EPA
United States
Environmental Protection
Agency

Issue Paper

Advances in Restoration Science

Number 1: Research Needs in Riparian Buffer Restoration

Eric E. Jorgensen, Timothy J. Canfield and Paul M. Mayer

Riparian buffer restorations are used as management tools to produce favorable water quality impacts; moreover, the basis for riparian buffers as an instrument of water quality restoration rests on a relatively firm foundation. However, the extent to which buffers can restore riparian ecosystems, their functionality and species composition, are essentially unknown. In light of the foregoing, two broad areas of research are indicated. First, data are needed to document the relative effectiveness of riparian buffers that differ according to width, length, and plant species composition. These questions, of managing buffer dimension and species composition for functionality, are of central importance even when attenuation of nutrient and sediment loads alone are considered. Second, where ecosystem restoration is the goal, effects to in-stream and terrestrial riparian biota need to be considered. Relatedly, the effects of the restoration on the landscape need to be considered. Particularly, at what rate do the effects of the riparian buffer on in-stream water quality, biota, and habitat diminish downstream from restored sites? Answers to these important questions are needed to further the advance of riparian restoration from art form to science and to maximize the societal value of future restorations.

For further information contact Eric Jorgensen (580) 436-8545, or Timothy Canfield (580) 436-8535, or Paul Mayer (580) 436-8647 at the Subsurface Protection and Remediation Division of the National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Ada, Oklahoma.

Riparian Restoration through Buffer Management

Aquatic ecosystems have been altered through the combined effects of municipal, industrial, and agricultural activities (National Research Council, 1992). Municipalities spend large amounts of money to remedy non-point pollution problems in their drinking water (Schultz et al., 1995). Nonpoint pollution is the major remaining cause of surface water pollution (U.S. EPA, 1989; Baker, 1992). Sedimentation and excess nutrients are the two leading nonpoint pollution problems in rivers and estuaries (Baker, 1992). Nitrogen and phosphorus contribute to eutrophication of surface waters and nitrogen is frequently limiting in estuaries (Smith et al., 1987), thereby altering biotic interactions and competitive regimes. Estuaries are the ultimate sinks for most riverine discharge in the eastern United States.

Buffer strips, areas of planted or preserved vegetation between developed land and surface water, are effective at reducing sediment and nutrient loads (Lowrance et al., 1985; Groffman et al., 1990; Castelle et al., 1994; see also reviews in Castelle et al., 1992). Buffer strips reduce the severity of impacts to riparian areas caused by storm events (Bertulli, 1981) that can incise channels and adversely affect riparian ecosystem function (Henshaw and Booth, 2000). A relatively sound scientific foundation exists to support the use of riparian buffer strips to manage nutrients and sediment and to support an expectation of their success as an ecosystem management tool. (Bren, 1993; National Association of Conservation Districts, 1994; NRC, 1992; USDA, 1996). Further, it is also believed that even greater benefits will be realized through incorporation of wetlands as components of buffers (Zak and Grigal, 1991; Niswander and Mitsch, 1995); that is, while either buffers or wetlands alone are expected to provide benefit, integration of these together will likely provide unexpectedly high rates of success (Lowrance et al., 1995).

The role of denitrification, a microbially meditated process, in processing nutrient inputs to riparian zones is an area of primary importance (Jones and Holmes, 1996; Boulton et al., 1998). Denitrification requires anaerobic conditions and is strongly influenced by ground-water dynamics (Burt et al.,1999; Devito et al., 2000), typically occurring in hyporheic zones (Dahm et al., 1998; Baker et al., 1999) where stream geomorphology interacts with ground water and affects sediment deposition, nutrient flux, and stream temperature (Naiman, 1988; Naiman et al., 1994; Fennessy and Cronk, 1997). Interaction of these factors can produce high quality habitat for biota including fish (Boulton et al., 1998).

ADVANCES in RESTORATION SCIENCE

In the eastern United States, agriculture, forestry, and other economic developments are frequently conducted in areas that closely border rivers, streams, and reservoirs. Restoration of these border areas, in the form of buffer strips, should have a measurable impact on water quality (Rodgers and Dunn, 1992). This may be especially true in lower order streams where nutrient processing can be especially efficient (Alexander et al., 2000; Peterson et al., 2001). Nonetheless, substantial questions remain: how do buffers function in various landscapes and precisely which ecosystem services can buffer strips restore (Osborne and Kovacic, 1993; Schultz et al., 1995)?

Design criteria have been identified as an area of information deficiency (van der Valk and Jolly, 1992). In the ecosystem context, design criteria refer not only to functional relationships sufficient to produce a desired water quality result, but also refer to functional relationships relative to wildlife, biodiversity, sustainability, and aesthetics. Although riparian buffer areas have been proposed and are being evaluated as a nutrient management method nationwide, the exact design requirements of these riparian areas (including size of buffer zone, species composition, interaction between surface and ground water, stream flow regulation, provision of in-stream habitat, function for terrestrial wildlife, sediment transport reduction, and maintenance of biotic integrity) are incompletely understood and must be evaluated along with nutrient management.

Research Environment

We will now describe the scope and content of research projects that are needed to help elucidate, define, and quantify the function of riparian buffers as instruments for riparian restoration. Frequently, function and design criteria for reducing nutrient inputs are of central interest to buffer designers. Therefore, function and design criteria for riparian buffers for reducing nutrient inputs are of central interest. However, ecosystem and/or watershed restoration are by definition concerned with more than water quality. The ecological functions and landscape characteristics of riparian buffers as expressed by soil, flora, and fauna are also of primary interest and do interact with nutrients to a large degree.

The efficacy of riparian buffers as tools of ecosystem restoration can be established by measuring and comparing effects among three types of riparian buffers: TYPE 1 areas are stream reaches that have received plantings and undergo associated management with the purpose of restoring the riparian buffer; TYPE 2 areas are stream reaches that are initially similar to those in TYPE 1 but that do not receive plantings or undergo associated management to restore the riparian buffer; and, TYPE 3 areas are stream reaches that are effectively undisturbed or mature, and that represent stream reaches that TYPE 1 areas are supposed to resemble 30+ years after initiation of the restoration. Comparing these three basic types of stream reach will allow researchers to quantify restoration endpoints (TYPE 3 areas), and measure success (TYPE 2 areas contrasted with TYPE 1 and TYPE 3 areas). These measures of endpoints and success are critical components of restoration and are frequently the subject of administration, management, landowner, and researcher initiated questions for which there is too often little or no data. This is a void that research can fill.

Research Questions

There are five general questions driving riparian buffer research:

1) *What are the characteristics of existing riparian buffer zones and surrounding landscape areas?*
2) *How do riparian areas function?*
3) *Where should riparian buffers be placed on the landscape?*
4) *What aspects of riparian ecosystems can be restored with riparian buffers?*
5) *How effective is the restoration?*

These general questions guide development of focused research needs. In the enumeration of tasks that follows, it will be apparent that some tasks are closely related and may be accomplished together. The tasks are not meant to describe discrete research efforts; rather, they are meant to describe discrete data needs that, although in some cases are related, stand on their own as being important areas where information relative to determining the ecological function of riparian buffers is needed, including restoration of water quality, in-stream and terrestrial riparian habitat for flora and fauna, and landscape function relative to adjacent land use, upstream activities, and downstream benefits.

Water Quality Effects

Task 1: *In-Stream Water Quality as a Function of Riparian Buffer Condition.*

Where water quality, especially regarding reduction of nutrients and suspended sediments, is an important motivation for developing restored riparian buffers, data concerning the ability of restorations to provide these services, compared to unrestored and mature communities, are needed.

Task 2: *In-Stream Water Quality as a Function of Riparian Buffer Width.*

The width of riparian buffer can affect water quality at the stream. It is unclear whether these improvements to water quality accumulate linearly with increasing buffer width, or whether the rate of improvement declines with increasing buffer width.

Task 3: *In-Stream Water Quality as a Function of Riparian Buffer Length.*

It is reasonable to expect that the length (of stream reach) of restored riparian buffer will affect water quality to at least the extent of buffer width. The effect of buffer length needs to be quantified.

Task 4: *In-Stream Water Quality as a Function of Riparian Buffer Plant Community Composition.*

It is hypothesized that the composition of the plant communities that make up restored riparian buffers will have an impact on the resulting in-stream water quality (i.e., nutrients and sediment). The effects of plant community composition and interactions with buffer condition, width, and length need to be determined.

Task 5: *Measure the Relative Contributions of First, Second, and Third Order Streams to Watershed Loads of Nutrients and Sediment.*

Although there is substantial speculation, the relative contributions of first, second, and third order streams to watershed loads of nutrients and sediment need to be more clearly quantified. This information can be used to target restoration activities to locations where the greatest amounts of nutrients and sediment are entering the system.

Task 6: *Measure the Relative Contributions of Mixed Riparian and Wetland Complexes to Watershed Loads of Nutrients and Sediment.*

There is substantial reason to expect that wetland restorations, integrated and designed as part of riparian restoration, can enhance the ability of these riparian areas to remove and reduce nutrients and sediment from non-point source runoff. It is thought that the dynamic nature of the wetland system, coupled with the long-term stability of the riparian area, will have a synergistic effect and function better than either type system (riparian or wetland) alone. The effect of integrating wetland and riparian restoration needs to be better understood and evaluated.

In-Stream Flora and Fauna Effects

Task 1: *In-Stream Flora Response to Riparian Buffer Restoration.*

Ultimately, a primary reason for restoring riparian buffers is restoration of riverine flora. The re-establishment and growth of native aquatic plants is an important water quality and habitat result that is expected to follow riparian buffer restoration. The effects of restoration condition and buffer width and length on the ability of riverine vegetation to re-establish and prosper needs to be documented.

Task 2: *In-Stream Fauna Response to Riparian Buffer Restoration.*

Ultimately, a primary reason for restoring riparian buffers is restoration of riverine fauna. The re-establishment of native aquatic fauna is an important water quality and habitat output that is expected to follow riparian buffer restoration. The effects of restoration condition and buffer width and length on the ability of riverine fauna to re-establish and prosper needs to be documented.

Task 3: *Document the Characteristics of Plant and Animal Communities Associated with In-Stream Riparian Habitat.*

Determine population and community characteristics and habitat associations of extant in-stream flora and fauna. What changes could be expected if buffer restorations are implemented?

Terrestrial Riparian Flora and Fauna Effects

Task 1: *Riparian Buffer Terrestrial Flora Response to Riparian Buffer Restoration.*

An important reason for restoring riparian buffers is restoration of associated terrestrial riparian-habitat dependent flora. The re-establishment and growth of native terrestrial plants is an important restoration and conservation result that is expected to follow riparian buffer restoration. The effects of restoration condition and buffer width and length on the ability of terrestrial vegetation to re-establish and prosper needs to be documented.

Task 2: *Riparian Buffer Terrestrial Fauna Response to Riparian Buffer Restoration.*

An important reason for restoring riparian buffers is restoration of associated terrestrial riparian-habitat dependent fauna. The re-establishment of native terrestrial fauna is an important restoration and conservation result that is expected to follow riparian buffer restoration. The effects of restoration condition and buffer width and length on the ability of terrestrial fauna to re-establish and prosper needs to be documented.

Task 3: *Riparian Buffer Terrestrial Microbe Response to Riparian Buffer Restoration.*

Microbial communities play a substantial role in the nitrogen cycle and are especially important relative to the production and retention of nitrate. The role of microbial denitrifying activity relative to buffer condition and buffer width needs to be documented. It is not expected that buffer length will affect microbial denitrifying activity to any great extent.

Task 4: *Document the Characteristics of Plant and Animal Communities Associated with Terrestrial Riparian Habitat.*

Determine population and community characteristics and habitat associations of extant terrestrial - riparian habitat dependent - flora and fauna. How do these conditions differ from the desired state and what changes are expected if buffers are restored?

Task 5: *Measure the Benefits to Terrestrial Diversity from the Placement of Riparian Buffers, and Document Interactions between Such Diversity and Buffer Function, Sustainability, and Succession.*

Buffer placement on the landscape can be expected to play a substantial role in determining its final functionality. This is especially true regarding effects on diversity, where the size and shape of the restored buffers will interact with proximity to other restorations and undisturbed native sites to determine the ultimate benefit. The interaction of these various conditions relative to use of riparian buffers as tools to conserve biodiversity needs to be documented.

Task 6: *Determine the Extent to Which Riparian Buffers Function as Habitat for Terrestrial Species and the Extent to Which They Function as Corridors and Refugia.*

Riparian buffers have the capacity to act as dispersal corridors, refugia, or habitat for many terrestrial fauna. These tendencies need to be documented and management prescriptions regarding buffer size and placement need to be formulated to assure that restored riparian buffers function as intended.

Landscape Scale Considerations

Task 1: *Mapping of Stream Reaches and Watersheds that are Highly Suitable for Riparian Buffer Restoration Based Upon Proximity of Denitrifying Subsurface Strata.*

Research indicates that an important factor that limits nitrate concentration in surface waters is the proximity of denitrifying strata to the surface. In areas where this denitrifying stratum is below the root zone of plants, little water quality impact relative to reduction of nitrate concentration in surface waters can be expected. It is necessary to map the extent of these denitrifying strata and determine the miles of stream reach where water quality restoration relative to nitrate loading is so limited.

Task 2: *Determine Whether Relationships Exist Between Watershed Size and Proportionate Land Use and the Design Requirements of Riparian Buffer Restorations.*

The type and extent of land uses that are found within individual watersheds may play an important role in determining the types and extents of buffer restorations that are appropriate. In some cases, large extensive restorations may be necessary to provide desired improvements to water quality and habitat; in other watersheds, several small restorations may provide equivalent improvements. The ecological, social, and economic characteristics of individual watersheds that may affect the types and extent of necessary restorations need to be documented.

Task 3: *Determine the Landscape Conditions and Spatial Extent Over Which Substantive Ecosystem Benefits Cannot be Expected to be Achieved with Restored Riparian Buffers Alone.*

Riparian buffers cannot address all resource management questions. The subset of questions that buffers can be used to impact needs to be distinguished from the subset that they cannot. Particularly, spatial and temporal scale concerns need to be addressed relative to this question.

Task 4: *Measure the Distribution of Riparian Buffer Widths Associated with Each Stream Order and Document Their Distribution.*

Determine the extant coverage and frequency distributions of buffer widths by stream order. Assess how these values compare among watersheds, particularly contrasting watersheds with good versus poor water quality.

Task 5: *Measure the Effects of Improvements Attributable to Riparian Buffer Restoration in Parts of the Watershed not Directly Restored. Particularly, to What Extent are Downstream Areas Cumulatively Impacted?*

Determine the extent to which the water quality and in-stream biota of areas downstream of riparian buffer restorations can be positively affected. In particular, is it realistic to expect water quality and habitat to improve in estuaries because of riparian buffer restorations?

Task 6: *Measure and Document Interactions Among Upstream Land Use and Downstream Aquatic and Terrestrial Effects.*

To an extent, restoration of riparian buffers can only be expected to produce a limited suite of outputs. The effects of upstream activities also play a large role in determining the final function of the buffers on the landscape. The extent to which upstream activities limit the range of outcomes that can be seen downstream needs to be documented.

Monitoring and Indicators

Task 1: *Determine Which Variables to Monitor to Assess Restoration Success Over Short, Intermediate, and Long Time Periods.*

Identify indicators that can be used to assess short, intermediate, and long-term performance and function of restored riparian buffers. Identify the variability of the indicators – determine the conditions under which they can be appropriately used – and assess error rate.

Task 2: *Identify Biotic and Abiotic Indicators, and Sampling Schedules for Such Indicators, that will Help Determine Restoration Effectiveness and Measure Senescence - Such that the Need to Renovate or Otherwise Maintain Restored Riparian Buffers can be Determined.*

Identify indicators and concurrent monitoring schedules that can track restoration senescence and predict the need to conduct renovation – including expected renovation benefits and costs.

Physical Sciences

Task 1: *Measure the Extent to Which Restored Riparian Buffers Influence Hydrology.*

Riparian buffers are hydrologically connected to streams and stream processes. Thus, to what extent are water quality and habitat limited by the characteristics of hydrology that may be amenable to engineered manipulations? For example, denitrification, a microbially mediated process in which nitrate nitrogen is converted to gaseous nitrogen, is strongly influenced by ground-water dynamics in riparian zones. When the water table is close to the soil surface, nitrate in the ground water interacts with carbon-rich soils in an anaerobic environment creating high potential for denitrification. Natural or anthropogenic factors that lower water tables greatly reduce riparian denitrification potential and other biogeochemical processes.

Task 2: *Measure the Extent to Which Riparian Buffers Influence Flood Plain Processes.*

Riparian zones represent a distinct component of stream flood plains. Riparian zones and associated buffers may influence annual overbank flows and/or in-stream flow dynamics, consequently affecting biogeochemical processes. For example, beavers (Castor canadensis) are natural engineers that manipulate stream flow dynamics through construction of impoundments. Such impoundments may have watershed-wide influences on sediment deposition, nutrient flux, and stream temperature.

Task 3: *Measure the Extent to Which Riparian Buffers Influence Hyporheic Zone Processes.*

Riparian buffers may influence the way in which ground water and surface water interact in stream ecosystems. Such hyporheic zones are regions of high microbial activity that greatly influence rates and fluxes of nutrients and oxygen through assimilation and respiration. Consequently, hyporheic zones represent productive, high quality habitats for both invertebrates and vertebrates including fish.

Task 4: *Document Differences in Restoration Potential for Riparian Zones in Urbanized Areas versus Streams in Less Affected Ecosystems.*

In urban areas, high volume diversions of storm water runoff into stream channels cause stream incision that disconnects floodplains from ground water processes. Similarly, infiltration of runoff is reduced under zones of pavement or other impervious surfaces, thereby reducing riparian water tables in urban watersheds. The extent to which effects attributable to these and related alterations limit stream restoration potential needs to be well understood.

Socio-Economic Perspectives

Task 1: *Measure Economic Impacts of Riparian Buffer Restorations, Especially Relative to Reduced Crop Yields Attributable to Buffer Shading and Competition, But Also Accounting for Economic Gains Attributable to Improved Nutrient Management.*

Where the establishment of restored riparian buffers depends to a large extent on the cooperation of private landowners, especially agriculturists, the economic impacts of buffer placement relative to crop shading and potential competition need to be documented in concert with potential economic benefits that may accrue due to improved efficiency in use of fertilizer and to improved fin- and shell-fish fisheries.

Integrated Research

Task 1: *Determine Whether Riparian Buffer Function Varies Quantitatively or Qualitatively in Relationship to Varying Types of Adjacent Land Use. This Includes the Functions of Nutrient and Sediment Attenuation and Provision of In-Stream and Terrestrial Riparian Habitat for Plants and Animals.*

The questions of whether and how adjacent land use affects riparian buffer function – for water quality improvement and for provision of plant and animal habitat - need to be investigated. For instance, do buffers adjacent to industrial, residential, and farming operations provide the same quality and quantity of benefit, or does the adjacent land use limit the effectiveness of the buffer in some regard?

Task 2: *Measure Differences in Riparian Buffer Function, Especially Relative to Nutrient and Sediment Attenuation – but also Including Provision of In-Stream and Terrestrial Riparian Plant and Animal Habitat - Among First, Second, and Third Order Streams.*

Just as adjacent land use can be expected to have an influence on buffer, stream order may also have an effect. Wherein a buffer in a first order stream may intercept 70% of the water that enters the stream and may therefore have a large effect on water quality and habitat – so may a buffer in a third order stream only intercept 10% of the water entering the stream, and thereby have a small effect on water quality and habitat.

Task 3: *Measure the Rate at Which Benefits Attributed to Restored Riparian Buffers are Attenuated Downstream, Especially Relative to Nutrients and Sediment.*

Realistically, riparian buffer restorations can only be conducted along a relatively modest number of stream reaches. It is thought that these will be mostly first, second, and third order streams. The ability of supposed water quality improvements occurring within these stream reaches to propagate downstream and be maintained is unknown.

Task 4: *Determine Types of Engineering Controls that can be Used to Complement Restored Riparian Buffers to Provide or Enhance Benefits Relative to Nutrient and Sediment Attenuation, and Provision of In-Stream and Terrestrial Riparian Plant and Animal Habitat.*

Under what conditions can engineering controls be used to complement riparian buffer restorations? Which engineered solutions have the greatest promise of working? What are the complementary benefits to terrestrial and aquatic riparian ecosystems that are expected from engineered solutions?

Task 5: *Measure the Effects of Above-Ground Biomass, Plant Communities, and Animal Communities on Surface Water Runoff and Surface Water/Ground Water Interactions, Especially Relative to Nutrient and Sediment Transport.*

Animal communities affect plant communities and plant communities affect subsurface chemistry, and ultimately interact with the chemical characteristics (particularly regarding nutrients) of in-stream water and in-stream habitat. Therefore, interactions between terrestrial riparian flora and fauna and the chemical characteristics of riparian ecosystems need to be understood to help design buffers that will remove or otherwise retain nutrients and sediment.

Conclusion

This issue paper identifies subject areas where there are critical data gaps concerning the function of riparian buffers as ecosystem and watershed restoration tools. We acknowledge that whereas there is a reasonable foundation of data to support an expectation that restored riparian buffers can provide some water improvement relative to reduced loads of nutrients, there are insufficient data concerning other benefits to aquatic and terrestrial riparian biota and habitat to allow the generalization that restored riparian buffers can function as tools for ecosystem restoration. Therefore, we identify research that focuses on water quality measured at the stream while concurrently measuring other biotic and abiotic responses.

Restoration of the Nation's waters will require manipulation of upstream watersheds, including buffer management. The relative contributions of activities in these watersheds and the ability to manage the effects of these activities with riparian buffers are important questions that bear upon research needs described in this paper. Care must be taken to ensure that the contributions of all watersheds are considered and statistically represented in any proposed management solutions that rely upon buffers. The effects of small headwater, first, and second order watersheds relative to the larger ones need to be clearly understood.

Notice

The U.S. Environmental Protection Agency through its Office of Research and Development funded and managed the preparation of this Issue Paper. It has been subjected to the Agency's peer and administrative review and has been approved for publication as an EPA document. The authors acknowledge help provided by Frederick W. Kutz on an earlier draft of the paper.

Literature Cited

Alexander, R.B., R.A. Smith, and G.E. Schwarz. 2000. Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico. Nature 403:758-761.

Baker, L.A. 1992. *Introduction to nonpoint source pollution in the United States and prospects for wetland use*. Ecological Engineering 1:1-26.

Baker, M. A., C.N. Dahm, and H.M. Valett. 1999. Acetate retention and metabolism in the hyporheic zone of a mountain stream. Limnology and Oceanography 44:1530-1539.

Bertulli, J.A. 1981. Influence of a forested wetland on a southern Ontario watershed. *In* A. Champagne, ed. *Proceedings of the Ontario wetlands conference. Federation of Ontario Naturalists and Dept. of Applied Geography*, Ryerson Polytechnical Inst., Toronto, Ontario. 193 pp.

Boulton, A.J., S. Findlay, P. Marmonier, E.H. Stanley, and H.M. Valett. 1998. The functional significance of the hyporheic zone in streams and rivers. Annual Review of Ecology and Systematics 29:59-81.

Bren, L. L. 1993. *Riparian zone, stream, and floodplain issues: a review*. J. Hydrol. 150: 277–299.

Burt, T.P., L.S. Matchett, K.W.T. Goulding, C.P. Webster, and N.E. Haycock. 1999. Denitrification in riparian zones: the role of floodplain hydrology. Hydrological Processes 13:1451-1463.

Castelle, A.J., C. Conolly, M. Emers, E.D. Metz, S. Meyer, M. Witter, S. Mauermann, T. Erickson, and S.S. Cooke. 1992. *Wetland buffers: use and effectiveness*. Publication 92-10. Adolfson Assoc., for Shorelands and Coastal Zone Management Program, Washington Dept. of Ecology, Olympia, WA.

Castelle, A.J., A.W. Johnson, and C. Conolly. 1994. *Wetland and stream buffer size requirements; a review*. Journal of Environmental Quality 23:878-882.

Dahm, C.N., N.B. Grimm, P. Mormonier, H.M. Valett, P. Vervier. 1998. Nutrient dynamics at the interface between surface waters and groundwaters. Freshwater Biology 40:427-451.

Devito, K.J., D. Fitzgerald, A.R. Hill, and R. Aravena. 2000. Nitrate dynamics in relation to lithology and hydrologic flow path in a river riparian zone. Journal of Environmental Quality 29:1075-1084.

Fennessy, M.S. and J.K. Cronk. 1997. The effectiveness and restoration potential of riparian ecotones for the management of nonpoint source pollution, particularly nitrate. Critical Reviews in Environmental Science and Technology 27:285-317.

Groffman, P.M., A.J. Gold, T.P. Husband, R.C. Simmons, and W.R. Eddleman. 1990. *Final report; Narrangansett Bay project; an investigation into multiple uses of vegetated buffer strips*. University of Rhode Island, Kingston.

Henshaw, P.C. and D.B. Booth. 2000. Re-equilibration of stream channels in urban watersheds. Journal of the American Water Resources Association 36:1219-1236.

Jones, J.B. Jr. and R.M. Holmes. 1996. Surface-subsurface interactions in stream ecosystems. Trends in Ecology and Evolution 11:239-241.

Lowrance, R., R. Leonard, and J. Sheridan. 1985. *Managing riparian ecosystems to control nonpoint pollution*. Journal of Soil and Water Conservation 40:87-91.

Lowrance, R., G. Vellidis, and R. K. Hubbard. 1995. Denitrification in a restored riparian forest wetland. Journal of Environmental Quality 24:808-815.

Naiman, R.J. 1988. Animal influences on ecosystem dynamics. BioScience 38:750-752.

Naiman, R.J., G. Pinay, C.S. Johnston, and J. Pastor. 1994. Beaver influences on the long-term biogeochemical characteristics of boreal forest drainage networks. Ecology 75:905-921.

National Association of Conservation Districts. 1994. *Riparian ecosystems in the humid U.S: functions, values and management*. Washington, D.C.

National Research Council (NsRC). 1992. *Restoration of aquatic ecosystems*. National Academy Press, Washington, D.C. 552 pp.

Niswander, S.F. and W.J. Mitsch. 1995. Functional analysis of a two-year-old created in stream wetland: hydrology, phosphorus retention, and vegetation survival and growth. Wetlands 15:212-225.

Osborne, L.L. and D.A. Kovacic. 1993. *Riparian vegetated buffer strips in water-quality restoration and stream management*. Freshwater Biology 29:243-258.

Peterson, B.J., W.M. Wollheim, P.J. Mulholland, J.R. Webster, J.L. Meyer, J.L. Tank, E. Marti, W.B. Bowen, H.M. Valett, A.E. Hershey, W.H. McDowell, W.K. Dodds, S.K. Hamilton, S. Gregory, and D.D. Morrall. 2001. Control of nitrogen export from watersheds by headwater streams. Science 292:86-90.

Rodgers, Jr., J.H. and A. Dunn. 1992. *Developing design guidelines for constructed wetlands to remove pesticides from agricultural runoff*. Ecological Engineering 1:83-95.

Schultz, R.C., J.P. Colletti, T.M. Isenhart, W.W. Simpkins, C.W. Mize, and M.L. Thompson. 1995. *Design and placement of a multi-species riparian buffer strip system*. Agroforestry Systems 29:201-226.

Smith, R.A., R.B. Alexander, and M.G. Wolman. 1987. *Water-quality trends in the nation's rivers*. Science 235:1607-1615.

USDA. 1996. *Engineering field handbook*. Chapter 16; streambank and shoreline protection. NRCS.

U.S. EPA. 1989. *Nonpoint sources: agenda for the future*. WH-556. U.S. EPA, Office of Water, Washington, D.C., 31 pp.

U.S. EPA. 1997. *1997 Update to ORD's strategic plan*. EPA/600/R-97/015.

van der Valk, A.G. and R.W. Jolly. 1992. *Recommendations for research to develop guidelines for the use of wetlands to control rural nonpoint source pollution*. Ecological Engineering 1:115-134.

Zak, D.R. and D.F. Grigal. 1991. Nitrogen mineralization, nitrification and denitrification in upland and wetland ecosystems. Oecologia 88:189-196.

United States
Environmental Protection
Agency

National Risk Management
Research Laboratory
Cincinnati, OH 45268

Official Business
Penalty for Private Use
$300

EPA/600/S-02/002
June 2002

Please make all necessary changes on the below label, detach or copy, and return to the address in the upper left-hand corner.

If you do not wish to receive these reports CHECK HERE ☐; detach, or copy this cover, and return to the address in the upper left-hand corner.

PRESORTED STANDARD
POSTAGE & FEES PAID
EPA
PERMIT No. G-35