A REVIEW OF THE SCIENTIFIC LITERATURE ON RIPARIAN BUFFER WIDTH, EXTENT AND VEGETATION

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for the

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Revised Version • March 5, 1999

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The publication of this paper was made possible by support from the Turner Foundation, R.E.M./Athens, L.L.C., and the University of Georgia Office of the Vice President for Public Service and Outreach.

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EXECUTIVE SUMMARY

Many local governments in Georgia are developing riparian buffer protection plans and ordinances without the benefit of scientifically-based guidelines. To address this problem, over 140 articles and books were reviewed to establish a legally-defensible basis for determining riparian buffer width, extent and vegetation. This document presents the results of this review and proposes several simple formulae for buffer delineation that can be applied on a municipal or county-wide scale.

Sediment is the worst pollutant in many streams and rivers. Scientific research has shown that vegetative buffers are effective at trapping sediment from runoff and at reducing channel erosion. Studies have yielded a range of recommendations for buffer widths; buffers as narrow as 4.6 m (15 ft) have proven fairly effective in the short term, although wider buffers provide greater sediment control, especially on steeper slopes. Long-term studies suggest the need for much wider buffers. It appears that a 30 m (100 ft) buffer is sufficiently wide to trap sediments under most circumstances, although buffers should be extended for steeper slopes. An absolute minimum width would be 9 m (30 ft). To be most effective, buffers must extend along all streams, including intermittent and ephemeral channels. Buffers must be augmented by limits on impervious surfaces and strictly enforced on-site sediment controls. Both grassed and forested buffers are effective at trapping sediment, although forested buffers provide other benefits as well.

Buffers are short-term sinks for phosphorus, but over the long term their effectiveness is limited. In many cases phosphorus is attached to sediment or organic matter, so buffers sufficiently wide to control sediment should also provide adequate short-term phosphorus control. However, long-term management of phosphorus requires effective on-site management of its sources. Buffers can provide very good control of nitrogen, include nitrate. The widths necessary for reducing nitrate concentrations vary based on local hydrology, soil factors, slope and other variables. In most cases 30 m (100 ft) buffers should provide good control, and 15 m (50 ft) buffers should be sufficient under many conditions. It is especially important to preserve wetlands, which are sites of high denitrification activity.

To maintain aquatic habitat, the literature indicates that 10-30 m (35-100 ft) native forested riparian buffers should be preserved or restored along all streams. This will provide stream temperature control and inputs of large woody debris and other organic matter necessary for aquatic organisms. While narrow buffers offer considerable habitat benefits to many species, protecting diverse terrestrial riparian wildlife communities requires some buffers of at least 100 meters (300 feet). To provide optimal habitat, native forest vegetation should be maintained or restored in all buffers.

A review of existing models for buffer width and effectiveness showed that none are appropriate for county-level buffer protection. Models were found to be either too data-intensive to be practical or else lacked verification and calibration. Potential variables for use in a buffer width formula were considered. Buffer slope and the presence of wetlands were determined to be the most important and useful factors in determining buffer width.

Three options for buffer guidelines were proposed. All are defensible given the scientific literature. The first provides the greatest level of protection for stream corridors, including good control of sediment and other contaminants, maintenance of quality aquatic habitat, and some minimal terrestrial wildlife habitat. The second option should also provide good protection under most circumstances, although severe storms, floods, or poor management of contaminant sources could more easily overwhelm the buffer.

Option One:

- Base width: 100 ft (30.5 m) plus 2 ft (0.61 m) per 1% of slope.
- Extend to edge of floodplain.
- Include adjacent wetlands. The buffer width is extended by the width of the wetlands, which guarantees that the entire wetland and an additional buffer are protected.

- Existing impervious surfaces in the riparian zone do not count toward buffer width (i.e., the width is extended by the width of the impervious surface, just as for wetlands).
- Slopes over 25% do not count toward the width.
- The buffer applies to all perennial, intermittent and ephemeral streams.

Option Two:

The same as Option One, except:

- Base width is 50 ft (15.2 m) plus 2 ft (0.61 m) per 1% of slope.
- Entire floodplain is not necessarily included in buffer, although potential sources of severe contamination should be excluded from the floodplain.
- Ephemeral streams are not included; affected streams are those that appear on US Geological Survey 1:24,000 topographic quadrangles. Alternatively, buffer can be applied to all perennial streams plus all intermittent streams of second order or larger

Option Three:

- Fixed buffer width of 100 ft.
- The buffer applies to all streams that appear on US Geological Survey 1:24,000 topographic quadrangles or, alternatively, all perennial streams plus all intermittent streams of second order or larger (as for Option Two).

For all options, buffer vegetation should consist of native forest. Restoration should be conducted when necessary and possible.

All major sources of contamination should be excluded from the buffer. These include construction resulting in major land disturbance, impervious surfaces, logging roads, mining activities, septic tank drain fields, agricultural fields, waste disposal sites, livestock, and clear cutting of forests. Application of pesticides and fertilizer should also be prohibited, except as may be needed for buffer restoration.

All of the buffer options described above will provide some habitat for many terrestrial wildlife species. To provide habitat for forest interior species, at least some riparian tracts of at least 300 ft width should also be preserved. Identification of these areas should be part of an overall, county-wide wildlife protection plan.

For riparian buffers to be most effective, some related issues must also be addressed. These include reducing impervious surfaces, managing pollutants on-site, and minimizing buffer gaps.

Contents

I. Background and Introduction

Riparian buffers have gained wide acceptance as tools for protecting water quality, maintaining wildlife habitat and providing other benefits to people and the environment (Lowrance 1998, USEPA 1998). Today in Georgia, as in many other states, local governments are developing programs to protect riparian buffers. Laws such as the Georgia Planning Act and the Mountain and River Corridor Protection Act give counties and municipalities strong incentives to incorporate aquatic resource protection into their plans and ordinances. However, scientifically-based guidelines for local riparian buffer ordinances are not readily available. The minimum standards issued by the Department of Natural Resources' Environmental Protection Division (EPD) are not based on current scientific research and do not provide a strong level of resource protection. Many local governments are interested in developing effective, comprehensive riparian buffer regulations, but fear that without solid scientific support, such ordinances would not be legally defensible.

The purpose of this document is to provide a scientific foundation for riparian buffer ordinances established by local governments in Georgia. To achieve this goal more than 140 articles and books were reviewed with an eye toward determining the optimal width, extent (i.e., which streams are protected) and vegetation (e.g., forest or grass) of riparian buffers. This task is challenging due to the lack of research in certain geographic regions. Although a large number of riparian buffer studies have been conducted in the Georgia Coastal Plain (see Figure 1), there has been very little research specific to the physiographic provinces of North Georgia (Piedmont, Blue Ridge, Valley and Ridge) or to urban and suburban areas. Nevertheless, it is apparent in reviewing the literature that there are general trends which cut across geographic boundaries. Based on current research, it is possible to develop defensible guidelines for determining riparian buffer width, extent and vegetation that are applicable to much of Georgia and beyond. Naturally, these recommendations will not be as accurate as those supplied by data-intensive models applied on a site-by-site basis (such as the REMM model developed by Richard Lowrance and colleagues). However, these guidelines have the virtue of being simple enough to be incorporated into a county or municipal ordinance.

The guidelines proposed in this document should be viewed as a reasonable interpretation of the best available scientific research. If additional riparian buffer studies are conducted in North Georgia, urban areas, and other neglected regions, it may be possible to refine the recommendations. However, this in no way means that the current state of our knowledge is insufficient to develop good policy guidelines and implement effective buffer ordinances. As Lowrance et al noted in 1997:

> *"Research is sometimes applied to broad-scale environmental issues with inadequate knowledge or incomplete understanding. Public policies to encourage or require landscape management techniques such as riparian (streamside) management will often need to proceed with best professional judgment decisions based on incomplete understanding."*

Local officials and natural resource managers are making decisions on riparian buffers today. The scientific community would be remiss if it failed to provide these decision makers with the best available information.

To ensure that this review has covered the most relevant research and has made reasonable conclusions, other members of the scientific community were asked to review its findings. These reviewers included:

- Richard Lowrance, Ph.D., USDA-Agricultural Research Service
- David Correll, Ph.D., Smithsonian Environmental Research Center
- Cathy Pringle, Ph.D., University of Georgia
- Laurie Fowler, J.D., L.L.M., University of Georgia
- Judy Meyer, Ph.D., University of Georgia
- Ronald Bjorkland, University of Georgia
- Michael Paul, University of Georgia

Figure 1. Physiographic Provinces of Georgia.

Although there has been a signficant amount of riparian buffer research in the Georgia Coastal Plain, there has been much less research conducted in the other physiographic provinces (Keys et al 1995, as modified by J. P. Schmidt)

(Map of physiographic provinces)

The corrections, additions and changes made by these reviewers, as well as the comments and suggestions other people have made on an earlier draft of this document, have been incorporated into this revised version.

Acknowledgments

This review would have been impossible without the assistance and support of numerous people, and much of the credit for this project lies with these individuals. **Laurie Fowler** suggested the idea of the project and helped to guide its progress, while **Cathy Pringle** made certain it remained focused and manageable. **Ronald Bjorkland** made extremely thorough and thoughtful comments on a draft version of this document. **Richard Lowrance** and **David Correll**, two of the leading researchers on riparian buffers, were generous enough to provide expert criticism and made important corrections. Many others have lent their expertise and have patiently taken time to answer my questions. Some of their personal comments and expert opinions are included in this review.

- Katherine Baer, Sally Bethea and Alice Champagne, Upper Chattahoochee River Keeper
- Jimmy Bramblett, Natural Resources Conservation Service
- Miguel Cabrera, University of Georgia
- Robert Cooper, University of Georgia
- Gail Cowie, Institute for Community and Area Development
- Bruce Ferguson, University of Georgia
- Christa Frangiamore, University of Georgia
- Charlie Frear, Limestone Valley Resource Conservation and Development
- Byron J. “Bud” Freeman, University of Georgia
- Mary Freeman, University of Georgia
- Robin Goodloe, U.S. Fish and Wildlife Service
- Gene Helfman, University of Georgia
- Tara Hottenstein, University of Georgia
- Rhett Jackson , University of Georgia
- Bob James, Gently Down the River
- Carl Jordan, University of Georgia
- Elizabeth Kramer, University of Georgia
- James Kundell, University of Georgia/Carl Vinson Institute of Government
- Steve Lawrence, Natural Resources Conservation Service
- Judy Meyer, University of Georgia
- Ken Patton, Manager, Cherokee County Planning and Zoning Office
- Michael Paul, University of Georgia
- Scott Pohlman, University of Georgia
- Todd Rasmussen, University of Georgia
- Rebecca Sharitz, University of Georgia
- Chris Skelton, Georgia Department of Natural Resources
- Brian Toth, J.P. Schmidt and Karen Payne, NARSAL, University of Georgia
- David Walters, University of Georgia
- The rest of the Pringle and Fowler Labs and my other colleagues at the Institute of Ecology

Scope of Review

There are literally hundreds of articles and dozens of books written on the subject of riparian buffer zones. The 1997 version of David Correll’s riparian bibliography (Correll 1997), which is limited to works on nutrients, sediments and toxic contaminants, lists 522 citations. John Van Deventer published a bibliography in 1992 of an astounding 3252 articles that relate to riparian research and management, though most of the literature cited does not directly address *buffer* zones (Deventer 1992). Given the volume of literature available, it was apparent from the beginning that this review would have to be limited in some ways. Priority was given to:

- articles which specifically deal with the issues of riparian buffer width, extent and vegetation
- previous literature reviews
- articles focused on Georgia and the Piedmont
- seminal articles in the field

- recent articles (1990-1998) especially those not included in prior literature reviews
- articles from refereed journals (although several good government documents and other works from the "grey literature" are included)

Over 140 sources are included in this review.

Why Another Literature Review?

As of this writing there exist several excellent literature reviews on riparian buffer zones. The U.S. Army Corps of Engineers New England Division conducted a 1991 literature review for the State of Vermont called *Buffer Strips for Riparian Zone Management* that is similar in scope and purpose to this document. It differs from most other reviews in that it covers virtually all of the functions of riparian buffers, including instream and riparian wildlife habitat as well as water quality functions. It also shares this document's focus on buffer width, although it ultimately makes no width recommendations. Another thorough and useful review is Desbonnet et al's 1994 *Vegetated Buffers in the Coastal Zone: A Summary Review and Bibliography.* Despite its title, this work reviews research from many regions, not just the coastal zone. The review is rather weak on wildlife habitat studies, however, since it predates much of the best literature. Lowrance and a team of riparian buffer researchers collaborated on a 1997 paper that synthesizes research on sediment and nutrient retention and presents guidelines for buffers in the Chesapeake Bay watershed. Other useful reviews include Clinnick et al 1985, Muscutt et al 1993, Osborne and Kovacic 1993, Castelle et al 1994, Fennesy and Cronk 1997 and Bjorkland (unpublished).

As useful as these previous works were, a new review was necessary to include recent studies, to consider the full range of buffer functions (nutrient reduction, wildlife habitat, etc.), and to address the primary issue of concern: determining the optimal width, extent and vegetation for buffer zones in Georgia. This works relies heavily on previous reviews, although in most cases the original research articles were consulted as well.

Background on Riparian Zones

Definitions

Before proceeding it will be helpful to establish definitions for some key concepts. The word **riparian** is especially subject to confusion, and currently there appears to be no universally accepted definition of the term. One of the better definitions comes from Lowrance et al (1985): "'Riparian ecosystems' are the complex assemblage of organisms and their environment existing adjacent to and near flowing water." Malanson (1991) offers an attractively simple definition: "the ecosystems adjacent to the river." Bjorkland (unpublished) provides a thorough review of published definitions for the term. Some of these definitions even use "riparian" to refer to the edges of bodies of water other than streams and rivers. This broader usage reflects the original, legal definition of the term, which referred to land adjoining any water body (David Correll, pers. com.). In this review the term is used in two ways: (1) to refer to the "natural" riparian area (Figure 2), the zone along streams and rivers that in its undisturbed state has a floral and faunal community distinct from surrounding upland areas, and (2) in the most general sense to refer to the zone along streams and rivers which might benefit from some type of protection. Stream corridor and river corridor will sometimes be used synonymously with riparian zone.

A riparian zone that is afforded some degree of protection is a **riparian buffer zone.** The word "buffer" is used because one of the functions of the protected area is to buffer the stream from the impact of human land use activities, such as farming and construction. Numerous other terms are also used to refer to this protected zone, both in this document and in the scientific literature: riparian management zone, riparian forested buffer strip, stream buffer zone and protected stream corridor are all taken to be synonymous with riparian buffer zone for the purposes of this review. Within this document the term is also frequently shortened to buffer zone, riparian buffer or simply buffer. Note that in some fields, especially agricultural research, the term buffer is applied in a more general sense to a variety of **conservation practices.** The terms vegetated buffer strip and vegetated filter strip (VFS) are often used to refer to strips of grass or other plants installed between or below agricultural fields to reduce erosion and trap contaminants. For the sake of clarity, these terms are not used in this review.

Significance of Riparian Zones

Riparian zones are a type of ecotone, or boundary between ecosystems. Like many other ecotones, riparian buffer zones are exceptionally rich in biodiversity (Odum 1978, Gregory et al 1991, Malanson 1993, Naiman et al 1993). Naiman et al (1988) noted that ecotones can display a greater variation in characteristics than either of the systems they connect; rather than being averages of the two systems, they are something unique. For this reason alone riparian zones can be considered valuable. In addition, however, riparian zones perform a range of functions with economic and social value to people:

- Trapping /removing sediment from runoff
- Stabilizing streambanks and reducing channel erosion
- Trapping/removing phosphorus, nitrogen, and other nutrients that can lead to eutrophication of aquatic ecosystems
- Trapping/removing other contaminants, such as pesticides
- Storing flood waters, thereby decreasing damage to property
- Maintaining habitat for fish and other aquatic organisms by moderating water temperatures and providing woody debris
- Providing habitat for terrestrial organisms
- Improving the aesthetics of stream corridors (which can increase property values)
- Offering recreational and educational opportunities

(based on Schueler 1995a, Malanson 1993)

Because they maintain all of these services, riparian buffers can be thought of as a “conservation bargain”: preserving a relatively narrow strip of land along streams and rivers— land that is frequently unsuitable for other uses— can help maintain good water quality, provide habitat for wildlife, protect people and buildings against flood waters, and extend the life of reservoirs. “Vegetative buffer programs, however, are rarely developed to fully consider the multiple benefits and uses that they offer to resource managers and to the general public” (Desbonnet et al 1994). Often, buffer programs are developed for a single goal, such as preventing erosion and sedimentation. However important this goal may be, programs with such a narrow focus inevitably undervalue buffers (and riparian zones in general) and may lack popular support if this goal is not met. On the other hand, programs that promote the multiple functions of buffers are likely to enjoy a wider and stronger base of support, especially when people recognize the economic benefits they can provide. It is hoped that this document will encourage the establishment of multifunctional riparian buffer protection programs.

That said, it must be acknowledged that certain buffer functions are given a higher priority than others by local governments. Water quality and aquatic habitat functions are generally considered of greatest importance. Of slightly less concern are terrestrial wildlife habitat, the floodwater storage functions of the riparian buffer, recreation and aesthetic values. The organization of this review reflects this hierarchy. The next two sections review literature on the water quality functions of riparian buffers. Section four reviews aquatic habitat functions. Section five considers the literature on buffers as terrestrial habitat, along with other functions not yet discussed. Finally, section six develops guidelines for buffer width, extent and vegetation, taking into consideration various factors and reviewing other models of buffer function. Section seven is a discussion of important related issues, such as impervious surface limits and riparian buffer crossings.

A note on measurements: Riparian buffer widths given in this review are for one side of the stream measured from the bank. Therefore, a 50 ft (15 m) buffer on a 25 ft (7.6 m) stream would actually create a corridor 125 ft (38 m) wide. Measurements are given in metric or English units, according to how they were reported in the literature, with the conversion in parentheses. Buffer recommendations are made first in English units because legislation in Georgia generally uses this system.

II. Sediment

In terms of volume, sediment is the largest pollutant of streams and rivers (Cooper 1993). In much of Georgia, sediment levels in streams have historically been high due to agricultural activities. The decline in row crop acreage and improvements in erosion control practices have led to decreased agricultural sedimentation, but in urbanizing parts of the state these gains have been offset by sedimentation from construction (Kundell and Rasmussen 1995).

Effects

Excess amounts of sediment can have numerous deleterious effects on water quality and stream biota. For a full discussion of this topic, refer to Waters 1995 and Wood and Armitage 1997. The following brief list summarizes the major sediment effects.

- Sediment in municipal water is harmful to humans and to industrial processes.
- Sediment deposited on stream beds reduces habitat for fish and for the invertebrates that many fish consume.
- Suspended sediment reduces light transmittance, decreasing algal production.
- High concentrations of fine suspended sediments cause direct mortality for many fish.
- Suspended sediments reduce the abundance of filter-feeding organisms, including mollusks and some arthropods.
- Sedimentation reduces the capacity and the useful life of reservoirs.

Sediment must be filtered from municipal water supplies at considerable cost. The greater the turbidity levels in water, the higher the price of treatment (Kundell and Rasmussen 1995). Note that both suspended sediment (sometimes approximated by turbidity measurements) and benthic sediment have detrimental biological effects, and that benthic sediment can become resuspended during high flows. Certain fish are more responsive to sediments than others. Although many species of fish found in Georgia's waters are sediment tolerant, many of the threatened and endangered species, such as darters, tend to be very sensitive to siltation (Kundell and Rasmussen 1995, Freeman and Barnes 1996, Barnes et al 1997, Burkhead et al 1997). The many endangered species of native mussels may be the most sensitive organisms of all (Morris and Corkum 1996).

Sources

Sediment in streams either comes from runoff from upland sources or from the channel itself. Upland sources include row crop agricultural

Figure 2. View of a River with an Intact Riparian Zone.

This is the Etowah River in Cherokee County, GA.

fields, exposed earth at construction sites, and logging roads, for example. Channel-derived sediment may result from the erosion of poorly stabilized banks and from scouring of the stream bed. Livestock watering in streams can contribute significantly to bank destabilization and erosion (Waters 1992). Note that much channel-derived sediment may originally have been upland sediment that is temporarily stored in the streambed or riparian zone (Trimble 1970, Wood and Armitage 1997).

Construction Sites

In urban and urbanizing areas, construction is likely to be the major source of sediment (see Figure 3). Streams draining urban areas often have higher sediment loads than those in agricultural watersheds (Crawford and Lenat 1989) and certainly have higher rates than forested areas (Wahl et al 1997). A recent report by the U.S. Geological Survey found that urban streams in Georgia are the most degraded (Frick et al 1998).

Mining

Various forms of mining can produce severe sedimentation (Waters 1992, Burkhead et al 1997). Gravel dredging can be considered a form of mining which is especially harmful because it takes place within the river itself. This has direct negative effects on stream organisms and increases downstream turbidity, as local residents and canoeists have observed (Bob James, pers. com.). In addition, dredging may release sediment-bound contaminants (Burruss Institute 1998) and contributes to stream downcutting, both at the site and upstream (Pringle 1997).

Agricultural Sources

According to Waters (1992), row-crop agriculture and livestock are the top two sources of sediment nationwide. Row crop agriculture is no longer widely practiced in much of North Georgia, and in South Georgia row-crop agriculture tends to be concentrated in upland areas (Frick et al 1998). However, cattle are raised throughout Georgia (GA Department of Agriculture 1997) and frequently are permitted direct access to streams and rivers, resulting in bank erosion (pers. obs.; see Figure 4).

Forestry

Streams in forested areas are not necessarily pristine. Improperly stabilized logging roads can yield over 350 tons of sediment per acre per year (Kundell and Rasmussen 1995). Some of the first research on riparian buffers was initiated to determine logging road setbacks (e.g., Trimble and Sartz 1957). The Georgia Forestry Commission advocates Best Management Practices (BMPs) for logging operations, but compliance is voluntary. The most recent BMPs have placed limits on logging in “streamside management zones” (buffers), which vary in width from 20-100 ft (6-30 m) depending on slope and stream type (Georgia Forestry Commission 1999).

Historic Sedimentation

Many streams and rivers in Georgia have experienced a long history of sedimentation. Throughout the 1800s and up until the 1940s, massive soil erosion from cotton farming and other forms of row crop agriculture led to severe sedimentation of streams all across the Georgia

Figure 3. Impacts of Development.

This riparian zone has been stripped of vegetation in preparation for the construction of subdivisions. A properly enforced riparian buffer ordinance could prevent this type of problem.

Piedmont (Trimble 1970, Kundell and Rasmussen 1995). Some areas, such as the upper Chattahoochee and Etowah Rivers, were also impacted by hydraulic gold mining, when "entire hillsides" were washed into streams (Glenn 1911), leading to rapid sedimentation and aggradation of rivers and floodplains (Leigh 1994). The channels of many streams were entirely filled with sediment over time. For example, the bed of the Etowah River at Canton, GA, rose 4.8 ft (1.46 m) between 1890 and 1949 (Walters unpublished). With the decline of gold mining and agriculture in the region, as well as the adoption of better soil conservation practices, sedimentation rates decreased and many Piedmont streams experienced downcutting, as channels carved deeper and wider into the loose beds of sand (Trimble 1970, Burke 1996). There is evidence, however, that as of the 1980s sedimentation is again increasing in some Piedmont rivers, perhaps as a result of construction (Burruss Institute 1998, Walters unpublished).

Figure 4. Bank Erosion from Livestock Intrusion.

Livestock intrusion into the riparian zone results in stream bank erosion and water contamination.

It appears likely that sediment now stored in stream channels continues to cause high turbidity during storms (Trimble 1970; Rhett Jackson, pers. com.). Sediment in the larger Piedmont streams and rivers may also increase as sand from tributaries migrates downstream. Riparian buffers will probably little effect on this sediment source (except as they contribute to bank stability), but they are essential in preventing additional degradation to water quality, especially in smaller tributaries.

Literature Review

Riparian buffers can reduce stream sedimentation in six ways:

1) by displacing sediment-producing activities away from flowing water (setbacks)
2) by trapping terrestrial sediments in surface runoff
3) by reducing the velocity of sediment-bearing storm flows, allowing sediments to settle out of water and be deposited on land (this includes sediments previously suspended in the river that are borne into the riparian buffer during floods)
4) by stabilizing streambanks, preventing channel erosion
5) by moderating stream flow during floods, reducing bed scour, and
6) by contributing large woody debris (snags) to streams; these can trap considerable sediment, at least temporarily

(adapted in part from US ACE 1991)

Functions one, two and three are primarily concerned with preventing terrestrial sediment from reaching the water. Functions four and five involve reducing channel erosion. This review of sediment-related literature is divided into two subsections corresponding to these two major topics. The literature on large woody debris is reviewed separately in the section regarding in-stream habitat protection.

Sediment in Surface Runoff

Numerous studies have documented the effectiveness of buffers in trapping sediment transported by surface runoff. The challenge lies in determining the necessary width of the buffer.

Width

One of the greatest challenges in trying to develop buffer width recommendations is that most studies only examined one or a few buffer widths. Fennesy and Cronk (1997) noted this problem:

> *"One problem in assessing minimum widths necessary to protect adjacent surface water is that many studies that make recommendations regarding the minimum width necessary have arrived at the figure as a byproduct of sampling design rather than deriving it experimentally."*

Nevertheless, from the research that exists it is evident that there is a positive correlation between a buffer's width and its ability to trap sediments. In their 1994 review, Desbonnet et al determined that increasing buffer width by a factor of 3.5 provides a 10% improvement in sediment removal. According to the reviewers, the most efficient width of vegetated buffers for sediment removal is 25 m (82 ft). For total suspended solids, buffer widths need to increase by a factor of 3.0 for a 10% increase in removal efficiency, and 60 m (197 ft) wide buffers provide the greatest efficiency. It is important to note that Desbonnet et al based this relationship on a composite of data from studies conducted with various methods at different location. It may not be appropriate to compare such study results. It is more illuminating to examine data from studies that compared multiple width buffers in the same location under the same study conditions. Six studies (Young et al 1980; Peterjohn and Correll 1984; Magette et al 1987, 1989; Dillaha et al 1988, 1989) have examined the effectiveness of buffers of two widths in trapping total suspended solids (TSS). In every case, buffer effectiveness

Author	Width (m)	% Slope	% Removal of TSS
Dillaha et al (1988)	4.6	11	87
Dillaha et al (1988)	4.6	16	76
Dillaha et al (1988)	9.1	11	95
Dillaha et al (1988)	9.1	16	88
Dillaha et al (1989)	4.6	11	86
Dillaha et al (1989)	4.6	16	53
Dillaha et al (1989)	9.1	11	98
Dillaha et al (1989)	9.1	16	70
Magette et al (1989)	4.6	3.5	66
Magette et al (1989)	9.1	3.5	82
Peterjohn & Correll (1984)	19	5	90
Peterjohn & Correll (1984)	60	5	94
Young et al (1980)	21.3	4	75-81
Young et al (1980)	27.4	4	66-93

Table 1. Riparian Buffer Width, Slope and TSS Removal Rates.

The ability of riparian buffers to trap suspended solids is positively correlated with width and negatively correlated with slope.

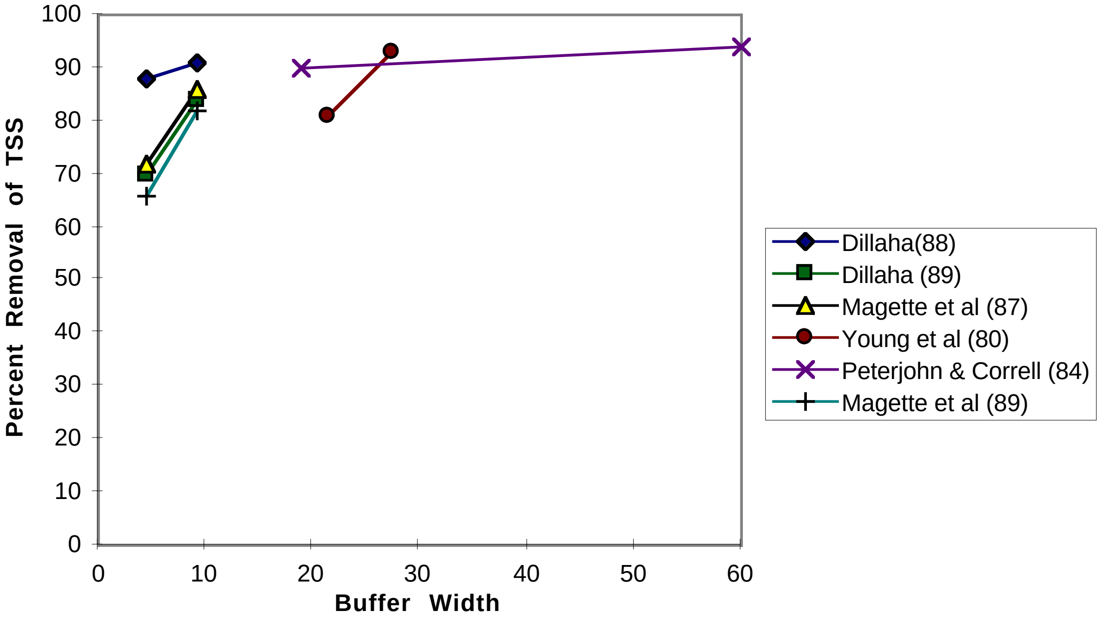


Figure 5. Removal of TSS by Buffers of Different Widths.

The ability of a riparian buffer to remove total suspended solids (TSS) from runoff is a function of the buffer's width. Note that with the exception of Peterjohn and Correll (1984) these are short-term studies; long-term studies have suggested that much wider buffers are necessary. This figure is only intended to convey the consistent relationship of buffer width and effectiveness.

increased with buffer width, although the relationship varied. Table 1 and Figure 5 summarize the results of these studies [Data from Magette et al (1987) which appear in Figure 5 were taken from Desbonnet et al (1993) because the original document was not readily available].

In a series of studies using orchardgrass buffers downslope from a simulated feedlot, Dillaha et al (1988) reported average TSS reductions of 81% for a 4.6 m (15 ft) buffer and 91% for a 9.1 m (30 ft) buffer. Dillaha et al (1989) later repeated the study using buffers of the same width and vegetation below fertilized bare cropland. This time they found average sediment reductions of 70% and 84% for buffers of 4.6 m and 9.1 m width, respectively. Magette et al (1989) conducted a similar study with grassed buffers of 4.6 m and 9.1 m downslope from plots to which they added liquid nitrogen or chicken waste. They found average sediment reductions of 66% and 82%, respectively.

Coyne et al (1994) also conducted a study of similar design, although they only used strips of 9 m (30 ft) width and conducted only one rainfall simulation rather than a series. The researchers added poultry waste to a test plot and found that the grass buffers trapped 99% of sediment. Young et al (1980) tested the efficiency of buffer strips of corn, orchard grass, oats and sorghum/sudangrass at reducing surface runoff from feedlots. They found that buffers of 21.34 m (70 ft) reduced total suspended solids by an average of 78%, while 27.43 m (90 ft) wide buffers reduced TSS by an average of 93%. Buffer slope averaged four percent.

Peterjohn and Correll (1984) found that a 50 m (164 ft) riparian buffer in an agricultural catchment in the Mid-Atlantic Coastal Plain trapped 94% of suspended sediment that entered. Ninety percent was trapped in the first 19 m (62 ft). Average slope of the buffer was about five percent.

Only a few researchers have found buffer width to be unimportant. Daniels and Gilliam (1996) found that 6 m (20 ft) wide grassed buffers and 13 m (43 ft) or 18 m (59 ft) wide combination forest/grassed buffers all reduced sediments by about 80%. However, the wider buffers included a farm vehicle access road which provided an additional source of sediment, so comparisons are not valid. Gilliam (1994) mentions that a "narrow" buffer in the Piedmont was found to trap 90% of sediment. Rabeni and Smale (1996) suggest that width of buffer may not be as important as other, qualitative characteristics, such as whether or not the topography can maintain sheet flow.

Most of the studies described above were short-term. There is significant evidence from long-term analyses that wider buffers are necessary to maintain sediment control. Lowrance et al (1986) used sediment budgets to calculate that a low-gradient riparian buffer ecosystem in the Georgia Coastal Plain trapped large amounts of sediment (35-52 Mg/ha per year) between 1880 and 1979. Later studies by Lowrance et al (1988) based on cesium-137 concentrations yielded a much higher reduction rate of 256 Mg/ha per year for the period between 1964 and 1985. The researchers found that sediments from agricultural fields were deposited throughout the riparian forest. The greatest amount (depth) of transported sediment was found 30 m (98 ft) inside the forest and the greatest cesium signal occurred 80 m (262 ft) into the forest. The results are confounded slightly by the higher affinity of cesium-137 to clay particles, which are transported farther than sand and silt (possibly leading to a higher signal deeper in the buffer), and deposition of sediment within the riparian zone by floodwaters from the stream. A similar Cs-137 study by Cooper et al (1988) in the North Carolina Coastal Plain reached similar conclusions. The riparian buffer trapped 84-90% of the sediment eroded from agricultural fields, although nearly 50% was transported more than 100 m (328 ft) into the buffer. Slopes ranged from 0-20%. These two studies suggest that although riparian zones are efficient sediment traps, the width required for long-term retention may be substantially more than is indicated by short-term experiments. Buffers of 30-100 m (98-328 ft) or more might be necessary.

Davies and Nelson (1994) found that buffers can be highly effective in reducing sedimentation to streams in logged forests, and buffer width is the determining factor. "All effects of logging were dependent on buffer strip width and were not significantly affected by [buffer] slope, soil erodibility or time (over one to five years) since logging." The authors found that a 30 m (98 ft) buffer was necessary to prevent impacts. These recommendations are in agreement with a 1985 review of the use of riparian buffers to mitigate the impacts of logging on forest streams (Clinnick 1985). One study cited in that review found that "streams with buffers of at least 30 m width exhibited similar channel stability and biological diversity to unlogged streams, whereas streams with buffers less than 30 m showed a range of effects similar to those found where no stream protection was provided" (Erman et al 1977, as cited in Clinnick 1985).

The sediment trapping efficiency of buffers can be expected to vary based on slope, soil infiltration rate, and other factors. Slope may be the best studied of these relationships. Dillaha et al (1988, 1989) found that as buffer slope increased from 11% to 16%, sediment removal efficiency declined by 7-38% (See Figure 6). The most thorough investigations of the relationship between buffer width and slope have been conducted by forestry researchers. Trimble and Sartz (1957) examined erosion of logging roads in the Hubbard Brook Experimental Forest in New Hampshire to determine how far roads should be set back from streams. They suggested a simple formula:

25 ft + (2.0 ft)(% slope).

For municipal watersheds where water quality is of very high importance, the setback should be doubled. Trimble and Sartz' formula was the basis of a Forest Service standard for many years. Swift (1986) proposed an alternative formula based on work in the Nantahala National Forest in western North Carolina. He found that when brush barriers are employed below a road, erosion is reduced dramatically. He proposed a buffer width formula of

32 ft + (0.40 ft)(% slope).

If barriers are not used the buffer width should be increased to:

43 ft + (1.39 ft)(% slope) (Swift 1986).

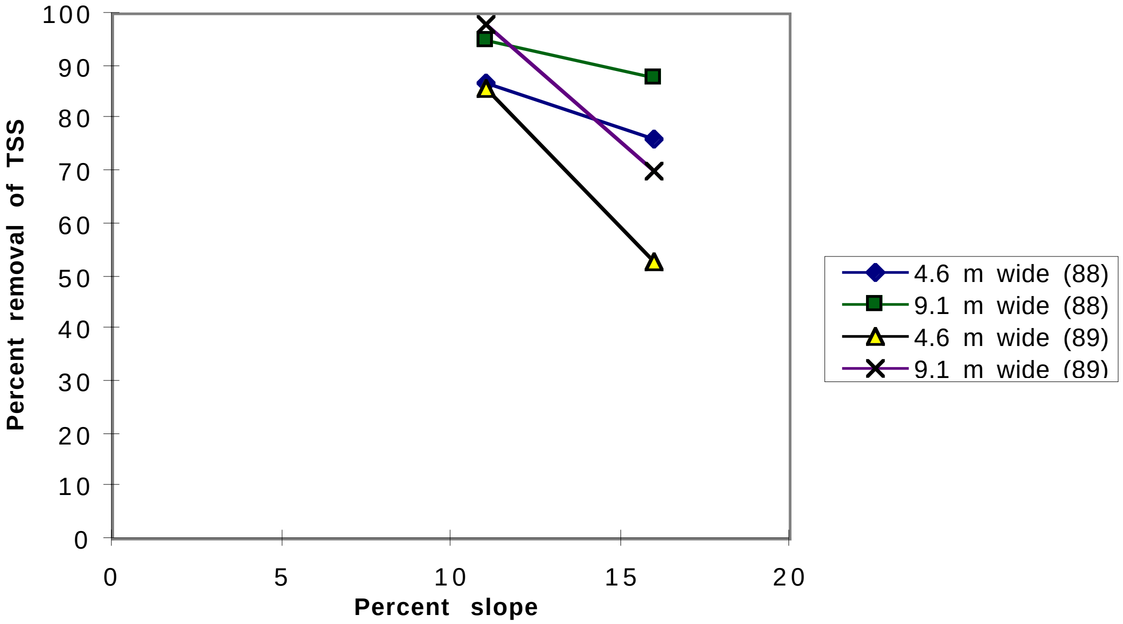


Figure 4. Removal of TSS by Buffers of Different Slopes.

Studies by Dillaha et al revealed an inverse relationship between buffer slope and reduction of total suspended solids (TSS). Slope is an important variable to use in determining riparian buffer width.

Swift only measured coarse sediment in his study, not silt and clay, which are transported much further through a buffer. This suggests that his buffer recommendations are insufficiently wide.

Lowrance et al (1997) made some generalizations about buffer effectiveness in different physiographic provinces. They noted that buffer effectiveness has been well established in the Coastal Plain, where much research has been conducted. For the Piedmont and Valley and Ridge provinces, they predicted sediment reductions of 50-90%, although they did not discuss widths necessary to achieve this reduction. The Blue Ridge province was not discussed in their review. Daniels and Gilliam (1996) suggested that the high level of runoff from Piedmont fields makes buffers valuable. They also pointed out, however, that steeper slopes and lower soil infiltration rates may make Piedmont buffers less effective in terms of trapping efficiency than buffers in the Coastal Plain.

Extent

It is very important that buffers be continuous along streams (Rabeni and Smale 1996). Gaps, crossings or other breaks in the riparian buffer allow direct access of surface flow to the stream, compromising the effectiveness of the system. The problem of buffer gaps is discussed further in Section VI.

Riparian buffers are especially important along the smaller headwater streams which make up the majority of stream miles in any basin (Osborne and Kovavic 1993, Binford and Buchenau 1993, Hubbard and Lowrance 1994, Lowrance et al 1997). These streams have the most land-water interaction and have the most opportunities to accept and transport sediment. "Protecting greenways along low-order streams may offer the greatest benefits for the stream network as a whole" (Binford and Buchenau 1993).

Ideally, therefore, a system of riparian buffers should protect all streams and rivers, regardless of size. Even ephemeral streams should be protected, since these waterways can carry appreciable flow and sediment during storms. Although such universal protection will generally not be feasible, buffer ordinances should be written to protect as many stream miles as possible— at least all perennial streams, as well as intermittent streams of second order or larger.

Vegetation

The studies reviewed above have found that for purposes of trapping sediment, both grass and forested buffers are effective. Grass buffers, although more likely to be inundated by exceptionally high levels of sediment, are useful for maintaining sheet flow and preventing rill and gully erosion. In sum, however, forested buffers have other advantages (discussed in later sections) which recommend them over grass in most cases. A combination of grass and forested buffers has been advocated by many researchers (e.g. Welsch 1991, Lowrance et al 1997) and represents a reasonable compromise.

Limitations

Buffers are most effective when uniform, sheet flow through the buffer is maintained; they are less effective in stopping sediment transported by concentrated or channelized flow (Karr and Schlosser 1977, Dillaha et al 1989, Osborne and Kovacic 1993, Daniels and Gilliam 1996). When these conditions occur, riparian buffers cannot slow the flow sufficiently to allow infiltration of water into the soil, although some sediment may still be trapped by vegetation. Clay particles are unlikely to be trapped because they form colloids in solution. Jordan et al (1993) reported that sediment *increased* across a 60 m (197 ft) wide riparian buffer in the Delmarva Peninsula because of rill erosion. Daniels and Gilliam (1996) noted that ephemeral channels in the North Carolina Piedmont were ineffective sediment traps during high-flow events. They recommended dispersing the flow from these channels through a riparian area rather than allowing them to empty directly into a perennial stream. Sheet flow can be encouraged by the use of level spreaders and other structural techniques. Welsch (1991) recommended planting a strip of grass 20 ft (6.1 m) wide at the outer edge of a riparian buffer to help convert concentrated flow to dispersed sheet flow.

It is possible for buffer vegetation to be inundated with sediments and decline in effectiveness, although under normal conditions vegetation should be able to grow through the sediment (Dillaha et al 1989). Sediment can also accumulate to the point where it forms a levee that blocks the flow of water from the slope to the stream (Dillaha et al 1989). Flow then runs parallel to this berm until it reaches a low spot, at which time it crosses into the stream in concentrated flow. Buffers on agricultural land with very high erosion may require regular maintenance to remain effective and should always be used in conjunction with other erosion control methods (Barling 1994). The importance of on-site sediment control is discussed further in a later section.

Channel Erosion

In a long-term study between 1983 and 1993, Stanley Trimble found that in San Diego Creek in suburban Los Angeles, two thirds of stream sediment resulted from channel erosion. He concluded that “stream channel erosion can be the major source of sediment in urbanizing watersheds, with deleterious downstream effects” (Trimble 1997). Clinnick’s 1994 review also noted the importance of channel erosion, citing a 1990 study by Grissinger et al that suggested that “better than 80% of the total sediment yield for Goodwin Creek in northern Mississippi originates as channel and gully erosion.” Likewise, Rabeni and Smale (1995), Cooper et al (1993) and Lowrance et al (1985) found that the channel can be a significant source of sediment.

One of the most important roles of protected riparian buffers is to stabilize banks. A study (Beeson and Doyle 1995) of 748 stream bends found that 67% of bends without vegetation suffered erosion during a storm, while only 14% of bends with vegetation were eroded. Non-vegetated bends were more than 30 times as likely to suffer exceptionally severe erosion as fully vegetated bends. The authors concluded, unsurprisingly, that “the denser and more complete the vegetation around a bend, generally the more effective it is in reducing erosion” (Beeson and Doyle 1995). Barling and Moore (1994) note that buffers can prevent the formation of rills and gullies in riparian areas that are otherwise highly susceptible to erosion.

Bank stabilization will not be effective if the underlying causes of channel erosion are not addressed. The major problem in urban and suburban areas is increased storm flows due to elevated surface runoff from impervious surfaces. This is discussed in more detail in Section VI. In rural areas, livestock that graze on banks and enter streams are a direct source of severe channel erosion (Figure 4). A solution is to fence the livestock out (Waters 1995) and provide alternate means of watering the animals. Use of offstream watering tanks is the preferred method, but a narrow, stabilized stream access point can also be considered as a compromise (Cohen et al 1987).

Stream channelization contributes to channel erosion by increasing stream power, leading to incision (Karr and Schlosser 1977, Malanson 1993). Formerly, stream channelization was encouraged by government agencies such as the Soil Conservation Service (now the Natural Resources Conservation Service). However, channelization is now recognized as a short term solution to drainage problems that results in long-term damage to streams and agricultural fields. In a channelized stream in Illinois, flood waters from one storm eroded as much as 1150 tons of soil from a single bank in 1982 (Roseboom and Russell 1985). In 1978 Karr and Schlosser (1978) noted that "money spent on preventing sediments from entering streams will have minimum return value in improving the quality of biota, if present channelization practices continue to destroy the habitat of stream organisms." Channelization and gravel mining can also lead to upstream impacts, resulting in headward erosion and channel downcutting (Pringle 1997).

Width

Few studies have attempted to correlate stream bank stability with riparian buffer width. Common sense suggests that relatively narrow vegetative buffers should be effective in the short term (USACE 1991). As long as banks are stabilized and damaging activities are kept away from the channel, width of the riparian buffer would not appear to be a major factor in preventing bank erosion. However, it is important to recognize that some erosion is inevitable and stream channels *will* migrate laterally, which could eventually move the stream outside the protected area. Therefore, the buffer zone should be wide enough to permit channel migration. To allow for all possible migration would require a buffer the width of the active (100-year) floodplain (Rhett Jackson, pers. com.), but a narrower buffer may still permit migration over a shorter period of time. As a general rule, buffer widths sufficient for other purposes should also be sufficient to prevent bank erosion and allow reasonable stream migration.

Extent

All channels, regardless of stream size and frequency of flow, can be subject to erosion if not properly stabilized. In their 1985 review, Clinnick et al (1985) note:

> *"During storm events it is often the ephemeral elements of the stream system that act as a source of surface flow to permanent streams (Hewlett and Hibbert 1967). The prevention of sediment accession to streams thus relies primarily on protection of these ephemeral elements."*

Daniels and Gilliam (1986) found that forested ephemeral channels were temporary sediment sinks during dry seasons but were sources of sediment during storm events. Binford and Buchenau (1993) note that such gullies and tributaries naturally have dense growth and should have excellent capacity for sediment and nutrient retention. It is essential to maintain these ephemeral channels in a vegetated condition to allow them to slow water flow, trap sediment and to prevent their serving as sediment sources (Cooper et al 1987, Binford and Buchenau 1993). Clinnick et al (1985) advocate a minimum of a 20 m wide buffer on ephemeral channels. This may not be practical in many situations, but at the least, the banks and even the bed of such channels should be vegetated and livestock intrusion should be minimized.

Vegetation

To be effective, bank vegetation should have a good, deep root structure which holds soil. Shields et al (1995) tested different configurations of vegetation and structural controls in stabilizing banks. They found that native woody species, especially willow, are best adapted to recolonizing and stabilizing banks. The authors noted that the persistent exotic vine kudzu may be the most serious barrier to vegetation restoration because it can outcompete native vegetation. Other restoration ecologists believe that kudzu and certain other exotics may still have a role in streambank restoration because they can provide good root structure (Carl Jordan, pers. com.).

Artificial methods of streambank stabilization, such as applying riprap or encasing the channel in cement, may be effective in reducing bank erosion on site but will increase erosion downstream and have negative impacts on other stream functions. Artificially stabilized banks lack the habitat benefits of forested banks and can be expensive to build and maintain. Overall, the negative consequences of artificial bank stabilization generally outweigh the benefits.

Summary and Recommendations

Riparian buffers are generally very effective at trapping sediment in surface runoff and at reducing channel erosion. Studies have yielded a range of recommendations for buffer widths; buffers as narrow as 4.6 m (15 ft) have proven fairly effective in the short term, although wider buffers provide greater sediment control, especially on steeper slopes. Long-term studies suggest the need for wider buffers. It appears that a 30 m (100 ft) buffer is sufficiently wide to trap sediments under most circumstances. This is consistent with the review of Castelle et al (1993), which found that buffers must be 30 m wide to maintain a healthy biota. This width may be extended to account for factors such as steep slopes and land uses that yield excessive erosion. It is possible to also make the case for a narrower width, although the long-term effectiveness of such a buffer would be questionable. An absolute minimum width would be 9 m (30 ft). For maximum effectiveness, buffers must extend along all streams, including intermittent and ephemeral segments. The effectiveness of a network of buffers is directly related to its extent; governments that do not apply buffers to certain classes of streams should be aware that such exemptions reduce benefits substantially. Buffers need to be augmented by limits on impervious surfaces and strictly enforced on-site sediment controls (discussed in Section VI).

Riparian buffers should be viewed as an essential component of a comprehensive, performance-based approach to sediment reduction. Periodic testing of instream turbidity should be conducted to assess the effectiveness of sediment control measures. Kundell and Rasmussen (1995) recommend a maximum instream standard of 25 NTU (nephelometric turbidity units), measured at the end of a designated segment (not below site of impact). Regular monitoring and enforcement of this standard will help ensure the effectiveness of riparian buffers and other sediment-control practices.

III. Nutrients and Other Contaminants

A. Phosphorus

Effects

Phosphorus has long been implicated in the eutrophication (overfertilization) of lakes. Eutrophication unbalances an aquatic ecosystem, leading to massive blooms of some types of algae. When these algae die off and decay, oxygen is consumed, sometimes to the point where fish and other animals cannot survive. Eutrophication can lead to other harmful effects, such as the blooms of the dinoflagellate *Pfiesteria* documented in East Coast estuaries in recent years. *Pfiesteria* has been linked to massive fish kills and releases toxins that are poisonous to humans (Burkholder 1998). In at least some Georgia lakes and reservoirs, such as Lake Allatoona, phosphorus is the most problematic nutrient and possibly the greatest pollutant overall (Burruss Institute 1998).

Sources

Potential nonpoint sources of phosphorus include:

- Fertilizers applied to agricultural fields
- Animal wastes from concentrated animal feeding operations (CAFOs) spread onto fields
- Septic drain fields
- Leaking sewer pipes
- Fertilizers applied to lawns

The relative impact of each of these sources will vary across the state. Cropland fertilization is probably not a major problem in most of north Georgia, but land-applied chicken waste from CAFOs is likely to be a significant source of pollution in some watersheds (Burruss Institute 1998, Frick et al 1998). There are hundreds of millions of chickens raised in North Georgia (Bachtel and Boatright 1996). In suburban areas septic drain fields are probably more significant, and sewer lines, especially those that run through stream valleys, can also be important phosphorus sources. The impact of lawn fertilization is unclear but potentially quite high. In 1984, the EPA estimated that Americans apply nearly a million tons of chemical fertilizers to their lawns per year. According to surveys, about 70% of lawn acreage is fertilized regularly whether or not additional nutrients are required (Barth 1995). The 1998 USGS report on the Appalachicola-Chattahoochee-Flint basin reported the highest phosphorus levels in streams draining urban, suburban and poultry-producing regions (Frick et al 1998).

Literature Review

Width

Since most phosphorus arrives in the buffer attached to sediment (Karr and Schlosser 1977, Peterjohn and Correll 1985, Osborne and Kovacic 1993) or organic matter (Miguel Cabrera, pers. com.), buffer widths sufficient to remove sediment from runoff should also trap phosphorus. In the short term researchers have found riparian buffers retain the majority of total phosphorus that enters, and retention increases with buffer width. Studies in Sweden by Vought et al (1994) determined that after 8 m (26.2 ft), grassed buffers retained 66% of phosphate in surface runoff while after 16 m (52.5 ft) 95% was retained. Mander et al (1997) in Estonia found total phosphorus trapping efficiencies of 67% and 81% for riparian buffer widths of 20 m (65.6 ft) and 28 m (91.9 ft), respectively.

A number of studies (Dillaha et al 1988 and 1989, Magette 1987 and 1989) have documented the performance of grass buffer strips in reducing total phosphorus levels (the design of these studies was briefly described in the previous section on sediment). The results are summarized in Table 2. These authors all noted that effectiveness of the buffers declined over time (the data in Table 2 represent averages of several trials), and that soluble phosphate reductions were lower than total phosphorus reductions. In one case, Dillaha et al (1988) noted that the buffer released more phosphorus than entered. Presumably this increase represented previously trapped phosphorus that was remobilized. With the exception of Dillaha et al 1988, these studies show that increasing buffer width reduces the concentration of phosphorus in runoff. Desbonnet et al also observed this correlation in their 1993 review. Based on data from a number of studies, they reported that buffer width must increase by a factor of 2.5 to achieve a 10 percent increase in phosphorus removal. Figure 7 displays the results shown in Table 2 along with results from Vought et al (1994) and Mander et al (1997).

Study	**Total P Removal**	
	4.6 m buffer	**9.1 m buffer**
Dillaha et al 1988	71.5%	57.5%
Dillaha et al 1989	61%	79%
Magette et al 1987	41%	53%
Magette et al 1989	18%	46%

Table 2. Removal of Total Phosphorus by Grass Buffers.

With one exception, studies by Dillaha et al and Magette et al found a positive correlation between the width of grass riparian buffers and the ability to trap total phosphorus in surface runoff.

Limitations

The long-term effectiveness of riparian buffers in retaining available phosphate is questionable. Whereas nitrate can be denitrified and released into the atmosphere, phosphorus is either taken up by vegetation, adsorbed onto soil or organic matter, precipitated with metals, or released into the stream or groundwater (Lowrance 1998). It is possible for a buffer to become "saturated" with phosphorus when all soil binding sites are filled; any additional phosphorus inputs will then be offset by export of soluble phosphate (Daniel and Moore 1997; Miguel Cabrera, pers. com.; Dave Correll, pers. com.). Soils become saturated at different rates, depending on factors such as cation exchange capacity and redox potential. Harvesting vegetation may be the only reasonable management technique that permanently removes phosphorus from the system. Such harvesting can destabilize the riparian area and lead to erosion, however (USACE 1991), and so should be restricted to areas well away from the stream bank. Welsch (1991) recommends 15 ft (4.6 m), although 25-50 ft (7.6 -15.2 m) would provide a greater margin of safety.

Riparian buffers are typically effective at short-term control of sediment-bound phosphorus but have low net dissolved phosphorus retention (Lowrance et al 1997). For example, Daniels and Gilliam (1986) found that riparian buffers of unspecified width reduced total phosphorus by 50%, while soluble phosphate declined by only 20%. Peterjohn and Correll (1984) found that 84% of total phosphorus and 73% of soluble phosphate were removed from surface runoff passing across a 50-m (164 ft) riparian buffer in the Maryland Coastal Plain. On the other hand, Young et al (1980) reported little difference in the reductions of soluble phosphate and total phosphorus across a 21 m (68.9 ft) wide buffer of corn. Total phosphorus declined by 67%, while soluble phosphate was reduced by 69%.

The sediment-bound phosphorus trapped by buffers may slowly be leached into the stream, especially once the buffer is saturated (Omernik et al 1981, Osborne and Kovacic 1993, Mander 1997). A number of studies have shown either no net reduction or a net increase in groundwater phosphate as it crosses the riparian buffer. Studies in which swine waste was applied to 30 m (98.4 ft) buffer strips in South Georgia showed no reduction of phosphate in shallow groundwater (Hubbard 1997). In fact, phosphate levels increased from 0.5 mg/L to 1.0 mg/L over the course of the study, although whether this represented a trend or an anomaly was unclear. Peterjohn and Correll (1984) likewise found that total phosphorus concentrations in shallow groundwater rose at their 50-m (164 ft) riparian buffer study site. In one transect, phosphorus concentrations doubled and in another they quadrupled. A study by Osborne and Kovacic (1993) found that neither a 16 m (52.5 ft) wide forested buffer nor a 39 m (128 ft) wide grass buffer reduced subsurface phosphate loads from crop land.

Note, however, that even when saturated, riparian buffers may still perform a valuable service by regulating the flow of phosphorus from the land to the stream. Sediments and organic materials that carry phosphorus in runoff during storms can be trapped by riparian vegetation. The phosphorus will still slowly leak into the water, but the stream is protected from extreme nutrient pulses (Ronald Bjorkland, pers. com.).

Vegetation

Both grass and forested buffers have been proven effective at reducing total phosphorus, and both vegetation types have also been shown to lose phosphate to the stream. Osborne and Kovacic found that forested buffers leaked phosphate to the stream faster than grassed buffers. Mander et al (1997) found that uptake in younger riparian forest stands was higher than that in more mature stands. Several researchers (Lowrance et al 1985, Groffman et al 1991, Vought et al 1994) suggest periodic harvesting of riparian vegetation to maintain higher nutrient uptake. Such harvesting is recommended in zones two and three (zones greater than 15 ft (4.6 m) from the stream) of the three-zone system promoted by the USDA (Welsch 1991). Other researchers have noted, however, that even mature forests can accumulate nutrients (USACE 1991), and Herson-Jones et al (1995) declared that "Mature forests are thought to have the greatest capacity for modulating the flow of nutrients and water throughout the ecosystem."

Similarly, phosphorus could be permanently removed before it reaches the buffer if an additional field of unfertilized crops or mowed

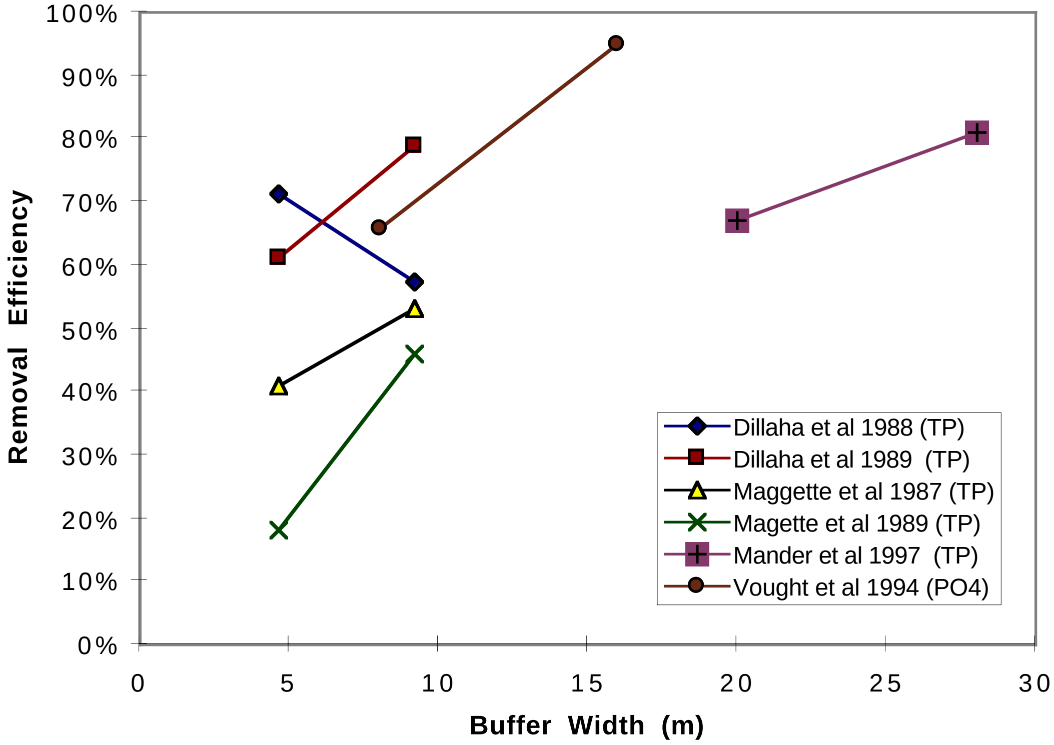


Figure 7. Phosphorus Removal from Surface Runoff by Buffers of Different Widths.

All but one study (Dillaha et al 1988) showed that the phosphorus trapping ability of a riparian buffer increases with width. In most cases, the data points shown here represent the averages of multiple runs.

hayfields were planted between the phosphorus source and the riparian buffer. Young et al (1980) found average total phosphorus reductions of 83% in 27 m (89 ft) and 21 m (69 ft) wide cropped buffers. Cropping allows for productive use of land and permanent removal of much phosphorus before runoff reaches the riparian buffer.

Extent

As for sediment control, effective nutrient control requires continuous buffers on all streams. Gilliam (1994) has noted that for purposes of nutrient reduction, "there should be a strong effort to preserve a wet, vegetated buffer next to ephemeral and intermittent channels or streams." Despite their limitations, riparian buffers are still very important because they separate phosphorus-producing activities from streams. Every unprotected stream segment or gap in the stream represents a point at which pollution can have direct access to the water. In areas without buffers, phosphorus-laden sediments and soluble phosphate can run directly into waterways with very little chance of removal. Sorrano et al (1996) predicted that in an agricultural watershed in Wisconsin, converting all riparian (within 100 m (328 ft) of a stream) agricultural land to forest would reduce phosphorus loading by 55% during a high runoff year, even assuming no net retention of phosphorus by the riparian zone.

Summary and Recommendations

Although riparian buffers can effectively trap phosphorus in runoff, they do not provide long-term storage and are not effective at filtering soluble phosphate. Phosphorus trapped in a buffer may gradually leak into the stream, especially once the buffer becomes P-saturated. Harvesting of riparian vegetation does provide a method of permanently removing some phosphorus from the system.

Riparian zones wide enough to provide sediment control (15-30 m, increasing with slope) should provide short-term control of sediment-bound phosphorus. Wider setbacks should be considered for application of animal waste, fertilization, and other activities that yield large amounts of nutrients. Buffer zones should be placed on all streams. For phosphorus removal, both forested and grassed buffers are equally useful.

Due to their limitations, riparian buffers should not be viewed as a primary tool for reducing phosphorus loading of streams. Every effort should be made to reduce phosphorus inputs at their sources. This can be accomplished through effective erosion control methods; judicious application of fertilizers; proper placement, inspection and maintenance of sewer lines; and restrictions on the land application of waste from concentrated animal feeding operations (CAFOs). If phosphorus is managed responsibly on-site, buffers can store significant amounts of the excess; but if phosphorus is uncontrolled, buffers can quickly become saturated and overwhelmed. Even with their limits, buffers still perform a valuable service by displacing phosphorus-producing activities away from streams and regulating the flow of phosphorus.

B. Nitrogen

Effects

Like phosphorus, nitrogen contributes to the eutrophication of waters. Nitrogen occurs in numerous organic and inorganic forms which are interconvertible under suitable circumstances. Nitrate (NO_3^-) has been the target of many buffer programs because it is potentially toxic to humans and animals at concentrations greater than 10 mg/L. Ammonium (NH_4^+) is another common form of nitrogen that is toxic to many aquatic organisms and is readily taken up by plants and algae. Removal of nitrate and ammonium from drinking water can be a significant water treatment expense (Welsch 1991).

Sources

Nonpoint sources of nitrogen are similar to those of phosphorus: fertilizers applied to agricultural fields; waste from concentrated animal feeding operations (CAFOs); septic drain fields; leaking sewer pipes; and fertilizers applied to lawns. The relative significance of these sources will vary from region to region.

Literature Review

In their 1994 literature review, Desbonnet et al concluded that total nitrogen removal rates for buffers are good, but nitrate reductions are variable and low. There is significant evidence that this is not a valid conclusion. A number of studies either not included in the Desbonnet et al review or published more recently show significant nitrate reductions. Fennesy and Cronk (1997) reviewed riparian buffer literature with a focus on nitrogen reduction and concluded that riparian buffers of 20-30 m (66-98 ft) can remove nearly 100% of nitrate. Gilliam (1994) declares that,

> *"Even though our understanding of the processes causing the losses of NO_3^- are incomplete, all who have worked in this research area agree that riparian zones can be tremendously effective in NO_3^- removal."*

On a landscape level, channelized tributaries with little or no riparian buffer zones may have two to three times the annual nitrate concentration of natural stream reaches with wetland or riparian buffers (Cooper et al 1994).

There are two major ways in which a riparian buffer strip can remove nitrogen passing through it, both of which can be significant:

- Uptake by vegetation
- Denitrification

Denitrification is the conversion of nitrate into nitrogen gas by anaerobic microorganisms. It represents a permanent removal of nitrogen from the riparian ecosystem and may be the dominant mechanism of nitrogen reduction in many riparian systems. Denitrification also occurs within stream channels themselves, though at rates much lower than in riparian areas, especially wetlands (Fennessy and Cronk 1997).

Unlike phosphorus, nitrate is quite soluble and readily moves into shallow groundwater (Lowrance et al 1985). In many areas, most nitrate enters the riparian zone via subsurface pathways (Lowrance et al 1984, 1985, Haycock and Pinay 1993, Muscutt et al 1993, Fennesy and Cronk 1997; but see Dillaha et al 1988). The amount of nitrogen reduction depends a great deal on the nature of these pathways: if the flow is shallow and passes through the root zone of riparian vegetation, vegetative uptake and denitrification can be significant. If the flow bypasses the riparian zone and recharges an aquifer or contributes to base flow of a stream, nitrogen loss may be much less (see Figure 9). This review first looks at the buffer width necessary to remove nitrogen from surface runoff, then considers nitrogen removal from subsurface flow. Denitrification is then examined in greater detail.

Width

Reduction of various forms of nitrogen in surface runoff is reasonably well correlated with buffer width. Dillaha et al (1988) found that 4.6 m (15 ft) and 9.1 m (30 ft) grassed filter strips were moderately effective in removing total nitrogen from surface runoff from a simulated feed lot, but ineffective in removing nitrate. Other studies of similar design by Dillaha et al (1989) and Magette et al (1987, 1989) yielded similar results. Total nitrogen removal efficiencies in all studies increased with buffer width (Table 3).

In their feedlot studies, Young et al (1980) found that 21.34 m (70 ft) buffers of cropped corn reduced total Kjeldahl nitrogen by 67% and ammonium by 71%, though nitrate increased across the buffer. Extrapolating from the data, Young et al suggested that 36 m (118 ft) wide buffers are sufficient to protect water quality.

Study	**Total N Removal**	
	4.6 m buffer	**9.1 m buffer**
Dillaha et al 1988	67%	74%
Dillaha et al 1989	54%	73%
Magette et al 1987	17%	51%
Magette et al 1989	0%	48%

Table 3. Removal of Total Nitrogen by Grass Buffers.

Studies by Dillaha et al and Magette et al found a positive correlation between the width of grass riparian buffers and the ability to trap total nitrogen in surface runoff.

Vought et al (1994) reported surface nitrate reductions of 20% after 8 m (26.2 ft) and 50% after 16 m (52.5 ft) for grass buffers in Sweden. They concluded that "a buffer strip of 10-20 m will, in most cases, retain the major part of the nitrogen and phosphorus carried by surface runoff." Jacobs and Gilliam (1985) found that in buffers downslope from Coastal Plain fields without artificial drainage, the nitrate concentration in surface runoff was reduced from 7.9 mg/l to 0.1 mg/l (99%). Though they did not report width of buffer strips used, the authors said that buffer strips of 16 m (52.5 ft) were effective.

A study by Daniels and Gilliam (1996) in the North Carolina Piedmont determined that grassed buffers of 6 m (20 ft) width and combination grass-forested buffers of 13 m (42.7 ft) and 18 m (59.1 ft) width retained 20-50% of ammonium and 50% of both total nitrogen and nitrate. Because sites had different characteristics it is not possible to determine whether width was a factor. In addition, like the Dillaha (1988, 1989) and Magette (1987, 1989) studies summarized above, Daniels and Gilliam only studied surface flow, not subsurface flow. Since in many cases most nitrate passes through buffers in the interflow, studies that ignore it may greatly underestimate (or, in some cases, overestimate) nitrate reduction.

In their studies in the Mid-Atlantic Coastal Plain, Peterjohn and Correll (1985) found that a 50 m (164 ft) buffer reduced all forms of nitrogen in surface runoff. Nitrate in shallow groundwater was reduced considerably across the buffer, but other forms of nitrogen increased in the subsurface flow. These results are summarized in Table 4.

Like Peterjohn and Correll, many other researchers have found that nitrate reduction in subsurface flow is high, although the optimal buffer width depends on factors such as the hydrologic pathway and denitrification potential. Hanson et al (1994) reported that a 31 m (102 ft) wide riparian buffer downslope from a septic tank drain field reduced shallow groundwater nitrate concentrations by 94%, from 8 mg/L to 0.5 mg/L. Jordan et al (1993) found that a 60 m (197 ft) wide riparian buffer adjacent to cropland in the Delmarva Peninsula reduced subsurface nitrate levels from 8 mg/L to less than 0.4 mg/l (95%). Most of the change occurred abruptly within the riparian forest at the edge of the floodplain, where conditions were optimal for denitrification. Mander et al (1997) found total groundwater nitrogen removal efficiencies of 81% and 80% for riparian buffer sites of 20 m (65.7 ft) and 28 m (91.9 ft) width, respectively.

Researchers at the USDA Agricultural Station in Tifton, Georgia applied swine waste to 30 m (98.4 ft) riparian buffer strips of various types. Preliminary results from 1996 showed that shallow groundwater nitrate levels were reduced from 40 mg/L at the top of the plots to 9 mg/L at the lower end of the plots, a reduction of 78% (Hubbard 1997). Previous research in the region had determined that buffers less than 15 m (49.2 ft) wide can remove significant amounts of nitrate in surface and subsurface flow (Hubbard and

		Nitrate (mg/L)	**Exchangeable NH4+ (mg/L)**	**Particulate Org. N (mg/L)**
Surface Runoff	Initial:	4.45	0.402	19.5
	Final:	0.91 (79%)	0.087 (78%)	2.67 (86%)
Subsurface Transect 1	Initial:	7.40	0.075	0.207
	Final:	0.764 (90%)	0.274 (increase)	0.267 (increase)
Subsurface Transect 2	Initial:	6.76	0.074	0.146
	Final:	0.101 (99%)	0.441 (increase)	0.243 (increase)

Table 4. Nitrogen Reductions Reported by Peterjohn and Correll (1985).

Values show initial concentration of nutrients entering the 50-m buffer and final concentrations after passing through the buffer. Values in parentheses are the percent reductions across the buffer.

Lowrance 1994). Another study in the Tifton area (Lowrance 1992) had determined that a 50-60 m (~160-200 ft) wide riparian buffer reduced groundwater nitrate levels from 13.52 mg/L to 0.81 mg/L (94%) at depths of 1-2 m (3.3 - 6.6 ft). The greatest reduction occurred in the first 10 m (33 ft). Still another study using a mass balance approach (Lowrance 1984) found that a buffer of unspecified width removed 68% of total nitrogen.

Osborne and Kovacic (1993) reported that a 16 m (52.5 ft) wide forested buffer in Illinois reduced shallow groundwater nitrate levels of 10-25 mg/L to less than 1.0 mg/L (a maximum 96% reduction). A 39 m (128 ft) wide grassed buffer in the same area reduced nitrate levels of 15-44 mg/L to about 2.4 mg/L (a maximum 95% reduction).

In reviewing other studies, Vought et al (1994) concluded that nitrate reduction in subsurface flow approaches 100% between 10 m (33 ft) and 20 m (66 ft) into the buffer; increasing the riparian width beyond 20-25 m (62-82 ft) had no further effect. Pinay and Descamps, as referenced by Muscutt et al (1993), concluded that 30 m (98 ft) buffers are sufficient for removing nitrogen. Results from these studies are summarized in Table 5 and Figure 8.

Denitrification

There is an ongoing debate as to which is the dominant mechanism for nitrogen removal: denitrification or vegetative uptake. Fennessy and Cronk (1997) claim that denitrification is the most significant, and there is some evidence to

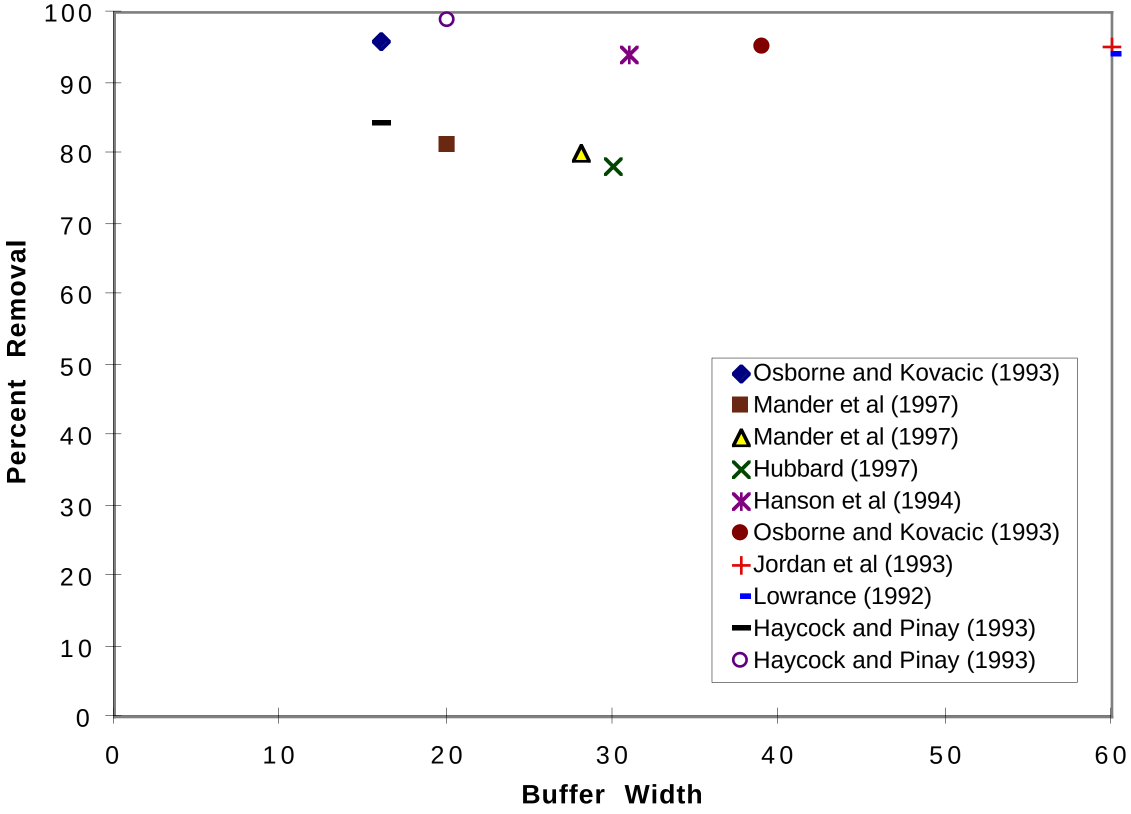


Figure 8. Subsurface Nitrate Removal in Several Studies.

Numerous studies of riparian buffers have reported high rates (>75%) of nitrate removal from shallow groundwater. There is not a clear correlation between nitrate removal rate and riparian buffer width, however.

support this view (e.g., Jacobs and Gilliam 1985, Peterjohn and Correll 1985). Lowrance (1992) has made the case for vegetative uptake and has emphasized that, whichever method is dominant, vegetation is necessary for nitrogen removal. Lowrance (1992) and Hanson et al (1994) have reported significant nitrate reductions in shallow groundwater one to two meters deep that appear to be correlated with high denitrification rates at the surface. It appears that vegetation takes up the nitrate and transfers it to the surface layer, where it is denitrified. In the end, local conditions will likely determine which mechanism dominates (Gilliam 1994).

Denitrification is one of a number of coupled processes which are best described by thermodynamic theory (Hedin 1998). Interestingly, there is a significant inverse relationship between denitrification and phosphorus removal. Highly reducing conditions that are suitable for denitrification also favor reduction of iron oxyhydroxides, which can release bound phosphorus and increase the phosphate that is exported from the buffer (Jordan et al 1993).

Soil microorganisms have the capacity to process nitrate at much higher concentrations than they normally experience (Duff and Triska 1990, Groffman et al 1991a, b, Lowrance 1992, Hanson et al 1994, Schnabel 1997). Denitrification rates can increase quite rapidly in response to nitrate increases. In some cases, microorganisms can denitrify all of the available nitrate, but ammonium and organic N pass through the buffer because they are not processed (nitrified) quickly enough (Lowrance 1992). Many soils are also carbon limited or become carbon limited at high nitrate levels (Groffman et al 1991a, b; Hedin et al 1998). Hedin et al (1998) reported on a carbon-limited site with very high nitrate levels close to the stream; when sufficient carbon was added, denitrification levels were exceedingly high (equivalent to 6600 kg N/ha per year). To promote more carbon availability, Hedin et al recommended maintaining organically rich riparian wetlands. Duff and Triska (1990) observed denitrification in the hyporheic zone of a small headwater stream. In their study site, groundwater had a high concentration of dissolved organic carbon (DOC) which was reduced

	Width (m)	% Reduction	Final Conc. (mg/L)
Osborne and Kovacic (1993)	16	96	<1.0
Haycock and Pinay (1994)	16	84	N.R.
Haycock and Pinay (1994)	20	99	N.R.
Mander et al (1997)	20	81	N.R.
Mander et al (1997)	28	80	N.R.
Hubbard (1997)	30	78	9
Hanson et al (1994)	31	94	0.5
Osborne and Kovacic (1993)	39	95	<1.0
Jordan et al (1993)	60	95	0.4
Lowrance (1992)	60	94	0.81

Table 5. Nitrate Removal in Shallow Groundwater.

Studies have demonstrated consistently high removal rates for nitrate from shallow groundwater passing through riparian buffers. “Final Conc.” is the concentration of nitrate in groundwater leaving the riparian buffer. Concentrations over 10 mg/L (ppm) are considered potentially harmful.

as it passed through the riparian zone. Denitrification was greatest farther from the stream where nitrate was in greatest supply. Rhodes et al (1985) reported 99% nitrate removal in riparian forests and wetlands at a high-altitude undisturbed watershed in Nevada.

Denitrification takes place under conditions of reduced oxygen availability and is correlated with soil moisture. Rates are typically very high in wetlands (Groffman et al 1991a, b; Hanson et al 1994; Collier et al 1995b). In field studies in Rhode Island Groffman et al reported that variability in nitrate reduction in subsurface flows (ranging from 14% to 97%) was almost entirely explained by soil moisture. Wetland soils had consistently high nitrate removal, while better drained upland soils had lower and more variable nitrate removal efficiencies. Since denitrification is the most permanent method for removing nitrogen, good management practices call for preservation of areas of high denitrification activity, such as wetlands (Collier et al 1995b, Hedin et al 1998). Note, however, that denitrification has also been observed under well oxygenated soil conditions, presumably indicating that there can be sites of local anoxia (Duff and Triska 1990).

Nitrate loss does not appear to be limited to warm months. In a study during the winter season in Britain, Haycock and Pinay (1993) reported that a 20 m (65.6 ft) wide poplar forested site retained 99% of the nitrate that entered, no matter how high the load level. A 16 m (52.5 ft) wide grass riparian zone retained nearly 100% of nitrate at lower concentrations but only 84% at high concentrations. All flow was subsurface. In the poplar site nitrate reduction was essentially complete after the first 5 m (16 ft) of flow. Bacterial denitrification was assumed to be the mechanism for nitrate loss, since the vegetation was dormant and uptake rates would be low. The variation between the sites may have been due to the larger amounts of carbon contributed by the poplars (Haycock and Pinay 1993). Lowrance (1992) and Osborne and Kovacic (1993) also reported nitrate removal rates that were independent of season. Lowrance noted that dormant season nitrate removal is not just due to denitrification but can result from uptake by trees as well. Groffman et al (1991b) conducted analyses of denitrification in surface soils at sites in Rhode Island. They reported total nitrogen removal efficiencies of 40% to 99% for overland flow during the summer, but rates of less than 30% in the winter. Additional field studies conducted by the same team failed to find an influence of seasonality on nitrate removal. They theorized that elevated water tables in winter may have brought denitrifying bacteria into contact with more nitrate-laden water, compensating for the lack of vegetative uptake (Groffman et al 1991b).

The characteristics of groundwater flow will determine where within the riparian buffer denitrification will occur. Lowrance (1992) found that most nitrate loss occurred at the buffer-field interface. Hedin et al (1998) and Schnabel et al (1997) studied systems in which shallow groundwater with very high nitrate concentrations entered the buffer very close to the stream. Some studies (e.g. Jordan et al 1993) have shown that denitrification rates are greatest at the edge of the floodplain. In all cases, nitrate removal occurred at locations where the water table was near the surface and both carbon and nitrate were in good supply. Determining all these factors in the field is not easy and the hydrology of many riparian areas is still poorly understood, making accurate predictions of nitrogen removal difficult (Gilliam 1994).

It appears that few researchers have documented nitrate reductions in subsurface flow in the Piedmont or Blue Ridge physiographic provinces. Lowrance et al (1997) cited data from studies by Daniels and Gilliam that show large reductions in groundwater nitrate levels in North Carolina Piedmont locations. The study sites were characterized by high water tables and shallow groundwater flow through the root zone of riparian vegetation (see Figure 9-a). When these conditions are present, as in areas of thin soils, high rates of nitrate reduction should occur (Lowrance et al 1997). However, in Piedmont soils underlain by schist/gneiss bedrock, an appreciable amount of flow may move into regional aquifers in the saprolite, bypassing the riparian root zone and contributing to the base flow of streams (Figure 9-b). A moderate level of denitrification is expected under these conditions (Lowrance et al 1997). In Piedmont soils underlain by marble bedrock, most flow may enter regional aquifers and nitrate loss in riparian areas

Figure 9. Different Possible Groundwater Flow Paths.

Based in part of Lowrance et al (1997).

Figure 9a. Groundwater flow paths across a riparian buffer with shallow soils or an aquitard (semi-impervious layer). Flow should pass through the root zone, allowing significant removal of nutrients and contaminants.

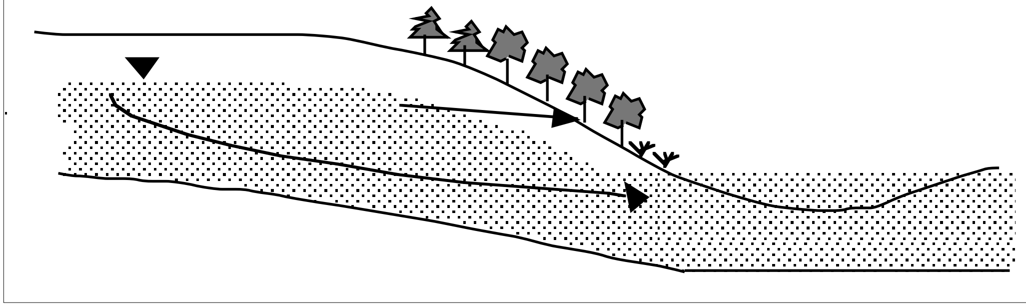


Figure 9b. Groundwater flow paths across a riparian buffer with moderately deep soils. Some flow should passes through the root zone, but some bypasses the riparian area. The area of greatest nutrient removal may be very close to the stream.

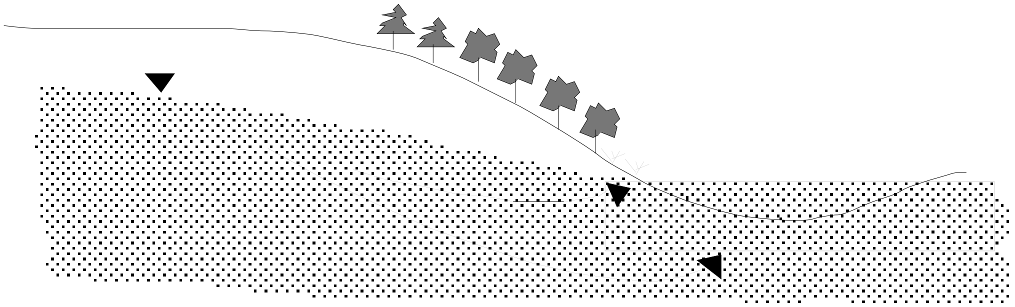


Figure 9c. Groundwater flow paths across a riparian buffer across a wide, flat floodplain with a high water table. Area of greatest nutrient removal will likely be the edge of the floodplain.

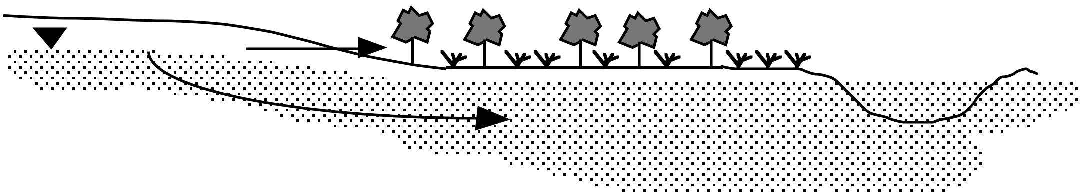
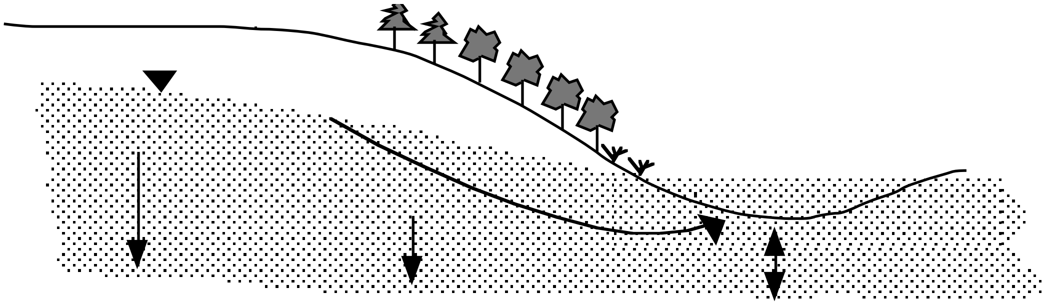


Figure 9d. Groundwater flow paths across a riparian buffer with very deep soils or fractured bedrock. Much groundwater bypasses the riparian buffer, and nutrient removal may be lower than in other systems.



is probably much less significant (Lowrance et al 1997) (Figure 9-d). However, in their study of riparian sites in the Valley and Ridge physiographic province, Schnabel et al (1997) found significant denitrification rates where nitrate-rich groundwater emerged close to the stream bank. These sites had flow-restrictive layers 8-10 m (26.2 - 32.8 ft) below the surface, as would Piedmont soils with marble bedrock. The deeper flow paths changed the location of denitrification activity but did not prevent nitrate reduction. Hedin (1997) also observed a similar phenomenon at a site in Michigan with deep glacial soils.

Even within the Coastal Plain hydrology can vary significantly, affecting how nutrient reduction takes place. Human modifications also alter these patterns. Jacobs and Gilliam (1985) found that at a site in the Middle Coastal Plain of North Carolina most transport was via subsurface pathways. In a Lower Coastal Plain site, on the other hand, most movement was by surface flow. Fields in this area were drained by ditches, and a dense clay B layer prevented deeper subsurface flow.

Rates of nutrient reduction are influenced by the length of time water is retained in the buffer (Fennessy and Cronk 1997), which in turn is determined by slope, rainfall, soil characteristics, hydrologic flow path, and the width of buffer (Phillips 1989a,b). Retention time may actually be longer than would be indicated by these factors, because some researchers have shown that the flow of water is not perpendicular to the channel but oblique to the channel. Residence times in a 27 m wide buffer along a Thames, England headwater stream ranged from 12 days to over three years (Fennessy and Cronk 1997). Research on the Georgia Coastal Plain showed that it can take several seasons for nutrients and contaminants to pass through a 50-m wide riparian buffer where shallow lateral flow is the dominant pathway (Hubbard and Lowrance 1996). On the other hand, when overland flow occurs, water can pass through the buffer in a matter of minutes. Models have been developed to predict buffer effectiveness based on detention time (Phillips 1989a, b), but their accuracy is unproven.

Extent

As discussed in previous sections, protection of water quality requires preservation of buffers on as many streams as possible.

Vegetation

Both grass and forested buffers have been shown to reduce nitrogen effectively. In studies in Rhode Island, Groffman et al (1991a) found that when nitrate was added to soil cores, soils from grass plots exhibited denitrification rates an order of magnitude higher than those from forested plots. Schnabel et al (1997) also reported higher denitrification rates for grassed buffer sites. Haycock and Pinay (1993) and Osborne and Kovacic (1993), on the other hand, found higher rates of nitrate retention in forested buffers. Lowrance has concluded that overall, grass buffers are not effective at removing nutrients from shallow groundwater (Lowrance 1998).

Both grass and forested buffers have proven effective in removing surface nutrients from surface runoff, although grass buffers have been more heavily studied.

Summary and Recommendations

The nitrogen removal capacity of riparian buffers has been well established. Nitrogen removal in surface runoff has been correlated with buffer width, but rates appear to be lower than for subsurface reduction. Studies have documented high levels of nitrate removal from shallow groundwater, which is the dominant mode of nitrate transport through many buffers. Nitrate may be removed by both vegetative uptake and denitrification. The buffer width necessary for nitrate reduction depends greatly on the hydrologic flow paths, and numerous studies would be required to fully characterize the pathways of shallow groundwater flow in all areas of Georgia. However, based on existing research, most areas of Georgia should generally support significant nitrogen removal in the riparian buffer.

Because the distribution of denitrification sites vary spatially, wider buffers will on average include more denitrification sites than narrower buffers. A minimal width of 15 m (50 ft) is probably necessary for most buffers to reduce nitrogen levels. Wider buffers of 30 m (100 ft) or greater would be more likely to include other areas of denitrification activity and provide more nitrogen removal. Buffers should be preserved along as many streams as possible, and it is especially important to preserve riparian wetlands, which are sites of high nitrogen removal.

C. Other Contaminants

Organic Matter and Biological Contaminants

Human and animal waste contribute to aquatic degradation in ways other than nutrient contamination. First, these wastes carry with them an array of pathogenic microorganisms. Secondly, when organic matter is broken down by aerobic bacteria in water, oxygen is consumed rapidly. High levels of organic matter with high biological oxygen demand (BOD) can use up all of the available oxygen in a stream, river or lake, killing fish and other organisms. Whereas surface waters naturally have a BOD of 0.5 to 7 mg/L, chicken wastes may have a BOD of 24,000 to 67,000 mg/L (Cooper et al 1993).

Fecal coliform is used as an indicator of pathogenic microorganisms. The levels of fecal coliform can vary temporally at a single site and can be quite high, even in areas of Georgia considered less impacted. At a monitoring station in Lake Allatoona near where the Etowah River enters the reservoir, fecal coliform levels ranging from 1.8 colonies (in May) to 24,000 colonies (in November) per 100 ml were recorded. For reference, the recommended limit for water that people directly contact (i.e., the “primary contact standard”) is 200 colonies / 100 ml.

Sources of organic matter and biological contaminants include leaking sewer pipes, improperly functioning septic systems, animal waste sprayed onto fields and animal waste lagoons. Burkholder et al (1998) documented a large fish kill in deoxygenated water after a swine lagoon ruptured into the Neuse River in North Carolina.

Riparian buffers can trap waste transported in surface runoff in the same way that they trap sediments and associated nutrients. In the face of very high waste levels, however, trapping efficiency may not be adequate to reduce contaminants to a safe level. Coyne et al (1995) applied poultry manure to two test plots and measured fecal coliform reduction across 9 m (30 ft) wide grass filter strips. After artificial rain was applied, researchers found that fecal coliform concentrations were reduced by 74% and 34% in the two strips. Nevertheless, runoff exceeded the primary contact standard in every sample. A 1973 study by Young et al found that a 60 m (197 ft) long grass filter strip reduced fecal coliform by 87%, total coliform by 84% and BOD by 62% (Karr and Schlosser 1977). Cooper et al (1993) found that constructed wetlands removed 76% of BOD when coupled behind an anaerobic lagoon. There do not appear to be other studies which have addressed this issue.

Pesticides and Metals

Pesticides are intended to be toxic. When these chemicals are introduced into aquatic systems they can cause both direct mortality to organisms and various sublethal effects (Cooper et al 1993). Although a number of the most persistent and toxic pesticides have been banned in the U.S., many that are currently applied are still quite dangerous. According to Cooper et al (1993), "Some insecticides in current use not only accumulate, they can be as toxic as and often more toxic than banned organochlorines."

Besides their use in row crop agriculture, pesticides are gaining favor in forestry in the Southeast (Neary et al 1993) and are commonly used on lawns and plantings in urban areas. The EPA estimates that nearly 70 million pounds of active pesticide ingredients are applied to urban lawns each year. One survey of 500 homes found that 50 different pesticides were used (Schueler 1995a, b). Even long-banned insecticides like DDT and chlordane are commonly found in urban streams. Chlorpyrifos also appears in runoff at levels toxic to a range of wildlife including geese, songbirds and amphibians (Schueler 1995b). A recent study by the U.S. Geological Survey found that urban and suburban streams in the Atlanta region had levels of diazinon and carbaryl that exceeded aquatic life criteria (Frick et al 1998). Heavy metals are usually associated with industrial activities, and concentrations tend to be highest in streams draining urban areas (Crawford and Lenat 1989).

Buffers are very important in displacing pesticide application away from streams, preventing direct contamination and reducing the danger of drift. Many pesticides are broken down within buffer soils, while metals may bind to soil particles. Greater buffer width increases the retention time for chemicals (allowing more opportunities for contaminants to decompose) and provides more sites for binding metals. Frick et al (1998) attribute the unexpectedly low pesticide levels in agricultural Coastal Plain streams to the largely intact forested wetlands and floodplains.

The mechanisms of pesticide transport are not well understood (Muscutt et al 1993). Lowrance et al (1997) examined changes in pesticide concentrations crossing a 50-m (164 ft) wide buffer in the Georgia Coastal Plain. Atrazine and Alachlor were reduced from 34 μg/L and 9.1 μg/L, respectively, to less than 1 μg/L. The chemicals took three years to enter groundwater, and it appeared that they first moved laterally across the buffer before infiltrating deeply. Hatfield et al (1995) found that grassed filter strips of 40 ft (12.2 m) and 60 ft (24.4 m) removed 10-40% of the atrazine, cyanazine and metolachlor passing across them. Arora et al (1996) found that 20.12 m (66 ft) wide riparian buffers of 3% slope retained 8-100% of the herbicides (atrazine, metolachlor and cyanazine) that entered during storm events. The variation was related to the amount of runoff that occurred during the storms. None of these studies examined the long-term fate of pesticides or their degradation products.

Neary et al (1993) reviewed recent studies in the Southeast on the use of buffers in reducing pesticide contamination of water. They found that cases of high concentrations of pesticides in water only occurred when no buffer was used or when they were applied within the buffer (i.e., the buffer was violated). Regular use of buffer strips kept pesticide residue concentrations within water-quality standards. Neary concluded that "Generally speaking, buffer strips of 15 m (49 ft) or larger are effective in minimizing pesticide residue contamination of stream flow."

Herson-Jones et al (1995) concluded that urban buffers have shown a moderate to high ability to remove or retain hydrocarbons and metals from surface runoff. They cited data from a 1992 study by the Metropolitan Seattle Water Pollution Control Department which found removal rates exceeding 40% for lead, 60% for copper, zinc and iron, and 70% for oil and grease. Studies in Rhode Island (Groffman et al 1991b) also found high metal retention rates. The authors reported that riparian buffers retained all the copper that was added to them. This retention depends on cation exchange capacity (CEC) of the soil, however, and it is possible for buffer CEC to become saturated, just as it can under high phosphorus loads.

Summary and Recommendations

Based on the limited studies available, riparian buffers are useful for reducing levels of biological contaminants and organic matter, but by themselves may not be sufficient to protect water quality. Buffers at least 9 m (~30 ft) wide and probably much wider are needed; width should be extended for steeper slopes that would reduce buffer contact time. Every effort should be made to reduce these contaminants at their source, and it is wisest to prohibit sources within the floodplain, regardless of buffer width.

Buffers can remove pesticides and heavy metals, but the width necessary is unclear from the existing research. Neary's (1993) recommendation of 15 m (49 ft) should be viewed as a minimum width, since the studies by Hatfield et al (1995) and Lowrance et al (1997) suggest that significantly wider buffers may be required.

IV. Other Factors Influencing Aquatic Habitat

Aquatic habitat quality is very important in the Southeast, which has a high level of fish and mussel diversity. Probably the most important factor affecting the habitat of aquatic organisms is sediment, discussed in detail in Section II. This section will discuss other factors that influence the habitat of stream organisms and the characteristics of buffers required to support high quality habitat.

Woody Debris and Litter Inputs

Large woody debris (LWD) deposited into the stream from the riparian zone provides essential habitat for many fish. According to May et al (1996), LWD is the most important factor in determining habitat for salmonids (salmon, trout and related fish). Leaf litter and other organic matter from riparian forests, including terrestrial invertebrates that drop into the water, are an important source of food and energy to stream systems.

In studies in Alaska, researchers found that during the winter, salmonid survival depended upon the amount of debris in streams (Murphy et al 1986). Stream reaches that were protected by 15-130 m (49-427 ft) wide riparian buffers were found to be similar in habitat quality to old growth reaches. Clear cutting led to short-term increases in summer salmonid populations because overall stream production increased, but in the winter there was insufficient debris to provide shelter for fish. Forested stream corridors are necessary to provide regular inputs of LWD and removal of riparian forest can have long-term negative effects. Gregory and Ashkenas note that "of all the ecological functions of riparian areas, the process of woody debris loading into channels, lakes and floodplains requires the longest time for recovery after harvest" (Gregory and Ashkenas 1990). Collier et al (1995a) recommend a buffer width of at least one tree height to maintain inputs of LWD, although for stability purposes (i.e., to prevent windthrow) they suggest that a width equal to three tree heights may be necessary.

The type and amount of riparian vegetation is correlated with different fish communities (Baltz and Moyle 1984), and studies indicate that native vegetation is important for proper stream functioning (Abelho and Graça 1996, Karr and Schlosser 1978). Stream organisms may not be adapted to the leaf fall patterns or the chemical characteristics of leaves from nonnative trees, suggesting that management schemes should include the maintenance and restoration of native vegetation (Abelho and Graça 1996).

Removal of riparian forests can cause a fundamental shift in stream energy dynamics, moving the system from heterotrophy (where production is based on inputs of leaves and other terrestrial matter) to autotrophy (where production is based on algae) (Allan 1995). This shift also alters the seasonal dynamics of the stream (Schlosser and Karr 1981). Streams with riparian vegetation experience a peak in organic matter in the fall, but streams without riparian vegetation experience peaks in the summer.

Aquatic invertebrates are important components of the stream system, so much so that they are commonly used as indicators of stream health.

Aquatic invertebrates are the major food source for many, if not most freshwater fish. Riparian vegetation, in turn, provides leaves and other forms of litter that feed these invertebrates. Additionally, most aquatic invertebrates emerge from the stream as adults and use the riparian zone for reproduction (Erman 1984). Riparian vegetation also influences the amount and type of *terrestrial* invertebrates that fall into streams. Some fish, such as brown trout, may rely on terrestrial invertebrates for most of their food (Dahl 1998). A study in New Zealand found that pasture streams had a much lower biomass (1/6th to 1/12th) of terrestrial invertebrates than either ungrazed grassland or forest streams (Edwards and Huryn 1996). Other factors, such as altitude and stream width, were not found to be significant in the study. Of course, the importance of terrestrial organisms as a food source is most important in headwater streams and less significant in larger streams and rivers that have higher algal production (Vannote et al 1980).

Temperature and Light Control

In Georgia, like most of the U.S., the native vegetation in riparian zones is hardwood forest. These forests keep headwater streams cool by providing shade for the surface water and reducing the temperature of the shallow groundwater that feeds the stream. Removing these riparian forests will increase stream temperatures, and even minor changes in temperature can cause major changes in the fish community (Baltz and Moyle 1984).

Although increases in temperature and light can generate increased aquatic production in some cases, many aquatic organisms can only survive within a relative narrow temperature range (Allen 1995). Trout are a well-known and commercially important example of a fish that cannot tolerate high temperatures. Thermal fluctuations can have a range of direct effects on mussels, including reproductive problems and death (Morris and Corkum 1996). Higher water temperatures also decreases oxygen solubility, which harms many organisms and also reduces the water's capacity to assimilate organic materials and increases the rate at which nutrients solubilize and become readily available *(Karr and Schlosser 1978).*

Factors other than shading affect stream temperature, however. Dams can cause profound changes to the stream thermal regime that override the influence of riparian forests. Impoundments that release water from the top increase downstream water temperature, while bottom-release dams decrease downstream water temperature. Additionally, discharges of cooling water from power plants can greatly increase water temperature.

On small streams, however, shading is likely to be the most important factor. A study by Barton et al (1985) found that most of the variation in the maximum water temperature was related to the fraction of forested bank within 2.5 km upstream of the study site, while maximum weekly temperature was correlated with buffer length and width. This regression accounted for 90% of temperature variability. The authors reported that water temperature was the only important factor determining the presence of trout. For these fish to be present, 80% of banks within 2.5 km upstream had to have forests of at least 10 m (33 ft) wide, or sufficient to shade the stream (Barton et al 1985). In Georgia, Gregory et al (in press) found that mean water temperatures in some Coastal Plain streams with no riparian cover approached 37° C in the summer, while nearby streams with forested riparian zones were 15° cooler. Temperature in the streams varied by as much as 20° C in the winter and spring. The authors suggested that the thermal variability was likely to be a factor in the variability in aquatic invertebrate communities they found in the streams.

A study of mussels in Ontario found dramatic differences between mussel communities in forested and agricultural catchments (Morris and Corkum 1996). Agricultural streams were dominated by one species of tolerant mussel (*Pyganodon grandis*), which represented 62.5% of individuals in those rivers (and only 1% in forested basins). The authors identified temperature as an important variable influencing the shift, although nutrients may also have been a factor.

In a review of several articles on the subject, Osborne and Kovacic (1993) concluded that buffer widths of 10-30 m (33-98 ft) can effectively maintain stream temperatures. Shading has the greatest impact on smaller streams. Collier et al (1995b) note that "generally, protecting or planting small headwater streams achieves the greatest temperature reduction per unit length of riparian shade." This again indicates the need to establish buffers on even the smallest streams when possible.

Summary and Recommendations

Removal of riparian forests has a profoundly negative effect on stream biota. Davies and Nelson (1994) summarized the range of effects clearcutting can have on stream communities: "Logging significantly increased riffle sediment, length of open stream, periphytic algal cover, water temperature and snag volume. Logging also significantly decreased riffle macroinvertebrate abundance, particularly of stoneflies and leptophlebiid mayflies, and brown trout abundance." The researchers recommended a 30 m (98 ft) buffer to mitigate these effects. At a minimum, a 50 ft (15 m) buffer appears necessary to provide woody debris inputs to the stream. No tree harvesting should occur within 25 ft (12 m) of the stream (50 ft/15 m is preferable), and harvesting in the remainder of the buffer should leave some mature and senescent trees. Native vegetation should be preserved whenever possible. To maintain stream temperatures, riparian buffers must be at least 10 m (30 ft) wide, forested, and be continuous along all stream channels to maintain proper stream temperatures. It is important to note that while some other riparian functions (e.g., sediment and nutrient retention) can be performed adequately by grassed buffers, forested buffers of native vegetation are vital to the health of stream biota.

Article	Widths Studied (m)	Min. Width Recommendation (m)
Hodges and Krementz (1996)	36-2088	100
Keller et al (1993)	25-800	100
Kilgo et al (1998)	25-500	both narrow and wide
Kinley & Newhouse (1997)	14-70	70
Smith & Schaefer (1992)	20-150	no recommendation
Spackman and Hughes (1995)	25-200	150-175
Thurmond et al (1995)	15-50	15
Triquet et al (1990)	15-23	no recommendation

Table 6. Riparian Buffer Recommendations from Avian Studies.

The recommendations of the literature on riparian corridor widths for birds are summarized here. The second column shows the range of buffer widths studied by the authors. The third column shows the authors' recommendations for the minimum corridor widths necessary to support bird populations.

V. Terrestrial Wildlife Habitat

Riparian corridors support an exceptional level of biodiversity, due to natural disturbance regimes, a diversity of habitats and small-scale climatic variation (Naiman et al 1993). Gregory and Ashkenas (1990) found that riparian forests in the Willamette National Forest support approximately twice the number of species than are found in upland forests. Riparian zones also support many rare species (Naiman et al 1993). Riparian areas are a declining habitat, however. Malanson (1993) estimates that 70% of natural riparian communities have been lost; in some areas losses may be as high as 98%. Naiman et al (1993) put the loss at an average 80% for North America and Europe.

Literature Review

Gregory and Ashkenas (1990) have noted that riparian buffers established for water quality and fisheries needs may not meet the habitat requirements of terrestrial wildlife. The ability of a stream corridor to support wildlife is usually directly related to its width (Schaefer and Brown 1992). Narrow buffers may support a limited number of species, but wide buffers will be required to maintain populations of riparian-dependent interior species. Generally, most researchers advocate preserving as wide a buffer as possible. Schaefer and Brown (1992) have suggested that a protected river corridor should cover the floodplain and an additional upland area on at least on one side. Other researchers have attempted to quantify the necessary width according to the needs of various riparian-dependent species.

Birds

Over the last decade there has been an abundance of research on the use of riparian corridors by birds. The recommendations of many of these studies are summarized in Table 6.

Triquet et al (1990) examined bird populations in mature forest, clearcut forest, and clearcuts with a 15-23 m (49-76 ft) wide riparian buffer. They found that retaining the buffer provides habitat for some species of mature-forest and edge-dwelling songbirds that otherwise would be absent. Birds associated with mature forests virtually disappeared from the clearcut site, though at the buffer strip site the decline was much less (Triquet et al 1990).

Keller et al (1993) assessed bird species at 117 riparian corridors of 25 m (82.0 ft) to 800 m (2624 ft) width in Maryland and Delaware. They found that the total number of neotropical migrant species increased with forest width, and ten species increased in abundance as width increased. Keller et al recommended preserving riparian corridors at least 100 m (328 ft) wide, and even wider corridors when possible. Where intact riparian areas exist, they suggested giving priority to the widest corridors available. However, they said efforts to create or increase riparian forest width should focus first on streams with no vegetation and then on narrow (<50 m / 164 ft) forests: “The presence of even a narrow riparian forest dramatically enhances an area’s ability to support songbirds compared to a stream surrounded only by agricultural fields or herbaceous riparian habitats” (Keller et al 1993).

In surveys in Vermont forests, Spackman and Hughes (1995) found that 90% of bird species are included within 150-175 m (492-574 ft) buffers along most streams. At two streams the distance was less. For most sites, 90% of plant species are represented within 15 m (49 ft) of the stream. Because Spackman and Hughes studied riparian areas that were part of intact mature forests, however, their findings are not completely relevant to riparian buffers bounded by open fields or urban development.

Kilgo et al (1998) studied bird richness and abundance in bottomland hardwood forests in Southern South Carolina. Widths of forests ranged from less than 50 m (164 ft) to over 1000 m (3280 ft), measured on both sides of the stream (except on the Savannah River, where forest on only one side was measured because the river was a flight barrier). Uphill land cover was either closed-canopy pine or field-scrub. The authors reported that species richness showed a strong positive correlation with bottomland forest width, even though the adjacent habitat was also forested. They did not find a significant buffering effect of the pine habitat. That is, sites with field-scrub habitat uphill rather than pine forest showed no decrease in bird abundance and richness. This may be due to the great width of most of the buffers the researchers studied. Kilgo et al (1998) recommend protecting both narrow and wide riparian buffers, although they point out the importance of preserving the few remaining areas of wide bottomland hardwood forest.

In a study in the Altamaha basin of the Georgia Coastal Plain, Hodges and Krementz (1996) measured densities of neotropical migrant birds in narrow (36-330 m/118-1082 ft), medium (440660 m/1443-2165 ft) and wide (1520 - 2088 m/~0.95-1.3 mi) riparian corridors. They found a significant increase in bird densities for several species between 50 m (164 ft) and 100 m (328 ft). Beyond 100 m, there was little increase associated with wider corridors. The researchers suggested that "forest corridors of about 100 m should be sufficient to maintain functional assemblages of the six most common species of breeding neotropical migratory birds."

Thurmond et al (1995) examined bird populations in narrower riparian corridors in the Ogeechee River basin in the Upper Coastal Plain of Georgia. Riparian buffers of 50 ft (15.2 m), 100 ft (31 m) and 164 ft (50 m) adjoining pine plantations of less than five years age were compared to mature riparian areas. The authors found that breeding forest interior species were virtually absent from all buffer strips, although overall abundance and densities in these strips were higher than in the adjacent pine plantations. They concluded that narrow protected stream corridors are important in maintaining greater bird diversity even though they are insuffcent for protecting interior species.

Smith and Schaefer (1992) found small differences between bird populations in narrow (20-60 m/ 66-197 ft) and wide (75-150 m/246-492 ft) naturally vegetated buffers in an urbanized North Florida watershed. Area-sensitive species such as Acadian Flycatchers and Hooded Warblers were not found in the narrow buffers. Summer Tanagers were not recorded anywhere in the urbanized area, but they were found in a nearby undisturbed riparian forest. The researchers found that during spring, bird species diversity and evenness were less in Hogtown Creek, but average density was greater. During winter, bird density and richness were greater in Hogtown Creek.

Kinley and Newhouse (1997) studied breeding bird populations in riparian buffers of 14 m (46.0 ft), 37 m (121 ft) and 70 m (230 ft) in British Columbia. They found that densities of all birds increased as buffer width increased, and they concluded that "narrower riparian reserve zones are of less value than wider reserve zones."

Researchers have frequently reported bird densities and richness that are equal or greater in narrow buffers or clearcut areas. After clearcutting, bird diversity and abundance may increase because of the influx of open-habitat and edge-habitat birds (e.g., Triquet et al 1990). This is an example of the edge effect: boundaries like forest edges (and riparian zones) tend to be especially rich in biodiversity. It is a management problem in some ecosystems to maximize both edge habitat and interior habitat. In addition, many species require more than one ecological system in which to complete their life cycles (Naiman et al 1988). However, generally speaking, animals that exploit impacted areas and edges are more likely to be habitat generalists that are less in need of protection. Measurements of species richness and population density are less useful than indices of similarity between developed and undeveloped sites. Management on the local scale for maximum richness and density will almost certainly result in the loss of habitat specialists.

Mammals

Few studies have explicitly addressed the issue of how wide riparian buffers need to be to support mammal populations. Cross (1985) found that riparian zones in mixed conifer forest sites in southwest Oregon supported a higher diversity and density of small mammal species than upland habitat. Diversity and species composition in a 67 m (220 ft) wide riparian buffer bordered by a clearcut were found to be comparable to undisturbed sites.

Large mammals, as well as large reptiles such as alligators, are also important for the role they play in determining the structure of streams and riparian zones (Naiman and Rogers 1997). For example, beavers create wetlands in areas where they would otherwise not exist, increasing the overall diversity of the aquatic community in those regions (Snodgrass and Meffe 1998). Removal of large animals leads to simplification of the ecosystem and loss of diversity (Naiman and Rogers 1997).

Reptiles and Amphibians

Riparian zones are often rich in both diversity and abundance of reptiles and amphibians. In some mountainous areas the number and biomass of salamanders can exceed that of birds and mammals (Brode and Bury 1984).

Reptiles and amphibians vary in their dependence upon riparian areas. Many amphibians spend their entire lives within the stream and riparian zone, while other species use it for breeding or as part of a larger range (Brode and Bury 1984). In Western Oregon reptiles and amphibians that are dependent upon riparian areas may require buffers of 75-100 m (246-328 ft) (Gomez and Anthony 1996). The authors noted that many species may also require preservation of large areas of old growth and upland habitat as well. Likewise, in a study of Carolina Bays, Burke and Gibbons (1995) found that a 275 m (902 ft) upland buffer is required to protect all nest and hibernation sites for certain freshwater turtles. Beyond a certain width, however, habitat heterogeneity is probably more important than habitat width. Burbrink et al (1998) found that 100 m (328 ft) naturally vegetated riparian zones supported reptile and amphibian diversities that were as high as 1 km (0.62 mi) wide naturally vegetated riparian zones.

Vegetation

Relatively few riparian studies have focused on the needs of native terrestrial vegetation. Gregory et al (1992) observed that "riparian zones are commonly recognized as corridors for movement of animals within drainages, but they also play an important role within landscapes as corridors for dispersal of plants." Riparian zones provide areas of habitat heterogeneity and can support high plant diversity. In the Vermont Appalachians, Spackman and Hughes (1995) found that 90% of plant species surveyed were represented within 15 m (49 ft) of the stream.

Many floodplain plants require regular cycles of flooding for seed dispersal and germination. Dam regulation of the Savannah River has desynchronized the conditions necessary for germination of tupelo and cypress seeds (Schneider et al 1989; Sharitz et al 1990). As a result, these once-dominant species are no longer reproducing effectively, which may ultimately lead to a shift in the forest composition. Similarly, dam-altered flow regimes have prevented regeneration of cottonwood trees in areas of the western United States (Poff et al 1997).

In terms of vegetation required for terrestrial wildlife, it is almost axiomatic that native plants are necessary to support healthy populations of native species. Studies have shown that pine plantations and other monoculture or nonnative vegetation tend to support a lower abundance and diversity of wildlife (e.g., Dickson 1978). Native riparian vegetation should always be protected and restored when necessary. Preserving the natural hydrology of the stream system will also help preserve native plants.

Riparian Buffers as Movement Corridors

One of the incidental benefits frequently ascribed to riparian buffers is their use as movement corridors for terrestrial wildlife. Riparian corridors may be more suitable in this role than other types of corridors because they tend to be environmentally diverse (Cross 1985). However, there has been considerable debate concerning whether animals actually use corridors and whether corridors should be a conservation priority. Reed Noss (1983, 1987) has been a strong advocate of movement corridors for connecting preserves and maintaining genetic exchange between animal populations. Simberloff and Cox (1987) and Simberloff et al (1992) have pointed out that corridors have some potential negative consequences and are not always the wisest use of conservation funds. A lack of empirical research on both sides of the issue has prevented resolution of the debate.

Harrison (1992) suggested minimum corridor widths for migration of large mammals, but the scale of his recommendations (0.6 to 22 km wide) is not appropriate for most riparian corridors. Machtans et al (1996) examined songbird abundance in 100 m (328 ft) wide buffer strips adjacent to clearcut forest to determine whether birds used them as movement corridors. They found that juveniles do use the corridors for dispersal, but that the adults in the buffer are probably residents. Given the lack of consensus and research on the use of riparian buffers as movement corridors, it is more defensible to base buffer width on habitat requirements of terrestrial organisms. Because there is general agreement that riparian buffers offer important high-quality habitat, there is little need to debate their merits as movement corridors at this time.

Summary and Recommendations

While narrow buffers offer considerable habitat benefits to many species, protecting diverse terrestrial riparian wildlife communities requires some buffers of at least 100 m (~300 ft). Bird abundance and diversity may be high in impacted areas, but sensitive interior-dwelling species will be lost unless some wide riparian tracts are preserved. To provide optimal habitat, native forest vegetation should be maintained or restored in all buffers. Riparian buffers may also serve as movement corridors, but considering the contentiousness of this issue it is most defensible to base buffer width on habitat requirements.

However desirable they might be, however, 300 ft wide buffers are not practical on all streams in most areas. Therefore, minimum riparian buffer width should be based on water quality and aquatic habitat functions. This should result in an abundance of narrow riparian corridors that will offer good habitat for many terrestrial species. In addition, at least a few wide (300-1000 ft/~90300 m) riparian corridors and large blocks of upland forest should be identified and targeted for preservation. This will provide habitat for those species that rely on areas of interior forest. Protection of these wide riparian corridors for terrestrial wildlife should be a part of an overall habitat-protection plan for the county or region.

Flood Control and Other Riparian Buffer Functions

Flooding is a natural feature of aquatic and riparian ecosystems. The frequency, duration and magnitude of floods helps to determine both the physical and biological characteristics of the riparian zone (Junk et al 1989). As discussed above, many riparian plants rely on cycles of flooding for seed dispersal and recruitment, while many fish species use riparian zones as nurseries, spawning grounds or feeding areas during high flows. A healthy riparian zone and a healthy stream system requires the maintenance of the natural flow regime (Poff et al 1997).

Of course, while floods are good for the stream and the riparian zone, they can be very damaging to human structures and activities. Removal of riparian vegetation, drainage of wetlands and development of floodplains leads to larger magnitude floods that cause greater damage to property (Poff et al 1997, FIFMTF 1996). Michener et al (1998) reported that flooding in South Georgia in 1994 and 1997 was greatly ameliorated by the largely intact natural riparian areas. Riparian wetlands are especially valuable for flood water storage.

Other factors can exacerbate flooding and need to be considered. Channelization, although in many cases conducted for flood control purposes, can actually increase the magnitude of flooding downstream (Roseboom and Russell 1985, Poff et al 1997). The Federal Interagency Floodplain Management Task Force now discourages such structural controls on flooding and promotes the preservation of floodplains in a natural state (FIFMTF 1996). Impervious surfaces also greatly increase stream storm flows, as discussed in Section VID.

To provide maximum protection from floods and maximum storage of flood waters, a buffer should include the entire floodplain. Short of this, the buffer should be as wide as possible and include all adjacent wetlands.

As outlined in the introduction, riparian buffers perform a number of other important functions, such as providing recreational and aesthetic benefits. These are beyond the scope of this document, although some of the economic benefits of buffers are discussed in a separate paper.

VI. Development of Riparian Buffer Guidelines

From the literature discussed above, it is relatively easy to recommend guidelines for buffer extent and vegetation:

Extent: Buffers should be placed on all perennial, intermittent and ephemeral streams to the maximum extent feasible. The overall effectiveness of the buffer is a function of how many stream miles are included. A good practical goal is to protect all perennial streams as well as all intermittent streams of second order and higher.

Vegetation: Buffers should consist of native forest along the stream to maintain aquatic habitat. Further from the stream (at least 25-50 ft), some harvesting of trees may be permissible and an outer belt of mowed grass can be useful for retaining nutrients and dissipating the energy of runoff.

Width, however, is somewhat more problematic. Although some buffer functions do not demand great width, others (especially removal of sediment) require significant width under some conditions. Current regulations in Georgia mandate fixed width buffers, regardless of topographic conditions or other factors. However, it is evident from the discussion so far that numerous variables influence buffer function. The question is, which of these variables are the most important? Is it possible to incorporate the most significant factors into a variable-width formula? To help answer these questions, several previously developed models and formulae for describing buffer function or determining buffer width are reviewed.

A. Review of Models to Determine Buffer Width and Effectiveness

Phillips (1989a, 1989b) derived two equations to describe buffer performance, both of which compare a given buffer with a reference buffer. The first (the Hydraulic Model) focuses exclusively on overland flow of sediments and sediment-bound contaminants:

$$B_b/B_r = (K_b/K_r)(L_b/L_r)0.4(s_b/s_r)\text{-}1.3(n_b/n_r)0.6$$

Where B=buffer effectiveness, K=saturated hydraulic conductivity, L=width of buffer, s=slope, and n=Manning's roughness coefficient. Subscripts b and r denote the buffer in question and the reference buffer, respectively.

The second formula, the Detention Model, considers both overland flow and subsurface flow.

$$B_b/B_r = (n_b/n_r)0.6(L_b/L_r)2(K_b/K_r)0.4(s_b/s_r)\text{-}0.7(C_b/C_r)$$

Where C= soil moisture storage capacity and the other variables are the same as in the above equation.

As noted by Muscutt et al (1993), Phillips did not verify his models experimentally, nor were they field-tested or calibrated. It is also important to note that the equations are only as good as the reference buffer selected for comparison. The parameters for reference buffers in Phillips' studies were not based on real reference sites, but rather were based on typical recorded values from the regions under study. Phillips admits his choices are "somewhat arbitrary" (Phillips 1989b). Although his second model is designed to address nitrogen removal, many factors influencing denitrification and vegetative uptake of nutrients (the two major mechanisms for nitrogen reduction) are ignored. Thus, according to the model, wetland areas are poor riparian buffers, a prediction that runs counter to both scientific research and common sense. Nevertheless, Phillips' model may represent a good starting point and could prove somewhat useful if experimentally verified and calibrated.

Despite the limitations of Phillips' model, Xiang (1993, 1996) and Xiang and Stratton (1996) used Phillips' detention model as a basis for a series of studies using a Geographic Information System (GIS) to delineate buffers in North Carolina. Although these studies provide an excellent example of the utility of GIS for large-scale delineation and study of buffers, they are still based on an untested formula.

The Riparian Ecosystem Management Model simulates the daily processing of water, sediment, carbon, and nutrients in a three-zone buffer system (Lowrance 1998). It is a computer simulation that allows buffer managers to determine the water quality impacts of buffer systems of different widths, slopes, soils, and vegetation. So far it has been tested and calibrated at sites near Tifton, Georgia, in the Coastal Plain, and additional verification is planned for other sites around the country. Initial testing revealed that REMM is accurate at predicting buffer function under many conditions, but at times appreciable error was observed (Lowrance 1998).

REMM is probably the most detailed and realistic model of riparian buffer function developed so far. Once it has been tested and calibrated for different regions, it should be a very useful tool for determining buffer characteristics on a site-by-site basis. Sensitivity analyses may also reveal which environmental factors are the most significant in different areas, and this information could be used to develop a simpler model that could be applied county- or municipality-wide. At this point, however, REMM is too data-intensive to be useful for policy purposes.

Williams and Nicks (1988) used the Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model to evaluate grass filter strips of widths of 3-15 m, slopes of 2.4-10% and various roughness coefficients on a 1.6 ha wheat site. They concluded that CREAMS "can be a useful tool for evaluating filter strip effectiveness in reducing sediment yield." The authors only conducted one experimental verification, however, which showed moderately close correlation (erosion was overestimated by 38%). Flannagan et al (1989) found that under ideal conditions, CREAMS can effectively predict sediment deposition in grass filter strips. The authors developed a simplified version of the model with extremely good correlation (r^2= 0.99) to the original. In a later study, Williams and Nicks (1993) used CREAMS and WEPP (Water Erosion Prediction Project) to evaluate the effectiveness of riparian buffers of 20-30 m at 200 Conservation Reserve Program sites in Central and Eastern U.S. Only selected results were reported. Predictions from WEPP and CREAMS varied, sometimes greatly: in one case, WEPP predicted an 85% reduction in soil loss while CREAMS predicted a 10% reduction. No attempt was made to verify predictions with field observations.

Mander (1997) also developed a model for buffer width:

$$P=(tqfi^{1/2})/(mK_i n)$$

Where P= buffer width, t= a conversion constant (0.00069), q= the mean intensity of overland flow, f= either the distance between stream and watershed boundary or the ratio of catchment area to stream segment length, i= slope, m= roughness coefficient (not Manning's), K_i= water infiltration rate and n= soil adsorption capacity.

At this time, there does not appear to be any published verification of Mander's model.

Nieswand et al (1990) determined that slope and width were the main factors influencing the effectiveness of buffers in trapping sediment and associated pollutants. They developed a simple formula for determining width based on a modified Manning's equation:

$$W= k(s^{1/2})$$

Where W= width of buffer in feet

k = 50 ft (constant)

s = percent slope expressed as a whole number (e.g., 5% slope=5)

The constant "50 ft" is somewhat arbitrary; it was chosen based on common buffer recommendations, with the assumption that a 50 ft buffer at one percent slope provides adequate protection to streams. The authors also recommend that slopes greater than 15% and impervious surfaces are ineffective and should not be credited in buffer width calculations (Nieswand et al 1990).

An unusual system of determining buffer width was developed by Budd et al (1988) for a county east of Seattle, Washington. While not a formula or model as such, it is worth mentioning because it purports to consider various stream corridor variables. The method for width determination involves a subjective evaluation of stream buffer characteristics, such as erosion potential, wildlife habitat quality, etc., along with the threats to the stream segment. Based on these factors, the assessor recommends a width for protected buffers, much as a doctor recommends a prescription for a patient. It is unclear, however, how the assessor actually determines the width. No rules or guidelines are supplied. When Budd et al (1988) applied this method to Bear-Evans Creek in Washington, they almost invariably recommended a width of 50 feet, regardless of local conditions. Clearly the results of such a survey will reflect the biases of the assessor, and without guidelines such a protocol is of little practical use.

It is evident that none of these models are appropriate for delineating riparian buffers at the county scale. Some are too data-intensive to be easily applied on large scale, some have not been properly field-tested or calibrated, some do not account for factors influencing significant processes, and some yield inconsistent results with one another. A new, simple formula is needed. The next section considers what variables should be incorporated into this formula.

B. Factors Influencing Buffer Width

It is evident from the preceding sections that there are a range of variables that influence the effectiveness of buffers. These include:

- slope of banks and areas contributing flow to the stream segment
- rainfall
- soil infiltration rate (saturated hydraulic conductivity) and other soil factors (redox potential, pH, temperature)
- soil moisture content
- floodplain width
- catchment size
- land use
- impervious surfaces
- vegetation, including litter and other surface cover characteristics (often quantified as a roughness coefficient such as Manning's N)

Clinnick (1985) identified soil type, slope and cover factors as important variables. Binford and Buchenau (1993) thought the most important factors were catchment size, slope, and land use. Fennessy and Cronk (1997) identified detention time as the most important variable; this is actually an aggregate of several variables, including slope, soil factors, surface cover characteristics, hydrological factors, and others. Osborne and Kovacic (1993) suggested that factors influencing nutrient removal efficiency of buffers include sedimentation rates, drainage characteristics, soil characteristics (i.e. redox potential), organic matter content and type, temperature, successional status and nutrient loading rates.

The following is a discussion of each of these factors and considerations on the practicality of incorporating them into a variable-width buffer formula that can readily be applied county-wide. As will be seen below, in many cases it is clear that some factors are important, but practical considerations make it difficult to incorporate them on a large scale. The purpose of this paper is to develop guidelines that are not only scientifically defensible and reasonably accurate, but that can also be readily applied to any property with minimal effort and data collection. When it is possible to conduct a detailed analysis of on-site conditions to determine the optimal buffer for a specific tract of land, additional variables should be considered. In that case, a more accurate model, such as REMM, should be used.

Slope

The slope of the land on either side of the stream may be the most significant variable in determining effectiveness of the buffer in trapping sediment and retaining nutrients. The steeper the slope, the higher the velocity of overland flow and the less time it takes nutrients and other contaminants to pass through the buffer, whether attached to sediments or moving in subsurface flow. Slope is a variable in virtually all models of buffer effectiveness and should definitely be included in a formula for buffer width.

Although Nieswand et al (1990) make a case for a width that varies exponentially with slope, research by Trimble and Sartz (1957) and Swift (1986) found a linear relationship in their field studies. Trimble and Sartz suggested that width should increase by either two or four feet for each percent increase in slope; Swift suggested that width should increase either 0.40 or 1.39 feet for each percent increase in slope. Since Swift ignored small silt and clay particles, his variables are apt to be low. Therefore, this review follows Trimble and Sartz' recommendation of increasing the buffer by 2 ft per 1% increase in slope.

Many researchers have noted that very steep slopes cannot effectively remove contaminants, though there is debate over what constitutes a steep slope. Among the recommendations are:

- 40% slope (Cohen et al 1987)
- 25% slope (Schueler 1995a)
- 15% slope (Nieswand et al 1990)
- 10% slope (Herson-Jones et al 1995)

Georgia's minimum standards for Mountain Slope Protection apply to certain slopes over 25%. Soil surveys typically do not recommend agriculture on slopes over 10% because of the erosion hazard. On the other hand, Swift found that riparian buffers on logging roads were able to trap sediment even on extremely steep (80%) slopes, though again small particles are not considered. There appear to be no other studies which evaluate buffer effectiveness at greater than moderate slopes. Any cutoff will be somewhat arbitrary, but 25% appears to be reasonable given the range shown above, until further research can clarify the issue. Therefore, the buffer width should increase by two feet for each slope percent up to 25%. Slopes steeper than this are not credited toward the buffer width.

Rainfall

The pattern and intensity of rainfall are important factors in determining the effectiveness of buffers. Daniels and Gilliam (1996) found that most of the sediment that passed through a riparian buffer did so during a single storm. One study cited by Karr and Schlosser (1976) found that 75% of agricultural erosion occurs during four storms a year, but another study they cite found that smaller rain events caused at least 50% of erosion and there was significant regional variability. It would be expected that in regions where rainfall is uniform and light, narrower buffers may effectively manage most of the sediment and nutrients that enter them. In areas that experience seasonal storms of high intensity, wider buffers may be necessary. However, there do not appear to be any studies that quantify the relationship between rainfall and buffer effectiveness. Several studies (e.g. Dillaha et al 1988, 1989; Magette et al 1987, 1989) described in this review simulated heavy rainfall conditions on test plots, but the studies were short-term and rainfall intensity comparisons were not made. Magette (1987) reported that buffer effectiveness declined as rainfall events increased. Others (Cooper et al 1987, Lowrance et al 1988) have examined the effectiveness of buffers over a sufficiently long time frame to include large storms. These long-term studies indicated the need for wider buffers than were recommended by most short-term studies. Groffman et al (1991b) suggested that denitrification rates are lower during storms because buffer residence times are decreased, but no empirical evidence was available. Hanson et al (1994) reported increases in denitrification rates in response to storms. Precipitation is incorporated into the "R" factor of the Universal Soil Loss Equation, which provides a rough estimate of erosion from agricultural fields or other plots. It may be possible to use this factor in a formula for buffer width; this warrants further investigation.

Buffers should be designed to effectively handle runoff and subsurface flow-rates from a one-year storm event. Just as for other stormwater best management practices, allowances should be made for exceptional (10-year or 25-year) events. In the absence of hard data, however, it is not possible to draw a valid relationship between rainfall patterns and buffer width. When possible, buffer effectiveness should be assessed through stream water quality measurements during or after storms. When buffers are found to be ineffective they should be widened or additional on-site controls should be implemented.

Catchment Size/Hydraulic Loading

It is logical that an increase in catchment size will demand an increase in buffer width. That is, a stream segment that drains five acres will collect more pollutants than one draining two acres, and a larger buffer will be required. The relationship may not be so simple, however. Sorrano et al (1996) argue that sediment/nutrient loading models that directly correlate loading rate with catchment area ignore the fact that as distance from the stream increases, sediments and nutrients are less likely to actually enter surface water. In other words, the areas closest to stream channels are far more important than more distal areas, and an increase in contributing area does not necessarily correspond to an increase in contaminant loading. Hatfield et al (1995) reported that catchment size had little influence on pesticide removal by buffer strips.

Additionally, denitrification rates usually increase to accommodate increased nitrate loading rates, as long as carbon does not become limiting. Haycock and Pinay (1993) reported 99% nitrate reductions in 20 m (66 ft) wide wooded riparian buffers regardless of the level of nitrate loading. Mander et al (1997) found that nutrient retention bears a strong log-log relationship with nutrient load; i.e., as load increases, retention increases (They also make a rather unconvincing case that retention efficiency declines slightly with higher loads). It appears that increased nutrient and/or hydraulic load does not necessarily require a wider buffer. In any case, the relationship is sufficiently complex that catchment size is not a reasonable variable to include in a simple buffer model.

Soil Factors

Soil characteristics determine in large part whether or not overland flow occurs, how fast water and contaminants move to the stream, and other factors relevant to the effectiveness of the riparian buffer. Denitrification rates are strongly influenced by soil moisture and soil pH (Groffman et al 1991a,b).

However, determining soil characteristics on a county-wide scale is somewhat problematic. According to Steve Lawrence of the Natural Resources Conservation Service, soil survey maps may not be sufficiently accurate for application in a model for buffer width (pers. com.). The minimum mapping unit is 3-4 acres, and inevitably some “inclusions” occur: these are small areas of different soil type lumped in with the dominant soil type. Mapping accuracy is even lower for soils that have been disturbed by construction or other activities (Elizabeth Kramer, pers. com.). Therefore, without detailed and potentially expensive on-site soil analyses, it is unlikely that including soil factors as variables would add greatly to the accuracy of a model. Of course, it may be reasonable to consider very general soil characteristics, such whether a soil is hydric (frequently flooded) and the overall hydrology of the area. In cases where on-site analysis is possible, it may be reasonable to adjust buffer width accordingly.

Soil Moisture & Wetlands

Denitrification rates show a positive correlation with soil moisture content (e.g. Groffman et al 1991a, b, Hanson et al 1994, Schnabel et al 1997). Wetlands, those soils with the highest moisture levels, have long been recognized for their value in trapping sediment and nutrients. They are also recognized as important animal habitat and are valuable in reducing flood impacts.

Riparian wetlands are significant enough to merit automatic inclusion in a buffer system. The width of the buffer should be extended by the width of all adjacent wetlands. For example, if a site that would otherwise have a 75 ft (22.9 m) wide buffer is found to include part of a 50 ft (15.2 m) wide area of riparian wetlands, total buffer width should be extended to 125 ft (38 m). Constructed wetlands are becoming more common as a component in human and animal waste treatment systems. However, natural wetlands require buffers of their own and should never be used to process untreated waste (Lowrance 1997b, Hubbard 1997).

Floodplain

The floodplain represents the region of material interchange between land and stream, as well as the limits of stream channel migration. Studies reviewed above have shown that the entire floodplain can be a site of significant contaminant removal. For this reason, it makes sense to extend the buffer to the edge of the floodplain whenever possible. In their buffer guidelines for Willamette National Forest, Gregory and Ashkenas (1990) declare that “the riparian management zone should include the entire [100 year] floodplain. Failure to do so will seriously jeopardize the riparian management objectives during major floods.” Schueler (1995) also recommends including the floodplain.

Including the entire floodplain is, naturally, also the best way to minimize damage from floods.

Therefore, whenever feasible, the riparian buffer should be extended to the edge of the 100-year floodplain. Even when this is not possible, certain activities and structures should be excluded from the floodplain because of the risk they pose to the stream. These include animal waste lagoons, animal waste spray fields, hazardous and municipal waste disposal facilities, and other potential sources of severe contamination.

Land Use

Urban and agricultural watersheds experience greater sedimentation and eutrophication than forested watersheds (Crawford and Lenat 1989). A study in coastal South Carolina found that a stream draining an 11 ha urbanized watershed had a 66% greater sediment load than a stream draining a 37 ha forested watershed, despite its smaller catchment area (Wahl et al 1997). Studies by Crawford and Lenat (1989) clearly showed that for all indicators (sediment, nutrients, metals, fish, invertebrates), urban streams are more heavily impacted than either forested or agricultural streams. Agricultural watersheds also display serious impacts, although they can still retain a healthy (if altered) biota (Crawford and Lenat 1989). A recent study by the U.S. Geological Survey found that Piedmont, Georgia streams draining watersheds that are mostly forested maintain the healthiest fish communities. Agricultural and suburban streams are worse, and urban streams tend to be the most degraded.

Incorporating land use into a formula for riparian buffer width presents some practical difficulties, however, because the relationship is quite complex. For example, even though urban streams tend to suffer greater impacts than other streams, urban buffers also tend to be less effective because storm drains deliver a large proportion of runoff directly to the channel. Therefore, widening a buffer in an urban area may have less of an effect on water quality than widening a buffer in an agricultural area. In a similar vein, does a pristine stream running through a forest need a smaller or larger buffer than an agricultural stream? Although the stream may not appear to be threatened, the absence of a sufficiently wide buffer might allow a logging road to be built too close, damaging the stream with sediment. Furthermore, land uses of the same general category (e.g., farming) could have very different effects on a stream. For example, one property zoned agricultural might be planted to cotton and produce massive sediment loads, while another might be planted to unmanaged pine trees. Administration of such a program would be difficult and subject to frequent challenges.

A more practical approach is to establish riparian buffer widths that are sufficiently wide to mitigate the great majority of land use impacts. Specific activities that are especially damaging should be subject to additional setbacks. In addition, pollution should be managed on-site, impervious surfaces should be limited and riparian buffer bypasses should be minimized (see below). These controls may do more to improve stream water quality and habitat than additional increases in the riparian buffer width.

Impervious surfaces

Because impervious surface area is so closely correlated with stream water quality, it may be considered as a variable for determining buffer width. It is far more effective, however, to treat impervious surface as a controllable variable and implement impervious surface limits and controls. This is discussed in more detail in a later section. In any case, however, preexisting impervious surfaces near the stream will not effectively perform buffer functions and should not count toward buffer width. For example, if a 30 ft wide road parallels a stream, the riparian buffer should be increased by 30 ft on the road side.

Vegetation

Vegetation characteristics may influence buffer effectiveness and therefore necessary width. However, in this report vegetation is considered a factor under management and not a width variable.

C. Buffer Guidelines for Water Quality Protection

In the previous section it was established that buffer width should vary based on slope and should include wetlands. One final task remains before buffer guidelines are presented: to determine the minimum width of the buffer. Without considering terrestrial habitat, most recommendations for minimum buffer widths range from 15 m (~50 ft) to 30 m (~100 ft). It might be possible to determine the correct width from within this range by conducting additional research in the region of interest. In the absence of this, however, the choice of minimum width amounts to a choice regarding margin of safety or, conversely, acceptable risk. The greater the minimum buffer width, the greater the margin of safety in terms of water quality and habitat preservation. Accordingly, several options are proposed: The first two are variable-width options, one with a 100 ft base width, and one with a 50 ft base width. The first can be considered the "conservative" option: it meets or exceeds many buffer width recommendations, and therefore should ensure high water quality and support good habitat for native aquatic organisms. The second is the "riskier" option: it should, under most conditions, provide good protection to the stream and good habitat preservation, although heavy rain, floods, or poor management of contaminant sources could more easily overwhelm the buffer. All of these options are defensible given the literature reviewed here. As a third option, a 100 ft fixed-width riparian buffer is recommended for local governments that find it impractical to administer a variable-width buffer.

Option One:

- Base width: 100 ft (30.5 m) plus 2 ft (0.61 m) per 1% of slope.
- Extend to edge of floodplain.
- Include adjacent wetlands. The buffer width is extended by the width of the wetlands, which guarantees that the entire wetland and an additional buffer are protected.
- Existing impervious surfaces in the riparian zone do not count toward buffer width (i.e., the width is extended by the width of the impervious surface, just as for wetlands).
- Slopes over 25% do not count toward the width.
- The buffer applies to all perennial, intermittent and ephemeral streams.

Option Two:

The same as Option One, except:

- Base width is 50 ft (15.2 m) plus 2 ft (0.61 m) per 1% of slope.
- Entire floodplain is not necessarily included in buffer, although potential sources of severe contamination be excluded from the floodplain.
- Ephemeral streams are not included; affected streams are those that appear on US Geological Survey 1:24,000 topographic quadrangles. Alternatively, the buffer can be applied to all perennial streams plus all intermittent streams of second order or larger.

Figure 9 shows an example of how Option Two can be applied to a theoretical riparian landscape.

Option Three:

- Fixed buffer width of 100 ft.
- The buffer applies to all streams that appear on US Geological Survey 1:24,000 topographic quadrangles or, alternatively, all perennial streams plus all intermittent streams of second order or larger (as for Option Two).

All of the buffer options described will provide habitat for many terrestrial wildlife species. However, significantly wider buffers are necessary to provide habitat for forest interior species, many of which are species of special concern. The most common recommendation in the literature on wildlife (most of which focuses on birds) is for a 100 m (300 ft) riparian buffer. Although this is not practical in many cases, local governments should preserve at least some riparian tracts of 300 foot width or greater. Identification of these areas should be part of an overall, county-wide wildlife protection plan.

Activities Prohibited in the Buffer

As a general rule, all sources of contamination should be excluded from the buffer. These include:

- land disturbing activities
- impervious surfaces
- logging roads
- mining
- septic tank drain fields
- agricultural fields
- waste disposal sites
- application of pesticides and fertilizer (except as necessary for buffer restoration)
- livestock

One exemption to this list that local governments may wish to consider is construction of a single family home. Minimum standards for river corridor protection issued by the Environmental Protection Division cannot by law prohibit the building of a single-family dwelling within the buffer for protected River Corridors (OCGA 12-2-8). Local governments that develop ordinances more stringent than the minimum standards may also wish to make this exemption.

The Three-Zone Buffer System

A three-zone riparian buffer system has been suggested for agricultural areas to allow some limited use of riparian land while preserving buffer functionality (Welsch 1991). Zone one, which extends from the bank to 15 ft (4.6 m) within the buffer, is undisturbed forest. Zone two is a managed forest, beginning 15 ft (4.6 m) from the bank and extending to 75 ft (22.9 m). Periodic harvesting and some disturbance is acceptable within this zone. Zone 3 is a grassed strip, beginning 75 ft (22.9 m) from the bank and extending to the buffer's edge at 95 ft (29.0 m). Controlled grazing and mowing may be permitted in this zone.

While the three-zone system represents a good compromise for buffers on agricultural land, it introduces an added level of complexity to a buffer ordinance that may not be warranted, especially if a variable-width system is used. Local governments may want to encourage the three-zone system as a voluntary practice on

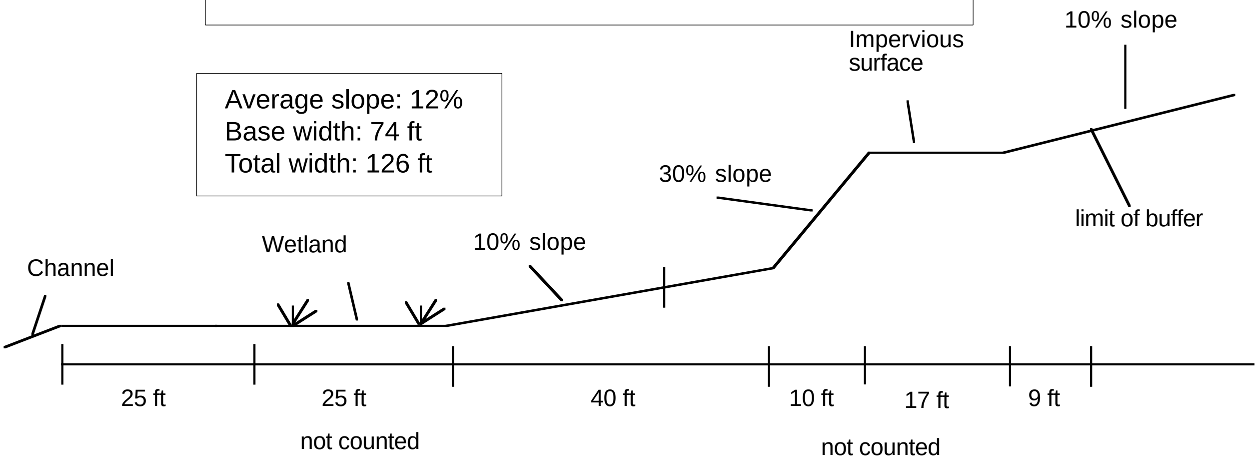


Figure 10. Example of the Application of Buffer Guidelines to a Hypothetical Riparian Landscape.

Base distance is calculated as 50 ft (for "Option 2") plus 2 ft per 1% slope. Wetlands, slopes over 25%, and impervious surfaces do not count toward the buffer width.

agricultural lands. Additional information is available from the Natural Resources Conservation Service.

Is This Possible?

An ordinance that establishes 100 ft or wider buffers on all perennial streams may sound unrealistic or too heavy-handed for most local governments. But such an ordinance is not as draconian as it first sounds. It is important to bear in mind that in most areas, such land use laws must of necessity exempt existing land uses: no local government is going to tell a small property owner that he must move his house or convert his lawn to forest (although he could be actively encouraged to do the latter). The people who are most affected are developers, who must now incorporate buffers into their designs. This will not necessarily have a negative economic impact. Several studies have shown that people will pay a premium to live or work near greenways or other protected areas, and this allows the developer to recoup at least some of the costs of not developing up to the stream bank. Finally, any buffer ordinance should always include clear, fair rules for variances, which will insure that anyone who is unfairly impacted by the law can obtain relief. More information on how local governments can develop and implement riparian buffer ordinances is included in a separate "Guidebook for Developing Local Riparian Buffer Ordinances," available from the University of Georgia Institute of Ecology Office of Public Service and Outreach. The document discusses various tools for protecting buffers, case studies of existing buffer protection programs, important issues of concerns such as "takings," and includes model riparian buffer ordinances.

D. Other Considerations

Establishing a system of protected riparian buffers is an important step in preserving healthy streams. However, a number of other steps must be taken if buffers are to be truly effective.

Reducing Impervious Surfaces

In a natural forested watershed, overland flow is quite rare, occurring only during the most severe rainstorms. Impervious surfaces, on the other hand, transfer most precipitation into runoff, leading to increased surface erosion, higher and faster storm flows in streams, and increased channel erosion. As a consequence, urban streams characteristically have greatly elevated sediment levels (Wahl et al 1997, Frick et al 1998). Flow from impervious surfaces also carries pollutants directly to streams, bypassing the natural filtration that would occur by passage through soil. Impervious surfaces are so closely correlated with urban water pollution that they are commonly used as an indicator of overall stream quality (Arnold and Gibbons 1996). May et al (1997) note that impervious surfaces are the "major contributor to changes in watershed hydrology that drive many of the physical changes affecting urban streams." Trimble (1997) ascribed the cause of large-scale channel erosion in San Diego Creek to increased impervious surfaces in the watershed. Impervious surfaces also decrease groundwater recharge and stream base flow levels (Ferguson and Suckling 1990). In a study of Peachtree Creek in Atlanta, Ferguson and Suckling (1990) also linked impervious surfaces to an increase in evapotranspiration; water evaporates quickly from impervious surfaces, creating a warm microclimate which increases transpiration rates in trees and plants. This further reduces stream flows, except during rainstorms. In short, impervious surfaces cause "flashy" streams with low base flows and very high storm flows.

Riparian buffers cannot protect a stream from channel erosion if the stream is constantly scoured by high storm flows caused by runoff from impervious surfaces. All municipalities and counties experiencing urban and suburban growth should consider enacting impervious surface controls in addition to riparian buffer ordinances. These limits can range from 10-12%, the point at which streams are considered impacted, to 30%, the point at which streams can be considered degraded (Klein 1979). If existing technologies were vigorously applied, impervious surfaces could be nearly eliminated (Bruce Ferguson, pers. com.). Further information on reducing impervious surfaces is available in the publication *Land Development Provisions to Protect Georgia Water Quality* (UGASED 1997) and in a recent publication of the Etowah Initiative (Miller and Sutherland 1999).

On-Site Management of Pollutants

Riparian buffers alone are not enough to mitigate the effects of otherwise uncontrolled upland activities (Binford and Buchenau 1993). As Barling (1994) notes, "buffer strips should only be considered as a secondary conservation practice after controlling the generation of pollutants at their source." In many cases it may be easier, cheaper and preferable to prevent pollutants from moving off site in the first place.

Sediment

In the case of agricultural regions, erosion reduction efforts should focus on keeping soil in fields, where it is usable, rather than trapping it in the riparian zone, where it is much more difficult to salvage. The Natural Resources Conservation Service, the Georgia Soil and Water Conservation Commission, extension agencies and other governmental and non-governmental organizations can provide detailed information on effective best management practices to reduce erosion. It is essential to follow these BMPs *in addition* to protecting functioning riparian buffer strips. Local governments need to take a coordinating role in ensuring that the various agencies and the agricultural community cooperate to reach water quality goals for the basin.

Likewise, BMPs must be faithfully implemented and enforced in construction projects. A review by Brown and Caraco (1997) found that in many cases, half of all practices specified in erosion and sediment control (ESC) plans were not implemented correctly and were not working. Contractors habitually saved money by cutting ESC installation and maintenance. Surveys also found that ESC practices rated as "most effective" by experts were seldom applied while those rated "ineffective" are still widely used. The authors also report that a field assessment of silt fences found that 42% were improperly installed and 66% were inadequately maintained. They conclude that while a substantial amount of money is now spent on ESC practices, "much of this money is not being well spent— practices are poorly or inappropriately installed, and very little is spent on maintaining them" (Brown and Caraco 1997). Kundell and Rasmussen (1995) have noted the importance of inspections and enforcement of BMPs in Georgia.

Nutrients

Because riparian zones can become saturated with phosphorus, it is very important to manage sources of this nutrient. Septic drain fields and sewer pipes can leak soluble phosphorus and should be located as far from streams as possible. Frequently, however, sewer pipes are routed through stream corridors, creating an extreme hazard if they should leak. Although a review of setback recommendations for septic tank drain fields and sewer pipes is beyond the scope of this document, a minimum distance of 100 ft (~30m) appears prudent considering the magnitude of the risk. Sewer pipes should only cross streams when absolutely necessary.

Concentrated Animal Feeding Operations (CAFOs) typically dispose of large amounts of nutrient-rich waste by holding it in waste lagoons and applying it to fields either as fertilizer or simply as a disposal method (Linville 1997). Large CAFOs may be considered point source polluters and can be required to obtain a federal permit (issued in Georgia by the EPD), but nationally only 12% of CAFOs are actually permitted (Linville 1997). Waste lagoon spills can be devastating to rivers (Burkholder 1997, Linville 1997), and placement of such lagoons should be carefully regulated. It is probably best to determine placement on a site-by-site basis to ensure that if a spill occurs, its effect on the stream system will be minimized. At the least, lagoons should be located outside of riparian buffers and the 100-year floodplain.

Because riparian buffers are generally effective at removing nitrogen from animal waste (Groffman et al 1991a), manure application strategies should be based on phosphorus, especially in watersheds where it is a limiting nutrient (Daniel and Moore 1997, Miguel Cabrera, pers. com.). Studies by Miguel Cabrera have shown that the concentration of phosphorus in runoff is proportional to the amount applied to the field, and that current application rates are many times higher than they should be to maintain phosphorus at acceptable levels (pers. com.). New approaches to phosphorus management are gaining acceptance and hold some promise for reducing the amount of phosphorus that can reach the stream. However, even with the best available controls, manure application rates likely will need to be reduced substantially to prevent phosphorus pollution of streams (Miguel Cabrera, pers. com.).

Riparian Buffer Crossings/Bypasses

Road crossings and other breaks in the riparian buffer effectively reduce buffer width to zero and allow sediment and other contaminants to pass directly into the stream (Swift 1986). Buffer crossings, or even just narrow points in the buffer, may be the locations of the majority of contaminant transport to the stream (Weller et al 1998). All buffer crossings should be minimized, but when they are necessary, Schueler (1995) suggests the following guidelines:

- Crossing width should be minimized
- Direct (90 degree) crossing angles are preferable to oblique crossing angles
- Construction should be capable of surviving 100-year floods
- Free-span bridges are preferable to culvertizing or piping the stream

Special care must be taken to stabilize banks around the buffer crossing. Crossings should be regularly monitored, especially after severe storms and floods, to determine if excessive sedimentation is occurring. Sewer lines which cross streams should also be inspected to ensure they are not leaking or damaged in any way.

It is also essential to minimize practices which cause water flow to bypass the riparian zone. Drain tiles used to improve drainage from agricultural fields discharge flow directly into the stream (Fennessy and Cronk 1997, Osborne and Kovacic 1993, Vought et al 1994). Jacobs and Gilliam (1985) compared fields drained by a riparian buffer with fields drained by ditches and drain tile. They observed high nitrate reduction in the riparian buffer, but much lower nitrate loss in drainage ditches and very little nitrate removal for fields drained by tile. Nitrate levels in tile drains in Georgia agricultural fields have been found to be several times higher than the levels in the shallow aquifer (Frick et al 1998). Constructing riparian wetlands at the outfall of the drain tile would help to slow the transport of pollutants into the stream and permit nutrient uptake and removal (Osborne and Kovacic 1993).

Similarly, in urban areas, storm drains carry contaminant-laden water from impervious surfaces directly into streams. This practice should be discontinued. Ideally, runoff should be allowed to infiltrate into the soil as close as possible to the source. If some drainage is required, outflow should either be directed in the form of sheet flow across a suitably wide riparian buffer or into a storm water detention ponds or constructed wetlands. When necessary, constructed wetlands may be incorporated into the riparian buffer if they are properly located and do not harm existing wetlands or other critical riparian features (Schueler 1995a).

For More Information

For additional information on how local governments can develop riparian buffer ordinances, a “Guidebook for Developing Local Riparian Buffer Ordinances,” is available from the University of Georgia Institute of Ecology Office of Public Service and Outreach (phone: 706-542-3948; email: lfowler@uga.cc.uga.edu). For additional scientific information on riparian buffers, all of the sources cited in this review are listed in the References section which follows.

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