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AN OVERVIEW OF THE MANAGEMENT OF CONTAMINATED SITES IN THE US: THE CONFLICT BETWEEN TECHNOLOGY AND PUBLIC POLICY

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ABSTRACT

Since the late 1970s, the US has utilized a variety of strategies to manage the problem of contaminated land and groundwater within the 50 states, a problem whose dimension is still not well defined. Recent estimates indicate that the US may spend up to 1 trillion dollars over the next 20 to 30 years undoing the environmental damage caused by improper storage and disposal of hazardous materials and toxic wastes over the past several decades, but predominantly since the end of World War II. Whether these expenditures will provide an equivalent level of benefit or risk reduction to US citizens is a subject of current debate. The effective management and remediation of this complex array of sites is proving both difficult and expensive. Research over the past decade has shown that in many cases, technology is limited in its ability to restore contaminated sites to pre-industrial conditions. In the US, new policy initiatives are being developed that insure both protection of human health and the environment, but at significant reduction in life cycle costs to society. Risk-based decision making is replacing rigid politically driven remediation decisions. The changes in the US model for management of contaminated sites provides valuable insights to other nations who are or will be faced with the same difficult choices balancing the costs of remedial strategies against potential reduction in risks to human health and the environment. Copyright © 1996 IAWQ. Published by Elsevier Science Ltd.

KEYWORDS

Contaminated sites; groundwater contamination; intrinsic biodegradation; public policy; risk-based decision making; technical impracticability.

INTRODUCTION

In the US, and throughout the world, contaminated soil and groundwater appear to pose serious threats to human health and the environment. In addition, contamination of soil and groundwater inflicts economic hardship on property owners, whose property value is diminished, and on those dependent for their drinking water on groundwater requiring, in the past, minimal, if any, treatment. The potential cost of restoring soil and groundwater resources to pre-industrial conditions, a requirement often demanded by regulatory agencies in the US and other industrialized countries, may be too large a burden for many countries to bear, and often diverts financial resources from other more productive uses of capital.

The fundamental cause of soil and groundwater contamination is the improper management of hazardous wastes and hazardous materials. The exact magnitude of the problem is unknown, however, in part because data on annual production of hazardous wastes by individual countries are limited. Table 1 contains a summary of readily available data on generation of hazardous wastes from 13 countries with per capita GNP greater than US$6,000 (1980-1983 data are used because hazardous waste generation data were available for the early 80's) (see e.g. Central Intelligence Agency, 1983; Forester & Skinner, 1987; Batstone *et al.*, 1989; Shin, 1992; Lidskog, 1993; Cho *et al.*, 1992). These data indicate an average annual per capita hazardous waste generation for these countries of approximately 150 kg/capita/yr and an average annual waste generation of about 20,000 metric tons per billion US$ of gross national product (GNP). However, the data are not normally distributed with a median value of 60 kg/capita/yr for per capita production, and about 6500 metric tons per billion US$ of GNP. The US reportedly has the highest per capita hazardous waste production of over 1100 kg/capita/yr, while Switzerland exhibits the lowest production of only 15 kg/capita/yr. Data are highly dependent on the regulatory definition of hazardous waste and the extent of reporting by industry (Forester and Skinner, 1989).

Table 1. Comparison of hazardous waste generation for selected countries*

Country	Per Capita GNP (US$)	Per Capita Waste Production (kg/capita/yr)	Waste Production per GNP (MTon/US$ Billion)
Austria	8,763	53	6027
Denmark	11,359	18	1549
FRG	11,098	73	6589
France	10,421	37	3515
Italy	6,212	35	5714
Japan	9,463	151	15958
Netherlands	9,740	70	7143
USA	13,154	1127	85696
Sweden	13,516	60	4440
UK	8,982	89	9927
Korea	1,517	24	15966
Switzerland	15,350	15	1008

* 1980-1983 data on population, income and hazardous waste production. Data from various sources. See text.

It is likely that per capita or per GNP generation of hazardous waste has decreased since the early 1980s given government and industry initiatives stressing recycling, pollution prevention, and life-cycle assessments of industrial products.

A country's annual rate of hazardous waste generation does not necessarily correlate with the number of contaminated sites with unacceptable levels of soil and groundwater contamination that will likely require remediation. National quantitative assessments of this problem are even more limited and uncertain than data on national hazardous waste generation. The dimensions of this problem in the USA are perhaps better characterized than in most other countries. Of the more than 3 million potential sites in the USA, The Environmental Protection Agency (EPA) has estimated that over 400,000 sites are likely to require some form of remediation. (EPA, 1993). The key categories include up to 2000 national priority list sites, established under the Superfund statute, approximately 2600 active operating industrial facilities that require corrective action in order to obtain long-term operating permits under the US Resource Conservation and Recovery Act (RCRA), more than 20,000 sites under the ownership of the Departments of Energy and Defense, and at least 350,000 sites contaminated by leaking underground storage tanks.

Table 2 summarizes selected data from 11 countries taken primarily from non-peer-reviewed sources on the estimated number of contaminated sites in each country that will likely required some type of remediation (Forester and Skinner, 1987; Frost and Sullivan, 1992; Helmut Kaiser, 1990; EPA, 1993a). This analysis indicates that for this limited data set, these countries exhibit an average of about 90 sites per 1000 square kilometres, and about 700 sites per million inhabitants with a wide range of values reported. The coefficient of variation for these data is greater than 50 percent. Compared with other countries, the US reports the highest number of sites per million inhabitants (over 1700), although the number of sites per square kilometres (43) is below the average, reflecting the relatively low population density in the US. This wide range of values probably reflects different legal and technical definitions of contaminated sites, different legal requirements for reporting of contaminated sites, and the intensity of private or public investigations into potential contaminated sites and the definition of clean-up requirements for such sites

Table 2. Comparison of magnitude of contaminated sites in selected countries*

Country	Number of Potential Sites	Sites per M inhabitants	Sites per 1000 sq.-km
Austria	5000	660	60
Denmark	4000	782	93
FRG	51000	829	205
France	35000	641	63
Italy	30000	532	100
Netherlands	6000	417	177
USA	400000	1708	43
Sweden	5000	600	11
UK	20000	357	82
Spain	25000	654	50
Switzerland	5000	774	121

* 1983 data on population and 1990-1991 data on number of contaminated sites likely to require remediation. Data from various sources. See text.

It is thus difficult to draw accurate general conclusions on the magnitude of the contaminated site problem based on such parameters as population density, GNP, or area extent of a country. The data presented here may be useful guides for planning purposes, however.

The US model for management of these sites is well known. The two primary enabling statutes are the 1980 Superfund Act, which addressed past contamination problems at sites with and without clear ownership, and RCRA which was passed by Congress in 1976. This Act focuses primarily on contamination at existing and operating facilities where hazardous wastes are generated, treated, stored or disposed of on site. These two statutes, subsequent regulations, guidance documents, and legal case law specify the procedures at contaminated sites for identification, prioritization for evaluation, characterization, selection and implementation of remedial actions, and finally, allocation of financial responsibility, an area of continuing disagreement in the USA, and, most likely, in other countries.

In the US, debates continue over the costs to remediate these sites, and the benefits of these expenditures. A recent study conducted by the University of Tennessee in the USA (Russell *et al.*, 1991), indicated a wide range of costs to remediate the universe of US sites, ranging from US$ 250 billion to over US$1 trillion, to be spent over the next 30 to 50 years. The minimum and maximum estimated costs are dependent on the clean-up levels required. As anticipated, the highest estimate corresponds to costs associated with a strategy of complete restoration of all sites.

No benefit-cost analyses have been completed to evaluate the utility of this level of expenditure. It is thus unclear if these costs are justified. Based on epidemiological studies in the USA, contaminated sites do not appear to have caused serious acute or chronic health effects to significant numbers of exposed or potentially exposed people (National Research Council, 1994) with the exception of a few well publicized cases (National Research Council, 1991). Potential future risks appear to be manageable in all cases. It is indisputable, however, that groundwater contamination in the US continues to be a significant natural resource damage issue.

The inherent conflict in the US model for management of contaminated sites derives from legal statutes developed by elected officials that drive remediation programs at most sites towards complete restoration. Soil clean-up is often based on highly conservative assumptions regarding exposure pathways, the concentration of the contaminant causing the risk at the point of exposure, and conservative future land use scenarios, often residential land use (Wassersug, 1992; National Research Council, 1994). Groundwater remediation in the US is also driven by highly conservative assumptions and legal mandates in states that require non-degradation of the states' water resources. Usually this means, at a minimum, that groundwater cleanup levels are defined based on maximum contaminant levels (MCLs) specified for constituents regulated under the US Safe Drinking Water Act. For groundwater, however, inherent complexities of the subsurface make restoration to these low levels often impractical and not necessarily "reasonably achievable".

LIMITATIONS TO GROUNDWATER REMEDIATION

Limitations to remediation of contaminated groundwater became apparent in the mid 1980s as data from groundwater remediation projects in the US became available (EPA, 1989; Mackay and Cherry, 1989; Travis and Doty, 1990). Groundwater restoration has been required at more than 80% of those sites where active remediation has been or is likely to be required (Environmental Protection Agency, 1993a).

The predominant groundwater remediation strategy in the US has been application of the so-called "pump-and-treat" technology (EPA, 1989; American Petroleum Institute 1993). As is well known, this technology involves extraction of the contaminated groundwater at rates sufficient to provide flushing of the contaminants out of the saturated zone, combined with appropriate treatment, and disposal of the treated water. Because of growing concerns in the US that this technical strategy was not likely to achieve target levels in many cases, and that predictions of clean-up times were seriously underestimated, an independent assessment of the issues was needed. This assessment was provided by a committee established in 1992 under the auspices of the US (NRC), which manages outside peer review activities of the US National Academies, namely the National Academy of Science, National Academy of Engineering and Medicine, and the Institute of Medicine. The committee's findings were published in 1994. (National Research Council, 1994).

This committee evaluated groundwater monitoring data from 77 sites where pump-and-treat systems had been in operation for at least 5 years to determine if the systems had achieved two performance goals, hydraulic containment of the contaminant plume and achievement of the target clean-up level. Although this represented a small fraction of the estimated 3000 groundwater remediation systems in operation at the time (1992), the sample was thought to be representative of the generic types of groundwater remediation problems expected at all sites.

The committee found that 40 of the sites reported complete hydraulic control of the contaminants but that in most cases, hydraulic control was achieved if this was the primary objective of the pump-and-treat system. However, only 8 of the 77 sites reported reaching the remediation clean-up level, which in all cases was the MCL for the compound of concern. Of these eight sites, six were contaminated with petroleum hydrocarbons (primarily benzene, ethyl benzene, toluene and xylenes (BETX)) released from leaking underground fuel tanks, and ketones (mainly methyl isobutyl ketone), compounds known to degrade readily under aerobic conditions (Wilson *et al.*, 1991). The other two sites were contaminated with chlorinated hydrocarbons (mainly trichloroethene and 1,1,1-trichloroethane). All other sites reported that the clean-up goals had not been reached. In most cases, the concentration of the target compounds in the extracted water had reached a constant or asymptotic level.

The committee confirmed that pump-and-treat technologies were quite limited in their ability to remove contaminant mass from the subsurface, but were effective, if designed properly, for hydraulic control of the plume. Contaminated groundwater sites could be categorized into three groups, namely: 1) those where remediation to MCLs is possible; 2) those where remediation is improbable but not impossible, and 3) those where remediation is unlikely in a reasonable time frame and at a reasonable cost.

Over 95 percent of the sites reviewed in the NRC study fall in the latter two categories. In the US, the distribution of sites between these three categories is unknown, but is likely to exceed 80 percent. In other countries, data are insufficient to support any conclusions, but it is likely that experiences in the USA are reflective of the situation elsewhere.

In retrospect, the NRC findings are not surprising. Even when a pump-and-treat system has been designed optimally, restoration of groundwater is limited by four factors which are inherent to the problem of removing contaminants from the subsurface. These are:

1) compounds strongly adsorbed to aquifer solids (Mackay and Cherry, 1989);

2) highly heterogeneous subsurface environments containing zones of low permeability (e.g. clay lenses);

3) slow mass transfer of contaminants from aquifer solids to the bulk interstitial fluid(e.g. see Brusseau and Rao, 1989); and

4) the widespread presence of non-aqueous phase liquids (NAPLs), particularly those that are more dense than water , i.e. DNAPLs (Mercer and Cohen, 1990).

Each of these factors increases the degree of difficulty in removing contaminants to levels prescribed by MCLs. Sites contaminated with DNAPLs ,which, in the USA, represent at least 60% (and probably more) of the sites where groundwater has been impacted by organic chemicals (EPA, 1993a) usually represent an insurmountable technical problem. DNAPLs are difficult to find and remove (Cohen and Mercer, 1993). They dissolve slowly during pump-and-treat remediation, and provide a long-term source of on going contamination of the groundwater (Mercer and Cohen, 1990).

The committee provided a simple conceptual model of groundwater remediation which provides a qualitative basis for determining the likelihood of success for groundwater remedial actions. Of the many variables impacting the performance of groundwater remediation projects, two key factors predominate, namely, the geological complexity of the saturated zone and the physical-chemical properties of the target compounds. Table 3 illustrates the relationship between these two factors.

Sites designated as level 4 are unlikely to be restored in a reasonable time frame or at reasonable costs, regardless of the technology used. Examples shown include sites where DNAPLs, such as liquid TCE, are trapped within fractured bed rock, or heterogeneous aquifers with multiple layers of varying hydraulic conductivity. Sites considered as level 2 or 3 sites will be difficult to remediate, but target clean-up levels may be achieved using a combination of technologies in addition to pump-and-treat. Such technologies could include the use of air sparging, lowering of groundwater elevation combined with soil vapor extraction, use of high-vacuum extraction technologies, and the application of engineered bioremediation systems. Finally, traditional pump-and-treat technologies are likely to achieve target clean-up levels at sites characterized as level 1.

Table 3. Relative ease of cleaning contaminated aquifers as a function of contaminant chemistry and hydrogeology*

Hydrogeology	Contaminant Chemistry: Mobile, dissolved	Strongly sorbed, dissolved	LNAPL	DNAPL
Homogeneous, single layer	1**	2	2-3	3
Homogeneous, multiple layers	1	2	2-3	3
Heterogeneous, single layer	2	3	3	4
Heterogeneous, multiple layers	2	3	3	4
Fractured bedrock	3	3	4	4

* Source, NRC, 1994; slightly modified from original table
** Relative ease of cleanup, where 1 is easiest and 4 is most difficult

Numerous technical options have been proposed to overcome the technical barriers inhibiting successful extraction of contaminants from the saturated zone (MacDonald and Kavanaugh, 1994). Although these technologies show promise in removing a greater fraction of the contaminant mass from the saturated zone compared to pump-and-treat technologies, they are also constrained by the same factors noted earlier inhibiting the effectiveness of pump-and-treat.

ALTERNATIVE POLICY OPTIONS

As a consequence of these findings, EPA and other US regulatory agencies have been developing alternative policy approaches to remediation of sites with contaminated groundwater. In 1986, the US Congress approved the Superfund Amendment and Reauthorization Act (SARA) which, among other issues, addressed the question of clean-up standards or goals for remediation of contaminated groundwater at Superfund sites nationwide. Section 121 of SARA stated that alternative clean-up levels could be specified if it could be demonstrated that it was "technically impractical" to achieve the statutory clean-up levels, which as mentioned earlier were either MCLs, or background levels. However, until 1993 this so-called technical impracticability waiver was only used to alter clean-up levels from a target of background to MCLs (National Research Council, 1994). EPA subsequently recognized that in many cases, as pointed out by the NRC study, among others, MCLs could not be achieved in a reasonable time frame and at a reasonable cost.

EPA has recently completed guidance documents (EPA, 1993b) that provide for more frequent use of the technical impracticability waiver to establish clean-up levels that are more likely to be achieved , but are still protective of human health and the environment. Policy is shifting towards increased use of containment, long-term maintenance, and institutional controls, such as deed restrictions to deal with level 3 and 4 sites, particularly when the relative risk reduction is low compared to relative costs of alternative remedial actions.

More recently, the State of California is pursuing a slightly different approach to the EPA. Its proposed policy, which is likely to be approved in the Fall of 1996, rests on the definition of a so-called "containment zone", defined as a subsurface volume where it is unreasonable to remediate the groundwater to meet the non-degradation water quality objective as specified by State law (California EPA, 1996). Within this containment zone, no further remediation will be required, except continued monitoring. A management plan is required that must include a contingency plan in case of continued releases or lack of hydraulic containment within the containment zone.

This policy is fairly restrictive, however, and numerous conditions have to be met. It remains to be seen how far the State of California is willing to go with this policy, but in the near term, more than ten sites have been designated "containment zones", resulting in significant savings to the responsible parties, according to State regulators. Similar initiatives are in progress in a few other states in the US.

Recently, new studies have revealed that threats to human health and the environment from leaking underground fuel tanks (LUFTs) containing fuel hydrocarbons (FHCs) may be considerably less than originally perceived. In California, as of 1983, over 200,000 potential Underground storage tank sites had been identified, and over 20% of these were expected to have leaked. Remediation of these sites to meet State mandated soil and groundwater clean-up standards is projected to exceed available funds by US$ 1.5 billion dollars. Because of this shortfall, the State funded a study by the Lawrence Livermore National Laboratory (LLNL), Livermore, California, to determine whether an alternative remediation approach could be implemented that would be less costly but still protective of human health and the environment. LLNL completed a detailed analysis of over 1,500 LUFT cases to evaluate the impact of releases on the environment (Rice *et al.*, 1995b).

The study reported that few public water supply wells had been impacted by releases from LUFTs, and that the volume of groundwater containing benzene, the most mobile of FHCs present in gasoline and other petroleum hydrocarbon products, above the State MCL of 1.0 ppb represented less than 0.0005% of California's total groundwater resource. This observation reflects the fact that the leading edge of benzene plumes (defined loosely as the zone in which oxygen is still present, and benzene levels are near the MCL of 1 ppb) in groundwater stabilize quickly and at relatively short distances from the release site, provided that the source of the release is eliminated. On average, the LLNL study reported that benzene plumes stabilized within approximately 250 feet of the original release point. These findings further confirm the now widespread observation that naturally occurring subsurface microorganisms can, given the appropriate geochemical environment, initiate biodegradation of many petroleum hydrocarbons, thus stabilizing or reducing the size of fuel hydrocarbon plumes for compounds that degrade rapidly under aerobic conditions (see e.g. Barker *et al.*, 1987).

Although the recommendations of the LLNL study (Rice *et al.*, 1995a) are having a significant impact on regulatory approaches to clean-up of LUFT sites, the study did not address all contaminants that can be found at such sites. One group of compounds, the organic oxygenates that are now being frequently used in gasoline to increase octane levels, and to reduce the concentration of aromatics have not been routinely monitored at LUFT sites, particularly in California. The most well known example of fuel oxygenates is methyl tert-butyl ether (MTBE), a compound that is highly soluble in water, much more mobile in the subsurface compared to BETX compounds, and exhibits a relatively slow rate of biodegradation.

Based on this study, LLNL recommended (Rice, *et al*, 1995a) the use of a risk-based approach to corrective action that is designed to exploit "intrinsic biodegradation" which, for example, has been shown in some field studies to result in removal of more than 1% per day of benzene (Wilson *et al.*, 1991). Use of a risk-based corrective action approach, developed by a group of experts working under the auspices of the American Society for Testing and Materials (ASTM) and now available as an ASTM standard (ASTM, 1995) has been endorsed by many State regulators, and is receiving widespread support throughout the US by the regulatory community who recognize that expenditures for low-risk sites must be minimized to ensure sufficient funds for the higher-risk sites.

SUMMARY

In summary, the US model for management of contaminated sites is over 16 years old. Its successes and failures provide important lessons for all countries faced with difficult decisions on allocation of societal resources to deal with contaminated soil and groundwater. Some of the key lessons include the following.

1. **Land Use as Major Driver**: Land use must be a dominant factor in selecting remedial action strategies. Containment and long-term maintenance with institutional controls may be acceptable under many land use scenarios. This leads to significant cost savings.

2. **Technical Impracticability:** As noted, in many situations, it is not technically feasibility to restore contaminated groundwater to pre-industrial conditions. Technical infeasibility must be integrated into the decision process for selecting remedial strategies, making maximum use of new or innovative technologies, but recognizing technical limits of any subsurface remediation system.

3. **Exploitation of Intrinsic Processes in the Subsurface**: Where applicable, policy should permit maximum use of intrinsic degradation processes - the degradation capacity of the subsurface - to reduce costs of remediation. Research work in this area is rapidly providing the quantitative tools needed to maximize the ability of the subsurface to transform organic and inorganic contaminants into less harmful or environmentally innocuous compounds. These processes will lead to significant reduction in costs of remediation.

4. **Eliminate Exposure Pathways:** It is considerably cheaper to eliminate exposure pathways rather than expend funds on remediation strategies that may provide only limited reduction of risks to human health.

5. **Risk-Based Decisions on Remediation**: Risk analysis (human health risk assessment and ecological risk assessment if warranted) can provide a consistent basis for decision-making in environmental restoration. This process is essential for establishing funding priorities to direct financial resources to the highest-risk sites first.

Recent US policy initiatives are examples of the observational approach as applied to engineering decisions under uncertainty. These new policies are appropriate responses to lessons learned over the past 15 years, and they should lead to a more rational allocation of financial resources for management of contaminated sites. These initiatives should be carefully monitored by other nations seeking ways to reduce costs for management of contaminated sites, while minimizing natural resource damages and still providing sufficient protection to human health, and the environment.

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