Ecological Wastewater Treatment for Appalachia:

Constructed Wetlands and Related Innovations

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EXECUTIVE SUMMARY

This emerging issue paper on sustainable technologies for wastewater treatment was funded by the Appalachian Regional Commission (ARC) and produced by Rural Action, a community development organization based in southeast Ohio. The paper summarizes literature on the effectiveness of constructed wetlands and related innovations to address contamination of ground and surface water by wastewater in the Appalachian region.

1. Problem Surface and groundwater contamination resulting from failing and inadequate septic systems is a serious environmental and public health concern in Appalachia. Site constraints, including clay soils, high water tables, and steep slopes, contribute to the inadequacy of conventional sewage treatment facilities. Many low-income communities cannot afford conventional treatment systems, and alternatives are not readily accessible. Although alternatives exist that can provide environmentally sound and cost-effective solutions, there are wide areas of Appalachia with no applications of these ecological treatment systems.

2. Literature Review This paper investigates the use of constructed wetlands for residential and public wastewater treatment. A constructed wetland is an ecological wastewater treatment system engineered to mimic the physical, chemical, and biological purification processes of a natural wetland. The effectiveness of constructed wetlands in removing pathogens, organics, and nutrients from public wastewater has been clearly demonstrated.[1] This review summarizes available information on the technology, including design innovations that address treatment deficiencies and environmental constraints common to Appalachia. Gaps in the literature are discussed.

3. Research Prospectus The lack of more widespread use of constructed wetlands in Appalachia may be attributed to:

1. limitations of early constructed wetland systems in relation to treatment goals and environmental constraints;
2. lack of consensus on design criteria;
3. regulatory barriers and lack of a consistent national or regional policy;
4. lack of educational materials produced for Appalachian regulators and citizens.

Rural Action proposes to conduct further assessment of factors critical to the success of constructed wetlands and produce an Appalachian Resource Guide to Constructed Wetlands for Wastewater Treatment with a video of slides and audio recordings gathered at selected sites. The guide will serve policy makers, communities, and individual homeowners interested in constructed wetlands as a solution to wastewater treatment problems for both new construction and retrofits to assist failing systems.

INTRODUCTION: STATEMENT OF THE PROBLEM

The purpose of this paper is to evaluate information on constructed wetlands and related innovations appropriate for Appalachia. Technologies have been chosen for study that can be both ecologically sound and economically viable for the inhabitants of Appalachia, making use of locally available resources while promoting resource conservation and recovery. Because they best fulfill these criteria, constructed wetlands and related innovations are the technologies selected for study.[2] Constructed wetlands do not require significant chemical or energy inputs to treat wastewater and, given availability of appropriate sites, have lower construction, operation, and maintenance costs than conventional treatment systems.[3] Constructed wetlands can contribute to the improvement of public health and environmental conditions in Appalachia by providing treatment and disposal of waste that protect groundwater supplies, recreational swimming and fishing areas, and aquatic ecosystem health.

CONTEXT

Environmental and Public Health Considerations

Sewage disposal is a primary public health concern in Appalachia as well as in the rest of the United States. Approximately 25 percent of the nation uses onsite septic systems to treat wastewater,[4] and approximately three billion cubic meters of septic tank effluent are discharged into soils for treatment each year.[5] The leach field component of a conventional septic system relies on native soils to attenuate contaminants in the waste stream. It has been estimated that fewer than half the native soil types can adequately treat wastewater.[6] Poor soil conditions can lead to numerous problems; for example, thin or sandy soils may not provide adequate treatment, while clay-rich soils can cause ponding over the leach field.[7] Failing and inadequate septic systems are the most frequently reported source of groundwater contamination.[8]

About half of all known waterborne disease outbreaks in the United States are attributed to contaminated groundwater; an estimated four to five million illnesses per year may be caused by consumption of bacteria-contaminated groundwater from public supplies alone.[9] Bacterial and nutrient contamination of private water wells is also significant but is difficult to assess due to lack of regulation and reporting requirements for private wells.

Economic Considerations

A 1992 United States Environmental Protection Agency (US EPA) report estimates that cities and towns in the United States require up to $108 billion for enlargements, upgrades, and new construction of wastewater treatment facilities. According to the report, small communities in the United States have unmet wastewater treatment needs of over $13 billion.[10] Of the 16,439 community water systems found in violation of drinking water regulations in 1991, 90 percent were small systems.(p. 11)

From 1979 through 1987, an average of $388 million was invested annually in twenty seven hundred projects considered to be Innovative or Alternative I/A.[11] By fiscal year 1993, such funding had been gradually reduced to only $880,000.(p. 33) In February 1993, President Clinton outlined a new Environmental Technology Initiative (ETI) to accelerate both environmental protection and infrastructure development. The goal of the initiative is to support the transition away from a defense-oriented economy by stimulating private sector environmental technology research and development, thus expanding export potential. The EPA developed a four-point technology innovation strategy to accomplish ETI goals. This strategy includes:

1. adapting regulatory policy and compliance framework to promote innovation;
2. strengthening the capacity of environmental technology developers;
3. investing in the development of promising new technologies;
4. accelerating the diffusion of innovative technologies.[12]

The EPA has recently instituted an Environmental Technology Verification Program (ETV) to quantify the performance of innovative technologies that provide solutions to problems which threaten human health or the environment.[13] The ETV program provides technology purchasers, developers, and regulators with verified environmental performance data on commercial-ready technology. A current ETV project evaluates an ecological waste treatment system discussed in this paper.[14]

SIGNIFICANCE TO APPALACHIA

A primary source of surface and groundwater pollution in the Appalachian region is failing septic systems.[15] Onsite septic systems with leach fields, widespread in rural areas where large gravity sewers with centralized mechanical and chemical treatment are not available, frequently fail due to unsuitable site characteristics such as steep slopes, thin clay soils, and high water tables.[16] Rural residents who use septic systems to treat their wastewater often rely on groundwater wells as a source of drinking water. About one-half of Appalachians rely on groundwater for drinking.[17] In Appalachian Ohio, 1,026 of 1,141 public water systems rely on groundwater.[18]

Evidence of bacteria-contaminated groundwater exists in Appalachia. For example, the Alabama Department of Public Health has estimated that 75 percent of private drinking water wells in the Sand Mountain area of northeast Alabama are bacteria-contaminated. Primary causes have been attributed to improper onsite sewage disposal and a high septic tank failure rate, the latter probably a result of poor tank manufacturing and installation techniques.[19]

Surface water is also impacted by sewage contamination. A study of four Appalachian North Carolina counties found 30 percent of homes assessed had bacteria-contaminated drinking water from surface water sources; 74 percent of water samples from monitoring sites upstream of any public or other point-source discharge had fecal coliform levels significantly above EPA recreational stream standards of 200 fecal coliform units (fcu) per 100ml.[20] Improvements to existing waste treatment systems must be made in order to bring failing and inadequate systems into compliance with National Pollution Discharge Elimination System (NPDES) permit limits.[21]

LITERATURE REVIEW

Published information researched for this report included current publications, periodicals, and government databases. Federal and state agencies, educational centers, and design and engineering consultants were contacted for additional information. In particular, the US EPA, Tennessee Valley Authority (TVA), Small Flows Clearinghouse, and Texas Water Resources Institute were sources of extensive information.

DEFINITION

A constructed wetland is a wastewater treatment system engineered to mimic the physical, chemical, and biological purification processes of a natural wetland. Natural and constructed wetlands can reduce suspended solids, biological oxygen demand (BOD),[22] nutrients, metals, and pathogens from inflowing water by a variety of processes including sedimentation, filtration, microbial metabolism (both anaerobic and aerobic), plant uptake/respiration, and other chemical processes.[23] The main difference between a natural and a constructed wetland is that the constructed wetland enables wastewater treatment designs to be based on specific effluent-quality goals. Constructed wetlands can provide secondary and tertiary wastewater treatment and can be used to de-water sludge.[24] They are used both for onsite treatment for individual residences and for multi-household treatment, referred to as public or municipal treatment systems.

Constructed wetlands are classified as either free water surface wetlands (FWS) or subsurface flow wetlands (SF), also commonly known as plant rock or rock reed filters. FWS wetlands consist of vegetated water-filled basins or channels. The water in these systems is exposed and provides wildlife habitat and bird-watching opportunities. SF wetlands also consist of vegetated basins or channels, but the bed is filled to a suitable depth with a porous medium, or substrate, usually river rock or gravel. Emergent vegetation is rooted in the substrate, and the water level is kept below the surface of the medium. This report concentrates on SF constructed wetlands because they have several advantages over FWS wetlands: less odor, less risk of insect vectors, faster treatment, smaller area requirements, and greater heat retention.[25] Subsurface flow wetlands are recommended in regional design manuals for individual residences[26] and have been used in several public treatment systems across Appalachia.[27]

SF wetlands provide secondary treatment of wastewater after primary screening and sedimentation by a septic tank or lagoon,[28] which also removes some of the BOD.[29] A standard multi-compartment septic tank is the recommended preliminary treatment component for onsite systems.[30] A filter may also be installed on the effluent side of the septic tank to reduce solids and organic load to the wetland beds. Filters are typically cost-effective and low maintenance.(p. 6)

Public SF wetland systems often use a combination of pretreatment techniques. In these systems, individual residences may each have a standard septic tank from which effluent is piped through small diameter sewers to a central facility for advanced treatment, or wastewater may be piped directly to a central facility for pretreatment.[31] Lagoons are often the method used for centralized primary treatment and storage of wastewater but have large land requirements and may generate hydrogen sulfide gasses in the winter and algal problems in warmer weather.[32]

Following primary treatment, wastewater flows into one or two wetland beds. (SEE DIAGRAM #3) These wetland beds essentially replace the leach bed component of conventional onsite systems.[33] The shape and size of wetland beds can vary greatly, depending on the shape and slope of the lot and the design being followed. Advantages of a single bed include simplicity of design and construction; advantages of multiple beds include adaptability to difficult topography and easier repairs, if the units are built in parallel.[34] Disposal of effluent after treatment in onsite systems can be into unlined secondary beds,[35] through subsurface drainpipe into subsurface soil layers,[36] or to an approved absorption area.[37] In public systems, effluent disposal is usually to surface waters but must be approved by appropriate state agencies and designed to meet effluent standards.[38]

Emergent vegetation in the wetland beds is extremely important to the physical and chemical processes of the wetland.[39] The primary function of vegetation in SF wetlands is the provision of oxygen to bacteria essential for purification of wastewater.[40] A wide variety of plants, including many native and ornamental species, has been used. Locally grown native plants are frequently recommended because they are regionally adapted.[41] Commonly used plants include cattails *(Typha)*, bulrush *(Scirpus)*, and reeds *(Phragmites)*.[42] Recommended plant species[43] and planting guidelines[44] are discussed in the literature. However, further research is needed to determine optimal vegetation and better understand its role in providing oxygen in wetland systems.[45]

HISTORY

Constructed wetlands have been used to treat wastewater in Europe since the 1960s and in the United States since the late 1970s. Designs were first developed in western Europe in the 1960s by Seidel, followed by Kickuth in the late 1970s. As of 1990, over five hundred of Kickuth's "reed bed" systems were installed throughout Germany, Denmark, Austria, and Switzerland. In 1985, Kickuth's designs were modified for installations in Great Britain to use gravel instead of soil as a substrate.[46] The European Community/European Water Pollution Control Association published guidelines in 1990 on the use of constructed wetlands.[47]

The United States began researching the use of constructed wetlands for wastewater treatment in the early 1970s, when experimental work was conducted by Wolverton in Louisiana and later by Gersberg in California.[48] The TVA was one of the first organizations to conduct constructed wetland research in Appalachia, publishing a design manual in 1988. The original TVA manual has recently been revised to include some new design standards.[49]

APPALACHIAN CONTEXT

The North American Constructed Wetland Treatment System Database (US EPA) lists approximately 160 constructed wetlands, each treating more than 50,000 gal/day of public wastewater. Of these, 14 are located in five Appalachian states. At least fifty-five Appalachian counties have onsite systems for individual residences. Although New York and South Carolina have no confirmed public or residential constructed wetlands in Appalachian counties, there are public facilities in other parts of these states. Throughout Appalachia, publicly accessible facilities are sparsely distributed over a wide area. Many parts of the region do not have public facilities where citizens can observe the operation of these environmental technologies. (SEE DIAGRAM #2)

REGULATORY STATUS

Despite the evidence that constructed wetlands are effective in removing organics, metals, and nutrients from municipal wastewater, acid mine drainage, industrial effluents and agricultural sources,[50] they are viewed as an alternative technology in most of the United States, because limited data exist on their long-term effectiveness. Implications include a lack of consistent regulatory policies and approved design criteria[51] and frequently difficult permitting procedures. According to the US General Accounting Office (GAO), restrictive state and local codes and regulations are a barrier to the use of constructed wetlands and other alternative technologies for wastewater treatment.[52]

Appalachian State Regulations

Constructed wetlands are viewed as experimental in most states and are included under provisions for technologies classified as Innovative and Alternative (I/A). The process for permitting and approval of constructed wetland treatment systems varies among the Appalachian states. Specific regulations, policies, and design guidelines are described below.[53]

Alabama. Onsite Sewage Disposal and Subdivision-Onsite Sewage Systems, Water Supplies and Solid Waste Management (Chapter 420-3-1, July 1992). Alabama state regulations are under revision and are expected to be adopted in the fall of 1997. Regulations (1992) provide for I/A technologies to be approved under variances or by the State Board of Health. Their Board Approval Process reviews experimental treatment processes for a one-year period on conventional lots; permits are given on a case-by-case basis. State regulations do not allow surface discharge of effluent from onsite systems. Modified TVA guidelines for constructed wetlands are used in Alabama.

Georgia. New state regulations give county health departments authority to approve constructed wetlands for onsite use. Public systems are approved by the Department of Natural Resources, State Environmental Protection Division. I/A technologies without a three year proven track record in other states are considered experimental and, if they are onsite subsurface discharge systems, must be submitted for a technical review by the State Department of Environmental Health. I/A technologies used for public or onsite systems with surface discharge must be approved by the Department of Natural Resources, Environmental Protection Division. System designs that have received experimental approval to date have been based on TVA guidelines.

Kentucky. Construction Standards for Components of Onsite Sewage Disposal Systems (KAR 10:081); Kentucky Onsite Sewage Disposal Systems Regulation (KAR 10:085). State regulations are scheduled to be updated by fall 1998. Regulations, (1994) provide for experimental approval of plans submitted to the state health department on a case-by-case basis. However, in counties with several operating constructed wetlands, the county health department may be given authority to grant permits. Some state-level guidelines have been developed, and local health departments have published comprehensive guidelines.[54] State-level onsite certification training programs are offered for inspectors and installers.

Maryland. Sewage Disposal and Certain Water Systems for Homes and Other Establishments in the Counties of Maryland Where a Public Sewage System Is Not Available (Title 26, Subtitle 04, Chapter 02, October 26,1992); Water Supply and Sewerage Systems in the Subdivision on Land in Maryland (Title 26, Subtitle 04, Chapter 03, October 26, 1992). Maryland onsite wastewater regulations were last updated in 1992, and there are no plans to revise the current regulations. I/A systems are not permitted for new construction but are permitted for upgrades to failing systems. Local health departments are responsible for permitting onsite systems; public systems are administered by the Department of the Environment.

Mississippi. Mississippi has recently published revisions to their 1995 regulations. Individual Onsite Wastewater Disposal Regulations are established by the Mississippi Department of Health. Individual systems are permitted by county environmental extension agents certified by the State Department of Health. Public treatment systems are regulated by the Mississippi Department of Environmental Quality, Office of Pollution Control. Guidelines for system designs previously recommended adhering to early parameters established by research at the National Aeronautics and Space Administration (NASA).[55] New regulations make recommendations to follow EPA design guidelines.

New York. Wastewater Treatment Standards Individual Household Systems (Appendix 75-A, December 1990). New York onsite regulations were updated in 1990, and there are no plans to revise the current regulations. New York does not have regulations which specifically mention constructed wetlands. Alternative technologies for individual residences must be designed by a design professional who certifies that the site and soil evaluation plan meets specified criteria and who supervises construction. These requirements may be waived by the county health department.

North Carolina. Wastewater Systems (Article 11, Chapter 130A, April 1993); Sewage Treatment and Disposal Systems (Section 1900, April 1993). North Carolina revised its regulations concerning onsite wastewater treatment in 1993. Jurisdiction for permitting and approval of public constructed wetland treatment systems is divided between the Department of Environmental Management, the Department of Environmental Health, and local health departments. Permitting of systems for individual residences is by approval of a county extension agent certified by the State Department of Environmental Health.

Ohio. Household Sewage Disposal Rules (Chapter 3701-29, July 1977). Ohio has plans to revise its existing regulations, which were last updated in 1977. County health departments have authority to issue permits for individual residential systems. Public treatment systems are permitted by the Ohio Environmental Protection Agency. A county health department has published an installers' guide to constructed wetlands.[56]

Pennsylvania. Standards for Sewage Disposal Facilities (Title 25 Environmental Resources Chapter 73, August 1991). Pennsylvania regulations authorize local sewage enforcement officers to issue experimental permits to individual homes for I/A technologies, such as constructed wetlands. If there is effluent discharge from these systems into surface water, then an NPDES permit is required. Public treatment systems are administered by the Bureau of Water Quality Management. Pennsylvania design parameters are based on US EPA guidelines and on a series of manuals developed by the US Department of Agriculture in cooperation with US EPA Region 3.[57]

South Carolina. Individual Waste Disposal Systems (Regulation 61-56, July 1986). South Carolina regulations for onsite wastewater were last updated in 1986. Permits for individual systems are issued by county health departments. Public systems are regulated by the Environmental Quality Control Section of the South Carolina Department of Health and

Environmental Control. The South Carolina Department of Health offers a training and certification program for county regulators of onsite systems.

Tennessee. Regulations to Govern Subsurface Sewage Disposal Systems (Chapter 1200-1-6, January 1995). Tennessee updates its onsite regulations on a yearly basis; revisions are scheduled for publication in 1997. Regulations (1995) specify that the Tennessee Department of Environment and Conservation is responsible for reviewing permit applications for I/A technologies.

West Virginia. Design Standards for Individual and Onsite Sewage Systems (part V, Individual Sewage Systems Chapter 16-4, Series VII, December 1983); Sewage System Rules (Chapter 16-1, Series XI, May 1983). West Virginia last updated its regulations for onsite wastewater treatment in 1983. These regulations are currently under revision and scheduled to be published in 1997. Local county sanitarians can issue permits for onsite systems on a case by case basis. The West Virginia Office of Environmental Quality regulates public treatment systems. West Virginia will permit discharge to surface water for failing systems but not for new systems. If such surface discharge exceeds 6000 gallons per day, then an NPDES permit is required. The Office of Environmental Health offers a certification program for installers of sewage systems. Regulations accept variations of designs developed by TVA, NASA, and US EPA.

Virginia. Sewage Handling and Disposal Regulations (May 1989). Virginia is scheduled to publish revisions of its 1989 regulations sometime in 1997. Applications for individual systems are reviewed at the State of Virginia Office of Environmental Health Services (OEHS). Public systems are regulated by the OEHS Wastewater Engineering Division, and permitting and monitoring are done by the Division of Environmental Quality.

COSTS

Several reviews of constructed wetland treatment systems conclude that this technology can provide cost-effective wastewater treatment, given the availability of suitable land at a reasonable price.[58] Analysis reported in the 1994 US EPA Wetlands Treatment Database indicates that average construction and operation costs for SF wastewater treatment systems were equivalent to or less than for conventional treatment methods.[59] These results confirm earlier estimates and predictions[60] and concur with conclusions of other studies.[61]

Additional research has compared the cost of SF wetlands to FWS wetlands. SF wetlands were found to be cheaper than FWS wetlands when compared on the basis of volume treated, in spite of SF wetlands' greater construction costs, because each acre of SF wetland can treat significantly more sewage than an acre of FWS wetland.[62] However, more recent SF wetland designs call for larger treatment areas which will result in higher unit costs.[63]

The actual cost effectiveness of constructed wetlands is dependent on site-specific conditions and treatment requirements,[64] affected by variables such as:

- cost of substrate, which will depend on type, local transportation costs, and proximity of a source[65]
- cost of land[66]
- soil type (with clay the most economical, because no imported clay or liners will be necessary)[67]
- water table (with close proximity adding cost of site studies and liner) (p. 17)
- slope (too little or too much requiring a less passive, more expensive design) (p. 18)
- primary site vegetation (whether clearing or planting of winter shelter belt will be necessary and whether appropriate inexpensive wetland vegetation is available) (p. 18)
- rainfall (with pumps and berms to prevent flooding adding to costs) (p. 19)

- climate (with cool temperate regions requiring insulation,[68] recirculating filters, intermittent loading, or other mechanisms to ensure adequate nitrogen removal,[69] or temporary storage of the wastewater, all raising costs)
- zoning and local regulatory requirements for wetland siting, capacity, components, access, and effluent quality.[70]

LIMITATIONS AND INNOVATIONS

A review of literature reveals that the effective application of constructed wetland technology in Appalachia depends on continuing evaluation of working systems to develop solutions to recurrent problems. Limitations of constructed wetland treatment systems are a result of environmental constraints and treatment deficiencies. Several design innovations will be discussed that have been developed to address these concerns.

Environmental Constraints

Climate. Climate conditions present challenges to the use of constructed wetlands, as treatment efficiencies are temperature- and season-dependent.[71] Seasonal variations are due primarily to the life cycles of plant and microbes, which provide more efficient treatment capacity during warm periods and reintroduce nutrients during decay in cold periods.[72] Insulation, such as foam or straw, can be applied to retain heat from the wastewater.[73] Another design modification, to prevent freezing during cold weather, is to use a deeper bed to allow for greater water depths.[74] However, this can lead to inadequate treatment, as water may flow below the root zone.[75] A third design approach, for public systems, is to store water in lagoons in winter to be later discharged for treatment in warmer months. This type of operation is unusual, as most systems operate year-round.[76] In extremely cold conditions, the use of Advanced Ecologically Engineered Systems (AEES)[77] is being evaluated for treating wastewater to acceptable standards.[78] A discussion of this technology follows the treatment deficiency section on page 24.

Another climate condition that presents challenges to constructed wetlands is drought. During dry weather, wetland vegetation may be damaged if water levels are reduced for extended periods. Supplemental water may be needed if periods of dry weather coincide with periods of low flow.[79] One approach is to recycle the effluent back into the beds during dry spells,[80] but this may add to construction and pumping costs and lead to salination of beds when evaporation rates are high.[81] Other approaches include flooding the bed prior to low flow or dry weather periods to reduce the impact of evaporation and transpiration,[82] or installing structures to divert rainwater into the wetlands during periods of low flow.[83]

A third climatic challenge for constructed wetlands is high rainfall, which can shorten the residence time of wastewater and temporarily reduce treatment efficiency. In addition, sediment carried by floodwaters can clog SF wetland beds. Adequate berms must be constructed both to exclude runoff and to contain water from high rainfall events.[84] Water levels in beds should be manipulated to optimize the hydraulic loading, or influent rate and volume, during these periods.(p. 51) Placement of SF wetlands in areas of regular flooding is discouraged.[85]

Land Requirements. Cost and availability of land can restrict the practical application of constructed wetland technology.[86] Some areas simply will not be suitable due to the extensive land requirements of these systems. One alternative is to use composting toilets in conjunction with a wetland system,[87] which can reduce the necessary size of the wetland by about 40 percent.[88] Space limitations have also been addressed by using a switchback design to shorten the drainage system.[89] Another option, for public systems, involves use of an AEES, which has a smaller footprint than does a constructed wetland.[90]

Slope. Slope can affect feasibility and cost-effectiveness of constructed wetlands. Slopes in excess of 15 percent have been cited as presenting considerable challenges for FWS wetlands in Texas, as costly excavation may be required.[91] The relationship between slope and cost-effectiveness of SF wetlands or in Appalachian soil types is not evaluated in the literature. SF constructed wetland beds can be terraced to fit onto steep slopes,[92] allowing them to be fed and drained by gravity.[93] The reduced operation costs of such passive systems can offset the initial expense for excavation.[94] However, at least one regulator has expressed concerns about the long-term viability of placing these systems on steep slopes, unless the beds are positioned on thoroughly compacted native soil profiles and include retaining walls anchored into the bedrock to prevent subsidence, which would compromise treatment efficiency.[95] Slopes of less than 2 percent may require pumps to circulate water, increasing costs.[96]

Soils and Depth to Groundwater. High groundwater and insufficient soil structure can impede the use of conventional treatment systems and are often reasons that constructed wetlands are considered.[97] However, these conditions also present challenges for constructed wetlands. High groundwater or sandy soils may necessitate use of a bed liner, such as a bentonite clay mixture or synthetic material, to prevent untreated wastewater from seeping into groundwater and prevent groundwater from entering the wetland system.[98] Inadequate soil structures may prohibit subsurface disposal of effluent without additional treatment.[99] To make effluent safe for disposal in sandy soils, wastewater can be treated with ultraviolet light (UV) prior to discharge.[100] Decreased discharge methods such as evapotranspiration,[101] onsite irrigation,[102] and reuse for flushing toilets[103] can address problems of poor percolation and ponding in clay soils and rapid percolation of inadequately treated effluent in sandy soils.

Substrate. Substrate normally accounts for just over 50 percent of SF wetland costs.[104] The possibility of using local and recycled materials for substrate must be explored in order to reduce costs. Alternative substrates have been tested by the TVA, Texas A&M, and the Appalachia–Science in the Public Interest (ASPI) center. The TVA found that mine spoil could be effectively used as a substrate material.[105] Given the availability of such material throughout Appalachia, this may be a viable substrate alternative. Texas A&M tested the use of shredded tires and found that they also worked as a substrate, although two problems were noted: sharp iron fragments, which added small amounts of dissolved iron to the water and posed a potential safety hazard, and a thin layer of grease produced by the tires during the first month of operation.[106] Despite these problems, high hydraulic conductivity values and low material cost make tires a substrate to consider. The ASPI educational center has demonstration constructed wetlands that use a native sandstone. Use of such locally available substrate options can reduce material and transportation costs.[107]

Treatment Deficiencies

Given particular treatment goals and environmental constraints, certain design elements of constructed wetlands may result in treatment deficiencies. Treatment deficiencies are addressed by modifications of the wetland design or maintenance procedures, as well as by integrating other components or innovative technologies to work together with the wetland beds. Phosphorus removal presents the greatest challenge to public constructed wetlands, followed by ammonia/nitrogen removal. Ponding, or surface flow, resulting in treatment deficiencies, has occurred in wetlands constructed early in the technology's development. This problem is considered less significant than either phosphorus or ammonia/nitrogen removal, because it has been addressed by recent design and maintenance practices. Finally, sludge disposal may present problems that can be addressed by various innovations.

Phosphorus Removal. SF constructed wetlands systems have a limited capacity for phosphorus removal due to short hydraulic residence times (HRT), the average time that water remains in the wetland, and lack of interaction with soil minerals.[108] Insufficient HRT can present problems when systems discharge into surface waters, because phosphorus can cause eutrophication.[109] While chemical additives may be a cost-effective method of phosphorus removal, [110] such additives may generate significant amounts of sludge.[111] High phosphorus removal rates without chemical additives may require a very large land area or alternative treatment components that provide more interaction with soil minerals.[112]

Principal mechanisms for phosphorus removal in constructed wetlands are plant uptake and retention by soils.[113] Effective removal of phosphorus in SF wetlands has been associated with interaction with minerals, such as iron, aluminum, and calcium, in the bed media. The long-term effectiveness of this process is limited, because removal decreases as adsorption sites on media become filled.[114] FWS wetlands, with longer hydraulic retention times and increased interaction with soils, have a better short-term removal rate, but their long-term effectiveness is unlikely for the same reason as in SF wetlands.[115]

Alternative treatment components that provide sufficient phosphorus removal or eliminate excess phosphorus discharge include aquatic plant harvesting from shallow ponds, subsoil discharge, and zero discharge methods such as onsite irrigation and evapotranspiration beds. Harvesting of emergent plants for phosphorus removal has met with limited success, as relatively small amounts of phosphorus are recovered in this process, and the harvesting of plants is labor-intensive and costly.[116] However, construction of a pond component and harvesting of duckweed (*Lemna*), a floating aquatic plant, can provide an inexpensive method to reduce phosphorus effectively and is endorsed as an I/A by the US EPA.[117] One limitation of this treatment is the limited growing season in Appalachia, where duckweed can only be grown six to nine months a year.[118] Furthermore, the large shallow bodies of water necessary make them difficult to use in urban areas or in regions where flat land is scarce or expensive.[119] Harvesting of duckweed for phosphorus removal may need to be done on a weekly basis during warm periods,[120] but its value as a source of animal feed may offset the expense of this maintenance requirement.(p. 51)

A second treatment method that can eliminate phosphorus discharge is in-ground disposal, in which wastewater has additional contact with soil minerals.[121] Increased interaction with soil minerals can be achieved in onsite systems by using unlined secondary beds. Sites with good to marginal soil percolation typically have no surface discharge from unlined beds.[122] However, use of unlined beds in areas of high groundwater or bedrock, high soil permeability, or proximity to waterways can pose problems, as certain effluent constituents may be less thoroughly treated in unlined beds.[123] Furthermore, while costs are reduced by eliminating liners, unlined beds are prone to plant damage during extended periods of low flow or dry weather.

Zero discharge methods such as onsite irrigation and evapotranspiration beds have been used to address phosphorus disposal problems. Onsite irrigation is an accepted method of effluent treatment and disposal for large public systems but may require hundreds of acres of land to receive the wastewater from pressurized sprinkler systems.[124] Recent use of this approach for onsite irrigation of landscape plantings is being demonstrated in AEES facilities.[125] Enclosed evapotranspiration beds can also achieve zero discharge of effluent and offer advantages in circumstances where phosphorus discharge is unacceptable. Evapotranspiration beds require relatively large capital costs, but regular harvest of marketable crops from these beds can offset some of the expense.[126]

Ammonia and Nitrogen Removal. Ammonia and nitrogen must be adequately removed by waste treatment systems in order to protect groundwater and aquatic ecosystems. High ammonia levels kill juvenile fish and other aquatic organisms.[127] High nitrogen levels increase algae growth. When these algal blooms die, oxygen content of the receiving water is depleted, causing death of aquatic organisms.[128] Nitrogen can also be a source of nitrate contamination of groundwater,[129] which is associated with negative health effects, including death to infants, the elderly, and livestock.[130]

The nitrogen cycle is complex; there are various mechanisms for nitrogen removal, depending on its chemical state. The five basic processes which transform nitrogen from one form to another--

ammonification, nitrification, denitrification, nitrogen fixation, and nitrogen assimilation--all can occur in properly designed wetlands to create environments for both nitrate and ammonia removal.[131] Primary mechanisms for nitrogen removal in constructed wetlands are nitrification and denitrification.[132] In the nitrification phase, ammonia is oxidized by anaerobic bacteria into nitrite and nitrate. In the denitrification phase, anaerobic bacteria convert nitrate into nitrogen gas, which is released into the atmosphere.[133]

Ammonia and nitrogen removal deficiencies have been reported in most early constructed wetland treatment systems.[134] Availability of oxygen is considered to be the limiting factor for effective removal of ammonia and nitrogen in these systems.[135] Cost-effective methods of improving oxygenation include installing vertical flow system components, increasing HRT of wastewater, and enhancing root penetration.[136] Experimental methods, which may not always be cost-effective, include batch load operation and the use of step aeration.

Vertical flow (VF) beds are reported to be more effective at nitrification than are horizontal flow systems such as SF wetlands,[137] because air-filled pore spaces of VF wetlands provide higher rates of oxygen diffusion than do the water-saturated pore spaces of SF wetlands. However, because VF beds do not provide anaerobic environments necessary for denitrification, they must be followed by SF beds or other system components. Vertical flow beds are connected in series, with varying layers of sand and gravel media, and are used prior to the horizontal beds to remove suspended solids and decrease BOD. While continuous loading of these systems has resulted in clogging, the units have performed reasonably well when receiving intermittent applications of wastewater.[138]

Vertical flow beds have been used in Europe since the 1950s but are not a common component of constructed wetlands in the US. However, interest in VF systems is being revived,[139] because they promise “a cost effective method for achieving effective nitrogen removal...either as a retrofit for existing systems or a component in new designs."[140] The original European design has been modified to achieve greater treatment efficiency, based on evaluations recently conducted in the United States.[141] Deeper media depths and recirculation have been identified as factors needing further study to optimize performance of VF beds.[142]

Increased HRT has been cited as a method of achieving improved oxygenation in wetland beds. Most SF wetlands with successful ammonia removal rates have an HRT time of six days or more.[143] Shorter retention times do not provide adequate treatment, while longer HRT can lead to stagnant, anaerobic conditions.[144] The primary method for varying HRT is the regulation of water levels in the wetland beds.[145]

Enhanced root penetration, attributed to shallow bed depths or intermittent loading, has been very successful at providing increased oxygenation in SF constructed wetlands.[146] The depth of the wetland bed should not exceed the root depth of the species used; root penetration in most wetlands is about one foot, regardless of the species used.[147] Shallow beds minimize the flow of wastewater below the root zones, where oxygen may be unavailable for nitrification. Texas A&M is experimenting with shallow beds and a wide variety of plant types; researchers hope to increase wastewater interaction with root zones and thus improve treatment.[148] Another method to induce deeper root penetration is by alternately operating parallel beds;[149] this form of intermittent operation may enable the wetland to maintain an oxidized state.[150]

Batch flow wetlands use single beds or beds in series, in contrast to alternating parallel beds. These systems are operated on a flush and fill cycle designed to provide oxygen to the plant root systems similar to wave action of tidal estuaries. A recent study concluded that, although it did not have a significant effect on the removal of nitrogen, the periodic draining of these systems did flush out large amounts of suspended solids. Flushing of solids from the wetland did not negatively affect the treatment of the wastewater and could potentially extend the operating life of these systems.[151]

Step Aeration, from structures such as cascades, waterfalls, and open channels at transects within the wetland cells, has been incorporated into wetland system designs in order to improve oxygen diffusion. Although previous designs did not provide sufficient oxygenation to justify the expense of pumping and transect area required,[152] gravity fed flowforms[153] between terraced beds would eliminate the need for pumping and should be studied for use on steep slopes.

Surface Flow. Ponding, or surface flow, is experienced in treatment wetlands constructed early in the technology's development.[154] Surface flow is problematic, because it allows water to pass through the system without being properly treated and is a source of odors and mosquito breeding areas.[155] One cause of surface flow is clogging. Initial approaches to solve this problem involved the use of larger particle sizes. However, larger diameter rock has less surface area for microbes and plant roots and therefore may decrease treatment efficiency.[156] Rock dust and soil present in the substrate material may also cause clogging.[157] Excess soil from the roots of vegetation can be introduced during planting,[158] from the tires of gravel trucks during construction,[159] and from introduction of sediment during rains. To avoid this problem, gravel should be washed[160] and cells should be bermed to prevent introduction of soil particles into the substrate.[161]

Surface flow may also result from inadequate hydraulic design.[162] Many of the early constructed wetlands were designed with length-to-width ratios of 10:1 or more; such high ratios have been cited as causing surface flow problems.[163] A length-to-width ratio of 0.4:1 to 3:1 has been recommended to address these concerns.[164]

Installing control structures to regulate water levels as needed can also reduce problems of surface flow.[165] Lowering the water level at the end of the bed produces the head pressure required to overcome resistance to flow through the media.[166] Placement of the effluent manifold at or below the bottom of the bed can provide this regulation as well as a way to drain the beds and measure flow and effluent constituents.[167]

Sludge Disposal. Onsite constructed wetlands frequently require mechanical pumping of the septic tank and remote disposal of sludge, which can account for significant costs and energy requirements. Despite cultural and economic barriers that limit the wide applicability of composting toilets,[168] use of these devices in conjunction with constructed wetlands should be considered, because they can reduce the necessary size of the wetland and frequency of pumping, transport, and disposal of septic tank sludge.[169]

Public wastewater treatment systems have incorporated constructed wetland beds specifically dedicated for sludge de-watering, thus decreasing greatly the amount of sludge that must then be transported for remote disposal. Such dedicated reed beds have been used in AEES facilities[170] and could be used with public constructed wetlands as well.

ADVANCED ECOLOGICALLY ENGINEERED SYSTEMS

One solution to various problems of environmental constraints and treatment deficiencies for public systems is to use AEES facilities, either in conjunction with or instead of SF wetlands. AEES are constructed aquatic treatment systems that utilize a unique combination of biological treatment processes to treat wastewater and sludge. AEES systems are more ecologically and technologically complex than SF constructed wetlands. The treatment ponds that do much of the biological processing of the waste are constructed in greenhouses, under light shelters, or outdoors, depending on the climate. AEES may be particularly useful for public systems where harsh climate, limited land area, steep slopes, or high groundwater tables make use of SF wetlands cost-prohibitive.[171] AEES facilities have been used to treat waste from production of food,[172] cosmetics,[173] public wastewater,[174] and sewage sludge.[175] AEES facilities by themselves can adequately address removal of total suspended solids, BOD, and ammonia-nitrogen, but not phosphorus.[176] Components used in conjunction with AEES, such as evapotranspiration beds or onsite irrigation, can provide adequate phosphorus removal. Additional benefits of AEES include its use of primarily solar energy; its construction in modules, so that additional capacity can be added as needed; its production of less sludge than conventional facilities, due to the diversity of waste-processing organisms;[177] and its unique environment for year-round public education through demonstration of biological purification and recycling of wastewater.[178]

A typical AEES facility consists of the following basic components and processes:[179] Primary treatment of effluent starts with a three stage bio-reactor [180] for reduction of BOD and total suspended solids and for sludge digestion. Reactor effluent is piped to covered, aerated tanks for odor removal; exhaust gasses are routed to an underground earth filter.[181] Biological, bacterial, and mineral additives are applied to the aerated effluent in order to enhance nitrification of ammonia, health of plants in the system, and breakdown of grease and sludge.[182]

Secondary treatment begins when the effluent enters a series of aerated tanks with floating aquatic plants, such as water hyacinth and pennywort. Aeration from a series of three small blowers keeps solids in suspension for rapid circulation and continuous contact with the root systems of floating aquatic plants. After passing through a small clarifier for removal of suspended solids, the wastewater enters a series of Ecological Fluidized Beds that contain an inner tank of pumice gravel media. The pumice media has a low density, making it nearly buoyant, and a high surface-to-volume ratio, which provides for attachment of nitrifying bacteria critical to the ammonia removal process. The Ecological Fluidized Beds are the principal mechanism for ammonia and nitrogen removal in the AEES units and also provide for the removal of suspended solids, which are periodically recycled into the three stage bio-reactor. The surface of these aerated tanks is used to culture tree seedlings and other plants hydroponically.[183] Although the plant roots provide minimal treatment capacity, they can be sold as a source of revenue.[184] The wastewater then passes through a second clarifier for additional sludge removal.

Some designs of AEES have included tertiary treatment with the addition of a high rate marsh for final polishing and production of horticultural plants that provide a source of revenue.[185] Additional treatment of sludge has been incorporated into AEES facilities through the use of reed beds specifically dedicated for sludge de-watering.[186]

AEES facilities were developed by John Todd, president of Ocean Arks International, a non-profit research and education organization established in 1980 in Falmouth, Massachusetts.[187] Todd also founded a for-profit company, The Four Elements,[188] to market the solar aquatic wastewater treatment systems. This company was bought out by Living Technologies, Inc.[189] Todd subsequently formed a limited partnership with Ecological Engineering Associates, which markets AEES under the name "Solar Aquatics Systems."[190] All of these systems utilize similar ecological and microbiological treatment processes and will be referred to as AEES technologies in this discussion. AEES have been installed in eight states as well as in Canada, Australia, England, and Scotland. The technology can be licensed from Living Technologies, Inc.; support is provided with bid preparation, engineering, and design.[191]

The development of demonstration-scale AEES technology has been supported by a total of $5.75 million in federal funding.[192] A recent EPA-supported Environmental Technology Verification study is evaluating four AEES facilities, including Burlington, Vermont, and Frederick, Maryland, as part of a national demonstration project. The Burlington AEES facility was chosen to demonstrate that the treatment process could remove nitrogen from wastewater in extremely cold temperatures.[193] Conclusions from the Frederick report are summarized below.

Tests at the Frederick, Maryland facility indicate that certain AEES components are more effective than others for specific treatment processes. The three stage bio-reactor was responsible for a majority of the removal of BOD, suspended solids, and total phosphorus. The ecological fluidized beds were responsible for removing most of the nitrogen and ammonia.

Conclusions of the Frederick study outlined limitations of AEES and recommended modifications to improve performance. While the anaerobic bio-reactor was found to be an excellent primary component, modification of the second chamber was suggested to allow for more digestion time and sludge storage, necessitating less frequent sludge removal.[194] Phosphorus removal was found to be inadequate; additional process modification was recommended. Results also indicated that plants in the system made only minor contributions to nitrification, due to the low surface-to-volume ratio of the tanks, providing insufficient area for plant growth. Clarification after the aerated tanks was found to be inadequate; piping changes were suggested to reduce necessary backflushing, as was addition of a pump to recycle effluent through the Ecological Fluidized Beds. The pumice media was found to be too soft to withstand inter-particle abrasion resulting from regular backflushing to remove suspended solids. Clarification and filtering prior to these beds and use of a low-density, abrasion-resistant material were recommended. A current experiment involves substitution of shredded tires for the pumice media.[195]

Capital costs of the AEES process evaluated in the ETV study were estimated for units treating 40,000 gallons per day (gpd), 80,000 gpd, and 1 million gpd. Estimated capital, operational and maintenance costs for systems operating at flow rates of 80,000 gallons per day or less are approximately the same as for conventional wastewater treatment technology. At higher flow rates, conventional treatment systems are likely to be more economical. This is probably a result of multiple tanks and greenhouses necessary for larger AEES facilities, compared to the few large tanks of conventional systems. Cost-effectiveness for AEES processes will improve if the number of tanks is reduced and tank and liner materials are improved to require less repair and replacement. (14-2, 14-3)

Regulatory officials have expressed some concerns about the potential limitations of the AEES technology, particularly in its treatment of sewage sludge. Verification is needed to assess the ability of AEES to handle sludge loads with high concentrations of commercial and industrial effluent which may be entering public systems. Sources of such loads could be car washes, photo labs, and funeral homes, as well as hazardous waste that may be discharged without regulation. In response to these concerns, there are proposals to mix these loads into a large equalization tank, or to add them slowly to less toxic sludge and blend it into the treatment system at rates the system can process effectively.[196]

Regulators have also expressed concerns about the potential solid waste disposal problems associated with the disposal of composted aquatic vegetation that has concentrated heavy metals or other toxic substances. Concerns about concentration of toxic substances in plants grown at these treatment plants are being addressed in several ways. Most of the aquatic vegetation used is fast growing; heavy metals do not reach hazardous concentrations in these plants. Another approach is use of species selected for their ability to uptake and concentrate high levels of heavy metals, so that the metals can be recovered and efficiently recycled. A third method is to produce non-edible market crops, such as tree seedlings, bedding plants, cut flowers, and sod, that are effective at removing pollutants.[197]

CASE STUDIES

The viability of using constructed wetlands to treat wastewater economically and efficiently is demonstrated in four case studies conducted in Appalachian counties: Iselin Marsh, Pennsylvania; Monterey, Virginia; Sand Mountain, Alabama; and Bear Creek, Alabama. In addition, a case study of an AEES facility in Ottsville, Pennsylvania is included, because it provides a solution to common Appalachian site constraints.

Iselin Marsh, Pennsylvania

The Iselin Marsh constructed wetland is one of three used by the TVA to determine design parameters for its constructed wetland design manual. The TVA found several flaws in the Iselin Marsh system, but it proved very efficient in nitrate/ammonia removal.[198] The ammonia removal rates are important, since many larger wetland systems have difficulty meeting ammonia effluent standards. The system consists of a constructed marsh, pond, and meadow and includes mechanical aeration and chlorination devices.[199] Both marsh and meadow cells are subsurface flow cells that use sand as a substrate. However, data collected several years after installation indicate that the sand substrate led to clogging of the inlet area and that a larger material should be used. The data also suggest that the meadow and marsh components have high enough removal rates that the mechanical aeration cell and chlorinator are probably unnecessary. A major cost of the wetland was the extensive grading; it was determined that flat or no-slope wetland bottoms could be utilized and would lower the cost. Finally, installation of flow control structures was recommended to improve vegetative growth and treatment efficiencies.[200]

Monterey, Virginia

Cost-effectiveness of wetland technology was demonstrated in the small town of Monterey. The town was faced with a mandatory upgrade of secondary treatment, which the city engineer estimated would cost approximately $500,000 for conventional treatment. This was not feasible due to Monterey's low average household income. The town decided to construct a SF wetland with assistance from NASA. Construction costs were approximately $166,000, and the wetland required minimal energy use and maintenance. The system is extremely efficient in BOD and total suspended solids removal[201] but has had difficulty meeting ammonia limits. This may be due in part to poor primary treatment.[202]

Sand Mountain, Alabama

The Sand Mountain area was considered Alabama's primary non-point source pollution problem.[203] Private drinking water wells were contaminated, principally due to improper waste treatment; stream quality was significantly degraded. A demonstration project initiated in 1993, funded by the ARC, built sixteen constructed wetlands for rural, low-income households. The demonstration project familiarized local contractors and officials with constructed wetland design, construction, and operation. In addition, the TVA developed design, operation, and maintenance guidelines for small systems, including individual residences, based on this project.[204] Constructed wetlands were placed on sites where conditions would not allow conventional septic systems. Specific site problems included steep slopes, limited land area, and high groundwater. Wetland design solutions varied among sites. The average cost was $5,563, with materials comprising approximately half. The cost is believed to have been very competitive with other alternatives.[205] A comprehensive monitoring study is being carried out by Alabama A&M University under contract with the Alabama Department of Public Health. A final report on the Sand Mountain monitoring project is due to be published in December, 1997.[206]

Several innovative construction approaches were employed at various Sand Mountain sites. Use of plywood frames to form vertical wetland bed walls allowed for quicker and easier installation, provided a solid base for anchoring synthetic liners and timber berms, and helped minimize shoveling and land area required.[207] Reinforced concrete structures were used for bed liners at two sites with steep slopes. Gravel-less drainfields were installed on sites with shallow bedrock and high groundwater at a rate of 50' of 8" pipe per bedroom, providing for quick and easy installation on difficult sites.[208] This size is significantly smaller than that required in a conventional system and is a criterion adopted by the 1993 TVA guidelines.

Bear Creek, Alabama

Phillips High School had a conventional treatment system that was discharging effluent above NPDES permit limits and was identified as a source of fecal coliform contamination to Bear Creek Floatway. The TVA chose this school for an innovative technology demonstration project and developed the conceptual design. A subsurface flow wetland was installed in 1988 to treat the effluent from the conventional treatment plant and alleviate the high school's discharge problems. This system was constructed in a marshy area containing clay soils with low permeability. State, federal, and local governments and citizens worked together to design, fund, and construct the wetland. Partners included the Natural Resources Conservation Service, TVA, Alabama Department of Environmental Management, Marion County Board of Education, a local land donor, and others.[209] Influent and effluent monitoring revealed excellent removal rates, with only two NPDES non-compliance readings for pH in the first year (5.8 and 5.9 instead of the minimum 6.0). (p. 13-18) The excellent ammonia/nitrate removal rates may be attributed to an oxidizing environment within the gravel substrate, probably as a result of shallow cell depths with exceptional root penetration and a low hydraulic loading rate.[210] Very high phosphorus removal efficiency was recorded for this system. Iron oxides coating the gravel may have provided the adsorption sites for improved phosphorus removal.[211] The effectiveness of the wetland is expected to increase as vegetation becomes more established. Total cost for the system was $36, 266.[212]

Ottsville, Pennsylvania

The twenty-six residents of Ottsville, Pennsylvania could not use conventional leach fields due to a high groundwater table and steep slopes. The community decided to use a greenhouse-enclosed series of aquaculture tanks (subsequently called AEES) and constructed wetlands to alleviate sewage disposal problems. Wastewater enters a two-compartment septic tank located at each home and then flows through four-inch diameter pipes to two community septic tanks located uphill from the greenhouses.[213] Use of these small diameter pipes can save small communities significant costs, as sewer collection systems can represent 70 to 90 percent of total system costs.[214] Primary treatment of the wastewater occurs in these septic tanks rather than in the anaerobic bio-reactors of some larger system designs. The effluent then flows through the first wetland bed, after which it is either pumped back to the homes for use as flush water or transferred to enclosed evapotranspiration (ET) beds. The innovative ET beds drain to standpipes, which contain small pumps that periodically spray the wastewater to maximize evapotranspiration. There is no effluent from the ET beds, so an NPDES permit is not necessary. The system cost $169,000, which is 30 percent more than a conventional system. However, year-round production of marketable crops is expected to offset construction costs. In addition, the greenhouse system does not require chemicals, an NPDES permit, or a licensed operator, so operation and maintenance cost savings are expected.[215] The system was designed by a local engineering firm that was licensed to build this facility.

REPLICABILITY

The constructed wetlands system is an emerging technology continually being adapted as new data are assembled and performance limitations addressed. Therefore the focus of study must be on applying knowledge gathered from many data sources rather than on replicating any one project or program. Monitoring of current research is essential to develop successful new facilities and to improve established sites. Research to address problems of non-chemical phosphorus removal and installations in cold climates or on steep slopes is especially important, as discussed above. Technological innovations, such as vertical flow wetlands and AEES, that offer particularly promising solutions to limitations of SF wetlands require continuing research and development.

While the technology from any particular project may not be directly replicable due to site considerations and ongoing technological modifications, specific project approaches can be replicated. The Sand Mountain Demonstration Project is one approach worth replicating. This project was designed to familiarize health department officials, contractors, and environmental technology advocates with constructed wetland treatment systems and to meet existing wastewater treatment needs. Insights and innovations gained from the demonstration were used to update TVA design guidelines. The project is unique in that it simultaneously addresses needs of low-income Appalachian residents and expands knowledge of the technology throughout and beyond the region.[216]

A Texas project of interest is *The Feasibility of Constructed Wetlands in The Trinity River Watershed*, a study developed by the Trinity River Authority. The study developed a systems model, used to assess feasibility of constructing wetlands for wastewater treatment at various sites within a watershed.[217] The model uses a site questionnaire "to enable a designer or client to quickly ascertain a site's feasibility and cost-effectiveness."[218] The questionnaire addresses factors that determine costs, including slope, clay content of soil, availability of low-priced land, and depth to bedrock. Slopes of 2 to 5 percent are listed as ideal for wetland construction, with less slope requiring mechanical pumping and greater slope requiring more excavation. Slopes in excess of 15 percent are deemed too steep for FWS wetlands to be cost-effective.[219]

The project also used published information to rank areas on relative cost of constructing and maintaining a treatment wetland. Site-factor maps were produced to identify where wetlands can be cost-effective. The maps can be used by regional planners to determine potential costs of constructed wetlands based on map location. A specific design was also developed for each of the eco-regions in the watershed.

The Trinity River Watershed Study offers two important models to Appalachia: its systems model site questionnaire and its site factor maps. However, the Trinity study questionnaire does not address SF wetlands, substrates, wetland vegetation, or regulatory issues. Adapting it to evaluate these critical factors, as well as Appalachian soils, slopes, and climate conditions, will be necessary to make it a useful tool for Appalachian site evaluations. The Texas study's map development process is an excellent model to use to develop site factor maps for Appalachia. These maps should identify areas where geologic and topographic factors make the technology cost-effective.

The Small Towns Environment Program (STEP) is an innovative community "self-help" program that entails assisting communities capable of self-help, guided by private engineering expertise and government assistance, to direct appropriate projects to solve wastewater problems. "By helping themselves, these communities cut costs, achieve faster results, control the selection of reliable technologies that meet their needs, and gain community self-reliance."[220] STEP could serve Appalachian communities well if adapted to address feasibility and cost-effectiveness of constructed wetlands and other innovative wastewater treatment systems.

CONCLUSIONS

Constructed wetlands are especially applicable to Appalachia where clay soils, affordable land, and need for economical alternatives make the technology particularly appropriate. Constructed wetlands can contribute to the effective treatment of onsite and public wastewater. Constructed wetland designs have been refined to include innovative solutions to some of the problems encountered early in the development of the technology, such as surface flow and inadequate ammonia and nitrogen removal. However, problems of non-chemical phosphorus removal and installations in cold climates have not been adequately addressed. System adaptations for steep hillsides need to be more thoroughly evaluated to determine feasibility and cost-effectiveness for a range of slope and soil types. Furthermore, because substrate comprises as much as half the cost of an SF wetland system, alternative substrate materials need to be more thoroughly evaluated for feasibility and cost-effectiveness.

Constructed wetlands are still considered alternative treatment technologies. Most state and regional authorities lack permitting criteria specific to constructed wetlands, making permitting often difficult.[221] This problem may be due, in part, to lack of federal regulation for constructed wetland waste treatment systems and lack of adequate knowledge among regulators about these systems.[222] While some Appalachian states restrict local permitting of constructed wetland systems, publication of state guidelines and simplification of permitting have facilitated implementation. For example, since 1992, when Kentucky developed guidelines and authorized restricted local approval of constructed wetlands, over twelve hundred residential systems have been installed in the state. In Mississippi, where early NASA guidelines were used to help communities design and build constructed wetlands, over one thousand residential systems have been constructed.

Public education is critical to the spread of ecological wastewater treatment systems in Appalachia.[223] Low-income communities surveyed by the authors have expressed distrust of outside intervention and concerns about expensive treatment systems mandated by regulatory authorities. Where public education by enthusiastic users, public officials, and technical experts has occurred, the use of constructed wetlands has proliferated.[224] A problem for much of Appalachia, however, is the lack of proximate functioning systems and accessibility to people knowledgeable about the technology. Therefore written materials are important for continuing development of the technology in the region. These materials should be designed for the layperson and discuss feasibility, cost effectiveness, implementation, and maintenance. Such materials are not readily available.

Materials that are available include design manuals and guides, a national wetland case-study collection, the Texas Constructed Wetlands Feasibility Study, and the STEP program. The contributions and limitations of each to the literature are important to specify in order to identify gaps that should be filled.

Several design manuals and guides are valuable resources or models of the kind of information needed in Appalachia. Recent publications[225] propose solutions to some of the earlier problems in the technology, although they do not address feasibility or cost-effectiveness for a given site or permitting procedures. Furthermore, inadequate funding limits accessibility of relevant manuals. For example, a concise and informative Pennsylvania handbook[226] is already out of print and may not be available in any libraries in the region.[227] In addition, the Pennsylvania guide does not adequately address alternative substrates, effluent disposal, cost-effectiveness in relation to slope, or important innovations, such as vertical flow wetlands and AEES.

After reviewing existing manuals, it is clear that there are no standard design guidelines for constructed wetlands. This can be problematic since some manual specifications directly conflict with information in other manuals. The US EPA is in the process of revising its design manual; the revision may eliminate some of the differences of opinion on recommended length-to-width ratios, types of materials used, sizing calculations and removal efficiencies. The US EPA, however, must consider a full spectrum of situations not specific to Appalachia and may not adequately address the site constraints typical of Appalachia. Therefore, a design manual specific to Appalachia should also be developed. Since Kentucky has the most working constructed wetlands (over 1200) for onsite treatment, it may be wise to use its guidelines as the basis for a regional Appalachian design manual. This will enable Ohio and other states that have limited experience with constructed wetlands to review designs proven effective elsewhere in Appalachia.

The 1993 EPA wetland case-study collection[228] provides a model of an accessible, informative constructed wetland survey that could be adapted to a study of Appalachian systems. Such a survey, providing portraits of successful applications of the technology in the region, would be a compelling educational tool for communities addressing wastewater treatment problems. The EPA case studies focus on FWS constructed wetlands for large systems; a similar set of case studies should be published to include a discussion of SF wetlands, for both public and onsite systems, as well as AEES technologies. Due to the sparseness of operating systems in many parts of Appalachia and the inability of many people in the region to see first-hand how these systems work, a published case study guide, written for the layperson, would be a valuable resource for accelerating the application of this technology.

The Trinity River Watershed Study offers two important models to Appalachia: its systems model site questionnaire and its site factor maps. Adapting them to evaluate SF wetland feasibility and factors critical to Appalachian conditions, especially the relationship between slope and cost-effectiveness, will be necessary to make them useful tools for this region.

The STEP model, as noted above, can offer significant savings to poor communities[229] and thus provides another important framework for community education, assessment, and implementation of wastewater treatment systems. Use of the model to guide constructed wetland implementation in Appalachia should be seriously considered. Information gathered on uses of STEP in other regions can provide a model of effective community wastewater treatment problem-solving and alternative technology implementation.

Missing from the literature is an accessible homeowners' operation and maintenance manual with illustrations. Current substitutes, such as the nine pages of the TVA manual distributed to homeowners by the Alabama Department of Health, are inadequate, providing no illustrations and insufficiently addressing regular seasonal maintenance requirements and special circumstances, such as extreme weather or extended lack of use.

Several educational publications describe aspects of constructed wetlands technology, cost effectiveness, system design, and maintenance. However, there are few comprehensive sources of such information and none directly applicable to Appalachia. Needed are:

- site specific maps and systems models to determine potential cost-effectiveness throughout the Appalachian region,
- introductory materials, including discussions of important innovations and permitting, directed at citizens with little knowledge of how these systems work and can work for them, and
- operation and maintenance manuals written for homeowners.

The production of a comprehensive resource guide, including Appalachian case studies and testimonials of how these systems can work effectively for residents of the region, should contribute to use of this technology in Appalachia.

Public health and environmental integrity depend on the availability of cost effective systems, easy to operate and requiring few energy inputs. Constructed wetlands can provide solutions to these problems for more residents of Appalachia only if comprehensive information is accessible. Addressing these issues provides a unique opportunity to involve rural Appalachians in a collaborative effort to address water-quality concerns, protect aquatic resources, and improve both regional infrastructure and social capital through increased environmental awareness and training.

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1 US EPA, *Engineering Bulletin: Constructed Wetlands*, 1.

2 Although composting toilets conserve a large percentage of household wastewater, do not require chemical or significant energy input, produce an end product that can be recovered for use on-site as fertilizer or soil conditioner, and can be used to reduce the area required for drain-fields or wetlands to treat wastewater, there are cultural, regulatory, and economic barriers to their broad-scale application in Appalachia. Major cultural barriers include a lack of public familiarity with these systems (Geist, *Composting Privy,* 36) and a reluctance to handle and bury the composted waste. (Averill, *Wood Frame Composting,* 14) Regulatory barriers include restricted or inconsistent state health department approval and wide variability of local regulations regarding waste disposal. (Fritsch, *Domestic Wastewater,* II-26) For example, some local plumbing codes require homeowners to install full-sized septic tanks to treat graywater on site (Clayton, *Gap Mountain Permaculture,* 5) or install sewer lines and a flush toilet as a back-up. (Riggle, *Technology Improves,* 39) The major economic barrier is the cost of properly treating the remaining graywater, which can contain bacterial and viral pathogens. (Berkowitz, *Wastewater Treatment,* 50; Kreissl, *Experience with Biological Toilets,* 97) An initial objective of this research was to develop composting toilet plans for use in home repair programs for low-income households. However, several existing designs have been identified that can be used for this purpose. (Clayton, *Gap Mountain Permaculture;* Costner, *Downstream,* 40; Fritsch, *Domestic Water,* II-22, II-23; and Mother Earth, *Composting Commode*) Due to the existence of these designs and to the limitations of composting toilets for public use, this project's focus has shifted to constructed wetlands and AEES as alternative technologies for potential

widespread application in Appalachia. Composting toilets are self-contained, waterless units designed to facilitate the decomposition of human waste and render it safe for subsurface soil application. Waste must be transported from the unit for appropriate burial. Composting toilets can conserve the 40% of household potable water normally consumed by flush toilets. (Clayton, *Gap Mountain Permaculture,* 3; and Fritsch, *Domestic Water and Waste,* 18) Composted human waste can be used as a fertilizer and soil conditioner around fruit trees, shrubs and ornamental plantings but must be buried at least six inches below the soil surface (Kreissl, *Experience with Biological Toilets,* 94; Clayton, *Gap Mountain Permaculture,* 6; Kourik, *The Straight Poop,* 22; and Fritsch, *Domestic Wastewater,* 18) and two hundred feet from water sources to prevent contamination. (Cook, *Field Evaluation,* 90) Certification of composting toilets by the National Sanitation Foundation International (NSFI) is a widely accepted means of determining their efficiency and required by at least 5 of 12 Appalachian states, according to a NSFI 1993 survey. Introduced into the US in the 1970s, by 1981 there were an estimated 5,000 units in use. (Smith, as cited in Kreissl, *Experience with Biological Toilets,* 93) An authors' survey concluded there are approximately 25,000 now in use. Although no statistics are available for the number of units sold to Appalachian residents, a leading distributor in the Appalachian region reported sales of 250 units since 1990. Composting toilets have been installed at public locations in at least 26 Appalachian counties. SEE DIAGRAM # 1. The Gap Mountain Permaculture Project's passive solar composting toilet is designed to function in cold climates and require less turning of the composting material. Compost removal is required only every two to four years. The free-standing unit costs about $1,300 for materials; units incorporated into initial construction cost only about $400. Gap Mountain staff have stated that the main limitation to use of their systems is cultural beliefs about human waste and regulations which enforce them. (Clayton *Gap Mountain Permaculture*) Other innovative approaches to composting toilet design include vermicomposting, (Clayton, *Gap Mountain Permaculture,* 6; Riggle, *Technology Improves,* 42; White, *Plan for Remote Alaska,* 3) remote monitoring equipment, (Riggle, *Technology Improves,* 43) and solar- and wind-powered fans and heating units. (White, *Plan for Remote Alaska,* 3) Efforts to address economic barriers have resulted in development of low-cost, owner-built solar-heated units. (Clayton, *Gap Mountain Permaculture*; Costner, *Downstream,* 41; Fritsch, *Domestic Water;* II-22, II-23 and Mother Earth, *Composting Commode*) Plans for these systems can be readily obtained, but none of the owner-built units have been certified by the NSFI.

3 US GAO, *Water Pollution Information,* 4; Reed, *Wastewater Treatment,* 149.
4 US GAO, *Water Pollution Information*; Sauter, *Natural Home Remedy,* 1.
5 Office of Water Supply, *Waste Disposal Practices,* 1.
6 Macler, *Update on Groundwater Disinfection,* 14.
7 US GAO, *Water Pollution Information,* 12, 14.
8 Office of Water Supply, *Waste Disposal Practices,* 22.
9 Hagedorn, *Groundwater Pollution,* 192; and Macler, *Update on Groundwater Disinfection,* 14.
10 US GAO, *Water Pollution Information,* 9.
11 Innovative technologies are considered cutting edge and not fully proven. Alternative technologies are considered relatively more proven and have been used or demonstrated.
12 US EPA, *Environmental Technology Initiative,* ii.
13 US EPA, *"Living Machine,"* i.
14 ETV program brochure - US EPA National Risk Management Research Lab., Washington, D.C.
15 Berkowitz, *Onsite Wastewater Treatment,* 46; and Watson, *Demonstration on Sand Mountain,* 1.
16 Berkowitz, *Onsite Wastewater Treatment,* 46; and Gover, *Park Showcases Treatment,* 1.
17 Author's survey of state health department officials; statistics provided were estimates.
18 Ohio EPA, *Management Systems Information Database.*
19 Watson, *Demonstration on Sand Mountain,* 1.
20 Berkowitz, *Onsite Wastewater Treatment,* 46.
21 "NPDES permits specify allowable flows and chemical quality discharges into waters of the U.S. based on established water quality standards for those receiving waters." (Kadlec, *Treatment Wetlands,* 587.)
22 BOD is comsumption of oxygen by biological and chemical reactions
23 Kadlec, *Treatment Wetlands,* 44. Aerobic processes take place in the presence of free or elemental oxygen. Anaerobic processes take place in the absence of free or elemental oxygen.

[24] Farrell, *Treating Sewage Naturally,* 82.
[25] US EPA, *Subsurface Flow Wetlands,* 2-1. SF wetlands have particular advantage over FWS wetlands in cold climates due to subsurface water levels and the insulation provided by the decaying vegetation. (Sabo, *Constructed Wetlands,* 79; and US EPA, *Subsurface Flow Wetlands* , 2-1)
[26] Amberg, *Rock-Plant Filter*; ASPI, *Constructed Wetlands*; Jester, *Onsite Plant-Rock Filter*; Jester, *Plant Rock Filter*; Smith, *Design Consideration*; and Steiner, *General Design Guidelines.*
[27] US EPA Constructed Wetland Treatment Systems Database.
[28] Kadlec, *Treatment Wetlands,* 572-3.
[29] Corbitt, *Wastewater Treatment,* 231; and Watson, *State of the Art,* 14.
[30] Lorain County Health Department, *Installers Guide,* 1; and Steiner, *Design Guidelines,* 6.
[31] US GAO, *Water Pollution Information,* 18-19.
[32] US EPA, *Design Manual,* 25.
[33] US GAO, *Water Pollution Information,* 14; and Wolverton, *Aquatic Plant Systems,* 5.
[34] Jester, *Plant Rock Filter,* 3.
[35] Jester, *Plant Rock Filter,* 13; and Steiner, *Design Guidelines,* 9.
[36] Steiner, *Design Guidelines,* 22; and Watson, *Sand Mountain,* 5.
[37] Sabo, *Constructed Wetlands,* 79; and Steiner, *Design Guidelines,* 22.
[38] Steiner, *Design Guidelines,* 22.
[39] Kadlec, *Treatment Wetlands,* 76.
[40] Watson, *State of the Art,* 24.
[41] Smith, *Design and Construction,* 8; and Steiner, *Design Guidelines,* 22.
[42] Reed, *The First Generation,* 777.
[43] Corbitt, *Wastewater Treatment,* 235; Jester, *Plant-Rock Filter,* 47-60; Kadlec, *Treatment Wetlands,* 142-143; Lorain County Health Department, *Your Wetland,* 1-6; and Steiner, *Design Guidelines,* 23.
[44] Jester, *Plant-Rock Filter,* 43-45; and Steiner, *Design Guidelines,* 23.
[45] Steiner, *Design Guidelines,* 24; and US EPA, *Subsurface Flow Wetlands,* 8-1.
[46] US EPA, *Subsurface Flow Wetlands,* 2-1, 2-2.
[47] Water Research Centre, *European Guidelines.*
[48] Jester, *Plant Rock Filter,* 1; and Wolverton, *Enhanced Purification Systems, 20.*
[49] Steiner, *General Design Guidelines.*
[50] US EPA, *Engineering Bulletin,* 1.
[51] Pennison, *Microbial Filters,* 1.
[52] US GAO, *Water Pollution Information,* 4.
[53] Information on regulatory policy and design guidelines was obtained from a database entitled *A Guide To State Level Onsite Regilations*, available from the Small Flows Clearinghouse. Additional information was obtained from numerous telephone conversations with state and local officials.
[54] Jester, *Onsite Plant-Rock Filter*; and Jester, *Plant Rock Filter.*
[55] Jester, *Onsite Plant-Rock Filter,* 3; and Watson, *State of the Art,* 7.
[56] Lorian County General Health District, *Installer's Guide to Constructed Wetlands.*
[57] Davis, *Handbook, Vol. 1-5.*
[58] Cueto, *Criteria for Design,* 99-103; Reed, *Wetlands for Wastewater,* 149; and US EPA, *Engineering Bulletin,* 8.
[59] Waterman, *Wetlands Database,* 88.
[60] Steiner, *Municipal Wastewater,* 1; Reed, *First Generation,* 781; Watson, *Performance at Iselin,* 13; US EPA, *Subsurface Flow Wetlands,* 9-1; Watson, *Municipal Treatment,* 1; and Wolverton, *Enhanced Purification Systems,* 12.
[61] Cueto, *Criteria for Design,* 102; Kadlec, *Treatment Wetlands,* 634-8; Reed, *Wetlands for Wastewater,* 149; US GAO, *Water Pollution Information,* 4; and Wolverton, *Natural Purification Systems,* 9.
[62] Reed, *First Generation,* 778.
[63] US EPA *Subsurface Flow Wetlands,* 5-2.
[64] Steiner, *Design Guidelines,* 4; and US EPA, *Engineering Bulletin,* 8.
[65] US EPA, *Subsurface Flow Wetlands,* 5-2.

[66] Although cost of land can involve significant initial expense, land in a constructed wetland should not depreciate in value, unlike capital expenditures of conventional systems. Thus Kadlec argues that land costs should not be included in cost assessments. (*Treatment Wetlands,* 635-7)

[67] Piney Woods, *Trinity Watershed,* 17.

[68] Jenssen, *Northern Environments,* 2.

[69] Reed, *Wetlands for Wastewater,* 155.

[70] Piney Woods, *Trinity Watershed.*

[71] Bastian, *Treatment and Recycling,* 65; Davis, *Handbook Vol. 2,* 6; and Ogden, *Ammonia Removal,* 120.

[72] Ogden, *Ammonia Removal,* 127; and Black Gearheart as cited in Watson, *Design and Performance at Iselin, 12.*

[73] Jenssen, *Adapting Wetlands,* 3.

[74] Steiner, *Design Guidelines,* 11.

[75] Jaster, *Plant Rock Filter,* 12; Jenssen, *Adapting Wetlands, 3rd page;* and US EPA, *Subsurface Flow Wetlands,* 3-14.

[76] Gover, *Winter's Chill,* 4.

[77] Advanced Ecologically Engineered Systems (AEES) are constructed aquatic treatment systems that utilize a combination of biological treatment processes to treat wastewater and sludge. The treatment ponds that do much of the biological waste processing are constructed in greenhouses, under light shelters, or outdoors, depending on the climate.

[78] BioCycle, *Less Chemicals, More Plants,* 21; Peterson, *Greenhouse Aquaculture,* 91; and Spencer, *Solar Aquatic Treatment,* 90.

[79] Davis, *Handbook, Vol. 2,* 7; and Watson, *Bear Creek,* 70-71.

[80] Piney Woods, *Trinity Watershed,* 40; and Watson, *Design and Performance at Iselin,* 6.

[81] Davis, *Handbook, Vol. 2,* 10.

[82] Watson, *Design and Performance at Iselin,* 6.

[83] Watson, *Bear Creek,* 70.

[84] Piney Woods, *Trinity Watershed,* 46.

[85] Pers. com, Chris Wilson - Design and engineering consultant, Jan. 1997.

[86] Gillette, *Wetlands Treatment,* 78; Reed, *Wastewater Treatment,* 149; and US EPA, *Subsurface Flow Wetlands,* 9-1. See endnote 66 for further discussion.

[87] ASPI, *Technical Paper,* 1.

[88] Clayton, *Gap Mountain Permaculture,* 3; and Fritsch, *Domestic Wastewater and Waste,* 18.

[89] ASPI, *Artificial Wetlands,* 4.

[90] US EPA, *"Living Machine,"* (Parsons Evaluation), 2-1.

[91] Piney Woods, *Trinity Watershed,* 18.

[92] Jester, *Plant Rock Filter,* 3; Steiner, *Design Guidelines,* 9; US EPA, *Wetlands for Wastewater,* 45; and Watson, *Sand Mountain,* 4.

[93] US EPA, *Wetlands for Wastewater and Wildlife,* 45.

[94] Piney Woods, *Trinity Watershed,* 42.

[95] Pers. com, George Allison, Alabama Department of Public Health, June 1997.

[96] Piney Woods, *Trinity Watershed,* 18.

[97] US GAO, *Water Pollution Information,* 12, 14; and Watson, *Sand Mountain,* 3.

[98] Recommended liners include heavy duty, UV resistant, 30-45 mil. membrane, such as ethylene propylene diene monomer (EPDM) rubber, polyvinyl chloride, or polyethylene. Exfiltration may also prevent water levels adequate to maintain wetland plants. Infiltration of groundwater can decrease hydraulic retention time by overloading the system. (Steiner, *Design Guidelines,* 15)

[99] Piney Woods, *Trinity Watershed,* 40; Sabo, *Constructed Wetlands,* 79; and US GAO *Water Pollution Information,* 12, 14.

[100] Farrell, *Treating Sewage Naturally,* 31; and Zavoda, *Greenhouse Filter System,* 17.

[101] Sabo, *Constructed Wetlands,* 79; and Zavoda, *Greenhouse Filter System,* 17.

[102] BioCycle, *Less Chemicals, More Plants,* 21; Larson, *Living Machines,* 34; Sabo, *Constructed Wetlands,* 79; US EPA, *Wetlands for Wildlife,* 78, 148; US GAO, *Water Pollution Information, 15, 16;* and Waste Dynamics, *Ecological Treatment,* 21.

[103] Florida Naturalist, *Wastewater at Corkscrew;* Larson, *Living Machines,* 34; Waste Dynamics, *Ecological Treatment,* 21; and Zavoda, *Greenhouse Filter System,* 17.
[104] US EPA, *Subsurface Flow Wetlands,* 5-3.
[105] Brodie, *Evaluation of Substrate,* 393.
[106] Turner, *Bed Media,* 5.
[107] ASPI, *Appalachian Alternatives (Spring 1995),* 2.
[108] Jensson, *Adapting Wetlands,* 2; Reed, *Performance Evaluation,* 244; and US EPA, *Design Manual,* 22-23. Hydraulic residence time refers to the amount of time wastewater spends in a wetland bed or other system component. HRT is, expressed as the mean volume divided by the mean outflow rate.
[109] Jensson, *Adapting Wetlands,* 2. Eutrophic water has an excess of plant growth nutrients, resulting in algal blooms and dissolved oxygen concentrations.
[110] Davies, *Phosphorous Removal,* 319; and US EPA, *Design Manual,* 58.
[111] Farrell, *Treating Sewage Naturally,* 83.
[112] US EPA, *Subsurface Flow Wetlands,* 3-17.
[113] US EPA, *Design Manual,* 10.
[114] US EPA, *Subsurface Flow Wetlands,* 3-17; Watson, *Bear Creek,* 17. Adsorption is the adherence of a dissolved chemical, liquid, or gas to the surface of a solid.
[115] Reed, *First Generation,* 780.
[116] Kadlec, *Treatment Wetlands,* 445.
[117] Platt, *Cleaning Water,* 30.
[118] US EPA, *Design Manual,* 48-51.
[119] Platt, *Cleaning Water,* 30.
[120] US EPA, *Design Manual,* 53.
[121] Reed, *Wetlands for Wastewater,* 153.
[122] Steiner, *Design Guidelines,* 21.
[123] Jester, *Plant Rock Filter,* 13.
[124] US EPA, *Wetlands for Wildlife,* 78, 148.
[125] BioCycle, *Less Chemicals, More Plants,* 21; Larson, *Living Machines,* 34; National Audubon; Waste Dynamics, 3, 21; and Zavoda, *Greenhouse Filter System,* 17.
[126] Zavoda, *Greenhouse Filter System,* 17-18; Pers. com. Michael, Zavoda, Jan. 1997.
[127] Davis, *Handbook Vol. 2,* 12; Ogden, *Ammonia Removal,* 120; Reed, *Performance Evaluation,* 246; US EPA, *Subsurface Flow Wetlands,* 3-10; and Watson, *State of the Art,* 11.
[128] Davis, *Handbook Vol. 2,* 12; Ogden, *Ammonia Removal,* 120; and Reed, *Performance Evaluation,* 246.
[129] Lesikar, *Systems for Treatment and Reuse,* 1.
[130] Farrell, *Wastewater in Greenhouses,* 31; and Ohio Cooperative Extension, *Bulletin 744.*
[131] Kadlec, *Treatment Wetlands,* 380, 422.
[132] Davis, *Handbook, Vol. 2,* 25; and US EPA, *Design Manual,* 10.
[133] Farrell, *Treating Sewage Naturally,* 83.
[134] US EPA, *Subsurface Flow Wetlands,* 9-1; Watson, *State of the Art,* 16.
[135] Burgoon, *Batch Load,* 855; Watson, *Performance at Benton, Hardin, and Pembroke,* 179; and Watson, *State of the Art,* 11, 17, 18.
[136] Reed, *Performance Evaluation,* 247-8; and US EPA, *Subsurface Flow Wetlands,* 2-2.
[137] Watson, *State of the Art,* 19.
[138] Watson, *Pilot Scale Studies,* 301.
[139] Watson, *State of the Art,* 12.
[140] Reed, *Performance Evaluation,* 248.
[141] Watson, *Pilot-Scale Studies,* 302.
[142] Watson, *State of the Art,* 19.
[143] US EPA, *Subsurface Flow Wetlands,* 8-1.
[144] US EPA, *Design Manual,* 25.
[145] Reed, *First Generation,* 780.
[146] Freeman, *Experience in the Southeast,* 6; US EPA, *Subsurface Flow Wetlands,* 3-13; and Watson, *Bear Creek,* 16.
[147] Reed, *Performance Evaluation,* 247.
[148] Canody, *Texas Studies,* 9.

[149] Davis, *Handbook Vol. 2,* 14; Reed, *Performance Evaluation*, 247; and US EPA, *Subsurface Flow Wetlands*, 4-16.
[150] Freeman, *Experience in the Southeast*, 6; and Watson, *Bear Creek*, 16.
[151] Burgoon, *Batch-Load,* 860.
[152] Reed, *State of the Art,* 21; and Watson, *Performance at Benton, Hardin, and Pembroke,* 11.
[153] Alexandersson, *Living Water,* 135. Flowforms are used to aerate wastewater by the Swathworth Foundation near Munich, Germany. (Bill Mollison, *The Global Gardener*)
[154] Kadlec, *Treatment Wetlands,* 217; and Watson and Hobson, and Choate as cited in Watson, *Bear Creek*, 14.
[155] Sabo, *Constructed Wetlands,* 79.
[156] Freeman, *Experience in the Southeast,* 5; and US EPA, *Subsurface Flow Wetlands,* 4-6.
[157] US EPA, *Subsurface Flow Wetlands,* 4-3.
[158] Kadlec, *Treatment Wetlands,* 215.
[159] Kadlec, *Treatment Wetlands,* 215; and Reed, *First Generation,* 780.
[160] Reed, *First Generation,* 780.
[161] Amberg, *Rock-Plant Filter,* 5; Sabo, *Constructed Wetlands,* 78; and Steiner, *Design Guidelines,* 13.
[162] Reed, *Performance Evaluation*, 248.
[163] Freeman, *Experience in the Southeast,* 5; and US EPA, *Subsurface Flow Wetlands,* 4-5.
[164] Davis, *Handbook Vol. 2,* 22; Freeman, *Experience in the Southeast*, 5; and US EPA, *Subsurface Flow Wetlands,* 4-5.
[165] Reed, *First Generation,* 780.
[166] Davis, *Handbook Vol. 2,* 22.
[167] Reed, *First Generation,* 780.
[168] See endnote # 2 for discussion and references.
[169] Fritsch, *Domestic Wastewater and Waste,* 18.
[170] BioCycle, *Less Chemicals, More Plants,* 21; Farrell, *Treating Sewage Naturally,* 82; Farrell, *Purifying Wastewater,* 33; Larson, *Living Machines,* 34; Peterson, *Greenhouse Aquaculture, 2-3*; and Spencer, *SolarAquatic Treatment.*
[171] Gillette, *Close to Nature, 78;* US EPA *"Living Machine,"* (Parsons Evaluation) 2-1; and Zavoda, *Greenhouse Filter System,* 17.
[172] Farrell, *Treating Sewage Naturally,* 82; Larson, *Living Machines,* and Victory, *Chocolate Factory.*
[173] Farrell, *Treating Sewage Naturally* , 82; and Waste Dynamics, *Ecological Treatment,* 21.
[174] Farrell, *Treating Sewage Naturally,* 82; Florida Naturalist, *Wastewater at Corkscrew*; Meadows, *New Alchemist*; and Zavoda, *Greenhouse Filter System.*
[175] BioCycle, *Less Chemicals, More Plants,* 21; Farrell, *Treating Sewage Naturally,* 82; Farrell, *Purifying Wastewater,* 33; Larson, *Living Machines,* 34; Peterson, *Greenhouse Aquaculture, 2-3*; and Spencer, *Solar Aquatic Treatment.*
[176] US EPA, *"Living Machine."* 13-3.
[177] Waste Dynamics, *Ecological Treatment,* 3, 21.
[178] US EPA, *"Living Machine,"* v-vi.
[179] US EPA, *"Living Machine."*
[180] This unit is a partially buried, 15' wide by 28' long anaerobic reactor tank containing a six foot internal dam with a permanent sludge blanket. Strips of poly-propylene mesh netting are suspended from the reactor cover that span the full tank width. Sludge settles within this unit and is removed on a weekly basis. (US EPA "Living Machine," 2-3).
[181] A bio-filter containing compost and soil to remove odor (Farrell, *Treating Sewage Naturally,* 80.)
[182] Bacterial additives are Bactapure N for nitrification and XL for breakdown of grease and sludge. Mineral additives consist of Mariah powder to improve mineral content for plant health. Biological additive is kelp meal to supplement potassium content of wastewater.
[183] US EPA, *"Living Machine,"* 2-3, 2-5.
[184] US EPA, *"Living Machine,"* 2-5; and Zavoda, *Greenhouse Filter System,* 17.
[185] US EPA, *"Living Machine,"* 2-5, 2-6.
[186] BioCycle, *Less Chemicals, More Plants,* 21; Farrell, *Treating Sewage Naturally,* 82; Farrell, *Purifying Wastewater,* 33; Larson, *Living Machines,* 34; Peterson, *Greenhouse Aquaculture, 2-3*; and Spencer, *SolarAquatic Treatment,*

[187] Farrell, *Treating Sewage Naturally,* 80; Spencer, *Solar Aquatic Treatment,* 67; and US EPA, *"Living Machine,"* 2-1.

[188] The Four Elements Company built an early AEES at the Sugarbush Ski Resort near Warren, Vermont (Meadows, *New Alchemist,* 40)

[189] Meadows, *New Alchemist,* 40. Living Technologies was formerly named Advanced Greenhouse Systems. (Farrell, *Purifying Wastewater in Greenhouses,* 31)

[190] Peterson, *Greenhouse Aquaculture,* 1.

[191] Farrell, *Treating Sewage Naturally,* 82.

[192] US EPA, *"Living Machine," v.*

[193] BioCycle, *Less Chemicals, More Plants,* 21; and Farrell, *Treating Sewage Naturally,* 82.

[194] US EPA, *"Living Machine,"* 14-1, 14-3.

[195] Farrell, *Treating Sewage Naturally,* 83.

[196] Spencer, *Solar Aquatic Treatment,* 69-70.

[197] Spencer, *Solar Aquatic Treatment,* 69-70.

[198] Conway, *The Iselin Marsh,* 139; Davido, *Nitrification at Iselin,* 480; and Watson, *Design and Performance at Iselin,* 11.

[199] Davido, *Nitrification and Denitrification,* 477-478.

[200] Watson, *Performance at Iselin,* 13-15.

[201] Wolverton, *Natural Purification Systems,* 9.

[202] US GAO, *Water Pollution Information,* 14; and US EPA, *Subsurface Flow Wetlands,* B-2.

[203] Watson, *Demonstration on Sand Mountain,* 1.

[204] Steiner, *Design Guidelines*; and Watson, *Demonstration on Sand Mountain,* 2.

[205] Watson, *Demonstration on Sand Mountain,* 8.

[206] Pers. com, George Allison, Alabama Department of Public Health. Jan. 1997.

[207] Steiner, *Design Guidelines,* 22; and Watson, *Demonstration on Sand Mountain,* 4-5.

[208] Watson, *Demonstration on Sand Mountain,* 4-5.

[209] Watson, *Bear Creek,* 2.

[210] Freeman, *Experience in the Southeast,* 6; US EPA, *Subsurface Flow Wetlands,* 3-13; and Watson, *Bear Creek,* 16.

[211] Reed, *First Generation,* 247; Watson, *Bear Creek,* 17.

[212] Watson, *Bear Creek,* ix.

[213] Zavoda, *Greenhouse Filter System,* 17-18.

[214] US GAO, *Water Pollution Information,* 10.

[215] Zavoda, *Greenhouse Filter System,* 17-18; Pers. com, Zavoda, Michael. Jan. 1997.

[216] Watson, *Sand Mountain,* 2-3.

[217] Texas Onsite Insights, *Method to Assess Site,* 4.

[218] Piney Woods, *Trinity Watershed.*

[219] Texas Onsite Insights, *Method to Assess Site,* 4-5; and Piney Woods, *Trinity Watershed,* 17-21.

[220] Hollon, *Innovative STEP Program,* 6.

[221] US GAO, *Wastewater Pollution Information,* 27.

[222] "Alternative systems are sometimes avoided even when they offer potentially substantial cost savings because of uncertainties about their performance and/or costs. Proponents of alternative wastewater systems and skeptics agree that credible, up-to-date performance and cost data are needed to reduce the uncertainties." (US GAO, *Wastewater Pollution Information,* 4-5)

[223] Pers. com, James Watson, Tennessee Valley Authority. April, 1997.

[224] Pers. com, George Allison, Alabama Department of Public Health, January 1997; Pers. com, Jennifer Hause, Technical Systems Specialist, Small Flows Clearinghouse, April 1997; Pers. com. Ralph Turnbow, Mississippi Department of Health, May 1997; Freeman, *Experience in the Southeast*, 2; and Gillette, *Close to Nature,* 74-75.

[225] ASPI, *Constructed Wetlands*; Davis, *Handbook Vol. 1-5*; Jester, *Plant Rock Filter*; Smith, *Design Considerations*; and Steiner, *General Design Guidelines.*

[226] Davis, *Handbook Vol. 1-5.*

[227] Pers. com, T. Murphy, USDA - NRCS. Harrisburg, PA. April 1997.

[228] US EPA, *Wetlands for Wildlife.*

[229] Hollon, *Innovative STEP Program.*

APPALACHIAN REGION

Appalachian Counties with Composting Toilets at Public Sites

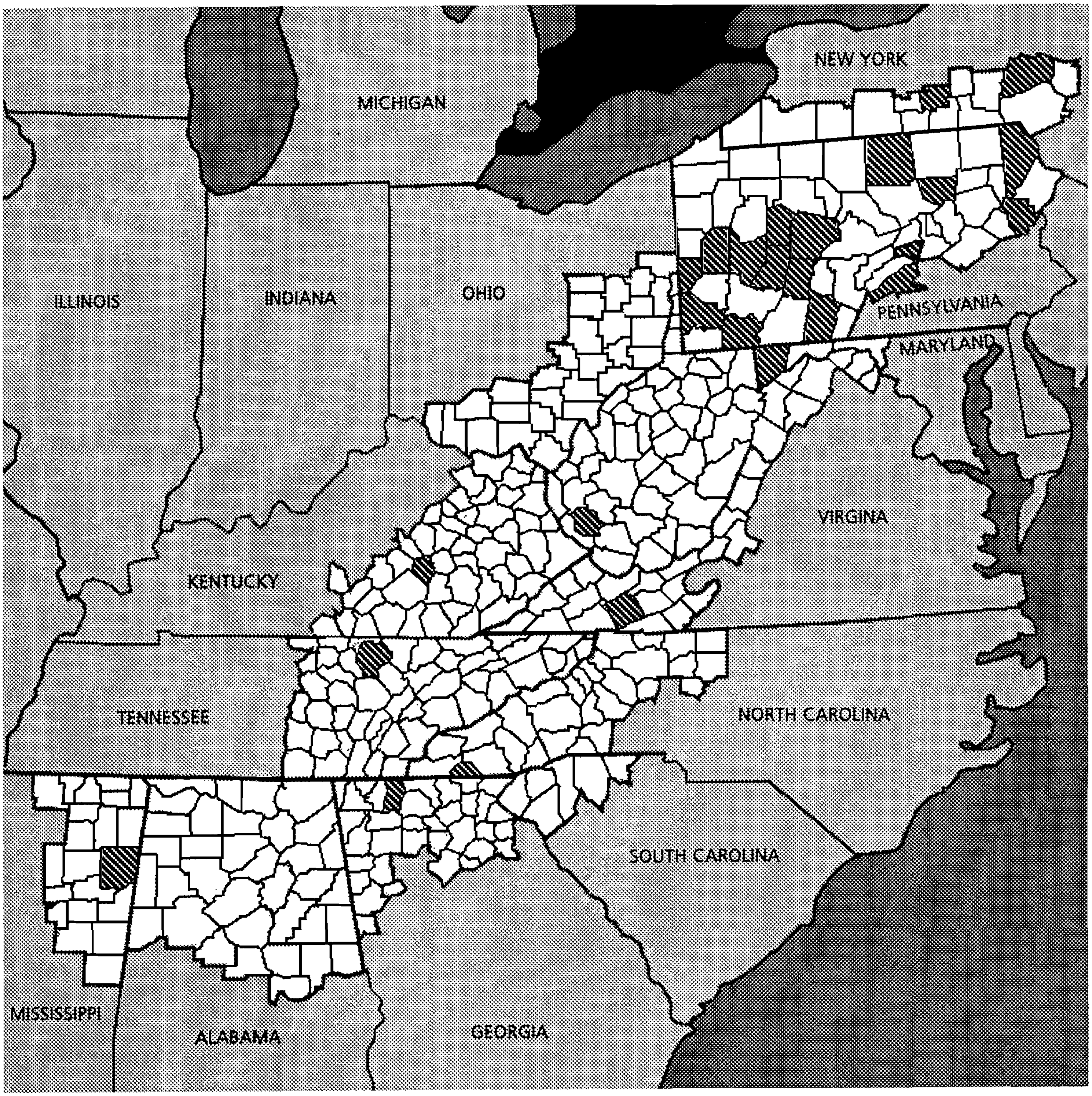
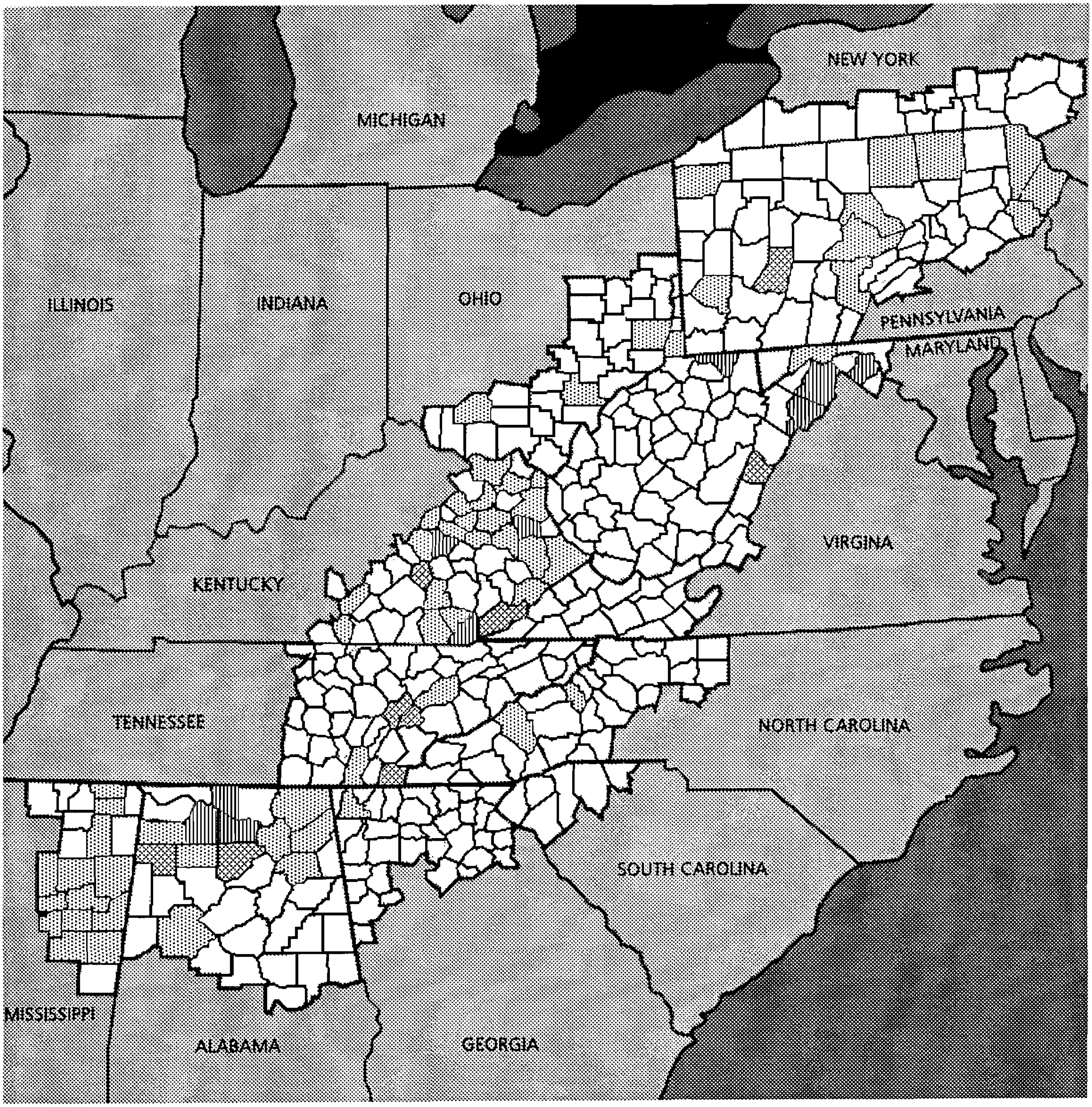


DIAGRAM #1

APPALACHIAN REGION

Appalachian Counties with Residential and Public Wetland Sewage Treatment Systems



RESIDENTIAL
PUBLIC
BOTH RESIDENTIAL & PUBLIC

DIAGRAM #2

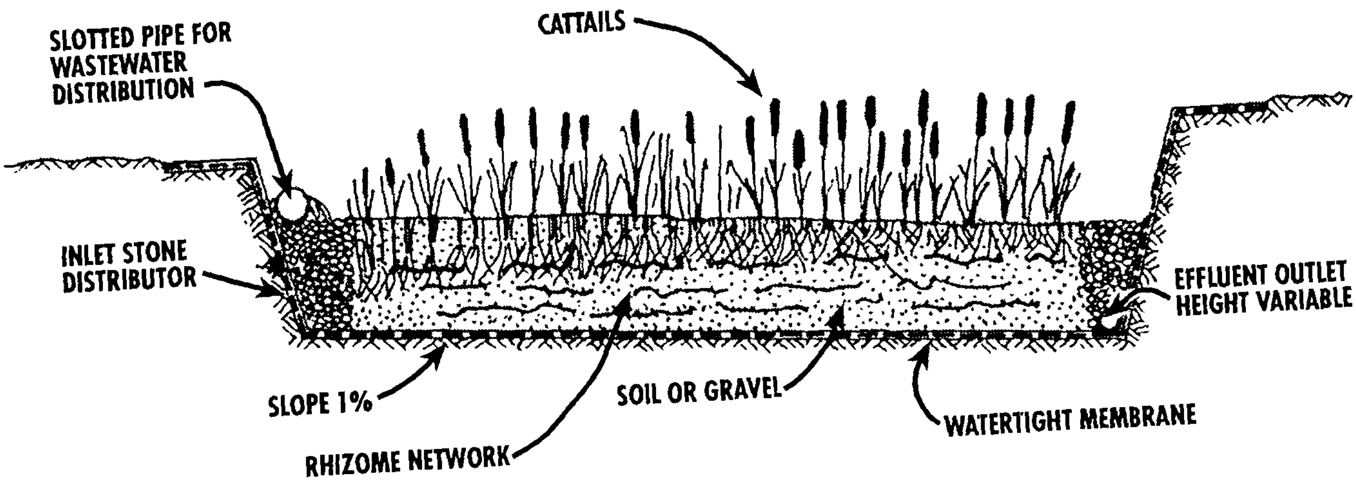

SLOTTED PIPE FOR WASTEWATER DISTRIBUTION
CATTAILS
INLET STONE DISTRIBUTOR
EFFLUENT OUTLET HEIGHT VARIABLE
SLOPE 1%
SOIL OR GRAVEL
WATERTIGHT MEMBRANE
RHIZOME NETWORK

DIAGRAM #3

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