Understanding the Science Behind Riparian Forest Buffers:

Effects on Water Quality

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The riparian area is that area of land located immediately adjacent to streams, lakes, or other surface waters. Some would describe it as the floodplain. The boundary of the riparian area and the adjoining uplands is gradual and not always well-defined. However, riparian areas differ from the uplands because of high levels of soil moisture, frequent flooding, and the unique assemblage of plant and animal communities found there. Through the interaction of their soils, hydrology, and biotic communities, riparian forests maintain many important physical, biological, and ecological functions, and important social benefits.

Understanding the Science Behind Riparian Forest Buffers:

Effects on Water Quality

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Introduction

Over a third of our nation's streams, lakes, and estuaries are impaired by some form of water pollution (U.S. E.P.A. 1998). Pollutants can enter surface waters from **point sources**, such as single source industrial discharges and waste-water treatment plants; however, most pollutants result from **nonpoint source** pollution activities, including runoff from agricultural lands, urban areas, construction and industrial sites, and failed septic tanks. These activities introduce harmful sediments, nutrients, bacteria, organic wastes, chemicals, and metals into surface waters. Damage to streams, lakes, and estuaries from nonpoint source pollution was estimated to be about $7 to $9 billion a year in the mid-1980s (Ribaudo 1986).

Nonpoint source pollution can be difficult to control, measure, and monitor. In most cases, a combination of practices are required to address the problem. This may include the proper application of fertilizers and pesticides or the introduction of practices to reduce stormwater runoff and soil erosion. These practices are commonly known as Best Management Practices (BMPs). One BMP which can be very effective in influencing water quality is the construction of riparian forest buffers along streams, lakes, and other surface waters. Through the interaction of their unique soils, hydrology, and vegetation, riparian forest buffers influence water quality as contaminants are taken up into plant tissues, adsorbed onto soil particles, or modified by soil organisms.

Effects of Riparian Buffers on Sediment, Nutrients, and Other Pollutants

Sediment

Sediment refers to soil particles that enter streams, lakes, and other bodies of water from eroding land, including plowed fields, construction and logging sites, urban areas, and eroding stream banks (Figure 1) (U.S. E.P.A. 1995). Sedimentation of streams can have a pronounced effect on water quality and stream life. Sediment can clog and abrade fish gills, suffocate fish eggs and aquatic insect larvae, and cause fish to modify their feeding and reproductive behaviors. Sediment also interferes with recreational activities as it reduces water clarity and fills in waterbodies. In addition to mineral soil particles, eroding sediments may transport other substances such as plant and animal wastes, nutrients, pesticides, petroleum products, metals, and other compounds that can cause water quality problems (Clark 1985, Neary and others 1988).

Figure 1. Sediment enters surface waters from eroding land, including plowed fields, construction sites, logging sites, urban areas, and eroding streambanks. (photo courtesy Robert Baldwin, Delaware Department of Natural Resources & Environmental Control - Sediment & Stormwater Program)

Studies indicate that both forest and grass riparian buffers can effectively trap sediment. For example:

- Researchers in Blacksburg, Virginia, found that orchard grass filter strips 30 feet wide removed 84 percent of the sediment and soluble solids from surface runoff, while grass strips 15 feet wide reduced sediment loads by 70 percent (Dillaha and others 1989).
- In the Coastal Plain of Maryland, KY31 tall fescue filter strips 15 feet wide reduced sediment losses from croplands by 66 percent (Magette and others 1989).
- In North Carolina, scientists estimated that 84 percent to 90 percent of the sediment from cultivated agricultural fields was trapped in an adjoining deciduous hardwood riparian area (Cooper and others 1987). Sand was deposited along the edge of the riparian forest, while silt and clay were deposited further in the forest.
- Along the Little River in Georgia, scientists found that a riparian forest had accumulated 311,600 to 471,900 pounds per acre of sediment annually over the last 100 years (Lowrance and others 1986).
- Researchers in the Piedmont of North Carolina found that grass and grass-forest filter strips were equally effective in removing sediments, reducing loads from 60 percent to 90 percent (Daniels and Gilliam 1996).

However, researchers have observed that the effectiveness of grass filter strips may decrease over time as the strip becomes inundated with sediment or as the ground becomes saturated with runoff. For example, in an experiment at Virginia Tech, researchers demonstrated that a filter strip which initially removed 90 percent of the sediment was removing only 5 percent of the sediment after six trials (Dillaha and others 1989). Buffers may be most effective at removing large particles such as sand, but may be less effective at

removing small clay particles. In Arizona, researchers found that sand particles could be removed by grass buffers within a fairly short distance from the field edge (as little as 10 feet), while the removal of silt particles required a buffer of 50 feet (Wilson 1967). Filter strips 300 to 400 feet wide were required to remove clay particles.

Many factors influence the ability of the buffer to remove sediments from land runoff, including the sediment size and loads, slope, type and density of riparian vegetation, presence or absence of a surface litter layer, soil structure, subsurface drainage patterns, and frequency and force of storm events (Osborne and Kovacic 1993). Riparian buffers must be properly constructed and regularly monitored in order to maintain their effectiveness. Probably the most important consideration is the maintenance of shallow sheet flow into and across the buffer. Where concentrated flow paths begin to form or deep sediments begin to accumulate, the buffer can no longer maintain its filtering ability. Maintaining shallow sheet flow into the buffer can be especially troublesome in the Ridge and Valley region of Virginia and some areas of the Piedmont, where slopes are steep and surface flows tend to concentrate.

Nutrients

Nutrients are essential elements for aquatic ecosystems, but in excess amounts, they can lead to many changes in the aquatic environment and reduce the quality of water for human uses (Dupont 1992). Some nutrient inputs into surface waters are entirely natural, such as nutrients contained in plant materials or naturally eroding soils (Clark and others 1985). However, most nutrients in surface waters today result from human activities. Lawn and crop fertilizers, sewage, and manure are major sources of nutrients in surface waters. Industrial sources and atmospheric deposition also contribute significant amounts of nutrients (Guldin 1989).

Nationwide, agricultural lands are the primary source of nutrient inputs into streams, contributing nearly 70 percent of the total loads of nitrogen (almost 7 million tons) and phosphorus (3 million tons) each year (Chesters and Schierow 1985). On a per-acre basis, intensive livestock operations (such as feedlots) release more nutrients into the environment than any other agricultural activity (Beaulac and Reckhow 1982). Row crops, small grains, and pasture contribute lesser amounts on a per-acre basis, but more land is devoted to these uses.

Nutrients can enter surface waters in subsurface or surface flows (as a dissolved form or attached to soil particles) (Gilliam and others 1997). For example, nitrogen is most commonly transported as dissolved nitrogen through subsurface flows, with peak nitrate levels occurring during the dormant season after crops have been harvested and soil evaporation rates are reduced. In contrast, phosphorus most often enters the stream adsorbed into soil particles and organic materials in surface runoff after storm events (Pionke and others 1995).

Probably the most significant impact of nutrients on streams is eutrophication, the excessive growth of algae and other aquatic plants in response to high levels of nutrient enrichment (U.S. E.P.A. 1995). When plant growth becomes excessive, the water body may become depleted of dissolved oxygen and choked with large unsightly mats of algae and decaying organic matter, resulting in water with an undesirable color, taste, and odor (Figure 2). Eutrophication can affect the stream's ability to support plant and animal life, interfere with water treatment, and diminish the recreational and aesthetic values of the area. Some algae may also form toxins which are directly harmful to aquatic organisms and humans.

Figure 2. Nutrient enrichment of surface waters can result in the excessive growth of algae and other aquatic plants, reducing the water's ability to support aquatic organisms and diminishing recreational and aesthetic values of the area.

In addition, some forms of nutrients can be directly toxic to humans and other animals (Chen and others 1994, Evanylo 1994). For example, high levels of nitrates can induce methemoglobinemia (a reduction in the oxygen-carrying capacity of the blood) in infants and may be linked to an increased risk of birth defects and stomach cancer in adults (Hall and Risser 1993). Nitrate contaminated water can also be a problem for livestock when it adds to high nitrate concentrations already present in feeds. Chronic nitrate poisoning in cattle has been shown to produce a number of physical ailments, including anorexia, vasodilation, lowered blood pressure, and abortion, reduced lactation, and other reproductive problems (Johnson and others 1994a).

Riparian forests have been found to be effective filters for nutrients, including nitrogen, phosphorus, calcium, potassium, sulfur, and magnesium (Lowrance and others 1984a, 1984b). Because excessive levels of nitrogen and phosphorus are of particular concern in the nation's streams and lakes, the ability of riparian buffers to filter these nutrients has been the focus of much research.

Nitrogen. Riparian forests have been reported by many scientists to remove nitrogen from agricultural runoff. For example:

- Researchers at the U.S. Department of Agriculture, Agricultural Research Service in Tifton, Georgia, have maintained studies since the early 1980s where deciduous forest buffers have reduced nitrogen from agricultural runoff by 68 percent (Lowrance and others 1984b).
- On the western shore of the Chesapeake Bay in Maryland, scientists estimated a riparian buffer removed 89 percent of the nitrogen from field runoff, mostly in the first 62 feet of the buffer (Peterjohn and Correll 1984).
- On Maryland's Eastern shore, scientists found riparian buffers removed 95 percent of the nitrates from agricultural runoff (Jordan and others 1993).
- Recent studies in the Nomini Creek watershed northeast of Richmond, Virginia, demonstrated that forested riparian buffers could reduce concentrations of nitrate-nitrogen in runoff from croplands by 48 percent (Snyder and others 1995).

Other studies, including research in Iowa, Wisconsin, New England, and New Zealand, that confirmed the role of forested buffers in removing nitrogen and nitrate (NO_3^-) also have shown that not all areas of the buffer function equally in reducing nitrogen levels. For example:

- Researchers in Wisconsin found that nitrogen levels were reduced most in the areas of the riparian forest that were frequently flooded; nitrogen levels remained high in drier areas of the buffer (Johnston and others 1984).
- Scientists in New England found a similar pattern. Where the water table was within 20 inches of the soil surface, nitrate removal rates were as much as 70 percent higher than where drier soils occurred (Gold and Groffman 1995). They also found that the nitrate removal capacity of a riparian buffer remains high even during the winter months. In fact, the highest rates of nitrate removal occurred during the dormant season, when there was maximum leaching of nitrate from agricultural fields. Furthermore, their studies showed that the availability of carbon was a limiting factor in nitrate reduction.
- Likewise, in New Zealand, Cooper (1990) found that where subsurface flows of water moved through organic soils before entering streams, levels of nitrates were reduced by as much as 100 percent. However, mineral soils located along the same streams exhibited little capacity to decrease nitrogen. These soils showed corresponding low levels of denitrifying bacteria and low levels of available carbon.
- Recent studies in the Nomini Creek watershed near Richmond, Virginia, demonstrated that nitrate reduction is greatest in riparian forests with a high water table and highly organic soils (Snyder and others 1995). Associated laboratory tests showed that denitrification rates were as much as ten times greater in muck soils (16 percent organic matter) than in soils containing only 1.5 percent organic matter.

These studies and others support the hypothesis that the primary mechanism for nitrate removal by riparian forests is denitrification. Denitrification is a process whereby nitrogen in the form of nitrate (NO_3^-) is converted to gaseous N_2O and N_2 and released into the atmosphere. In order for denitrification to occur, certain soil conditions must be present:

1) a high or perched water table;
2) alternating periods of aerobic and anaerobic conditions;
3) healthy populations of denitrifying bacteria; and
4) sufficient amounts of available organic carbon (Lowrance and others 1985, 1995).

Denitrification offers an important means for the permanent removal of excess nitrogen from the riparian area because nitrates are converted to nitrogen gas and released to the atmosphere.

Other mechanisms for nitrate removal include uptake by vegetation and soil microbes and retention in riparian soils (Beare and others 1994, Evanylo 1994). Plants can take up large quantities of nitrogen as they produce roots, leaves, and stems. However, much of this is returned to the soil as plant materials decay. For example, scientists in Maryland estimated that deciduous riparian forests took up 69 pounds of nitrogen per acre annually, but returned 55 pounds (80 percent) each year in the litter (Peterjohn and Correll 1984). In North Carolina, researchers estimated that only 3 percent to 6 percent of the nitrogen passing through an alluvial swamp forest was taken up and stored in woody plant tissues (Brinson and others 1984). Nevertheless, Correll (1997) suggested that vegetative uptake is still a very important mechanism for removing nitrate from riparian systems, because vegetation (especially trees) removes nitrates from deep in the ground, converts the

nitrate to organic nitrogen in plant tissues, then deposits the plant materials on the surface of the ground where the nitrogen can be mineralized and denitrified by soil microbes.

Grass buffers may also reduce nitrogen levels from agricultural runoff. For example, scientists in the Piedmont of North Carolina found that both grass and grass/forest riparian buffers reduced total nitrogen by 50 percent (Daniels and Gilliam 1996). On experimental plots at Blacksburg, Virginia, orchard grass buffers 30 feet wide reduced total nitrogen by 76 percent (Dillaha and others 1989). However, scientists in England reported that although both grass and forested buffers can effectively remove nitrogen, forested buffers may be more efficient (Haycock and Pinay 1993). They found that a buffer of poplars adjacent to cereal croplands could remove 100 percent of the nitrate that entered the buffer, even in the dormant season, compared to a perennial ryegrass buffer which removed only 84 percent. They attributed the difference to the larger amount of carbon available year-round in the forested buffer. Likewise, a study in central Illinois comparing the ability of a mixed hardwood riparian forest and a reed canarygrass filter strip to filter nutrients found that both were effective filters for nitrate-nitrogen, but on an annual basis, grass was less effective than the forest (Osborne and Kovacic 1993). The scientists suggest that this may be associated with the form of carbon available in the forested buffer for denitrification.

Current studies in the Ridge and Valley region of Pennsylvania suggest that neither grass nor forest provides a consistently more favorable environment for denitrification (Schnabel and others 1995). Rather, it is the presence of certain soil and hydrological conditions which promote denitrification. However, their study confirmed the importance of carbon in fueling denitrification processes; denitrification rates increased on both the grass and forested sites when they were amended with additional carbon. Likewise, studies conducted on Virginia's Eastern Shore by the U.S. Geological Survey suggest that the mere presence of forested buffers may not significantly decrease nitrogen loads to streams (Speiran and others 1998). Here, soil texture, organic matter content, and groundwater flow paths were reported to be the most important factors influencing the fate of nitrogen.

Phosphorus. Riparian areas can be important sinks for phosphorus; however, they are generally less effective in removing phosphorus than either sediment or nitrogen (Parsons and others 1994). For example, only half the phosphorus entering a riparian forest in North Carolina was deposited within the forest (Cooper and Gilliam 1987). Lowrance reported only a 30 percent reduction of phosphorus by a hardwood riparian forest in Georgia (Lowrance and others 1984b). Yet, in Maryland, scientists found that deciduous hardwood riparian buffers removed nearly 80 percent of the phosphorus from agricultural runoff, primarily particulate phosphorus (Peterjohn and Correll 1984). The riparian buffer had little effect on phosphorus in the form of dissolved phosphate.

The primary mechanism for phosphorus removal by riparian buffers is the deposition of phosphorus associated with sediments (Brinson and others 1984, Walbridge and Struthers 1993). In addition to the settling of particulate phosphorus, dissolved phosphorus may also be removed from runoff waters through adsorption by clay particles, particularly where there are soils containing clays with high levels of aluminum and iron (Cooper and Gilliam 1987). Some have suggested that because clays tend to accumulate in riparian soils, riparian areas play an important role in the removal of dissolved phosphorus (Walbridge and Struthers 1993). However, others have found that soils are limited in their capacity to adsorb large loads of phosphorus, and in areas where excessive phosphorus enrichment occurs, soils become saturated within a few years (Cooper and Gilliam 1987, Mozaffari and Sims 1994). Unlike nitrogen, phosphorus absorption is reduced in soils with high organic matter (Sharpley and others 1993, Walbridge and Struthers 1993).

Some phosphorus may be taken up and used by vegetation and soil microbes, but like nitrogen, much of this phosphorus is eventually returned to the soil. For example, researchers estimated that less than 3 percent of the phosphate entering a floodplain forest in eastern North Carolina was taken up and converted to woody tissue, while scientists in Maryland reported a deciduous riparian forest buffer took up 8.8 lb/A/yr phosphorus but returned 7 lb/A/yr (80 percent) as litter (Brinson and others 1984, Peterjohn and Correll 1984). In some riparian areas, small amounts of phosphorus (0.05-2.14 lb/A/yr) may be stored as peat (Walbridge and Struthers 1993).

Grass buffers may reduce phosphorus levels as well as forested buffers. Researchers in Illinois compared the ability of a mixed hardwood riparian forest and a grass filter strip to reduce phosphorus loads from agricultural runoff (Osborne and Kovacic 1993). They found that while the forest buffer removed more phosphorus initially, the forest buffer also released more phosphorus during the dormant season. On an annual basis, the grass buffer was a more efficient sink for phosphorus than was the forest buffer. Studies in the Coastal Plain of North Carolina suggest that grass buffers can reduce

phosphorus loads by as much as 50 percent to 70 percent (Daniels and Gilliam 1996). Studies by Dillaha and others (1989) at Virginia Tech reported similar results; orchardgrass buffer strips 30 feet wide removed 89 percent of the phosphorus from runoff, while filter strips 15 feet wide removed 61 percent. However, their research also suggests that grass buffers may only trap particulate phosphorus temporarily, then release it during later storm events.

Other Contaminants

Other contaminants which may reduce water quality include pathogens and toxins. The fate of these contaminants in riparian areas is not well understood. However, it has been suggested that riparian areas may at least slow the movement of contaminants to surface waters and increase the opportunity for the contaminants to become buried in the sediments, adsorbed into clays or organic matter, or transformed by microbial and chemical processes (Johnston and others 1984).

Pathogens

Pathogens such as waterborne bacteria, viruses, and protozoa are the source of many diseases, including salmonellosis, mastitis, scours, anthrax, tuberculosis, brucellosis, tetanus, and colibaciliosis, that infect humans, livestock, and other animals (Chesters and Schierow 1985, Palmateer 1992). Pathogens can enter streams and lakes from various sources: improperly treated sewage, wildlife, stormwater runoff, leaky septic systems, runoff from livestock operations, or as sewage dumped overboard from boats (Figure 3). The 1998 Virginia Water Quality report indicates that bacterial contamination is a major pollutant in the state's streams and estuaries. The primary source of this contamination is livestock operations and municipal sewer overflows.

Disease-causing organisms generally die off fairly quickly once they enter surface waters, however, if they come in contact with sediments or organic matter they may become adsorbed into these materials and can survive for longer periods of time (Palmateer 1992). High nutrient levels and turbidity in the water also increase survivability of bacteria by providing a source of nutrition and reducing the amount of sunlight which penetrates the water. Many pathogenic viruses and bacteria are not directly harmful to aquatic organisms; however, pathogens can be passed on to humans when contaminated fish and shellfish are ingested (U.S. E.P.A. 1998). Pathogens can also be transmitted to humans, livestock, and other animals through direct contact with contaminated water.

Figure 3. Pathogens can enter streams through runoff from livestock operations, the discharge of improperly treated sewage, stormwater runoff, wildlife, or sewage dumped from boats.

There is little information available on the ability of riparian buffers to reduce contamination by fecal coliform bacteria and other pathogens. However, scientists in Minnesota conducted simulated rainfall tests to measure the ability of various types of vegetation to reduce levels of fecal coliform bacteria and other pollutants in runoff from a cattle feedlot (Young and others 1980). They found that strips of corn, oats, orchardgrass, and sorghum/sudangrass were all effective in reducing bacterial levels by nearly 70 percent. They estimated a buffer 118 feet wide would be required to reduce total coliform bacteria to levels acceptable for human recreational use. Other researchers have demonstrated the ability of grass sod filter strips to trap bacteria from dairy cow manure under laboratory conditions (Larsen and others 1994). They found that even a narrow (2 foot) strip successfully removed 83 percent of the fecal coliform bacteria, while a 7 foot filter strip removed nearly 95 percent.

Toxins

Although many chemicals have toxic effects if present in large amounts, chemicals with adverse and long-term effects are referred to as toxins. Once toxins have entered aquatic systems, they may settle out and persist in the sediments for decades (Guldin 1989, U.S. E.P.A. 1998). Disruption of the sediments (for example, from boating activity or dredging) may release pollutants into the water years after they are introduced.

Toxic pollutants can affect aquatic organisms by increasing their susceptibility to disease, interfering with reproduction, and reducing the viability of their young. Toxins can cause behavioral changes (for example, decreased ability to swim) and adverse physiological effects (such as decreased growth or altered blood chemistry) which result in the reduced ability to feed and escape predation (Firehock and Doherty 1995). Because not all organisms are equally affected by environmental toxins, some species may be eliminated from the environment while others survive.

In humans, toxins have been shown to cause disorders of the immune, reproductive, developmental, and neurological systems (U.S. E.P.A. 1995). Humans can be exposed to toxins by eating contaminated fish or drinking or swimming in contaminated water (Figure 4). The toxins of greatest concern in aquatic systems are pesticides, toxic metals, PAHs (polycyclic aromatic hydrocarbons), and PCBs (polychlorinated biphenyls). Limited research suggests that riparian buffers may help mitigate pesticides and metals from runoff.

Figure 4. Humans can be exposed to toxins by eating contaminated fish or drinking or swimming in contaminated water.

Pesticides are used extensively throughout the U.S., primarily in agricultural areas. Pesticides also find wide use on utility right-of-ways, golf courses, urban lawns and gardens, and in plant nurseries (Johnson and others 1994b). Pesticides enter streams through surface runoff, either dissolved in water or attached to soil particles. They may also be discharged into streams from contaminated groundwater or be deposited into surface waters through atmospheric deposition (McConnell and others 1995).

Although pesticides have the potential to cause significant damage to aquatic communities, pesticide losses from farm fields under typical conditions are generally very low (less than 5 percent of applied pesticides), and pesticide levels in surface waters are considered extremely low (Baker 1985, Chesters and Schierow 1985, Johnson and others 1994b). However, contamination of surface waters by pesticides can occur. For example, in north-central Missouri, where an extensive clay pan underlies an agricultural area, widespread contamination of streams has been confirmed (Donald and others 1995, Blanchard and others 1995).

Few studies have been made to examine the fate of pesticides in riparian areas. However, where the proper conditions exist, riparian forest buffers have the potential to remove and detoxify pesticides in runoff. Pesticides, like other organic chemicals, are acted upon by various chemical and biological processes in the soil environment (Cook 1996). Probably the most important process is the breakdown of organic chemicals by soil microorganisms (MacKay 1992). For decades, scientists have observed that soil microorganisms adapt to the presence of a pesticide and begin to metabolize it as an energy source (Fausey and others 1995). As it is metabolized, the pesticide is broken down to various intermediate compounds, and ultimately carbon dioxide. In addition, most pesticides have a high affinity for clay and organic matter, and may be removed from the soil water as they are bound to soil particles. Once bound, pesticides are often difficult to desorb (Clapp and others 1995).

Several studies have examined the effectiveness of grass filter strips in reducing pesticide levels in agricultural runoff. Scientists in southern Georgia found that grass filter strips successfully removed as much as 86 percent to 96 percent of the herbicide trifluralin from agricultural runoff (Rhode and others 1980). About half of the herbicide was adsorbed onto vegetation or organic matter, while soil infiltration accounted for one-third. However, studies on the effect of bromegrass filter strips on the herbicides atrazine, cyanzine, and metolachlor showed that the filter removed only 10 percent to 40 percent of the herbicide entering the filter strip (Hatfield and others 1995). Most of this reduction occurred in the upper 2 inches of the soil surface where high organic matter encouraged rapid infiltration and a high adsorption rate. Likewise, scientists in Iowa found that atrazine adsorption was greatest in soils with high organic matter. In their study, half of the atrazine became irreversibly bound to soil particles, while 10 percent to 15 percent of the atrazine was broken down by soil microorganisms (Moorman and others 1995).

Certain pesticides can be harmful to soil microorganisms. The use of the insecticide aldicarb has been shown to reduce the rate of denitrification in surface soils, presumably because it decreased populations of denitrifying bacteria (Meyer and others 1994).

Metals may be released into the aquatic environment through industrial processes, mining operations, urban runoff, transportation activities, and application of sewage sludge. Trace metals may also be introduced with agricultural pesticides and fertilizer. Metals pose a particular threat to aquatic environments because they do not degrade and tend to accumulate in the bottom sediments. Metals may also accumulate in plant and animal tissues. In Virginia, portions of the North Fork of the Holston River, the South River, and the South Fork of the Shenandoah River have been closed due to mercury contamination. Metals released from mining operations are the primary pollutants of streams in the western corner of the state.

The fate of metals in riparian areas is not well understood. However, scientists in Virginia have found significant amounts of lead, chromium, copper, nickel, zinc, cadmium, and tin buried in the sediments in the floodplain along the Chickahominy River downstream of Richmond (Hupp and others 1993). Analysis of the woody tissues of the trees reveal that these compounds are also taken up by the trees. Therefore, sediment deposition and uptake by woody vegetation may help mitigate heavy metals in riparian areas.

Factors Affecting the Water Quality Benefits of Riparian Buffers

As these studies indicate, riparian buffers can reduce the amount of sediment, nutrients, and other contaminants that enter surface waters. However, the studies also suggest that these effects vary from one riparian area to another. The degree to which the riparian buffer protects water quality is a function of the area's hydrology, soils, and vegetation.

Hydrology

Probably the most important factor affecting water quality at a particular site is hydrology (Schnabel and others 1994, Lowrance and others 1995). Riparian area hydrology is influenced by local geology, topography, soils, and characteristics of the surrounding watershed. Riparian forests will have the most influence on water quality where subsurface runoff follows direct, shallow flow paths from the uplands to the stream, causing most of the drainage to pass through the riparian area before exiting into the stream. Where deep groundwater flow paths cause drainage to bypass the riparian zone, riparian buffers are not as effective. Similarly, when surface runoff becomes concentrated and runs through the buffer in defined channels, the ability of the buffer to influence surface waters is limited. However, in areas where slope is minimal and surface water flows are slow and uniform, riparian areas can be highly effective in slowing the force of stormwaters and reducing the amount of sediment, crop debris, and other particulate materials that reach streams.

Soils

Soils in riparian areas are highly variable, a combination of local soils weathered in place, deposits of sediments from storm events, and the accumulation of organic debris (Lowrance and others 1985). For example, scientists in southern New England have observed that riparian soils vary considerably in a distance of as little as 30 feet (Gold and Groffman 1995). Soil features which influence water quality include the depth to the water table, soil permeability, soil texture, soil chemistry, and organic matter content (U.S. E.P.A. Chesapeake Bay Program Forestry Work Group 1993). These features affect the way and the rate at which water flows over and through the riparian area, the extent to which groundwater remains in contact with plant roots and with soil particles, and the degree to which soils become anaerobic. Riparian forests with organic soils have great potential to enhance water quality, by infiltrating a large amount of surface runoff, adsorbing nitrogen and other contaminants, and supplying carbon needed to fuel microbial processes. In fact, a recent study in the Midwest concluded that the major factor influencing the movement of nutrients and herbicides through the soil was its organic carbon content (U.S.D.A. A.R.S. 1995).

Many of the water quality functions of the riparian area are a result of the activity of soil microorganisms (Palone and Todd 1997). Soil microorganisms influence water quality in several ways. Like plants, microorganisms take up and convert nutrients to forms which are less biologically available and more readily stored in the soil. Soil microorganisms also utilize and metabolize organic chemicals (such as pesticides) as energy sources, and in the process, transform the chemicals to less toxic compounds. Finally, soil microorganisms are responsible for many chemical reduction reactions that occur in the soil, including denitrification and the reduction of sulphur, iron, and other compounds (Mitsch and Gosselink 1993).

Vegetation

Riparian vegetation influences water quality as it captures runoff, builds organic matter content, and provides protection from the elements. By creating roughness along the surface of the ground, the vegetation decreases water velocity and allows time for water to infiltrate the soil and for sediments to drop out (Lowrance and others 1986, Dillaha and others 1989, Daniels and Gilliam 1996). Sediments are also removed as they are deposited on plant tissues. Furthermore, riparian plants loosen the soil, allowing for increased infiltration of runoff. Riparian vegetation is also critical to maintaining high levels of organic carbon in the soil, necessary to fueling denitrification and other biochemical processes (Correll 1997). Likewise, riparian vegetation plays an important role in removing dissolved pollutants from soil water, as nutrients and other substances are taken up and incorporated into plant tissues (Brinson and others 1984, Peterjohn and Correll 1984, Hupp and others 1993). Plants also protect the surface of the soil from wind and water erosion, stabilize streambanks and modify temperature, light, and humidity within the riparian area and the stream itself.

Riparian Vegetation: Grass or Forest?

While there is much debate concerning whether riparian buffers should be revegetated with trees or grasses, research to date does not allow a definitive answer. A number of studies have been done on both types of buffers, but differences in study design and site characteristics do not allow for accurate comparisons between them. Furthermore, studies on grass buffers have largely been made on cool-season pasture grasses rather than native warm-season grasses (warm-season grasses may offer several advantages to cool-season grasses, because they are longer-lived, highly productive, and have extensive, deep root systems). However, these studies indicate some general trends:

- Both grass and forest buffers can reduce levels of nutrients and sediments from surface runoff, and reduce levels of nitrates from subsurface flows. Higher rates of denitrification are often observed in forested buffers, and researchers attribute this to the greater availability of organic carbon and interactions which occur between the forest vegetation and the soil environment (Lowrance and others 1995, Correll 1997). However, denitrification is also dependent on certain soil and hydrological conditions, which do not exist in all riparian areas.
- Grass buffers are more quickly established, and in terms of sediment removal, may offer greater stem density to decrease the velocity of water flow and provide greater surface area for sediments to be deposited. Forested buffers, though, offer the advantage that the woody debris and stems may offer greater resistance and are not as easily inundated, especially during heavy floods (U.S. E.P.A. Chesapeake Bay Program Forestry Work Group 1993). However, neither buffer will be effective where the volume and velocity of flood waters and the sediment loads which they carry are large.
- Neither buffer is particularly effective in reducing concentrations of dissolved phosphorus; however, where flow is shallow and uniform, control of sediment-associated particulate phosphorus can be quite effective.

Whether grass or forest, riparian buffers should be considered as part of a unified land management plan, including sediment and erosion control and nutrient management practices. They will be most effective where vegetation and organic litter are adequate; where subsurface flows of water pass through the plant root zone; and where the presence of moisture, carbon, oxygen, and populations of bacteria encourage denitrification and other biogeochemical processes.

Additional Considerations

Some researchers point out that where water quality is the primary management objective, other Best Management Practices may be equally, or more, effective than riparian forest buffers. For example, in Indiana, Pritchard and others (1993) predicted that buffering a small watershed entirely with forested buffers would remove 442 acres of land from production and reduce sediment loadings in the watershed from 1560 tons per year to 1141 tons per year (a reduction of 27 percent), at a cost of $91 per ton. However, removing 442 acres of the most erodible land from production in the watershed would reduce sedimentation by 31 percent (to 1074 tons per year) at a cost of $78 per ton. In Idaho, researchers predicted that protecting 100 percent of the riparian areas in forest would reduce erosion by 47 percent and other pollutants by 61 percent. However, using other conservation measures (a combination of minimum and/or reduced-tillage and cross and/or contour-slope farming) could reduce erosion by 77 percent and other pollutants by 80 percent, although at a higher cost to farmers (Prato and Shi 1990). It should be noted, though, that both studies were based on predicted (not actual) values and did not consider the value of the other important benefits that riparian forest buffers can provide.

It is also important to consider that the long-term effectiveness of the riparian forest buffer in assimilating and permanently storing sediments, nutrients, and other contaminants is not well understood (Brinson and others 1984). Denitrification offers the most permanent removal of nitrogen, as it is released into the atmosphere. In some areas, sediment deposition can serve as an important sink for sediments and sediment-attached nutrients, metals, pesticides, and other compounds. However, riparian areas have a limited storage capacity for these materials and sediments. Phosphorus and other materials may be eroded or solubilized into suspension again (Johnston and others 1984). Nutrients may also be taken up and incorporated into woody biomass. Several scientists have recommended periodic harvest of riparian vegetation to maintain nutrient uptake, although studies monitoring the impact of harvest on nutrient levels are generally lacking (Lowrance and others 1985).

Others question whether it is the presence of forested buffers or the presence of forest in general that contributes to improved water quality. For example, Omernick and others (1981) compared 80 watersheds with varying amounts of forested and agricultural land. They found that nutrient concentrations in streams could be predicted by the percent of land cover in forest or agriculture, but there was no significant

relationship between the proximity of the forest to the stream. Their study suggests that as the amount of forest cover decreased from more than 75 percent to less than 25 percent of the watershed, there was a corresponding increase in nitrogen and phosphorus concentrations in streams, regardless of whether the forest was located adjacent to or away from the stream itself.

Suitability of Riparian Forest Buffers for Water Quality in Virginia

The Commonwealth of Virginia crosses three primary physiographic regions: the Coastal Plain in the east, the Piedmont of central Virginia, and the mountains in the west. Variations in soils, topography, and hydrology in each of these regions influence the capacity of riparian forest buffers to influence water quality.

Coastal Plain

Virginia's Coastal Plain is an area consisting of deep deposits of sand, gravel, fossil shells, and clay. Streams within the Coastal Plain region are typically low-gradient, low velocity streams that in their natural condition are relatively clear, dark with humic acids, and low in pH, dissolved solids, dissolved oxygen, and nutrients (Figure 5) (Kuenzler 1988). Much of the Coastal Plain is underlain by a confining layer (aquitard) that restricts the movement of groundwater downward. When groundwater reaches the confining layer, it begins to move laterally, until it exits into a stream or other surface waters. Due to the shallow aquifer, water tables are high, and the floodplain is often inundated for months during the winter and spring. Of all the physiographic regions, streams in the Coastal Plain often benefit significantly from the presence of riparian forest buffers. The flat, gentle topography means that storm waters flow relatively slowly across the surface of the land, which allows time for sediments to be removed by riparian vegetation. More importantly, most water enters streams through shallow surface aquifers, moving through the root zone of the riparian buffer where nutrient removal is very high. However, even within the Coastal Plain, variability in soils, topography, groundwater flow patterns, and land uses can influence the movement of nonpoint source pollution to streams (Figure 6) (Staver and Brinsfield 1994, Speiran and others 1998). For example, in well-drained upland areas, the water table is much deeper and rainwater is more likely to bypass riparian vegetation and enter streams through the stream bottom. Here, there is little chance for nitrate removal from the root zone, although deep-rooted trees immediately adjacent to small streams may intercept deeper groundwater before it enters the stream. These trees may also provide an important source of carbon for denitrification in and around the stream channel. Other areas of the Coastal Plain where riparian buffers have less impact on water quality are tidally-influenced streams, where lands have been ditched to promote drainage of agricultural fields, and areas that are bordered by tall cliffs.

FIgure 5. Streams within the Coastal Plain are typically low-gradient, low-velocity streams .

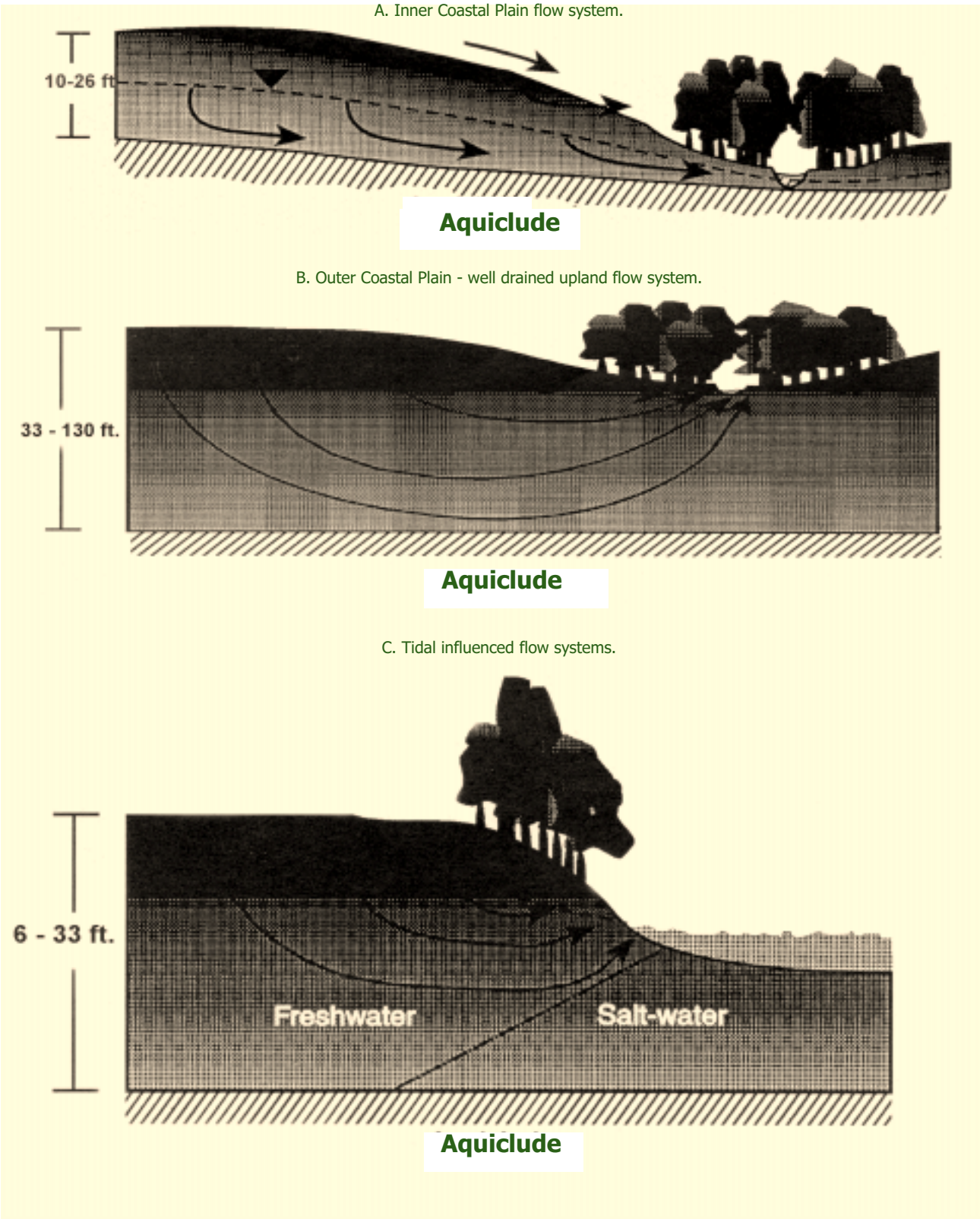
Piedmont

The Piedmont region in central Virginia is an area characterized by rolling hills and underlain by a complex of igneous and metamorphic rocks (Lowrance and others 1995). The geology and soils of the Piedmont region are quite variable. In much of the Virginia Piedmont, water flows to streams through shallow groundwater paths, providing ideal conditions for riparian buffers to remove contaminants from subsurface flows before they enter streams. In other areas of the Piedmont, deeper soils result in flow patterns which may cause drainage to bypass the forest buffer altogether and seep from the stream bottom (Figure 7). These areas offer little opportunity for the removal of nutrients or other contaminants from subsurface flows. However, areas with very gentle slopes offer a good opportunity for riparian buffers to remove sediment, sediment-bound nutrients, and contaminants from surface flows. Sediment control in areas with steeper slopes will depend to a large degree on how effectively the runoff is controlled and spread out before the water reaches the buffer. Where runoff is rapid and forms channels, water will flow quickly through the buffer, offering little time for infiltration.

Mountains

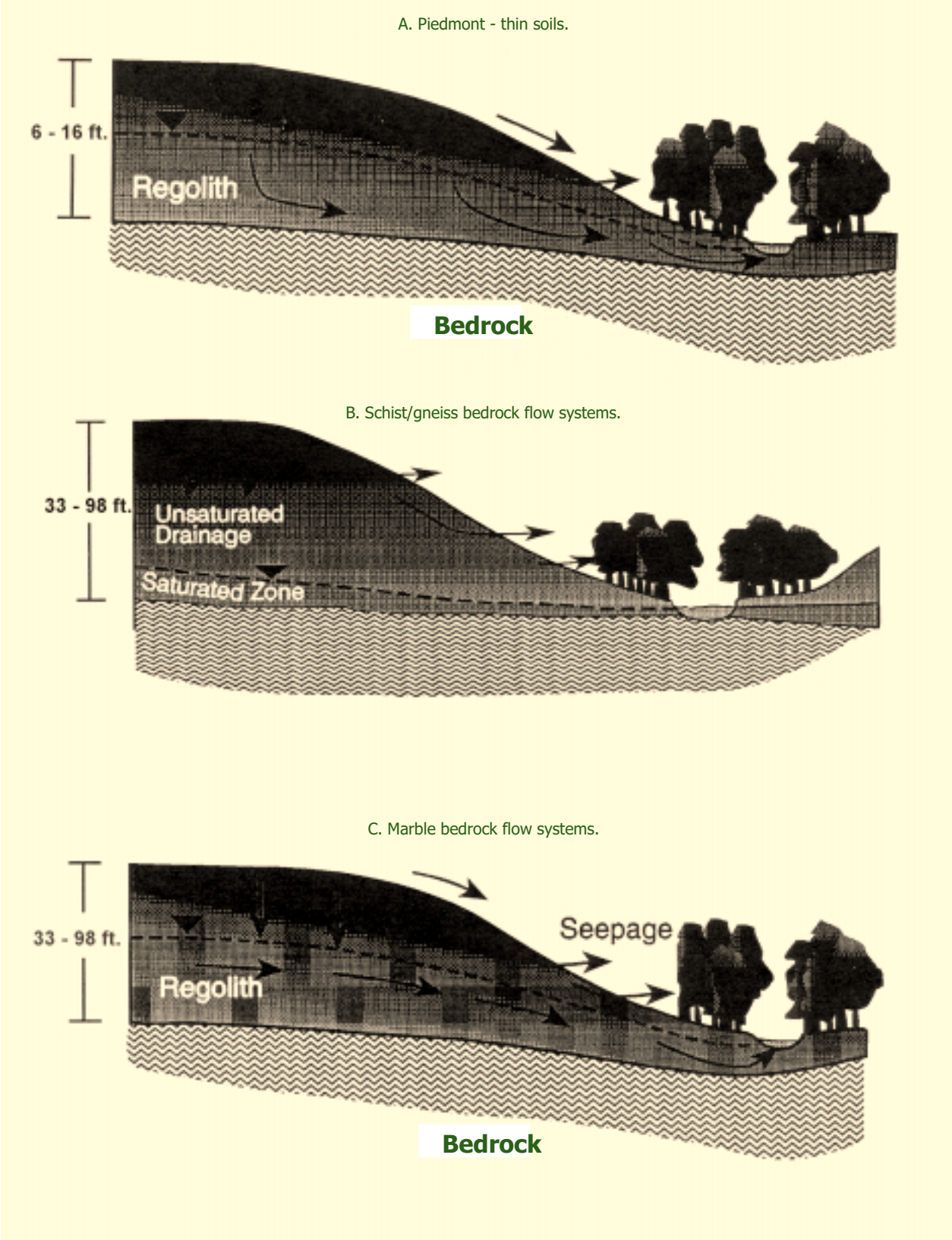
Western Virginia is dominated by mountains. The eastern-most band of mountains, the Blue Ridge, is underlain with hard granite, quartzites, and greenstone which originated as ancient lava flows. Just west of the

Fig. 6. Coastal Plain flow systems.*



*From Lowrance and others,1995. Used with permission.

Fig. 7. Piedmont flow systems.*



*From Lowrance and others, 1995. Used with permission.

Blue Ridge lie the Appalachian Mountains and the Cumberland Plateau, where erosion-resistant quartzites and sandstones lie along the ridges, with softer limestones and shales in the lower valleys (Virginia DEQ/DCR 1998).

In the mountains, small, steep stream channels drain the ridges, eventually joining large streams that flow through valley bottoms (Figure 8). Subsurface water movement in this area is complicated and not well understood. In areas underlain by limestone bedrock, water may flow quickly through cracks and cavernous openings to deep aquifers, then travel many miles underground before it is released into surface waters. Where bedrock is harder and resistant to weathering, groundwater is more likely to move toward the stream closer to the surface, providing a greater opportunity to come in contact with the root zone of vegetation (Figure 9). Therefore, the degree to which riparian buffers may protect streams from contamination in this region is highly variable (Lowrance and others 1995). Along valley floodplains and around seeps and springs where groundwater discharge occurs, forested buffers will have their greatest influence on stream water quality. In other areas, their effects may be minimal. However, streamside buffers continue to play a very important role in controlling stream temperatures and providing food and habitat to aquatic ecosystems throughout the mountain region.

Figure 8. In the mountains, small, steep stream channels drain the ridges, eventually joining large streams that flow through valley bottoms.

Impact of Human Activity in Riparian Areas

Intensive activities in riparian areas can lead to serious losses of stream habitat and water quality. Natural drainage is interrupted as riparian soils become compacted, sedimentation rates increase, solar radiation increases, and stream channels are altered. Examples of habitat alteration include the removal of streamside vegetation, removing woody debris and boulders from streams for navigation, stream channelization, damming, and dredging (Figure 10) (U.S. E.P.A. 1995). Streams can also be degraded by activities in the surrounding watershed.

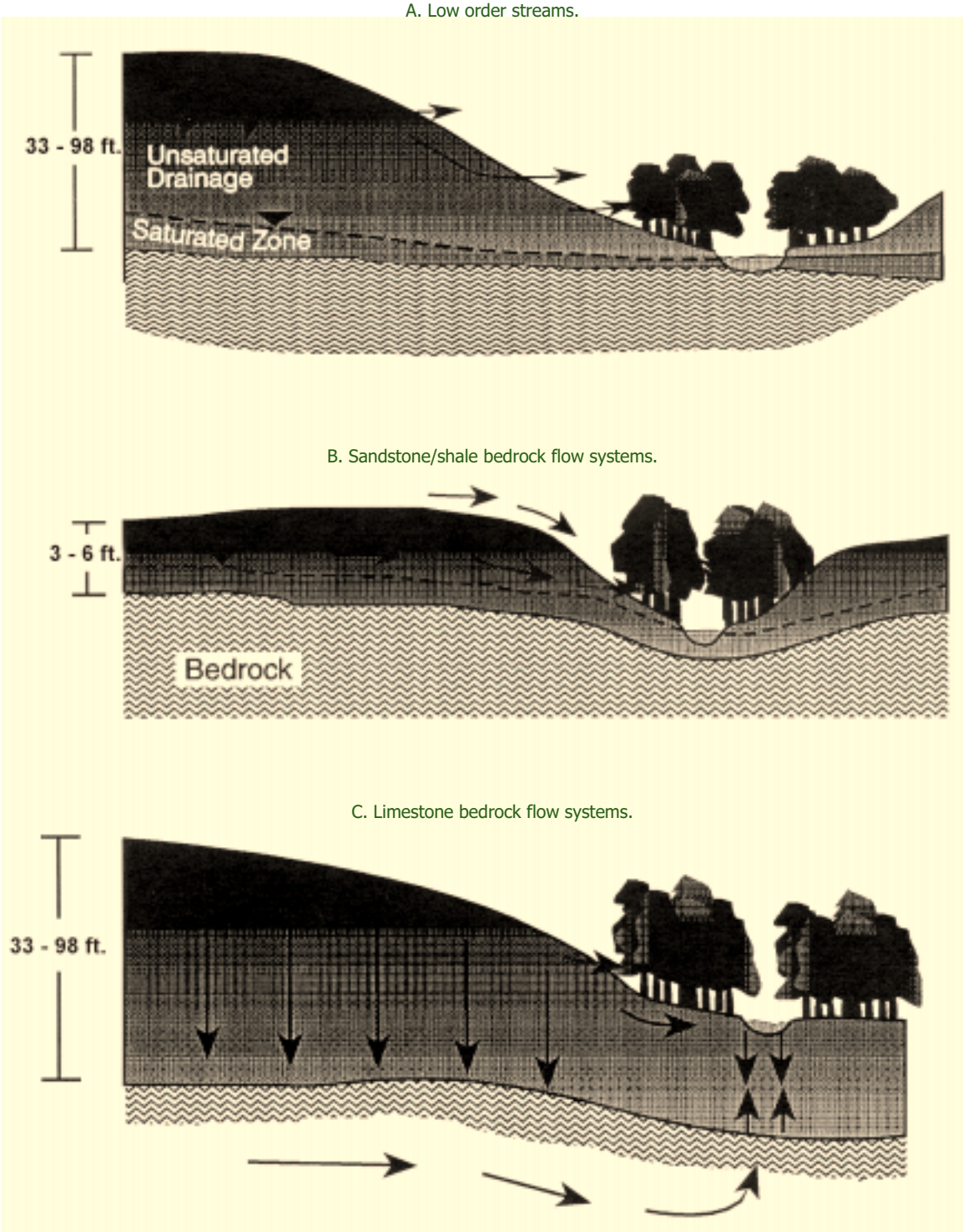
Fig. 10. The removal of streamside vegetation can degrade water quality and riparian habitats.

In agricultural areas, riparian areas are often converted to productive crop and grazing lands. Riparian areas are also cleared to increase drainage, reduce competition with crops for moisture and sunlight, remove sources of noxious weeds, allow easier operation of farm machinery, and remove habitat for wildlife that may damage crops (Osborne and Kovacic 1993). Livestock can be particularly damaging where they have unrestrained access to streams (Kauffman and Krueger 1984, Kasi and Botter 1994). Livestock erode the streambank as they climb in and out of the stream, causing the stream to become wider and shallower. Grazing the riparian area alters the riparian plant community, compacts and erodes riparian soils, and interferes with wildlife use of the area. Stream water quality is also impaired as stream temperatures increase (as the stream becomes more shallow and vegetation decreases) and manure is deposited or washed into streams, introducing organic matter, nutrients, and pathogenic organisms (Overcash and others 1983).

In urban areas, streams are often degraded as they are diverted through stormwater systems, riparian vegetation is removed, and the watershed becomes covered by roads, parking lots, and buildings (Figure 11). Changes in the vegetative cover in the watershed can cause changes in the amount and timing of water flows in stream channels (Chesters and Schierow 1985, Guldin 1989, Booth and Reinelt 1994). Where stormwater once soaked into the ground, it now must flow over hard surfaces, picking up sediments, petroleum products, chemicals, metals, and other pollutants and discharging them directly into storm drains and streams. Increases in the frequency and magnitude of flood events cause damage to streams and riparian plants and animals and cause stream channels to erode their banks and beds (Booth and Reinelt 1994). In-

Fig. 9. Ridge and Valley flow systems.*

A. Low order streams.



B. Sandstone/shale bedrock flow systems.

C. Limestone bedrock flow systems.

*From Lowrance and others, 1995. Used with permission.

creases in sediment entering the stream also result in changes in the stream, including a widening and shallowing of the streambed, a loss of aquatic habitat, and a decrease in the streambed "roughness" as pools become filled and the streambank is covered with fine soils (Booth and Reinelt 1994, Prestegaard 1986). Streams also tend to be warmer in urban areas, due to warmer inputs into the stream and the loss of streamside vegetation.

FIgure 11. Homes, roads, and sewer lines alter riparian habitat.

Summary and Recommendations

Riparian forests protect water quality by reducing the amount of sediment, nutrients, and other pollutants that enter streams, lakes, and other surface waters. This occurs as contaminants are buried in sediments, taken up by riparian vegetation, adsorbed onto clay and organic particles, or converted by soil microorganisms into less toxic forms.

Many factors affect the ability of the riparian forest to remove pollutants from runoff, including pollutant load, field slope, type and density of vegetation, soil structure, subsurface drainage patterns, and the frequency and force of storm events (Osborne and Kovacic 1993). Riparian forests will have the most influence on water quality where field runoff follows direct, shallow flow paths from the uplands to the stream. Riparian forests will have less impact on water quality where surface runoff is concentrated and runs through the buffer in defined channels, or where deep subsurface flows cause groundwater to move below the roots of trees.

The design of riparian forest buffers to improve water quality must take into account the area's hydrology, soils, pollutant loadings, and adjoining land uses. Riparian forest buffers should be recognized as only a part of a comprehensive land management plan. Where pollutant loads are high, slopes are steep, or erosion is severe, Best Management Practices must be installed upslope from the buffer in order for the riparian forest to be effective.

The riparian forest buffer design must address three different types of pollutants: sediment-adsorbed pollutants in surface runoff, dissolved pollutants in surface runoff, and dissolved pollutants in groundwater (Palone and Todd 1997).

Buffers of 50 to 100 feet are generally recommended to trap sediments, with the buffer expanding where there are high sediment loads or steep slopes (as a rule of thumb, the buffer should expand about 5 feet for every 1 percent increase in slope) (Palone and Todd 1997). On flat sandy soils where sediment loads are low, narrower buffers may be effective (Magette and others 1989). However, Wilson (1967) demonstrated that grass filter strips 300 to 400 feet wide would be required to successfully remove clay sediments.

The ability of the buffer to remove dissolved pollutants, such as nitrate, is highly variable and tied to the site's soils and hydrology. For example, when Phillips (1989) examined the buffering capacity of various riparian soils in North Carolina, he found that a buffer width of anywhere from 16 to 300 feet would be required to remove nitrates from the field drainage. Most frequently, widths of 35 to 125 feet are recommended to remove dissolved pollutants, depending on loads and site conditions (Palone and Todd 1997).

As a general guideline for restoring riparian buffers to meet water quality functions, David Welsch of the U.S. Forest Service Northeast Area recommends a width of 75 feet on both sides of the stream based on a "three-zone system" (Zone 1, adjacent to the field: 15 feet of grass; Zone 2: 60 feet of managed forest; and Zone 3, adjacent to the stream: 20 feet of forest with restricted harvest) (Welsch 1991). However, he suggests that the buffer should expand:

1) where frequent flooding occurs (soils of Hydrologic Groups C and D);
2) where certain soil types are present, for example very shallow or erodible soils (Soil Capability Class IIIe/s, IVe/s: increase the combined width of Zones 1 and 2 to 100 feet; Soil Capability Class VIe/s, VIIe/s and VIII: increase to 150 feet); and
3) on steep slopes (increase width to one-third of the distance from the stream to the top of the slope).

The U.S. Department of Agriculture Natural Resources Conservation Service recommends a minimum buffer width of at least 30 percent of the geomorphic floodplain, or at least 15 feet for Zone 1 and 20 feet for Zone 2 on all streams.

Dillaha and Hayes (1991) of Virginia Tech have recommended delineating "subwatersheds" (drainage areas) within the area to be protected and designing buffers to fit each.

Whether riparian buffers should be revegetated with trees or grasses is a question of ongoing discussion. Both grass and forest buffers can reduce levels of nutrients and sediments from surface runoff, and reduce levels of nitrates from subsurface flows. Grass buffers are more quickly established, and in terms of sediment removal, may offer greater stem density to decrease the velocity of water flow and provide greater surface area for sediments to be deposited. Forested buffers, though, offer the advantage that the woody debris and stems may offer greater resistance and are not as easily inundated, especially during heavy floods (U.S. E.P.A. Chesapeake Bay Program Forestry Work Group 1993). Higher rates of denitrification are often observed in forested buffers, presumably due to the greater availability of organic carbon and interactions which occur between the forest vegetation and the soil environment (Lowrance and others 1995, Correll 1997).

Whether grass or forest, riparian buffers should be considered as part of a unified land management plan, including sediment and erosion control and nutrient management practices. They will be most effective where vegetation and organic litter are adequate; where subsurface flows of water pass through the plant root zone; and where the presence of moisture, carbon, oxygen, and populations of bacteria encourage denitrification and other biogeochemical processes.

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List of Common and Scientific Names

Bromegrass	*Bromus spp.*
Corn	*Zea mays*
KY-31 tall fescue	*Festuca arundinacea*
Oats	*Avena sativa*
Orchard grass	*Dactylis glomerata*
Perennial ryegrass	*Lolium perenne*
Poplar	*Populus spp.*
Reed canarygrass	*Phalaris arundinacea*
Sorghum	*Sorghum spp.*
Sudangrass	*Sorghum sudanense*

Riparian forests are forests which occur adjacent to streams, lakes, and other surface waters. Through the interaction of their soils, hydrology, and biotic communities, riparian forests protect and improve water quality, provide habitat for plants and animals, support aquatic communities, and provide many benefits to humans. Virginia, along with other states in the Chesapeake Bay region, has recognized the importance of riparian forests by implementing a plan to restore forested buffers along streams, rivers, and lakes. This series of publications by Virginia Cooperative Extension reviews selected literature on riparian forest buffers, including water quality functions, benefits to fish and wildlife, and human benefits. The review also discusses riparian buffer restoration and some of the costs and barriers associated with riparian forest buffer establishment. Information on financial and technical assistance programs available to Virginia landowners is included.

Other Publications in this series:

Understanding the Science Behind Riparian Forest Buffers: an Overview (VCE Pub# 420-150)

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Understanding the Science Behind Riparian Forest Buffers: Resources for Virginia Landowners

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