Scientific Recommendations on the Size of Stream Vegetated Buffers Needed to Protect Water Quality

PART ONE of a Series entitled:
The Need for Stream Vegetated Buffers:
What Does the Science Say?

Janet H. Ellis
Montana Audubon
Helena, Montana
(406) 443-3949
www.mtaudubon.org

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Introduction

Montana's vast landscape and water resources are critical to the economy, public welfare, and the quality of life of the state's local communities. Each year, development modifies these resources. Riparian areas and their associated wetlands, where water and land come together, are particularly sensitive to changes from development.

As a result of increasing pressures, representatives from local and state governments are discussing ways to protect streams, rivers, and their associated riparian areas from unplanned, sprawling development. One of the main tools available to local governments interested in protecting these resources is to set back structures and protect streamside buffers of native vegetation (hereafter referred to as "building setbacks with vegetative buffers"). In order to use this tool, decision makers and citizens alike must understand the science behind buffer widths.

The vegetated buffer is the "work horse" portion of this tool because it is the area that filters out pollutants, helps prevent unnatural erosion, works to minimize the impact of floods, sustains the food and habitat of fish and wildlife, and more. As a result, relevant scientific studies focus on the vegetated buffer portion of this tool. For more information on how building setbacks relate to vegetated buffers, see page 3.

Protecting water quality is one of the important functions of vegetated buffers. Consequently, this first report in a series summarizes the scientific recommendations underlying the vegetated buffer size needed to protect water quality. Two other reports have been developed in this series on other key elements of stream protection: fisheries and wildlife:

- *Part II: Scientific Recommendations on the Size of Stream Vegetated Buffers Needed to Protect Fish and Aquatic Habitat;* and
- *Part III: Scientific Recommendations on the Size of Stream Vegetated Buffers Needed to Protect Wildlife and Wildlife Habitat.*

Each of these reports is designed to explain the science behind one of the many functions provided by vegetated buffers found along streams. Other topics for this series are currently being considered because building setbacks and vegetated buffers should also consider floodplains and seasonal water levels, stream migration corridors, density of development adjacent to the riparian corridor, and other factors.

Building Setbacks and Vegetated Buffers

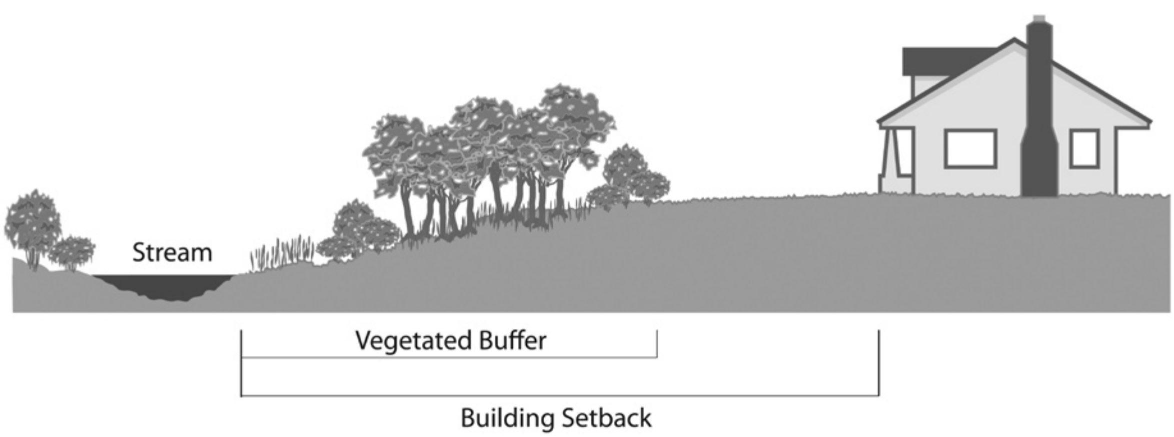
In order to understand setbacks and buffers, it is important to understand the following concepts:

Building setbacks or "no build areas" are the distance from a stream's ordinary high water mark to the area where new structures and other developments (such as highly polluting land uses—including roads, parking lots, and waste sites) are allowed.

Vegetated Buffers are not an additional area, but rather the portion of the building setback that is designated to remain undisturbed. These buffers are areas where all native vegetation, rocks, soil, and topography are maintained in their natural state, or enhanced by additional planting of native plants. Lawns should not be considered part of the vegetated buffer. With their shallow roots, lawns are not particularly effective at absorbing and retaining water, especially during heavy rains. Consequently, they do not significantly filter out water pollutants. They can also be a major source of fertilizers and pesticides—substances that should be prevented from entering our streams and rivers.

How much space should be placed between a building and a vegetated buffer? The building setback should be wide enough to prevent degradation of the vegetated buffer. As an example, most families use the area between their home and the vegetated buffer for lawns, play areas, swing sets, picnic tables, vegetable gardens, landscaping, etc. As a result, the building setback should extend at least 25–50 feet beyond the vegetated buffer (Wenger 1999). A smaller distance between a building and a vegetated buffer, such as 10 feet, will most likely guarantee degradation of the vegetated buffer. A greater distance between structures and a vegetated buffer is recommended if the:

- River has a history of meandering; the setbacks should ensure that people and homes will not unwittingly be placed too close to the river's edge, in harm's way.
- Vegetated buffer is narrower than scientific studies recommend; a deeper building setback can help protect water quality, fisheries, and aquatic habitat.
- Land is sloped and runoff is directed toward the stream (the steeper the slope, the wider a buffer or setback should be)
- Land use is intensive (crops, construction, development)
- Soils are erodible
- Land drains a large area
- Aesthetic or economic values need to be preserved
- Wildlife habitat needs to be protected
- Landowners desire more privacy



Vegetated Buffers and Clean Water

All Montanans depend upon clean water. Vegetated buffers along streams break down and/or retain nutrients, salts, sediments, chemical pesticides, and organic wastes. Buffers also act like giant sponges to filter and reduce the amount of pollutants that enter streams, groundwater, and—ultimately—drinking water, in runoff originating from sources such as city streets, lawns, construction sites, and agricultural fields.

Examples of common vegetated buffer restrictions include:

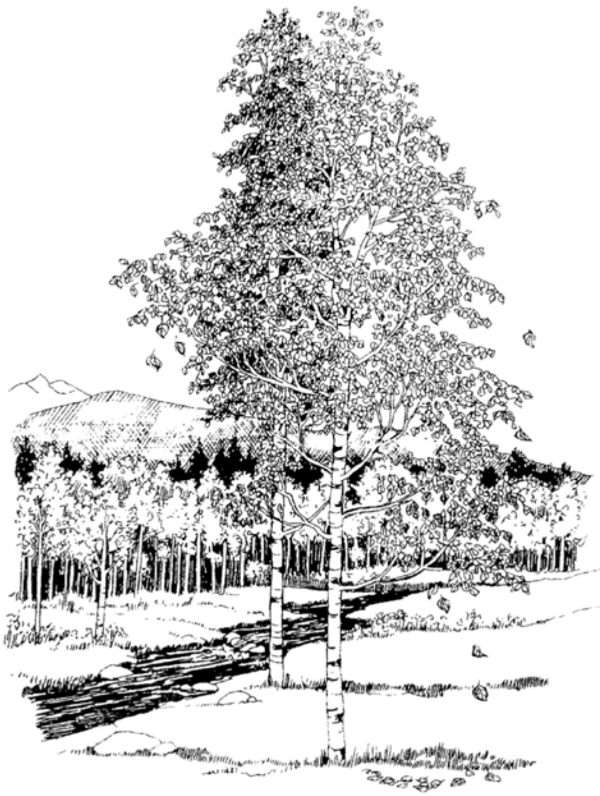
- Minimizing removal of native vegetation;
- Using native vegetation in plantings and restoration;
- Prohibiting non-native plants (including lawns);
- Prohibiting the use of pesticides and fertilizers;
- Avoiding use of heavy equipment that compacts soil; and
- Restricting mowing and managing grazing so as to avoid loss of riparian vegetation.

It should be noted that the ability of vegetated buffers to provide adequate water quality protection depends upon the slope, vegetation, floodplains, soils, and other similar factors. The following descriptions explain why these factors influence how effective a vegetated buffer is in protecting water quality:

Steep Slopes. From a water quality perspective, the most effective buffers are flat. Scientific research shows that the width of buffers should be increased when slopes are steeper, to allow more opportunity for the buffer to capture pollutants (Castelle et al 1994; Fischer et al 2000; Mayer et al 2005; Knutson and Naef 1997; and Wenger 1999). The greater the slope, the faster water flows over the surface. Researchers have noted that very steep slopes cannot effectively remove contaminants, though there is debate over what constitutes a steep slope, with ranges suggested between 10% and 40%. One model suggests that slopes over 25% should not count towards a buffer (Wenger 1999).

Vegetation. Natural vegetated buffers are important to water quality, because the longer runoff is detained in a buffer, the fewer pollutants will enter the stream. Physically, plants act as a barrier, slowing down water flow, giving sediments and other contaminants time to settle out of runoff, and allowing more water to move into the soil. Plant roots trap sediments and other contaminants in shallow groundwater, take up nutrients, hold banks in place, and prevent erosion. Runoff that seeps into shallow groundwater increases groundwater recharge and temporarily stores and slowly discharges precipitation and snowmelt to surface waters over a longer period of time.

Although vegetated buffers with woody plant species (trees and shrubs) and native grasses are both effective at trapping pollutants, those with woody plants provide the most effective water quality protection for several reasons. First, by providing a canopy, trees and shrubs reduce the velocity of raindrops and lessen runoff and soil erosion. Trees and shrubs also have longer, more complex root systems, which increase their ability to absorb nutrients and curtail erosion. Overhanging branches provide shade that reduces stream temperatures. Litter (leaves and organic debris) from trees and shrubs also increase the infiltration and pollution-absorbing ability of soil. And finally, trees and shrubs provide the most diverse fish and wildlife habitat in Montana, providing cover, nesting sites, and food. Native grasses also have complex root systems—especially compared



to the root systems of lawn grass—but they are not as deep-rooted as trees and shrubs.

As stated above, lawns—with their shallow roots—are not particularly effective at absorbing and retaining water, especially during heavy rains. Consequently, they do not significantly filter out water pollutants. Lawns can also be a major source of fertilizers and pesticides—substances that need to be prevented from entering our streams and rivers.

Surfaces without vegetation—including parking lots, compacted or paved roads, and other impervious surfaces—reduce the filtering capability of buffer areas, increase surface erosion, and lead to higher and faster storm flows in streams. As a result, restrictions on impervious surfaces should be considered in order to ensure that buffers are effective.

Floodplains. Because much pollution can enter streams during storm events caused by snowmelt or heavy rainstorms, protection of a stream or river's floodplain is important. Floodplains covered with native vegetation can significantly remove contaminants, minimize damage from floods, and reduce the amount of unnatural erosion that takes place. For these reasons, it is recommended that vegetated buffers encompass the entire floodplain whenever possible (Wenger 1999). This recommendation is particularly important in Montana's valleys, where streams and rivers meander.

Soils. Different soils have different abilities to filter out sediment and pollutants. Consequently, activities that compact soils or increase erosion (such as vegetation removal) should be avoided in vegetated buffers. The speed with which water and dissolved substances percolate through the soil depends upon the amount of organic material and the size of the spaces between the grains of soil. As an example, in fine clay soils, pollutants may take months or years to move into streams and groundwater. In porous soils (e.g. with more sand and gravel), pollutants can flow almost directly into streams or groundwater.

Contaminants Impacting Water Quality

Many of the substances covered in this report can degrade water quality. Vegetated stream buffers are an important tool that local governments can use to filter out these pollutants. Tables II and III summarize the information from scientific studies that tested how stream vegetated buffers filtered out the following contaminants (which are listed in alphabetical order, and not in order of importance):

Ammonium (NH_4) is a form of nitrogen (*see Nitrogen below*) found in human and animal waste (hence in sewage and septic field leakage) and in some fertilizers. It is toxic to fish and many other

Lawns—with their shallow roots—do not significantly filter out water pollutants. They can also be a source of fertilizers and pesticides, substances that should not enter streams and rivers. Montana Dept. of Natural Resources and Conservation photo library.

forms of stream life. Like all forms of nitrogen, ammonia can contribute to eutrophication (over-fertilization) of lakes, wetlands, and slow-moving streams (*see Nutrients below*).

Fecal coliform bacteria are found in the fecal material of humans or other animals and are used as an indicator of the likely presence of bacteria and viruses that cause a wide range of diseases. Sources of such bacteria and viruses include leaking sewer pipes, sewer overflows, failing septic systems, and areas where concentrations of animals are found, such as animal feedlots, city parks frequented by dogs, and areas with colonial nesting birds. The higher the levels of fecal coliform bacteria in water the greater the risk to human health because of the many waterborne pathogenic diseases associated with bodily wastes.

Heavy metals, such as lead, mercury, cadmium, copper, and zinc, occur naturally in streams and soils. However, many human activities increase the movement of these substances from land into water, raising the concentration of these metals to levels that are toxic to aquatic life. At very high levels, such metals may quickly kill aquatic life. Even at fairly low levels, metals may gradually accumulate in the liver or kidneys of animals, causing failure of these organs. The main sources of these contaminants are industrial and consumer waste, including power plant and other industrial emissions, old mining operations, runoff from roads and parking areas, and fertilizers.

Nitrogen (N) is an essential nutrient for all life. Under natural conditions it is often in short supply, limiting plant growth. However, many kinds of human activity increase availability of nitrogen, stimulating growth of plants. In water, excess nitrogen is a pollutant that can cause eutrophication (over-fertilization) (*see Nutrients below*) in surface water and contamination of groundwater. As a drinking water pollutant, nitrogen is particularly dangerous for infants. Streams receive nitrogen from sources such as fertilizers, animal wastes, leaking sewer lines and septic systems, and runoff from highways. The U.S. Environmental Protection Agency considers nitrogen one of the "top stressors in aquatic ecosystems" (Mayer, et al 2005). Nitrogen occurs in many forms, including nitrates, nitrites, ammonium, and particulate nitrogen.

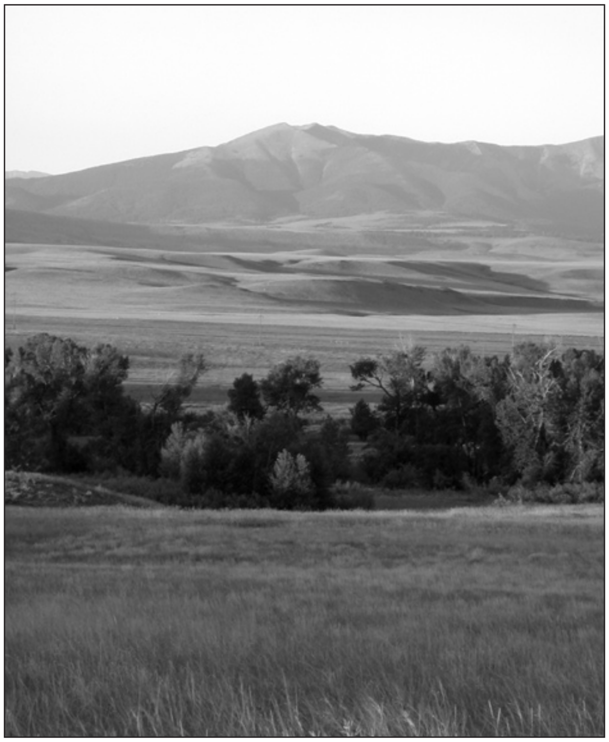
Nitrates (NO_3) and Nitrites (NO_2) are forms of nitrogen that occur in fertilizers, animal wastes, septic tanks, municipal sewage treatment systems, and decaying plants (see *Nitrogen above*). Nitrates/nitrites can move quickly through the soil and into groundwater and surface water. However, nitrate/nitrite levels in shallow groundwater can be reduced before reaching surface water in two main ways: (1) uptake by the roots of plants in vegetated buffers, or (2) use by bacteria that live in water-saturated soils which convert nitrates/nitrites to harmless nitrogen gas (a process called denitrification).

Nutrients are substances that are essential to life and include certain forms of nitrogen (*see above*) and phosphorus (*see below*). Increases in availability of nutrients may stimulate additional growth of plants. In water, excess nutrients increase the rate of eutrophication of lakes and slow-moving streams. Eutrophication can stimulate abundant plant growth in water bodies, which can lead to toxic algae blooms, excessive growth of nuisance aquatic plants, the depletion of oxygen in water, and—ultimately—the death of fish and other organisms. Hence at excessive levels, nutrients are considered water pollutants.

Pesticides, including both herbicides and insecticides, are designed to be toxic. The main sources for these chemicals include spraying of crops, weed-infested rangelands, lawns, and ornamental plants. At high enough concentrations in streams, pesticides may kill stream life outright, or weaken organisms so they die more readily from 'natural causes.' Pesticides also pose a risk to human health, especially those that biomagnify in the food chain. Biomagnification refers to the process where certain substances increase in concentration as they move from one link in the food chain to another.

Phosphorus (P) is an essential nutrient for plant growth that is found naturally in soils and streams, but exists in much higher levels in fertilizers and in human and other animal waste. It enters streams in waste water or in runoff polluted with fertilizers or animal wastes, including from leaking sewer pipes or septic drain fields. Stream vegetated buffers are typically effective at short-term control of phosphorus that is bound to sediment particles—they are *less* effective at (1) filtering out phosphorus that is dissolved in water, or (2) providing long-term storage of phosphorus (Wenger 1999). Increased levels of phosphorus can contribute to eutrophication (see *Nutrients* above).

Sediments are a common type of pollutant found in streams and rivers. Sediments come from a variety of sources, including natural and human-driven stream bank erosion, agricultural fields, exposed earth at construction sites and on dirt roads, and other activities that remove vegetation and expose soil. Excess sediment has numerous impacts, including degrading municipal water supplies and, as a result, increasing water treatment costs and/or posing a threat to human heath when treatment is made less effective. It can also degrade habitat for fish and the aquatic life that they eat and can clog drainage ditches, stream channels, water intakes, and reservoirs.



About This Report—Methods Used

This report summarizes the recommendations of 77 scientific studies that tested how various stream vegetated buffers protected water quality (*see Appendix I*). These scientific studies were reviewed by the authors of 5 review publications. Please note that the information in this report was taken from the text and tables of 5 review publications—and that the original studies were not reviewed in this report. The 5 review publications are:

- Castelle, A.J., A. W. Johnson, and C. Conolly. 1994. Wetland and stream buffer size requirements — a review. J. Environ. Qual. 23: 878–882.
- Fischer, R.A., C.O. Martin, and J.C. Fischenich. 2000. Improving riparian buffer strips and corridors for water quality and wildlife. International Conference on Riparian Ecology and Management in Multi-Land Use Watersheds. American Water Resources Association. August 2000. 7 pp.
- Knutson, K.L. and V.L. Naef. 1997. Management recommendations for Washington's priority habitats: riparian. Wash. Dept. Fish and Wildlife, Olympia, WA. 181 pp.
- Mayer, P.M., Steven K. Reynolds, Jr., Timothy J. Caneld. 2005. Riparian buffer width, vegetated cover, and nitrogen removal effectiveness: a review of current science and regulations. U.S. Environmental Protection Agency, EPA/600/R-05/118, National Risk Management Research Laboratory, Ada, OK. 28 pp.
- Wenger, S.J. 1999. A review of the scientific literature on riparian buffer width, extent and vegetation. Athens: Institute of Ecology Office for Public Service and Outreach, University of Georgia. 59 pp.

Appendix II contains the original references cited in the 5 review publications described above, allowing individuals using Appendix I to see the full title of all original references, as well as have sufficient information to access all references, if necessary.

Summary of Scientific Recommendations

All Montanans depend upon clean water—and streamside vegetated buffers play an important role in water quality protection. These areas break down and hold nutrients, chemical pesticides, salts, sediments, and organic wastes. They reduce the amount of pollution that enters streams, rivers, groundwater, and—ultimately—drinking water, in runoff originating from sources such as city streets, leaking sewer lines and septic systems, lawns, construction sites, and agricultural fields. As a result:

In order to protect the water quality of streams, scientific studies generally recommend that at least a 100-foot (30-meter) vegetated buffer be maintained. Steeper slopes and other local factors may require larger vegetated buffers. A minimum of a 50-foot (15-meter) buffer may be sufficient to protect certain aspects of water quality. However, for significant removal of nitrates, sediments, and pathogenic bacteria, at least 100 feet is recommended.

This recommendation is drawn from the conclusions of the 5 publications that reviewed a total of 77 separate scientific studies on water quality and stream vegetated buffers. Specific conclusions and recommendations by the 5 review publication authors are quoted in Table I.

This conclusion is also supported by the State of Montana's Nonpoint Source Management Plan, which was approved by the U.S. Environmental Protection Agency (EPA) in July 2007. It states that a "buffer of at least 100 feet is recommended for water quality protection. . . . Minimum widths for buffers should be 50 feet for low order headwaters streams, with expansion to as much as 200 feet or more for larger streams." Montana's Nonpoint Source Management Plan identifies locally-adopted water body setbacks as important "Best Management Practices" to protect and improve water quality from nonpoint source pollution. Nonpoint sources of pollution in urban areas include parking lots, streets, and roads where stormwater picks up oils, grease, metals, dirt,

Table I. A summary of the specific conclusions and recommendations of 5 review articles on vegetated buffer size and water quality protection. All authors emphasized that water quality protection depends on the slopes, soils, vegetation, floodplains, and similar factors.

Castelle et al 1994	"Based on existing literature, buffers necessary to protect wetlands and streams should be a minimum of 15 to 30 meters in width" (50–100 feet).
	Buffers less than 10 meters (33 feet) "provide little protection of aquatic resources under most circumstances."
Fischer et al 2000	Concluded that "most buffer width recommendations for improving water quality tend to be between 10 and 30 m" (33–100 feet).
Knutson and Naef 1997	Concluded that scientific studies indicated that vegetated buffers to protect water quality should be between 24 and 42 meters (78–138 feet).
Mayer et al 2005	Concluded that "wider buffers (>50 m) [167 feet] more consistently removed significant portions of nitrogen entering a riparian zone."
	[W]hile some narrow buffers (1–15 m) [3–50 feet] removed significant proportions of nitrogen, narrow buffers actually contributed to nitrogen loads in riparian zones in some cases."
Wenger 1999	To protect water quality overall, "a 100 ft [30 meter] fixed-width riparian buffer is recommended for local governments that find it impractical to administer a variable-width buffer."
	For long-term sediment control and short-term phosphorus control, a "30 m (100 ft) buffer is sufficiently wide to trap sediments under most circumstances."
	For nitrogen control, in "most cases 30 m (100 ft) buffers should provide good control, and 15 m (50 ft) should be sufficient under many conditions."
	For pesticide and heavy metal control, "the width is unclear from the existing research," with 15 meters (50 feet) seen as a bare minimum, and 50 meters (164 feet) shown to filter out much of two specific pesticides.

salts, and other toxic materials. In areas where crops are grown or in areas with landscaping (including grassy areas of residential lawns and city parks), irrigation and rainfall can carry soil, pesticides, fertilizers, herbicides, and insecticides to surface water and groundwater (Montana Department of Environmental Quality, 2007).

Several additional recommendations are worth noting:

- "The greater the minimum buffer width, the greater the safety margin in terms of water quality and habitat protection." (Wenger 1999)

- "Removal of riparian vegetation, drainage of wetlands and development of floodplains leads to larger magnitude floods that cause greater damage to property." (Wenger 1999)

- "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." (Wenger 1999)

- "Riparian buffers are especially important along the smaller headwater streams which make up the majority of stream miles in any basin." (Wenger 1999)

- "It is very important that buffers be continuous along streams. Gaps, crossings, or other breaks in the riparian buffer allow direct access of surface flow to the stream, compromising the effectiveness of the system." (Wenger 1999)

- "[E]xtensive experimental support for buffer zones <10 meters [33 feet] . . . is lacking." (Mayer et al 2005).

In order to better understand the range of scientific studies that went into the above conclusions, Appendix I contains study-specific information for all 77 scientific studies reviewed. It should be noted that many of these studies underwent extensive peer review before they were published in a peer-reviewed journal or report of a scientific government agency. The summarized studies show a range of buffer widths, because the ability of buffers to trap pollutants is affected by slope, soil type, vegetation type and density, climate, floodplains, and many more factors. It would be very costly to duplicate these studies in every situation; hence the recommendations given here are intended to be protective in most situations, based on the findings of a wide range of studies. If localized information on area conditions is available (vegetation maps, floodplain maps, etc.), this information can also be used to determine vegetated buffer sizes, ensuring that these buffers more accurately fit local conditions.

And finally, because Appendix I contains a lot of detailed information, which can be difficult to interpret, we created Table II. Table II is designed to organize the findings of the 77 scientific studies by activity (erosion and flood control) or type of pollutant (nutrients, ammonia, fecal coliform, nitrates, nitrogen, pesticides, phosphorus, and sediment)—giving readers a snapshot of the vegetated buffer width needed to control individual pollutants. As explained below, we did not use all scientific studies to create Table II—just those that reduced a specific water pollutant by 80% or more. The 80% threshold was chosen as a reasonable goal for nonpoint source pollution control; it may be insufficient for some pollutants, such as ammonia and fecal coliform. It is interesting to note that if pollutants are removed by 80% or more, it appears that stream vegetated buffers should be at least 130 feet, and not 100 feet, as recommended by the authors of the 5 review articles featured in this report.

Table II. Summary of stream vegetated buffer widths recommended to protect water quality. This table was compiled using information from the scientific studies reported in Appendix I below, as reported in the 5 review articles featured in this report. This table gives the average vegetated buffer width recommended to filter out approximately 80% of the following pollutants: ammonia, fecal coliform, nitrates, nitrogen, pesticides, phosphorus, and sediment. Desired buffer width was calculated by averaging the recommended buffer width for all studies that met or exceeded the 80% removal criteria. Where studies reported a range of values, the median of that range was used to calculate the average (mean) buffer width. In addition to an average buffer width, the range of buffer sizes from all studies meeting or exceeding the 80% reduction level is provided. Please note that nutrient reduction studies were treated slightly differently: because reviewed nutrient studies did not include a figure (e.g. 80% threshold) for the amount of pollution removed, the average buffer width for this pollutant was calculated using all scientific studies reviewed (12 studies total).

Type of Water Pollution	Average Stream Buffer Width	Number of Studies Used in Calculating Desired Buffer Width
Erosion control	100-year floodplain, but at least 100 feet	Review article conclusion (Wenger 1999)
Flood control, includes channel migration ability	100-year floodplain	Review article conclusion (Castelle et al 1994)
Nutrient	100 feet (range 33–600 feet)	12
Ammonia reduction (78% reduction)	164 feet	1
Fecal coliform	129 feet (range 100–600 feet)	4
Nitrates in surface runoff	113 feet (range 33–279 feet)	5
Nitrates in shallow groundwater	168 feet (range 3–721 feet)	31
Nitrogen	87 feet (range 5–164 feet)	4
Pesticides	182 feet (range 164–200 feet)	2
Phosphorus	106 feet (range 53–200 feet)	6
Sediment	103 feet (range 30–300 feet)	19
Average Stream Buffer Width Needed to Filter Approximately 80% of Pollutants	**132 feet**	

Appendix I.

A Summary of 77 Scientific Studies Conducted on the Size of Stream Vegetated Buffers Needed to Protect Water Quality. The information in this appendix was taken from the text and tables of 5 review articles described above. The table summarizes (1) the purpose of the vegetated buffer that was tested in a scientific study (Vegetated Buffer Function); (2) the size (in meters and feet) of the vegetated buffer(s) tested; (3) the author of the scientific study who tested the buffer's function and size; and (4) the name of the review article where the scientific study was summarized. As much as possible, the studies in this table are listed from most protective to least protective. Note that information about maintaining water temperatures, recruiting large woody debris, and maintaining microclimate influences and instream habitat appear in Part II of this report series, *Scientific Recommendations on the Size of Stream Vegetated Buffer Needed to Protect Fish and Aquatic Habitat*.

FILTER POLLUTANTS—Nutrients* ***Depends on slope, soils, etc.**				
	Meters	**Feet**	**Author of Original Scientific Study**	**Name of Review Article**
Nutrient removal—using the multi-species riparian buffer strip system described by the authors	20	66	Schultz et al 1995	Knutson and Naef 1997
Nutrient reduction—suggested distance to protect water quality	36	118	Young et al 1980	Knutson and Naef 1997; Wenger 1999
Nutrient reduction—buffers needed in forested riparian areas	30	100	Terrell and Perfetti 1989	Knutson and Naef 1997
Nutrient reduction—buffers needed in herbaceous or cropland riparian areas	183	600	Terrell and Perfetti 1989	Knutson and Naef 1997
Nutrient reduction—improve or protect water quality	≥10	≥33	Corley et al 1999	Fischer et al 2000
Nutrient reduction—improve or protect water quality from logging	≥30	≥100	Lynch et al 1985	Knutson and Naef 1997; Castelle et al 1994; Fischer et al 2000
Nutrient reduction—improve or protect water quality	≥18	≥60	Lynch et al 1985	Fischer et al 2000
Nutrient reduction—improve or protect water quality	≥15	≥50	Woodard and Rock 1995	Fischer et al 2000
Nutrient reduction—improve or protect water quality	≥25	≥82	Young et al 1980	Fischer et al 2000
Nutrient reduction—minimum buffer size recommended	10	33	Petersen et al 1992	Knutson and Naef 1997
Nutrient reduction	4	13	Doyle et al 1977	Knutson and Naef 1997; Castelle et al 1994; Fischer et al 2000
Nutrient reduction	16	52	Jacobs and Gilliam 1985	Knutson and Naef 1997
Nutrient reduction	30–43	100–141	Jones et al 1988	Knutson and Naef 1997

FILTER POLLUTANTS—Animal Waste* *Depends on slope, soils, etc.				
	Meters	**Feet**	**Author of Original Scientific Study**	**Name of Review Article**
78% ammonium reduction from surface water	50	164	Peterjohn and Correll 1984	Wenger 1999
71% ammonium reduction from surface water	21	70	Young et al 1980	Wenger 1999
20–50% ammonium reduction	6–18	20–50	Daniels and Gilliam 1996	Wenger 1999
Fecal coliform removed	30	100	Grismer 1981	Knutson and Naef 1997
Fecal coliform removed	30–43	100–141	Jones et al 1988	Knutson and Naef 1997
Fecal coliform removed	30	100	Lynch et al 1985	Knutson and Naef 1997
87% of fecal coliform removed	60	197	Karr and Schlosser 1977	Wenger 1999
34–74% of fecal coliform removed	9	30	Coyne et al 1995	Wenger 1999
Feedlot waste—distance needed to filter confined animal waste	183	600	Terrell and Perfetti 1989	Knutson and Naef 1997
80% of feedlot waste removed	91–262	300–860	Vanderholm and Dickey 1978	Castelle et al 1994
92% of suspended sediment removed from feedlot waste	24	80	Young et al 1980	Castelle et al 1994
33% of suspended sediment removed from feedlot waste	23	75	Schellinger and Clausen 1992	Castelle et al 1994

FILTER POLLUTANTS—Nitrogen in various forms* *Depends on slope, soils, etc.				
	Meters	**Feet**	**Author of Original Scientific Study**	**Name of Review Article**
NITRATES IN SURFACE RUNOFF				
Nearly 100%' nitrate reduction	20–30	66–100	Fennesy and Cronk 1997	Wenger 1999
Nitrates removed to meet drinking water standards	30	100	Johnson and Ryba 1992	Knutson and Naef 1997
99% nitrate reduction in forested buffer	10	33	Xu et al 1992	Castelle et al 1994
79% nitrate reduction in forest buffer	70–85	230–279	Peterjohn and Correll 1984	Wenger 1999; Mayer et al 2005
78% nitrate reduction in forest buffer	30	98	Lynch et al 1985	Mayer et al 2005
27–57% nitrate reduction in grassland buffer	5–9	15–30	Dillaha et al 1989	Mayer et al 2005
20–50% nitrate reduction in grassland buffer	8–16	26–53	Vought et al 1994	Wenger 1999
16–76% nitrate reduction in grassland buffer	26	85	Schwer and Clausen 1989	Mayer et al 2005

	Meters	Feet	Author of Original Scientific Study	Name of Review Article
NITRATES IN SURFACE RUNOFF (continued)				
12–74% nitrate reduction through wetland vegetation	20	66	Brüsch and Nilsson 1993	Mayer et al 2005
8% nitrate reduction in grassland buffer	27	89	Young et al 1980	Mayer et al 2005
Nitrates *increased* across buffer	21	70	Young et al 1980	Wenger 1999
Nitrates *increased* in grassland buffer	5–9	15–30	Dillaha et al 1988	Wenger 1999; Mayer et al 2005
NITRATES IN SHALLOW GROUNDWATER				
100% nitrate reduction	30	98	Pinay and Decamps 1988	Mayer et al 2005
100% nitrate reduction	30	98	Pinay et al 1993	Mayer et al 2005
100% nitrate reduction	40	131	Puckett et al. 2002	Mayer et al 2005
100% nitrate reduction	10–20	33–66	Vought et al 1994	Wenger 1999
99% nitrate reduction	50	164	Jacobs and Gilliam 1985	Mayer et al 2005
99% nitrate reduction	10	33	Cey et al 1999	Mayer et al 2005
98% nitrate reduction	100	328	Prach and Rauch 1992	Mayer et al 2005
97–99% nitrate reduction in grass-forest area	33–66	108–216	Vidon and Hill 2004	Mayer et al 2005
97% nitrate reduction	165	541	Hill et al. 2000	Mayer et al 2005
96% nitrate reduction in clay soils	1	3	Burns and Nguyen 2002	Mayer et al 2005
96% nitrate reduction	15	49	Hubbard and Sheridan 1989	Mayer et al 2005
95% nitrate reduction	200	656	Fustec et al 1991	Mayer et al 2005
95% nitrate reduction	60	197	Jordan et al 1993	Wenger 1999; Mayer et al 2005
94–98% nitrate reduction in forest area	204–220	669–721	Vidon and Hill 2004	Mayer et al 2005
94% nitrate reduction	50–60	160–200	Lowrance 1992	Wenger 1999; Mayer et al 2005
94% nitrate reduction	85	280	Peterjohn and Correll 1984	Mayer et al 2005
91% nitrate reduction	6	20	Borin and Bigon 2002	Mayer et al 2005
91% nitrate reduction	70	230	Hubbard and Lowrance 1997	Mayer et al 2005
90–99% nitrate reduction	50	164	Peterjohn and Correll [1] 1984	Wenger 1999
89% nitrate reduction	16	52	Haycock and Burt 1993	Mayer et al 2005

	Meters	Feet	Author of Original Scientific Study	Name of Review Article
NITRATES IN SHALLOW GROUNDWATER (continued)				
84–99% nitrate reduction	16–20	52–66	Haycock and Pinay 1993	Wenger 1999; Mayer et al 2005
84–98% nitrate reduction	25–50	82–164	Hefting and de Klein 1998	Mayer et al 2005
84–97% nitrate reduction	6–15	19–50	Simmons et al 1992	Mayer et al 2005
83% nitrate reduction	55	180	Lowrance et al 1984	Mayer et al 2005
83% nitrate reduction	20	66	Schultz et al 1995	Mayer et al 2005
82–99% nitrate reduction	10	33	Schoonover and Williard 2003	Mayer et al 2005
82–95% nitrates reduction	16–39	52–128	Osborne and Kovacic 1993	Wenger 1999; Mayer et al 2005
80–100% nitrate reduction	50–70	164–230	Martin et al 1999	Mayer et al 2005
80–81% nitrate reduction	20–28	66–92	Mander et al 1997	Wenger 1999
78% nitrate reduction	30	100	Hubbard 1997	Wenger 1999
78% nitrate reduction	38	125	Vellidis et al. 2003	Mayer et al 2005
64–100% nitrate reduction	100–200	328–656	Spruill 2004	Mayer et al 2005
60–99% nitrate reduction in grassland area	25–30	82–98	Vidon and Hill 2004	Mayer et al 2005
59–94% nitrate reduction[2]	31	102	Hanson et al 1994	Wenger 1999; Mayer et al 2005
58–96% nitrate reduction	10–50	33–164	Hefting et al 2003	Mayer et al 2005
52–76% nitrate reduction	5	16	Clausen et al. 2000	Mayer et al 2005
NITROGEN				
Nitrogen removed	30	100	Muscutt et al 1993	Wenger 1999
90–99% nitrogen reduction	5–9	15–30	Madison et al 1992	Castelle et al 1994
89% nitrogen reduction	19	62	Shisler et al 1987	Castelle et al 1994; Fischer et al 2000
86% nitrogen reduction in surface water	50	164	Peterjohn and Correll [1] 1984	Wenger 1999
67–74% nitrogen reduction	5–9	15–30	Dillaha et al 1988	Wenger 1999
67% nitrogen reduction	21	70	Young et al 1980	Wenger 1999
54–73% nitrogen reduction	5–9	15–30	Dillaha et al 1989	Castelle et al 1994; Wenger 1999
38% nitrogen reduction in grassland	91	299	Zirschky et al 1989	Mayer et al 2005
28–51% nitrogen reduction in grass/forest	8–15	25–50	Schmitt et al 1999	Mayer et al 2005
17–51% nitrogen reduction	5–9	15–30	Magette et al 1987	Wenger 1999

	Meters	Feet	Author of Original Scientific Study	Name of Review Article
NITROGEN (continued)				
Buffer zones less than 10 meters (33 feet) lack extensive experimental support	>10	>33	Hickley and Doran 2004	Mayer et al 2005
Nitrogen *increased* or reduced by 48%	5–9	15–30	Magette et al 1989	Wenger 1999; Mayer et al 2005
Nitrogen *increased* in groundwater	50	164	Peterjohn and Correll [1] 1984	Wenger 1999

FILTER POLLUTANTS—Pesticides and Heavy Metals* *Depends on slope, soils, etc.				
	Meters	**Feet**	**Author of Original Scientific Study**	**Name of Review Article**
Pesticides—buffering distance for sediment with pesticides—ungrazed buffers	61	200	Terrell and Perfetti 1989	Knutson and Naef 1997
Pesticides—various types—almost 100% over 3 years	50	164	Lowrance et al 1997	Wenger 1999
Pesticides—various types—8–100% reduction	20	66	Arora et al 1996	Wenger 1999
Pesticides—various types—10–40% reduction	12–60	40–60	Hatfield et al 1995	Wenger 1999
Lead removal	61	200	Horner and Mar 1982	Castelle et al 1994

FILTER POLLUTANTS—Phosphorus* *Depends on slope, soils, etc.				
	Meters	**Feet**	**Author of Original Scientific Study**	**Name of Review Article**
100% phosphorus reduction	61	200	Horner and Mar 1982	Castelle et al 1994
80% phosphorus reduction	19	62	Shisler et al 1987	Castelle et al 1994; Fischer et al 2000
73–84% phosphorus reduction—in surface water	50	164	Peterjohn and Correll 1984	Wenger 1999
67–81% phosphorus reduction in short-term study	20–28	66–92	Mander et al 1997	Wenger 1999
83% phosphorus reduction in short-term study	21–27	70–90	Young et al 1980	Wenger 1999
66–95% phosphorus reduction in surface water in short-term study	8–16	26–53	Vought et al 1994	Wenger 1999
61–79% phosphorus reduction in short-term study	5–9	15–30	Dillaha et al 1989	Castelle et al 1994; Wenger 1999
58–72% phosphorus reduction in short-term study	5–9	15–30	Dillaha et al 1988	Wenger 1999
41–53% phosphorus reduction in short-term study	5–9	15–30	Magette et al 1987	Wenger 1999
18–46% phosphorus reduction in short-term study	5–9	15–30	Magette et al 1989	Wenger 1999

FILTER POLLUTANTS—Sediments* ***Depends on slope, soils, etc.**				
	Meters	**Feet**	**Author of Original Scientific Study**	**Name of Review Article**
Sediment removal—adequate buffer for cropland, animal waste across ungrazed buffer, and for pesticides	61	200	Terrell and Perfetti 1989	Knutson and Naef 1997
Sediment removal	30	100	Moring et al 1982	Knutson and Naef 1997
Sediment removal—to prevent impacts in logged forest	30	100	Davies and Nelson 1994	Wenger 1999
Sediment removal—based on multi-year studies	30	100	Cooper et al 1988	Wenger 1999
Sediment removal—minimum needed	30	100	Erman et al 1977	Wenger 1999
Effective sediment removal—most effective width of vegetated buffers	25	82	Desbonnet et al 1994	Wenger 1999
Effective sediment removal—adequate buffer for logging practices on steep slopes—buffer measured from edge of floodplain	61	200	Broderson 1973	Knutson and Naef 1997; Castelle et al 1994
Effective sediment removal—buffer strip width to control non-channelized sediment flow	60–91	200–300	Belt et al 1992	Knutson and Naef 1997
99% sediment reduction in short-term study (1 rainfall)	9	30	Coyne et al 1995	Wenger 1999
90–94% sediment reduction in short-term study	19–60	62–197	Peterjohn and Correll 1984	Wenger 1999
90% sediment reduction at 2% grade	30	100	Johnson and Ryba 1992	Knutson and Naef 1997
85% sediment reduction	9	30	Ghaffarzadeh et al 1992	Castelle et al 1994
80% sediment reduction	61	200	Horner and Mar 1982	Castelle et al 1994
76–95% sediment removal in short-term study	5–9	15–30	Dillaha et al 1988	Wenger 1999
75–80% sediment reduction from logging activity	30	100	Lynch et al 1985	Knutson and Naef 1997; Castelle et al 1994; Fischer et al 2000
75–80% sediment reduction from stormwater in logged areas; more effective where runoff is in sheets; less effective where surface flows are channelized	30	100	Johnson and Ryba 1992	Knutson and Naef 1997
75% sediment reduction	30–38	100–125	Karr and Schlosser 1977	Knutson and Naef 1997
70–84% sediment reduction	5–9	15–30	Dillaha et al 1989	Castelle et al 1994; Wenger 1999
66–93% sediment reduction in short-term study	21–27	70–90	Young et al 1980	Castelle et al 1994; Wenger 1999; Fischer et al 2000
66–82% sediment reduction in short-term study	5–9	15–30	Magette et al 1989	Wenger 1999
50% sediment reduction—based on muti-year studies	100	328	Lowrance et al 1988	Wenger 1999
50% sediment reduction	88	289	Gilliam and Skaggs 1988	Knutson and Naef 1997

1 NOTE: Wenger (1999) refers to two articles written by Peterjohn and Correll: one from 1984 and one from 1985. It appears that the article he cited was Peterjohn and Correll 1984.

2 NOTE: Wenger (1999) reported a 94% reduction in nitrates for this study while Mayer et al (2005) reported a 59% reduction. Both figures are presented.

Appendix II

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