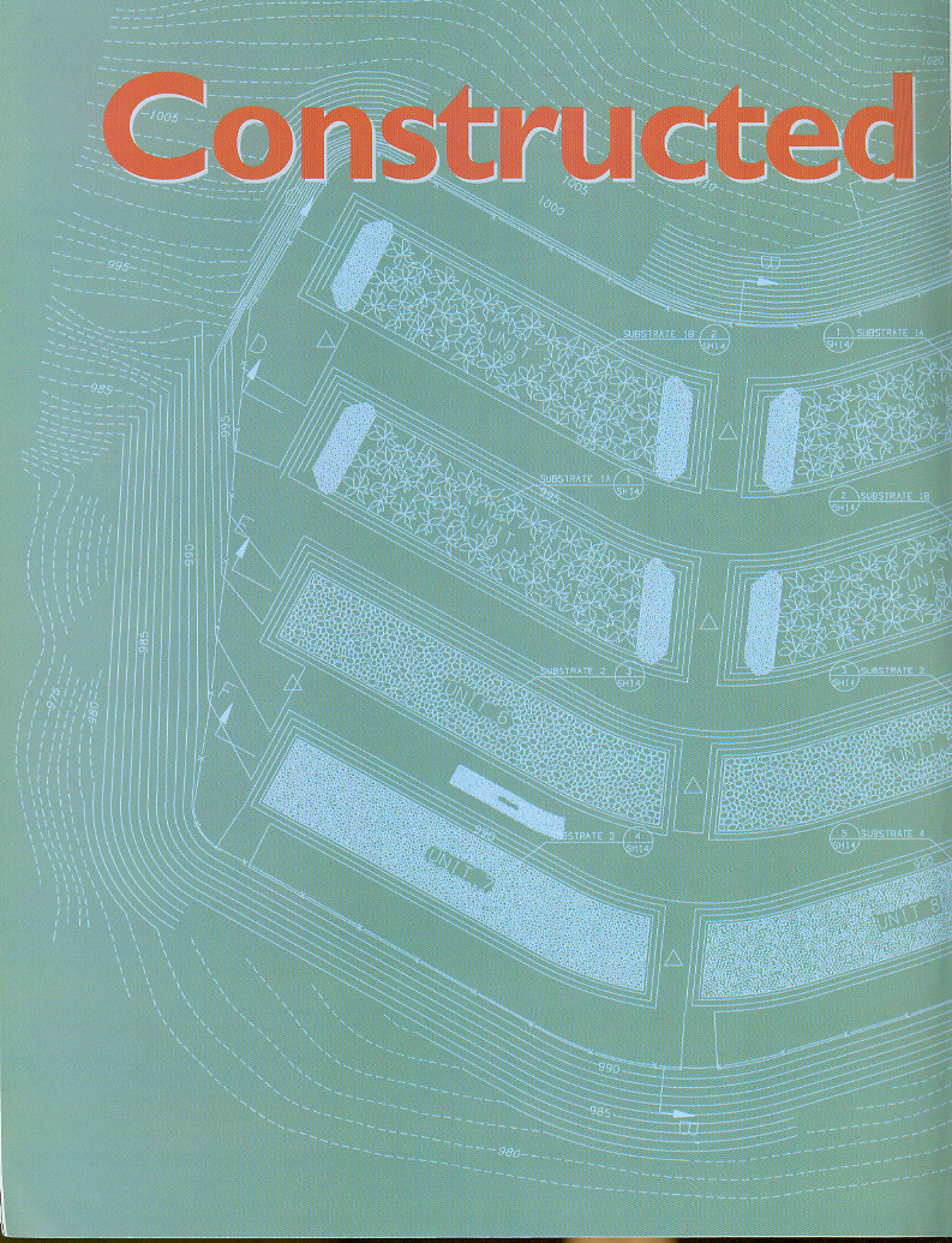
Constructed

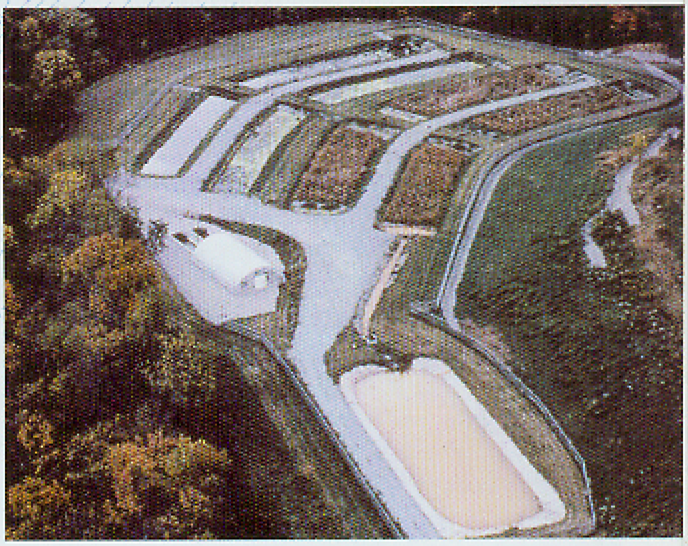


Wetlands

Treat Wastewater Naturally

THE STORY IN BRIEF

By imitating and enhancing the natural cleansing functions performed by wetland ecosystems, constructed wetlands can successfully treat a variety of wastewaters. Through collaborative efforts at sites across the United States, EPRI is directing an applied research program to engineer and optimize constructed wetlands for treating leachate from coal combustion by-products, coal pile runoff, acid mine drainage, and other metal-bearing utility wastewaters. Meanwhile, in complementary laboratory research, the natural biological, chemical, and physical removal mechanisms that occur in wetland soils, microorganisms, and plants are being explored at unprecedented levels of detail, and genetic engineering and other innovative approaches are being applied to accelerate treatment processes.



BY CHRISTOPHER R. POWICKI

Wetlands are among the most productive of natural ecosystems, sharing the characteristics of terrestrial and aquatic environments and acting as buffers between them. In these transition zones, plants and microorganisms interact with water and sediments, reducing the biological, chemical, and physical impacts of the intersecting ecosystems on one another while fueling wetland productivity.

From ancient civilizations in China, Mexico, and Egypt all the way up to the present, human and other waste streams have been directed to wetlands. Wetland processes have thus been protecting surface waters from terrestrial discharges for thousands of years, but their purification potential was not formally recognized until the 1960s. Since then, intensive research and municipal, industrial, and agricultural experience indicate that filtering, flocculation, precipitation, nutrient uptake, photosynthesis, decomposition, volatilization, and other natural processes transform many pollutants—such as excess nitrogen, excess phosphorus, suspended solids, and heavy metals—into biomass, harmless byproducts, or useful nutrients.

Natural wetlands, however, do not always function in the predictable fashion critical to effective environmental control. Moreover, they have great value beyond their control capabilities: they offer unique ecological, aesthetic, and practical benefits, including wildlife habitat, recreational opportunities, groundwater recharging, flood control, and coastal protection. Constructed wetlands enable society to reproduce and exploit the treatment capabilities of natural wetlands while protecting and preserving those dwindling ecosystems.

In constructed wetlands, the processes intrinsic to natural systems occur in a highly engineered environment, with soils and other substrates, vegetation, microbial consortia, flow patterns, size, and other characteristics tightly controlled to reduce variability and increase treatment effectiveness. Many processes are decoupled and isolated in individual wetland cells that perform specific treatment functions or target specific contaminants. Wastewater flows by gravity—either above or below the ground—through these cells, which wetland designers select, sequence, and size on the basis of discharge characteristics and treatment goals.

"Properly designed wetlands greatly exceed the treatment capabilities of natural systems, even though they may look wholly unlike wetland ecosystems," says John Goodrich-Mahoney, EPRI project manager. "What appear to be lifeless ponds, mats of algae, or piles of rocks are actually highly engineered treatment cells; the cleansing processes occur in substrates, the water column, and aquatic plants and organisms, all of which are manipulated to optimize retention, absorption, transformation, and control of specific pollutants."

Intelligent design and engineering of constructed wetlands are the keys to cost-effective cleansing of utility wastewaters. The constructed wetland at Allegheny Power's closed ash management facility near Springdale, Pennsylvania, includes four vegetated aerobic cells. To create these cells, basins were excavated and lined, substrates were installed, and various species of aquatic vegetation were planted.

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Technology drivers

Tighter restrictions are being considered for chemical releases to surface water bodies regulated under the National Pollutant Discharge Elimination System (NPDES). Although a number of states have adopted aggressive toxics control programs, the Great Lakes Water Quality Initiative, or GLI—an international effort to ensure long-term protection of North America's largest freshwater ecosystem—is the force behind many of the changes at the federal level.

Heavy metals commonly found in utility wastewaters are among the GLI's primary targets. Although typically found in discharges at very low levels, these metals can contaminate sediments and can bioconcentrate in aquatic food chains, posing potential risks to wildlife and humans. In the Great Lakes watershed and other basins, traditional discharge standards, which are based on the treatment capabilities of existing technologies, are proving inadequate to mitigate these risks. More-stringent water-quality-based effluent limits—possibly set at or below detection levels for trace elements—are under consideration. In addition, NPDES permits that do not currently incorporate limits on trace elements may be rewritten, and previously unregulated discharges are facing scrutiny.

Conventional chemical treatment technologies for metal-bearing utility discharges are resource-intensive, requiring chemical additions, energy inputs, human supervision, and regular maintenance. Hazardous by-products like chemical sludges can be generated, resulting in disposal costs. And these systems may not even be able to reduce trace element concentrations to the levels called for by emerging water quality criteria. Constructed wetlands, by contrast, are largely self-perpetuating. Resource inputs are minimal once a wetland is installed, and no undesirable by-products are generated. Gravity typically controls flow, and treatment is mediated by microbial processes, aquatic plant growth, and natural chemical and physical mechanisms. Fuel and manpower requirements are at an absolute minimum, resulting in significantly lower operating and maintenance (O&M) costs.

"In numerous municipal, agricultural, and industrial applications over the past 20 years, constructed wetlands have proved highly effective at reducing trace metal concentrations to extremely low levels," says Robert Brocksen, manager of EPRI's Water Toxics Assessment & Watershed Management Business Area. "Meanwhile, the rapid evolution of the electricity enterprise is creating a market incentive for transfer of the technology to the power industry. Constructed wetlands align with both cost reduction and environmental stewardship—near-ubiquitous business goals in the increasingly competitive marketplace."

In collaboration with utilities, environmental engineering firms, and the University of California at Berkeley, EPRI is directing a comprehensive program to develop design and engineering guidelines for the treatment of common metal-bearing waste streams. Ongoing activities include demonstration projects to broaden the experience base; field and laboratory work to increase mechanistic understanding of treatment processes; and experimental work to accelerate or otherwise enhance removal of specific contaminants.

"EPRI's program is introducing new dimensions to constructed-wetland technology," says Goodrich-Mahoney. "Never before have fundamental treatment mechanisms been explored at the levels of detail afforded by advanced analytical techniques, and our efforts to optimize these processes are on the leading edge of microbiology, plant physiology, genetic engineering, and other disciplines."

A brief history

The power industry's experience base with constructed wetlands is relatively limited. And results have been mixed. Most utility systems were designed and constructed in the middle to late 1980s on the basis of numerous successful applications by the coal mining industry. Acid mine drainage is similar to such metal-bearing utility wastewaters as runoff and seepage from coal storage and preparation areas and leachate from some combustion by-product disposal facilities. Common concerns include low pH; high acidity; high concentrations of iron, manganese, and aluminum; and trace concentrations of arsenic, boron, cadmium, chromium, copper, lead, nickel, selenium, zinc, and other chemicals.

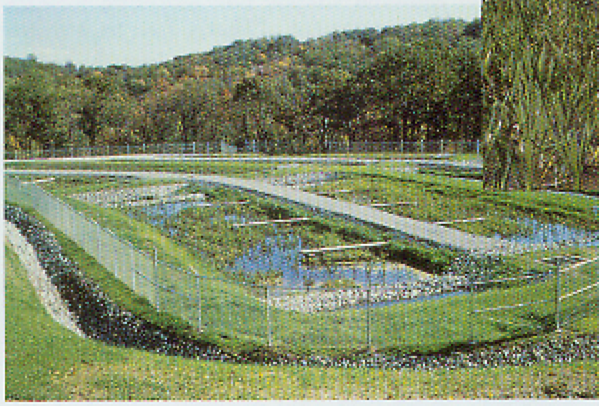
In 1985, the Tennessee Valley Authority installed the industry's first constructed wetland—a system to treat acid seepage from an earthen dike surrounding a coal slurry pond at the utility's Fabius coal preparation plant in Jackson County, Alabama. This initial TVA system, an impoundment that is still operating today, has always produced compliance-quality discharges requiring no additional chemical treatment. "That's not to say we haven't had to climb a learning curve in terms of design, construction, and operation," says Greg Brodie, TVA program manager for water and wastewater. "The impoundment has succeeded only because of serendipity," he explains. "Seepage just happens to flow through a berm constructed largely of limestone; that introduces alkalinity, which results in efficient iron removal. It took us quite a while to figure out why the system worked. We know a lot more now than we did in the 1980s."

Other early utility systems have been plagued by problems. One example is a constructed wetland designed to treat highly acidic seepage from an ash pile in western Pennsylvania. Although the system reduces acidity levels and concentrations of iron, manganese, and aluminum, it produces a noncomplying discharge because it is undersized for the incoming mass loading and lacks the alkalinity-producing components now recognized as critical. In addition, the system has been overwhelmed by high flows during storms. As a result of these problems, the wetland is functioning only as a pretreatment unit; its effluent flows to a chemical system for additional acidity reduction and metals removal.

"The problems experienced at this wetland site are completely avoidable today,"

At the Springdale wetland, the leachate is pumped over a concrete aerator on its way to an equalization basin, where most of the iron removal occurs. The aerator introduces the oxygen necessary for the chemical reaction for iron removal.

Water, sediment, and vegetation samples from the Springdale wetland cells are being analyzed to increase understanding of treatment mechanisms.



says Goodrich-Mahoney. "The keys are increased knowledge of wetland processes and intelligent system design and engineering."

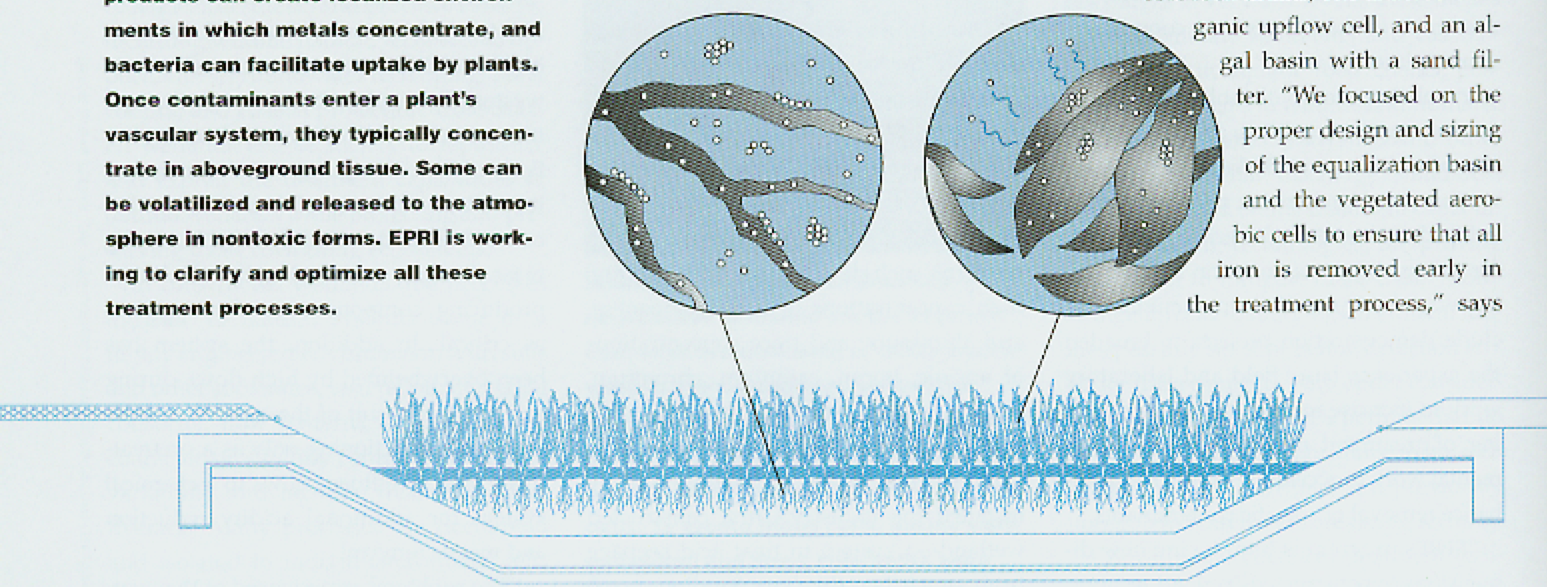
Intelligent engineering

A constructed wetland installed under tailored collaboration with Allegheny Power illustrates the detailed engineering process required to develop effective treatment systems. Located at a closed ash management facility near Springdale, Pennsylvania, the system was designed to treat an underdrain discharge from the facility into Riddle Run, a small tributary of the Allegheny River.

"Because the Springdale site is unmanned, we were looking for a passive, economical treatment technology with low O&M requirements and the ability to meet stringent NPDES limits for iron and other contaminants," says Rick Herd, strategic environmental management advisor at Allegheny Power. "Since 1988, we'd been operating a relatively primitive constructed wetland at our Albright ash disposal facility with mixed results: compliance with iron limits but less luck with manganese and a couple of other trace elements. We were confident that the lessons learned at Albright, along with the expertise and resources EPRI brought to the table, would result in a more intelligent and effective design for Springdale."

The Springdale system's design is based on PERT®—Phased Element Removal Technology. The PERT approach for identifying, ordering, and sizing treatment process steps has these underlying principles: to effect early removal of high-concentration contaminants or constituents that could cause operational problems downstream; to ensure compatible input and output conditions between cells as well as optimal treatment conditions within cells; to maintain close hydraulic control; and to provide conservative flow and treatment capacity margins. "These principles guide the engineering of site- and discharge-specific designs for constructed-wetland systems," says Terry Rightnour, president of EES Consultants, the design contractor. "Designs employing a series of treatment cells have proved to be most effective: each cell can be customized, and a compartmentalized layout enables individual cells to be maintained without disrupting the treatment process."

The Springdale leachate is characterized by a neutral pH and average total iron and manganese concentrations of 13.48 mg/L and 2.74 mg/L, respectively. The constructed wetland, installed in the summer of 1995, consists of an equalization basin followed by eight sequential treatment cells: four vegetated aerobic cells, two aerobic rock drains, one anaerobic organic upflow cell, and an algal basin with a sand filter. "We focused on the proper design and sizing of the equalization basin and the vegetated aerobic cells to ensure that all iron is removed early in the treatment process," says



In vegetated aerobic wetland cells, aquatic plants and soil microorganisms work together to remove heavy metals and other discharge constituents. In the root zone, roots and associated microbes can alter soil chemistry to sequester contaminants, root byproducts can create localized environments in which metals concentrate, and bacteria can facilitate uptake by plants. Once contaminants enter a plant's vascular system, they typically concentrate in aboveground tissue. Some can be volatilized and released to the atmosphere in nontoxic forms. EPRI is working to clarify and optimize all these treatment processes.

Goodrich-Mahoney. "Failure to remove sufficient iron can affect microbial processes that control downstream manganese removal and can also result in the clogging of sensitive substrates critical to the extraction of trace metals," he explains.

Leachate is pumped from the toe of the ash disposal facility over a concrete aerator and into the equalization basin. The basin, basically a concrete-lined pond, moderates flow to the downstream cells and removes most of the dissolved iron. The aerator introduces the oxygen necessary for hydrolysis of the dissolved iron and subsequent settling of iron precipitates. About 70% of total iron is removed by the basin. Some trace metals are also removed there, binding to and coprecipitating with the iron hydroxides.

After flowing by gravity through a rock-lined ditch where additional aeration and iron precipitation occur, the basin's effluent enters the first of the four vegetated aerobic cells. The system components that look and function most like natural wetlands, these cells support various species of aquatic vegetation—including cattails and several grasses—on a submerged, high-organic-content substrate. Numerous environmental control processes occur in the water column, in sediments, and in the root zone (rhizosphere) and vascular system of the aquatic plants.

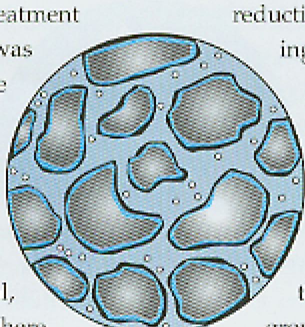
On the basis of early studies of wetland processes, the dominant treatment mechanism for heavy metals was believed to be direct uptake and sequestration by aquatic plants. Now microbially mediated transformations are recognized as the most important mechanism, but wetland plants are essential, creating the oxidized rhizosphere that fosters the growth of specialized microbial communities. In the rhizosphere, these aerobic bacteria facilitate root system uptake of metals from the soil; plants transport these substances to aboveground biomass, where most concentrate but some volatilize to the atmosphere. Roots and their associated microorganisms also can alter soil chemistry, stabilizing and reducing the bioavailability of metals. In addition, roots can create chemical environments that promote the absorption and sequestration of pollutants and support microbial degradation.

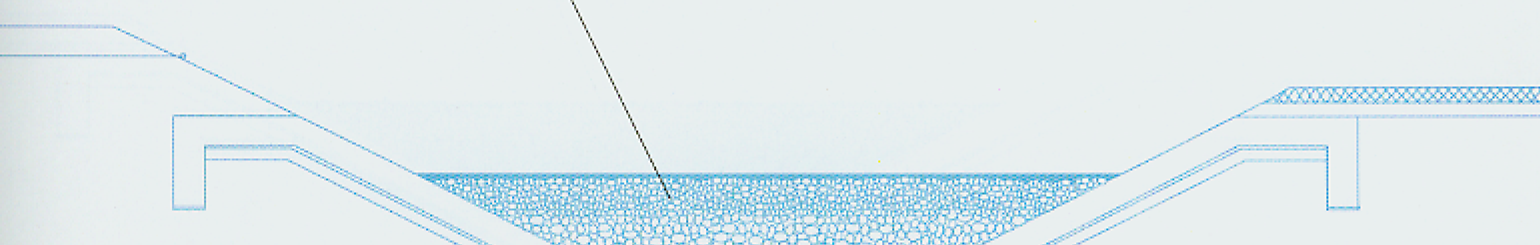
Two rock drains at the Springdale wetland harbor microorganisms that promote manganese removal. Because iron is known to impede manganese uptake and sequestration, the system was designed to remove all iron from the leachate before it enters these drains.

At the Springdale site, the four wetland cells remove residual iron, most of the dissolved manganese, and some trace metals. The initial cell removes most of the residual iron, lowering its concentration to 0.3 mg/L. This cell also removes approximately half the manganese, with further reductions occurring in the remaining three cells.

The first of two aerobic rock drains receives effluent from the final aerobic wetland cell. As the effluent flows over and between rocks of various sizes, the rock surfaces provide a growth substrate for "black slime" bacteria. Although the physiological treatment mechanisms have not yet been identified, these bacteria oxidize dissolved manganese and sequester it as manganese dioxide, reducing its concentration to less than 0.1 mg/L after the initial rock drain.

Effluent from the second rock drain enters an anaerobic organic upflow bed, which was installed to remove trace metals via bacterial sulfate reduction in an anoxic environment. The upflow configu-



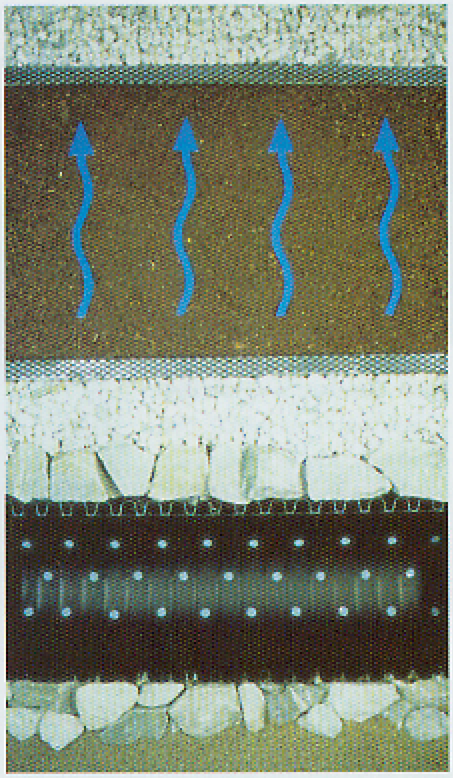


In rock drains, stacked layers of limestone riprap provide surfaces for the colonization and growth of biofilms composed of "black slime" bacteria. As the leachate flows around and between individual rocks, these microorganisms oxidize and sequester dissolved manganese. The biochemical reactions underlying this process are not fully understood, but the end result is that a manganese dioxide precipitate forms on the rock surfaces beneath the biofilm.

ration, in which the discharge flows through perforated pipes installed at the bottom of the bed and then upward through a spent mushroom compost substrate, maximizes hydraulic control. Bacteria in the anoxic substrate generate sulfide, thus promoting the scavenging of trace metals and the subsequent precipitation of metal sulfides.

The final cell is a combined algal basin and sand filter. It removes suspended solids, providing final polishing and clarification of the discharge before its release through a flow measurement flume and into the high-quality receiving-water stream.

Since being brought on-line in the fall of 1995, the Springdale system has removed an average of 97% of total iron and 98% of dissolved iron, bringing the 43-gal/min (average) discharge well under its NPDES limit for this constituent. Removal efficiencies of 89% for manganese and 79% for aluminum have been achieved. In addition, significant fractions of the trace elements arsenic, beryllium, molybdenum, nickel, and zinc are being extracted.



The Springdale discharge flows upward through an anaerobic organic bed where the removal of trace metals is facilitated by microorganisms. The upflow configuration maximizes hydraulic control.

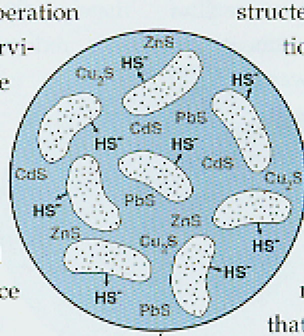
"Our constructed wetland not only achieves permit compliance but also is more cost-effective than conventional chemical systems," says Allegheny Power's Herd. According to the first detailed economic comparison of treatment alternatives, the total projected costs over the next 50 years are $2.5 million for the Springdale installation versus $4.8 to $8.8 million for comparably sized chemical systems. The wetland's advantages arise from low O&M costs: passive operation minimizes the need for supervision; no chemical additions are required; no sludge is generated; and the only regular maintenance task is to remove iron precipitate accumulations, which is expected to be necessary about once every 10 years.

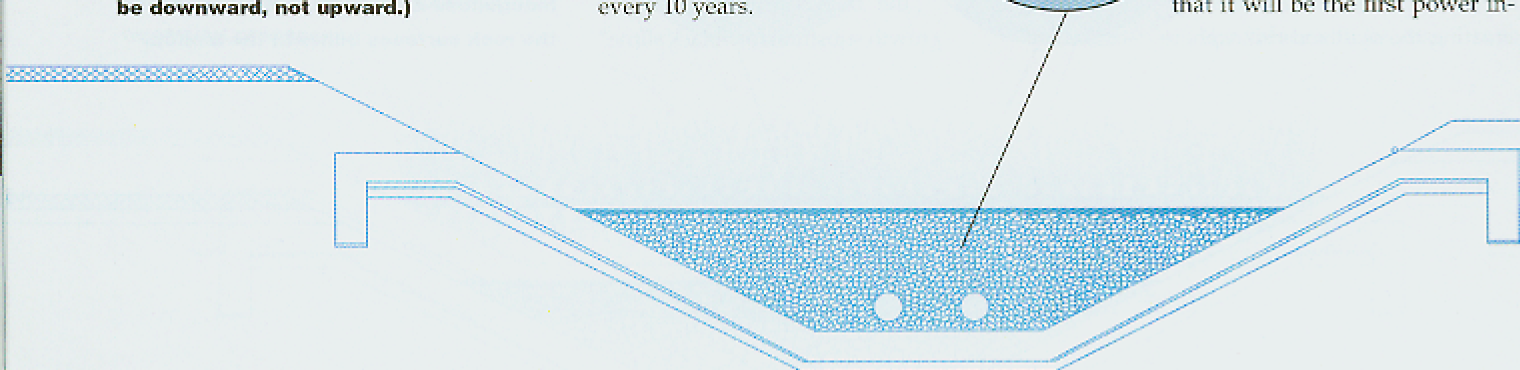
In recognition of these attributes, Allegheny Power received a 1996 Industrial Excellence Award from the Pennsylvania Water Environment Association for the most promising and cost-effective new wastewater treatment system constructed in Pennsylvania. According to Herd, the company plans to mentor the technology in partnership with the state's Department of Environmental Protection, working with citizens' groups, schools, and customers to promote industrial applications of constructed wetlands in its service territory.

The use of constructed wetlands at other Allegheny Power facilities is currently under evaluation. In addition, knowledge gained from the Springdale site is being applied to upgrade the utility's initial Albright system. A rock drain is being added to provide a final treatment cell that will increase the removal of manganese, a problem constituent since the wetland was first installed.

New application

Coal pile runoff is the treatment target for a wetland system being designed and constructed under tailored collaboration with Alabama Power. "Unlike the Springdale leachate, this storm water discharge is highly acidic and thus is similar to metal-bearing acid mine drainage," says Goodrich-Mahoney. "What makes the system unique is that it will be the first power in-





Because research has shown that trace metals can be effectively removed by sulfate-reducing bacteria in an anoxic organic environment, the Springdale designers included an anaerobic upflow bed in the system. The leachate, introduced through perforated pipes at the bottom of the bed, flows upward through spent mushroom compost. Bacteria in this anoxic compost produce hydrogen sulfide, which reacts with trace metals to result in the precipitation of metal sulfides. (A wetland being constructed by Alabama Power will also have an anaerobic bed, but for site-specific treatment reasons, flow in that bed will be downward, not upward.)

dustry application of constructed wetlands for treating this common nonpoint source of pollution."

The runoff has a pH of less than 3 and high concentrations of iron and aluminum —all characteristics known to create operational problems in constructed wetlands. Anoxic limestone drains (ALDs) are the conventional approach for producing the alkalinity required to neutralize acidic waste streams that have low levels of dissolved oxygen, such as coal mine drainage. As a surface discharge, however, the coal pile runoff has enough dissolved oxygen to oxidize dissolved iron. The resulting precipitate would form an armoring layer on the limestone surfaces, eliminating an ALD's buffering capacity.

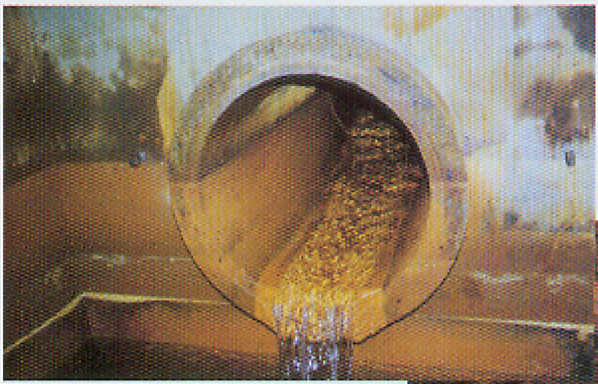
Successive alkalinity-producing systems (SAPS) are an emerging buffering approach that will be a key component of the Alabama Power wetland. SAPS have a rich organic layer with an inherent oxygen demand; this layer, which is similar to anaerobic organic upflow beds like the one installed at Springdale, sits atop a conventional ALD. In the Alabama Power application, the acidic discharge will flow from a detention pond into the SAPS. The discharge will move downward through the organic layer, which will reduce its dissolved-oxygen content and thus prevent iron precipitation when the discharge flows through and is buffered by the limestone bed. Sulfate-reducing bacteria in the organic layer will provide additional buffering. At the SAPS outlet, the discharge will be characterized by near-neutral pH, and it thus will be ready to flow by gravity to an equalization basin for iron precipitation and then to other cells for manganese, aluminum, and trace element removal.

A storm water conveyance system and a detention pond are under construction. According to Bill Garrett, senior environmental engineer in Alabama Power's Environmental Affairs Department, pilot-scale tests will be conducted during the fall and winter to examine various ways to prevent the plugging of wetland cells, a common problem for discharges with a high aluminum content. Construction of the actual wetland system is planned for 1998.

"This project represents a unique opportunity for Alabama Power," says Garrett. "Because we are under no regulatory pressure to treat the coal pile runoff, we can be environmentally proactive while developing in-house expertise in constructed wetlands and exploring environmental control approaches that appear extremely promising for some of our other waste management challenges."

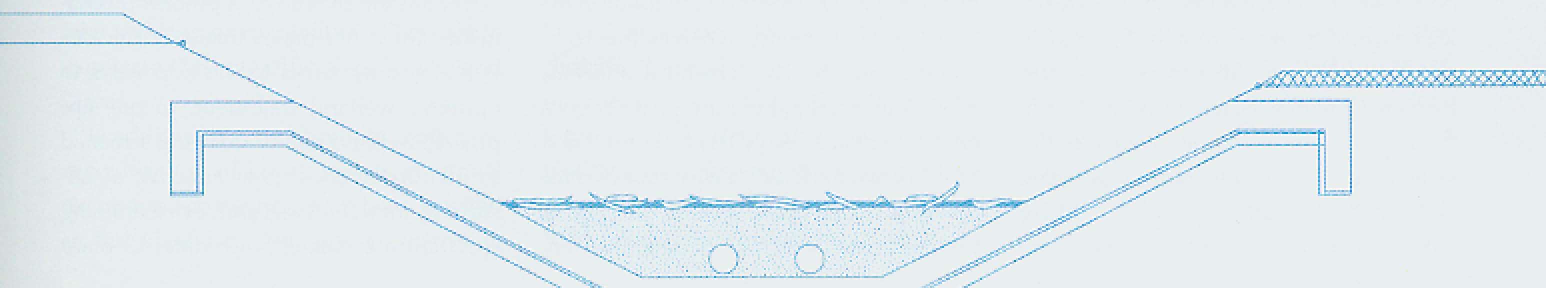
Treatment optimization

Complementing EPRI's constructed-wetland demonstrations are intensive field and laboratory studies that aim to increase mechanistic understanding of treatment processes and develop methods for maximizing the removal of specific trace elements. "Determining the fate of trace elements is critical to optimizing wetland



Allegheny Power's Springdale wetland is cost-effectively transforming a metal-bearing leachate (left) into a compliance-quality discharge (below).

A combined algal basin and sand filter provides final cleansing of the Springdale effluent before its release to Riddle Run, a tributary of the Allegheny River. Suspended solids introduced by the anaerobic upflow bed settle out of the effluent, and residual metals may be removed by wetland plants and microorganisms that have naturally colonized the basin. Additional plants and microbes may be introduced on the basis of laboratory and field studies at Springdale and at other wetlands being monitored in EPRI's constructed-wetland program.



design and management and to minimizing risks," explains Goodrich-Mahoney. "We need to know how these elements are removed from a discharge, where they reside, how long they stay there, and what chemical form they take."

At present, the only data available are from preliminary analyses of a TVA wetland that has been used since the mid-1980s to comply with permit standards for a metal-bearing discharge. Core samples

Greenhouse-covered experimental cells at Springdale enable Allegheny Power and EPRI to field-test the treatment effectiveness of wetland plant species.

from this system, analyzed by using the U.S. Environmental Protection Agency's toxicity characteristic leaching procedure, indicate that after 10 years of operation, its sediments are nonhazardous. Toxicants are present but not at high concentrations, which suggests that metals are being removed from the discharge and transformed to nontoxic forms or sequestered in sediments, eliminating risks to downstream ecosystems.

EPRI studies to determine precisely how trace elements cycle through constructed wetlands are being conducted by a multidisciplinary team of scientists from the University of California at Berkeley under the direction of Norman Terry, professor of plant biology. Surface water, sediment, pore water, and vegetation samples are being collected monthly from the Springdale site, TVA's Widows Creek installation, and the new Corcoran system in north central California. (The Corcoran wetland, designed and built by a team from Berkeley and other UC campuses and the Tulare Lake Drainage District, has 10 experimental cells for treating an agricultural waste stream containing selenium and other trace elements common to utility discharges.) Samples from all the wetlands are being analyzed to calculate the extent to which each of 26 trace elements is retained in sediments and waters or assimilated into the roots and shoots of vegetation. A primary goal is to better understand the role of various species in the cycling of these elements through wetland ecosystems.

An advanced analytical technique, high-energy X-ray absorption spectroscopy, is enabling the UC-Berkeley scien-

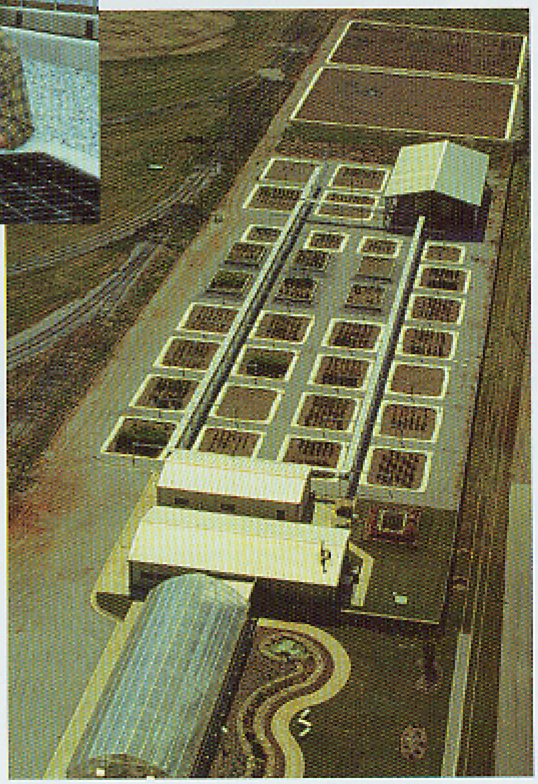


PHOTO COURTESY TENNESSEE VALLEY AUTHORITY

Novel concepts for optimizing the removal of specific chemicals are being evaluated at TVA's constructed-wetland research laboratory.

tists to examine the chemical transformations that occur as aquatic plants absorb and process trace elements. "Conventional methods physically alter plant tissue in examining its chemistry, whereas this technique allows in vivo chemical analysis, providing a unique picture of what goes on inside plants," says Terry. "For the first time, we can track the valence state of trace elements to determine whether they are in toxic or nontoxic forms." To date, a variety of aquatic plants have been identified that absorb selenium and toxic metals and metabolize them to nontoxic chemical forms. For example, water hyacinths can convert toxic hexavalent chromium (Cr^{6+}) to nontoxic trivalent chromium (Cr^{3+}). From a practical perspective, the ability to identify whether a trace element is being converted to a nontoxic form or whether a particular plant can render a specific pollutant nontoxic is a major advance. A wetland could be vegetated with a species known to eliminate a contaminant's toxicity, for example; then, at the end of the growing season, the biomass could be harvested and used or discarded with no fear of future toxic effects.

Studies of trace element volatilization by aquatic vegetation have also generated significant results. Typically pollutants are absorbed and immobilized in plant tissues, but some plants can volatilize trace elements and release them to the atmosphere. "Volatilization is a particularly attractive treatment mechanism, since it removes pollutants from an aqueous medium and releases them in nontoxic form to the atmosphere," says Goodrich-Mahoney. For a constructed wetland in the San Francisco Bay Area, UC-Berkeley scientists have determined that volatilization plays a significant role in selenium removal. They have also identified controlling variables, including temperature, water levels, pollutant concentration, and plant growth stage. Shoot removal was found to stimulate volatilization in bulrush plants, suggesting that vegetation management could be employed to increase trace element removal efficiency in constructed wetlands.

In addition to studying process mechanisms, the other major thrust of the UC-Berkeley program is to develop ways to optimize wetland treatment. In one approach, wetland plants are being screened to identify species most effective at absorbing, immobilizing, and/or volatilizing specific trace elements. To date, 13 plant species have been screened for the uptake of 10 trace elements. Some species—including water zinnia, parrot feather, and umbrella plant—appear to be particularly effective for sequestering specific elements. Patent protection is being considered for another promising species never before considered for application in constructed wetlands.

The influence of rhizosphere microorganisms on trace element immobilization, transformation, and uptake by aquatic vegetation is also being investigated to identify and isolate particularly effective microbes. In studies of soil microbes at the San Francisco Bay Area constructed wetland mentioned earlier, bacteria located in the rhizosphere of aquatic plants showed higher selenium volatilization rates than those in the surrounding soil. "Surprisingly, they also enhance selenium uptake by the plants," says Terry. "These accelerated transformation capabilities almost certainly represent adaptations to a selenium-enriched environment. We have identified microbe-plant associations that exhibit enhanced removal, suggesting a possible management option: the introduction of the microbes to the water inlet of a constructed wetland to promote colonization and thereby increase treatment capabilities."

In controlled laboratory experiments at UC-Berkeley, modern molecular biology techniques are being applied to genetically engineer plant species with superior capabilities for trace element uptake, detoxification, and removal. Several promising transgenic Indian mustard lines have been developed. Some of these produce increased levels of the enzymes that mediate selenium uptake and volatilization. Others exhibit increased tolerance to heavy metals, such as cadmium. (If a plant species is to provide effective heavy metal treatment, its normal physiological functions must not be adversely affected by its metal uptake and storage capabilities.) Plans are to duplicate these modifications in wetland plants.

In addition, a gene known to control the detoxification of heavy metals in animal tissue has for the first time been isolated in the plant kingdom. By incorporating the gene into suitable wetland plant species, the UC-Berkeley researchers hope to increase the efficiency of heavy metal detoxification and sequestration by constructed wetlands.

"The preliminary results of our genetics program are extremely exciting," says Goodrich-Mahoney. "We've only scratched the surface, but already there are tantalizing indications that we could modify wetland plants to improve their physiological abilities for accumulating and detoxifying heavy metals and volatilizing selenium and other constituents."

PHOTO COURTESY UNIVERSITY OF CALIFORNIA, BERKELEY

Indian mustard plants with potential for enhanced selenium uptake and volatilization have been genetically engineered in early EPRI work to develop superior wetland species.

Treatment optimization methods developed during the course of the EPRI program will be tested in four off-line cells installed solely for research purposes at Allegheny Power's Springdale site. Because these cells can be covered with a greenhouse, experiments are not limited to the normal growing season in the northeastern United States. Also, controlled studies can be conducted to determine the effectiveness of monocultures or mixed-species assemblages for immobilizing specific contaminants. The research cells are currently being used to examine plant species with an affinity for boron, a constituent of the Springdale leachate that is less amenable to biological uptake than are other trace elements.

EPRI is also monitoring ongoing work at TVA's state-of-the-art constructed-wetland research laboratory in Muscle Shoals, Alabama, as well as at other TVA treatment facilities. "There are a lot of novel treatment concepts that could further increase the cost-effectiveness of constructed wetlands," says Frank Sikora, a TVA research chemist. "Promising areas we are studying include new cell configurations for increasing trace metal removal efficiencies, rock biofilters for removing manganese, phosphate rock drains and downflow anaerobic systems for treating acid drainage, and methods for eliminating plugging problems in ALDs."

On the basis of experience and information gained from coordinated field and laboratory studies, EPRI will issue a manual for designing and engineering constructed wetlands to comply with NPDES permit limits for metal-bearing discharges. In addition, the development of a model called TWED (Treatment Wetlands Evaluation and Design) is planned. TWED will simulate treatment processes in vegetated aerobic cells by building on an existing EPRI model for the management, restoration, and mitigation of natural wetlands and on that model's understanding of wetland hydrology, biogeochemistry, and vegetation. TWED will also incorporate new knowledge specific to treatment processes in rock drains, upflow beds, and other constructed cells. By inputting the chemical and physical characteristics of specific waste streams into TWED, utilities will be able not only to assess the feasibility of using constructed wetlands to meet specific discharge goals but also to gain preliminary system design and cost information.

"Constructed-wetland technology is really in its infancy, yet it has proved cost-effective and successful around the world for all types of wastewaters," says Goodrich-Mahoney. "I believe that natural biological, physical, and chemical treatment processes exist for every wastewater challenge; we need only identify, duplicate, amplify, and accelerate them. Our goal is to develop an industry-specific knowledge and experience base now, ensuring the intelligent design and engineering of passive, low-cost systems to meet future discharge restrictions—regardless of their stringency." ■

Background information for this article was provided by John Goodrich-Mahoney of the Water Toxics Assessment & Watershed Management Business Area.