Introduction

This book is an environmental history of the biological sewage treatment plant. Biological sewage treatment, like electricity, power generation, telephones, or mass transit, is one of the key technologies of the late-nineteenth- and twentieth-century city (figure 0.1). Present in almost every town and city in developed nations, sewage treatment plants are a major part of their urban infrastructure, responsible for protecting not only public health, but also the ecology of rivers, lakes, and oceans. In the United States alone, there were over 16,500 sewage treatment plants in 2004. The estimated capital stock of public sewerage facilities in 1997 was $274 billion, with annual spending for construction and operation and maintenance of almost $50 billion.[1]

Besides being a ubiquitous engineering component of the modern city, biological sewage treatment plants are also ecosystems. As such, they rely on the ability of microorganisms and other plants and animals to degrade sewage and produce a pure effluent. Ecosystems can be defined as biophysical systems in which communities of organisms—bacteria, fungi, plants, animals—consume food, energy, and nutrients. In turn, these communities transform the energy and resources, cycling various substances back to the environment. In a biological sewage treatment plant, bacteria convert the organic matter in waste to carbon dioxide and methane and proteins and organic nitrogen to ammonia, nitrate, and nitrogen gas. The cells of the bacteria grown on the sewage, along with any remaining organic matter, make up the solid waste of the treatment plant, the sludge or so-called biosolids. The sewage treatment plant differs from natural ecosystems, though, in the extent of human intervention in its creation and management. This book documents and explores these complex relations between society and nature that were involved in the establishment and operation of the sewage treatment plant ecosystem, from the mid-nineteenth century to the present.

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Figure 0.1
Jones Island Treatment Plant, Milwaukee Sewerage Commission, c. 1927. When this plant, located in Milwaukee's harbor, began operation in 1925, it was the largest sewage treatment plant in the world. Milwaukee had established a testing station there in 1915 that was instrumental in the development of the activated sludge process. The plant is still operating today. *Source*: Milwaukee Metropolitan Sewerage District

The Industrial Ecosystem

The sewage treatment plant was the most important example of a novel kind of ecosystem that proliferated in the late nineteenth century, what I call the *industrial ecosystem*. In the industrial ecosystem, the metabolic processes of an ecosystem are exploited to extract resources such as food, fabrics, pharmaceuticals, or fuel.[2] The biological sewage treatment plant was critical to the development of the industrial ecosystem more broadly. It is now the most common industrial ecosystem, and as a critical tool for protecting public health and the environment, it has occupied the attentions of an extremely large group of scientists, engineers, city and public health officials, and workers in the plants themselves. Advances in the understanding of microbial biology and ecology made in studies of sewage treatment spread to public health, microbiology, agriculture, and industry. Further, the sewage treatment plant did important cultural work in changing ideas about the relation between the natural and industrial that has had profound impacts on the history of biotechnology and genetic engineering today.

Like the sewage treatment plant, the industrial ecosystem had its origins in practices that relied on the power of microorganisms. But even before microorganisms were identified or their functions understood, people had been using them to produce beverages like wine, sake, and beer; foods such as bread, sauerkraut, and vinegar; and industrial products like flax and saltpeter. With the rise of microbiology as a science, however, and the coalescing of Darwin's theory of evolution with physiology and botany into the science of ecology, scientists developed the theoretical background and understanding to deliberately intensify and simplify these biological processes and turn them to mass production. Traditional practices were thus transformed into industrial ecosystems. The industrial ecosystem was just one aspect of the industrialization of nature, a part of the broader shift in the mode of production toward mechanization, fossil fuels, and the factory. As Edmund Russell notes, "Industrialization was a biological process as well as a mechanical process."[3]

Biological sewage treatment, scientific brewing using pure yeast culture techniques, and the use of bacterial fermentation to produce industrial chemicals all came about simultaneously in the late nineteenth century.[4] Emil Christian Hansen in Denmark and Max Delbrück in Germany applied the ideas of natural selection and the struggle for existence to the culture and use of yeast in beer making. In the United States, sanitary scientists William Sedgwick and E. O. Jordan used Darwin's theory to understand the role of bacteria in purifying sewage. Massachusetts chemist Charles Avery manipulated environmental conditions of bacterial fermentation to produce lactic acid, the first explicit application of bacteria to the commercial production of chemicals.

These theories and techniques quickly coalesced into a general program for the management of industrial fermentation that focused on the relation between organisms and environment. "A very thorough knowledge of the nature of those organisms and of the influence of environment on their chemical activities is essential to efficient and successful factory work," argued an early advocate for industrial microbiology. "For every organism," he continued, "there is a particular set of conditions, the observance of which is absolutely essential to successful working."[5] These conditions were to be based on a knowledge of the distribution of the organisms in nature, their "probable habitat." Microbiology was thus connected to ecological science and the theoretical underpinnings of the industrial ecosystem were established.

From its origins in the late nineteenth century, the industrial ecosystem quickly spread. Craft processes like brewing or vinegar making were industrialized while fermentation scientists discovered new microbial pathways for chemical production. Hansen's pure yeast culture in brewing expanded across Europe and the United States.[6] Microbiologists at the Pasteur Institute in Paris identified novel fermentation products. As scientists worked out the biology and chemistry of fermentation, they created other industrial ecosystems that provided bulk chemicals, like acetone or butyl alcohol (figure 0.2), enzymes like cellulase or protease, pharmaceuticals like antibiotics and vitamins. The scale of these industrial ecosystems could be enormous. The largest industrial ecosystem in the early twentieth century was probably the Curtis Bay acetic acid factory in Baltimore. In response to the huge need for acetic acid as a feedstock for explosives in World War I, the factory had scaled up the traditional method of making vinegar in which wine was dripped through a wooden cask containing beech or birch shavings. The Curtis Bay plant consisted of over one thousand fermentation tanks, each eighteen feet tall and over ten feet in diameter, covering over twenty-seven acres of ground. The fermenters were filled with birch shavings over which alcohol from an adjacent factory was dripped in a constant stream. The bacteria that grew on the wood shavings converted the alcohol to acetic acid.[7]

The industrial ecosystem now pervades modern food, chemical, and pharmaceutical manufacturing. The bacterium *Corynebacterium glutamicum*, for instance, is used to produce the amino acids L-glutamic acid and L-lysine. These two amino acids are the basis of a $4 billion global industry, L-glutamic acid in the flavor enhancer MSG, and L-lysine as an animal feed additive.[8] The bacterium is grown in huge stainless steel fermentation tanks, and fed either molasses or corn syrup. Production plant operators induce the bacteria to produce the amino acids in excess of their own metabolic requirements by manipulating the environmental conditions in the tanks. Mining companies use bacteria to extract gold, copper, uranium, and other metals from low-grade ore. These bacteria use the minerals in the ore for energy, producing sulphuric acid that leaches the precious metals from the crushed rock. In this "biological smelting," hundreds of thousands of tons of ore are piled over thirty feet high, and water that has been inoculated with bacteria is trickled through the pile, collected at the base, and pumped back to the top. After about six months, the bacteria have completely leached the available metals.[9] The cephalosporin antibiotics, a $6.5 billion worldwide market, are produced by the fungus *Acremonium chrysogenum*, which is grown industrially on sugars, oils, and oilseed meal. By changing the food source, the industrial operator can induce the fungus to change its growth pattern and begin making antibiotics.[10]

Industrial ecosystems like these are an increasingly dominant mode of production. As the price of oil that fuels the petrochemical industry climbs, and advances in

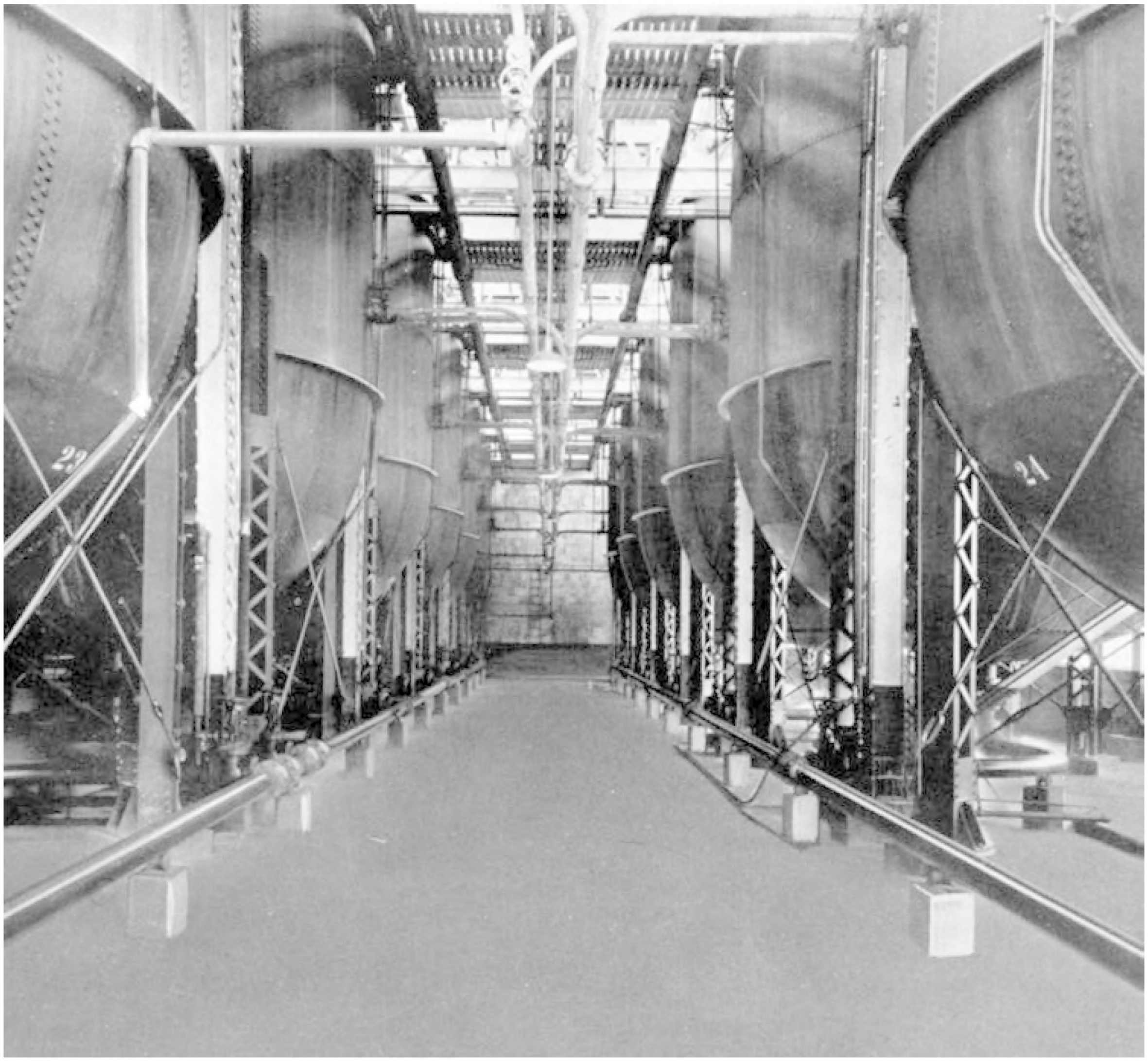

Figure 0.2
Fermenter Room at the Terre Haute plant of Commercial Solvents Corporation, 1929. In these tanks a strain of *Clostridium* bacteria first identified by Chaim Weizmann fermented corn starch to produce butyl alcohol, acetone, and ethanol. Each of the fifty-two tanks at the plant would be filled with 40,000 gallons of corn starch paste and 800 gallons of bacterial culture. After about twenty-four hours, "the whole content of the great tank is seething and foaming," and after forty-eight hours, the fermentation would be complete. *Source*: *Commercial Solvents Corporation*, 1929, Community Archives, Vigo County Public Library

genetic engineering provide more efficient biological production, the share of global production from industrial ecosystems is rapidly increasing. One study suggested that by 2010, industrial microbes would be responsible for one-fifth of all global chemical production, totaling $1.6 trillion.[11] This rapid increase is creating conflict in its wake. As biofuels become an increasingly important source of energy, people worry that their production will usurp a large proportion of the food grain market, driving up prices and fueling conversion of forests to cropland. As biotechnology generates novel organisms for producing pharmaceuticals and other products, activists are concerned about the patenting and privatization of fundamental products of nature, including the human genome. As sewage treatment plants apply their waste sludge as fertilizer and soil conditioner to agricultural fields, they also apply the trace quantities of heavy metals and other toxics concentrated into the sludge. As the industrial ecosystem expands to include much of the wild rivers, forests, and oceans, the logic of the industrial ecosystem comes to dominate the natural world as well.

In this book, I use the history of the biological sewage treatment plant to trace the origin and growth of the industrial ecosystem and to explore its logic. I examine the forces that shaped the ecosystems in the plant itself. Given that societies decided that sewage should be treated, why did sewage treatment take the particular form it did? To answer that question, I examine the sewage scientists, engineers, and sanitarians who theorized, designed, and built sewage treatment plants, as well as the operators who managed them.

“Like Sailing on Top of a Cesspool”

Sewage treatment arose in nineteenth-century England, where the twin processes of urbanization and industrialization first accelerated. London, Birmingham, Manchester, and other cities increased in size exponentially during the nineteenth century. Industrial discharge and human excrement overwhelmed the technical, legal, and administrative systems already in place for dealing with waste and nuisance. At the same time, advances in chemistry and microbiology and the birth of the science of ecology led to the scientific understanding of decomposition as a biological process. The biological sewage treatment plant, as an explicitly biological entity, or ecosystem, came out of these parallel developments.

By polluting water supplies, sedimenting rivers, and creating both a foul nuisance and a public health problem, sewage disposal became one of the most taxing problems facing the industrial city, first in nineteenth-century England, and later across the Continent and in the United States.[12] In the first part of the nineteenth century, human waste was collected in each household in a privy vault or cesspool, to be periodically carried away by scavengers to either be used as “night soil” or fertilizer or dumped on empty lands or in nearby water bodies (figure 0.3). Even water closets, introduced in the early nineteenth century, often emptied into cesspools rather than sewers. Sewers, where they existed, were often covered-over stream channels or other natural drainage ways, and were primarily for carrying away storm drainage, not waste. Indeed, it was often illegal to place household or sanitary waste in the sewers.

The broad acceptance of the water closet had to await the widespread availability of municipal water systems. But the combination of piped water and the flush toilet soon overwhelmed the capacity of the cesspools and privy vaults, as well as the early sewer drains. In response to the sanitary problems of cesspools and other disposal methods that kept waste in the vicinity of households, sanitarians began to advocate for a water carriage system, in which wastes would be transported by water from water closets and sinks through networks of self-cleansing sewers. By the mid-nineteenth century, cities began to expand their systems of sewers to efficiently drain both storm water and waste. London built its intercepting sewers in 1865, Brooklyn, New York, in 1855, Chicago in 1859. By the end of the century, the great majority of cities in Europe, Great Britain, and North America had sewerage systems.

But by combining waste with the water used to convey it through the sewer system, Victorian sanitary reformers created a new problem: sewage. Sewage was a new and distinct substance from the wastes that emptied into privy vaults and cesspools. That material was primarily human feces and urine. In contrast, sewage was a highly variable substance, containing the "solid and liquid excrements of the population," but also "the ingredients of soap, the refuse from kitchens, the drainings and washings from markets, stables, cow-houses, pigsties, slaughterhouses, etc., the refuse drainage from many factories and trading establishments, the washings of streets and other open surfaces." What before had been an often barely manageable volume of waste was now mixed with two hundred times its weight of water.[13]

Most cities took the expedient solution of simply dumping the liquid waste in the nearest body of water. When the fouled rivers became intolerable, sewers were extended to move the sewage farther away. In London, sewage flowed through an outdated network of ancient and more recently built sewers to the Thames River. With the increasing flow of sewage, concern over the quality of the Thames began increasing in the 1820s, reaching a crescendo following the "Great Stink" of 1858. The solution for Londoners was to build intercepting sewers, large sewers that captured the flow of all of the smaller sewers draining toward the river, and carrying that flow along the banks of the Thames to points downstream of the city. Completed in 1865, this system greatly improved the quality of the Thames in the city. But the problem of pollution was simply concentrated and transferred downstream.[14]

Nineteenth-century documents describe the horrific state of the rivers downstream of large cities. Boating on the Thames was "like sailing on top of a cesspool,"

FIG. 2

MANCHESTER CORPORATION DRY ASH CLOSET

a.a. Screens to separate cinders from ashes and to direct the latter into the excrement pail.

Figure 0.3

Dry ash closet. Ashes were used to help deodorize excrement in the dry earth system of waste disposal. Before the common use of water closets and sewers created the sewage problem, households used various privies, cesspools, or ashpits for collecting and removing excrement. The dry earth closets were an improvement on these early disposal systems, and competed with the water carriage system. In some cities, like Manchester, the dry earth system persisted long after sewerage became widespread. These systems have been recently revived in composting toilets and advocated in books like *The Humanure Handbook*. *Source*: Samuel M. Gray, Proposed Plan for a Sewerage System, and for the Disposal of the Sewage of the City of Providence, 1884 wrote engineer John Baldwin Latham evocatively. As one riverman on the Thames put it, "You could see lumps of stuff rise from the bed of the river, and then they would break open, and a fearful stench came from them when they broke open." Thames harbor masters described the river as "nearly black at half tide" and "little better than an open sewer." The nuisance was "spoken of on all sides" of the river. As the pollution killed the fish in rivers, fishermen had to find new livelihoods. One London fisherman, Henry Jones, was able to continue making a living off the river. He became a scavenger, collecting the fat and grease that floated on the river and making what some called "Thames mud butter." He and a handful of other scavengers steamed the grease in barges on the river and sold it for lubricating oil, or more fearfully perhaps, "Dutch Butter," reputed to be the "slimy sewage of the Thames . . . sent to Holland and from thence imported back to London markets" for human consumption.[15]

Industrialization and urbanization came later to the United States, and the resulting sewage as well. But soon these problems led to the widespread pollution of rivers and lakes. In 1904, Upton Sinclair described one arm of the Chicago River, known as "Bubbly Creek," downstream of the meatpacking district (figure 0.4). "One long arm of it is blind, and the filth stays there forever and a day. The grease and chemicals that are poured into it undergo all sorts of strange transformations, which are the cause of its name; it is constantly in motion, as if huge fish were feeding in it, or great leviathans disporting themselves in its depths. Bubbles of carbonic acid gas will rise to the surface and burst, and make rings two or three feet wide. Here and there the grease and filth have caked solid, and the creek looks like a bed of lava; chickens walk about on it, feeding, and many times an unwary stranger has started to stroll across, and vanished temporarily."[16]

"The New Problem of Sewage Disposal"

The creation of this new substance called "sewage" with all of its attendant problems led to "the new problem of Sewage Disposal," explained C.-E. A. Winslow, a leading American sanitary engineer, in 1915.[17] The water carriage system had removed wastes from households and neighborhoods, but had transferred the problem to "the end of the pipe," as noted by Martin Melosi. Because of its enormous volume and highly variable makeup, the disposal of sewage was far more complex than the disposal of privy waste had been.

The first comprehensive examination of the sewage disposal problem was initiated in 1857, with the establishment of a British Royal Commission to investigate the ways British cities might dispose of their sewage. The commission concluded that "the present state of sewage outfalls in many towns give rise to nuisance and danger of a formidable character."[18] Other commissions followed that investigated

Figure 0.4
Bubbly Creek at Morgan St., Chicago, 1911. The water carriage system, coupled with industrialization and urbanization, led to severe pollution of rivers, lakes, and estuaries. Bubbly Creek, near the stockyards of Chicago, was so named because the gases of putrefaction from sewage and industrial waste would constantly rise to the surface. Conditions like this led to the demand for sewage treatment. *Source*: Chicago History Museum, *Chicago Daily News* negatives collection, DN-0056839

the state of rivers in the United Kingdom, the efficacy of the various sewage disposal technologies, and potential laws and administrative structures that could solve the problem of pollution caused by sewage.

The reports of these commissions were highly influential, both in Great Britain and abroad. Sanitarians in the United States paid close attention to the so-called Blue Books and developments in Britain. U.S. cities sent delegations to Great Britain to investigate the advances in treatment technology. In the United States, recently established state boards of health began to investigate sewage problems, and individual cities convened commissions and conducted studies to find solutions to their pollution crises. American cities hired British sanitary engineers to conduct studies and draft reports on their sewage situations. In both countries, constructing sewage works was primarily left to individual cities. As a result, cities' engineers began conducting research into sewage treatment, and many of the most important developments were the result of this publicly funded and conducted research.

Despite the reports of the commissions and other investigative bodies, it was not clear that any single best means of treating sewage existed.[19] Various municipalities, based on their local situation and political and legal pressure to treat sewage, tried many different techniques, none with perfect success. When the 1857 Commission on Town Sewage issued its final report in 1865, it declared that the best method for treating sewage was to apply it to land, and land treatment or sewage irrigation became established as the primary means for treating sewage in England. Irrigation mirrored previous uses of human waste as fertilizer, and it involved spreading the sewage water over land, irrigating and fertilizing the soil simultaneously. There, the soil was thought to act as a filter that removed the solid particles in sewage and purified the effluent. The city of Edinburgh, regarded as the first city to use irrigation extensively, had disposed of its sewage in the Craigentinny Meadows since the beginning of the century, where it fertilized lush crops of grasses. Many other towns and cities in England and on the Continent followed. Cities like Berlin and Paris managed large farms that used and purified those cities' wastes. In a rapidly urbanizing world, however, sewage farms also required a large amount of expensive land. In humid climates like England, the water in sewage often presented a further problem. Most times of the year, there was plenty of rain, and the additional water in sewage simply flooded farm fields, leaving the land "sick," with sewage pooling on its surface.

The second major royal commission on sewage, the 1868 Commission on River Pollution, was dominated by the work of Edward Frankland, one of the most prominent chemists of his era.[20] Frankland conducted influential experiments on the ability of soils to filter sewage. Using glass tubes 6 ft. long and 1 ft. in diameter, filled with mixtures of sand and soil, he passed sewage taken from the London sewers through the tubes. Frankland found that sewage was only purified effectively if air were allowed to enter the soil. He concluded that the purification process was one of chemical oxidation.[21] Engineer John Bailey Denton built on this suggestion to develop a practical system of intermittent downward filtration in which extensive beds of soil would be allowed to rest between applications of sewage, allowing air to enter the soil and replenish the oxygen used to oxidize the sewage. Denton also abandoned the idea that growing crops was necessary for purification. Intermittent filtration thus severed the connection between farming and land treatment.

As an alternative to land treatment, chemists developed a myriad of techniques for separating out the solid particles in sewage by adding various kinds of chemicals, like aluminum or manganese salts, that would precipitate out the materials in suspension. The water, cleared of these solids, could be discharged into rivers, leaving what chemists (and investors) hoped would be a valuable fertilizer in the precipitated solids. Chemical precipitation was an industrial solution to the problem of industrialization and urbanization. Precipitation, however, was severely criticized, both because it failed to purify the effluent of the dissolved contaminants, and because it was often too expensive, costing more than the value of the fertilizer produced.

Beginning in the late 1880s, sanitary scientists began to understand the role of microorganisms in purifying sewage in soil. Engineers and scientists at the Lawrence Experiment Station of the Massachusetts State Board of Health were critical in this development. They built on the ideas of Frankland and Denton on downward filtration, but they also incorporated the recent advances of Pasteur and Darwin in microbiology and evolution. They began to understand the role of microorganisms in purifying sewage and developed explicitly biological processes of sewage treatment. Intermittent downward filtration soon morphed into the biological filter (figure 0.5). At the same time, London chemist William Dibdin began experimenting with biological treatment using what he called the contact bed. Both the biological filter (also called a trickling filter or percolating filter) and contact bed mimicked the treatment of sewage on land but concentrated it in a smaller area. In these systems, engineers built artificial beds of sand, gravel, clinker, slate, or other material and poured the sewage into the tank. Bacteria and other organisms grew on the material and purified the sewage.

These methods all relied on aerobic bacteria that required oxygen. Another set of processes developed in the 1890s and first decade of the twentieth century utilized anaerobic bacteria that were able to grow in the absence of oxygen. The septic tank, invented by Donald Cameron, the cultivation filter bed of W. Scott Moncrieff, Arthur Travis's hydrolytic tank, and the Imhoff tank were all closed tanks in which anaerobic bacteria could thrive. These bacteria tended to digest or liquify the sewage solids, reducing the amount of solid material in the waste stream, which could then be more efficiently treated in the various aerobic sewage filters.

In 1914, chemists Gilbert Fowler, Edward Ardern, and William Lockett of Manchester, UK, introduced the last major innovation in biological sewage treatment: the activated sludge process. In this process, sewage flowed into tanks which were bubbled with air to maintain aerobic conditions. Large populations of bacteria grew in the roiling tanks of sewage, feeding on the ammonia and organic matter. When the air was turned off or the sewage pumped to a quiescent clarifying tank, the bacteria would settle, cleansing the sewage of solids as they settled to the bottom of the tank, and leaving a clear effluent. Like a sourdough starter or the "mother of vinegar" used to make vinegar, the collected bacteria at the bottom of the clarifier would be recycled back into the activated sludge tank to keep the process going.

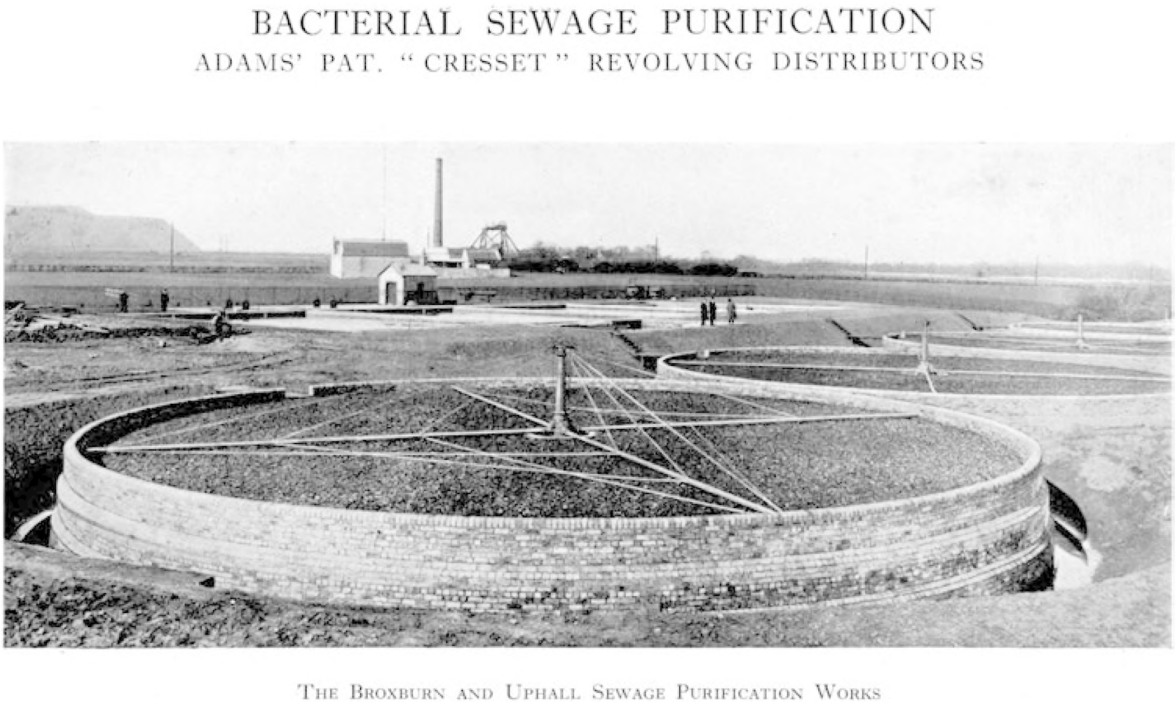

Figure 0.5
A trickling filter, Broxburn and Uphall Sewage Treatment Works. These circular beds would be filled with stone, slate, clinker, or other material. Sewage was sprayed over the top in a constant stream by the rotating arms. Bacteria that grew on the surfaces would purify the sewage as it trickled through the bed. Other microscopic organisms as well as insects and snails would also live on the filter, creating a complex ecosystem. *Source*: *Bacterial Sewage Treatment*, catalog from Adams Hydraulics, 1921, Milwaukee Metropolitan Sewerage District

The Contradictions of Biological Sewage Treatment

By 1914, then, the main processes of sewage treatment—the septic tank, the biological filter, and activated sludge—were established. These processes quickly dominated sewage treatment and remain the dominant treatment processes to this day. As Christopher Hamlin points out, though, the application of biological theories to sewage treatment was not a simple case of applying scientific knowledge to sanitary "problems" or of improvements in scientific understanding yielding corresponding improvements in treatment. Rather, these new treatment methods were adopted in a complex social context in which supporters of a variety of purification methods battled on political, cultural, economic, and scientific grounds. Sewage science was a highly contentious arena.[22] Physicians, scientists, engineers, public health officials, and treatment plant workers all argued over almost every aspect of the design and operation of treatment plants.

As these participants fought over the natural or artificial nature of the biological sewage plant, whether sewage processes could be patented and natural processes made private, whether sewage plants should be managed using scientific theory or industrial craft, or if sewage treatment should value potential profit from fertilizer over the greater purification of sewage, their disagreements highlighted the fundamentally contradictory nature of the biological sewage treatment plant and the industrial ecosystem more broadly. The resolution of these multiple contradictions occupied scientists, physicians, engineers, and industrial workers over the following century of development, construction, and operation of sewage treatment plants and other industrial applications of microorganisms. How these contradictions played out had enormous implications not only for the practice of sewage treatment but for other industrial ecosystems, including modern biotechnology. In attempting to resolve these contradictions, sewage workers created a new, hybrid form of nature, the industrial ecosystem.

Hybrid Nature is organized around the multiple contradictions that define the industrial ecosystem. Each chapter focuses on one of these contradictions, to produce overlapping narratives of the history of the sewage treatment plant. The sewage treatment plant was the most important industrial ecosystem, but its history paralleled and influenced other industrial ecosystems like brewing, chemical manufacture, and biotechnology. I follow these other systems as well in this narrative. Throughout I focus on the connected histories of sewage treatment in England and the United States. Most of the techniques for treating sewage were first developed in England. As industrialization spread from England across the Atlantic, so too did industrialization's environmental problems. Theories of microbial action in biological sewage treatment also crossed back and forth across the Atlantic as did many individual sewage scientists and engineers. Just after English researchers introduced the activated sludge process, World War I interrupted the progress England was making in sewage treatment, and the United States moved to the fore in research and development. For the period after the war, my focus shifts more heavily to the United States.[23]

The industrial ecosystem combined the natural and industrial in new, dynamic ways. In chapter 1, I examine the central contradiction of the industrial ecosystem, whether it was or should be considered a natural or artificial environment. Sanitarians of the nineteenth century placed great rhetorical importance on the "natural," and much of the justification for the treatment of sewage on land came from this understanding. In contrast, biological sewage treatment was originally characterized as an artificial process. Only through the naturalization of biological sewage treatment was it able to compete politically with land treatment. Coupled with this naturalization, however, was a drive to industrialize the biological processes. Scientists and engineers sought to accelerate, intensify, and regulate the biological activity of the treatment plant. The development of biological sewage treatment from land treatment to biological filters to activated sludge was thus a simultaneous process of naturalization and denaturing.

Chapter 2 examines the long-running conflict among engineers over the ethics of patenting and the public or private nature of fundamental biological processes. Both the septic tank and activated sludge were patented by English engineers who sought to enforce their patents in the United States, and many sanitary engineers organized nationally to resist the sewage syndicates and block the patents. These engineers viewed the patenting of sewage treatment processes as a transfer from public to private hands of a technology critical for the public health. This conflict exposed deep professional divisions between engineers. Municipal engineers viewed their work from the perspective of the public interest and criticized their colleagues who had patented advances in sewage treatment. For engineers working for industrial firms, in contrast, patent monopoly was a key business strategy. The challenges to the sewage patents were eventually defeated in the courts, with important implications for industrial microbiology in general, as well as modern biotechnology.

In chapter 3, I move into the plant itself and examine how it was managed by both engineers and workers. The category “worker” was fundamentally ambiguous, used to refer to both the human labor operating the plant as well as the bacteria responsible for the biological transformations. In a professional struggle for jurisdiction, sanitary engineers, using scientific process control, and operators, using factory craft, competed to exert control over the new space of the sewage treatment plant. Sewage professionals were from a diverse mix of disciplines, including chemistry, agriculture, medicine, public health, biochemistry, ecology, and engineering. A history of sewage treatment is also a history of professional identity and conflict. Through professionalization, training, and certification, engineers sought to control the unruliness of both bacterial and human labor by applying the principles of scientific management and laboratory control. At the same time, operators developed their own techniques for managing the plants that relied more on experience, close observation, sight, and smell.

The production and marketing of sewage fertilizer is the focus of chapter 4. Cities often hoped to profit from sewage treatment by recycling the sewage as fertilizer. In the mid-nineteenth century, a number of commercial firms were established to profit from sewage purification. These hopes, however, were repeatedly dashed as cities confronted what many thought to be a fundamental contradiction between purification and profit. Cities could either purify sewage, but at great cost, or produce a marketable fertilizer, but at the expense of adequate treatment. With the invention of the activated sludge process, hopes were renewed that sewage treatment could be profitable. Most notably, Milwaukee, Wisconsin, embarked on an almost century-long effort to produce and market sewage sludge. But by entering the marketplace, Milwaukee has been subject to the fundamental contradictions of purification and profit as well as the contradictions of capitalism.

Chapter 5 examines the sewage treatment plant ecosystem roughly from the passage of the 1972 Clean Water Act in the United States to the present. Despite a century of biological sewage treatment, the contradictions of the industrial ecosystem have persisted and continue to dramatically shape society's response to sewage pollution. Privatization, scientific control, profit, and ideas of nature all became intertwined as sewage treatment plants struggled with the increasing demands placed on them. What has remained constant, however, is the continued importance of the living organism in sewage treatment. But as the pressures placed on the sewage treatment plant to deal with newer and more pollutants have increased, the industrial ecosystem is teetering. Despite the diversity and adaptability of the bacteria responsible for treatment, the living organism is not infinitely malleable.

In chapter 6, I broaden the focus and trace the importance of sewage treatment to modern biotechnology and explore how the contradictions of the industrial ecosystem persist in and structure industries based on genetic technology. The sewage patent cases played a crucial role in the landmark Supreme Court case *Diamond v. Chakrabarty* that laid the intellectual property framework for biotechnology. This case ruled that for the first time living organisms themselves could be patented. The decision was based on legal precedents first established in the sewage patent cases, but also on the cultural work that both naturalized and denatured microbial processes. As the "natural" became incorporated into the industrial ecosystem, the industrial moved into the wild. I trace how genetic material from activated sludge plants has become incorporated into wild species. The industrial ecosystem has literally hybridized with the wild.

Finally, in the conclusion, I consider the hybrid nature of the industrial ecosystem more explicitly. The biological sewage treatment plant and the industrial ecosystem are hybrids, systems composed of elements of both the natural and artificial. As sanitary engineers and industrial microbiologists have been creating these hybrids, society has often been unable to recognize and come to terms with their hybrid nature. As the logic of the industrial ecosystem expands to include much of the larger biosphere, we are hybridizing the industrial and the wild and extending the contradictions of the industrial ecosystem to include much of the "natural" world of rivers, forests, and oceans. Coming to terms with these hybrid ecosystems will be essential to prevent their uncontrolled proliferation.

1

Natural vs. Artificial: “The Right Way to Dispose of Town Sewage”[1]

At the close of the nineteenth century, prominent physician and sanitarian George Vivian Poore spoke to a London medical society on urban sanitation: “We see the pipes, the engines, the ventilators, the hospitals, and the smoke of the destructor; we hear the incessant thud of steam machinery.” “But,” he continued, contrasting this industrial scene to the healing powers of nature, “we never get a glimpse of the bright side of the matter, the return which Nature inevitably makes to nourish our bodies, gladden our senses, and freshen the air.”[2] Describing a scene that might have come out of Charles Dickens’s *Hard Times*, Poore was drawing upon a well-established literature contrasting the nineteenth-century industrial and pastoral landscapes of England.[3] However, Poore was not describing, like Dickens, the steam engines, smoke, and polluted rivers of the woolen mills, dye factories, and machine shops of England’s industrialized cities. Rather, he was criticizing the industrial nature of the sanitary apparatus itself. Sanitarians were responding to the health problems and river and air pollution caused by industrialization by building their own industrial apparatus: vast networks of sewers and pumping plants, huge furnaces for incinerating the sewage of cities, giant schemes to treat sewage with the products of England’s expanding chemical industry (figure 1.1).

Other sanitary scientists and engineers, however, saw industrialization of the sanitary apparatus as a necessary response to the impact of urbanization and industrialization itself. “The requirements of civilized man have created certain artificial conditions which can only be met by corresponding artificial treatment,” wrote a correspondent to the *Times*, also in 1898. Unlike Poore, though, these sanitarians did not see the solution as pitting the industrial against the natural. Rather, they proposed a hybrid solution, in which the natural processes of purification advocated by Poore would be put to work in concentrated form. In creating their solution to the sanitation problem, these writers advocated for the recently developed processes of biological sewage treatment, in which “the law of nature need not be transgressed or departed from.”[4] Rather nature would be used, improved upon, sped up, and intensified. Biological sewage treatment, as envisioned by writers like these, combined the