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Vegetative Filter Strip Design for Grassed Areas Treated with Animal Manures

VEGETATIVE FILTER STRIP DESIGN FOR GRASSED AREAS TREATED WITH ANIMAL MANURES

D. R. Edwards, T. C. Daniel, P. A. Moore Jr.

ABSTRACT. *Vegetative filter strips (VFS) are a low-cost management option that have been demonstrated to be effective in reducing runoff transport of fertilizer constituents applied to grassed areas (pasture or meadow). Runoff quality studies involving fertilizers applied to grassed areas suggest that VFS can be designed by assuming that (1) only infiltration is responsible for pollutant removal, (2) the first post-application runoff event is most important from a water quality perspective (enabling a design event approach), and (3) no pollutant build-up that degrades VFS performance will occur. The purpose of this study was to develop a VFS design algorithm for grassed areas that uses available information on the water quality dynamics of these systems to simplify the design process to the greatest degree practical. The design algorithm consists of the SCS (1972) Curve Number method for runoff estimation and the Overcash et al. (1981) equation for predicting concentrations of pollutants exiting a VFS as a function of VFS and runoff parameters. The procedure can be used to determine the VFS length required to meet either an allowable pollutant runoff concentration or allowable pollutant mass transport. As an alternative, the process can be used to determine VFS length required to achieve given relative reductions in incoming pollutant runoff concentrations and mass transport. This algorithm can be used quickly and with minimal data to determine the VFS length requirement necessary to provide any desired degree of effectiveness given inputs such as incoming pollutant runoff concentration, background pollutant runoff concentration, soil hydrologic properties, and design storm parameters. Charts are presented that eliminate the need for computations in selected cases.*
Keywords. Nonpoint source pollution, Runoff, Buffer strips, Animal manure.

Manures from confined animal production systems (e.g., swine and poultry) are typically land-applied as fertilizer to crops and grasses. Rainfall that occurs soon after manure application, however, can cause runoff losses of manure constituents such as nitrogen (N) and phosphorus (P), with the greatest loss generally associated with the first post-application, runoff-producing storm (McLeod and Hegg, 1984; Edwards and Daniel, 1994). Runoff losses of N and P typically are not of magnitudes that are an agronomic concern, but could be sufficient to cause undesirable water quality impacts in downstream surface waters. The agronomic and managerial benefits of land-applying animal manures thus should be balanced by maintaining acceptable water quality.

A variety of management options have been developed to minimize runoff losses of animal manure. Vegetative filter strips (VFS), vegetated areas that can remove pollutants from incoming runoff, are a low-cost example of such options and have successfully been applied to cropland (Dillaha et al., 1989; Magette et al., 1989; Michelson and Baker, 1993), feed lots (Westerman and

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Overcash, 1980; Young et al., 1980; Dickey and Vanderholm, 1981; Edwards et al., 1983; Dillaha et al., 1988; Schellinger and Clausen, 1992), and grassed areas (Chaubey et al., 1994, 1995). Depending on parameters such as vegetation characteristics, amount and characteristics of incoming pollutants, type of flow within the VFS, and VFS length, the previously cited studies indicate that VFS can remove as much as 90% or more of the incoming pollutant mass.

There is a need for design procedures that result in adequate VFS effectiveness without making an unnecessary proportion of land unavailable for manure application. In order to be widely applied, the design process should be as simple as possible, and subject to available information on VFS effectiveness and tools available to assess VFS performance. Design procedures for VFS have been developed in some cases, but there are fewer accounts of designing VFS to function downslope of grassed areas treated with animal manures.

Reported studies on water quality impacts of animal manure applied to grassed areas suggest that VFS design for such areas might be much simpler than for cropland. For example, the first post-manure-application runoff event has the greatest impact on runoff quality; after two or three runoff events, runoff concentrations of various animal manure constituents have been reported at near-background levels (McLeod and Hegg, 1984; Edwards and Daniel, 1994). Therefore, a VFS might be designed based only on controlling pollutant losses from the first post-application runoff event (i.e., a design event approach), when the majority of pollutant transport generally occurs. If pollutant losses were more uniformly distributed in time, then a design event approach would not apply, and VFS design

would be complicated by the need to estimate pollutant losses for several runoff events. The effects of buildup of pollutants (especially sediment) on VFS effectiveness should be minor for grassed areas relative to cropland or feedlots. In comparison to cropland, TSS concentrations in runoff from grassed areas receiving animal manures are very low (Giddens and Barnett, 1980; McLeod and Hegg, 1984; Edwards and Daniel, 1993a, 1994; Storm et al., 1992) and are probably mostly organic, and thus biodegradable. The nutrient export from such can be quite low in comparison to the amount applied (Westerman et al., 1983; McLeod and Hegg, 1984); thus, there should be little danger of a build-up of nutrients that might subsequently degrade VFS performance. There is also information to indicate that both N and P can be transported in runoff from grassed areas primarily in soluble rather than particulate form (Edwards et al., 1996). If such is the general case, then VFS should be designed on the basis of infiltration and other pollutant removal mechanisms rather than on the basis of deposition of solid-phase pollutants. Other recent findings (Edwards et al., 1996) indicate that under some conditions, concentrations of various animal manure constituents in runoff from grassed areas do not vary significantly with overland flow lengths greater than 3 m, a finding that could further simplify the VFS design process by eliminating any need to adjust concentrations on the basis of overland flow length.

The objective of this work was to develop a readily applicable procedure for designing VFS to remove soluble animal manure constituents from runoff from pasture or meadow land uses. The procedure capitalizes on previous findings with respect to quality of water from grassed areas by using the assumptions that (1) pollutant transport is primarily in soluble forms, (2) no build-up of nutrients or solids will occur to a degree that would negatively affect VFS performance, and (3) only the first post-application runoff event is significant in terms of runoff quality. The design procedure that will be discussed and demonstrated can be applied with minimal inputs and computations. However, it does depend on parameters that may be best determined through governmental agency policy decisions.

DESIGN ALGORITHM

PRIMARY EQUATIONS

The primary equation used in VFS design is that developed by Overcash et al. (1981):

$$C_X = C_B + \left(C_O - C_B\right) e^{\left(\frac{1}{1-D}\right) \ln \left(\frac{1}{1+K}\right)} \qquad (1)$$

where

C_X = concentration (mg/L) of the pollutant exiting the VFS

C_O = concentration (mg/L) of pollutant entering the VFS

C_B = background concentration (mg/L)

D = ratio of infiltration to runoff

K = ratio of VFS length to manure-treated length

$$D = \frac{I}{R} = \frac{R - Q}{R} \qquad (2)$$

$$K = \frac{X}{W} \qquad (3)$$

where

I = infiltration (mm)

R = rainfall depth (mm)

Q = runoff depth (mm)

X = VFS length (parallel to the direction of runoff, m)

W = manure-treated length (parallel to the direction of runoff, m) (fig. 1)

Equation 1 was developed by considering infiltration of soluble pollutants to be the only treatment mechanism operative in the VFS and by assuming that (1) rainfall and infiltration are at steady-state, (2) rate of pollutant mass entry into the buffer zone is a constant proportional to D, and (3) complete mixing of rainfall and runoff occurs. Equation 1 is thus applicable to any pollutant (whether from organic or inorganic fertilizers) that is transported largely in soluble form and is conservative during the time step considered.

Mass transport of pollutants exiting the VFS can be computed by noting that the total volume of runoff, V, per unit VFS width is:

$$V = Q (W + X) \qquad (4)$$

which results in V having units of L/m VFS width. Since mass transport is the product of runoff volume V and pollutant concentration, mass transport of pollutants exiting the VFS is given by:

$$M_X = \frac{Q(W + X)}{1,000,000} \left[C_B + \left(C_O - C_B\right) e^{\left(\frac{1}{1-D}\right) \ln \left(\frac{1}{1+K}\right)}\right] \qquad (5)$$

where M_X is mass transport per unit VFS width (kg/m) of the pollutant exiting the VFS. The factor $1/1,000,000$ in the first term of equation 5 is necessary to convert milligrams to kilograms. Equations 1 and 5 enable estimation of pollutant concentrations and mass transport in runoff exiting a VFS as a result of both background and fertilizer contributions.

Overcash et al. (1981) also developed equations to express reductions in pollutant concentration and mass transport attributable to the VFS, given by:
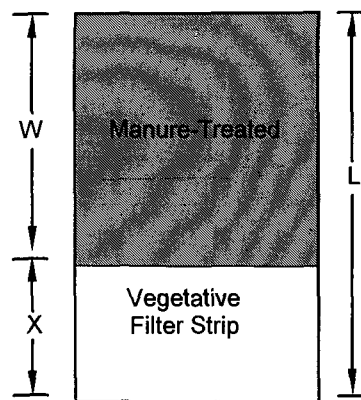

Figure 1–Definition of terms for VFS design.

$$p_C = \left[1 - e^{\left(\frac{1}{1-D}\right)\ln\left(\frac{1}{1+K}\right)} \right] \qquad (6)$$

and

$$p_M = \left[1 - (1+K)\, e^{\left(\frac{1}{1-D}\right)\ln\left(\frac{1}{1+K}\right)} \right] \qquad (7)$$

where p_C and p_M are the reductions (as proportions of incoming values) in concentration and mass transport, respectively, of pollutants entering the VFS. The relative reductions in pollutant concentrations and mass transport thus depend only on K and D and not C_B, C_O, or magnitudes of R and I. Equations 1 and 5 through 7 provide a framework for designing VFS to achieve a desired pollutant concentration or mass transport, or to achieve a desired reduction in pollutant concentration or mass transport.

Design of VFS to achieve some allowable concentration goal (fixed value or proportional reduction of incoming) is approached by solving equations 1 and 6 for K, leading to:

$$K = \left(\frac{C_A}{C_O - C_B} \right)^{D-1} - 1 \qquad (8)$$

and

$$K = (1 - p_C)^{D-1} - 1 \qquad (9)$$

where C_A is the allowable above-background concentration (mg/L) of the pollutant exiting the VFS. If C_B can be taken as negligible in comparison to C_O, then equation 8 simplifies to:

$$K = \left(\frac{C_A}{C_O} \right)^{D-1} - 1 \qquad (10)$$

If the goal of installing VFS is to reduce pollutant mass transport to a fixed per-unit-area mass or by some fixed proportion of incoming mass transport, then the background and pollutant mass transport can be separated in equations 5 and 7, and VFS length can be determined from the equations' manure transport components as:

$$X = \left[\frac{1,000,000\ M_A W^{\frac{1}{D-1}}}{(R-I)(C_O - C_B)} \right]^{\frac{D-1}{D}} - W \qquad (11)$$

and

$$K = \left(\frac{1}{1 - p_M} \right)^{\frac{1-D}{D}} - 1 \qquad (12)$$

where M_A is the allowable above-background mass transport (kg/m VFS width) of the pollutant exiting the VFS. Again, if C_B is small in comparison to C_O, then equation 11 may be simplified to:

$$X = \left[1,000,000\, \frac{M_A W^{\frac{1}{D-1}}}{(R-I)C_O} \right]^{\frac{D-1}{D}} - W \qquad (13)$$

The solutions to equations 5 and 7 for total (background and manure) mass transport are not presented because (1) assuming equal background pollutant concentrations for both the contributing area and VFS, the VFS can be effective in controlling only the fertilizer contribution to total pollutant concentrations and not the background contribution, and (2) the equations are implicit in K.

DETERMINATION OF INPUT VARIABLES

Input data requirements can be minimal when the VFS are designed to achieve only fixed proportions of reduction in incoming concentrations or mass transport, in which case the only inputs are D and p_C or p_M. A policy decision by some agency is needed to provide target values of p_C, p_M, C_A, and/or M_A. The resulting values should properly account for the desired status of the water that the VFS are to help protect, the economics involved, and other variables. Otherwise, the VFS might be inadequate for the pollutant(s) of interest or might not provide sufficient water quality improvement to be economically justifiable. Determining the best values of p_C, p_M, C_A, and/or M_A is a complex subject and is outside the scope of this article. We assume that the values will have been established and are available.

The value of D will, as a practical matter, have to be estimated on the basis of some standard conditions by some method of partitioning rainfall into infiltration and runoff. The Natural Resources Conservation Service (NRCS) Curve Number method (SCS, 1972) is used very widely in practical hydrology, and serves as the foundation for this procedure. Runoff is calculated in the Curve Number method from:

$$Q = \frac{(R - 0.2S)^2}{R + 0.8S}, \quad R > 0.2S \qquad (14a)$$

$$Q = 0, \qquad\qquad R \le 0.2S \qquad (14b)$$

where S is sometimes referred to as the maximum soil water retention parameter and is computed from:

$$S = \frac{25400}{CN} - 254 \qquad (15)$$

where CN is the Curve Number. Both runoff depth Q and S have units of millimeter. The NRCS has tabulated values of CN for pasture and meadow that depend on the hydrologic soil group (HSG; A through D with A being least pervious and D the most) and, for pasture, hydrologic condition of the land area (poor, fair, or good). Methods of adjusting CN based on antecedent rainfall condition (ARC; I through III with I denoting least rainfall received in the past five days and III the most) are also available (SCS, 1972). While the HSG for a particular application is certainly fixed, policy decisions might again be necessary to fix standard values of the other variables since hydrologic condition can vary

with time and since a design rather than observed or historical ARC is required. A design value of R is similarly required. The simplest way of expressing R is probably in terms of a return period and rainfall duration, e.g., R might be specified as the two-year, 0.5-h rainfall. This approach would facilitate associating probabilities with the protection the VFS is to provide and, at the same time, ensure that the value of R is based on a particular location. Given HSG, hydrologic condition, ARC, and R, a storm-average value of D can be computed from:

$$D = \frac{R-Q}{R} \qquad (16)$$

Acquiring the necessary input variables can be more difficult when the VFS are to be used to achieve fixed concentrations or mass transport. Similar to previous discussion, the target values of C_A and M_A and the design value for D will have to be determined, requiring a policy decision. Obtaining values of C_B and C_O will also be problematic. Data on C_B might be available from published studies or monitoring reports, but the general applicability of the data could be questionable. Data on C_O for various animal manures is even more sparse and variable. Studies that demonstrated the effects of application rate, rainfall intensity, soil, interval between application and rainfall, and other variables have been reported (e.g., Westerman et al., 1983; Edwards and Daniel, 1992, 1993a, b), and these studies often found high sensitivity of runoff concentrations to such variables. However, there is more information available on "near-worst-case scenarios" than on more typical situations. This information can provide some quantitative basis for conservative design of VFS. For example, Edwards and Daniel (1993a) presented regression equations for estimating runoff concentrations of various poultry manure constituents as a function of application rate for simulated rainfall occurring one day
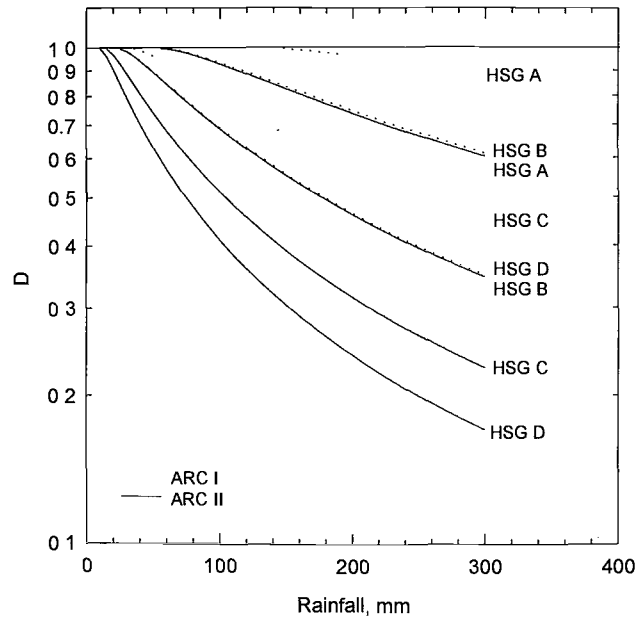

Figure 3–Ratio of infiltration to rainfall (D) as a function of rainfall, hydrologic soil group (HSG), and antecedent rainfall condition (ARC) for pasture in fair condition.

following manure application. If such "near-worst-case" situations provide the basis for determining C_O, then C_B might be assumed negligible without appreciable impact on the resulting VFS design and thus simplify the design procedure.

GRAPHICAL DETERMINATION OF VFS LENGTH

Figures 2 through 5 depict the solution of equation 16 for pasture land uses with good, fair, and poor hydrologic conditions and for meadow land use, respectively, for all HSGs. Only solutions for ARCs I and II are given, because (1) manure application permits (when applicable) usually
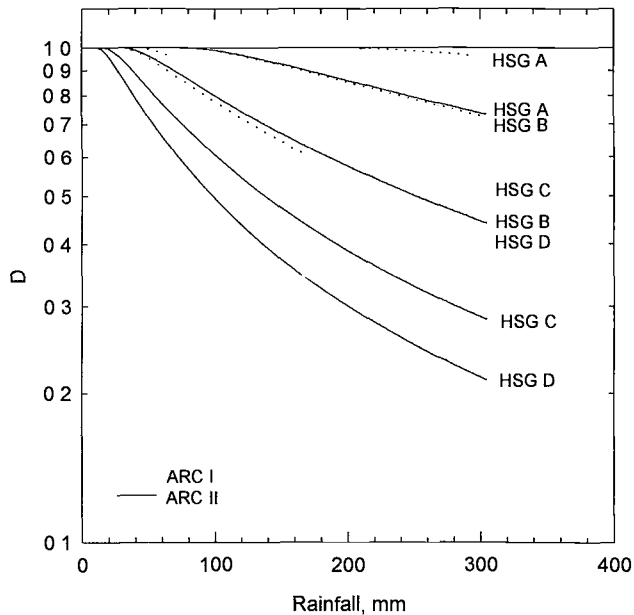

Figure 2–Ratio of infiltration to rainfall (D) as a function of rainfall, hydrologic soil group (HSG), and antecedent rainfall condition (ARC) for pasture in good condition.

Figure 4–Ratio of infiltration to rainfall (D) as a function of rainfall, hydrologic soil group (HSG), and antecedent rainfall condition (ARC) for pasture in poor condition.
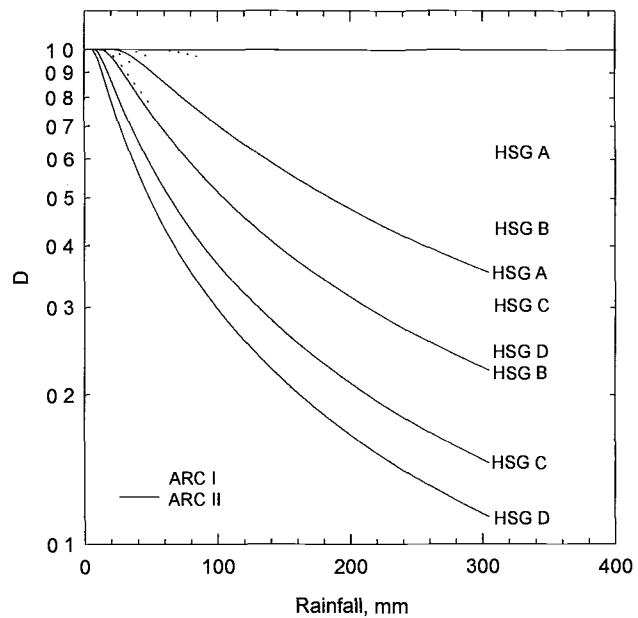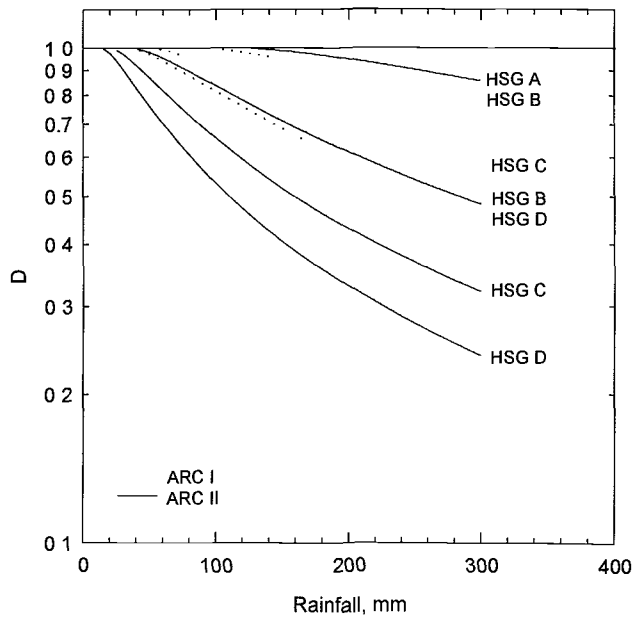
Figure 5–Ratio of infiltration to rainfall (D) as a function of rainfall, hydrologic soil group (HSG), and antecedent rainfall condition (ARC) for meadow.
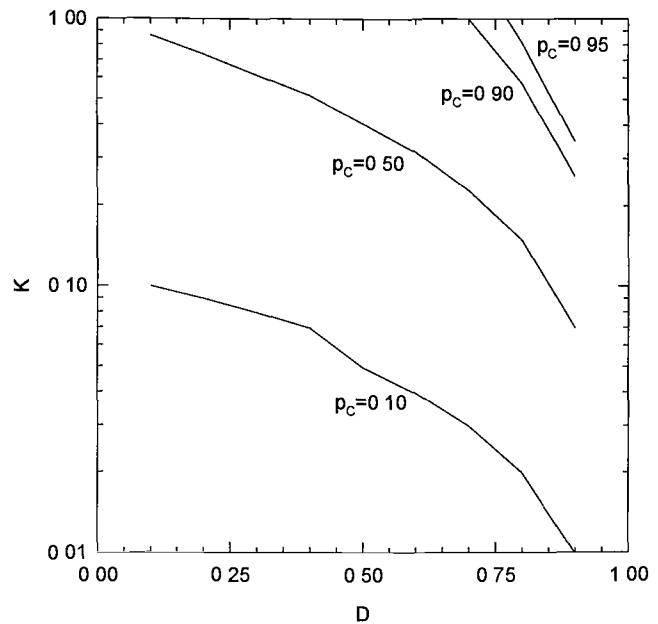

Figure 6–Ratio of VFS length to manure-treated length (K) as a function of the ratio of infiltration to runoff (D) and concentration reduction as a proportion of incoming (p_C).

prohibit application to very wet soils and (2) the relative trafficability of wet soils tends to preclude manure application when antecedent rainfall is high. These curves allow determination of D for given land use, HSG, ARC, and R assuming that the standard values of CN apply. If observed rainfall-runoff are available, or if there is other information that justifies use of different CN values, then new figures would be required.

In the cases for which a fixed proportion reduction in either concentration or mass transport is desired, complete graphical solutions for VFS length are possible since K depends only on D and p_C or p_M. Figures 6 and 7 provide solutions for K that correspond to a given value of D and selected values of p_C and p_M, respectively. Additionally, when the VFS are to be used to achieve some allowable concentration, figure 6 can be used to solve for VFS length by noting from equations 8 and 9 that:

$$1 - \left(\frac{C_A}{C_O - C_B} \right) = p_C \qquad (17)$$

In situations where the length of land available for both manure treatment and VFS is fixed, the area allotted to the VFS must be created from the area that would normally have received manure. The values of X and W must therefore sum to the total available field length L. The length of VFS that is required for a given K and for a fixed total length L can be determined from figure 8 except when the VFS is intended to achieve some allowable mass transport. If the VFS is to achieve an allowable mass transport, then equation 13 must be solved iteratively by computing X_1 for $W = L$, X_2 for $W = L - X_1$, etc.

EXAMPLE APPLICATIONS

In this section, the VFS design algorithm is applied to a hypothetical field in northwestern Arkansas. The field is a pasture with a HSG of C. The design rainfall event will be the two-year, 0.5-h rainfall amount (approximately 50 mm), the design ARC will be taken as II, and the design hydrologic condition will be assumed good. It will be
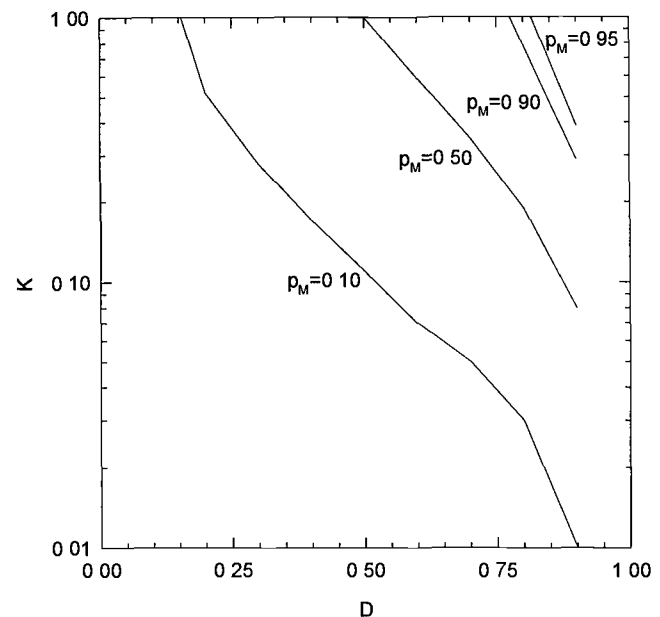

Figure 7–Ratio of VFS length to manure-treated length (K) as a function of the ratio of infiltration to runoff (D) and mass transport reduction as a proportion of incoming (p_m).
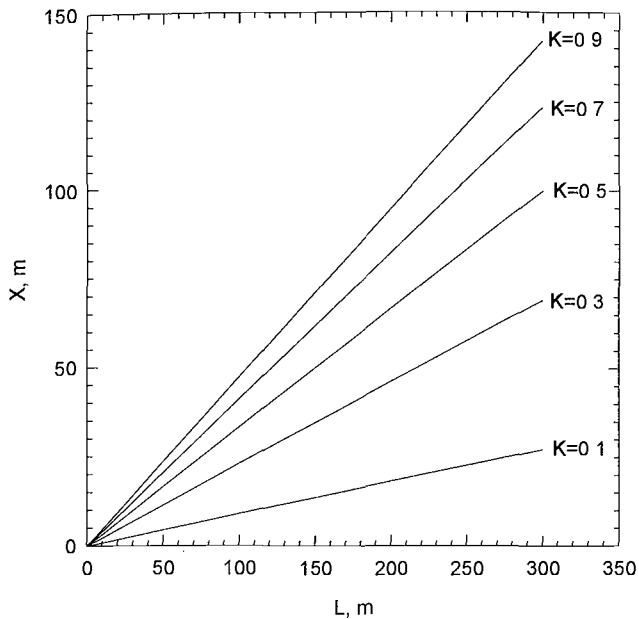
Figure 8–The VFS length (X) as a function of total field length (L) and the ratio (K) of X to manure-treated length.

further assumed that the VFS is to be used to control runoff losses of PO_4-P from surface-applied poultry litter. The design procedure will be used to determine the VFS length required to: (1) reduce exiting runoff PO_4-P concentration to 50% of incoming, (2) reduce runoff PO_4-P concentration to 1 mg/L above background PO_4-P concentration, (3) reduce PO_4-P mass transport to 50% of incoming, and (4) reduce PO_4-P mass transport to 0.3 kg/ha above background PO_4-P mass transport. The incoming and background concentrations (C_O and C_B, respectively) of PO_4-P are taken as 11.5 and 1.4 mg/L, respectively (Edwards and Daniel, 1994), and the manure-treated field length is assumed to be 100 m. The VFS will be created from the existing 100 m length of field rather than added to it.

CASE 1. PROPORTIONAL REDUCTION IN INCOMING CONCENTRATION

From figure 2 (pasture, good hydrologic condition), D may be determined from the HSG C, ARC II curve as 0.85, indicating that only 15% of the rainfall is translated to runoff. Entering figure 6 with D = 0.85, reading up to the p_C = 0.50 curve, and then reading to the left to the K scale gives a K-value of 0.10. If additional area were available to create the VFS, then the appropriate length would be (100 m) (0.1) or 10 m. Since only 100 m are available for both manure-treated and VFS lengths, figure 8 is needed. Entering figure 8 from the horizontal scale with L = 100 m, reading up to the K = 0.1 curve, then to the left to the X-scale results in an X-value of 9 m, leaving 91 m available for manure application.

CASE 2. ALLOWABLE CONCENTRATION

As pointed out earlier, the available information on C_O, C_B, and C_A allow computation of an equivalent proportion reduction in incoming concentration through equation 17. From equation 17, $(1 - p_C)$ is determined as 0.10, so p_c = 0.90. Figure 6 may be used with the previous D value of

0.85 to determine K as approximately 0.4. Upon interpolating between the K = 0.3 and K = 0.5 curves in figure 8, X is determined as approximately 30 m.

CASE 3. PROPORTIONAL REDUCTION IN INCOMING MASS TRANSPORT

Figure 7 may be used. Entering the figure with D = 0.85 and p_M = 0.5, the corresponding K-value is 0.13. From figure 8, X may be determined as 12 m. Comparing the results from cases 1 and 3 illustrates that a greater VFS length is required to reduce mass transport by a given proportion than to simply reduce concentration by the same proportion, since concentration is reduced by both dilution and infiltration.

CASE 4. ALLOWABLE MASS TRANSPORT

Equation 11 must be used. The allowable mass transport above background, M_A, must be converted to a per-unit-field width basis, yielding M_A = 0.003 kg/m field width. The runoff (R-I) is 15% of R, or 7.5 mm. From given information, the quantity ($C_O - C_B$) is 10.1 mg/L. For the first iteration, W is set to 100 m, resulting in an X-value of 18 m. For the second iteration, W is set to 82 m, giving an X of 11 m. After the fourth iteration, a stable X-value of 13 m is obtained.

DISCUSSION

The status of the water to be protected by the VFS should guide the design of the VFS. In other words, the pollutant that the VFS is intended to control should be identified on the basis of the water to be protected, particularly when the VFS is designed on the basis of an absolute concentration or mass transport. It would be pointless, for example, to design a VFS for N control when the water to be protected by the VFS is P-limited. The selected values of required concentration or mass transport reduction and allowable concentration or mass transport should similarly be chosen to reflect the needs of the water that is to be protected by the VFS, rather than simply selecting some arbitrary number that rounds to a multiple of 10. These decisions are essential in the VFS design process. They establish the purpose and goal of the VFS, and the design follows from these preliminary parameters.

Assuming that only infiltration is responsible for improvements in runoff exiting a VFS limits the approach in terms of pollutants. The methods presented in this article are not intended to be applicable to pollutants such as suspended solids, particulate organic carbon, bacteria, or any other pollutants that are not transported primarily in soluble form. Although this article addressed only manure-treated areas as pollutant sources, the procedures can be applied to other pollutant sources (e.g., inorganically fertilized areas) as long as the assumption of pollutant transport in soluble form is justifiable.

The VFS design procedure is sensitive to runoff estimation. The algorithm used to separate infiltration and runoff is thus an important component of the process. The use of the Curve Number method in computing average D values obviously gives rise to trade-offs between practicality and accuracy. If more detailed data such as Green-Ampt infiltration parameters are available, the resulting improvement in accuracy might justify use of

more complex rainfall-runoff components. Use of a different rainfall-runoff component would affect only the value of D used in the design process; other process components, such as the determination of K, would be affected only to the extent that D is affected.

Designing VFS on the basis of infiltration has significant implications on how they should be applied in a practical situation. It follows that if infiltration is the only significant pollutant removal mechanism, then the VFS will be most effective when flow is shallow and diffuse. In other words, given a fixed flow overland rate, less infiltration will occur when the flow is concentrated in a channel than if the flow occurs as diffuse overland flow. Dillaha et al. (1986) have strongly pointed out the dependence of VFS effectiveness on the flow regime (concentrated versus diffuse) within the VFS, noting that VFS effectiveness decreases dramatically following establishment of concentrated flow regions within the VFS. Therefore, VFS should be laid out on the contour and upslope of identifiable concentrated flow channels. This implies that the topography of the land, rather than field boundaries, should dictate the layout of VFS.

Laying out VFS on the basis of topography will obviously be more complicated for irregularly sloping fields than for those with a constant, uniform slope. Unfortunately, VFS applications to areas with regular slopes (fig. 9) will be rare in comparison to irregular slopes. In the case of irregularly sloping fields, it is possible to compute several required VFS lengths for corresponding overland flow lengths, and superimpose the VFS length requirements on a map; the results will provide the trace of the VFS. As an alternative, the VFS length corresponding to the longest overland flow length could be used throughout the field to simplify the design process and obtain a conservative design. A schematic example of VFS installation for an irregularly sloping field is given in figure 10.

Experimental evidence indicates that the grassed VFS will not be self-fertilizing when applied to pasture or meadow areas receiving animal manures at agronomic rates. The studies cited in the introductory section found
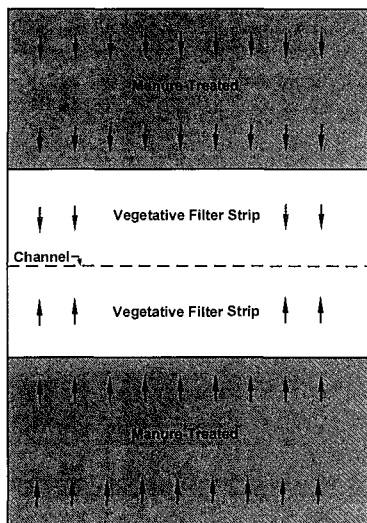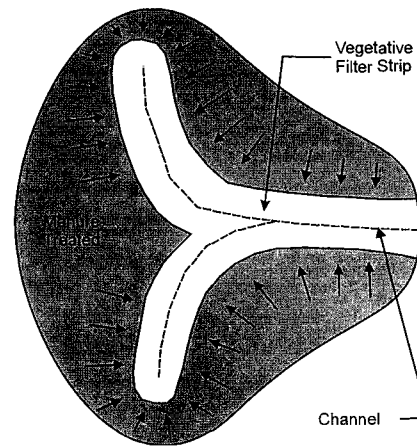

Figure 10–Example VFS installation for area with irregular topography. Small arrows indicate direction of overland flow.

that runoff losses of nutrients from treated fields were typically considerably less than 10% of the amounts applied. Thus, only a small fraction of the agronomic nutrient application rate may be potentially available to the entire VFS, with the majority of soluble nutrients infiltrating in the most upstream portion of the VFS. The VFS may therefore require fertilization to maintain a healthy stand of forage. The fertilizer could be applied to the VFS after the upslope area has been fertilized and has experienced at least one significant runoff event. This would enable the VFS to function properly during the first runoff event following fertilization of the upslope area, minimize total mass losses from the field, and maintain the VFS. The soil status of the VFS should also be monitored if there is a potential that the VFS fertilizer will cause an accumulation of the pollutant the VFS is designed to control. Applying animal manure as VFS fertilizer, for example, can cause elevated soil P within the VFS and therefore increase the background P concentration in runoff originating from within the VFS. Such a practice might not be desirable if the VFS were installed for runoff P control.

SUMMARY

This article presents a method of designing VFS for grassed areas receiving surface-applied fertilizers. The method makes use of available information on pollutant transport from such areas by considering infiltration to be the only significant mechanism of pollutant removal and by keying on the first post-application runoff event. The major algorithms in the method include the Overcash et al. (1981) equation for predicting concentrations of pollutants in runoff exiting a VFS and the SCS (1972) Curve Number method for estimating runoff. The data requirements for the algorithm can be minimal, depending on whether the VFS is to achieve a fixed pollutant concentration or mass transport, or some reduction in concentration or mass transport as a proportion of incoming values. Graphical design tools are presented to eliminate the need for manual computation in selected cases.

The design algorithm carries the limitations of how runoff is estimated as well as how values of incoming and background pollutant runoff concentration (C_O and C_B, respectively) are determined. Application of the algorithm

Figure 9–Example VFS installation for area with regular topography. Small arrows indicate direction of overland flow.

to a practical situation involving irregular topography can also be relatively difficult, although to no greater degree than would be experienced with more comprehensive methods. The greatest problem in implementing the algorithm, however, is identification of parameters such as the degree of protection that the VFS are designed to achieve and the design rainfall event. These parameters are often based on policy decisions but are critical to establish the purpose of the VFS, which is the starting point in the design process.

The relative simplicity of design procedure described in this article, as pointed out, is possible only through several assumptions necessary to "idealize" the situation to the greatest degree practical. In actuality, of course, VFS constitute complex, dynamic, and heterogenous systems, only the rudiments of which can be described by the equations presented herein. It is therefore essential that the necessary assumptions be noted and validated prior to using the methods of this article to ensure optimal results of implementing this process

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