

## Do-It-Yourself Wetlands

Bob Gearheart emerged as Arcata's marsh guru during the city's long battle with the state water bureaucracy. This unpaid post demanded that Gearheart crank out proposals for wetland treatment at a frenetic pace, knowing that the city's financial future depended on his work. He wore a smile, energized by the pressure.

Gearheart's son, Greg, grew up to become an environmental engineer working for the state water board. He earned his engineering degree at Humboldt State, studying with his father. He remembers his dad happily engaged during the battle for Arcata's alternative treatment system, at the same time he was teaching a full load of classes. "My dad likes a fight," Greg says. "He adapts well. People put an obstacle in front of him, and he figures out a way to make it look like it's not really a problem. He makes it look like it was stupid on his opponent's part to put the obstacle there."

In 1977, the elder Gearheart proposed a first: a wetland built to treat municipal wastewater to the standards required under the Clean Water Act. He possessed a serene certainty that he could make this untried system work. "I had no data until we did the pilot study," he remembers, "but I was one hundred percent confident."

The power of aquatic plants to cleanse polluted water had first been tested in the 1950s by Käthe Seidel, a researcher at the Max Planck Institute in Germany. She showed that while some wild plants were killed off by waters tainted with phenol—a toxic organic compound used in making plastics—others had a remarkable ability to adapt. At first contact, effluent containing phenol caused bulrush stems to wither away, but the roots survived and in time sent up healthy new shoots. Bulrush, it turned out, could break down phenol, metabolizing it into the amino acids that build protein.<sup>1</sup> The plant also thrived in domestic sewage.

Seidel used carefully groomed cultures of wetland plants, rooted in beds of gravel or sand through which effluent flowed. Oxygen was pumped into the system, and because the sewage was not exposed to light, algae did not grow. She proved that in addition to breaking down toxic industrial pollutants, these reed beds could dramatically decrease the level of biological oxygen demand (BOD), suspended solids, and fecal bacteria in the water.

Based on Seidel's work, reed beds were successfully used to treat sewage from a Dutch campground. The bed killed off coliform bacteria and absorbed BOD, nitrogen, and phosphorus. The key to the system's function was the amount of time sewage spent filtering through the plants, known to engineers as the detention time. Sewage held in the reed bed for ten days or more was cleaner than the effluent from most conventional sewage treatment plants.<sup>2</sup>

At the time of Humboldt County's sewage rebellion, a handful of US researchers were studying the interaction of sewage and natural wetlands. One example was Philadelphia's Tinicum Marsh, on Darby Creek, near Delaware Bay. Before European settlement, six thousand acres of tidal marsh hosted abundant wildlife at Tinicum. Destruction of the wetland began in the 1630s, when Dutch, Swedish, and English colonists diked and drained the land for grazing. As the city grew, the wetland dwindled. In 1968, when construction of a new highway threatened to destroy the surviving 523 acres of marsh, conservationists set out to prove its value.

Three sewage treatment plants discharged into Tinicum, carrying an overdose of nutrients. The marsh was dominated by blooms of cyanobacteria and algae and a few pollution-resistant creatures, including crayfish and topminnows.<sup>3</sup> Still, an analysis of water quality showed that passage through the marsh reduced loads of phosphorus and nitrogen and raised oxygen concentrations. These findings helped in the fight to save the marsh, which was protected in 1970 as the first National Urban Park in the US.<sup>4</sup>

Several North American cities had been releasing treated sewage effluent into natural wetlands for decades—because it was convenient, not because wetlands were understood to improve water quality.<sup>5</sup> In the mid-1970s, researchers began to track the water quality impacts of wetlands, and documented the same pattern seen at Tinicum. When sewage passed through a swamp or marsh, concentrations of nitrogen, phosphorus, and coliform bacteria dropped, while dissolved oxygen rose.<sup>6</sup>

The pioneering wetlands ecologist Howard Odum had built a series of estuarine ponds near the sewage outflow from Morehead City, North Carolina, to observe the consequent changes in pond communities. Marsh grass and algae flourished in the ponds receiving wastewater, producing much more biomass than control ponds. Passage through the ponds filtered pollutants out of the sewage, improving water quality. Odum felt that wetlands could serve as a low-cost form of advanced sewage treatment.<sup>7</sup> He and his students demonstrated the concept by running sewage from a Florida trailer park through a natural cypress swamp. They found that the process worked well and that the swamp ecosystem was better able to handle high nutrient loads than open waters.<sup>8</sup>

John Teal at the Woods Hole Institution on Cape Cod studied the effects of sewage sludge experimentally applied to a Massachusetts saltmarsh. Though the sludge contained toxic metals, it carried a pulse of nutrients that caused plant growth to boom. A few species of pollution-resistant plants and animals flourished, and the marsh filtered out the majority of the contaminants.<sup>9</sup> One quote from Teal's work particularly struck Gearheart, and he would use it in the uphill battle to convince regulators that a manmade marsh could cleanse Arcata's effluent:

Wetlands seem to be better processors of wastes than estuaries and coastal waters . . . [absorption of] nutrients, heavy metals, hydrocarbons, and pathogens are features of wetlands as they function naturally. They are in fact providing free waste treatment for contaminated waters already. It seems

imperative therefore to implement wetland conservation to maintain this subsidy intact.<sup>10</sup>

The only existing lab data on manmade surface wetlands—as opposed to the subsurface flow reed beds used by Seidel—came from a study by National Aeronautics and Space Administration (NASA) engineers looking for a low-cost way to treat wastewater from the National Space Technology Laboratories in Bay St. Louis, Mississippi. In greenhouse studies, they found that dense stands of water hyacinth or alligator weed could remove more than 90 percent of the nitrogen and BOD in effluent, and more than 50 percent of phosphorus.<sup>11</sup> The NASA team envisioned constructed wetlands as part of a low-tech system that would sequester toxic metals and convert excess nutrients into a crop of water hyacinth that could be used as food. Later, wetlands would be proposed as part of a resource recycling system for manned space flight.<sup>12</sup>

Thanks to Dan Hauser's political savvy and funding from the Coastal Conservancy, Arcata's imagined marshes were becoming real. The city intended to integrate the marshes into its sewage treatment system, but the priority was to get them built as soon as possible. Hauser's pitch to the Conservancy, made while the HBWA battle was still in progress, underscored the urgent need for wetland habitat on Humboldt Bay. Since the region was settled during the California gold rush, more than 90 percent of native wetlands had been lost to diking and drainage.

Bulldozers began to dig basins for the marshes in September 1979, less than a year after Hauser had first applied for a grant. The groundbreaking was a full-on Arcata party, attended by the city council and staff, as well as an excited contingent from Humboldt State. A guy dressed as a tufted puffin waddled around in dive fins and sipped beer through an elaborate, thick-beaked mask. A buffet table was set up in the tall grass at the edge of Mt. Trashmore, along with a half-keg of local brew. "This is the culmination of a dream," Hauser announced as the bulldozers pushed into the earth.

Gearheart told reporters the marshes would serve as a national model for innovative sewage treatment. The full-scale wetlands had not been approved by state water quality officials, however, and for a few years would be fed with water pumped out of a nearby creek rather than treated sewage.

The marshes quickly proved their worth as wildlife habitat. Within a year, the first flooded marsh hosted American bittern, northern harrier, and an abundance of ducks. In the first spring, about two hundred ducklings—teal and mallards—hatched and fledged on the marsh.

Meanwhile, Gearheart had designed a pilot project to satisfy the state board's requirements. It would test effluent treatment in a dozen narrow marsh cells, using different plant species and flow rates. Soon after the celebration at Mt. Trashmore, a dozen trenches were dug in a diked-off corner inside the city's sewage plant. The cells were planted with different varieties of bulrush, and watered with effluent from the oxidation ponds. Studies at the pilot marshes



**Figure 9.1** Bob Gearheart at this namesake marsh in Arcata, 1989. Photo courtesy Campus Faculty Files, Humboldt State University Library.

would carry on for more than twenty years, long after the marsh treatment system won approval (Fig. 9.1).

The lab at the pilot project was a decrepit single-wide mobile home. Gearheart's students busted out the interior walls and installed lab benches. The project's budget was minimal, and the main requirements for graduate students who worked on it were a sense of humor, a willingness to keep odd hours, and an ability to scrounge.

David Hull arrived as a fisheries graduate student in the summer of 1980. Gearheart hired him to run bioassays, a standard test in which fingerling salmon are put into sewage effluent for several days to test its toxicity. Hull needed dozens of glass tanks to do the work. "I had this brilliant idea," he remembers. "The Sparkletts water company was phasing out their five-gallon glass jugs, using plastic instead." He got the company to donate fifty of the glass containers. Using a homemade system of nichrome wire connected to a rheostat, Hull applied a jolt of electricity to cut the tops of the jugs off, like jack-o'-lantern lids. He had all the bioassay tanks he needed, free of cost.

In one corner of the lab, a computer geek named Nancy crunched water quality data on a Radio Shack computer with an eight-inch floppy disk, while in another, microbiologist Steve Wilbur peered at the tiny creatures that did the work of breaking down pollutants in the marsh. Wilbur was also a carpenter, who designed and built a greenhouse next to the trailer. The researchers used it to dry out plant samples, part of the process of measuring the biomass produced by the marsh cells.

The grad student who had spent the most time on the project was a wiry redhead named John Williams. He had been working with Gearheart since the

HBWA fight. For two years, Williams slept in the trailer cum laboratory to avoid the hassle and expense of paying rent on a place of his own. Gearheart's young kids called him Zonker because he looked so much like the Doonesbury character. His more official nickname was Marsh Man: He carried business cards inscribed with that title.

At one point the grad students decided to run a dye study, a way of tracking the speed at which wastewater moved through the marsh cells. They planned to take turns sampling each marsh cell hourly for 24 hours, but the water was moving slower than expected, and the process stretched out over five days of around-the-clock work. "You'd be out there in the middle of the night, falling in the test marshes because it was dark, and just having a good old time," recalls Hull.

"We got punchy," says Williams. "But we got it done."

Ask Hull about that time, and a wide grin spreads across his face. "We were a team, all in our twenties, making this project happen, working at the trailer at all times of the day and night." Over the months, they all learned about every aspect of the pilot and became adept at doing each other's jobs.

Bob Gearheart's son Greg was thirteen years old when the pilot marshes began running. Greg and his sister, Laura, spent a lot of time at the pilot project. "That trailer was like a clubhouse," remembers Greg. "There was a lot of work going on, and also a lot of fun." On the way to the marsh, the Gearhearts would stop at the Arcata Burger Bar. The woman who flipped the burgers there saved her gallon mayonnaise jars for the marsh researchers, who used them to collect samples. "I'm always happy to visit a treatment plant," Greg says, "because those places are so intertwined with my memories of eating delicious burgers and hanging with my dad."

By 1983, the pilot had demonstrated an ability to treat the city's effluent to a standard that met or improved on state water quality requirements.<sup>13</sup> The marsh's profound effect on water quality could be seen in samples of water taken at different points in the treatment process. Water that flowed out of the oxidation pond pea-soup green with algae emerged from the series of pilot marshes as clear as tap water.

"A marsh is a trickling filter set on its side," explains Williams. In a trickling filter, sewage is sprayed over a deep pile of rocks. A community of bacteria and fungi inhabit a biological slime coating the rocks, and do the work of breaking down organic matter. In a marsh, a similar slime coats the stems and roots of aquatic plants. Cattail and bulrush also pump oxygen into the system, helping the microbial community to thrive.

Studies on the pilot marshes increased Gearheart's understanding of how treatment wetlands work, and led to a major change in the design of the city's system. Instead of relying only on the three large enhancement marshes—dubbed Allen, Gearheart, and Hauser after the major players in Arcata's sewage rebellion—a series of densely vegetated treatment marshes were built beside the oxidation ponds. With their thick growth of cattail and bulrush shading the water, these marsh cells killed off algae, dramatically lowering suspended solids levels before the effluent was sent on to the larger enhancement wetlands. Arcata's natural

sewage treatment system wasn't designed in advance, Gearheart acknowledges: It evolved, shaped by both political demands and scientific experimentation.

The key to obtaining the best water quality from marsh treatment, Gearheart wrote, was to keep the sewage in the system long enough for any suspended gunk to settle to the bottom and for the microbes that thrived amid the roots and stems of the cattail to break down organic matter. In engineering lingo, effective wetland treatment required detention time: days or weeks during which the habitat's natural processes could do their work. A long detention time also killed off most fecal coliform bacteria.<sup>14</sup>

In summer, the system worked beautifully, often releasing treated effluent that was cleaner than required by state standards. During the heavy rains of winter, millions of gallons of stormwater would seep into Arcata's aging sewer pipes. The volume of sewage increased dramatically, forcing operators to move the water through the marshes quickly, or to bypass them entirely. In the rainy season, the city often violated the standards set in its discharge permit. During the first years of the wetland treatment system, however, this seemed like a minor problem; the fine for an occasional violation was affordable.

By 1983, the wildlife marshes had become a popular attraction for birders, hikers, and school groups (Fig. 9.2). The regional board was ready to grant Arcata permission to discharge sewage effluent through the marshes and into Humboldt Bay on a long-term basis, on the premise that the marsh project enhanced the bay



**Figure 9.2** River otter at the Arcata Marsh. Photo by Leslie Scopes Anderson.

in terms of both ecology and environmental education. The Department of Fish and Game, however, was opposed. Arcata's natural system didn't fit into state and federal regulatory schemes. Fish and Game biologists saw Allen, Gearheart, and Hauser marshes as habitats that had to be protected from pollution, rather than as part of the sewage treatment process. As for the regional board's wastewater engineers, they still refused to acknowledge the water quality benefits of treatment wetlands—despite the fact that Arcata's pilot marshes could produce an effluent similar to that released by high-tech tertiary treatment systems.

During the time he built Arcata's pioneering treatment wetlands, Gearheart was also spending months at a time traveling in the developing world to help create low-cost, low-tech systems to supply safe drinking water. In Ghana, he taught locals about simple filtration systems that could protect them from guinea worm infection. Among the Maasai in Kenya, he helped pinpoint the best spots to dig crevices that would store water in the dry season. He worked in Indonesia, Thailand, Sierra Leone, Tanzania, and Swaziland.

Gearheart encountered a successful low-tech, locally controlled water supply system among the nomadic Pokot tribe in Kenya. Tribal craftsmen had a long tradition of working metal. After a missionary taught them to weld, they began manufacturing high-quality water pumps. Each man signed his pumps, so that people would know who to find if it ever broke down. This simple approach gave people access to groundwater that was safe and free of pathogens. To show their appreciation for his help in locating the best places to dig wells, the Pokot presented Gearheart with a metal-tipped spear.

Gearheart saw that many water systems brought in by USAID and other First World agencies were too large, complex, and expensive for local people to maintain. For him, this made a clear parallel with Arcata's long struggle against the state water quality bureaucracy. Low-tech, local, sustainable technology made as much sense at home as it did in Africa or Asia.

Meanwhile, Hull and his fellow grad students continued to explore the mysteries of marsh treatment. Though the crew had carefully sown different types of plants in each pilot marsh cell, within a few months all the cells were dominated by a cattail, along with a scattering of bulrush. They soon realized that trying to enforce their experimental design on the plant community was a hopeless mission. "More important than the density and type of plants," Gearheart wrote, "is the distribution of plants in the flow pattern." The best arrangement for water quality purposes was a 60 to 80 percent cover of aquatic plants, and it was important that a dense stand be created adjacent to the outflow, to make sure suspended solids levels stayed low.

The pilot marshes cut the numbers of fecal coliform bacteria down to acceptable levels, without chlorination of the effluent, but this failed to impress the regional board's engineers. They insisted that Arcata's effluent be disinfected by chlorination twice: once before it was released to the enhancement marshes, and again before it flowed from the marshes to the bay. Chlorination reliably kills most pathogens and is standard practice at many wastewater plants. It also creates chlorinated organic compounds, which are toxic and persist in the environment.

Gearheart would spend decades struggling to get the chlorine out of Arcata's treatment system.

In 1986, Arcata finally received permission to flood its enhancement marshes with treated effluent. The influx of nutrient-rich water made aquatic plants grow like gangbusters. Marsh pennywort, a fast-growing native plant, formed floating mats that began to cover much of the surface, leaving little open habitat for waterfowl. Hull, who had finished his graduate work and been hired to manage the city's wetland system, continued his creative scrounging. He found a boat that had been abandoned on city property, painted it lime green, and rigged a rake on the bow. Puttering slowly through the marshes, Hull used the rake to rip out great mats of pennywort, which were later composted.

The Ford Foundation's Innovations in Government program awarded Arcata a \$100,000 prize for its treatment system, calling it "an imaginative response to some of society's toughest issues."<sup>15</sup> Reporters showed up from *Time* magazine and the *New York Times*. Hull gave them grand tours of the wetlands. "It may be wastewater to you," he told them, "but it's our bread and butter."

As word spread of Arcata's successful experiment, Hull began to get inquiries from all over the world, asking how to build a treatment wetland. He tacked a poster-sized map of the world to his office wall and stuck in colored pins to represent the location of every person who had written to ask him how to create their own version of Arcata's system. The pins were scattered across the globe: Europe, Asia, Africa, South America. Hull remembers receiving queries written in Russian and carrying them to a linguist at Humboldt State to get them translated. In a year or two, letters started arriving describing the success of far-flung treatment wetlands. One of the first projects to start running was in an indigenous Maori community in northern New Zealand. Wetlands not only saved money and energy, but they also fit much better with Maori traditions than conventional, mechanized treatment systems.<sup>16</sup>

The concept of treatment wetlands spread quickly. Wetlands are seldom practical for treatment of heavy loads of sewage in urban areas because they take up too much land in places where real estate is at a premium. In smaller and more remote communities, however, the technique is invaluable. In large swathes of Africa, Asia, and Central and South America, people have no electrical grid, no sewage pipes, and no money. A conventional treatment system requires expensive items like concrete, steel, and First World experts. Even when aid agencies donated state-of-the-art treatment systems, they never functioned for long because local people could not afford to maintain them. "Steel rusts away fast in the tropics," notes Steve McHaney, an engineer and one-time student of Gearheart's who has worked on treatment wetlands around the globe. By contrast, a wetland can be created using local materials and labor and will, for the most part, maintain itself.<sup>17</sup>

In 1992, a database recorded 127 treatment wetlands in North America. A year later, Gearheart helped the US Environmental Protection Agency (EPA) compile case studies of seventeen treatment wetlands in the US, including examples in Michigan, Oregon, California, Florida, Nevada, Arizona, and Illinois.<sup>18</sup> All of

these were surface flow wetlands, similar to the Arcata marsh, though some were much larger. Hundreds of projects were treating wastewater in Denmark, France, Germany, and the United Kingdom. The European systems were subsurface wetlands, in which sewage flows through a bed of gravel or sand holding a dense stand of aquatic plants. Each approach had its advantages. Surface flow wetlands are simple to construct and provide important wildlife habitat. In subsurface systems, higher loads of contaminants can be treated in a smaller space. The wastewater remains underground, avoiding the risk of creating mosquito habitat, or of human contact with pathogens.

US engineers began to build wetland systems to treat water tainted with industrial pollutants, including benzene, aniline, and acid mine waste. They also began to use wetlands to manage a manmade excess of the nutrients nitrogen and phosphorus.

A few years after the seat-of-the-pants process that he used to create the Arcata marsh, Gearheart designed wetlands that required meticulous forethought and testing. A prime example was the Apache Superfund site in Cochise County, Arizona. The Apache Powder Company had manufactured nitrogen-based chemicals and explosives at the site for more than seventy-five years.<sup>19</sup> The factory released nitrate-laden wastewater to the surrounding desert, where it percolated into groundwater tapped by local wells. As a result, the groundwater carried high levels of nitrate,  $\text{NO}_3$ , which can cause “blue baby” syndrome, a potentially fatal illness. The nitrate reacts with hemoglobin, rendering infants unable to carry oxygen in their blood—a condition that can cause coma and death if it’s not treated.<sup>20</sup>

Gearheart designed a series of wetlands that would transform nitrogen, moving it from the water into the air. In small-scale tests, he found that bacteria required plenty of carbon to fuel the process of denitrification, which transforms nitrate into  $\text{N}_2$  gas (see Chapter 3). At the Apache site, a series of wetland basins were dug in 1997, then planted with fast-growing cattail. It took a few years for the marshes to build up a layer of carbon-rich detritus from decaying plants. Even then, engineers had to add phosphorus to boost cattail growth, and molasses to increase carbon levels. When the treatment system finally went into full-scale operation in 2005, it proved able to take groundwater tainted with 200 mg/L of nitrate down to 10 mg/L, the federal drinking water standard.<sup>21</sup>

A breakthrough moment for emerging wetlands technology came in 1996 when the first comprehensive textbook on treatment wetlands was published. The lead author, Robert Kadlec, was a chemical engineering professor at the University of Michigan. He packed the text with mathematical formulae that helped to predict the complex biochemical interactions among plants, microbes, and pollutants. The book laid out principles that applied to surface as well as subsurface wetlands, and engineers on both sides of the Atlantic began to use both kinds of systems.

“Treatment wetland technology is growing exponentially,” says Scott Wallace, an environmental engineer who is the principal of the consulting firm Naturally Wallace and has focused on wetlands since 1989. Wallace collaborated with Kadlec on a second edition of the treatment wetlands textbook, published in 2009.

“Frankly, it’s beyond anyone’s ability to count the number of systems now in operation,” he says. “The global total is in the tens of thousands.”

The design of each treatment wetland is shaped by the kind of waste to be treated and the local environment. Often, notes Wallace, engineering decisions come down to a tradeoff between the cost of land and the impacts of climate. Surface flow wetlands, which nurture wildlife and act as magnets for hikers and birdwatchers, remain the most common kind of system in North America.

Subsurface wetlands have advantages in extreme climates. Cold slows down the microbe-mediated reactions that break down organic matter and cycle nitrogen. In Minnesota, where winter temperatures can plunge to 25 degrees below zero, Wallace opted for a subsurface wetland insulated with mulch. In Saudi Arabia, where water evaporates quickly into the hot, dry air, subsurface wetlands are the only option.

The understanding that wetlands store and purify water has fueled some creative efforts to protect natural wetlands. Much of the domestic and industrial wastewater from the city of Kampala, Uganda, flows through the Nakivubo wetland before it reaches Murchison Bay, an arm of Lake Victoria. The lake suffers harmful algal blooms fueled by an overload of nutrients. Rapid population growth and skyrocketing real estate values in Kampala have driven a binge of wetland drainage and conversion. The Nakivubo filters the city’s wastewater before it is released to Murchison Bay, just a few kilometers from Kampala’s drinking water intake.

In the 1990s, a team led by economist Lucy Emerton of the International Union for the Conservation of Nature (IUCN) analyzed the monetary value of Nakivubo wetland’s ecosystem services: its ability to break down organic matter, retain nitrogen and phosphorus, and kill off pathogens. Concluding that replacing these natural wetland functions would cost up to \$1.75 million, the study found that Kampala could not afford to let the habitat be further diminished.<sup>22</sup> Emerton warned that because the great value of the wetland did not translate into private profits, halting the conversion of habitat would take aggressive planning and enforcement efforts.

City officials chose not to perform an expensive upgrade to Kampala’s sewage treatment system and to rely on the Nakivubo wetland to purify its tainted waters instead. Unfortunately, loss of wetland habitat has accelerated: A recent study found that 62 percent of the area once covered by wetland vegetation was converted to croplands or buildings from 2002 to 2014.<sup>23</sup> As the population continues to grow, older drained areas on the marsh’s edge are used to build houses or factories. Impoverished farmers are forced to move farther into the wetland to find moist soil on which to raise yams and sugarcane.

Wetland protection policies are on the books in Uganda, but they’re not being implemented on the ground. The surviving segments of the wetland are contaminated with high concentrations of nutrients, coliform bacteria, and heavy metals. Recent evidence suggests that much of the natural filtering capacity of the Nakivubo wetland has been overwhelmed.<sup>24</sup>

In other parts of the developing world, constructed wetlands for water purification have boomed even as the loss of natural wetlands continues. The

South China Environmental Protection Agency built a demonstration treatment wetland in 1990.<sup>25</sup> Since then, China has embraced the new technology, studying ways to adapt its use from the tropical heat of Shenzhen to the chill northern provinces. In many small towns and rural areas, no conventional wastewater treatment facilities exist and constructed wetlands are of critical importance. Creation of treatment wetlands has accelerated in the twenty-first century, and much of the growing scientific literature on the subject now comes from Chinese researchers.

Environmental engineers have long referred to treatment wetland ecosystems as a “black box.” “We’ve got a huge, functioning mess called wetlands out there with all sorts of interesting things going on inside it,” Kadlec told a reporter in 1998.<sup>26</sup> “But we don’t have enough information about what goes on inside the system . . . to advance our knowledge, we need to understand the internal processes that lead to the observed performance.”

Researchers have begun to peer inside the black box. In the process, they have uncovered new and promising abilities of treatment wetlands to counter problems nobody was aware of in the days when Gearheart created Arcata’s marsh system. Molecular fingerprinting has made it possible to track the ecology of distinct bacterial species involved in breaking down organic matter and cycling nutrients, and to discern the fate of pathogenic microbes.<sup>27</sup> Wetlands can filter out 99 percent<sup>28</sup> of fecal coliform bacteria (used as indicators of the potential presence of waterborne pathogens) through a combination of processes: bacteria settle into the sediments, or attach to plant roots. There they die off of starvation, of exposure to light or low oxygen conditions, or are eaten by nematodes, rotifers, protozoa, and other minute predators.

Bacteria are capable of promiscuously swapping genes, both within and between species. Conventional activated sludge treatment plants are hotspots where genes for antibiotic resistance spread, ultimately releasing resistant bacteria into the environment. Evidence suggests that constructed wetlands do a better job of killing off antibiotic-resistant bacteria and preventing the resistance trait from being transmitted—though the reasons remain unknown.<sup>29</sup>

Antibiotics are not the only drugs that enter the flow of wastewater and impact aquatic life; many pharmaceuticals emerge intact from conventional treatment systems. Examples include pain relievers and anti-inflammatory drugs like ibuprofen and naproxen, and synthetic estrogens used in birth control pills. Levels of synthetic estrogens in lakes and rivers are high enough to feminize male fish of many species, causing them to produce eggs instead of sperm. This syndrome has been documented in fish worldwide, and is widespread among bass in US rivers scattered from the Savannah in Georgia to the Yukon in Alaska.<sup>30</sup> Synthetic estrogens and other endocrine disruptors pose a profound threat to wild fish populations.

The mix of aerobic and anaerobic microhabitats in treatment wetlands can combine to aid in the breakdown of a range of pharmaceuticals—called “contaminants of emerging concern” by the EPA, which does not set effluent limits for these compounds as it does for BOD or suspended solids. Some drugs, like caffeine and ibuprofen, break down better under aerobic conditions. Hormone pollutants, like

synthetic estrogen, can be degraded in both aerobic and anaerobic environments. Wetlands remove these contaminants through an array of processes: microbial breakdown, uptake and metabolism by plants, photodegradation.<sup>31</sup> Long retention times in wetlands increase the likelihood that pharmaceuticals will be broken down.

In the 1990s, scientists discovered a strain of bacteria in sewage sludge that was capable of cycling nitrogen in a previously unknown way.<sup>32</sup> These microbes grow slowly—one of the reasons they'd escaped identification for so long. They thrive in constructed wetlands, where a single cell can remain in place, metabolizing nitrogen and reproducing, for months.

The chemical trick these bacteria perform is known as Anammox, for anaerobic ammonia oxidation. In the absence of free oxygen, the microbes transform ammonia into harmless N<sub>2</sub> gas, removing nitrogen from the water. It's a radical twist on the classic model of the nitrogen cycle, which requires multiple species of bacteria and a mix of aerobic and anaerobic habitats to push nitrogen out of an aquatic environment. Because there's no need to push air into the system, as is done in activated sludge treatment, Anammox bacteria can take nitrogen out of wastewater using much less energy than conventional treatment.<sup>33</sup> The microbes have recently been harnessed to treat nitrogen-tainted water in specially designed reactors. But long before microbiologists had identified them, they'd been at work in wetlands.

The microbes that inhabit constructed wetlands live attached to sediments and to the underwater surfaces of plants, forming a biofilm. Levels of dissolved oxygen vary across the biofilm, allowing Anammox bacteria to coexist with the microbes that perform the classical nitrification and denitrification reactions—and conditions in a wetland can be manipulated to favor that coexistence. Together, the two classes of bacteria can dramatically reduce the amount of nitrogen in treated effluent.<sup>34</sup>

That's an important discovery, because wetlands are now being built to filter out the excess of nitrogen that modern humanity has unleashed on the planet. Lakes and estuaries in the US, and around the world, are choking on manmade overdoses of nitrogen and phosphorus. The nutrient overload runs off farm fields, lawns, and city streets—places where every scrap of wetland has long been drained or paved over.

## NOTES

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