Pollution Management in the Twentieth Century

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Abstract: A literature review is presented on the evolution of water pollution management and its impact on land pollution from 1900 to 2000 within an hypothesis of whether we could have done more, sooner. Stream pollution science in the context of the fundamental sanitary engineering concepts of reasonable use and assimilative capacity is examined in light of evolving regulatory frameworks from the early 1900s, when regulation and standards were mostly lacking, to the zero discharge goals and comprehensive federal command/control regulations of the late Twentieth Century. Details on the interplay through the years of improving environmental analytical chemistry, environmental quality definitions, wastewater control technologies, municipal–industrial wastewater differences, and regulatory will/diligence are provided. The pressure exerted on land and groundwater pollution as a result of water pollution control is emphasized. The author's conclusion is that more effective, faster pollution control evolution would have been difficult.

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Introduction

The Twentieth Century witnessed a revolution in waste management, environmental science, and societal views toward pollution. Scientific discovery, debates on societal priorities, and government awakening evolved through a century beginning with unhindered pollution and ending with attempts at total control. This paper presents some milestones and perspective on those hundred years with regard to water and land pollution.

Sanitary waste management in surface waters remained in many respects the top pollution priority throughout the Twentieth Century. Water-borne contagious disease still caused devastating epidemics in the early 1900s, compounded by growing, congested populations. Air pollution also grew to a high priority by midcentury because its impact was so observable and immediate. In many respects and for a number of reasons, the management of liquid and solid industrial waste received the lowest priority for much of the century because its nature is so diverse and sanitary waste control needs were so urgent. Today, we struggle with very costly, almost intractable land and groundwater pollution issues and seem to give them the highest priority. Should we have done more, sooner? Should we have known better? These questions, particularly as they pertain to industrial waste management, are currently of keen interest because of widespread cost recovery litigation and legislative debate regarding who should pay for environmental restoration from historically common and accepted practices of waste disposal on the land.

Although several historians have described the evolution of pollution control (Tarr et al. 1977; Pratt 1980; Tarr 1985, 1996; Colten and Skinner 1994; Colten 1998a), they often lack an engineering perspective by assuming that mere awareness could lead to instant solutions (Colten and Skinner 1996; Colten 1998b). Mutch and Eckenfelder (1993) added such engineering perspective, on which this paper will elaborate further based on the following points of premise:

1. To date, wastes remain a fact of life and there are only three places to dispose of wastes-air, water, or land. Waste management always involves tradeoffs. Even the destruction or transformation of waste (i.e., waste treatment or recycling) often leaves residuals that require disposal into one or more of these three media.
2. Historically, there has been a greater sensitivity to waste disposal into air and water due to their more directly perceived consequences. Land disposal of waste was typically the recommended alternative so as to avoid such perceived consequences in the other media.
3. "Reasonable use," a doctrine common and explicit in the history of water pollution control, has applied de facto to all media throughout human pollution history. Neanderthals stored their sanitary waste inside their caves in stealth from predators, but that "reasonable use" quickly became intolerable as the clan grew into villages. Simply stated, the doctrine of reasonable use recognizes that some pollution is permissible as long as other designated uses of a medium are not precluded. "Zero discharge," the antithesis of reasonable use, did not originate as a regulatory concept in this country until 1972 and remains today mostly an unmet goal due to technology limitations.
4. Our understanding of environmental contamination has depended on our ability to measure it. The advent of commercially available gas chromatography and atomic absorption spectrophotometry in the 1970s were major milestones in this respect.
5. The progression of scientific knowledge into firm regulatory and/or technological control is far from instantaneous. For any crucial scientific issue affecting society, there is a time-consuming process of discovery, testing, and debate on many

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Table 1. Decades of Progress

Decade	Progress
1900s	Essentially unhindered waste disposal.
1910s	More waste (WWI industrialization and urban growth) but continued limited control.
1920s	Advent of water pollution science and the quantitation of stream purification.
1930s	Evolution of engineering practices and state control.
1940s	Level of regulatory control debated extensively, but WWII hiatus.
1950s	Post war industrial boom added pressure as Federal and state regulation grew.
1960s	Birth of modern pollution legislation; Federal lead, states implemented.
1970s	Coalescence of total environmental control, zero discharge as a goal.
1980s	Hazardous waste site frenzy, everyone is guilty.
1990s	Regulatory refinement. Waste management is an integral part of doing business.

levels in order to explore the risks, benefits, tradeoffs, and costs to society. In reviewing benchmark scientific issues, it is thus meaningless to point retrospectively to a mere awareness of one or several facets and expect a sea change in societal behavior without this requisite progression of the issue through society's proving ground. The ongoing 25-year debate on global warming is a current example.

6. For any unfolding scientific issue, vastly different levels of knowledge are held by different population groups—academic scientists researching that issue, industry specialists affecting or affected by that issue, industry practitioners (who could be viewed generally as laymen) and the lay public. Although ignorance is "no excuse before the law," when the laws don't yet exist, various legitimate levels of ignorance are to be expected when viewing the issue in hindsight.

These points should underpin any retrospective consideration of the slow and tedious development of society's waste management practices in the Twentieth Century.

Evolution of Environmental Science

A number of keystone events defined the speed at which environmental management evolved through the Twentieth Century. Some of these events were scientific, such as stream self purification models, while others were socioeconomic, such as the two World Wars, which shifted American industry into a massive chemical production capacity. Such "driving" and "coping" events leapfrogged through the century so that, just as our environmental science brought us to one level of understanding, economic and population growth created new waste management demands that required a new responsive period of scientific/engineering adjustment.

Overall, it is useful to think of the evolution of environmental management in terms of decades because that appears to be the time scale of change in this area (Table 1). Little pollution control was practiced in 1900, the 1950s might be considered a turning point, but it was not until the 1970s/1980s that technology and regulations coalesced into comprehensive control objectives. However, the century closed with continued learning about how to meet such objectives.

Stream Pollution Science

At the onset of the century, stream pollution was viewed as a municipal wastewater problem (Clark 1901). Stream pollution historically was defined in terms of pathogens and dissolved oxygen levels, which were influenced by organic (i.e., carbonaceous) pollution loads. By this time, it was understood that sanitary and certain industrial wastes contained this organic contamination, or biochemical oxygen demand (BOD), which would decompose upon discharge to receiving waters causing impacts such as fish kills. Pasteur's pioneering microbiology (Pasteur 1868; Nicolle 1961) and Winkler's development of dissolved oxygen measurement in water (Than 1888) afforded early sanitary scientists both an understanding of and the ability to measure the relationship between organic waste and dissolved oxygen in receiving waters. The BOD measurement has evolved somewhat (cf. Caldwell 1889; Lederer 1914; Mohlman, Edwards, and Swope 1928; Theriault and McNamee 1932; Mohlman 1936; Ruchhoft 1941), but today's Dilution Method is fairly similar to that which prevailed since the 1930s.

It was recognized early on that oxygen deficits caused by BOD discharges could often cure themselves by self purification within the stream. This led to debate about allowable levels of BOD pollution because self purification was seen as making pollution a mostly transitory event. Streeter and Phelps (1925) and Imhoff and Mahr (1932) pioneered aeration/deaeration models that allowed scientists to predict allowable BOD loads to surface waters (Thomas 1948), i.e., waste load allocation. Reasonable use notions and waste load allocation science allowed waste discharges and other beneficial uses to be balanced. Today's policy debate on EPA's total maximum daily loads is the most recent version of waste load allocation.

The 1950s were a major turning point in pollution control. In 1949, the U.S. Public Health Service initiated a multiyear program to assemble basic factual information about water pollution in the United States. There were 20,000 significant sources of water pollution (Fuhrman 1951), equally divided between municipal and industrial sources, but there were only 6,700 municipal and 2,600 industrial treatment plants of various types in operation (Boyce 1952). These figures demonstrated a substantial unmet need for additional wastewater treatment as of 1950. New sources outpaced new treatment capacity throughout this decade. The U.S. Public Health Service estimated that 10,000 new plants or upgrades at a cost of up to $8 billion (1950 dollars, $50 billion in today's dollars) would be needed during the 1950s (Hollis 1951). This was three times the amount spent on pollution control during entire first half of the century. New municipal sewage treatment plant construction grew annually from only 23 to 93 to 167 to 208 during the period of 1946–1949 (Hollis 1951), indicating a slow start but quick growth of the pollution control industry at mid-century. In 1951, only 440 of those 10,000 needed plants were under construction with 2,300 more being planned (Boyce 1952).

By 1950, pollution debates focused on quality standards and stream use classification, necessary precedents to the development of waste management policy. The first stream classifications were established by Pennsylvania in 1923 to allow continued industrial pollution in low quality waters (Tarr et al. 1977). As of 1950, 13 states still had no laws or agencies dealing with water pollution (Rudolfs et al. 1951). Even major BOD dischargers such as Philadelphia, Pa., Los Angeles, Calif., and Boston, Mass. had not yet installed available secondary treatment technologies. While only 5% of the United States urban population remained unsewered, almost half still discharged wastewaters untreated in

1950 (Tarr et al. 1977). Wastewater treatment standards and practice development was also in its infancy in the 1940s and early 1950s. For example, in 1951, the engineering community first published "Tentative Standards for Sewage Works," in an attempt to standardize fundamental design requirements and practices (Boyce 1952). Furthermore, environmental scientists debated many elements of stream standards in the professional literature, and such standards were only slowly enacted by the states (cf. Streeter 1949). For example, the Detroit Regional Planning Commission, California, Maryland, and New York each proposed tentative water quality standards for the first time in 1950/1951. New York's standards accounted for seven different classes (i.e., different reasonable uses) of water (Rudolfs et al. 1952). New York's reasonable use principal was comparable to that of other states in the 1950s and acknowledged that "...disposal of wastes is one recognized best usage for waters in New York State." (Rudolfs et al. 1952). It was clear in the 1950s that the nation's waterways were to serve multiple uses including that of wastewater assimilation (Warrick 1951). In the first half of the century, the real debate was whether to allow uncontrolled pollutant discharges while relying on water supply treatment, or to treat polluted discharges so as to prevent pollution and thus minimize supply treatment needs (Tarr et al. 1977).

Although wastewater treatment increased significantly in the early 1950s, the problem of industrial wastewater control was still poorly defined compared to *municipal* sewage treatment (Cohen 1949). One indication of this was how little research was being performed—38 out of a total of 148 wastewater research projects underway at United States universities and other research institutions in 1953 addressed industrial waste (Black 1954). Furthermore, discussion of the need for wastewater treatment, along with instructional technical information, only started to migrate beyond the sanitary engineering literature and into industrial plant management literature during the 1950s (cf. Besselievre 1952; Moore 1957; Baldauf 1964).

Until the 1972 Clean Water Act, the regulation of stream pollution focused almost exclusively on BOD/dissolved oxygen, nutrients, and pathogenic contamination. By the 1970s, however, municipal wastewater treatment was more of a funding issue than a technical issue. Secondary treatment for up to 95% BOD removal and tertiary treatment for nutrient removal was fairly well defined and a major focus of implementing the 1972 Act was the Construction Grants Program aimed at getting municipal treatment plants built. This waste treatment, coupled with water supply chlorination, pretty much made water-borne epidemics a thing of the past in the United States by the 1970s. But much more subtle pollution issues—toxic chemicals—were taking shape in the 1970/1980 time frame. Section 307 of the 1972 Clean Water Act provided the framework for toxic chemical pollution control and a series of discoveries, such as carcinogens in the New Orleans, Mississippi water supply (Page et al. 1976) as well as in the Great Lakes (Jensen et al. 1969) catapulted industrial wastes to the spotlight.

Although general associations between chemical water pollution and fish toxicity were made as early as the beginning of the century (Shelford 1917; Willien 1920), systematic understanding of chemical pollution in the environment did not start until the 1970s. Even then, much of the early research on these chemicals such as polychlorobiphenyl (PCBs) and pesticides were aimed at merely cataloguing distributions and developing analytical tools, while questions of safe levels and remediation needs were rarely posed at this time (Shifrin and Toole 1998). Numerous scientific conferences were held in the 1970s to learn about "toxic pollution" (Train 1976), and the Chemical Industry Archives (www.chemicalindustryarchives.org), 37,000 pages of chemical company and Chemical Manufacturers Association documents, reflects industry's understanding at this time. The thrust of much of this material in the 1970s is related to the landfilling of chemical wastes as a reasonable alternative to surface water discharge.

Science of Land and Groundwater Pollution

In the Twentieth Century, perhaps the most significant influence on land disposal was our nation's emphasis on air and water pollution control. Pollution control residuals and, in some cases, raw wastes had to go someplace if not into our streams and air, and the land was our last resort, often the preferable alternative.

The science of predicting the impact of land disposal is quite recent in its development. It is actually a convergence of sciences—fluid flow, chemistry, and environmental sciences. Only when all of these pieces were melded together in the 1960s and 1970s were scientists able to predict in any formal way the environmental transport and fate of chemicals in the ground. Before this time the cause and effect of subsurface contamination was only anecdotal and there was no reason that laymen would understand it at all.

Anecdotal references to drinking water well contamination from a nearby waste source date back to the 1800s, but even as late as 1965 it was recognized that the ability actually to predict the impact of wastes on groundwater was very limited. Real scientific debate on groundwater contamination didn't start until the 1950s. Throughout this early literature, the notion of "reasonable use" persisted—some disposal of waste into the ground was acceptable but the key was to determine how much and how far to locate it from supply wells. The US Geological Service's review of groundwater contamination acknowledged the legitimacy of waste disposal in the ground while noting the tradeoffs of this reasonable use doctrine (LeGrand 1965): "It is the middle ground, somewhere between liberal and strict limits, that will allow community growth and fair industrial competition without creating the threat of pollution, a threat difficult to determine. In the interests of economy of money, of space, and of time, it would be desirable to know, for example how close we can locate each well from a waste disposal site without fear of contamination."

The poor understanding of groundwater contamination at midcentury, with a general belief that spills into the ground could be benign, is exemplified in a 1949 account of trichloroethene contamination of a well near an industrial spill, "...one might have expected that the movement of water through the gravel would have removed the contaminant." (Lyne and McLachlan 1949). There also was a general belief (or lack of understanding) that groundwater contamination would not necessarily migrate very far (Butler et al. 1954). A comprehensive Massachusetts Institute of Technology (MIT) study on land disposal sponsored by the Federal Housing Authority (FHA) (Stanley and Eliassen 1960) concluded that the then-present knowledge of groundwater contamination from the organic chemical industry was "not satisfactory" in terms of understanding: (1) permissible concentrations (in groundwater); (2) migration (of contaminants) into and through groundwater; (3) the ability of soils to attenuate the contamination; and (4) the ability to predict contamination. Moreover, with the exception of petroleum wastes, the FHA/MIT study gave organic chemical industry wastes almost the lowest priority, 18 out of 20, for groundwater contamination research needs. This argues strongly that, although the potential for groundwater contamination was acknowledged in the 1960s, few were alarmed by industrial landfilling and some degree of groundwater contamination, albeit poorly defined, was viewed as acceptable.

By mid-century, the American Water Works Association established a Task Group to study the effects of subsurface industrial waste disposal (Billings et al. 1953; Miller et al. 1957). They noted that an increasing public pressure to mitigate surface water pollution was forcing the use of more subsurface disposal. This theme was echoed many times, including in the US Congress' 1979 "Eckhardt Report," which was the springboard for Superfund. However, back in 1953 the AWWA report stated, "...ground water pollution by industrial-waste disposal is reported as relatively minor in many states, and even nonexistent in some..." A permit system was recommended by the Task Group for subsurface disposal, once again recognizing the doctrine of reasonable use for waste disposal. A World Health Organization review of groundwater contamination also acknowledged the validity of subsurface waste disposal but encouraged "safe practices" without really defining them (WHO 1957). This theme of "land-disposal-acceptability-but-doing-it-safely" was common in the mid-century technical literature along with a dearth of elaboration upon such "safe practices."

These examples demonstrate that in the 1950s and 1960s, the validity of subsurface waste disposal was acknowledged. They also demonstrate that a general knowledge of groundwater contamination and its relation to subsurface disposal did exist, but a specific science to manage the two did not yet exist. Geraghty (1962) was perhaps one of the first to describe cohesively the transport of contaminants in groundwater, but even his somewhat progressive paper did not offer evaluation tools for others to predict cause and effect on a site specific basis. Predictive tools were not developed until the 1970s, as discussed below.

Evolution of Groundwater Contaminant Transport and Fate Prediction

The first experimental study of groundwater flow was performed by Henry Darcy in the 1850s (Darcy 1856), which led to Darcy's Law, the basic groundwater flow equation used by scientists today. Darcy described purely the physics of flow in the subsurface and not the transport of pollution in groundwater. The basic physics and engineering of groundwater flow to supply wells was applied as early as the 1930s (Theis 1935). However, this also had nothing to do with groundwater pollution.

As noted in a prior section, the first pollution fate and transport modeling was developed for predicting sanitary sewage effects on dissolved oxygen in rivers (Streeter and Phelps 1925). This had nothing to do with the impacts of land disposal or spills on groundwater. It was not until the 1960s and 1970s that somewhat systematic scientific descriptions were offered of pollution transport in groundwater (Bear 1961, 1972; Ogata and Banks 1961; Freeze 1969; Ogata 1970, Konikow and Bredehoeft 1974). Groundwater fate and transport modeling as we know it today, where a chemical source in the ground is characterized and its impact on groundwater downgradient is predicted, often by computer models, was not developed until the late 1970s and 1980s (Konikow and Bredehoeft 1978; McDonald and Harbaugh 1988).

There are several reasons it took so long to synthesize the various sciences into a new science of groundwater contaminant fate and transport modeling: long cause—effect timescales, poor subsurface data, etc. In addition, there were no environmental regulations defining a groundwater "problem" that required a science to be developed in order to analyze it.

Prior to the 1970s, a layman such as an industrial plant operator might have seen groundwater in a pit but would have had little understanding how groundwater or solutes in groundwater migrated. There was no prevailing general concept, as there is today, that chemicals spilled or placed in the ground at one location would penetrate into aquifers and spread to other locations. In fact, laymen often believed the opposite—that the ground would purify any contamination. Even local ordinances, which permitted small separations between cesspools and supply wells, reflected this. Historically, in a few cases around the country where a nearby water supply well had a smell or taste from a nearby contamination source, the well was simply relocated to fix the nuisance without much fanfare or understanding of contaminant fate and transport (Willien 1920).

Not until the mid 1970s, with the passage of the Resource Conservation and Recovery Act (RCRA) with its "cradle to grave" management concept for industrial chemicals and with the Love Canal incident leading to Superfund in 1980, was there a widely perceived and regulatory motivation to understand groundwater contaminant fate and transport. The science developed very rapidly at that point and even many laymen acquired a conceptual understanding by the 1990s of the impacts of chemicals placed in or spilled on the ground.

Ability to Measure Environmental Pollution

Early methods of detecting contaminants in water and wastewater were generally not chemical-specific, thus offering severe limitations on the ability to define or control chemical pollution. Soil analysis for environmental pollutants was not discussed in the scientific literature until the 1970s. Also until the 1970s, water and wastewater analysis was generally limited to conventional parameters, such as BOD, turbidity, suspended solids, coliform bacteria, dissolved oxygen, nutrients, major ions, color, and odor. One exception to this general parameter approach was the analysis of phenols, which was needed due to its low taste threshold and which had convenient colorimetric methods. The state of the art remained basically unchanged through the 1950s, as noted by Middleton and Rosen (1956) and US Department of Health, Education and Welfare (USHEW 1962), who state, almost identically that "...specific methods, with few exceptions, for the analysis of the multitude of organic chemicals in water are lacking." Both of these papers also note that water treatment methods for such chemicals remained to be developed.

Table 2 presents a timeline for the evolution of analytical methods for environmental samples in the twentieth century. Hundreds of technical papers exist for the methods noted through time. For example, there are dozens of papers describing improvements in dissolved oxygen measurement up through the 1960s and hundreds of papers describing PCB and DDT measurements beginning in the late 1960s when this capability was first developed. Chromatography, and specifically gas chromatography with mass spectroscopy, introduced as an academic tool in the 1950s was a major turning point in our analytical capability for specific organic compounds in environmental samples. It took about 20 years, however, before this capability could be refined for quantitative environmental applications and an additional 10 years for it to be incorporated into our regulatory framework, as shown in the timeline.

The analysis of individual chemicals is a two-part problem for environmental samples: (1) isolation of the compound from the soil, water, or wastewater matrix and (2) accurate detection of its concentration. In the 1940s and 1950s, colorimetric, infrared, and ultraviolet spectroscopic techniques provided some advances to

Table 2. Evolution of Environmental Analytical Chemistry

Year	Event
1900s	• First "Standard Methods" publication—general parameters.
1910s	• 3rd Edition of "Standard Methods"—general parameters.
	• DO and BOD Method improvements.
	• Phenols > 100 mg/L.
1920s	• BOD method improvements.
	• Phenols > 10 mg/L.
1930s	• 8th Ed. of "Standard Methods"—general parameters.
	• BOD, COD, and DO method improvements.
	• Phenols > 10 mg/L.
	• Petroleum hydrocarbon fractions (not compound specific).
1940s	• Infrared (IR) methods for some organics > 500 mg/L.
	• Benzene > 100 mg/L.
	• DO by mercury electrode.
	• UV photometry for some organics > 30 mg/L.
	• Total petroleum (gravimetric).
1950s	• Portable DO meter.
	• Introduction of mass spectroscopy (MS).
	• Introduction of atomic absorption spectroscopy (AAS).
	• IR method advances.
	• Column chromatography.
1960s	• 11th Ed. of "Standard Methods"—added wet chemistry inorganics.
	• Paper and gas chromatography (GC) advances.
	• Fluorescence spectroscopy.
	• IR advances.
	• PCB and DDT research-level analysis by GC.
	• First commercial AAS.
1970s	• PCB Aroclor and separation refinement.
	• First government methods for pesticides.
	• GC refinements (cleanup, flame ionization, electron capture).
	• MS and nuclear magnetic resonance (NMR) refinements.
	• Inductively Coupled Plasma Atomic Emission Spectraphotometry (ICP).
	• First EPA manuals on organic and trace metal analysis.
1980s	• First EPA manual on hazardous waste analysis (SW846).
1990s	• 20th Ed. of "Standard Methods"—350 separate measurement methods.
	• Dioxin analysis > 1 part per quadrillion.

Note: DO=disolved oxygen; BOD=biochemical oxygen demand; COD =chemical oxygen demand; and PCB=polychlorobiphenyl.

this two-part problem for a limited number of individual chemical measurements (cf. Jacobs 1941; Wright 1941; Dolin 1943; Schumauch and Grubb 1954), but it was not until the advent of chromatography that substantial progress was made toward individual organic constituent analysis. The first advances used paper- or thin-layer chromatography (Lijinsky 1960; Ryckman et al. 1964) but these techniques still offered problems with convenient, accurate detection and quantification. It was not until the mid to late 1960s, when gas chromatography with sophisticated detection devices such as flame ionization, electron capture, and mass spectroscopy, were developed (Ettinger 1965; Holmes et al. 1967; Sugar and Conway 1968; Garrison et al. 1971), that the "modern era" was established for environmental analysis. These tools enabled us for the first time to understand subtle environmental problems such as the pesticide and PCB environmental issues that unfolded in the 1970s (Shifrin and Toole 1998).

For elemental and trace metal analysis, the development of commercial atomic absorption spectrophotometry (AAS) was the key milestone. Although its principles were known earlier in the century, the birth of AAS is generally attributed to Australia's Alan Walsh (Walsh 1955). The first practical American commercialization of the method came in 1962 with Perkin Elmer Corporation's "Model 303" instrument, used mostly at the time in hospitals and for industrial research. The AAS and its cousin, Inductively Coupled Plasma Atomic Emission Spectrophotometry, developed commercially in the 1970s, allowed for highly precise and low level analysis of inorganic environmental pollutants such as arsenic, mercury, and chromium, although as total amounts without regard to speciation.

Environmental Regulations and Standards

The regulatory framework we know today for pollution did not exist before the 1970s. Earlier in the century, with some minor exceptions, environmental laws focused more on problem definition, standards, and funding of basic services, all aimed mostly at surface water pollution. And most important, because it set the pace for progress in many respects, there were endless debates on where environmental regulation should reside—in the states or at the federal level.

In 1900 and for most of the century, few regulations related to waste disposal or environmental quality existed at any level of government. A timeline of environmental laws and related events is shown in Table 3. In the first half of the century, the Rivers and Harbors Act of 1899 was the primary water pollution law on the books. Not really aimed at pollution *per se*, its purpose was to promote unimpeded navigation.

It was not until 1909 that all states had public health departments. Massachusetts was first in 1869 and continued its leadership in public health and water pollution research well into the Twentieth Century through its renowned Lawrence Experiment Station. Federalization of public health issues began in 1912 with the passage of the Public Health Service Act. The US Public Health Service established by this law, with its later-formed Federal Water Pollution Control Administration, was the custodian of the environment until the formation of the US Environmental Protection Agency in 1971. Federalization continued during the Great Depression with a decade-long $550 million Construction Grants Program to build sewerage infrastructure. Debate at this time was on the use of separate or combined sewers and on the optimal point of treatment, at the discharge points or at the point of use (Tarr et al. 1977).

Another debate on state versus federal control was delayed by WWII, but the first federal water pollution law, the Federal Water Pollution Control Act, was passed in 1948. State's rights for pollution regulation remained protected while the federal role was limited to technical and financial assistance for sewerage improvements. Government leadership and little sense of urgency prevailed at this time, however, resulting in the $23 million/year Construction Grants program designated by Congress never being

Table 3. Environmental Legislation Timeline[a]

Year	Environmental Legislation
1899	***Federal Rivers & Harbors Act*** • Protect navigation from gross pollution.
1909	***State Boards of Health established in all states.***
1912	***Public Health Service Act*** • Established U.S. Public Health Service
1924	***Oil Pollution Act*** • Oil spills, coastal waters.
1933-1940	***Sewerage Construction Grants (not legislation)*** • $550 million for sewer and treatment plant construction.
1948	***Federal Water Pollution Control Act*** • State controls, federal assistance.
1955	***Air Pollution Control Act*** • Focus on research.
1956	***Federal Water Pollution Control Act*** • Continued state control but stronger federal intervention.
1961	***Federal Water Pollution Control Act Amendments of 1961*** • Extended federal enforcement authority to coastal and interstate waters. • Industrial pollution control remained with states.
1963	***Clean Air Act*** • Encouraged emission standards for mobile and stationary sources.
1965	***Water Quality Act*** • Required establishment of water quality standards for all interstate waters, but could vary by state. • Allowed for federal override if states defaulted their authority.
1965	***Solid Waste Disposal Act*** • Funding for improved solid waste management methods and problem definition.
1966	***Clean Water Restoration Act*** • Large increase in construction grants program—$3.6 billion through 1971; States still had control.
1967	***Federal Air Quality Act*** • Required air quality criteria, state development of air quality standards, and air quality control regions.
1970	***Clean Air Act and Amendments*** • Federal primary and secondary air standards and state implementation plans.
1970	***National Environmental Policy Act (NEPA)*** • Environmental Impact Studies; President's Council on Environmental Quality.
1970	***Resource Recovery Act*** • Studied US hazardous waste practices; promoted recycling and energy recovery.
1971	***Executive Order No. 11574 (Richard Nixon)*** • Established EPA and wastewater discharge permits for all non-municipal point sources (precursor to NPDES).
1972	***Federal Water Pollution Control Act Amendments of 1972*** • First comprehensive federal water law; treatment standards, NPDES, toxic chemicals.
1974	***Safe Drinking Water Act*** • National drinking water standards and reporting requirements for public supplies.
1976	***Resource Conservation and Recovery Act (RCRA)*** • First federal regulation of hazardous wastes, cradle to grave for operating facilities.
1976	***Toxic Substances Control Act (TSCA)*** • Toxicity testing requirements for new chemicals in commerce; PCB controls.
1980	***Comprehensive Environmental Response, Compensation and Liability Act (CERCLA)*** • Clean-up of abandoned or non-operating hazardous waste sites; unique liability net.
1984	***Hazardous and Solid Waste Amendments (under RCRA)*** • Banned liquid and other listed wastes from landfills; other landfill controls.

[a]For elaboration, see Tarr et al. 1977, and the discussions by former Representative Blatnick in Lund, 1971, who played a major role in the development of federal water pollution legislation. See also *Chemical Engineering*, October 14, 1968, for a summary of state environmental legislation at the time of "federal awakening."

fully distributed. The new water pollution law also established important research elements—the federal Environmental Health Center in Cincinnati (still an EPA research center) and the nationwide surface water quality monitoring of National Water Quality Network starting in 1957.

The 1948 law contained no enforcement objectives or mechanisms, nor did it establish any tangible environmental quality objectives. Its objective was to promote standards but it didn't establish any standards. Moreover, leaving responsibility for environmental management in the hands of 48 individual governments precluded cohesive policy. Water pollution was often viewed technically as at least a regional problem, and several important multistate cooperative efforts, such as Ohio River Valley Water Sanitation Commission (ORSANCO), were formed for better coordinated pollution control (Cleary 1967). A review of state environmental regulations in the 1960s (Chemical Engineering 1968) showed disparity around the nation.

The Water Pollution Control Act was subsequently amended by Congress numerous times, each time adding more federal authority over the states. The Construction Grants program persevered, although criticized for inefficiency and slow funding distribution. Federal authority grew by first precluding state vetoes of federal initiatives (1956), then by taking control of enforcement over coastal and interstate waters (1961), then by requiring water quality standards for all interstate waters, although they could vary by state (1965), and finally by assuming full control over wastewater discharges and surface water quality with the passage of the Federal Water Pollution Control Act Amendments of 1972 (the Clean Water Act).

The 1972 Clean Water Act was truly a turning point in environmental management in the United States. For the first time, it established a goal of zero discharge of pollution to surface waters and defined a timetable through 1983 for the first two major steps toward this goal. It established a national permit system for every point source discharge in the US. It required establishment of uniform national water quality standards. It recognized for the first time, federally, the need to control chemical pollution in addition to conventional BOD, nutrient, and pathogen pollution. It also boosted tremendously the Construction Grants program so as to allow municipalities to meet the law's aggressive goals, and it established a nationwide study of 50 major water basins to predict the impact of the new law's requirements and recommend improvements to Congress, if needed.

The context of the revolutionary 1972 Clean Water Act included a backdrop of Rachel Carson's pesticide warnings in Silent Spring (Carson 1962) and the first Earth Day (1970) energized by Vietnam War activism. President Nixon established the US EPA in 1971 to manage several other dramatic legislative environmental initiatives taken by Congress in 1970—the Clean Air Act, an atmospheric revolution, and NEPA (National Environmental Policy Act), which established requirements for impact studies of construction projects that could affect the environment and also established the President's Council on Environmental Quality. At this same time, the PCB issue unfolded (Shifrin and Toole 1998), which drove home the notion that barely measurable environmental levels of previously believed "wonder chemicals" possibly posed insidious and scientifically perplexing long term threats to human health and the environment. The switch had clearly been flipped on environmental concern by 1972, when the Clean Water Act was passed.

Although this initial regulatory burst clearly focused on air and surface water, solid wastes and land pollution were not entirely ignored. The first federal Solid Waste Disposal Act (1965) had been passed to provide financial aid to states and to promote research on management methods and issues definition. The law was aimed primarily at the municipal solid waste problems caused by rapidly growing cities. Traditionally, landfills were regulated by local government, if at all. As of 1973, the possibility of groundwater pollution from and the need for proper design of landfills was recognized in the regulations of only 22 states (van der Leeden 1973). In 1975, EPA estimated that only 25 states took any kind of regulatory responsibility for hazardous waste and such efforts were staffed by a total of only 50 people, nationwide (Kovacs 1986). The Resource Recovery Act of 1970 promoted recycling as an alternative to solid waste disposal and authorized a study to define the nature and extent of hazardous waste disposal in the United States. This put hazardous waste disposal on the radar screen and it rapidly grew to an issue of intense national and local focus, partly due to the other coincident environmental events, described above. The RCRA, was passed by Congress in 1976 and represented a comprehensive "cradle to grave" regulatory approach to solid and chemical waste disposal. It was not until 1980, however, that EPA developed the regulations for this management, a lengthy delay for which Congress criticized EPA. This delay was an indication of both the technical and regulatory unknowns involved with solid/chemical waste management at the time, as well as of the higher priority given to air and water media over land and groundwater pollution even up to 1980.

Other benchmark laws established in the 1970s to complete the nation's environmental portfolio included the 1974 Safe Drinking Water Act, the 1976 Toxic Substances Control Act (TSCA), and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (1980). The TSCA established toxicity testing for all new chemicals entering commerce and, probably because of the coincident timing of the issue and the legislation, became the main regulatory mechanism for PCBs. The CERCLA, or Superfund, was established to identify and to remediate the nation's abandoned or non-operational (as opposed to factory settings, which are regulated by RCRA) hazardous waste disposal sites. Perhaps CERCLA's most innovative element was its vast temporal and organizational liability net castable upon almost anyone even remotely responsible.

Thus, by 1980, the last regulatory hatch had been closed on environmental pollution. The nation's population and economic growth and the general lack of concern about land disposal up to the 1970s had created the sleeping giant of land and groundwater pollution. The mid-century emphasis on water and air pollution exacerbated the problem by shifting some pollution to the land. Traditional views of the transitory nature of pollution and self purification rapidly became challenged by the much longer timescales of subsurface pollution. As the Twentieth Century closed, we found ourselves slowly remediating these problems and wondering how clean it all needed to be.

The "how clean is clean" environmental quality issue is historically important because its evolution through the century reflected our growing understanding about the environment and public health. Three types of standards evolved—discharge standards, ambient environmental standards, such as water quality standards, and consumer standards, such as for drinking water. Environmental standards existing at 1900 were qualitative measures of gross effects causing nuisances—odors, smoke, "putrescible conditions," suspended or floating materials, discoloration, and fish kills. Early quantitative standards were related to BOD/dissolved oxygen conditions in streams, turbidity, and oil/grease. Early chemical contamination standards were limited to phenols and nutrients.

The development of standards has technical, economic, and even philosophical considerations related to the intended or reasonable use of the environmental medium. Paracelcius in the Seventeenth Century is credited with introducing the notion that the "dose makes the poison" and this continues to form the basis of environmental standard-setting. But our knowledge evolved slowly. Through the 1950s, the sanitary engineering profession was "...peculiarly unresponsive to problems of [chemical] toxicity" (Cleary 1954). This was not really peculiar, however, because basic sanitary issues still held priority in the 1950s and the tools available for understanding toxics were minimal. Even as late as the 1960s, our scientists recognized the limitations in understanding of chemical pollution (National Academy of Sciences 1966): "But, with a few exceptions, adequate research techniques are not now available to establish reliably the causal relationship between chemical contamination of water supplies and human health."

Continuing this theme into the 1970s, nonzero thresholds were still accepted (Santaniello 1971): "The intended end use of water determines the degree of pollution permissible by certain specific constituents or characteristics. The concentration at which the designation pollutant is earned varies for each constituent from relatively high levels to *any* level at all."

Ambient standards for water quality often take the form of criteria (i.e., a scientific judgment or recommendation), which were first developed nationally pursuant to the 1965 Water Quality Act by committees of the Federal Water Pollution Control Administration. The first version, the "Green Book" (U.S. Department of the Interior 1968), provided quantitative and qualitative criteria for five uses: recreation/aesthetics, water supply, fish/wildlife, agriculture, and industry. Consistent with the reasonable use doctrine, the Green Book presented many different values of permissible chemical concentrations for many different intended uses of ambient water. The criteria were updated in the Blue Book in 1973 and the Red Book in 1976. Some examples of these criteria are given in Table 4. Section 304 of the 1972 Clean Water Act required EPA to review periodically and publish water quality criteria. Following a lawsuit by the Natural Resources Defense Council in 1976 to force EPA to act on this requirement, the agency promised to establish criteria for 65 "Priority Pollutants"

Table 4. Examples of Water Standards and Criteria for Common Contaminants[a]

	Drinking Water (μg/L)[a]						Ambient water quality criteria (μg/L)[a]		
	1914	1925	1946	1968	1977	2000	1968	1980	1998
	Treasury Standards	USPHS	USPHS	Green Book (FWPCA)	EPA interim MCLs	EPA MCLs (primary)	Green Book (fish & wildlife)	EPA[a]	EPA[b]
Lead	—	100	100	50	50	15	—	50	65f
Arsenic	—	—	50	50	50	50	—	0.002	0.02
Zinc	—	—	15,000	5,000	—	—	4	5,000	120
Chromium[c]	—	—	50	50	50[d]	100T	20	50	16f
Mercury	—	—	—	—	2	2	—	0.0001	0.05
Phenolics	—	—	1	1	—	—	20–150	—	—
Phenol	—	—	—	—	—	—	15,000	3,500	21,000
Benzene	—	—	—	—	—	5	—	0.7	1.2
TCE	—	—	—	—	—	5	—	2.7	2.7
DDT	—	—	—	42	—	—	2–20	0.00002	0.0006
2, 4-D	—	—	—	100	100	70	~800	—	—
PCB	—	—	—	—	—	0.5	—	0.0008	0.0002
CCE[e]	—	—	—	150	—	—	—	—	—
BOD	—	—	—	—	—	—	—	—	—
Suspended solid[f]	—	—	10t	~0t	1t	1t	25,000	—	—
DO	—	—	—	≥3,000	—	—	7,000	—	—
Coliforms[g]	<2.2	<2.2	<2.2	2,000f	1	0f	—	—	—

Note: USPHS=United States Public Health Service; FWPCA=Federal Water Pollution Control Administration; EPA=Environmental Protection Agency; MCLs=maximum contaminant levels; TCE=trichloroethylene; DDT=dichloro diphenyl trichloroethane; PCB=polychlorobiphenyl; BOD=biochemical oxygen demand; and DO=disolved oxygen.

[a] Selected as representative of parameter groups. In some cases additional individual parameters were listed (sometimes rounded. Dash means no standard.) All units (μg/L) unless noted otherwise.

[b] Human health criteria at 10^{-6} risk or hazard index of <1 for consumption of drinking water and fish, unless noted as "f" for protection of freshwater life (human health criterion not available).

[c] Chromium (VI) unless total, noted by "T."

[d] To be changed to 10 mg/L.

[e] Carbon chloroform extract, a measure of total "organics."

[f] Turbidity units if noted by "t."

[g] Count per 100 mL, "f" indicates fecal, otherwise, total.

as a settlement of the suit. The EPA published notice of criteria for 64 of the Priority Pollutants (dioxin was delayed) for the first time in 1980 (Federal Register 1980). Examples of these criteria are also given in Table 4. The EPA continues to update criteria and add new chemicals periodically, and there are currently criteria for 157 chemicals (USEPA 1999).

Wastewater discharge regulation through the century has been based on the assimilative capacity of receiving waters. By the 1940s and 1950s, state agencies negotiated waste discharge concentration and load limitations with industries discharging to receiving waters having noticeable water quality problems (Adams 1942; Hollis 1951; Boyce 1952; Purdy 1967). Federal regulation of all point source discharges was initialized through the National Pollution Discharge Elimination System (NPDES) of the 1972 Clean Water Act. The NPDES made it illegal to discharge any wastewater from a point source (pipe) without a permit. The first round NPDES permits addressed mostly traditional parameters (e.g., BOD, suspended solids, nutrients, bacteria, heat, pH, etc.). By the century's end, many NPDES permits also contained specific chemicals.

The first drinking water standards on a national scale were qualitative and were established by Congress in 1890–1901 as sanitary controls (e.g., quarantine powers) for water-borne diseases, like cholera. Quantitative standards were first established by the United States Treasury in 1914 and amended several times as the Public Health Service (PHS) Drinking Water Standards in 1925–1962 (McDermott 1973; Taylor 1977; O'Connor 2002). Initially covering only bacteria, the "Treasury Standards," or PHS Standards added lead, copper, and zinc in 1925. By 1946, the Public Health Service published standards, recommended or required, for nine trace metals, three general parameters (e.g., chlorides, solids, sulfates), and phenolic compounds (Table 4). These standards were reviewed by the sanitary engineering profession in 1960, which concluded that they were generally satisfactory, fair, and effective although additional standards for cadmium, cyanides, nitrates and radionuclides were suggested (Hopkins and Gullans 1960; Welsh and Thomas 1960). By 1962 the list of mandatory or recommended values increased from 17 to 29 parameters. These standards prevailed until the passage of the 1974 Safe Drinking Water Act, which required EPA to develop drinking water standards for toxic compounds. EPA's work in this area dovetailed with its development of Water Quality Criteria, described above, to become the list of maximum contaminant levels (MCLs) for approximately 90 compounds, microorganisms, physical parameters, and radionuclides as of 2000. The MCLs are developed by considering both health-based criteria and economic or practicability issues.

Toward the end of the Twentieth Century, federal efforts turned to establishing contaminant criteria standards for soils (USEPA 1994b) and sediments (Long and Morgan 1990; USEPA 1993, 1994a, 1996b). As of 2000, these criteria were established for screening purposes, and cleanup criteria were still determined on a site specific basis. In the 1990s, many states also developed tiered (depending on intended use), quantitative soil standards for defining the need for remediation (cf. Massachusetts Contingency Plan, the Missouri Voluntary Cleanup Program, and Ohio's Voluntary Cleanup Program).

Industrial Waste Management

The management and cleanup of industrial wastes, past and present, was arguably the final frontier of waste management in the Twentieth Century. As with other sectors, industrial waste management first focused on stream pollution effects and then on land-side management. The most distinctive factor retarding development of a universal understanding of industrial wastes has been the diversity of wastes and control issues, driven to a large degree by the diversity of industry itself.

Industrial Wastes and Stream Pollution

Early Twentieth Century reviews of industrial pollution (Clark 1901) reflected a simpler industrial base of tanneries, paper mills, iron works, textile mills, basic chemicals (e.g., caustic soda), and mining, and were limited mostly to their sanitary significance (Leighton 1906). Although the negative impact of this pollution was recognized within the reasonable use framework, very little comprehensive waste management was required as of this early date. The tension was between the desire for economic development, the lack of adequate treatment technology, and the poor definition of how much treatment was needed.

The 1920s represented an awakening to industrial pollution issues. By this time, at least some trade groups, such as the American Gas Association, had formed committees to advance specific waste treatment needs of particular industries (Willien 1920), and technical journals on pollution control regularly reported on industrial wastes (Fales et al. 1923). In this decade, investigators also reported on pollution problems caused by a few individual chemicals, such as phenol (Bundesen 1928; Theriault 1929; Waring 1929) as well as by specific industries, such as coke ovens (Leitch 1925), food processing (Bartow 1926), and textiles (True 1924). Industry specific research and reporting continued through the next two decades with pollution control stories of varying success for specific companies such as Dow (Harlow 1939; Sewage Works Engineering 1946; Harlow and Powers 1947), Hoffman LaRoche (Lorentz 1950), and Dupont (deRopp 1951) as well as for certain industries (Rubber—Hebbard et al. 1947; Petroleum—Weston 1944; Chemicals—Hess 1949b; Pesticides—Sharp 1956; and Pharmaceuticals—Paradiso 1955; Barker et al. 1958) and industry in general (Besselievre 1931; Hurwitz 1931; Warrick 1938; Weston 1938, 1939; Howe and Van Antwerpen 1939; Knowles 1939; Mohlman 1939; Eldridge 1942; Goudey et al. 1944; Barnes 1947). States also reviewed industrial wastes within their borders, primarily in terms of stream quality, and reaffirmed the need for only partial treatment of industrial wastes, i.e., reasonable use (Wise 1945).

Industry became quite involved in pollution issues by mid century, particularly after WWII, but the focus remained on surface water quality protection and definition (Hess 1949a). There were only minor references to groundwater contamination from industrial wastewater or sludge disposal in this time period and subsurface disposal was viewed as a viable option so as to protect surface waters (Warrick 1951; Henkel 1953). The "Purdue conferences" on industrial wastes began in 1945, where papers were given and workshops held mostly on surface water pollution effects as well as on treatment technologies for specific industries (cf. Purdue University 1947). Annual conferences on industrial wastes aimed at protection of surface water and air quality, waste reuse, and waste prevention were also held to focus on regional issues such as those in the Pacific Northwest from 1949 to 1954 (University of Washington 1954). Sections on industrial wastes began appearing in the 1930s in annual technical reviews of the pollution literature, such as in the Sewage Works Journal (cf. Rudolfs 1935; Rudolfs et al. 1943) as well as in other pollution and engineering journals (cf. Mohlman 1946; Friel 1947; Fuhrman 1951; Hess 1953; Jacobs 1955). Such reviews continue to this day in the water pollution literature. Several conclusions can be made from this literature—the diversity of problems was so widespread as to be almost plant specific, only partial solutions were technologically possible during this time, some amount of disposal (e.g., to the land and surface water) was universally accepted, and the discourse was robust and public.

By the 1950s and 1960s, government and some industries had developed manuals of practice for industrial wastes and convened conferences on waste control technologies. For example, the second edition of the refinery waste disposal manual (API 1951) had a specific volume on chemical wastes. The paper industry issued a manual for treating de-inking wastewater (NCASI 1948). A pesticide waste disposal manual was published in 1965 (National Agricultural Chemicals Association 1965). The Manufacturing Chemists Association (1954, 1955) published Water pollution abatement manuals. British and American engineers met at a conference on industrial wastes (Society of Chemical Industry 1957) and the Purdue conferences continued annually. The US Public Health Service (USPHS) published manuals for the textile industry (USPHS 1959b), sugar (USPHS 1959a), wool processing (USPHS 1955), commercial laundering (USPHS 1956), and milk processing (USPHS 1953), among others. Even the insurance industry evaluated industrial waste issues in the form of a "Chemical Hazards Information Series" (cf. Association of Casualty and Surety Companies 1952 as cited in NIOSH 1976). Numerous textbooks on the principles of industrial waste treatment were also published during this time (cf. Rudolfs 1953; Gurnham 1955; Nemerow 1963; Besselievre 1969; Lund 1971; Neal 1971; Nemerow 1971).

Despite a robust post-1920 dialogue on industrial wastes, as suggested by the examples above, this was more an indication of the depth and breadth of the problem, rather than proof that the problems were solved during this era. Technological limitations were part of the problem since even as late as the 1960s, "...there [were] no known satisfactory methods of treatment for some wastes..." (Cleary 1967). The lack of clear environmental regulatory objectives during this time was another reason. For example, the 1972 Clean Water Act's technology-based objectives and timetable [best practicable treatment, by 1977 and best available treatment (BAT) by 1983] was more clearly interpretable for municipal than for industrial wastewaters.

As EPA and industry struggled with defining BAT and NPDES permits for industrial wastewaters, Congress' 1976 passage of RCRA, aimed at industry's "solid" waste stream, further forced a more comprehensive understanding of industrial wastes. Throughout the 1970s and early 1980s, EPA sponsored a series of industrial surveys to define the nature of the nation's major industries and their wastes. Reports were issued for many industries, including paint and allied products (*EPA/530/SW-119C*), organic chemicals (*EPA530/-SW-118C*), inorganic chemicals (*EPA/530/SW-104C*), electronic components (*EPA/530/SW-140C*), rubber and plastics (*EPA/530/SW-163C*), metal smelting and refining (*EPA/530/SW-145C*), petroleum refining (*EPA/530/SW-144C*), special machinery manufacturing (*EPA/530/SW-141C*), electroplating and metal finishing (*EPA/530/SW-136C*), leather tanning/finishing (*EPA/530/SW-131C*), textiles (*EPA/530/SW-125C*), and batteries (*EPA/530/SW-102C*), among others. Bibliographies of hundreds of studies on hazardous materials waste disposal were published by the federal government during the 1970s (Cavagnaro 1979) and the EPA sponsored national studies on industrial waste practices (Holcombe and Kalika 1973; Gruber 1975). The seeds of solution in the form of a systematic problem definition for industrial wastes and environmental objectives were finally being sown, but not until about 1980.

Industrial Wastes and Land Pollution

Industry and municipalities made use of the land for disposal of their solid wastes, of residuals from waste treatment, and for stabilization or disposal of some liquid wastes when direct disposal to surface water was undesirable. In addition to deliberate disposal to the land, inadvertent leaks and spills frequently occurred of materials onto the ground or into the subsurface from tanks and pipes, which offered another source of contemporary soil and groundwater contamination. Leaks were inadvertent but inevitable at chemical plants and one Monsanto plant even reported maintaining a "leak committee" in an attempt to manage the problem (Morriss 1954).

Beginning with the first known law regulating municipal dumping at Georgetown, Va. in 1795 (Wilson 1977), most regulation and literature on dumping through the mid-Twentieth Century focused on municipal waste and the evolution of the sanitary landfill method, which began in the 1930s (Moore 1920; Eddy 1934, 1937; Cleary 1938; Civil Engineering 1939; ASCE 1959; APWA 1966; Mantell 1975; Wilson 1977). Sanitary landfilling was developed to ensure efficient land use and to keep wastes covered to avoid disease vectors such as rats and insects. Groundwater contamination was not typically an issue. One of the first systematic studies of potential groundwater impacts from landfills was conducted in California and concluded that groundwater would not be impaired for beneficial use as long as landfills were located above the water table (California State Water Pollution Control Board 1954). By 1970, groundwater pollution from sanitary landfills had been studied quite widely and the conclusion still was that attenuation by surrounding soils often reduced impacts to groundwater supplies (Zanoni 1971, 1972).

The literature on land disposal of industrial wastes was more limited than that for municipal waste during the first half of the Twentieth Century. This in itself is proof of this issue's lower environmental priority at the time. By the 1950s, however, industrial waste land disposal was addressed somewhat widely in the technical literature, but more in terms of how to do it, not whether to do it (Rudolfs 1953; Stone 1953; Powell 1954; Black 1961; Rosengarten 1968; Snell and Corrough 1970; Overcash and Pal 1979). For example, the petroleum industry issued manuals of practice that described combined treatment/surface water discharge and land disposal options (API 1951), as did the pesticide industry (National Agricultural Chemicals Association 1965), and the National Safety Council in terms of generally acceptable practices for industry (Gurney and Hess 1948). Some states actually encouraged land disposal, such as Wyoming for refinery wastes (Williamson 1958). In most of the literature, industrial waste management by a combination of treatment and land disposal was typical (Paradiso 1955; Watson 1956; Gurnham 1960; Lombard 1969), and the need for ultimate disposal of residual sludges onto the land was well recognized (Burd 1968). By the 1970s, industrial solid waste management was reviewed annually in the technical literature (Sorg 1971), and a need was recognized for "chemical waste landfills" for some, but not all, hazardous wastes depending on their constituent concentrations, (USEPA 1973; Fields and Lindsey 1975; Skopp 1976; Sittig 1979).

Land disposal by the chemical industry is useful to demonstrate practices just prior to the "RCRA era" of comprehensive regulation. In 1967, the U.S. chemical industry consisted of 2,030 manufacturing plants (79% had fewer than 100 employees; 2% had greater than 1,000) generating an average of 33,000 t/year per plant of process waste (Holcombe and Kalika 1973). (By contrast, the American Chemistry Council estimated 2,000 times less process waste generated in 1998). The vast majority of these wastes consisted of flyash (52%), sludge (39%), and filter residue (4%) with tars and off-spec product contributing each about 2%. Land disposal was the ultimate fate of 72% of these wastes, with lagooning at 10%, incineration at 8%, and "other" at 10%. The majority of this land disposal was onto plant property, 58%, while 42% used public solid waste disposal sites. Only 69% of the land disposal was governed by any type of solid waste regulation at that time.

Despite industry's reliance on land disposal, an understanding of the resultant impacts on groundwater was sketchy, anecdotal, and generated highly variable levels of concern until the 1970s. Rosenau (1914), Willien (1920), and Chase (1939) all warned of well contamination in general terms and gave a few examples for certain industries. Lyne and McLachlan (1949) were surprised to observe the large distance TCE migrated from a spill, while Butler et al. (1954) observed quite short migration distances of tar constituents. The World Health Organization held European seminars in the 1950s, covering groundwater pollution, but the conclusions, which focused mostly on bacterial and chloride pollution, were quite general regarding industrial chemical waste disposal (WHO 1957). Miller et al. (1957, 1960) presented case studies illustrating the widespread presence but varied character of subsurface contamination issues. Several states were noted as having no subsurface issues at that time. Rorabaugh (1960) described in general how septic tank and waste lagoon leakage could reach underlying groundwaters. In one of the first attempts to infuse theory into these anecdotes, the California State Water Pollution Board (1961) described the potential effects of "refuse dumps" on groundwater quality.

By the late 1960s and early 1970s, systematic field studies of subsurface contamination migration were being performed (Andersen and Dornbush 1967; Gillham and Webber 1968; Cole 1972), thus making the transition from anecdotal to engineering understanding of the issues. Finally, by the mid 1960s, at least brief annual literature reviews of groundwater pollution were being published in the technical literature (cf. Ewing 1965; Ewing and Lau 1966). However, the President's Council on Environmental Quality, in its annual reports on the environment, did not even acknowledge groundwater quality as an issue until 1975 when it discussed the newly passed Safe Drinking Water Act.

Although general calls for preventative legislation existed as early as the 1940s literature (Doll 1947), and rudimentary fate/transport prediction was developing in the 1960s/1970s, only 13 states actually had laws aimed at protecting groundwater as late as 1970 (van der Leeden 1973). By the early 1970s, however, government and university research rapidly assembled a clearer picture of potential groundwater impacts from land disposal and other sources (Todd 1973; Weddle and Garland 1974; Todd and McNulty 1974; Miller et al. 1974; Fields and Lindsey 1975; USEPA 1977; Wilson et al. 1976). It was clear that the groundwater contamination issue was coming to a head as Congress passed RCRA in 1976. The Love Canal incident, starting in 1978, then whipped the issue into an absolute frenzy.

Love Canal triggered a style of government enforcement, technical pollution investigation, liability and public concern that forever changed the topography of environmental management. There remains today a certain hysteria in government oversight and public opinion about subsurface contamination due to the tone set by Love Canal. Current regulatory policies focusing on subsurface problems may not always be aligned with alternative environmental priorities that many scientists would recommend (USEPA 1987; 1989a; 1990).

Love Canal also served at the time to demonstrate our scientific and regulatory ignorance of subsurface contamination and resultant public health threats. From 1942 to 1953, 22,000 t of chemical process waste were dumped in a ditch near the Niagara River because its clay lining was expected to limit leakage. This feature actually became the landfill's downfall when heavy rains in 1978 caused a subsurface "bathtub overflow" effect and pushed liquid chemicals upward into basements and onto the ground surface. Despite warnings otherwise by Hooker Chemical Co. when it closed the landfill and transferred the land to the City of Niagara Falls, the City allowed development of the property for homes and a school in the 1950s/1960s. President Carter signed emergency proclamations in 1978 and 1980 that reimbursed and removed residents from over 800 homes. A multitude of environmental and health studies by the state and federal government slowly and tediously eventually led to a remedy of a leachate collection system and a 40 acre cap in the early 1980s to control, albeit not clean up, the problem. Over $480 million was spent on cleanup/control/relocation and government oversight (USEPA 1996a).

Just as Love Canal was breaking in the news, Congress completed a comprehensive study of industrial waste disposal sites in the US. The resultant "Eckhardt Report" (US Congress 1979) described its questionnaire-based study of the 53 largest chemical manufacturers (1,600 facilities, 3,000 dumpsites) and 12 in-depth site reviews. Some of the more interesting findings included: (1) 94% of the wastes disposed on the land by the industries surveyed (762 million t from 1950 to 1978) was dumped on-site; (2) many states required at the time little if any information about on-site disposal by industries; (3) EPA offered very little support to the states in this regard (only $5.1 million available in 1 year from EPA who requested no funding at all from Congress for this purpose in other years despite authorization of $25 million/year); (4) the total number of hazardous waste generators was estimated at 272,000, using up to 30,000 disposal sites; (5) the Clean Water Act was responsible for shifting a large portion of industrial pollution over to land disposal; and (6) RCRA was inadequate to deal with many of the problems observed because many disposal sites had been abandoned. A member of the Subcommittee, Representative Albert Gore, in his Additional Views attached to the Eckhardt report reflected the state of knowledge and concern about land disposal of hazardous waste up to that point in time (1979) as a, "... blind spot [that] has been an almost total ignorance of the real and potential consequences for land pollution." The report recommended legislation, which was created in 1980 and known as Superfund, to address abandoned or nonoperational hazardous waste sites.

The important lesson to be learned from Love Canal and the Eckhardt Report is that, even in 1980, there remained a tremendous ignorance as to the full dimensions of groundwater and other problems created by land disposal of chemical wastes, including ignorance of the technical characterization of the sources, health threats, natural resource threats, remedies, and appropriate regulatory frameworks. From 1980 to 2000, some progress was made, however. The EPA identified approximately 1,500 sites for Superfund action, 250 of which were remediated as of 2000. The EPA has also codified how sites should be evaluated and remediated through several editions of its National Contingency Plan (cf. 40 CFR Parts 300 to 399; Federal Register 1980) and numerous guidance documents on conducting site investigations (USEPA 1988), analyzing environmental samples for chemical wastes (USEPA 1986), hazardous site risk assessment (USEPA 1989b; Clay 1990), and remedial design/construction (USEPA 1986), among others. In addition to CERCLA for abandoned sites, RCRA was in full swing by 2000, regulating the treatment, storage, and disposal of all newly produced chemical wastes, as well as the cleanup and design/operation of "active" landfills or industrial waste facilities. Moreover, the Clean Water Act and the Clean Air Act continue to regulate emissions to streams and the air, while the Safe Drinking Water Act regulates contaminants on the "intake" side.

Although one would expect that all these regulations have solved our environmental problems, that is far from the case. Problem definition and control technologies still lag behind our legislative objectives and the economic tradeoff debates continue. Moreover, all of these laws dictate "command and control" regulation, which has become criticized for its rigidity compared to alternative "market-based" approaches. Thus, we enter the Twenty-first Century with more work to do on all fronts.

Conclusion

Pollution has always been both an economic and a technical issue. This complicates the answer to the question of whether we should have known better. Pollution issues often unfold in five phases: anectdotal (highly variable, sporadic knowledge); scientific (technical understanding of the cause/effect); economic (debate over how much control is required); engineering (practical technology development); and regulatory. Given the technical and economic complexities, polluters tended not to act until the regulatory framework became clear for fear of having to act (and pay) twice. Until 1980, when remediation of legacy problems became a fact of life, this slow resolution of pollution issues could be viewed as reasonable because there was a fundamental belief in the assimilative or purifying capacity of the environment.

There were three milestone periods of pollution control over the past century—1950, 1970, and 1980. The 1950s represent a turning point toward systematic pollution control in terms of the establishment of standards, more widespread regulation, and the construction of pollution control technology. But the 1950s and 1960s were still primarily a learning phase with an emphasis remaining on traditional sanitary wastewater issues. The new laws and regulations of the 1970s—for water, drinking water, air, ecosystems, and solid waste—assimilated that learning phase into environmental management. The imperative was clear, polluters accepted the need to spend, technology surged, and knowledge of environmental systems and how to measure them became much more sophisticated. But that decade came with growing pains, primarily in the form of exacerbated land pollution problems. And those land pollution problems finally made us realize that some pollution indeed was not well assimilated by nature. Which brought us to the final milestone of the century, the 1980s, where the focus for the first time turned to remediating legacy pollution.

So could we have done more, better, faster? Only incrementally. The technical and economic issues were complex and first required the proving ground of time described in this review. Throughout the debate, and to whatever extent pollution problems were obvious, reactions were tempered by the notions of reasonable use and assimilative capacity. A polluter in the first half of the century and perhaps as late as the 1970s would believe it was reasonable to continue polluting to some degree and would never have imagined that such pollution could leave a legacy that might require remediation in the far future. With the hindsight of today's technical knowledge and regulatory framework, it is too easy to criticize that Twentieth Century polluter, and such criticism is mostly unjustified.

Now, in the Twenty-first Century, we do know better. But it is curious that the key issue remaining today is the same issue persisting throughout the Twentieth Century—how much environmental and pollution control is necessary and economically viable? That is, the debate on reasonable use continues.

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