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The Three Rs of Remediation: A Comparative Analysis of the Risk, Real Estate, and Regulatory Drivers Affecting Remediation Technology Applications

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Abstract- *Time and cost often compete in guiding engineers during the design phase of remediation plans. While time and cost are primary focuses for most private industry clients, regulators, and citizens; choosing the correct technology to address the fate and transport of contaminants does not necessarily align to time and cost allotments. To ensure the success of a remediation plan in addressing the removal of contaminants, it is important to focus on the incentives behind the remediation effort. This review provides a comparative analysis of the three drivers of remediation: Risk, Regulation, and Real Estate. Based on the driving R, the selected remediation engineering technology can be more appropriate in serving the ecosystem needs and sociopolitical implications. While time and cost will remain major drivers, this comparative study demonstrates that the success of contaminant removal is equally dependent on the tools and technologies applied to the geospatial and geopolitical environment.*

Keywords: Remediation Engineering Drivers, Algorithm for Remediation Technologies, Contaminant Removal, Remediation Engineering Design.

Capsule: This review examines the 3Rs of remediation drivers: Risk, Regulation, and Real Estate, and cross-links these drivers to appropriate technologies in a simple to use algorithm.

1. Introduction

In 2004, the United States Environmental Protection Agency estimated that for the years 2004-2033 there will be approximately 294,000 hazardous waste sites to remediate and the cleanup costs will amount to nearly $209 Billion United States Dollars [1]. In response to this market trend, federal, state, and local government and private industry will tackle the anticipated demand by seeking 1) technologies, 2) skilled professionals, and 3) smarter and more cost/time effective solutions to existing and up and coming complex environmental pollution [1]. Investors on the other hand, will pursue innovative technologies and promising real estate that has a potential for a lucrative technical and financial future. In alignment with market needs, universities continue to adjust their curricula in environmental science and engineering to prepare future professionals for this complex challenge where no two remediation sites are alike.

As electronic applications dominate our daily lives, the field of remediation engineering remains dependent on geomechanical design processes set in design blueprints and spreadsheets. The complexity of this field from assessing the classification of contaminants, to determining the parameters for lab testing, to investigating soil types and elevations, and calculating water flow and pump curves, necessitates introducing easy to use matrixes for sound and quick decision-making.

As electronic algorithms become more functional through the smart application of data utilization and automated technologies, the matrix environmental professionals utilize to design remediation plans is outdated in comparison. Even though a smart app that resolves remediation strategies may be futuristic, the objective of this paper is to delineate the 3Rs that drive remediation projects. Based on the driving R: Risk, Regulation or Real Estate – the selected remediation

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engineering technology can be more appropriate in serving the ecosystem needs and sociopolitical implications. While time and cost will remain major drivers, this comparative study demonstrates that the success of contaminant removal is equally dependent on the tools and technologies applied to the geospatial and geopolitical environment. Using a matrix, that acknowledges which specific technologies will better perform based on the driving R, will facilitate the design of remediation plans and assure the proper management of the contaminant resulting in the long-term reduction of health costs, ecosystem impacts, and federal funds.

2. Background

In describing the complexity of the environmental field of remediation, Suthan S. Suthersan said it best:

"Scientists and engineers practicing remediation engineering have to learn the nuances of investigative techniques, data collection, and treatment technologies. This education includes a new understanding of the physical and chemical behavior of the contaminant, the geologic and hydrogeologic impacts on the fate and transport of these contaminants, the human and environmental risks associated with contaminations, and the selection of appropriate technologies to provide maximum mass transfer and destruction of the contaminants" [2].

In determining the protocol for this study it became apparent that one of the main objectives is to produce a graphical, easy to use, algorithm to guide decision makers and engineers in quickly selecting some of the available technologies based on the driving factor for the project in question. In the same way electronic algorithms learn and adapt to the consumer choices and behaviors, an engineering algorithm can provide the field with a tool that can be applied to the various project needs and parameters of interest. The key is to simplify the study tool to provide a first step approach to the plethora of available tools and matrixes in remediation technologies. The tool provides a unique approach by focusing on one of the 3Rs as a project driver: Risk, Remediation, or Real Estate versus time and cost.

Before creating the graphical algorithm to serve as a quick and easy reference and in order to comparatively cross-examine technologies to project drivers, the following two targets will be addressed:

- First: Define and select remediation technologies that are appropriate for various scenarios and are well established in the field. This will be conducted by investigating the literature and industry experts to produce a list of ten proven and commonly utilized technologies.
- Second: Provide a comparative analysis of the 3R drivers as they relate to priorities and success factors.

3. Study Targets: Remediation Techniques and Comparative Analysis of 3Rs

3. 1. Remediation Techniques

The Federal Remediation Technologies Roundtable (FRTR) produced a remediation reference guide in a cooperative effort by various federal agencies to include the United States (U.S.) Department of Defense, the U.S. Army, the U.S. Department of Energy, the U.S. Geological Survey, the U.S. Environmental Protection Agency and more. The reference guide also included a Treatment Technologies Screening Matrix [3]. The matrix is composed of approximately 60 treatment technologies grouped into water versus soil clean up applications. The matrix also provides a cost and time performance measure. To date, the FRTR matrix and reference guide remain as one of the most comprehensive and easily accessible guides to environmental engineers working in the remediation industry.

This study will utilize technologies that are aligned with the FRTR database. To better focus this paper, the ten technologies selected for this study are dominated by in situ treatment options with the exception of "Pump & Treat" and "Dig & Haul" options. In situ remediation uses on site methods to treat the contaminant on location in efforts to save money, time, transportation cost, liability, and disposal fees [4]. Moreover, the ten selected remediation technologies are well established and referenced in textbooks used to educate future engineers such as CRC Press's textbook titled Remediation Engineering Design Concepts [2]. The ten selected technologies are listed and described as follows:

3. 1. 1. Pump & Treat

Used primarily for groundwater decontamination applications. Contaminated groundwater is pumped to the surface. The contaminant is then removed from the groundwater by aboveground treatment methods, such as filtration, and the clean water is re-injected or released to either the sewer or a surface water body.

Another option after pumping the contaminated water is to dispose the contaminated water as a stored hazardous substance. Pump and Treat is common in treating dissolved chemicals in water. In addition, the pumping process contains the contaminant plume and prevents it from migrating to other water resources to include drinking water wells and wetlands [2], [5].

3. 1. 2. Dig & Haul

Dig and haul is an ex situ approach to soil remediation techniques that utilizes construction equipment and heavy machinery. Dig and haul focuses on excavating contaminated soils and disposing of them as hazardous material waste in appropriate landfills. Timely excavation of the contaminated soils can play a significant role in preventing the spread of the contaminant through the water table and wind dispersion [5].

3. 1. 3. Air Sparging

Used separately or integrated in conjunction with other techniques, air sparging is the pumping of air to volatize volatile organic compounds (VOCs) and semivolatile organic compounds sorbed to soil and in the groundwater. The addition of air specifically beneath the water table expedites the movement of volatiles through the path of least resistance towards the surface. Air compressors are usually utilized through injection wells to produce sufficient air pressure to mobilize contaminants [3], [5]. The addition of oxygen for air sparging has the added benefit of creating an aerobic environment that could assist with biodegradation levels.

3. 1. 4. Vacuum Enhanced Recovery

Also known as dual phase extraction, Vacuum Enhanced Recovery removes through negative pressure (high vacuum system) both dissolved and free phase non-aqueous phase liquid (NAPL) contamination, and vapors in groundwater and the vadose zone. While energy intensive, this remediation technique is effective and unique for extracting both liquid and vapors at the same time. Vacuum Enhanced Recovery is also referred to in the literature as vacuum enhanced extraction, and bioslurping [2], [3].

3. 1. 5. Reactive Walls/Zones

An in situ approach to mass removal and treatment of contaminants in large areas where other mechanical technologies may be cost prohibitive and troublesome due to generating hazardous waste for disposal. The approach of reactive walls/zones also known as "permeable reactive barriers" [5] is to utilize impermeable and permeable barriers and gates downgradient of the contaminant plume or a series of injection wells acting as a curtain to immobilize and/or transform the contaminant to non-harmful byproducts. This technique is also referred to in the literature as "funnel and gate systems" or "treatment walls" [2]. Decontamination usually occurs through chemical reagents addition, oxygen infusion, and/or filtration of the substance underground following a set hydraulic pattern.

3. 1. 6. Stabilization & Solidification

Stabilization and Solidification processes can range in implementation depending on whether the contaminant is encapsulated or bound onto a solid to prevent the contaminant migration and facilitate the excavation of the waste product [5]. The primary benefit of this technology is that solidification prevents contaminant leaching from surfaces and soils into the groundwater, surface water bodies, and stormwater runoff and drains. Specifically, the solidification process binds contaminants with reagents changing their physical properties -especially hardness, while stabilization refers to a chemical reaction that reduces waste leachability [6].

3. 1. 7. Soil Vapor Extraction

Soil Vapor Extraction is used to remediate soils from volatile and semi volatile organic compounds. Also known as soil venting and vacuum extraction, Soil Vapor Extraction utilizes in situ technologies to remove contaminant vapors through extraction wells with the use of blowers or vacuum pumps. The extracted vapors or "off-gasses" are then treated onsite with various above ground treatment methods such as thermal or catalytic oxidation or condensation. The Soil Vapor Extraction method is applicable to the vadose zone since extracting water will damage the system and will require the Vacuum Enhanced Recovery method instead. The mechanical set up of Soil Vapor Extraction is easily integrated to other remediation technologies such as Air Sparging [2], [5].

3. 1. 8. Bioventing

Bioventing refers to the use of low airflow to stimulate aerobic biodegradation of contaminants and mobilization of volatile compounds through the soil.

This technique is also compared to soil venting in the literature [3]. Bioventing not only reduces vapor treatment costs, but also can consequently remediate semi volatile organic compounds that are not directly volatized [2].

3. 1. 9. Bioremediation

Under both aerobic and anaerobic conditions, bioremediation is the degradation of organic contaminants in soil and water through microbial metabolism. Bioremediation can be enhanced through the addition of oxygen, hydrogen peroxide, nitrate, and nutrients. When acceleration of the naturally occurring biodegradation process is limited, bioaugmentation is utilized by adding exogenous microorganisms on site. The microorganisms, including bacteria and fungi, metabolize contaminated compounds to innocuous mineral products [2], [3].

3. 1. 10. Phytoremediation

Phytoremediation is the use of photosynthetic plants to uptake contaminants in the soil or water. Phytoremediation is especially effective for removing inorganic compounds, metals, pesticides, and explosives when the contaminant is at low levels tolerable by the plants. Phytoremediation provides the added benefit of soil stabilization -known as phytostabilization- by preventing wind and water runoff and dispersion of contaminants [5]. Phytoextraction is the process in which the plant extracts the contaminants above the soil surface into the plant shoot and leaves while contaminant degradation in the rhizosphere can also occur in the root zone of the plants with the symbiotic relationship augmenting the process by "incorporating bacterial, fungal, insect, and even mammalian genes into the plant genome" [2] to provide an opportunity for biodegradation at the root system.

3. 2. Comparative Analysis of the 3 R Drivers

3. 2. 1. Risk Drivers

When it comes to risk drivers, many stakeholders are involved in scrutinizing the remediation process of a contaminated site. These stakeholder entities range from state and federal agencies, environmental consulting engineers, to local citizen action and advocacy groups [7]. Yet, public pressure remains one of the strongest components in how risk is perceived and how regulatory standards react. Preferably, clients and companies will avoid environmental risk by taking risk precautions [8]. Unfortunately that is not always feasible based on cost and liability limitations. For example, depending on cost, a company might not be willing to invest large sums of money to avoid negligible risks perceived by the public. Contrarily, the public, investors, or companies may refuse to invest any money to reduce actual demonstrated risk due to associated costs or inconvenience [9]. This example is best demonstrated by the use of cell phones while driving in absence of local laws. Another validation are the survey results indicating that in the absence of state laws requiring passenger restraints/seat belts, only 15% of American drivers routinely use them [9].

As public perception is critical in the success of risk driven remediation projects, it is important to assess risk not only from a regulatory standpoint but also at a societal level. Society at large influences not only the level of perceived risk to human health but also the risk to ecosystem impacts, and the risk of mobilization, biomagnification, cross-contamination and chemical persistence. Meanwhile, regulatory drivers depend on established exposure limits by federal, state and local agencies and entities such as the Occupational Safety and Health Administration. In determining the regulatory exposure limits many risk assessment standards are considered for determining dosages. One value that is frequently used is "the No Observable (Adverse) Effect Level (NOEL). The NOEL includes effects, such as minor weight loss, that are not considered to be adverse. These values are applicable only to that species in which the test was conducted. Extrapolation to other species will require dosage adjustment" [9]. Regulatory standards are generally designed to stay within thresholds in which no adverse effect will occur. Especially when it comes to predicting cancer risk, many guidelines offer a NOEL of a 1/1,000,000 risk level as an acceptable risk [9]. Risk management thus, depends on evaluating various response alternatives, both regulatory and non regulatory [8].

Since risk assessment supports setting regulatory thresholds, and risk assessments are based on non-adverse and acceptable levels of risk as more stringent thresholds are cost prohibitive, it is important to then prioritize risk drivers as follows:

- Ability to "stop the bleeding": the technology that most rapidly immobilizes the contaminant to prevent migration and cross-contamination to include reducing short-term and long-term exposure limits through ingestion, inhalation and dermal absorptions.

- Cost-effectiveness: high energy intensive and mechanically dependent applications can be cost prohibitive as many of these facilities become a federal liability in the absence of private investors or responsible corporations.
- Public Acceptance of technology: it is important that the technologies utilized onsite or offsite not be intimidating to the public or ecosystem considering noise levels, byproducts and off gases (smell), risk of explosion, and accidents during operation.

3. 2. 2. Regulatory Drivers

In determining remediation mitigation plans, "both industry and government have their respective roles to play. Ever-increasing parts of that role, and the keys to success, are sound cost control practices and techniques" [7]. Due to the complex nature of these remediation plans, many of the regulation drivers place emphasis on schedule compliance rather than cost. There is a lack of guidance with regards to cost estimating (e.g., standardized cost databases and cost guides) to aid regulators in the process of identifying cost-effective and sound technology decisions and approaches. Nevertheless, corporations are becoming more aware that their environmental image and footprint is directly affecting their bottom line. The public attention on environmental impacts is significant and will continue to surge with increasing levels of public awareness [8]. Environmental compliance costs cannot only consider violation fees. There are costs related to complying with federal, state, and local requirements to include permitting costs, technology modification costs, changing source materials, environmental auditing, and creating and maintaining an environmental management system [8].

Therefore when prioritizing regulatory drivers, the following factors remain important in order of criticality, from most to less, as follows:

- Compliance of technique: prioritizing environmentally friendly low-impact and low-byproduct methods of decontamination, especially those of high public acceptance.
- Initial time to set up and implement cleanup technology: to achieve lower risk of mobilization of contaminant and halt the noncompliance regulatory fees.
- Cost-effectiveness: since as indicated by Richard A. Selg (1993), cost control practices are a key area for project success.

3. 2. 3. Real Estate Drivers

Real Estate drivers are compelled by a distinctive set of values that are primarily focused on profit, time and cost efficiencies, land value, property potential, and historical and social significance of the real estate. Private investors and land developers usually control the ownership of Real Estate driven remediation projects. Even though the developers will comply with regulatory requirements, the priorities rest in the efficiency of the cleanup versus the techniques utilized. Nevertheless, investors are now more aware of environmental concerns. This awareness is driven by the company's earnings, net worth, cash flow, acquisition potential, divestiture, and financing strategies that are impacted by environmental obligations and liabilities [8].

Remediation projects in the real estate industry are featured by specific characteristics. The language utilized to enhance and encourage property advancement in the future includes words such as "adaptive reuse" and "reconstruction" versus remediation. These words are selected carefully to entice and incentivize the future customer. Future customers include shoppers and recreational users that will invest in purchasing services and property in the residential, commercial, or retail real estate sectors. Examples of real estate developments on remediated sites include golf courses, commercial office space buildings, shopping centers, historical landmarks and more.

Richard Selg indicates that the "most common approach to eradicating cost growth is to revisit the basis of the estimate and to ensure that the current estimate accounts adequately for known scope as well as uncertainties surrounding the accomplishment of the current scope of work" [7]. In real estate driven remediation projects time is money setting the priorities as follows:

- Time Effectiveness: Efficiency of remediation plan to include quick set up and mobilization, fast contaminant removal, and utilization of existing on site construction material and equipment.
- Liability: The effectiveness of the remediation technology to comply with regulations and ability to transfer liability to other entities (for example landfills).

- Complexity: Less complex systems are attractive to real estate investors since they reduce the dependency on technology modifications, intellectual property, and the engagement with field specific contractors that take up time and cost to set up and mobilize.

4. Results and Algorithms

Real Estate driven environmental remediation projects are usually motivated by high cost, high energy, high mechanical expenditures, and fast treatment technologies that mimic construction sites. In contrast, Regulation drivers are lower cost, more environmentally friendly, and less mechanically intensive applications. Risk drivers are more socially acceptable technologies that prioritize halting the contaminant migration and providing further damage protection.

Figure 1 displays the compiled results of this study in a graphical algorithm that serves as a quick and easy reference guide of comparatively cross-examined technologies and project drivers.

4. 1. Influence of Risk Drivers on Remediation Technology Applications

The influence of risk drivers on remediation technology applications are determined from most applicable to minimally applicable, as follows:

Highly Applicable:

- Reactive Walls/Zones: Useful in containing hard to treat underground and groundwater plumes from migrating and posing risks to various other systems. Can be less energy intensive and less costly than pump and treat operations.
- Stabilization & Solidification: Attractive due to fast response stabilization and immobilization of contaminants especially in emergency response situations.
- Soil Vapor Extraction: More attractive than Vacuum Enhanced Recovery for removing VOCs and semi VOCs from a risk perspective since Soil Vapor Extraction is less mechanically intensive, easier to control off gases, and quick onsite set up and mobilization.

Moderately Applicable:

- Pump & Treat: Even though cost prohibitive and energy intensive, Pump and Treat can be one of the very few methods that allow for hydraulic manipulation to control groundwater plume migration.
- Dig & Haul: Cost prohibitive in many instances; however, timely excavation of contaminated soils provides reassurance that air dispersion and water contamination will be prevented.
- Vacuum Enhanced Recovery: Even though applicable, the highly mechanical set up poses risks of off gas explosions and other mechanical failures reducing attractiveness especially from public perspective.
- Bioventing: Bioventing relieves the concerns originating from high pressure air sparging. For long-term interventions, utilizing oxygen as a treatment method is publically acceptable.
- Bioremediation: Both regulators and the public embrace this method that was initially based on natural attenuation principles. Minimal risk can be incurred if bioaugmentation is introduced.
- Phytoremediation: As in bioremediation, this natural method of contaminant uptake is highly favorable. Risk concerns emerge due to contaminated plants (stalks and leafs) consumed by animals/birds and may require proper disposal offsite.

Minimally Applicable:

- Air Sparging: Potential to jeopardize foundations nearby, migration of plume due to air pressure, and potential to increase off gases in underground structures, conduits, and basements

4. 2. Influence of Regulation Drivers on Remediation Technology Applications

The influence of regulation drivers on remediation technology applications are determined from most applicable to minimally applicable, as follows:

Highly Applicable:

- Vacuum Enhanced Recovery: The dual phase extraction capability of this technique reassures regulators that both vapor and dissolved contaminants are addressed and provides a faster way for the client to reach compliance.
- Reactive Walls/Zones: An innovative technique that provides an in situ alternative for pump and treat and reduces hazardous disposal offsite. Can integrate many remediation media to address organic, inorganic, and elemental contaminants.
- Stabilization & Solidification: A time efficient technique that allows for emergency response. In addition, it prevents future contamination and reduces violations costs.

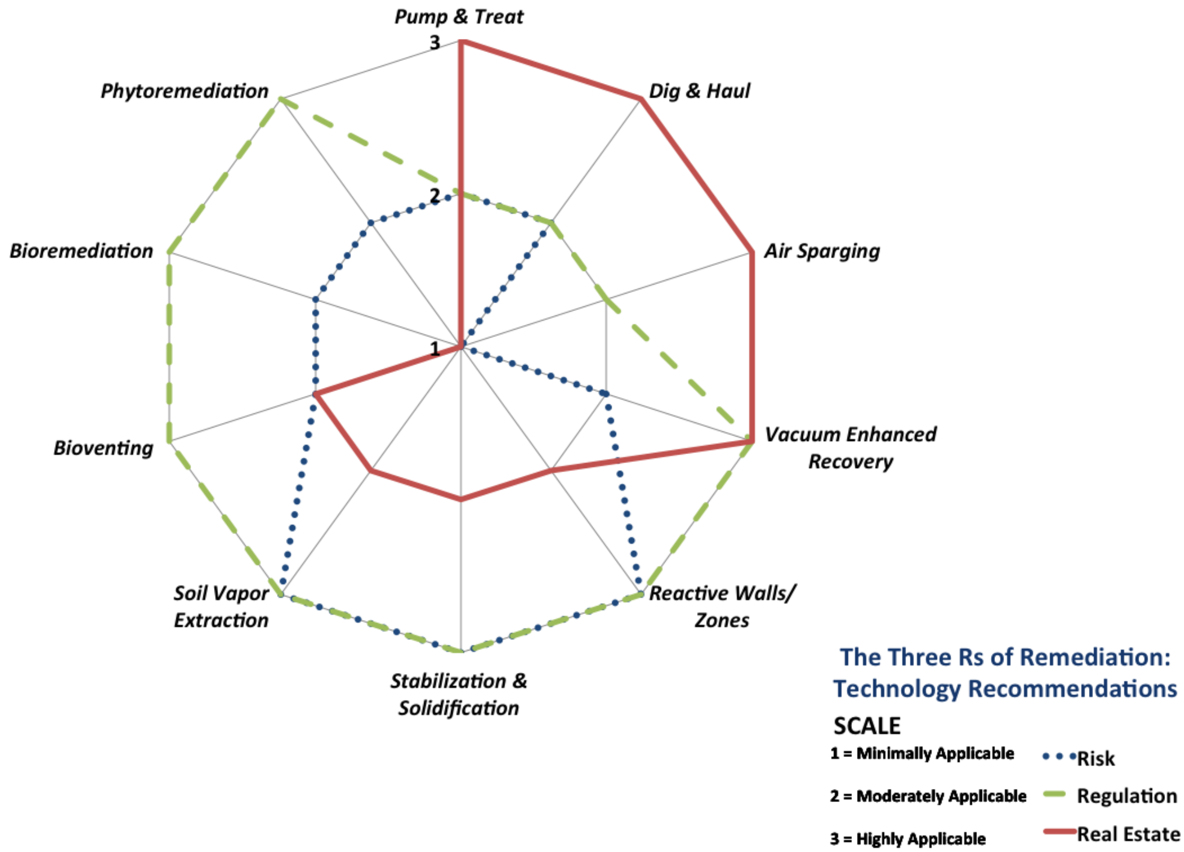

Figure 1. The Three Rs of Remediation Technology Recommendation Graphical Algorithm.

- Soil Vapor Extraction: A time proven method that allows for quick set up and mobilization when treating VOCs and semi VOCs.
- Bioventing: Regulators favor techniques that allow for low-risk natural methods such as bioventing, also known as soil venting.
- Bioremediation: A trendy method that allows for land and resource preservation using the basis of natural attenuation. Also, this technology provides clients/violators with mitigation negotiating possibilities.
- Phytoremediation: Added benefits of land stabilization, hydraulic cycle support and soil enrichment highlights this method of remediation.

Moderately Applicable:

- Pump & Treat: A high energy and high cost old school method has left regulators more impressed by reactive zone on site innovative methods especially when pumped water is disposed of as hazardous waste offsite or overwhelming local sewer plants (which require coordination with local authorities).
- Dig & Haul: Considered an effective yet old school method of remediation, regulators like to see technology innovation that reduces offsite hazardous waste transfer.
- Air Sparging: Some concerns emerge if foundations or basement/underground structures are nearby.

Minimally Applicable:

- Not applicable since all identified technologies in this study are accepted by regulatory agencies.

4. 3. Influence of Real Estate Drivers on Remediation Technology Applications

The influence of real estate drivers on remediation technology applications are determined from most applicable to minimally applicable, as follows:

Highly Applicable:

- Pump & Treat: Even though costly, real estate investors are happy to save time due to large coverage area and the option to store and dispose contaminated water offsite.
- Dig & Haul: Another costly technique, this method is highly applicable to contaminated soils allowing investors to use the same construction set-up and excavator machinery to remove contaminated soils and dispose of them in a timely manner in approved landfills.
- Air Sparging: The high pressure air sparging to stimulate biodegradation and assist the contaminants in volatizing is an attractive technique in larger project sites where there is no fear of jeopardizing residential basement structures/infiltration and the mobilization of plume to neighboring land.
- Vacuum Enhanced Recovery: Intensive mechanical and energy set up, yet dual phase extraction of both liquid and gas contaminants simultaneously covering large sites makes this attractive when cost is not an issue compared to time.

Moderately Applicable:

- Reactive Walls/Zones: Cost and time of trenching before utilizing trenches for treatment is not as attractive to real estate developers.
- Stabilization & Solidification: Solidification is more attractive in this driver if the material could be solidified and kept onsite without generating any risks.
- Soil Vapor Extraction: Vacuum Enhanced Recovery is usually preferred since it is a dual phase extraction process applicable to larger areas saving time.
- Bioventing: More applicable to low concentration of contaminants that are less volatile. Added advantage of biodegradation is not realized due to time requirements of biostimulation lag period.

Minimally Applicable:

- Bioremediation: Long period of acclimatization and contaminant degradation. In addition cannot be implemented on land to be redeveloped and constructed.
- Phytoremediation: Long period of plant growth and contamination uptake. In addition cannot be implemented on land to be redeveloped and constructed.

4. 4. Sample Case Studies

When approaching a newly discovered contaminated area or spill, professionals can be overwhelmed with the number of technologies and techniques available to remediate any given site. After all, the FRTR matrix provides approximately 60 treatment technologies. The objective of the 3Rs approach presented in this paper is to facilitate a broader method to initial selection of remediation techniques – independent of the nature of the contaminant or the environment affected. Figure 2 provides a questionnaire based decision matrix for guidance and to further demonstrate the application of each driver on choice of technology, Table 1 provides a list of case studies categorized by driver and technology listed by reference and location. Four case studies, included in Table 1, are further evaluated as follows:

Case Study 1: Risk

Removed in 2004 from the National Priority List of superfund sites, the South 8th Street Landfill in West Memphis, Arkansas [10] is a great example of a "Risk" driven remediation approach. The South 8th Street Landfill has completed the third five-year review with a determination that the site remains protective of human health and the environment and that the site controls prohibiting excavation and drilling within the specific landfill areas will prevent future exposure pathways. The 16-acre landfill site and two and a half acre oily sludge pit was a "Risk" driven project since the site is adjacent to the Mississippi River and is on the two-year flood plain. The groundwater table within the alluvial aquifer beneath the site sits just a few feet to 20 feet below the ground surface. It was important to protect the Wilcox aquifer that provides drinking water supply to the City of West Memphis approximately two to four miles from the site. The contaminants of concern included the oily sludge hydrocarbons, municipal and industrial waste, lead, and carcinogenic poly aromatic hydrocarbons to name a few. The site is treated with stabilization and solidification, which as shown in Figure 1 is a highly applicable method for risk driven projects due to the rapid "ability to stop the bleeding," lower cost in preventing contaminant migration, and public acceptance.

Case Study 2: Real Estate

The Vertac Superfund Site in Jacksonville, Arkansas in EPA Region 6 [11] is a great example of a "Real Estate" driven remediation plan. The site used since 1948 and purchased by Vertac Chemical Corporation in 1978 is now remediated with the third five-year review concluding that the site remains protective of human health and the environment as published on May 13, 2014. The 193 acres site was contaminated with chlorinated hydrocarbons with dioxin contamination found in both the soil and drummed waste. The site is not a direct threat to the public, and the underlying aquifer is not used for public water supply or domestic use. Approximately 1,000 residents live within one mile of the site. The site is also adjacent to industry and an air force base. Per Figure 1, the 3R driver focuses on "Real Estate" highly applicable technologies to include both "Dig & Haul" and "Pump & Treat". Excavation of contaminated soil was completed in the late 90s and groundwater extraction wells were installed to eliminate to retract the contaminant plume from the ground water. Other techniques were also used such as demolition of buildings, off-site incineration and decontamination, that align with the more expensive "Real Estate" priority of time effectiveness, compliance with regulation, and less complex systems to enhance repurposing efficiency. The industrial/commercially-zoned site is now repurposed to include the city's recycling center, and police and fire department training facilities.

Case Study 3: Regulation

Since all the techniques presented in this study are acceptable by regulatory agencies, perhaps some of the best case study demonstrating regulatory and penalty driven remediation projects, are dry cleaning establishments. For larger establishments, due to the associated cost and liability of remediation, many of these establishments after bankruptcy or abandoning the site become superfund sites and get placed on the national priority list depending on their risk to human health and the environment. However, this is not the case for many smaller businesses such as dry cleaners. A notable press release by the EPA in 2002 demonstrated the importance of penalties when it comes to compliance [12]. The EPA cited 11 dry cleaners in New Jersey proposing a total of $37,850 in fines. A total of 114 dry cleaners were also cited in New York and New Jersey combined [12]. The EPA has created many mechanisms to better educate and cooperate with dry cleaning establishments to reach compliance. One of the main objectives is to protect public health and the environment from percholoroethylene (a suspected carcinogen and irritant), and other toxic air pollutants. As a result many dry cleaners are now encouraged to use more environmentally friendly products to meet compliance and protect the workers and the public.

Case Study 4: Multiple Approaches and Multiple Drivers

In many cases, a cookie cutter approach to site management is not possible since many drivers compete for priorities in addition to the always-critical cost and time components. In such scenarios multiple technologies may be applicable. From Table 1, multiple case studies demonstrate a combination of regulatory and risk drivers. Similarly, a number of case studies include a combination of technologies such as "Soil Vapor Extraction" as well as "Air Sparging" which go hand in hand in removing VOCs. It is important to note that multiple approaches can be applicable and many decisions can fall back on the experience of the remediation engineer, contractors, and what they are more familiar in practicing. The proposed 3Rs approach is intended to serve as a reference that better organizes the technologies and options and provides guidance to engineers for determining a priority driver outside the given cost and time factors that are present in most projects.

5. Conclusions

The field of remediation engineering is highly complex and multidisciplinary. From assessing the classification of contaminants, to determining the parameters for lab testing, to investigating soil types and elevations, and calculating water flow and pump curves. This complexity necessitates the introduction of easy to use reference matrixes for sound and expedited decision-making. There is no cookie-cutter approach in remediation engineering; no two projects are alike. This study introduces a matrix that guides engineers to acknowledge specific drivers and technologies that better perform independent of the nature of the contaminant and the environment affected. In an effort to facilitate the initial set of decisions required to select adequate remediation technologies, this paper presents an approach that focuses on three prevalent drivers, the 3Rs: Risk, Regulation, and Real Estate.

Selecting the correct technology to address the fate and transport of contaminants does not only align with time and cost allotments. While time and cost will remain major drivers, the success of contaminant removal is equally dependent on the tools and technologies applied to the geospatial and geopolitical environment. There are multiple treatment technologies and hundreds of treatment technology combinations of which at least 60 are organized and referenced in the FRTR. To better focus the paper, ten remediation technologies that are well established in the field are identified, defined, and used for illustration purposes. Further research can extend the 3Rs method to include other remediation technologies in addition to the coupling of technologies and drivers through the proposed 3Rs approach. A remediation engineer can better navigate available and valuable information when better guided by a broadly applicable approach that defines the priorities for a successful outcome.

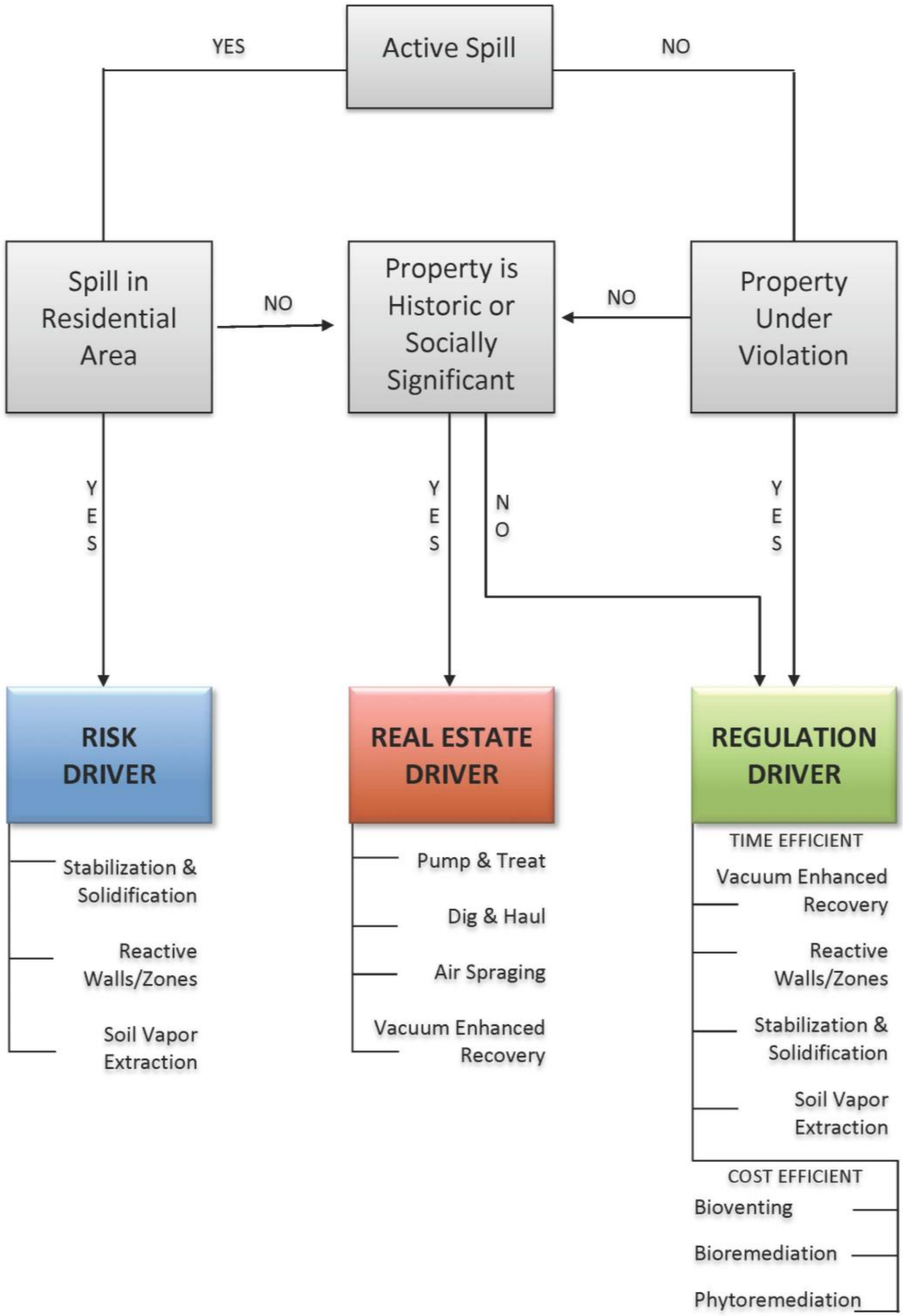

Figure 2. Questionnaire Algorithm for Guidance During Potential Border Driver Scenarios.

Table 1. Case Studies Demonstrating Remediation Driver by Technology and Location.

PROJECT	LOCATION	DRIVER	TECHNOLOGY	REFERENCE
Aberdeen Proving Ground	Edgewood, MD	Regulation	Phytoremediation	[13]
Amoco Petroleum Pipeline	Constantine, MI	Real Estate (Voluntary)	Air Sparging and Vacuum Enhanced Recovery	[14]
Baird and McGuire	Holbrook, MA	Regulation	Pump and Treat	[15], [16]
Big Tex Grain Site	San Antonio, TX	Real Estate	Dig and Haul	[17]
Butterworth Landfill	Grand Rapids, MI	Real Estate	Dig and Haul	[18]
Commencement Bay	Tacoma, WA	Risk	Soil Vapor Extraction	[14]
Federal Creosote	Manville, NJ	Regulation	Dig and Haul	[19]
French Limited	Crosby, TX	Regulation and/or Risk	Bioremediation/Stabilization	[14]
Highlands Acid Pit	Highlands, TX	Regulation and/or Risk	Dig and Haul; Phytoremediation	[20]
Highway 71/72 Refinery	Bossier City, LA	Real Estate	Dig and Haul	[21]
Hill Air Force Base, Site 280	Ogden, UT	Regulation and/or Risk	Bioventing	[14]
Hill Air Force Base, Site 914	Ogden, UT	Regulation and/or Risk	Soil Vapor Extraction and Bioventing	[14]
Iceland Coin Laundry	Vineland, NJ	Regulation	Bioremediation	[22]
Jibboom Junkyard	Sacramento, CA	Real Estate	Dig and Haul	[23]
Love Canal	Niagara Falls, NY	Risk	Pump and Treat; Stabilization and Solidification	[24]
Lowry Air Force Base	Denver, CO	Regulation and/or Risk	Bioventing	[14]
Luke Air Force Base	Glendale, AZ	Risk	Soil Vapor Extraction	[14]
MacGillis and Gibbs	New Brighton, MN	Real Estate	Dig and Haul; Stabilization and Solidification; Pump and Treat	[25]
Midvale Slag	Midvale, UT	Real Estate/Risk	Dig and Haul; Stabilization and Solidification	[26]
Old Esco Manufacturing	Greenville, TX	Risk	Dig and Haul	[27]
Parsons Chemical/ ETM Enterprises (Superfund)	Grand Ledge, MI	Risk	Stabilization and Solidification	[14]
Quarry Market	San Antonio, TX	Real Estate	Dig and Haul	[28], [29], [30]
South 8th Street Landfill	West Memphis, AR	Risk	Stabilization and Solidification	[10]
The Many Diversified Interests, Inc. Site-3617	Houston, TX	Real Estate	Dig and Haul	[31]
The Vertac	Jacksonville, AK	Real Estate	Dig and Haul; Pump and Treat	[32]
Times Beach	Times Beach, MO	Risk	Reactive Walls/Zones; Dig and Haul	[33]
Vienna PCE	Vienna, WV	Regulation	Soil Vapor Extraction	[34]

Secondary to cost implications, the case studies demonstrate that the underlying objective for a successful implementation plan can be attributed to either protecting public health, complying with regulations, profiting from potential real estate value, or a combination of the above. The comparative analysis concludes that "Real Estate" environmental remediation projects are usually driven by high cost, high energy, high mechanical expenditures, and fast acting treatment technologies that mimic construction sites. "Regulation" drivers are lower cost, more environmentally friendly, and less mechanically intensive. "Risk" drivers are more socially acceptable technologies that prioritize halting the contaminant migration and ensuring protection from further harm.

By addressing the Risk, Real Estate, and Regulation impacts of the project, the design process can more efficiently address the fate and transport of contaminants and associated hazards. Understanding the R driver of the remediation project -by focusing on Risk, Regulation, or Real Estate project incentives- will help engineers formulate a more systemic approach resulting in a more socioecologically friendly and publicly acceptable contaminant removal outcome.

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