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DEVELOPMENT OF A BUFFER ZONE EVALUATION MODEL/PROCEDURE

by

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FINAL REPORT

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EXECUTIVE SUMMARY

A procedure is presented for evaluating the impacts of proposed vegetative buffer modifications on buffer effectiveness. The procedure is based on the hydraulic and detention models developed by Phillips for evaluating buffer effectiveness. Phillips's original models were modified to correct several limitations encountered. The modified models consider the effects of concentrated flow and vegetative uptake on buffer performance.

The proposed model is relative simple in concept and application and is suitable for use by planners. All of the data required by the model can be collected on site or can be estimated from the literature. Labratory analysis of soil and bank samples, however, will greatly improve model reliability with respect to nutrient losses. In areas with shoreline erosion, the procedure also allows the benefits of shoreline control to be considered.

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INTRODUCTION

The original purpose of this project was to develop a qualitative technique for evaluating vegetative buffer effectiveness with respect to sediment and nutrient removal. The technique was intended for use by planners in evaluating the relative effectiveness of various buffer zone modification schemes. After field testing of the proposed procedure, it was agreed that the project objectives would be expanded to account for the effects of vegetative buffer modification due to shoreline stabilization practices. This was necessary because installation of shoreline stabilization systems may reduce vegetative buffer effectiveness by reducing vegetative buffer length, increasing vegetative buffer slope, and disturbing buffer vegetation. However, the benefits of shoreline stabilization for reduced sediment and nutrient losses due to control of shoreline erosion can more than compensate for reduced vegetative buffer effectiveness in most cases.

The resulting assessment process allows impact predictions to be made for site specific conditions of individual vegetative buffer alterations as well as relative effectiveness comparisons between vegetative buffers. The vegetative buffer zone evaluation procedure is designed to use soil survey data and other parameters including slope and surface roughness. The site evaluation methods will consider both surface runoff and subsurface flow within the buffer.

Specific objectives of the project were to:

1. Select a vegetative buffer assessment methodology best suited for soils and shoreline conditions in Virginia.

2. Modify the method as required to improve the method's suitability for Virginia conditions.

3. Determine the availability of physical parameters necessary to apply the selected buffer zone evaluation methodology. Define ranges of parameters suitable for application in Virginia's coastal zone.

4. Test the proposed methodology on specific sites in Virginia.

5. Prepare a final report and guide detailing the development, use and limitations of the proposed methodology.

LITERATURE REVIEW

Vegetative buffers (also referred to as vegetative filter strips, grass filter strips, buffer strips, vegetative buffers, riparian buffer zones, filter strips, etc.) are bands of planted or indigenous vegetation, situated between pollutant source areas and receiving waters. They are presumed to remove sediment and chemicals from runoff and ground water interacting with the buffer. Pollutant removal in vegetative buffers is accomplished by a variety of physical, chemical, and biological processes. These processes are poorly understood and there is considerable uncertainty as to the effectiveness of vegetative buffers in removing pollutants from surface runoff and ground water. Currently, there are no standards or widely accepted methods for evaluating vegetative buffer effectiveness. Consequently, it is difficult if not impossible to determine how effective vegetative buffers are in protecting water quality.

Numerous short-term studies have found that vegetative buffers are initially very effective in removing sediment and sediment-bound pollutants from surface runoff under shallow sheet flow conditions. The long-term (more than one-year) effectiveness of vegetative buffer for pollutant removal, however, has not been investigated very extensively. Riparian buffer zone design procedures, proposed over the past 10-years, have been research oriented and based on short-term experimental studies. These studies did not consider the long-term effects of sediment and nutrient accumulation in vegetative buffers. These studies and design methods also generally ignore the effects of concentrated flow conditions on vegetative buffer performance. This is unfortunate, as most flow in the real world will enter vegetative buffers as concentrated flow rather than the shallow sheet flow used in model development (Dillaha et al., 1989). Consequently, those equations that do exist, generally overestimate vegetative buffer effectiveness with respect to sediment and nutrient removal because they do not consider the effects of concentrated flow and the accumulation of sediment and nutrients in vegetative buffers over time.

The major pollutant removal mechanisms associated with vegetative buffers involve changes in flow hydraulics that enhance the opportunity for the infiltration of runoff and pollutants into the soil profile, deposition of total suspended solids (TSS), filtration of suspended sediment by vegetation, adsorption on soil and plant surfaces, and absorption of soluble pollutants by plants. For these mechanisms to be effective, it is essential that runoff pass slowly through the vegetative buffer to provide sufficient contact time for the removal mechanisms to function.

Infiltration is one of the most significant removal mechanisms affecting vegetative buffer performance. Infiltration is important since many pollutants associated with surface runoff enter the soil profile in the buffer area with infiltrating water. Once in the soil profile, many pollutants, particularly N and P, are removed by a combination of physical, chemical, and biological processes. Infiltration is also important because it decreases the amount of surface runoff, thus reducing the ability of runoff to transport pollutants. Since infiltration is one of the more easily quantifiable mechanisms affecting buffer performance, many vegetative buffers have been designed to allow all runoff from design storms to infiltrate into the buffer (Midwest Plan Service, 1985). This approach results in large land requirements because it ignores other removal mechanisms.

Vegetative buffers also purify runoff through the process of deposition. Because vegetative buffers usually offer high resistance to shallow overland flow, they decrease the velocity of overland flow immediately upslope and within the buffer, causing significant reductions in sediment transport capacity. If the transport capacity is less than the incoming suspended solids load, then the excess suspended solids may be deposited and trapped within the buffer. Sediment-bound pollutants will also be removed during the deposition process.

The filtration of solid particles by vegetation during overland flow and the absorption and adsorption processes are not as well understood as the infiltration and deposition processes. Filtration is probably most significant for the larger soil particles, aggregates, and organic particles while adsorption is thought to be a significant factor with respect to the removal of dissolved pollutants. The major questions concerning adsorption and absorption involve their long-term effectiveness as nutrients accumulate in the buffer (Lee et al., 1989; Dillaha et al., 1989).

Sediment Transport in Vegetative Buffers

Historically, the design of vegetative buffers has been based almost entirely upon local custom. Wilson (1967) presented the results of a sediment trapping study in grass buffers which gave optimum distances required to trap sand, silt, and clay in flood waters on flat slopes. He concluded that grass buffer length, sediment load, flow rate, slope, grass height and density, and degree of vegetative submergence all affect sediment removal. Neibling and Alberts (1979) used a rainfall simulator on experimental field plots with a slope of 7% to show that 0.6, 1.2, 2.4, and 4.9 m long grass buffers all reduced total sediment discharge by over 90% from a 6.1 m long bare soil area. Discharge rates for the clay size fraction were reduced by 37, 78, 82, and 83%, for the 0.6, 1.2, 2.4, and 4.9 m grass buffers, respectively. Significant deposition of solids was observed to occur just upslope of the leading edge of the grass buffer and 91% of the incoming sediment load was removed within the first 0.6 m of the grass buffer. Sediment discharge of clay sized particles (<0.002 mm) was reduced 37% by the 0.6 m strip. No equations were presented to estimate the influence of parameters on sediment yield.

The most comprehensive research to date on sediment transport in vegetative buffers has been conducted by a group of researchers at the University of Kentucky (Barfield et al., 1977; 1979; Kao and Barfield, 1978; Tollner et al., 1976; 1978; 1982; Hayes et al., 1979a,b; 1982). Tollner et al. (1976) presented design equations derived from experimental studies relating the fraction of sediment trapped in simulated vegetative media to the mean flow velocity, flow depth, particle fall velocity, filter length, and the spacing hydraulic radius (a parameter similar to the hydraulic radius in open channel flow that is used to account for the effect of media spacing on flow hydraulics). The Kentucky researchers reported high trapping efficiencies as long as the vegetative media was not submerged, but trapping efficiency decreased dramatically at higher runoff rates that inundated the media. The Kentucky researchers, like Neibling and Alberts (1979), observed that much of the sediment deposited just upslope of the filter and within the first meter of the filter, until the upper portions of the filter were buried in sediment. Subsequent flow of sediment into the filter resulted in the advance of a wedge-shaped deposit of sediment down through the filter. The Kentucky researchers did not consider nutrient trapping or the long-term effectiveness of vegetative buffers.

Hayes and Hairston (1983) used field data to evaluate the Kentucky model for multiple storm events in Mississippi. Eroded material from fallow cropland subject to natural rainfall was used as a sediment source. 'Kentucky 31' (*Festuca arundinacea*) tall fescue trimmed to 10 cm was used and the model predictions agreed well with the measured sediment discharge values.

Kao et al. (1975) proposed a vegetative buffer arrangement in which grass strips were alternated with strips of bare ground to solve the problems associated with sediment inundation of the filter and the killing of vegetation. Kao indicated that with the proper vegetative buffer area to source area ratio, most of the trapped sediment would be retained in the bare area just upslope of the buffer. The trapping of sediment upslope of the buffer maintained high buffer efficiencies and enabled periodic removal of deposited sediment without damaging the buffer. Kao's results were based upon laboratory studies with artificial media and were not tested in the field.

Nutrient Transport in Vegetative Buffers

Nutrient movement through vegetative buffers has been investigated by several researchers but no comprehensive design methods have been presented. Doyle et al. (1977) applied dairy manure to 7 x 5 m fescue plots on a Chester silt loam (fine-loamy, mixed, thermic, Typic Hapludult) soil with a slope of 10%. Dissolved nutrient concentrations were measured after passing through 0.5, 1.5, and 4.0 m of fescue buffer strips. Dissolved P was reduced by 9, 8, and 62% after passage through 0.5, 1.5, and 4.0 m buffers, respectively. Nitrate (NO_3) losses decreased by 0, 57, and 68%, respectively, but ammonia (NH_3) concentrations increased with increasing filter length presumably due to the release of NH_3 from decomposing organic N, which was trapped in the filter previously.

Young et al. (1980) used a rainfall simulator to study the ability of vegetative buffers to control pollution from feedlot runoff. Field plots were constructed on a 4% slope with the upper 13.7 m in an active feedlot and the lower 27.4 m planted in either corn (*Zea mays*), oats (*Auena sativa*), orchardgrass, (*Dactylis glomerata*) or a sorghum-sudangrass (*Sorghum vulgare-Sorghum sudanensis*) mixture. Water was applied to the plots to simulate a 25-year, 24-hour duration storm. Total runoff, sediment, P and N were reduced by 81, 66, 88, and 87%, respectively, by the orchardgrass and by 61, 82, 81, and 84%, respectively, with the sorghum- sudangrass mixture. The authors concluded that vegetative buffers were a promising treatment alternative.

Thompson et al. (1978) studied the effectiveness of orchardgrass buffers on a sandy loam soil in reducing nutrient loss from the application of dairy manure to frozen or snow-covered orchardgrass plots. Fresh dairy manure was applied to 24 m orchardgrass plots and runoff quality determined after traveling through 12 and 30 m of additional orchardgrass during natural runoff events. Total P, total Kjeldahl nitrogen (TKN), and N losses were reduced by an average of 55, 46, 41, and 45%, respectively, after passing through 12 m of filter. A 36 m filter resulted in P, NO_3, TKN, and N reductions of 61, 62, 57, and 69%, respectively. Nutrient concentrations in the runoff from the 36 m filters approached that from control plots to which no manure had been added. Bingham et al. (1978) applied poultry manure to 13 m long fescue grass plots on an eroded Cecil clay loam (clayey, kaolinitic, thermic Typic Hapludult) with 6-8% slopes. Buffer length/waste area length ratios of about 1.0 were reported to reduce pollutant loads to near background concentrations. Total P, TKN, NO_3, and total-N were reduced 25, 6, 28, and 28%, respectively.

Edwards et al. (1983) monitored storm runoff for 3 years from a paved feedlot. Storm runoff was measured and sampled as it left the feedlot, after passing through a shallow concrete settling basin, and after passing through two consecutive 30.5 m long fescue buffers. Runoff, TSS, P, and N were reduced by -2, 50, 49, and 48%, respectively, after passing through the first buffer and by an additional -6, 45, 52, and 49%, respectively, after passing through the second buffer. Total runoff from the buffers was greater than the incoming runoff because rainfall rates during runoff events exceeded the infiltration capacity of the buffers. This rainfall excess coupled with the added area of the buffers resulted in increased runoff. Removal efficiencies would have been higher if the settling basin located upslope of the buffer had not removed 54, 41, and 35% of the TSS, P, and N, respectively. Most of these solids and nutrients would have been removed in the buffers because they were either settleable solids or nutrients bound to settleable solids.

Patterson et al. (1977) applied liquid dairy waste through a gated pipe to a fescue buffer on Hosmer silt loam (fine-silty, mixed, mesic Fragiudalf) on a 3.4% slope. After applying dairy waste to the 35 m vegetative buffer for one year, pollutant reductions averaged 42, 38, 7, and 71% for BOD_5, NH_3, PO_4, and TSS, respectively. Nitrate loss from the filter was greater than NO_3 loading to the buffer, presumably due to mineralization of organic N and nitrification of NH_3 that had been trapped in the buffer previously. Paterson et al. (1977) also noted problems with maintaining a good grass cover on the buffer area. They recommended that several buffer areas should be use and rotated on a weekly basis to maintain good grass cover.

Magette et al. (1989) used a rainfall simulator on field plots to study the effectiveness of 4.6 and 9.2 m long grass buffers in removing nutrients and sediment from agricultural runoff. Nutrient removal appeared to decrease as the number of runoff events increased. Gross sediment, N, and P losses in surface runoff were reduced by 52, -15, and 6%, respectively, by the 4.6 m buffers, and 75, 35, and 20%, respectively, by the 9.2 m buffers. The buffers were reported to be much more effective in removing sediment than nutrients. Buffer effectiveness was also reported to decrease with time and with decreasing buffer to source area ratio.

Vegetative Buffer Research in Virginia

Researchers at Virginia Tech (Dillaha et al., 1986; 1987; 1988; 1989; and Lee et al., 1989) used a rainfall simulator to evaluate the effectiveness of grass buffers for the removal of sediment, N, and P from cropland runoff. Simulated rainfall was applied to nine experimental field plots on an eroded Groseclose silt loam soil (clayey, mixed, mesic Typic Hapludalt) with a 5.5 by 18.3 m bare cropland source area and either a 0, 4.6, or 9.1 m long grass buffer (5.5 m wide) located at the lower end of each plot. Fertilizer was applied to the plots at rates of 222 kg/ha of liquid N and 112 kg/ha of P_2O_5 and K_2O. Water samples were collected from the base of each plot and analyzed for sediment and nutrient content. One set of plots was constructed so that flow through the filters was concentrated rather than shallow and uniform. The 9.1 and 4.6 m grass buffers with shallow uniform flow removed 87 and 75% of the incoming suspended solids, 69 and 57% of the incoming P, and 72 and 61% of the incoming N, respectively. Dissolved nutrients in the buffer effluent were sometimes greater than the incoming dissolved nutrient load, presumably due to lower removal efficiencies for dissolved nutrients and the release of nutrients previously trapped in the buffers. Plots with concentrated flow were much less effective than the shallow uniform flow plots, with percentage reductions in sediment and nutrient loadings averaging 23 to 37% less for sediment, 46 to 53% less for N, and 43 to 46%

less for P.

The effectiveness of existing vegetative buffers in the Commonwealth of Virginia was qualitatively evaluated by visiting and observing vegetative buffers on 18 farms in Virginia (Dillaha et al., 1986). Buffers were evaluated by talking with landowners and soil conservationists and walking the length of the buffers to evaluate potential problems. All the vegetative buffers surveyed were composed of grasses and other low growing vegetation and were used in combination with cropland. Almost all the buffers were installed for water quality improvement in conjunction with Virginia's Chesapeake Bay Program. Buffers were rarely used before 1983 on cropland in Virginia because they were not a recognized conservation practice eligible for state or federal cost-sharing money. Buffer performance was generally judged to fall into two categories depending upon the topography of the site. In hilly areas, buffers were judged to be ineffective for removing sediment and nutrients from surface runoff because drainage usually concentrated in natural drainageways within the fields before reaching the buffers. Flow across the buffers during larger runoff producing storms (the most significant in terms of water quality) was therefore primarily concentrated and the buffers were locally inundated and ineffective. This assessment was confirmed by the fact that little sediment was observed to have accumulated in the majority of the buffers observed. Buffers in these areas, while not effective for trapping sediment and nutrients, were judged to be beneficial because they provided effective cover in areas immediately adjacent to streams that are often susceptible to severe localized channel and gully erosion. They also provide a narrow buffer between cropland and streams that may reduce the aerial drift of fertilizers and pesticides to streams during application.

In flatter areas, such as in the Coastal Plain, buffers appeared to be more effective. Slopes were more uniform, and significant portions of stormwater runoff entered the buffers as shallow uniform flow. This observation was supported by the presence of significant sediment accumulations in many of the Coastal Plain buffers surveyed. Several one to three year old buffers were observed that had trapped so much sediment that they were higher than the fields they were protecting. In these cases, runoff tended to flow parallel to the buffers until a low point was reached where it flowed across as concentrated flow. In this situation, the buffers acted more like a terrace than a vegetative buffer. Flow parallel to the buffers also was observed on several farms where moldboard plowing was practiced. When soil was turn-plowed away from the buffers, a shallow ditch was formed parallel to the field. If this ditch was not removed later by careful disking, runoff again concentrated and flowed parallel to the buffer until it reached a low point and crossed as channel flow. Conclusions drawn from the plot studies and on-site assessments of vegetative buffer effectiveness included (Dillaha et al., 1989):

1. Vegetative buffers are effective for the removal of sediment and other suspended solids from cropland runoff only if flow is shallow and uniform and if the buffers have not been previously inundated with sediment.
2. The effectiveness of vegetative buffers for sediment removal appears to decrease with time as sediment accumulates within buffers. This may or may not be a problem in "real world" buffers because vegetation may be able to grow through sediment accumulations.
3. Total N and P in runoff are not removed by vegetative buffers as effectively as sediment. Presumably, much of the N and P in cropland runoff is dissolved or associated with very fine sediment which vegetative buffers can not remove efficiently.
4. Shorter vegetative buffers (<10 m) are not effective in removing dissolved N and P from agricultural runoff. Dissolved P and N losses from the experimental vegetative buffer plots studied were often higher than the inflow, presumably due to the release of P and N trapped in the grass buffers previously.
5. Buffer strips characterized by concentrated or deeper channel type flow are much less effective for sediment, N, and P removal than vegetative buffers with shallow uniform flow. Buffers with concentrated flow were 40 to 60%, 70 to 95%, and 61 to 70% less effective with respect to sediment, P, and N removal than uniform flow plots.
6. Most on-farm vegetative buffers observed during the Virginia Tech study were judged to be ineffective for sediment and nutrient removal. The majority of flow entering the grass portion of the buffers was judged to be concentrated because runoff tended to accumulate in natural drainageways long before reaching the vegetative buffers. This was more of a problem in hilly areas and less of a problem in flatter areas such as the Coastal Plain.

The Virginia Tech researchers concluded that the effectiveness of the experimental vegetative buffers should not be used as a direct indicator of real world vegetative buffer effectiveness because of the concentrated flow problems previously discussed. Concentrated flow effects under real agricultural conditions were estimated to be orders of magnitude greater than those encountered during the experimental field studies (Dillaha et al., 1989).

Vegetative Buffer Models and Design Procedures

Kentucky Filter Strip Model: Barfield et al. (1979) developed a steady state model, the Kentucky filter strip model, for determining the sediment filtration capacity of grass media as a function of flow, sediment load, particle size, flow duration, slope, and media density. Outflow concentrations were primarily a function of slope and media spacing for a given flow condition.

The Kentucky filter strip model was extended for unsteady flow and non-homogeneous sediment by Hayes et al. (1979a). A graphical solution of the Kentucky model was described by Hayes et al. (1982). However, the complexity of the procedure makes solution of the equations difficult unless the sediment is well graded. Methods for determining the values of the hydraulic parameters required by the Kentucky model for real grasses were presented. Using three different types of grasses, model predictions were reported to be in close agreement with laboratory data (Hayes et al., 1978).

A simplified procedure derived from the Kentucky filter strip model was developed for the SCS to estimate the long-term effectiveness of grass filter strips (Hayes and Dillaha, 1992; Dillaha and Hayes, 1992). The procedure estimates the trapping efficiency of grass buffers with respect to sediment but does not consider other types of contaminants or buffer vegetation. The model is fairly simple to use but requires the use of the WEPP model (Lane and Nearing, 1989), which is not yet available to the public, to estimate sediment and surface runoff loadings to the buffer.

CREAMS Model: Agricultural Research Service researchers (Flanagan et al., 1986; Williams and Nicks, 1988) have attempted to evaluate the effectiveness of vegetative buffers for erosion control using the CREAMS model (Knisel, 1980). Williams and Nicks (1988) applied CREAMS to a 1.6 ha watershed in Oklahoma. Filter strip effectiveness was found to be dependent on strip length, Manning's n, slope, and slope shape. The authors concluded that CREAMS can be a useful tool for evaluating vegetative buffer effectiveness in reducing sediment yield. This model, like others mentioned previously, cannot consider the long-term effectiveness of vegetative buffers because it has no way of accounting for sediment accumulations within the vegetative buffer. Consequently, CREAMS would be expected to overestimate long-term sediment trapping. CREAMS also is severely limited by its sediment transport model that tends to overestimate sediment transport. The model also cannot account for concentrated flow effects, and Manning's n is the only factor used to simulate the effects of vegetative buffer vegetation. CREAMS does have nutrient transport submodels, but their use with vegetative buffers has not been reported. In summary, CREAMS was not developed to describe vegetative buffers and use of the model for vegetative buffer design is highly questionable since it does not simulate the principal physical processes affecting transport in vegetative buffers.

GRAPH Model: Lee et al. (1989) developed an event-based model, GRAPH (GRAss PHosphorus), to simulate P transport in vegetative buffers by incorporating chemical transport submodels into the grass filter strip model in SEDIMOT II (Wilson et al., 1984; Warner et al., 1984), a stormwater and sediment transport model developed for strip mine reclamation. The grass filter model in SEDIMOT II was derived from the Kentucky filter strip model, GRASSF, developed by Hayes (1979). GRAPH considers the effects of advection processes, infiltration, biological uptake, P desorption from the land surface to runoff, adsorption of dissolved P to suspended solids in runoff, and the effects of changes in sediment size distribution on P transport. Required data for the model includes: rainfall intensity and duration, an inflow hydrograph, a sediment graph, sediment size distribution, vegetative buffer dimensions and hydraulic characteristics, inflow graphs for dissolved P, P desorption and adsorption reaction coefficients for soil and plant matter, and the P content of each soil particle size class. GRAPH simulates time varying infiltration, surface runoff, sediment yield, particle size distribution, and dissolved and sediment-bound P discharge along with P and sediment trapping efficiencies in vegetative buffers. GRAPH was verified with data from vegetative buffer field plots. Model predictions and observed P transport in grass buffers compared favorably.

Phillips Model: Phillips (1989a,b) presented a theoretical method for evaluating the relative effectiveness of buffer zones in removing sediment, sediment adsorbed chemicals, and dissolved chemicals from surface and subsurface flow. The method does not make absolute predictions of buffer effectiveness but rather estimates the effectiveness of a given buffer relative to a reference buffer. Philips's method predicts the relative effectiveness of buffers for water quality improvement using two models, the hydraulic model and the detention model. Neither of the Phillips models have been validated or tested with field data because they attempt to characterize the long-term effectiveness of buffers and no long-term data on buffers has been collected with which to verify these or any other long-term models.

Phillips Hydraulic Model: The Phillips hydraulic model was developed to describe the transport of sediment and sediment-bound chemicals through vegetative buffer zones. The model assumes that sediment transport through the filter is a function of the energy of overland flow and is based on the Bagnold stream power equation. The detention model equation as originally proposed by Phillips is:

$$\frac{B_b}{B_r}=\left(\frac{K_b}{K_r}\right)\left(\frac{L_b}{L_r}\right)^{0.4}\left(\frac{s_b}{s_r}\right)^{-1.3}\left(\frac{n_b}{n_r}\right)^{0.6} \qquad [1]$$

where: K = saturated hydraulic conductivity of the buffer soils
L = buffer length
s = sin θ, where θ is the slope angle relative to the horizontal
n = Manning roughness coefficient
b = subscript denoting the buffer of interest, and
r = subscript denoting the reference buffer

The hydraulic model is derived as follows. For a given mass of water, Bagnold's stream power equation (Bagnold, 1977) can be used to estimate the sediment transport capacity. That is, the time rate of energy expendature per unit weight of flowing water is:

$$P_u = \frac{pgAL_rVs}{pgAL_r} = Vs \qquad [2]$$

where: p = density of water
g = gravitational constant
A = cross-sectional area of flow
L_r = length of the flow reach
V = mean flow velocity
s = slope of the hydraulic grade line ($\approx \sin\theta$)

For steady state flow conditions, the flow rate per unit width can be expressed as:

$$q = VA = Vy \qquad [3]$$

where y is the steady-state flow depth. Equation [3] can be rearranged to:

$$V = \frac{q}{y} \qquad [4]$$

The average flow velocity can be expressed with Manning's equation as:

$$V = \frac{1}{n} R^{2/3} s^{1/2} \qquad [5]$$

where R is the hydraulic radius of the flow. For shallow sheet flow conditions, $R = y$. Multiplying both sides of Equation [5] by the area per unit width gives the flow rate per unit width:

$$q = VA = \frac{1}{n} y^{2/3} s^{1/2} A \qquad [6]$$

For steady, shallow sheet flow conditions, $A = y$ and Equation [6] can be rearranged to:

$$y = \left(\frac{nq}{s^{1/2}}\right)^{3/5} \qquad [7]$$

Equations [2], [4] and [7] can then be combined to:

$$P_u = q^{0.4} s^{1.3} n^{-0.6} \qquad [8]$$

Phillips incorporated buffer length, L, into Equation [8] by assuming $q = Li$, where i is the steady-state excess rainfall rate. Equation [8] can then be expressed as:

$$P_u = L^{0.4} i^{0.4} s^{1.3} n^{-0.6} \qquad [9]$$

Then, denoting the saturated hydraulic conductivity, K, as an indicator of the infiltration capacity of the soil, a general index of buffer effectiveness relative to a reference buffer is obtained:

$$\frac{B_b}{B_r}=\frac{K_b}{K_r}\left(\frac{L_b}{L_r}\right)^{0.4}\left(\frac{i_b}{i_r}\right)^{0.4}\left(\frac{s_b}{s_r}\right)^{-1.3}\left(\frac{n_b}{n_r}\right)^{0.6} \qquad [10]$$

Assuming that rainfall intensity is the same on both the buffer of interest and the reference buffer, $i_b = i_r$, Equation [10] reduces to Phillips' hydraulic model (Equation [1]).

<u>Phillips Detention Model</u>: The Phillips' detention model estimates the relative effectiveness of buffers in removing dissolved substances from surface and subsurface flow through vegetative buffer. Contaminate removal in the buffer is defined as a function of the total contact time of both surface and subsurface flow in the buffer. The model is derived from Darcy's law and the Manning equation.

$$\frac{B_b}{B_r}=\left(\frac{n_b}{n_r}\right)^{0.6}\left(\frac{L_b}{L_r}\right)^{2}\left(\frac{K_b}{K_r}\right)^{0.4}\left(\frac{s_b}{s_r}\right)^{-0.7}\left(\frac{M_b}{M_r}\right) \qquad [11]$$

where M is the soil moisture storage capacity and the other terms are defined as before. The soil moisture storage capacity is defined as the available soil moisture content (soil moisture content at field capacity minus soil moisture content at wilting point) times the lessor of the seasonable high water table depth or the depth to a confining soil layer.

Phillips derived the detention model as follows. The total contact time due to surface runoff through the buffer can be expressed as:

$$T_s=\frac{L}{V} \qquad [12]$$

where T_s is the detention time due to surface runoff in the filter. Combining Equations [2], [8], and [12] gives:

$$T_s=n^{0.6}s^{-0.3}q_s^{-0.4}L \qquad [13]$$

where q_s is the surface discharge.

For subsurface flow, Phillips used Darcys law to estimate the velocity of subsurface flow:

$$V=Ks \qquad [14]$$

where K = saturated hydraulic conductivity. Detention time due to subsurface flow, T_g, was then estimated as:

$$T_g=KsL \qquad [15]$$

Considering both surface and subsurface throughflow, Phillips defined an index of detention, T^*, for a given flow of:

$$T^{*}=T_{s}*T_{g}=[n^{0.6}Ls^{-0.3}(q/q_{s})^{-0.4}]*[KsL(q_{g}/q)] \qquad [16]$$

where q_g is the subsurface discharge component of flow. Phillips assumed that q, q_s, and q_g were a function of K. Phillips further assumed that "the portion of discharge which travels overland or in subsurface flow is a fucntion of the infiltration capacity, which is assumed to be a fucntion of K. For the overland flow component, detention time varies as the -0.4 power of q_s. For a given stormwater mass, since K is an index or surrogate of q_s, $T=f(K^{-0.4})$. Since the portion of the discharge traveling on the surface is an inverse function of K, the sign is reversed and $T=f(K^{0.4})$." The relative abilities of buffers to hold infiltrated water was given by M_b/M_r where M is the soil moisture storage capacity obtained by multiplying the available soil moisture capacity (field capacity minus wilting point) by the depth to the water table or a confining soil layer. Equation [16] can then be expresses as:

$$\frac{T^{*}_{b}}{T^{*}_{r}}=\left(\frac{n_b}{n_r}\right)^{0.6}\left(\frac{L_b}{L_r}\right)^{2}\left(\frac{K_b}{K_r}\right)^{0.4}\left(\frac{s_b}{s_r}\right)^{-0.7}\left(\frac{M_b}{M_r}\right) \qquad [17]$$

which is functionally identical to Equation [11].

Other Design Approaches: Procedures for the design of vegetative buffers with respect to organics removal have been presented by Norman et al. (1978) and Young et al. (1982). However, these procedures were based primarily on infiltration or limited organics removal data. Regression type design equations for P reduction were presented by Young et al. (1982), but details of their development were not presented and they have not been verified.

State and Federal Vegetative Buffer Programs

Chesapeake Bay Preservation Act: Regulations have been proposed in Virginia as part of the Chesapeake Bay Program to require vegetative buffers along all water bodies in designated Resource Protection Areas (Chesapeake Bay Preservation Area Designation and Management Regulations, Chesapeake Bay Local Assistance Board). The Resource Protection Areas are defined as "sensitive lands at or near the shoreline that have intrinsic water quality value ... and are sensitive to impacts which may cause significant degradation to the quality of state waters or loss of aquatic habitat." This definition includes all tidal and nontidal wetlands, tidal shorelines, and all tributary streams within Virginia's Chesapeake Bay drainage basin.

Along all tidal waters, a 100 ft (30.5 m) vegetative buffer zone is required, and a 50 ft (15.2 m) buffer is required along nontidal waters. The buffer length is measured from the mean high water level of nonvegetated wetlands and from the wetland for vegetated wetlands. If agricultural lands are adjacent to waters, then "the buffer zone area shall maintain as a minimum best management practice, a 25 ft (7.6 m) wide vegetative buffer measured landward from the mean high water level of tidal waters or tributary streams, or from the landward edge of any wetlands." Buffers will not be required for agricultural drainage ditches if the adjacent land has best management practices in place in accordance with a conservation plan approved by the local Soil and Water Conservation District. The regulation specifies that the vegetative buffer shall be composed of either trees with a dense ground cover, grass, or an approved legume cover which can be managed to prevent concentrated flows from breaching the vegetative buffer. The vegetative buffer must be maintained until the landowner has implemented an approved BMP program which provides water quality protection at least the equivalent of that provided by the vegetative buffer. The regulation specifies that for the purposes of the Act, 100 ft buffers remove 75 and 40% of the incoming sediment and nutrients, respectively.

The proposed regulations are a step in the right direction, but it is highly unlikely that they will result in 75% sediment and 40% nutrient reductions. In many areas, little if any runoff will flow across the buffers and in other areas most runoff will cross the vegetative buffer as concentrated flow. This will be a major problem with the proposed regulations because vegetative buffers will only be required along perennial streams depicted on USGS topographic quadrangle maps. Consequently, most surface runoff will collect in ephemeral drainageways before reaching the vegetative buffers and cross as concentrated flow. The state of Maryland has similar buffer zone requirements along shorelines and major tributaries but does not require vegetative buffers explicitly for removing pollutants from surface runoff.

Conservation Reserve Program: The use of constructed vegetative buffers in the United States has increased significantly in the past few years, because vegetative buffers were an approved USDA cost-share practice under the Conservation Reserve Program (CRP) of the Food Security Act of 1985. The CRP was established to encourage farmers to take highly erodible land out of crop production and convert the land to permanent (10 year) cover. This program was designed to reduce soil erosion, improve water quality and wildlife habitat, as well as eliminate production of excess commodities. Farmers participating in the CRP receive an annual rental payment for land enrolled in the program. As originally implemented, only land classified as highly erodible was eligible for participation in the CRP. In 1988, the CRP was modified to include vegetative buffers because of their potential environmental benefits. The requirement that the land be highly erodible was eliminated for vegetative buffers. Requirements for vegetative buffers under the CRP include:

1. The land must be adjacent and parallel to a stream, river, lake, estuary, or wetland greater than 2 ha (5 acres) in area.
2. The land must have been planted in an agricultural commodity

in at least two years from 1981 through 1985.
3. The land must still be suitable for crop production.
4. The land with a vegetative buffer must be capable of reducing sediment delivery to adjacent water bodies.
5. The land must be planted to permanent grasses, trees, or shrubs.
6. The vegetative buffer must be a minimum of 20 m (66 ft) in length and no more than 30 m (99 ft) in length.
7. The vegetative buffer may not be grazed or harvested during the 10 years of the contract.

National Vegetative Filter Strip Conservation Practice Standard: The U.S. Soil Conservation Service is currently in the process of updating the national conservation practice standard for vegetative buffers to overcome some of the limitations of vegetative buffers. The proposed standards define vegetative buffers as vegetated areas which are designed to remove sediment, nutrients, pathogens, organic materials, pesticides, and other contaminants from surface runoff by filtration, deposition, infiltration, adsorption, adsorption, decomposition, and volatilization. The key word here is "designed". This implies that vegetative buffers are not suitable for every site and that their length and position will be a function of local site conditions and hydrology.

An important part of the proposed standard is the statement: "The practice (vegetative buffer) applies ... in locations above the occurrence of concentrated flow and above conservation practices such as terraces or diversions which concentrate flow." The new standard relaxes previous requirements that vegetative buffers be located immediately adjacent to streams and instead says that they should be located where they will be the most effective for pollutant removal. This may be at the lower boundary of a field, or it may be within a field.

The proposed standards suggest that the design of vegetative buffers and the suitability of a particular site for vegetative buffers must consider (Dillaha, 1989):

1. Adequacy of soil drainage and depth to water table to ensure satisfactory vegetative growth and prevent prolonged saturation of the soil.
2. Provisions for preventing hillside seeps and other continuous discharge of water through the vegetative buffers.
3. Reduced effectiveness of vegetative buffers under snow or frozen ground conditions.
4. Vegetative buffer length required to provide the desired pollutant reduction over the design life of the vegetative buffer. In other words, pollutant accumulation and subsequent release from vegetative buffers must be a design constraint.
5. The effects of slope on vegetative buffer effectiveness.
6. Provisions for mowing to maintain the effectiveness of vegetative buffers composed of grass and similar vegetation.

7. Effects of grazing on vegetative buffer performance.
8. Effects of application of herbicides to vegetative buffers or adjacent fields for weed control. If herbicides are applied to fields, sprayers should be turned off before crossing vegetative buffers or using them for turn rows.
9. Vegetative buffers should be installed on the contour as much as possible to filter runoff before it concentrates in natural drainageways.
10. Care should be taken during tillage operations to avoid tilling into vegetative buffers and causing localized flow problems.
11. Large fields with significant natural drainageways or grassed waterways are acceptable for vegetative buffers only if the vegetative buffers are installed on both sides of internal field drainageways. This will allow pollutants to be trapped before they can enter the drainageways.
12. Some sites may require limited grading to correct flow problems within the vegetative buffers caused by gullies or high areas within or immediately downslope of the vegetative buffers.
13. Shrub and wildlife strips should not be permitted because they are relatively ineffective for water quality improvement when compared to grass and legume vegetative buffers.
14. At sites with significant flow along or parallel to vegetative buffers, shallow berms or diversions may be needed at 15 to 30 m intervals to intercept runoff and force it to flow through the vegetative buffer before it can concentrate further.
15. Vegetative buffers should not be installed in areas higher than the fields they are intended to protect.

Sediment and Nutrient Loadings Due to Eroding Banks

A major difficulty with the Chesapeake Bay Preservation Act as currently implimented is that the Act makes it difficlt to modify buffer zones even if the modifications would reduce sediment and nutrient loadings to the Bay and other water bodies. Consider the case of eroding banks. Ibison et al. (1990) examined the loss of sediments and nutrients from eroding tidal shorelines along the Chesapeake Bay and its tributaries. Eroding banks were reported to be responsible for 5.2 and 23.6% of the controllable N and P, respectively, entering Virginia's portion of the Chesapeake Bay. In a follow up study, Ibison et al. (1992) confirmed the results of the previous study and reported that the sheer mass of materials lost through shoreline erosion results in nutrient loading rates (on an areal basis) to the Chesapeake Bay several orders of magnitude higher than upland loading rates. For example, N and P losses from shoreline erosion were estimated to be approximately 25,000 kg-N/ha-yr and 15,000 kg-P/ha-yr versus losses of 2 to 80 kg-N/ha-yr and 0.3 to 19 kg-P/ha-yr for cultivated farm land. Consequently, stabilizing one hectare of eroding bank may reduce nutrient loadings to the Bay as much as stopping all nutrient loss from 300 to 800 ha of cultivated farmland.

Many of the actively eroding banks along the Chesapeake Bay and its tidal tributaries are characterized by high steep banks. The banks erode at an average rate of 0.2 m/yr (Byrne and Anderson, 1977) with reported rates as high as 3.3 m/yr (Ibison et al., 1992). To stabilize these banks, disturbance of the existing riparian zone is often required for the construction of shoreline structures or to grade the bank back to a stable slope of 2 to 1 (run to rise) or 50%. This necessitates removal of all vegetation during grading and then replanting after grading is complete. It may also be necessary to remove large trees on and in the vicinity of the bank to prevent mass slumping and loss of soil during large storms that cause trees to fall down the banks, bringing tons of soil with them. The Shoreline Programs Bureau recommends that all large trees be removed from steep slopes and that large trees also be removed from the zone within two bank heights distance from the top of steep banks. Removal of trees under these circumstances is estimated to reduce average annual soil loss from banks by approximately 10% (Hill, 1992).

Literature Review Summary

As discussed previously, vegetative buffers as presently implemented are unlikely to be very effective in removing sediment and nutrients from surface runoff because they are usually installed with little consideration of site conditions which affect their performance. Equations which have been developed for vegetative buffer design assume that runoff is uniformly distributed across the width of vegetative buffer as shallow sheet flow. This will rarely be the case in real world situations as flows in all but the most uniformly sloping fields tend to concentrate in internal field drainageways before reaching field boundaries where vegetative buffers are usually located. Consequently, significant portions of field runoff will cross the vegetative buffers as concentrated flow, locally inundating the vegetative buffers, and greatly reducing vegetative buffer effectiveness for sediment and nutrient removal. In addition, almost all vegetative buffer research reported has been of a short-term nature which did not consider the long-term effectiveness of vegetative buffers for pollutant reduction. The design equations and models developed from these studies do not consider the effects of sediment and nutrient accumulation in vegetative buffers. Consequently, they will probably over predict vegetative buffer effectiveness over the long run.

Of all the models reviewed, only the Phillips method was developed for vegetation other than grasses. The Phillips method, because of its theoretical basis and simplicity, is also easily modified to account for important factors such as concentrated flow and vegetative uptake which were not considered by any of the models discussed. Consequently, the Phillips method appears to be the most reasonable model for estimating relative buffer strip effectiveness and satisfying the objectives of this project.

MODEL DEVELOPMENT

The method developed by Phillips (1989a,b) was selected for evaluating buffer zone effectiveness. The method was modified to correct several errors and weaknesses in the model and to better reflect Virginia conditions. In addition, a procedure is presented to account for the benefits of shoreline protection structures in riparian buffer zones.

Phillips Hydraulic Model

Several limitations were encountered with Phillips's hydraulic model. First, the buffer length term, ***L***, is used to estimate the flow rate per unit width to the buffer zone. But buffer length does not give an estimation of unit loading to a buffer. What is needed to estimate loading is the length of the upslope area contributing runoff to the buffer plus the length of the buffer. Consequently, an additional term, L^*, must be defined that represents "the length of the upslope area contributing runoff to the buffer." The ***L*** in the Phillip hydraulic model can therefore be redefined as $L + L^*$.

A second limitation involves the saturated hydraulic conductivity term, ***K***, which is used to estimate infiltration in the buffer zone. Phillips's approach does not consider the effects of buffer zone length on infiltration, ie. infiltration losses from surface runoff would be as significant with a one meter length buffer as they would be for a 100 m buffer. To incorporate the effects of buffer length on total infiltration, the hydraulic conductivity term can be multiplied by the buffer length, ***L***.

A third limitation of Phillips's approach is the failure to consider the effects of concentrated flow. Concentrated flow effects can be incorporated into the model by incorporating the ratio of the fraction of flow entering the buffer and the reference buffer as shallow sheet flow.

The new hydraulic model with the above modifications can now be expressed as:

$$\frac{B_b}{B_r}=\left(\frac{K_bL_b}{K_rL_r}\right)\left(\frac{L_b^*+L_b}{L_r^*+L_r}\right)^{-0.4}\left(\frac{s_b}{s_r}\right)^{-1.3}\left(\frac{n_b}{n_r}\right)^{0.6}\left(\frac{C_b}{C_r}\right) \qquad [18]$$

where: ***K*** = saturated hydraulic conductivity of buffer soils
L = buffer zone length
L^* = length of area upslope of the buffer contributing runoff to the buffer
s = sin θ, where θ is the slope angle relative to the

horizontal
- ***n*** = Manning roughness coefficient
- ***C*** = fraction of surface runoff crossing the buffer as sheet flow
- ***b*** = subscript denoting buffer of interest, and
- ***r*** = subscript denoting reference buffer

Phillips Detention Model

In checking the derivation of the Phillips detention model, an error was found in the derivation. The model is rederived as follows. Given Equation [12] and Darcys law (Equation [14]), Equation [15] is actually:

$$T_g=\frac{L}{Ks} \qquad [19]$$

Equation [16] therefore becomes:

$$T^*=\left[n^{0.6}Ls^{-0.3}(q_s/q)^{-0.4}\right]*\left[\frac{L}{Ks}(q_g/q)\right] \qquad [20]$$

As with the hydraulic model, if ***K*** is substituted for ***(q_g/q)*** in the subsurface flow portion of Equation [20], the equation reduces to:

$$T^*=n^{0.6}L^2s^{-1.3}(q_s/q)^{-0.4} \qquad [21]$$

This equation is identical to Phillips' except the exponent of the slope term changes from -0.7 to -1.3. The saturated hydraulic conductivity can also be substituted for q_s/q, but in this case, the sign of the exponent of K must be reversed because surface runoff is inversely proportional to K since higher values of K indicate higher potential for infiltration and therefore reduced runoff. Equation [21] can therefore be simplified to:

$$T^*=n^{0.6}L^2s^{-1.3}K^{0.4} \qquad [22]$$

The resulting hydraulic model with the addition of the soil moisture storage capacity term discussed previously is:

$$\frac{B_b}{B_r}=\left(\frac{n_b}{n_r}\right)^{0.6}\left(\frac{L_b}{L_r}\right)^{2}\left(\frac{K_b}{K_r}\right)^{0.4}\left(\frac{s_b}{s_r}\right)^{-1.3}\left(\frac{M_b}{M_r}\right) \qquad [23]$$

As with the hydraulic model, a concentrated flow term should also be added to account for short circuiting due to concentrated flow effects. An additional term is also added to account for the relative ability of different types of vegetation and vegetative growth stages to assimilate nutrients. Since little information is available on nutrient uptake for the ecosystems of interest, the net productivity of relevant ecosystems is used as an indicator of nutrient uptake since they are proportional. This factor is incorporated into the model as a ratio similar to the way concentrated flow effects are handled. The resulting equation is:

$$\frac{B_b}{B_r}=\left(\frac{n_b}{n_r}\right)^{0.6}\left(\frac{L_b}{L_r}\right)^{2}\left(\frac{K_b}{K_r}\right)^{0.4}\left(\frac{s_b}{s_r}\right)^{-1.3}\left(\frac{M_b}{M_r}\right)\left(\frac{C_b}{C_r}\right)\left(\frac{V_b}{V_r}\right) \qquad [24]$$

where ***V*** is the vegetative uptake or net productivity of the vegetative buffers being compared. It is essential to consider both the type of vegetation and the maturity of the vegetative system when estimating net productivity. For example, a riparian zone in a rapidly growing early secession stage would be expected to be able to assimilate and hold more nutrients than a more stable mature riparian buffer approaching or at climax.

The original Phillips detention model did not consider the effects of the length of the buffer on the soil moisture capacity. Intuitively, one would expect the soil moisture capacity to be proportional to the area of the buffer since a buffer twice as long as another buffer, all other conditions equal, would be expected to have twice the soil moisture storage capacity. Consequently, ***M*** should be multiplied by ***L*** to account for the area of the buffer. The vegetative uptake factor, ***V***, is also multiplied by ***L*** for identical reasons. The resulting detention model is:

$$\frac{B_b}{B_r}=\left(\frac{n_b}{n_r}\right)^{0.6}\left(\frac{L_b}{L_r}\right)^{4}\left(\frac{K_b}{K_r}\right)^{0.4}\left(\frac{s_b}{s_r}\right)^{-1.3}\left(\frac{M_b}{M_r}\right)\left(\frac{C_b}{C_r}\right)\left(\frac{V_b}{V_r}\right) \qquad [25]$$

Readers should keep in mind that the the original Phillips models as well as the proposed model are theoretical and have not been verified due to a lack of adequate field data for validation.

Shoreline Erosion Model

Shoreline erosion: The proposed shoreline erosion model is simple but should provide a fairly good estimate of sediment and nutrient losses per meter of shoreline for both protected and unprotected shoreline. The model does not estimate sediment and nutrient losses from partially protected shorelines. For stabilized shorelines, shoreline erosion and nutrient losses are assumed to be zero.

If a shoreline is not protected and actively eroding, the sediment loss is estimated in a manner similar to that recommended by Ibison et al. (1992):

$$Y_B = H_B\, E_B\, \rho_B \qquad [26]$$

where: Y_B = bank sediment loss per unit width (kg/m-yr)
E_B = bank or shoreline erosion rate (m/yr)
H_B = bank height (m)
ρ_B = bulk density of bank soil (kg/m^3)

If the nutrient content of the bank is known or can be estimated then:

$$Y_{BN} = \frac{Y_B\ N_B}{1000} \qquad [27]$$

$$Y_{BP} = \frac{Y_B\ P_B}{1000} \qquad [28]$$

where: Y_{BN} = nitrogen lost in eroding bank sediment (kg/m-yr)
Y_{BP} = phosphorus lost in eroding bank sediment (kg/m-yr)
N_B = concentration of nitrogen in bank material (mg/g)
P_B = concentration of phosphorus in bank material (mg/g)

Upland Erosion: To determine the relative contributions of sediment and nutrients from shoreline erosion and disturbed upland requires an estimate of shoreline and upland contributions. Upland losses need to be estimated per unit width like the shoreline losses for comparison purposes. Since the actual trapping efficiency of the buffer is unknown, the conservative assumption is made that the buffer trapping efficiency is 100% for the portion of the runoff entering the buffer as shallow sheet flow. All sediment and nutrients in concentrated flow are assumed to pass through the buffer unattenuated. Sediment, nitrogen and phosphorus movement through the buffer can therefore be represented as:

$$Y_U^* = Y_U\ (1-C) \qquad [29]$$

$$Y_{UN}^* = Y_{UN}\ (1-C\ ) \qquad [30]$$

$$Y_{UP}^* = Y_{UP}\ (1-C\ ) \qquad [31]$$

where: Y_U^* = mass of sediment from upland area passing through buffer (kg/m-yr)
Y_U = sediment loading to the buffer from the upland contributing area (kg/m-yr)
C = fraction of surface runoff from the field entering the buffer as sheet flow
Y_{UN}^* = mass of nitrogen from upland area moving through buffer (kg/m-yr)
Y_{UN} = loading of nitrogen to buffer from upland area (kg/m-yr)
Y_{UP}^* = mass of phosphorus from upland area moving through buffer (kg/m-yr)
Y_{UN} = loading of phosphorus to buffer from upland area (kg/m-yr)

The sediment loading to the buffer from the upland contributing area, Y_U, can be estimated from published values for various landuses or it can be calculated directly using the Universal Soil Loss Equation (Wischmier and Smith, 1976), the Revised Universal Soil Loss Equation (Renard et al., 1992), WEPP (Lane and Nearing, 1989), or other similar erosion predictor. The estimate will probably be given in tons/acre-yr and will need to be converted to kg/m-yr to be consistent with the shoreline erosion units. If the soil loss units are in tons/acre-yr, then the estimated sediment loading to the buffer can be converted to kg/m-yr with the following equation:

$$Y_U = 2242 \; \frac{A_U \, E_U}{W_B} \qquad [32]$$

where: A_U = upland area contributing sediment to the buffer, acres
E_U = sediment loss from upland area contributing sediment to the buffer as predicted by USLE or other method, tons/acre-yr
W_B = buffer width (long dimension of buffer, dimension perpendicular to field slope direction), m

Similarly, if the nutrient loadings to the buffer are in lbs/acre-yr, they can be converted to kg/m-yr with the following equations:

$$Y_{UN} = C1 \; \frac{A_U \, N_U}{W_B} \qquad [33]$$

$$Y_{UP} = C1 \; \frac{A_U \, P_U}{W_B} \qquad [34]$$

where: N_U = nitrogen loading to buffer from upland area, M/L^2
P_U = phosphorus loading to buffer from upland area, M/L^2
$C1$ = units conversion factor
= 0.454 for nutrient loadings (N_U or P_U) in lb/acre and upland area (A_U) in acres
= 1.0 for nutrient loadings (N_U or P_U) in kg/ha and upland area (A_U) in hectares

Impact of Shoreline Stabilization: If modifications made to the buffer due to shoreline stabilization reduce the effectiveness of the buffer as predicted by Equations [18] and [25], then the combined effects of buffer effectiveness and shoreline stabilization must be evaluated to assess the effectiveness of the system as a whole. The combined effects of buffer modification and shoreline stabilization can be estimated as follows. To compare the effectiveness of the buffer and shoreline stabilization, it is necessary to come up with an estimate of the absolute (not relative) effectiveness of the proposed buffer. The modified Phillips models do not do this directly, but they can be used in an indirect way to do so.

First assume that the reference buffer is 100% effective in removing sediment from shallow sheet flow and totally ineffective in removing contaminants from concentrated flow. The amount of sediment and nutrients moving through the reference buffer can then be estimated using Equations [29], [30] and [31]. The relative effectiveness of the reference and proposed buffer is calculated using the modified hydraulic model, Equation [18]. The effectiveness of the buffer/shoreline stabilization system, E_s, can be estimated as:

$$E_S = \frac{Y_U^*}{(B_b/B_r)(Y_B+Y_U^*)} \qquad [35]$$

where B_b/B_r is the relative buffer effectiveness predicted with the hydraulic model. If $E_s<1$, the buffer/shoreline stabilization system has a net positive effect. If $E_s>1$, the negative consequences of buffer alteration outweigh the benefits of shoreline stabilization.

Buffer Evaluation Procedure

The steps to follow in applying the model are as follows:

1. Decide upon an acceptable effectiveness of the buffer relative to the reference buffer in advance. For example, if it is decided that the buffer must be at least as effective as the reference buffer then the ratio of B_b/B_r for both the hydraulic and detention models must be greater than or equal to 1.0. If the given buffer only needs to be 90% as effective as the reference buffer then the ratio of B_b/B_r would need to be greater than or equal to 0.9. The important idea is to decide on the required ratio before analysis.

2. Collect model data required to define the characteristics of the reference buffer and the buffer of interest. The reference buffer can be either a reference buffer whose characteristics are defined by a local regulatory authority or it may be the characteristics of the buffer you are considering modifying before modifications. Parameters that must be defined for both buffers include:

   K = saturated hydraulic conductivity of buffer soils
   L = buffer zone length
   L^* = length of area upslope of the buffer contributing runoff to the buffer
   s = sin θ, where θ is the slope angle relative to the horizontal
   n = Manning roughness coefficient
   C = fraction of surface runoff crossing the buffer as sheet flow (modify for proposed hydraulic modifications in proposed buffer)
   M = soil moisture storage capacity
   V = vegetative uptake or net productivity factor

   Procedures, sources of information and tables for estimating these values are given in the following section.

3. Estimate the effectiveness of the proposed buffer for removing sediment and sediment-bound chemicals using Equation [18], the hydraulic model. If the proposed buffer is not as effective as desired, consider increasing the buffer length and changing the proposed vegetation (higher density vegetation may be used to increase Manning's n). It may also be possible to reshape the upland area or install hydraulic structures to reduce concentrated flow and increase the proportion of sheet flow entering the buffer. It is unlikely that properties such as slope and hydraulic conductivity can be changed.

4. Estimate the effectiveness of the proposed buffer relative to the reference buffer for removing dissolved chemicals using

Equation [25], the detention model, and the data values collected in step 1. If the proposed buffer is not as effective as desired, consider increasing the buffer length and changing the proposed vegetation (higher density vegetation may be used to increase Manning's n and the vegetative uptake factor, V). It may also be possible to reshape the upland area or install hydraulic structures to reduce concentrated flow and increase the proportion of sheet flow entering the buffer. It is unlikely that properties such as slope and hydraulic conductivity can be changed.

5. If shoreline erosion is not a factor, the evaluation and/or design is complete. If shoreline erosion is to be considered, continue with steps 6 through 9.

6. Calculate sediment, nitrogen and phosphorus losses due to shoreline erosion using Equations [26], [27] and [28], respectively.

7. Estimate sediment, nitrogen, and phosphorus losses from the field contributing surface runoff to the buffer using the USLE or other soil loss estimation technique, estimates of soil nutrient concentrations, or general estimates of sediment and nutrient losses from the literature for various landuses.

8. Calculate sediment, nitrogen and phosphorus transport through the buffer using Equations [29], [30], and [31].

9. Calculate the overall effectiveness of the buffer/shoreline protection system using Equation [35]. If E_s<1 then the combined buffer/shoreline stabilization system is more beneficial than the original buffer alone. If E_s>1, shoreline stabilization results in increased sediment and nutrient losses.

DATA FOR BUFFER EVALUATION PROCEDURE

Data Requirements for the Hydraulic and Detention Models

The following values must be estimated to use the modified hydraulic and detention models:

- Saturated hydraulic conductivity of buffer soils, ***K***
- Buffer length, ***L***
- Length of area upslope of the buffer contributing runoff to the buffer, ***L'***
- Sin θ, where θ = slope angle relative to the horizontal, ***s***
- Manning roughness coefficient, ***n***
- Fraction of surface runoff crossing buffer as sheet flow, ***C***
- Soil moisture storage capacity, ***M***
- Vegetative uptake or net productivity factor, ***V***

These values can be estimated as follows.

Saturated Hydraulic Conductivity, *K*: can best be estimated from permeability values given in modern county soil survey reports. These values are generally presented in the "Physical and Chemical Properties of the Soils" table. Permeability values are usually given as a range in inches\hour. For planning purposes, use the midpoint of the range unless better information on the permeability value is available. Typical permeability ranges given in soil surveys are given in Table I. Hydraulic conductivity can also be estimate if the general soil texture is known as shown in Table II. Soil survey estimates are preferred, however.

Table I. Estimation of hydraulic conductivity values from Soil Survey permeability estimates.

Permeability Range, in/hr	Suggested Hydraulic Conductivity
0.06-0.2	0.13
0.2-0.6	0.40
0.6-2.0	1.30
0.6-6.0	3.30
6.0-10.0	8.00

Table II. Hydraulic conductivity as a function of soil texture.

Soil Texture	Hydraulic Conductivity, m/day Range	Suggested
Clay soils, surface	0.01-0.2	0.10
Loam soils, surface	0.1-1	0.50
Fine sand	1-5	2.00
Medium sand	5-20	10.00
Coarse sand	20-100	40.00
Clay, sand, gravel mix	0.001-0.1	0.05

Buffer Length, *L*: is the distance measured along the land surface between the upland edge of the buffer and the down slope edge of the buffer. Buffer length is best measured in the field but it may also be estimated from areal photos. Any units may be used as long as they are consistent with the units used in estimating the upslope slope-length contributing runoff to the buffer, L^*.

Upslope Slope-length Contributing Runoff to the Buffer, L^*: is the average length that surface runoff tranverses in the field or area before reaching the buffer. It is best estimated from on site field estimates, but it can also be estimated from areal photographs. The average upslope Contributing slope-length can also be estimated as:

$$L^* = \frac{A_U}{W_B} \qquad [36]$$

where A_U is the area of the field contributing runoff to the buffer, and W_B is the width of the buffer (long dimension of the buffer).

Sin θ, *s*: is a measure of the land slope across the buffer where θ is the slope angle relative to the horizontal. The value of s is best measured from in buffer surveys but it can also be estimated from topographic maps. Values for **Sin θ, *s*** can be estimated from estimates of buffer slope in percentage or degrees using the data given in Table III.

Table III. Estimates of Sin(θ) for various buffer slopes in percent and degrees.

Buffer Slope, percent	Buffer Slope, Degrees	*s*, Sin(θ)	Buffer Slope, percent	Buffer Slope, Degrees	*s*, Sin(θ)
0.5	0.3	0.0050	40	21.8	0.3714
1	0.6	0.0100	45	24.2	0.4104
2	1.1	0.0200	50	26.6	0.4472
3	1.7	0.0300	60	31.0	0.5145
4	2.3	0.0400	70	35.0	0.5735
5	2.9	0.0499	80	38.6	0.6247
6	3.4	0.0599	90	42.0	0.6690
7	4.0	0.0698	100	45.0	0.7071
8	4.6	0.0797	120	50.2	0.7682
9	5.1	0.0896	140	54.4	0.8137
10	5.7	0.0995	160	58.0	0.8480
12	6.8	0.1191	180	60.9	0.8742
14	8.0	0.1386	200	63.4	0.8944
16	9.1	0.1580	300	71.5	0.9487
18	10.2	0.1772	600	80.5	0.9864
20	11.3	0.1961	1200	85.2	0.9965
25	14.0	0.2425	2400	87.6	0.9991
30	16.7	0.2873	4800	88.8	0.9998
35	19.3	0.3304	9600	89.4	0.9999

Manning's Roughness Coefficient, *n*: is a measure of the roughness of the lands surface in the buffer. It is used to estimate how much surface runoff is retarded (reduction in velocity of overland flow) as it passes through the buffer. Manning's roughness coefficient is difficult if not impossible to measure directly, so it is usually estimated from tabular values that give the roughness coefficient as a function of land use and condition. The roughness coefficients used in the buffer evaluation procedure should be for shallow flow conditions, not for the more readily available channel flow conditions. Manning's roughness coefficient for shallow sheet flow conditions can be estimated from Table IV.

Table IV. Estimates of Mannings roughness coefficient as a function of landuse and condition for shallow sheet flow conditions (Engman, 1986).

Landuse and Condition	Suggested Value
Forest (light underbrush)	0.30
Forest (dense undergrowth)	0.40
Bare sand	0.01
Bare clay loam (eroded)	0.02
Fallow - no residue	0.05
Chisel plow <0.25t/ac residue	0.07
Chisel plow 0.25-1t/ac residue	0.18
Chisel plow 1-3 t/ac residue	0.30
Chisel plow >3 t/ac residue	0.40
Disk/harrow <0.25 t/ac residue	0.08
Disk/harrow 0.25-1 t/ac residue	0.16
Disk/harrow 1-3 t/ac residue	0.25
Disk/harrow >3 t/ac residue	0.30
No-till <0.25 t/ac residue	0.04
No-till 0.25-1 t/ac residue	0.07
No-till 1-3 t/ac residue	0.30
Moldboard plow (fall)	0.06
Coulter	0.10
Range (natural)	0.13
Range (clipped)	0.10
Grass (Bluegrass sod)	0.45
Short grass (prairie)	0.15
Dense grass	0.24
Bermuda grass	0.41

Fraction of surface runoff crossing buffer as sheet flow, *C*: is an estimate of the amount of surface runoff from the field contributing runoff to the buffer that enters and presumably crosses the buffer as shallow sheet flow. It is a difficult and somewhat arbitrary value to estimate. The fraction of surface runoff crossing the buffer as sheet flow can best be estimated using the following procedure:

1. Survey the area upslope of the buffer that contributes surface runoff to the buffer and estimate the area of the upslope contributing area, A_U.
2. Delineate the major drainageways within the upslope contributing area.
3. Delineate and measure the area, A_i, contributing surface runoff to each drainageway, i.
4. The fraction of surface runoff crossing the buffer as

shallow sheet flow can then be estimated as:

$$C = \frac{A_U - \sum A_i}{A_U} \qquad [37]$$

Soil moisture storage capacity, *M*: is defined as the available soil moisture storage capacity of the buffer soils times the lessor of the depth to the seasonal high water table or the depth to an impeding soil layer (i.e. impervious or semi impervious soil layer. Available soil moisture is defined as the difference between the soil water content at field capacity and the wilting point. Estimates of available soil moisture are given in the "Physical and Chemical Properties of the Soils" table of modern soil survey reports or in soil property databases (i.e. the Soils-5 database) as a function of soil type. Soil moisture storage capacity can therefore be estimated as:

$$M = \theta_A D \qquad [38]$$

where θ_A is the available soil moisture of the buffer soils and ***D*** is the lessor of the depth to the seasonably high water table or the depth to an impeding soil layer.

Vegetative uptake or net productivity factor, *V*: is used as an index of the buffer vegetation's ability to assimilate nutrients. Since little information was available on the nutrient assimilative capacity of vegetative ecosystems in Virginia, it was decided to use net primary productivity as an indicator of net nutrient uptake. This is reasonable since nutrient uptake and net primary productivity are highly correlated. Unfortunately, data on net productivity for Virginia ecosystems is almost as rare as data on net nutrient uptake, particularly as a function of sucessional stage. In instances where the buffer under study and the reference buffer are composed of the same type and age of vegetation, the vegetative uptake factor will have no effect on buffer performance. The values in Table V are gross estimates of net primary production. The user is encouraged to find better sources of information on net primary production or net nutrient uptake for the region being investigated if possible.

Table V. Net primary productivity (adapted from: Leith, 1975)

Vegetation	Net Primary Productivity, g/m^2-yr
Mixed forest, dense under story	1000
Mixed forest, sparce under story	500
Woodland, good cover	600
Woodland, sparce cover	400
Grass, good stand	500
Grass, poor stand	300
Woodland, shrubs, grass	800
Cultivated land	650
Swamps and marsh	2000

Data Requirements for Shoreline Stabilization Model

The following additional values must be estimated to evaluate the benefits of shoreline stabilization:

- Bank or shoreline erosion rate (m/yr), E_B
- Bank height (m), H_B
- Bulk density of bank soil (kg/m^3), ρ_B
- Concentration of nitrogen in bank material (mg/g), N_B
- Concentration of phosphorus in bank material (mg/g), P_B
- Sediment loading to the buffer from the upland contributing area (kg/m-yr), Y_U
- Nitrogen loading to buffer from upland area, N_U
- Phosphorus loading to buffer from upland area, P_U

These values can be estimated as follows.

Bank or shoreline erosion rates (m/yr), E_S: are very difficult to measure. Measurement techniques include interpretation of areal photos over a period of years or actual measurements of shorelines relative to fixed measurement points. In any case, years of measurements are required to obtain average annual erosion rates. Consequently, estimates of shoreline erosion for planning purposes are best obtained from published reports on shoreline erosion in Virginia (Byrne and Anderson, 1977; Ibison et al., 1990; 1992; Hardaway et al., 1992).

Bank height (m), H_B: measurements must be made in the field or from detailed topographic surveys of the study site if they exist. Bank height should be measured vertically from the base to the top of the bank.

Bulk density of bank soil (kg/m^3), ρ_B: can be determined in the laboratory from undisturbed field samples or from one or more field techniques. It can also be estimated from soil survey report descriptions of soil horizons. Soil bulk densities of coastal soils generally range from 1.3 to 1.8 g/cm^3 (multiply g/cm^3 by 1000 to get units of kg/m^3). If a soil bank has distinct horizons with varying bulk densities, the bulk densities of each horizon should be area weighted to calculate an average bulk density for the whole profile. If bulk density information is not available, assume an average value of 1.5 g/cm^3 (1500 kg/m^3).

Concentration of nitrogen, N_B, and phosphorus, P_B, in the bank material (mg/g): must be estimated from laboratory analyses as suggested by Ibison et al. (1992). To reduce the costs of laboratory analyses, a single composite soil sample can be created by combining soil samples from each soil horizon in proportion to the thickness of each horizon. If laboratory analysis of soil samples is not possible, then estimates of soil nutrient levels can be approximated with concentrations reported by Ibison et al. (1990, 1992) for similar landuses and locations.

Sediment loading to the buffer from the upland contributing area (kg/m-yr), Y_U: are best determined by direct calculation using the Universal Soil Loss Equation (Wischmier and Smith, 1976), the Revised Universal Soil Loss Equation (Renard et al., 1991), WEPP (Lane and Nearing, 1989), or other similar erosion predictor. The estimate will probably be given in tons/acre-yr (except WEPP predictions, which are given in kg/m-yr) and will need to be converted to kg/m-yr to be consistent with the shoreline erosion units. If the soil loss units are in tons/acre-yr, then the estimated sediment loading to the buffer in kg/m-yr can be determined with Equation [32]. Rough estimates of sediment loading as a function of landuse can also be obtained from the literature.

Nitrogen, N_U, and phosphorus, P_U, loading to the buffer: from upland areas can be estimated in several ways. First, estimates can be by collecting and analyzing soil samples from the area contributing runoff to the buffer. The average soil nutrient concentration can then be multiplied by the estimated soil loss from the area with appropriate unit conversions to estimate nutrient loadings to the buffer. Nutrient loadings can also be estimated using models such as CREAMS (Knisel, 1980). Lastly, nutrient loadings to the buffer can be estimated from published unit area nutrient losses for various landuses. For example, Beaulac and Reckhow (1982, cited by Ibison et al., 1992), reported nutrient losses from cropland of 1.9 to 71 lbs-N/ac-yr (2.1 to 80 kg-N/ha-yr) and 0.23 to 17 lbs-P/ac-yr (0.26 to 19 kg-P/ha-yr). Areal nutrient loadings can be converted to a per unit width basis using Equations [33] and [34].

PRACTICAL APPLICATION

Example Problem I

Problem Statement: For a site with the following conditions, determine how long a buffer is required to be at least as effective as the given reference buffer.

Data:

Reference buffer characteristics

- Buffer soil: Suffolk sandy loam (K = 1.3 m/day)
- Buffer length, L = 100 ft (30.5 m)
- Field slope-length, L^* = 400 ft (122 m)
- Buffer slope = 10% (s = 0.0995 from Table III)
- Buffer vegetation is forest with heavy undergrowth (n = 0.4 from Table IV)
- Fraction of runoff crossing buffer as sheet flow (C = 0.5)
- Soil moisture storage capacity (available soil moisture = 0.15 from soil survey and depth to water table = 5 m, M = 0.15*5 = 0.75)
- Vegetative uptake for forest (V = 1000 from Table V)

Study buffer

All conditions are the same except the landowner wants to thin the trees, without improving ground cover, to improve his view of the water.

- For forest with light under brush, n = 0.3 and V = 500. All other factors are the same except L and L^*.

Solution:

Since the new buffer must be as effective as the reference buffer, B_b/B_r must be greater tan or equal to 1. Substituting the known values into the hydraulic model, Equation [18]:

$$1.0=\left(\frac{1.3L_b}{1.3*100}\right)\left(\frac{500}{500}\right)^{-0.4}\left(\frac{0.0995}{0.0995}\right)^{-1.3}\left(\frac{0.3}{0.4}\right)^{0.6}\left(\frac{0.5}{0.5}\right)= 0.0084\ L_b$$

Solving the above equation gives L_b = 119 ft (36 m). Therefore, the landowner would be required to have a 118 ft buffer rather than a 100 ft buffer if the landowner wants to thin the forest vegetation according to the hydraulic model.

In a similar manner, the detention model, Equation [25], gives:

Solving the detention equation gives L_b = 124 ft (38 m). This value

$$1=\left(\frac{0.3}{0.4}\right)^{0.6}\left(\frac{L_b}{100}\right)^{4}\left(\frac{1.3}{1.3}\right)^{0.4}\left(\frac{0.0995}{0.0995}\right)^{-1.3}\left(\frac{0.75}{0.75}\right)\left(\frac{0.5}{0.5}\right)\left(\frac{500}{1000}\right)=4.29*10^{-9}L_r^4$$

is very similar to that recommended by the hydraulic model.

Example Problem II

Problem Statement: Now suppose the landowner in Example Problem I decides that she wants to protect her property from shoreline erosion. Given the following information, what would the impact of shoreline stabilization be on sediment and nutrient losses from her combined buffer/shoreline protection system?

Data:

Assume that the landowner's property has a steep bank immediately next to the shore. Characteristics of the bank are as follows:

- Bank or shoreline erosion rate (m/yr), E_B = 0.5 m/yr (1.64 ft/yr)
- Bank height (m), H_B = 5 m (16.4 ft)
- Bulk density of bank soil (kg/m^3), ρ_B = 1500 kg/m^3
- Concentration of nitrogen in bank material (mg/g), N_B=0.365 mg/g
- Concentration of phosphorus in bank material (mg/g), P_B=0.25 mg/g
- Sediment loading to the buffer from the upland contributing area (kg/m-yr), Y_U = 338 kg/m-yr for a 305 m wide buffer and a 9.18 acre field contributing runoff to the buffer with a soil loss rate of 5 tons/ac-yr
- Nitrogen loading to buffer from upland area, N_U= 10 kg/ha-yr
- Phosphorus loading to buffer from upland area, P_U= 5 kg/ha-yr

Solution:

To stabilize the shoreline requires that the bank be graded back to a grade of 2:1 and that all large tree be removed from a distance of 2 bank heights from the top of the new graded slope. This means that of the original 38 m (124 ft) buffer (from Example Problem I), 10 m will be graded and planted to grass, small trees and shrubs; the next 10 m will have all the large trees removed, and the remaining 18 meters will be the thinned trees described in Example Problem I.

For the 2:1 graded region, the slope will now be 30° or s=0.5. For the rest of the slope, s=0.0995. Area weighting the slope gives a mean slope of s=(10*0.5+28*0.0995)/38=0.2049

The weighted Manning's roughness coefficient for the buffer will be (n=0.24 for the stabilized grass slope, n=0.3 for the forested area): n=(10*0.24+28*0.3)/38=0.284. The vegetation factor will be v=500 since both light woods and grass have the same net primary productivity value.

Buffer effectiveness according to the hydraulic model is:

$$\frac{B_b}{B_r}=\left(\frac{1.3*124}{1.3*100}\right)\left(\frac{500}{500}\right)^{-0.4}\left(\frac{0.2048}{0.0995}\right)^{-1.3}\left(\frac{0.284}{0.4}\right)^{0.6}\left(\frac{0.5}{0.5}\right)= 0.395$$

Buffer effectiveness according to the detention model is:

$$\frac{B_b}{B_r}=\left(\frac{0.284}{0.4}\right)^{0.6}\left(\frac{124}{100}\right)^{4}\left(\frac{1.3}{1.3}\right)^{0.4}\left(\frac{0.2049}{0.0995}\right)^{-1.3}\left(\frac{0.75}{0.75}\right)\left(\frac{0.5}{0.5}\right)\left(\frac{500}{1000}\right)=0.376$$

Both the hydraulic and detention models predict greatly reduced buffer effectiveness due to the grading done to stabilize the shoreline bank. Both models predict that the buffer will only be about 40% as effective as the reference buffer.

However, if the benefits of shoreline stabilization are considered, the overall system may still be beneficial.

Sediment and nutrient losses due to shoreline erosion:

With the information given above, sediment loss due to shoreline erosion is:

$$Y_B = H_B\ E_B\ \rho_B = 5*0.5*1500 = 3750\ kg/m\text{-}yr$$

In a similar manner, nutrient losses due to shoreline erosion are:

$$Y_{BN} = \frac{Y_B\ N_B}{1000} = \frac{3750*0.65}{1000} = 2.437\ kg\text{-}N/m\text{-}yr$$

$$Y_{BP} = \frac{Y_B\ P_B}{1000} = \frac{3750*0.25}{1000} = 0.937\ kg\text{-}P/m\text{-}yr$$

Sediment and nutrient transport through the buffer:

Sediment passing through the buffer can be estimated as:

$$Y_U^{*}=Y_U(1-C) = 2242\ \frac{A_U\ E_U}{W_B}(1-C) = 2242\frac{8.63*5}{304.8}(1-0.5) = 159\ kg/m\text{-}yr$$

Similarly, nutrients passing through the buffer are:

$$Y_{UN}^{*}=Y_{UN}(1-C) = C1\ \frac{A_U\ N_U}{W_B}(1-C) = 1\frac{3.49*10}{305}(1-0.5)=0.057\ kg\text{-}N/m\text{-}yr$$

$$Y_{UP}^{*}=Y_{UP}\ (1-C) = C1\ \frac{A_U\ P_U}{W_B}\ (1-C)=1\frac{3.49*5}{305}(1-0.5)=0.029\ kp\text{-}P/m\text{-}yr$$

The overall effectiveness of the buffer/shoreline stabilization system for sediment reduction can then be represented by Equation [35]:
Since E_s<1, shoreline stabilization results in greater sediment loss reduction than the buffer alone. The shoreline stabilization system results in a 90% decrease in sediment losses. Equation [35] can

$$E_S=\frac{Y_U^*}{(B_b/B_r)(Y_B+Y_U^*)}=\frac{159}{0.395*(3750+159)}=0.102$$

also be applied to nutrient losses. The resulting values of ES for nitrogen and phosphorus are 0.058 and 0.076, respectively. This means that the shoreline stabilization/buffer system reduced overall nitrogen and phosphorus losses by 94 and 92%, respectively.

SUMMARY AND CONCLUSIONS

A procedure is presented for evaluating the impacts of proposed vegetative buffer modifications on buffer effectiveness. The procedure is based on the hydraulic and detention models developed by Phillips for evaluating buffer effectiveness. Phillips's original models were modified to correct several limitations encountered. The modified models consider the effects of concentrated flow and vegetative uptake on buffer performance.

The proposed model is relative simple in concept and application and is suitable for use by planners. All of the data required by the model can be collected on site or can be estimated from the literature. Labratory analysis of soil and bank samples, however, will greatly improve model reliability with respect to nutrient losses. In areas with shoreline erosion, the procedure also allows the benefits of shoreline control to be considered.

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