The other two quadrants are less obvious but may reflect frequent real-world situations. If the original risks are low and attenuating, while the impacts of remediation also are low (upper right quadrant), decision makers have a choice that probably must be based on other, nontechnical criteria, such as economic costs and to whom, public opinion, and the legal framework for a decision.

If, on the other hand, the original risks and the environmental risks are high (lower left quadrant), decision makers need to focus their attention most on improving the remediation technology to lower its embedded environmental impacts. This could include relying on natural attenuation for the long term, once the severe contamination has been removed by an active method that is focused on eliminating the high risks.

Unevaluated risks should not be assumed to be low risks, as this can bias the comparison.

Evaluating and considering embedded impacts should make it less likely that an active remedy is imposed as a "punishment" to a polluter, even though the active remedy does more to cause embedded harm than it does to eliminate risk from the original contamination.

Finally, an evaluation that estimates the embedded impacts also needs to have a realistic estimation of the risks. Unevaluated risks should not be assumed to be low risks, as this can bias the comparison.

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Throughout your environmental career, how many times have you heard someone jokingly say, "I wonder how many trees were killed to produce that report"? This question is typically forwarded as humorous small talk. However, this question also probes into whether the report could have been improved through a more visual presentation of the data rather than those voluminous appendices containing reams of cryptic laboratory data sheets and the like. Maybe an electronic copy of this information would have sufficed? Maybe this question was not a joke. This question may seek a serious answer as to whether the report will facilitate the attainment of tangible benefits that exceed the true costs of the document. After all, any industry should be evaluated based on what it collectively produces—positive as well as negative. We all understand that the environmental remediation field is aimed at the protection of human health and environment but one must ask the question, "What are the tangible benefits of what we are doing?" Are we actually improving the environment or making it worse through the raw materials consumed and the pollution produced to remediate contaminated sites? Many of the sites with ongoing remediation would never pose a serious risk to human health or the environment, yet we are spending billons of dollars and producing tons of secondary pollution to remediate these sites.

This response is *not* a general statement against taking aggressive action to reduce and eliminate receptor exposure; in fact, there are numerous sites that *do* pose a threat to human health and the environment and the authors believe that these sites *should* be aggressively remediated. Instead, this response is aimed at provoking thought regarding what is produced and consumed as part of environmental remediation projects. It is clear that reports that "kill trees" are a necessary and overall reasonable component of the site cleanup process to ensure that actions protective of human health and the environment are properly analyzed, implemented, and monitored. However, it is also reasonable and necessary to evaluate the broader impacts of remediation projects, something that is not typically done. It is common to hear an energetic argument that less energy-intensive remedies like monitored natural attenuation are unacceptable because the time to achieve cleanup is "too long" and more intrusive remedies need to be implemented to accelerate cleanup. However, this argument may not always have a scientific, rational, or practical basis with respect to actual risk reduction or the practicality of cleanup using existing technologies. The time frame for cleanup may only be substantially reduced after the removal of greater than 95 percent of the source (Freeze & McWhorter, 1997; Sale & McWhorter, 2001). For many hydrogeologic systems and contaminants, technologies capable of achieving this level of source removal do not currently exist. The more intrusive remedy may have limited effectiveness, be highly consumptive of resources, generate significant by-product pollution, and pose real risks to on-site workers and nearby residents that outweigh the benefits of the remedial action.

Each project and site is different. However, it is not uncommon for 10 to 15 years to elapse between initial site discovery and remedy selection. During this time, extensive resources are consumed to attend meetings, conduct technical and administrative work, collect and analyze samples, produce reports, and conduct feasibility/treatability studies, and so on. This time frame is often driven by, among other things, inadequate site characterization, hydrogeologic complexities, or unwillingness to accept realistic risk-based remedies. The unwillingness to accept risk-based remedies may be based upon personal skepticism, an unfounded belief in the efficacy of engineered remediation, an ideological belief that the polluter should pay, or, in some cases, stringent regulations or bureaucratic policy. Since the taxpayer and consumer ultimately pay for this process, the solution should be scientifically credible, equitable, and protective.

Naturally occurring biodegradation is particularly effective in treating the most soluble, volatile, and toxic components found in petroleum hydrocarbons such as benzene, toluene, ethylbenzene, and the xylenes (BTEX). From this perspective, natural attenuation is a fairly robust groundwater treatment and containment process for fuel hydrocarbon plumes. Because of the efficacy of natural attenuation for plumes of fuel hydrocarbons dissolved in groundwater, 95 percent of these plumes are less than 300 feet in length (Mace et al., 1997; Rice et al., 1995). Given the practical limitations for intrusive remedies to achieve high levels of source removal, successful intrusive remediation must expend significant resources to change the length, or the lifespan, of a solute plume. Interestingly, the excavation, extraction, or *in situ* treatment of contaminants like polynuclear aromatic hydrocarbons, heavier fuel hydrocarbons, and numerous heavy metals is very challenging and requires substantial resources. However, these contaminants are highly immobile at most sites. Thus, natural attenuation and land use control may effectively prevent receptor exposure. Where natural attenuation is considered inadequate (e.g., at really extensive methyl tertiary-butyl ether [MTBE] or chlorinated solvent plumes), intrusive remedies may approach technical infeasibility or insurmountable economic demands. In these cases, risk management is achieved primarily through land use control and institutional actions.

In many cases, remediation of a particular site may cause more risk or environmental damage through remedial attempts than if it were left alone and allowed to naturally attenuate.

In many cases, remediation of a particular site may cause more risk or environmental damage through remedial attempts than if it were left alone and allowed to naturally attenuate. This response discusses in broad terms the environmental impact/benefit of remedies that are more intrusive than natural attenuation. These remedies will be discussed with regard to contaminant-related risk reduction versus the risks, resources consumed, and pollution generated as a result of remedial actions. The following sections provide our opinions on the questions.

Is it relevant to consider how much pollution is created by "active" remedies in which electricity is consumed or air is polluted by diesel engine exhaust? Some remedies, such as air stripping, can simply transfer pollutants to another medium, and, in effect, trade one set of problems for another.

Some remedies, such as air stripping, can simply transfer pollutants to another medium, and, in effect, trade one set of problems for another.

Yes, it is relevant to consider pollution created not only by diesel exhaust but also by other emissions such as gasoline engine exhaust, pollution caused by the use of fuel oil or coal to produce electricity, the pollution generated by the production of raw materials, and the like. The transfer of pollutants between media is common for all extraction-based and *ex situ* remedies including pump-and-treat, excavation, soil vapor extraction, *ex situ* thermal remediation, air sparging, and bioventing. This list may constitute more than 90 percent of remedies applied at contaminated sites. In many cases, these remedies may cause exposure to contaminants or combustion by-products that would not have occurred if the contaminants were left in the subsurface to naturally degrade. In most cases, the use of these remedies will either transfer the contaminant to another media or location or cause the discharge of deleterious combustion by-products into the environment. Furthermore, it is unfortunate that the risk and pollution from incidental over-the-road transit, pollution from equipment manufacture, power generation, system operation, and the ultimate destruction or disposal of contaminants are mainly transferred to real receptors and other locations that are not considered in the risk assessment process. Thus, remedial action may be taken to protect theoretical receptors without regard for actual occupational or bystander receptors.

During intrusive remediation, contaminants are not removed without the consumption of resources and the production of pollution. Consider the following two examples.

Example 1—Groundwater Extraction, Treatment, and Reinjection System

This example presents site-specific estimates of the emissions generated for the production of electricity for a groundwater extraction, treatment, and reinjection (ETR) system for a site in Massachusetts. Exhibit 2 presents estimates of sulfur oxides (SO_X), nitrogen oxides (NO_X), carbon monoxide (CO), and particulate emissions from coal-fired, gas-fired, and #6 fuel oil–fired power plants to produce the electricity required to run the ETR system. This example includes treatment using granular activated carbon. Pollution released during power generation and off-site regeneration of granular activated carbon impacts communities that are unrelated to the polluted site. A rough estimate of the power requirements for this 5.2 million gallon per day (mgd) ETR system is 3.1 million kilowatt-hours per year (KW-hr/yr).

Please note that the emissions presented in Exhibit 2 consider only those emissions generated to produce the electricity required to operate the ETR system and do not consider those emissions produced by the gasoline, jet, and diesel engines required to transport equipment and personnel to and from the site for system installation and maintenance.

In order to compare the effectiveness of pump-and-treat versus monitored natural attenuation, fate and transport modeling was conducted. Field-calculated biodegradation rates were reduced four- to twentyfold in an effort to conservatively evaluate the contributions of natural attenuation to groundwater remediation. Natural attenuation alone for 50 years would achieve a 97.8 percent reduction in contaminant mass. A 50-year operation of the pump-and-treat system would achieve a 99.6 reduction in contaminant mass, a 1.8 percent increase over natural attenuation alone. The elapsed time for all contaminants to fall below maximum contaminant levels (MCLs) is indistinguishable for these two remedies. This case study is not an example of a poorly designed pump-and-treat system. Instead, it is an example of comparing the performance of monitored natural attenuation to an aggressive groundwater pumping strategy. Since natural attenuation occurs throughout this expansive 18,000-foot-long, 6,000-foot-wide, 100-foot-thick twin-lobed chlorinated solvent plume, it does more to reduce contaminant mobility, toxicity, and mass than a 5.2 mgd ETR system. This is more a function of plume geometry and aquifer geochemistry than poor design of the pump-and-treat system.

Example 2—Energy Usage, Waste Generation, and Resource Consumption Profile for Thermal Desorption

Exhibit 3 provides a summary of resources consumed and identifies a subset of the pollution generated during the thermal desorption of PAH and polychlorinated biphenyl compound (PCB)–contaminated soils at an industrial site. This summary outlines the energy-intensive aspects of implementing this technology as well as meeting stringent regulatory guidelines in a city with chronic nonattainment air quality problems. In this case, desorbed contaminants are transferred to granular activated carbon, condensate, and solid phase residuals. There were initial on-site pollution emissions, but contaminants transferred to other media and pollution associated with electrical generation, other incidental processes, and final incineration of contaminants and residuals impact off-site residents.

The authors are unaware of the risk management issues at this site. However, the risk management of low-mobility contaminants such as PAHs at an industrial site typically offers numerous alternatives. Exhibit 2 outlines resource consumption, pollution

Power Plant Fuel	Emissions Produced	Emission Rate (lbs/KW-hr)	Annual Emissions (lbs/yr)	Total Emissions (50 years) (lbs)
Coal	SO_X	0.02	62,000	**3,100,000**
	NO_X	0.008	24,800	**1,240,000**
	CO	0.0002	620	**31,000**
	Particulates	0.02	62,000	**3,100,000**
	Mercury	0.0008	248	**12,400**
Natural Gas	SO_X	0.000006	18.6	**930**
	NO_X	0.006	18,600	**930,000**
	CO	0.0004	1,240	**62,000**
	Particulates	0.00003	93	**4,650**
No. 6 Fuel Oil	SO_X	0.03	93,000	**4,650,000**
	NO_X	0.004	12,400	**620**
	CO	0.0003	930	**46,500**
	Particulates	**0.002**	**6,200**	**310,000**

Exhibit 2. Emissions produced to produce the power required to operate an ETR system

Activity	Resources Consumed	Pollution Generated
Worksite setup	• Fuel for vehicles 5-acre footprint • Cement for equipment pad • Paper	• SO_x, NO_x, uncombusted hydrocarbons • PAHs • Particulate matter and CO_2
Mobilization of equipment and operation staff of 17–21 members	• Fuel for 12 semi-truck loads	• SO_x, NO_x, uncombusted hydrocarbons • PAHs • Particulate matter and CO_2
Test burn plus the RCRA/TSCA air permit equivalency documents and a proof of performance test plan (normally requires engineering support for three to six months)	• Paper • Fuel for transportation • Natural gas for test burn	• SO_x, NO_x, uncombusted hydrocarbons • PAHs • Particulate matter and CO_2
Remediation system operation and maintenance	• Units per ton of soil treated: 1.36 to 2.58 million British Thermal Units, 13 to 37 kilowatt-hours, 47 to 132 cubic feet of nitrogen • 0.16 to 0.46 pounds of carbon	• SO_x, NO_x, uncombusted hydrocarbons • PAHs • Particulate matter and CO_2 • Miscellaneous supplies (filters, calibration gases, modified Level D PPE) • Aqueous condensate generation ranged from 24 to 60 gallons per ton of soil treated • Disposal of the recovered organic condensate by incineration for PCB and dioxin-/furan-contaminated soil and by combustion at a fuel recovery facility (e.g., cement kiln) for PAH-contaminated soil Production of organic condensate was estimated at a rate of 0.25 gallons per ton of soil treated • Recycling of scrubber blowdown filter cake to the thermal desorption unit dryer feed
System disassembly and demobilization	• Similar to mobilization of equipment	• Similar to mobilization of equipment

Source: U.S. Air Force (2002)

Exhibit 3. Thermal desorption implementation, resource consumption, and waste generation profile

generation, and health and safety issues that raise a question regarding the resultant benefits to human health and the environment.

Is there a practical way to quantify the net pollution created by various remedies and incorporates these considerations into the evaluation of monitored natural attenuation? Is this being done?

Although rare for sites in the United States, the net pollution caused by various remedies can and has been quantified. In the opinion of the authors, this should be done on a routine basis. In fact, the authors have done this on more than one occasion.

The Danish Railway Agency (2000) has developed a quantitative tool to quantify resource consumption, pollution generation, and overall cost/benefit of remedial actions. Pollutant emission rates for electrical power generation (US EPA, 1996, 1997) and all incidental energy utilization processes of environmental remediation can be estimated. However, a lack of emphasis by environmental remediation professionals appears to have left this important information buried in highly specialized power generation, automotive, and ambient air quality literature. The authors of this response agree that the environmental remediation field should consider these emission factors to avoid the embarrassment of converting a theoretical environmental risk into an actual exposure and/or degradation of the environment.

The following two subsections present, in broad terms, the causes of pollution that should be considered when evaluating the relative benefit of an intrusive remediation system.

Pollution Caused by Consumption of Raw Materials and Development of Infrastructure for Various Remediation Technologies

In many cases, the production of the raw materials and the development of the infrastructure required for various remediation technologies can cause more potential human exposure and damage to the environment than leaving contaminants in place to be treated by natural processes of contaminant attenuation. This is especially true when no risk to human health or the environment is caused by the contaminants if they are left in place to attenuate under natural conditions.

Consumables are utilized by the following broad categories involved in environmental remediation:

- in-office technical and professional services (professional office consumables);
- meetings;
- physical operation of the remediation system; and
- long-term monitoring and reporting.

This is especially true when no risk to human health or the environment is caused by the contaminants if they are left in place to attenuate under natural conditions.

These broad categories involved in environmental remediation result in the consumption of, at least, the following:

- production and refinement of crude oil for transportation and system operation;
- rubber;
- electricity;
- PVC for piping and monitoring wells;
- polyethylene tubing;
- steel;
- copper for wire;
- lead for batteries;
- cast iron for pipe fittings;
- concrete;
- solvents for metal and computer production;
- computers; and,
- trees for paper.

Pollution Caused by Atmospheric Discharges for Various Remediation Technologies

In the authors' opinions, the discharges produced by intrusive remediation may cause more potential human exposure and damage to the environment than leaving contaminants in the ground in many cases. Again, this is especially true when no risk to human health and the environment is caused by the contaminants if they are left in place to attenuate under natural conditions. The following is a partial list of the pollution caused by atmospheric discharges for various remediation approaches:

Contaminants cannot be removed from the subsurface without energy input, occupational risk, and pollution being generated.

- combustion discharges from work and transportation (CO_2, CO, NO_2);
- combustion gases from production of electricity (CO_2, CO, NO_X, SO_4);
- discharge of particulate matter (PM);
- mercury from coal-fired power plants;
- noise pollution; and,
- atmospheric discharges of organic compounds removed from the subsurface.

As an example, consider the pollution produced by simply driving to or from regulatory meetings or the contaminated site for routine maintenance of the remediation system. The combustion of fossil fuels is necessary for all aspects of environmental remediation, ranging from driving to meetings to fueling thermal desorption devices. For example, 10,500 to 25,000 micrograms (µg) of total polycyclic aromatic hydrocarbons and 55 to 400 µg of benzo[a]pyrene are produced for every gallon of gasoline consumed (Mi et al., 2001). Another study measured benzo[a]pyrene emission rates of 8 µg/mile and 25 µg/mile traveled for gasoline and diesel vehicles respectively (Cook & Somers, 1998). US EPA Region 9 Preliminary Remediation Goals (PRGs) for benzo[a]pyrene are 62 µg/kg of soil (56,000 µg/ton of soil). Thus, a 50-mile trip to an environmental meeting or remediation site produces enough benzo[a]pyrene to contaminate 7 to 20 kg of soil above its residential Region 9 PRGs. More important, benzo[a]pyrene as a fine particulate in air presents several orders of magnitude higher risk than when it is present in soil. A thermal desorption unit that requires 1.36 to 2.58 million British Thermal Units (MBTU) per ton of soil treated would require approximately 11 to 22 gallons of diesel fuel to support heating (excluding electrical and off-gas incineration, which also emit PAHs). Thermal desorption can be fueled by numerous sources. The authors have knowledge of diesel-fired thermal desorption projects at remote diesel spill sites and estimate that 20 gallons of diesel are burned for every gallon of diesel contained in the soil that is treated. The PAH (16 compounds) emission rates for industrial combustion processes are 0.00272 lb/ton coal and 0.0098lb/ton (0.000033lb/gal) fuel oil (US EPA, 1997). Thus, given known emission factors for combustion of fossil fuels, it is possible to quantify the pollution generated during intrusive remediation.

Summary

In many cases, monitored natural attenuation is more protective of human health and the environment than intrusive remedial systems, especially when one considers the amount of pollutants introduced into the atmosphere to install, run, and maintain these systems. Contaminants cannot be removed from the subsurface without energy input, occupational risk, and pollution being generated.

When considering the relative benefits of a given remediation system, the authors suggest that, at a minimum, the following should be considered:

- actual risk reduction over reasonable land use controls and institutional actions;
- paper consumed during technical and administrative work;
- fossil fuels consumed for travel, meetings, technical work, remedial actions, monitoring, and the like;
- particulates, PAHs, sulfur dioxides, nitrogen oxides, mercury, greenhouse gases, and the like released to the atmosphere;
- contaminants transferred to other media such as the atmosphere, landfills, and the like;
- risks to on-site workers and nearby residents;
- driving to and from contaminated sites; and
- application of funds where maximum and equitable environmental benefit can be achieved (e.g., separate environmental projects).

In summary, the field of environmental remediation was founded to protect human health and the environment. Thus, the cure should not be worse than the problem. Exposure management through land use control and institutional action will always be necessary at many sites. If intrusive remediation is to be undertaken, a high probability of success must exist and the potential negative impacts must be considered.

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