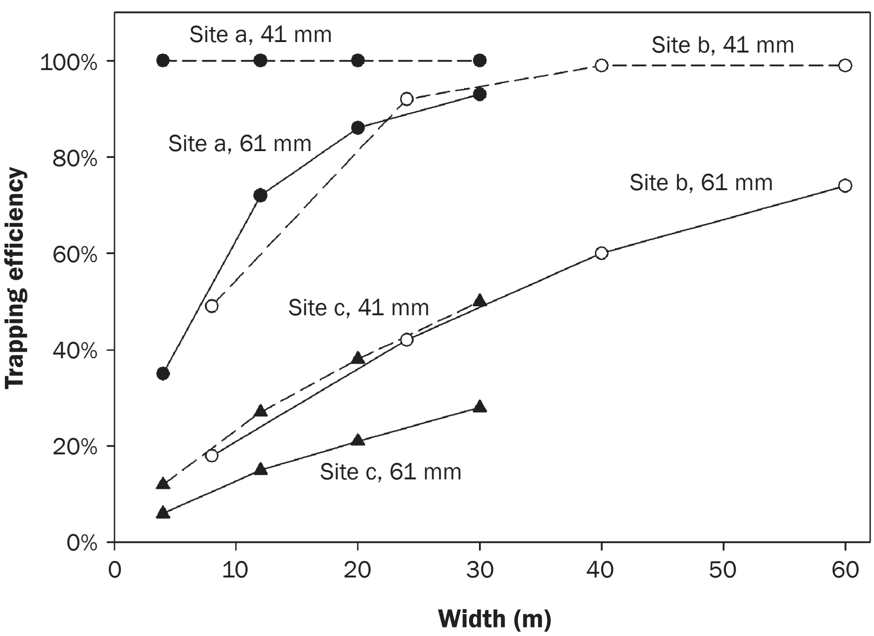
Frequency distribution of correspondences between the design aid-selected design line and the model-predicted line for the 13 study simulations not shown in figure 4 and for three additional simulations published in Dosskey et al. (2002).



Note: Each symbol represents one comparison.

Figure 6

Contrast between storm sizes (41 and 61 mm rainfall in 1 h) for the relationship between trapping efficiency and filter strip width under three different site conditions and pollutant types.



Notes: Site A (sediment trapping for silty clay loam, C factor = 0.5, field length = 200 m, slope = 2%), site B (water trapping for fine sandy loam, C factor = 0.5, field length = 400 m, slope = 2%), and site C (sediment trapping for silty clay loam, C factor = 0.5, field length = 200 m, slope = 10%). These data are from model simulations presented in Helmers et al. (2002).

it did for sediment. Some precision reduction for sediment trapping is probably due, in part, to reduced precision for water trapping since infiltration of runoff water affects sediment deposition by reducing sediment transport capacity of the remaining surface water flow.

The design aid was tested further by applying it as an assessment tool to field study sites reported in the literature by comparing the trapping efficiencies for specific widths measured in those studies with estimates using the design aid. We found only three reports of single rainfall events onto cultivated plots that had realistic field lengths and buffer area ratios (Arora et al. 1993, 1996; Parsons et al. 1990). This test was not rigorous since none of these studies had similar rainfall amount and intensity and antecedent soil moisture as those used in formulating the design aid, and the C factors had to be guessed from limited information about source area conditions. Despite these shortcomings, we found reasonable correspondence between design aid-estimated and field-measured levels of filter strip performance. Design aid-estimated trapping efficiencies of 4.3–, 8.5–, and 20.1–m (14.1–, 27.9–, and 65.9–ft) wide filter strips were lower than measured values for sediment (range of differences = –23 to +6; mean = –5; n = 6) and water (range of differences = -60 to +1; mean = –25; n = 8). Lower values are consistent with how performance would be affected by the larger rainfall amount and wetter antecedent soil moisture condition modeled with the design aid than what was experienced in these field studies.

Planners that have a deeper knowledge of agricultural runoff and filter strip processes may want to make finer adjustments than those listed in table 6. For example, interpolation between lines for differences in conditions that do not closely match the increments listed in table 6 might lead to better line selection from figure 4, as was done in our accuracy tests. Also, adjustments may be desired for additional variables that are known to affect runoff load or filtering capacity. The results shown in figures 2 and 3 indicate that any site condition that departs from design aid assumptions or reference line conditions that would double or halve the field runoff load should dictate an adjustment of one line below or one line above the initial reference line, respectively. For example, a planner may want to make adjustments for varying field practices represented by the USLE P factor and/or for nonuniform runoff patterns that concentrate or disperse runoff flow to a filter strip. If a planner prefers to design for a different size storm event, then a two-line adjustment would be appropriate for doubling or halving the storm size (figure 6) since a change in storm size does not affect runoff load in a directly proportional manner. Enabling interpolations and adjustments for additional site factors and design conditions broadens the range of planning circumstances to which the design aid could be applied.

The design aid does not account for how sediment build-up in a filter strip during one event affects functioning in subsequent events. Filter strips that trap sediment will fill with sediment sooner or later and stop functioning properly. Procedures have been developed to estimate the functioning life span of filter strips based on filter strip size, field runoff load, and trapping efficiency (Dillaha and Hayes 1991). Eventually, sediment must be removed in order to maintain the trapping efficiencies that are estimated by this design aid.

Summary and Conclusions

Simulations using the process-based VFSMOD model illustrate that the effectiveness of a filter strip can differ dramatically from one agricultural site to another and from one pollutant type to another. From a planner's perspective, a target level of water pollution reduction may be achieved on one site with only a narrow filter strip, while a much wider filter strip may be required at another site, or the target may be unattainable by a filter strip at still other sites. Slope and soil texture are the most influential site factors that determine how wide a filter strip must be to achieve a target trapping efficiency. Dissolved pollutants require much wider filter strips than sediment to achieve the same level of trapping efficiency.

A graphical design aid was developed that enables planners to quickly determine appropriate design widths for filter strips that can achieve target trapping efficiencies for a wide variety of field site conditions and pollutant types. It is simple to use, accounts for several major variables that determine filter strip performance, and is based on a validated, process-based, filter strip model. This design aid fills a large gap between existing complex assessment-type models and simple design guides. It can be applied quickly by site planners in a broad range of agricultural settings with greater accuracy than existing design guides. Furthermore, the logic behind the method is clear so that the design process can be modified as necessary based on the judgment of the planner. While modeling simplifications limit the accuracy of this design aid for estimating actual performance of a filter strip for a specific site or event, this design aid provides a more quantitative mechanism for determining appropriate width than is currently being used.

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