ARCADIS

Advances in Remediation, Volume 3

BOLD Innovation, RESILIENT Restoration

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Introduction

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People always innovate.

We moved from building treatment systems aboveground to building them in the subsurface. We learned that discrete flow pathways convey the most contaminant mass. We are embroiled in an arms race to identify methods to translate higher resolution data at increasingly finer scales into immediate optimization and remedy decisions. Innovation has affected our characterization methods, investigation tools, and remediation technologies. While the journey of environmental restoration set out with a macroscale view of aquifer processes and simple containment remedies, we now focus on the importance of small-scale processes and their keys to developing more elegant and focused solutions. In this, the little things matter.

Collectively, continued innovation has moved the needle. Cleanup timeframes and costs have declined and the degree of remedy certainty and risk avoidance have significantly improved. Through this, we have understood and refined remedial measures to address petroleum hydrocarbons, chlorinated solvents, PCBs, hexavalent chromium, MTBE and hundreds of other anthropogenic environmental contaminants. These compound classes comprise a wide array of physicochemical properties, including varying degrees of relative solubility, sorption behavior, molecular weight, recalcitrance, volatility and regulated drinking water standards; in some cases, these also encompass broad classes of individually regulated compounds. The trials of negotiating these chemical behaviors have positioned us to face current challenges, with PFAS compounds collectively exhibiting all of these in addition to resisting biodegradation, exhibiting surfactant properties, and being ubiquitous in our environment. As always, insights from past challenges will continue to provide the foundation for future innovation.

Acknowledging our challenges, successes and failures from the past four decades is key, as many technologies have come and gone. This reinforces the belief that technical knowledge, not technology, remains the critical element to our and our client's success. We foster this technology development internally, maintaining a funded pipeline of developing innovation concepts, as well as externally, through available research and academic partnerships. As highlighted in many articles within this catalog, we currently lead or are involved in 14 ongoing innovation projects funded by SERDP and ESTCP focused on the technical development and implementation of new technologies. This body of research is a testament to our investment in innovation and the continued refinement of our practice to restore our natural environment.

As we tackle contamination challenges both conventional and emergent, we are increasingly cognizant of the additional pressure on our industry that stems from broader global trends such as urbanization, climate change and digitalization. These larger trends provide the opportunity for bolder innovation and increased resilience from our investments in environmental restoration.

The following 11 articles enclosed in Arcadis' Advances in Remediation Volume 3 provide new insights from our scientists and engineers who continue to rethink the future of site evaluation and remediation while considering the prevailing global trends to provide value to our and our client's triple bottom line – people, planet and profit.

1. Leveraging digital data for advanced decision making

While the digital revolution represents the most transformative innovation period in human history, less than 50% of remediation programs have a guiding digital strategy (Horst et al. 2019). Within five years, however, ongoing developments in sensor technologies and connected Internet of Things (IoT) devices will transcend our remediation programs to generate exponentially more data, require less labor, and increase the health and safety of field personnel. Virtual work through the COVID-19 pandemic proved that we can effectively collaborate via augmented or virtual reality platforms which, coupled with sensor technologies and improved data management, significantly improve overall project sustainability.

2. Modeling our design future: BIM for remediation

Hand in hand with the technology progression outlined above, the use of digital twins in design engineering has become the gold standard to integrate design teams, drive efficiency and enable system troubleshooting prior to capital construction – while the design is underway. While we are "early adopters" of this for remedial designs, the BIM platform and workflows come well-vetted by other industries and enable integration of multiple software platforms to integrate treatment system mass loading, infrastructure specifications, project imagery, construction sequencing and costs.

3. PFAS – emerging contaminants driving rapid innovation

Wide and varied global use, recalcitrance to chemical and biological degradation, ranging chemical and ionic properties, and bioaccumulation potential have breathed new life in oft-overlooked technologies and investment in new techniques to monitor and efficiently remove PFAS from our environment. Whether present in surface waters, landfill leachates, groundwater, or soils, multi-stage treatment using innovative separation and sorption methods are best employed to remove or concentrate PFAS so they can be efficiently destroyed via high energy, low volume treatment. Fractionation, super-critical water oxidation and sonication are all methods that may not be new science but have emerged as viable methods to address the PFAS treatment challenge.

4. Expanding the 1,4-dioxane remediation arsenal

Detected in nearly 20% of our large-scale public water supplies, 1,4-dioxane has strained our natural resources and required significant investment in advanced oxidation systems to restore groundwater for beneficial use. Innovative and more sustainable treatment technologies have emerged, however, as we have pioneered innovative biological remedies available for both in situ and ex situ treatment that leverage naturally occurring microbial communities to achieve low drinking water standards.

5. The new CSM of groundwater transport and keys for large-plume remediation

High resolution characterization methods have completely changed our understanding of contaminant fate and transport through groundwater systems. This building awareness has translated to flux-focused remedies that strike a balance between strategic active remediation to address the risk-driving contaminants and low-risk management of stored contaminants inaccessible to treatment. The changing subsurface paradigm has also provided new modeling techniques to increase remediation efficiency with predicted project outcomes and optimization steps tailored to ramping down remedy operations as it proceeds.

6. Horizontal well applications for monitoring and remediation

The integration of mass flux decision-making in our remedy design has prompted a re-evaluation of effective mechanisms to stabilize project sites and achieve passive monitoring endpoints. Engineered for flux-control, HRX horizontal wells can be installed in passive or pumped configuration to achieve plume control where property features prevent vertical well installation (e.g., below buildings) or where ex situ treatment footprints are infeasible. Replaceable in situ treatment cartridges using a variety of media can be used to sustainably capture, degrade or destroy the full contaminant spectrum with very little O&M, oversight or energy input.

7. Innovations in sustainable remediation

Truly sustainable remediation has been a lofty aim for the past decade, but headwinds associated with the lack of broad multiparty consensus and regulatory directive have slowed adoption of the triple bottom line (economic, environment and social equity). We have been content to categorize all remediation as inherently sustainable. We have aged, however, and with momentum stemming from updated ITRC, SURF and ASTM guidance and a renewed stakeholder focus, there has been a surge in Sustainable Resilient Remediation (SRR) analytical tools and the application of solar energy, waste heat and repurposed raw materials to promote creativity in a spectrum of more sustainable solutions.

8. Tackling the challenge of global plastic pellet release

While most emerging contaminants are identified as dissolved-phase constituents with promulgated standards, environmental impacts aren't always measured based on toxicology or drinking water criteria. Releases of plastic pellets into the environment are persistent, highly visible, and pose a mitigation challenge. Beyond the public perception issue, plastic pellets wind up in fish, aquatic organisms, and accumulate carcinogenic compounds and biofilms that compromise a wide variety of ecosystems. Innovations in source control, characterization, and best available control technologies are all key to eliminating discharge from staging areas and during transport and will be critical steps to improving our global waterways.

9. Abandoned uranium mines – multiple lines of evidence for a regional issue

Abundant uranium deposits present on the Colorado Plateau spurred extensive mining operations during the Cold War arms race. These activities resulted in over 4,000 abandoned mine locations, many of which are currently located in Navajo Nation. The presence of naturally occurring radioactive material (NORM) at surface results in challenges associated with defining mitigation locations, assessing transport and understanding the associated risk and remediation needs. An innovative combination of mining forensics that entails aerial imagery, geological/geomorphological mapping, high-resolution gamma scans and target soil sampling all comprise a powerful playbook to distinguish undisturbed NORM from more radioactive areas that require abatement.

10. Controlling the unpredictable – innovations in incident and disaster response

Emergencies and disasters can create hazardous conditions, impact entire communities, disrupt business operations and pose threats to public health and the environment – all impacts to our quality of life. Appropriate incident management can help build community and regulatory trust, support lesson learning and process improvements, reduce risk and expedite business restoration. Fortunately, innovations in digital technologies like multi-spectral photography, integrated 3D topographic surveys and high-resolution characterization methods provide new ways to visualize the extent of release, refine the areas necessary for mitigation and achieve transparency with affected stakeholders and communities.

11. Preferential pathways – responding to changes in the vapor intrusion CSM

Growing recognition of subsurface vapor migration through sewer and utility preferential pathways has resulted in a cascade of most State and Federal guidance for VI investigations and has upended previous assumptions regarding vapor risk. The new guidance can be highly variable but can be effectively managed with upfront regulatory and stakeholder engagement and deployment of a combination of desktop assessment, targeted real-time field screening methods, pipe camera videography and passive sampling. Real-time sampling technologies (e.g., FROG-5000^{TM}) enable rapid data collection from pre-identified potential pathways and provide significant adaptability during field execution to shorten the investigation period and expedite the closure process.

Advancement of the restoration practice is both our mission and our passion, so that we can better engineer and execute more effective and efficient cleanup solutions. We thank you for your shared interest in some of our insights as we continue to strive to improve outcomes for our clients, stakeholders, and the environment.

Matt Schnobrich, PE, Leads Arcadis' Technical Communities of Practice for Resilience North America and is the global lead for In Situ Remediation. Mr. Schnobrich has 19 years of site characterization and remediation experience and was a co-author of Remediation Engineering, 2nd Edition (2017). In his North American role, Mr. Schnobrich leads a broad team of nationally-recognized subject matter experts who oversee innovation and the development of best practices and standard methods for the deployment of Arcadis services across the site evaluation and restoration fields. He also serves as a primary project strategist and technical lead for site characterization, conceptual site model (CSM) development, remedial strategy determination, and remedy implementation through closure to address contaminants including chlorinated solvents, petroleum hydrocarbons, metals, poly- and perfluorinated alkyl substances (PFASs), and 1,4-dioxane.

Digital Innovation: Leveraging digital data for advanced decision making

Monica Dupre, Nick Welty and Allison Yanites

Digital Innovation

Monica Dupre and Allison Yanites discuss digital innovations and how we can leverage technology on remediation projects.

8 minute podcast

Digital technologies are disrupting how people interact with information, fundamentally changing the landscape of society. Despite this disruption, the Architecture, Engineering and Construction (AEC) industry has lagged in wide-scale adoption of digital technologies, with data indicating less than 50% of remediation programs have a guiding digital strategy (Horst et al. 2019).

Digitalization is often considered more relevant for customer-centric Business-to-Consumer (B2C) companies where business models can be entirely based on digital products. Similar digital solutions cannot be easily applied in AEC, specifically in the remediation industry, which deals with more tangible assets. Complicating digital application in the remediation industry are complex and difficult questions related to new contaminants, mature and established portfolios, the increasing scale of contamination, and increased regulatory and public scrutiny. While challenging, these also represent a significant opportunity to leverage powerful digital capabilities to improve remediation success.

Technology trends and developments in other industries are accelerating the disruption of our industry, which is creating substantial business opportunities and refining the human experience across all aspects of the AEC industry with immersive technology, sensors and connected environments, cloud computing, automation, and artificial intelligence. Not only does new technology offer the possibility to optimize the current workflow, but it also enables a change in the value chain.

Success in this disruptive environment requires digital reinvention that goes beyond the creation of new individual value propositions. Digital reinvention is a fundamental reimagining of how an organization operates and the experience it provides to customers, employees, and stakeholders. It requires business leaders to focus and build new expertise in the following areas:

- **Doing things smarter:** process optimization using new technologies
- **Doing smarter things:** using data and insights to improve outcomes and create additional value
- **Doing new things:** taking advantage of the digital world to create new business models

As it has for other industries, digital reinvention in environmental remediation has the potential to transform the business and unlock new opportunities for value creation, and can change how we collect, clean, enrich, analyze, share, and visualize our data to generate greater insights and unlock unprecedented value.

Forward-thinking organizations are turning those insights into competitive advantage through:

- Improved operational efficiency or productivity, thereby reducing cost
- Increased compliance certainty, reducing both operational and reputational risks
- Informed funding prioritization decisions
- Improved health and safety, and
- Increased transparency for stakeholders
- These benefits arise from the concept of “doing things smarter”, and also enable organizations to not just learn and adapt but anticipate and correct to do “smarter things.” It also opens the door for companies to harness the constantly evolving technology landscape and ecosystem to leverage new business models for “doing new things” and provide services entirely based on digital products. This comes not just from new methods of collection or real-time access to data, but from the underlying governance, adaptable analytics, intuitive visual interfaces, and a willingness to approach operational challenges with a digitally centric perspective that support reliable insights and harness the value of data.

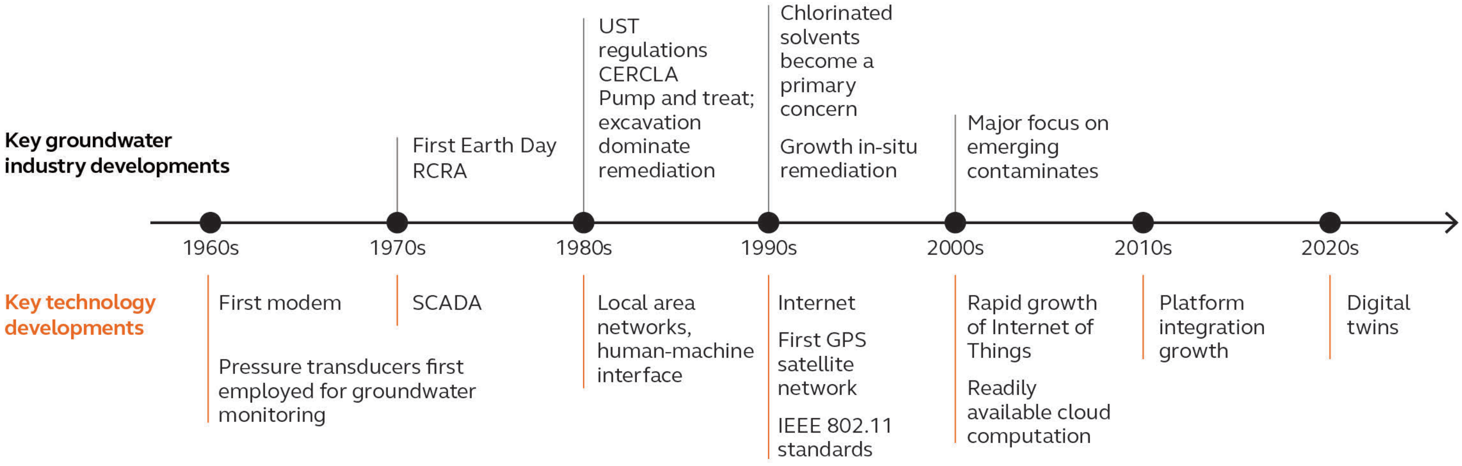


Figure 1: *Technological innovations from the past 60 years.*

The sections below elaborate on three areas of digital reinvention in the environmental remediation industry: Innovations in Sensors and the Internet of Things (IoT), Digital Twins, and Immersive Technologies.

Innovations in sensors and the Internet of Things

Sensors are being used to “connect” almost everything in the world around us, from cars to refrigerators to the lighting in homes, so it is no surprise that technological advances are providing an opportunity to improve the conventional environmental assessment approach using a variety of environmental sensors. Sensors reduce the physical travel, associated labor expense, sustainability costs (like emissions and generated waste), and reduce exposure to potential health and safety risks. Many of these environmental sensors also allow remote connection over the internet, supporting unattended data collection. This configuration is referred to as the IoT, with the number of sensor devices that provide this capability growing rapidly in the environmental space.

The ability of modern sensors to record complex phenomena in remote, rugged environments and wirelessly transmit that data back to a central collection point is the result of decades of technological innovations, from the development of the first modems over 50 years ago to more recent innovations like IoT and digital twins, Figure 1.

One result of increased sensor use is the generation of quantities of data not typically encountered on remediation projects. Therefore, successful use of sensors must occur with careful selection of how to store and manage the increased information transmitted through the data pipeline and how data analytics are applied to transform that stored data into valuable insights. Data management could be via data warehouses, where the underlying data is structured in a traditional/row column format, a data lake, where vast amounts of data are stored in native format, or a more familiar database, for simpler use cases.

As the available sensor technology and IoT capabilities advance, there will be opportunities to develop new applications that will transform the remediation market. Costs for data collection will go down, and health and safety will improve. At the same time, more effort will be spent on data analytics and drawing insights from new data streams. Projects will need to include more data scientists as part of the remediation team. Together, this will drive better outcomes – and reflect a significant opportunity for all stakeholders involved in the remediation lifecycle.

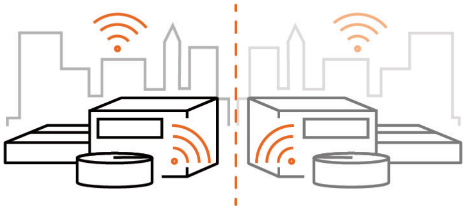


Figure 2: *A digital twin mirrors something real at a site – an asset, process, a treatment system, or an entire facility. The twin can continually study, monitor, and simulate potential futures for its physical counterpart using data. What it learns exploring challenges digitally is applied to make real-world improvements.*

Digital twins

Despite advances in data collection like IoT and sensors mentioned in the previous section, the remediation industry still faces significant fragmentation within project data streams. Tablet-collected field data, IoT data, site photographs, and 3D model files all reside in separate silos, making it time-consuming to understand the historical extent of contamination, current conditions, and plan for future remediation. Digital twins are a powerful way to harmonize each of these digital advancements and draw faster insights from remediation data. Digital twins were originally developed in the built asset world to represent the lifecycle and performance of an asset. A digital twin of an office building provides the building owner with live information about the usage of the different spaces and rooms, an overview of the energy consumption of the building, and insights from users

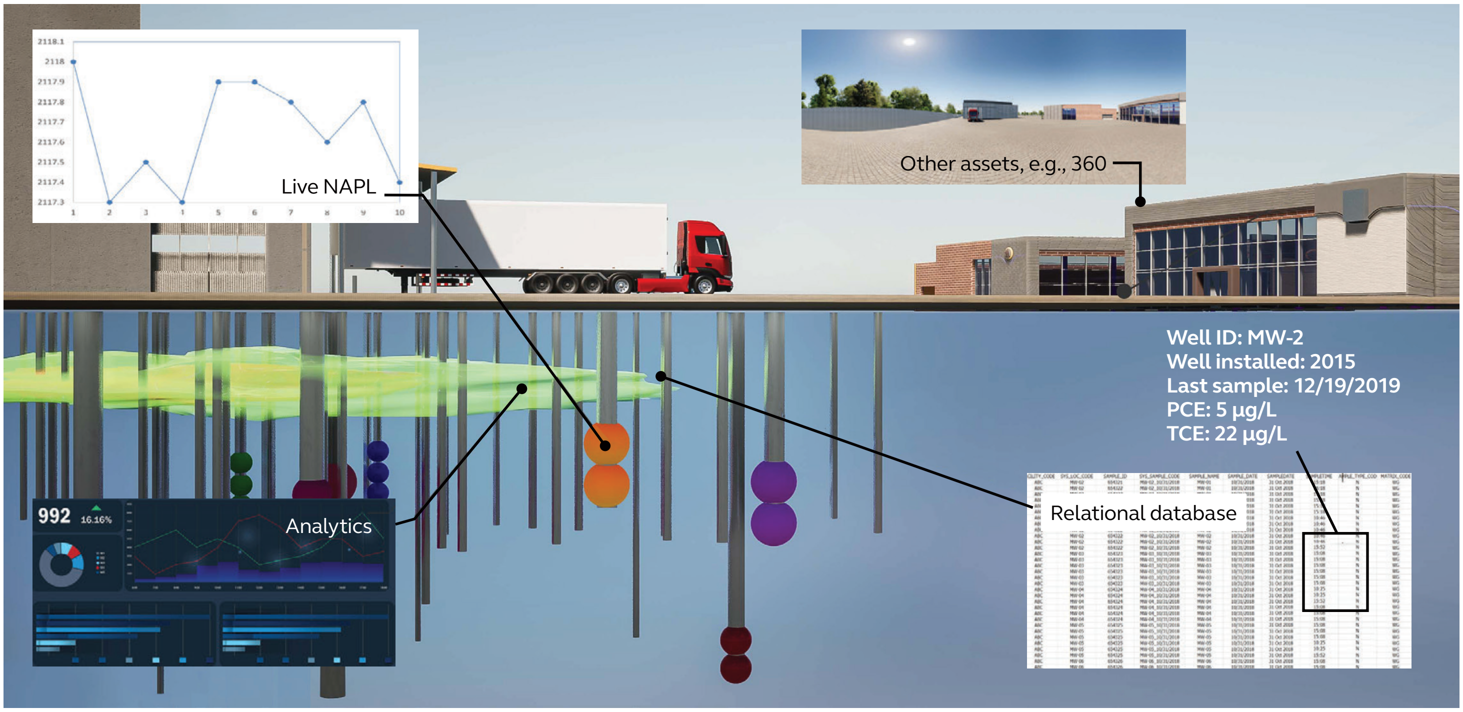


Figure 3: *A diagram of digital twin components from an active manufacturing site.*

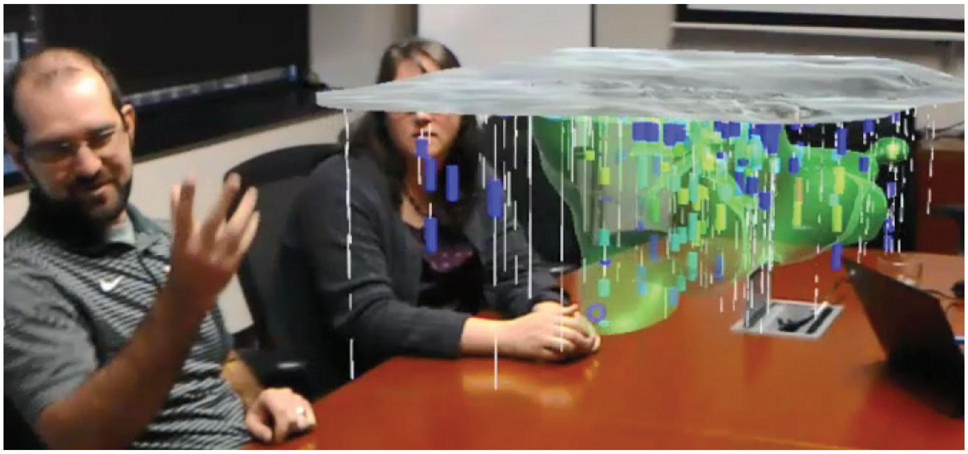
on improvements or maintenance needs. Digital twins provide a new way to collaborate, share, and consume information. In a single platform, one can visualize site conditions, stream real-time data, and interact with 3D historical data to selectively query hydrogeological or chemical data. Once the digital twin is created, we can add layers of automation and analysis to extract more insights from our remediation data.

Digital twins combine object-oriented, structured digital information models (like building information models [BIM], geographic information systems [GIS], supervisory control and data acquisition [SCADA], or three-dimensional contaminant & hydrogeologic data) with static and dynamic data (like photos, connected databases, and IoT), and deliver it via the web, mobile devices, and wearable devices (like augmented and virtual reality).

An example digital twin for an active manufacturing site is presented in the Figure 3. The site had shallow soil with volatile organic compounds (VOCs), and light non-aqueous phase liquid (LNAPL) from an historical release. LNAPL was being gauged and removed during regular trips to the site, and the site was using both a 3D model to understand the extent of LNAPL and soil contamination and dashboards for descriptive data analytics. A digital twin was developed to display the site 3D model and integrate data from IoT sensors that actively evaluated the LNAPL thickness to yield a 3D model with real-time water levels and LNAPL thickness measurements on a web-accessible platform.

The digital twin had several benefits on the project, ranging from greatly enhancing the understanding of the conceptual site model, to interpreting dynamic LNAPL changes to environmental conditions, to lowering costs for manual field tasks. Field visits were reduced, as the team could see LNAPL in real-time and receive alerts and notifications when site visits were necessary. This allows predictive system O&M, rather than fixed/routine O&M, limiting physical trips to the site, saving the client money, and reducing the carbon footprint of the project.

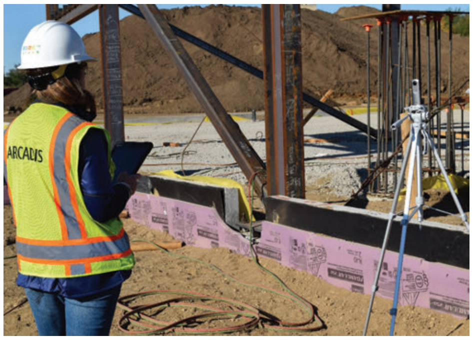
The digital twin can also be applied for remediation scenario analyses. Based on the site conditions, the team needed to understand if excavation would be a cost-effective approach for addressing the soil contamination. However, a portion of the excavation would be underneath the active facility, and it was not clear if the excavation would be feasible given the location of some of the fixed machinery in the building. Typically, this question would require a site visit and extensive photo documentation to answer, but because the remediation digital twin already contained both a BIM model of the manufacturing facility as well as 360-degree photos, the team could “slice” into the model and determine the extent of the highest concentrations and where they were located relative to fixed assets in the facility that could not be disturbed for excavation. The interactive nature of the digital twin allowed the team to identify an optimal footprint for excavation that balanced mass removal with facility constraints.



Arcadis was the first to create augmented reality visualizations of remedial conceptual site models, increasing engagement and understanding of risks as we communicated site findings with clients and stakeholders.

Immersive technologies

Immersive technologies are providing remediation practitioners new ways to interact with and understand environmental data in ways never before possible. Our remediation projects started to incorporate augmented reality (AR) and virtual reality (VR) media as early as 2016, as the emerging technology was introduced commercially. Early adoption of this technology, which included developing the first AR visualizations in the remediation industry, provided the first steps of valuable applications of immersive technology, including reality capture, assisted reality, augmented and virtual reality. Examples below highlight how these four types of immersive technology add value to remedial investigations, emergency response, remediation system design, and health and safety training.



360-degree cameras are routinely deployed to efficiently document site conditions to support project planning.

360-Degree Reality Capture: 360-degree cameras rapidly collect images that capture a complete site view. When paired with a dedicated web-based platform, the experience of viewing this imagery is like Google Map's Street View feature where the user can control their location and view of the environment. This imagery can be used as interactive virtual site-walks, a means to document and view time-lapses to monitor progress and minimize risks, or immersive training experiences to prepare personnel ahead of a site visit. Teams can also embed information, documents, and notations within virtual site models. We have leveraged this technology to document remedial site investigations, emergency response work, site conditions at routine sampling locations, remediation system design review, environmental construction tracking, site planning, safety training, and more.

Assisted Reality: Using real-time videoconferencing with handheld devices or durable hands-free headsets, we connect remote field staff, subject matter experts and clients to complete inspections and discuss projects virtually. Regardless of their physical location, the expert or client can see a live video stream from the field to provide expert guidance and communicate with field personnel and, in some applications, use augmented reality to digitally annotate the site for improved communication. We routinely deploy this technology to collaborate efficiently and safely on many types of remediation projects, including site investigations, excavations, emergency response, safety audits, and training oversight.

A field geologist live-streams a kick-off meeting using a hands-free headset. Remote participants can see site conditions clearly, including elevated surface water levels that affected planned excavation activities.

Augmented Reality: This technology merges physical and digital worlds and brings three-dimensional models to the jobsite. Field staff use a tablet, smartphone, or Microsoft HoloLens to see how a digital model fits with real-world conditions. For example, our inspectors have used augmented reality to see exactly how three-dimensional-modeled content will fit within the physical space to detect and resolve issues quickly and minimize rework and associated costs. Our field personnel have used augmented reality to visualize utilities and different work zones during environmental construction.

Virtual Reality: VR immerses users in a simulated or photo-captured environment and allows viewers to engage with the visualization. Using a smartphone with clip-on VR lenses, stand-alone wireless headsets, or other equipment, VR transports people to places and sites that cannot be experienced in reality from anywhere they happen to be located. We have leveraged VR technology to create advanced visualization experiences to help communicate both environmental risks and remedial design plans to stakeholders and we have integrated interactive, highly engaging training modules into our internal health and safety program.

Final Thoughts

It is an exciting time for the remediation industry. While practitioners are challenged by new contaminants, mature and established portfolios, the increasing scale of contamination, and increased regulatory and public scrutiny, digital technologies provide a critical part of the overall solution. Digital innovations help us meet these challenges, and in the process transform the industry, providing new ways of collecting, analyzing, and visualizing data. Employing digital technologies on remediation projects will unlock cost reductions, faster decision making, and improved health and safety.

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About the authors

Monica Dupre, has over 22 years' experience in environmental consulting, including providing digital leadership for the Resilience Environment Business Area in North America and for our clients. She enjoys engaging teams through technology, innovation, and data-driven methodologies to improve outcomes, and currently focuses on the standardization and scalability of services as part of Arcadis' business transformation effort.

Nicklaus Welty, PG, CPG, is a technical expert with over 15 years experience. He holds bachelor's and master's degrees in geology from The College of Wooster and Michigan State University, and has PG and CPG licenses. He led the high-resolution site characterization and overall site investigation community of practice (which included teams dedicated to investigating vapor intrusion, LNAPL, and high-resolution site characterization). His experience includes projects across the globe in different regulatory systems, and includes soil & groundwater investigations, DNAPL characterization, regulatory strategy development, conceptual site model development. He has a passion for digital technologies and how they can help improve the quality of life. He has implemented numerous projects using advanced digital technologies, including augmented reality, the Internet of Things (IoT), data analytics, and 3D visualization. Mr. Welty is a frequent contributor to the quarterly column titled Advances in Remediation published in Ground Water Monitoring and Remediation, the Journal of the National Ground Water Association, with topics including the digital transformation of remediation, digital twins, new methods for DNAPL characterization, and the industry's response to the COVID-19 pandemic. Finally, he is a co-author of the textbook Remediation Engineering: Design Concepts, Second Edition

Allison Yanites is the Immersive Technology Lead for Arcadis North America, where she collaborates with global leaders to advance immersive technology (AR/VR/MR) solutions that add value for owners across the life cycle of their infrastructure, building, water, and environmental assets. These solutions include on-site AR design visualization, hands-free remote assistance, 360-degree virtual asset data models, mobile AR, and VR design visualization. Ms. Yanites is focused on identifying and implementing immersive and wearable technologies to create intuitive and interactive experiences for project teams, owners, and stakeholders to improve communication, collaboration, understanding, and safety. In addition to immersive technology, she is a subject matter expert in 3D data visualization. She has extensive experience creating 3D visualizations of complex hydrogeologic datasets. Her work with immersive technology for environmental restoration earned Arcadis an Environmental Business Journal Award for New Practice Area (Augmented Reality) in 2018.

Modeling our future: BIM in remediation

Jon Spitzinger, PE

Environmental remediation professionals have been witnessing the accelerating digital transformation of our industry for multiple decades. As we've replaced our drafting tables with workstations and our filing cabinets with servers, the 21st century digital revolution dwarfs what many would consider massive improvements of the past. Changes that altered our field in fundamental ways now seem like small course corrections in hindsight – if we even remember them at all. This revolution has promised many things, like plug-and-play data collection, automatic data reduction and visualization, automated data analysis and decision-making, and even automated engineering design – many of which have now come to fruition. We have been dazzled by the notion of what we might deliver with streamlined workflows and intuitive visualizations. But we have also been lost in the mirror maze of software compatibility, licensing fees, and obsolescence. It is no surprise that a masterful presentation about a new digital tool can leave us eager to see what's around the corner in this new digital world while we simultaneously clutch our mechanical pencils and wonder if this might all just blow over. Can any of this really improve upon what we've been doing successfully for years? This type of cautious optimism from technically minded professionals is natural. In many cases it makes us better at what we do. But what if we were offered something innovative yet established? Both new and familiar? Something flexible enough to accommodate the unique variability in complexity and scale within our industry that has made quantifiable improvements in other fields? That tool, for design engineers in the remediation field, is Building Information Management, or BIM.

Figure 1: Dynamic Groundwater Recirculation (DGR™) System for Chloride, Hexavalent Chromium, and BTEX. *The BIM model for this DGR™ system was developed using Autodesk® BIM 360®, Revit®, Civil3D®, and Navisworks®. The model includes the treatment plant as well as the extraction and injection well networks. The model was incorporated into HoloBuilder™ and used alongside 360-degree photos and a virtual reality headset to facilitate construction using as much remote expertise as possible during the ongoing COVID-19 pandemic.*

Structuring a digital remediation design & engineering workflow around BIM has uncovered many of its advantages and enabled Arcadis to deliver an ever-growing number of creative solutions to our clients by uncapping our potential to utilize and visualize data. Perhaps the most comforting advantage is that we are not pioneering the use of this software. Autodesk® BIM 360® has become an industry-standard tool in the field of engineering, and early adopters continue to pave the way for the rest of us. The advantages of BIM are so immense for large engineering and construction projects that design & engineering firms who deliver those projects are more than willing to run into walls and collaborate with software developers to make things more user-friendly. To accomplish this, we have developed a team of professionals

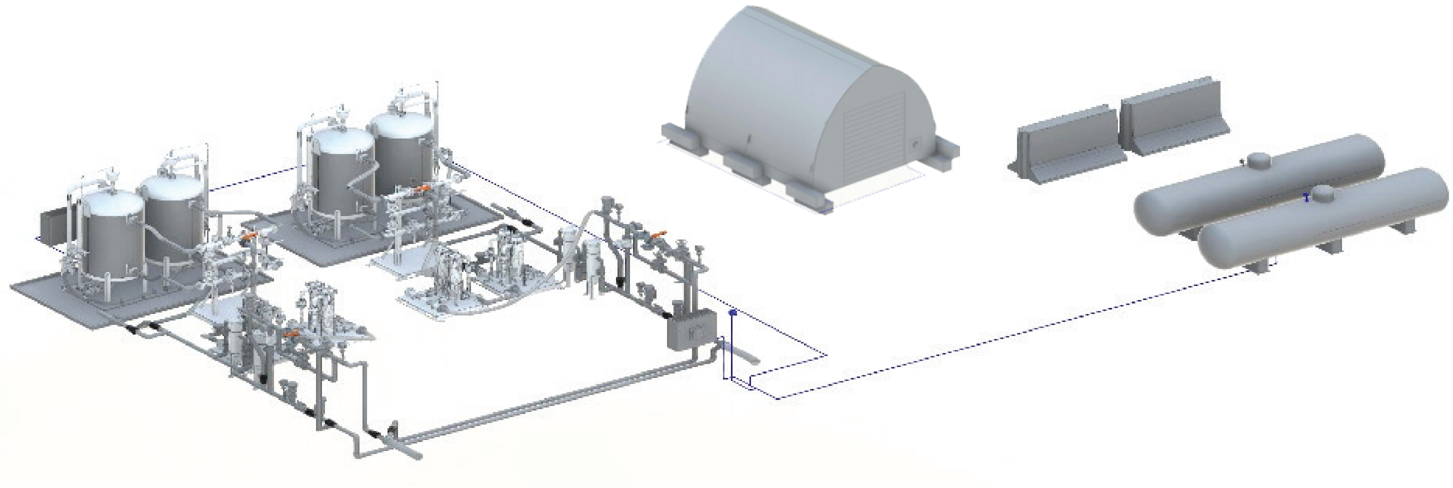


Figure 2: Off-grid, Gravity-fed Ion Exchange System for Radionuclides. *This innovative system was designed, constructed, and operated in a remote mountainous location with limited access and harsh winter conditions throughout half of the year. Rapid on-site construction and reliable remote operation with telemetry-based monitoring supported by limited personnel visits were paramount. Off-site fabrication, testing, on-site construction, and commissioning were all enhanced due to the use of BIM. The model also facilitated health & safety reviews during design by allowing engineers and the client to perform virtual walk-throughs before the design was complete. The early input from a broad team resulted in changes to equipment and piping layouts that enhanced safety, operability, and accommodated other activities specific to the site.*

who do just that. Other BIM platforms have emerged in the marketplace as well, and the power to share data between applications is not limited to a single vendor. Another advantage of BIM is that it is a process rather than a software. A workflow centered around BIM is a collaborative framework on which we build our designs using many different software packages that can then interact with one another. With BIM, the real magic is in the communication. Team members around the globe can work on a design simultaneously without passing files back and forth, breaking and re-establishing links, managing version control, or updating innumerable sheets and tables every time there is a design change. Design elements created with different software can share data, so each remains current throughout design. This comes as relief for any steadfast professional working on a Friday because of a last-minute design change, or waiting patiently to receive that Friday deliverable, wondering why that simple change is taking so long!

Following in the footsteps of large capital projects that came before us, we can now incorporate just about all the data we will need to design, procure, construct, and operate a remediation system on the front end. A digital twin. Data sharing between mass balances and design templates enables engineers to workshop various layouts early and collaborate real-time with clients and colleagues. Piping and instrumentation diagrams (P&IDs), mechanical arrangements, and site development plans are getting smarter and can contain information about equipment, processes, and site features. That information is stored and managed in BIM where it can be used during future phases of the design without additional handling. Layout drawings are completed in a 3D environment with each discipline collaborating in a single place to avoid interferences. Digital imagery can be pulled in and combined with design elements and topographic data to create stunning pictures and videos that speak to diverse stakeholder audiences, improving the expediency and quality of feedback early in the design process. If there are late-stage design changes, the most cumbersome of those can be addressed in the 3D environment where they will automatically trickle down through the 2D sheets that are automatically generated from the model.

When a design advances into procurement and construction planning, BIM excels there as well. The equipment and infrastructure information and other design details that the engineers have populated along the way is available to generate supporting documents for bid administration, such as equipment lists and construction takeoffs. Cost information can be used to inform cost estimates, and the costs will update as the design goes through revisions. Construction sequencing and scheduling information can do the same for construction planning and implementation. And once the system is running, operation data can be used to create a true digital twin model. Standardization and automation concepts enhance these features even more.

Figure 3: Dredged material processing facility for solids handling and water treatment. *The BIM model for this 60% design was created using Autodesk® BIM 360®, Revit®, Civil3D®, Navisworks®, and InfraWorks®. The model is used to visualize how the system fits within the space constraints. Existing aerial imagery was incorporated with the design elements added, bringing the entire project to life. A flyover video of the model was developed to efficiently show the entirety the design. During design development visualization allowed the design team to collaborate seamlessly in the cloud.*

Arcadis has written previously about digital twin models in remediation (Horst et. al. 2017, Horst et. Al. 2020). Though many of the problems identified during early attempts to digitize remediation (fragmentation, lack of platform synchrony, and resistance to adoption by stakeholders and practitioners) will continue to challenge us as technology changes and improves, we have reached a tipping point in remediation design engineering. The tools have matured, engineers are embracing the improvements in quality and efficiency resulting from these new workflows, and we are delivering a better product to our clients. Remediation systems are different from large capital engineering projects. They often play a supporting role during a single phase of the remediation lifecycle, acting simply as a tool to implement our most innovative remediation technologies. Bringing our expertise together with BIM and removing limitations on how we work with data facilitates a dynamic, collaborative process that can help remediation systems shine in their modest role. A well-designed remediation system is right sized for its purpose, appropriately simple or complex, fits within its surroundings, and operates smoothly enough that one could be forgiven for periodically forgetting it's out there diligently cleaning up after us. It brings our ideas to life and quietly makes the world a better place.

About the author

Jon Spitzinger, PE is an Associate Vice President and Design & Engineering Service Leader for the Environment Business Line in North America. He leads the Engineering & Treatment Systems (ETS) Community of Practice. ETS provides clients with technical leadership, multidisciplinary engineering services, and design management to ensure that the appropriate protocols for discipline and inter-discipline review of work products are established and implemented, and that the design work in general meets applicable industry, Arcadis, and client standards.

Poly- and Perfluoroalkyl Substances (PFAS): Emerging contaminants driving rapid innovation

Allan Horneman and Joseph Quinnan

The group of chemicals known as poly- and perfluoroalkyl substances (PFAS) are a very diverse class of “manmade” chemicals, united by the common structural element of a fully fluorinated alkyl chain, known as the perfluoroalkyl group (typically two to 18 carbon atoms in length). The whole PFAS molecule may be either fully (per-) or partly (poly-) fluorinated, but each compound always contains a perfluoroalkyl group. PFAS are used in a wide range of industrial applications and commercial products due to their unique surface tension and levelling properties. These applications include stain repellents for textiles and carpeting, grease-proof paper, water- and oil-resistant coatings, and mist suppressants used in metal plating. PFAS are also components of the Class B (flammable liquid) firefighting foams known as Aqueous Film Forming Foam (AFFF), Film Forming Fluoroprotein Foams (FFFP) and Fluoroprotein Foams (FP).

The physicochemical properties of PFAS conferred by their high degree of fluorination and the strength of the carbon-fluorine bond lead to unique partitioning behavior (i.e., both hydrophobic and oleophobic properties) and thermal stability. These same molecular features also result in extreme recalcitrance and resistance to chemical attack, making PFAS extremely difficult to remove and destroy using conventional water or soil treatment technologies.

As opposed to perfluoroalkyl substances, polyfluoroalkyl substances comprise compounds that are susceptible to abiotic and biological transformation, forming perfluoroalkyl acids (PFAAs) as terminal products. As a result, these compounds are often called PFAA precursors. The polyfluorinated compounds represent a much larger group of chemicals than the PFAAs, and most of them cannot currently be directly measured by conventional laboratory analytical methods that quantify PFAA (Figure 1).

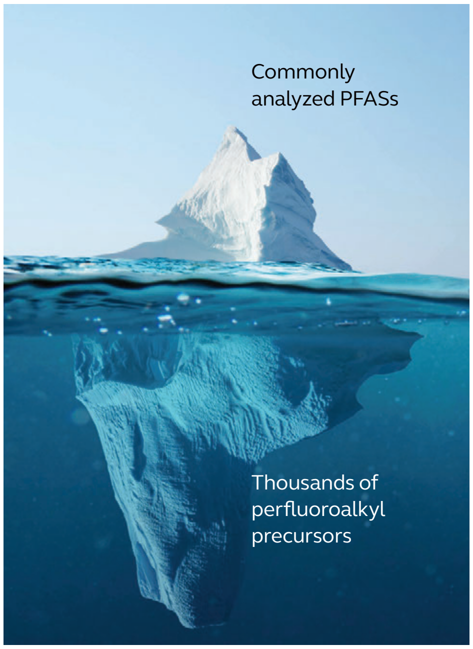


Figure 1: *Standard analytical methods only allow us to see the tip of the iceberg.*

In recent years, concerns around the human health impacts of certain PFAS have substantially increased the awareness and scrutiny of this class of chemicals as more is understood about their toxicity, environmental persistence, and potential to bioaccumulate. Regulatory agencies in North America and around the world are setting limits for select PFAS compounds in drinking water, especially perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA); however a broader group of PFAS are being regulated in several states, both as individual compounds, but also as summed concentrations. In addition to drinking water, states, and to some extent, the federal government are developing or have developed regulations targeting groundwater, surface water, soil, biosolids, Toxic Release Inventory (TRI), air emissions, as well as the general use of PFAS in products, including AFFF. The rapidly evolving regulations and innovation around measuring and treating PFAS make it difficult to chart the optimal management strategy for these chemicals. By examining our experiences working with PFAS from industrial, Federal, and public utilities perspectives,

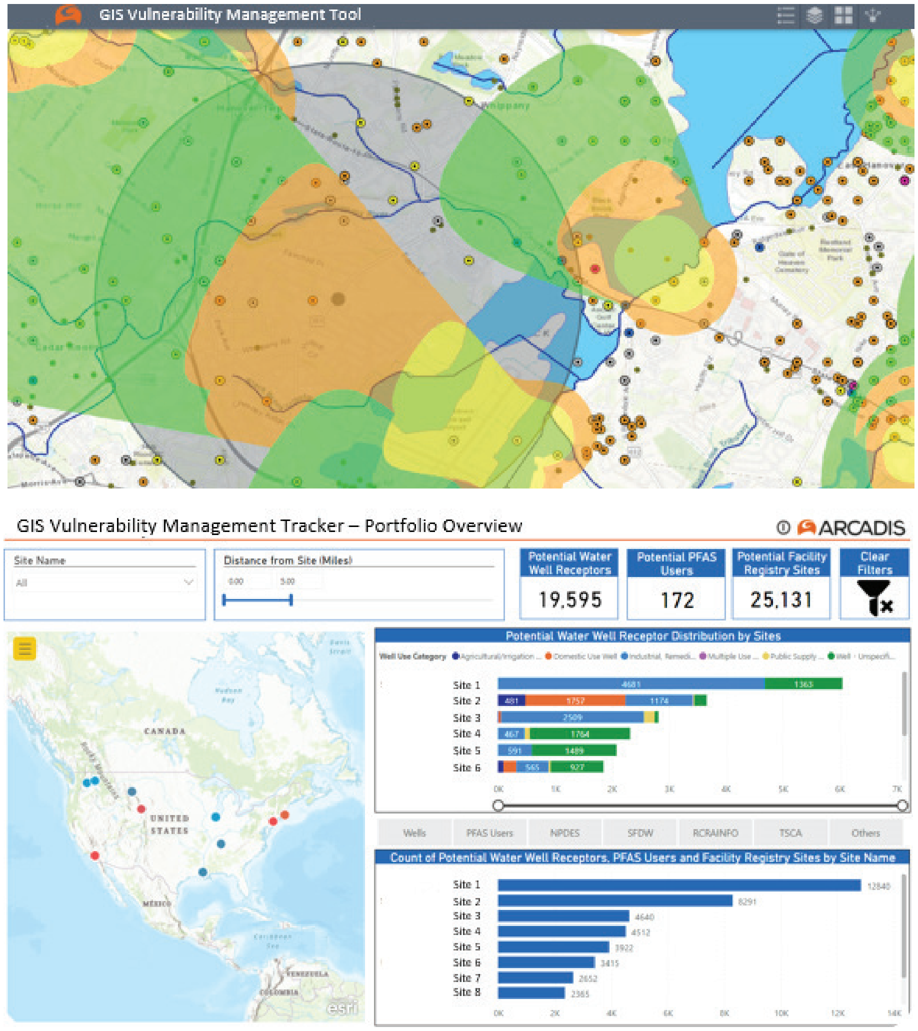


Figure 2: *Defining the "risk driver" PFAS allows transparent decision- making to define which PFAS are in need of treatment at each site and, thus, focuses the remedial objectives.*

we strive to increase stakeholders' abilities to manage PFAS impacts.

Arcadis has 18 years of history supporting clients navigating the challenges associated with PFAS. The early projects occurred in Northern Europe in the early 2000s and with the U.S. following reflecting the establishment of the EPA Health Advisory Limits (HAL) and PFAS in public and private water supplies throughout the U.S., and the resulting subsequent State regulations. Our PFAS services are underpinned by technical innovation understanding of our client's needs and objectives, and regulatory understanding.

Desktop evaluation and arcadis vulnerability management tool

Arcadis has performed desktop evaluations to support many clients' assessment of potential historical uses and releases of PFAS. The evaluations include review of manufacturing practices and products, chemical inventory, patent reviews and history, and potential storage or use of AFFF and typically focus on significant volume and or concentration. The evaluation is key in determining the need for potential environmental sampling and informing the sampling strategy, including where to sample.

Defining the "risk driver" PFAS allows transparent decision- making to define which PFAS are in need of treatment at each site and, thus, focuses the remedial objectives.

Arcadis developed its Vulnerability Management Tool (VMT) , which combines publicly available and client-specific information using geospatial analytics, to provide a visual summary of factors that may influence potential regulatory scrutiny, including municipal and residential drinking water wells, related PFAS data, well head protection areas; likely PFAS use based on industry use and discharge permits; and surface water classifications to understand drinking water and ecological receptors. The VMT is also used to support client's evaluation of their portfolio of sites, portfolio risk ranking, and support the client's decision process and investments through dashboards and PowerBi analytics. The VMT tool is scalable and customizable to meet your objectives and help you develop your PFAS plan. (Figure 2).

Site investigation, forensics and conceptual site models

Our team has performed several hundred PFAS investigations across the U.S. over the past 5 years, sites including DoD, municipal and public sector, industry, and solid waste sites and range from historical or active manufacturing sites, fire-training areas, and emergency response. No two sites are the same, and PFAS investigation requires an adaptive approach, including identifying the nature and location of the source and evaluating the presence or absence of potential risk to receptors, including drinking water and surface water. We have developed an investigation playbook based on years' of experience in high-resolution site characterization and flux-based conceptual models that can be tailored to meet individual client needs. The key elements include: integration with the VMT to understand locations of potential receptors during planning; early assessment of potential off-site migration pathways in groundwater and surface water to understand threats to receptors; source strength evaluations to rank and prioritize sources using mass loading from lysimeter porewater sampling, and stratigraphic flux to visualize migration pathways and focus remedies for cost-effective, efficient containment strategies. We developed a digital conceptual site model (digital CSM) application to streamline data analysis and collaboration with stakeholders, visualize data in three-dimensional models, and integrated PowerBI analytics to better understand trends – all designed to enable better decision making.

We are applying these techniques and the digital CSM to accelerate completion of four Air Force Phase I PFAS RIs (Buckley, Eielson, Ellsworth, and Peterson Air Force Bases) in less than 3 years, compared to a 5-year period of performance at typical RIs. The benefit is that stakeholders can make better decisions earlier in the remedial investigation process to ensure safe drinking water and take action to mitigate off-site migration. The application of stratigraphic flux provides flux-based transects at the downgradient perimeter and source strength assessment, which will enable environmental evaluation and cost assessment (EE/CA) activities sooner, including perimeter hydraulic containment and source removal to mitigate off-site migration. The Arcadis team is collaborating with DoD funded researchers at the University of Arizona in the Strategic Environmental Research and Development Program (SERDP) to collect data for use in vadose zone fate and transport modeling, which will enable stakeholders to develop site-specific soil standards to protect groundwater, rather than rely on conservative state and federal soil-to-groundwater pathway guidelines.

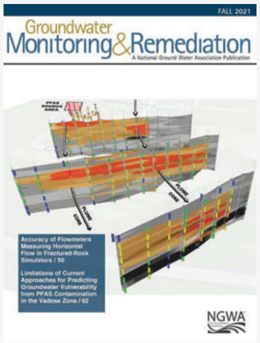
PFAS forensics lines of evidence

1. Hydrology
2. Spatial distribution
3. PFAS mixture or “fingerprint”
4. Linear vs branched isomers distribution

Forensics tools can provide important lines of evidence to distinguish PFAS impacts related to a facility from general background concentrations in a given region or in some cases to distinguish between impacts from different sources associated with different mixture of PFAS.

Foam transition

PFAS adhere to fire suppression system surfaces in contact with AFFF to form water resistant layers in foam systems. Replacing existing AFFF in foam equipment and suppression systems to fluorine free firefighting (FFF) foam requires removal of residual PFAS because these compounds can rebound into the replacement FFF foams causing contamination and a risk of continued environmental liability. Arcadis developed an effective biodegradable cleaning agent (FluoroFighter™) to remove PFAS buildup in fire suppression systems. Arcadis’ approach has been used at many commercial airports and industrial facilities throughout the world, leading to DoD-funded projects to demonstrate the cost and performance of FluoroFighter™ and our methods. Arcadis’ proven procedure for PFAS cleaning applications will remove PFAS by disrupting self-assembled layers on foam-wetted surfaces, providing assurance that PFAS impacts in newly installed foam are minimized. Using an effective cleaning agent in place of water reduces foam transition costs by reducing or eliminating time-consuming re-work, mitigating contamination of replacement foams and avoiding widespread component replacement.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Groundwater Monitoring&Remediation

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Accuracy of Flowmeters Measuring Horizontal Flow in Fractured-Rock Simulators / 50

Limitations of Current Approaches for Predicting Groundwater Vulnerability from PFAS Contamination in the Vadose Zone / 62

Arcadis’ ESTCP project ER19-5206 demonstrated the application of a PFAS mobile lab for real-time characterization of PFAS, enabling adaptive characterization of a PFAS source and groundwater plume at Camp Grayling in Michigan. The results of the project are summarized in the 2021 Remediation Journal article (DOI: 10.1002/rem21680) and detailed in the ESTCP Demonstration Report.

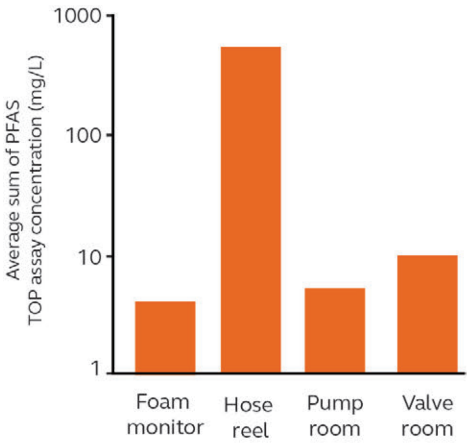


***Figure 3A:** Florine free foam following exposure to existing infrastructure with water only flushing during foam transition.*

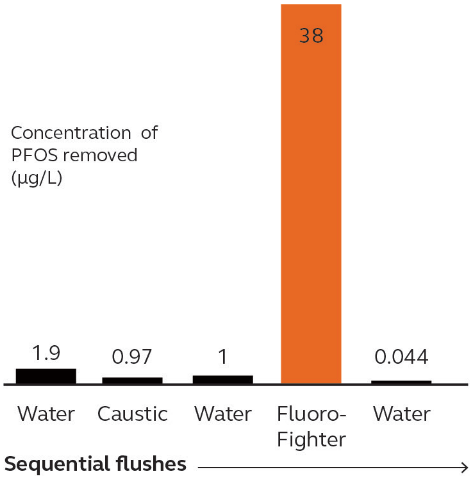


***Figure 3B:** FluoroFighter™ was most effective at removing PFAS from the AFFF impacted system.*

Innovation in remediation and PFAS destruction

The current state of the practice of remediation of PFAS is a treatment-train concept, primarily focused on reducing the treatment volume by concentrating the PFAS to be destroyed. This reduces the volume of waste requiring expensive treatment, which better matches the capabilities of these technologies. For water treatment, PFAS may be concentrated through adsorption or separation-based technologies: those technologies that exploit electrostatic and/or hydrophobic adsorption or partitioning to the gas-liquid interface. For soil treatment, PFAS may be concentrated through temperature-induced volatilization or through soil washing. Due to the extreme recalcitrance and mobility of the PFAAs, typical PFAS groundwater remediation entails transitioning from large-volume and low-concentration PFAS to more concentrated forms. This summary will explore optimization measures for adsorption-based remediation, highlight a case study using the emerging technology of fractionation to enhance the separation of PFAS from water, and lastly discuss promising destruction-based technologies for the residual waste stream. Relevant treatment technologies for soil and groundwater are presented on Figures 4A and 4B, respectively.

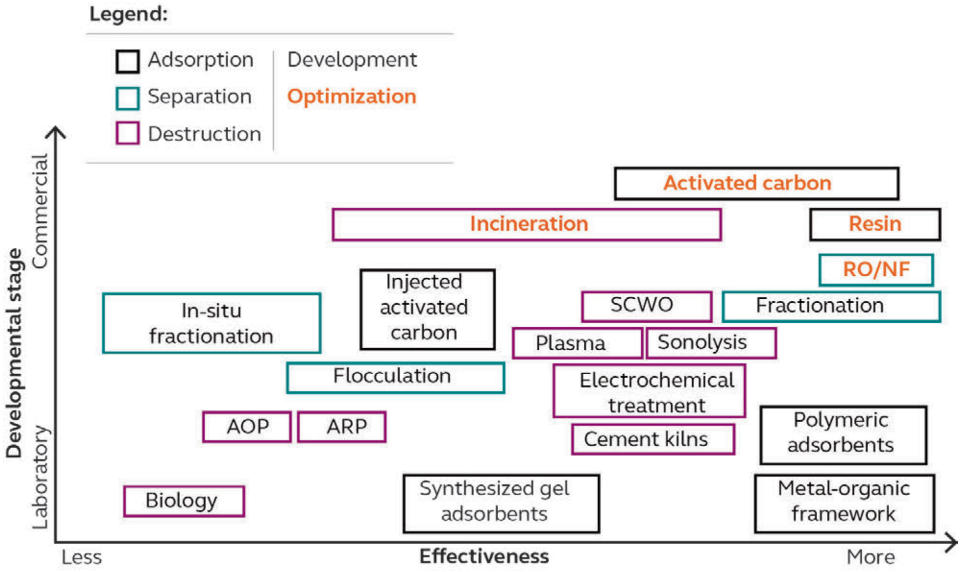


Figure 4A: *Treatment technologies for liquids*

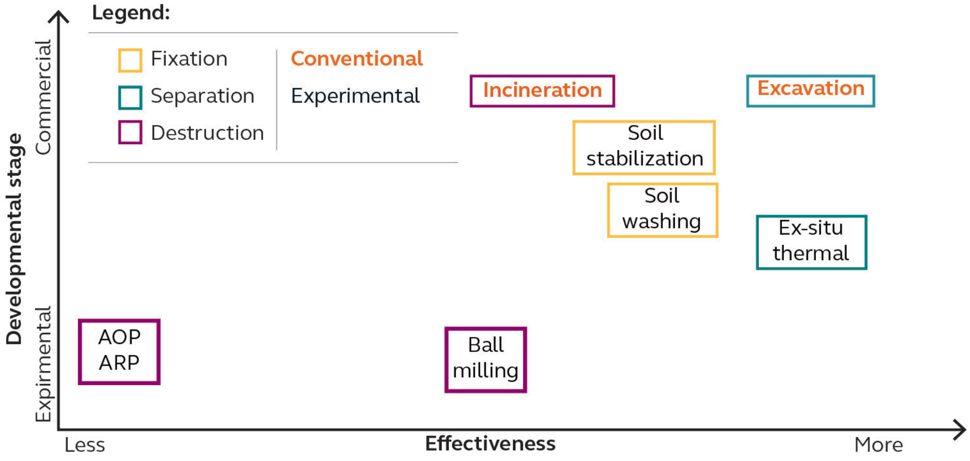


Figure 4B: *Treatment technologies for solids*

Adsorption-based removal of PFAS from water is currently being implemented using granular activated carbon (GAC) or ion exchange resins (IX), where GAC represents primarily hydrophobic adsorption, and IX can represent both hydrophobic and electrostatic adsorption. These conventional adsorption-based technologies are moderately effective at removing PFOA and PFOS from water. However, when it comes to the broader class of PFAS (including short-chain PFAA and variably charged polyfluorinated precursors), the effectiveness of these adsorption technologies is either reduced or largely unknown. For example, Dickenson and Higgins demonstrated that perfluorobutanoic acid (PFBA) was minimally adsorbed by GAC, with nearly immediate breakthrough, while Xiao et al. postulated marginal effectiveness of GAC to remove PFAA precursors. IX has demonstrated some affinity for short-chain PFAAs, but cationic and zwitterionic polyfluorinated precursor removal is largely unstudied in the literature. In typical anion exchange, anionic compounds are removed from solution through electrostatic adsorption, which is applicable to cations or cation- dominated zwitterions. Aside from the challenges and unknowns of adsorption- based removal of short-chain PFAA and PFAA precursors, the efficiency associated with PFOA and PFOS removal using GAC and IX typically results in less than favorable operation and maintenance (O&M) costs. The low to moderate affinity of PFOA and PFOS for the adsorbents and ppt removal targets can lead to unacceptable PFOA and/or PFOS breakthrough. Therefore, a focus on optimizing PFOA and PFOS removal using these conventional adsorbents is relevant. For example, natural organic matter (NOM) — often measured as total organic carbon (TOC) — may lead to faster breakthrough of PFOA and/or PFOS. In rapid small-scale column testing (RSSCT) conducted by Arcadis, an order-of-magnitude increase in TOC from 0.3 to 3 milligrams per liter (mg/L) resulted in a 75 percent reduction in throughput before breakthrough. Pre-treatment to remove NOM or change its interaction with GAC may improve PFOA and PFOS removal. For example, slight alkaline adjustments to the influent pH will deprotonate common organic acids while having no effect on the affinity of PFOA or PFOS for GAC. This imparts polarity on the organic acid, decreasing its affinity for the GAC.

Other optimizations for GAC include appropriately sized GAC vessels (Figure 5) for a given application, less-dense and equal- or better-performing forms of GAC (e.g., subbituminous coal versus bituminous coal), and increased mesoporosity (e.g., bituminous coal and over-activated coconut shell). Often, the capital cost of a GAC setup may influence the selection of the vessel size without consideration of more-frequent changeouts. Less- dense GAC that performs slightly better or equivalently to denser GAC can decrease the cost of changeouts because GAC is typically charged on a per-weight basis. RSSCT data generated by Arcadis and commercial laboratories suggests that a greater percentage of mesopores enhance PFOA and PFOS removal when compared to GAC with a greater percentage of microporosity. A comparison of capital expenditure and associated O&M costs considering the influence of variable concentrations of TOC is presented on Figure 6 and suggests that, over a 10-year operation period, 10,000-pound vessels have a comparable O&M cost and considerably fewer changeout disruptions than the 2,000-pound vessels. Although adsorption-based remedies are deployed rapidly, easily understood, and readily available, they come with a difficult-to-predict continuous O&M cost that needs to be considered and optimized.

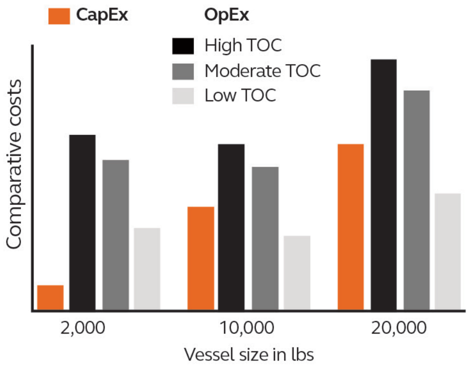


Figure 5: *10-year life-cycle costs comparing 2,000, 10,000 and 20,000 lb GAC vessels (two vessels each, installed lead-lag). Athough 10,000-lb vessels have a higher capital cost, (CapEx),there is a comparable O&M cost (OpEx) with far fewer GAC changeouts than the 2,000 lb vessels that may be advantageous in remote locations or where GAC changeouts cause disruptions to site activities. In addition, the influence of TOC removal on the O&M costs is clear, with considerable reductions in O&M costs for lower TOC concentrations.*

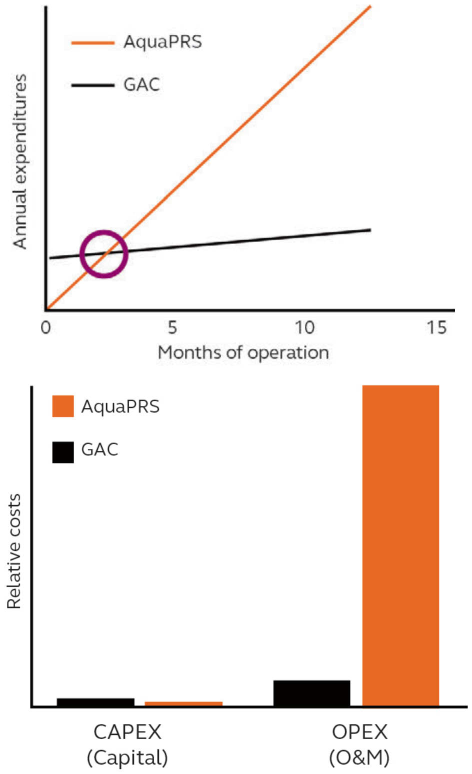


Figure 6: Cost assessment based on ESTCP results *Relative cost comparison of SPAC - CMF versus GAS for a 100 gpm system*
(HAGS water quality characteristics, 6,900 ng/L to <70 ng/L effluent PFOA + PFOS)

The 20-year lifecycle costs using HAGS Water Quality Characteristics and operation could be ***reduced by up to 90%, with a three month payback period.***

Recent advancement in application of Submicron Powdered Activated Carbon (SPAC) supports elevated efficiency for short chain removal relative to GAC as well significant long term cost reduction. Arcadis and Aqua Aerobic System Inc (AASI) conducted an ESTCP demonstration at Horsham Air Guard Station and the former Willow Grove Naval Air reserve station show cost and performance data similar to IX for PFAS-impacted groundwater, but with less pretreatment to avoid geochemical and biological fouling, due to the frequent wasting of the SPAC. AASI's AquaPRS automated system allows flexible operation by modulating the concentration of the SPAC in the reactor, allowing the system to be optimized as influent concentrations increase or decrease during operations. Due to its very high surface area to volume ratio, kinetics of adsorption are fast and provide ready access to meso and micro porosity. As a result specific sorbance rates are 100's if not 1,000's of times greater than GAC and similar to IX media.

The life-cycle cost comparison (Figure 6) for the Horsham site was developed by comparing GAC performance derived from RSSCTs and AquaAerobics pilot data scaled for a 100 gpm system of combined groundwater and surface water. Notably, the 100 gpm system would generate approximately 1,000 gallons of spent, concentrated SPAC through an automated wasting and concentration process. This enables the system to maintain greater than 99% uptime and dramatically reduces OpEx over the course of the 20-year life-cycle. Results for Willow Grove, which were based on 20 gpm treatment at approximately 30 ug/L PFAS concentrations from a bedrock groundwater source, showed significant savings compared to GAC and similar results to IX. Operation of dual-stage reactors in a lead-lag configuration enabled treatment to meet < 70 ng/L for the UCMR3 list of six PFAS at comparable cost and performance relative to treatment combining GAC and IX. Future evaluations will consider the AquaPRS system combined with IX to meet decreasing PFAS discharge requirements.

AASI continues to refine and scale the manufacturing of its AquaPRS media. Testing of a new version led to similar performance while reducing the production time by 90%. The final demonstration report and peer reviewed article summarizing the results will be available later this summer - contact us or visit the ESTCP website for more information.

Fractionation, has demonstrated the ability to remove >99.99 percent of total PFAS in a recent field-scale implementation in Australia. Fractionation exploits the physicochemical tendency of PFAS to partition to the gas-liquid interface, concentrating them in a resultant foam. The concentrated foam is separated from the treated water, achieving a reduction in the contaminated volume. Fractionation represents the state-of-the-practice treatment- train concept for PFAS removal from water by combining the foam fractionation step with an adsorbent or filtration polish with the intention of reducing the resultant volume for destruction and greatly increasing the concentration of the waste foam. Fractionation can be performed using air or ozone, or combinations of the two. A process flow diagram is provided as Figure 7.

Bench scale, pilot tests and full scale applications have demonstrated that under the right circumstances fractionation is effective as a stand-alone technology for low- to medium-flowrate applications and as an integral part of a treatment train for minimizing waste disposal costs by further reducing the volumes of high-concentration waste streams from membrane exclusion and filtration technologies. The volume reduction can be up to 99.5% with fractionation, reducing disposal or destruction costs significantly.

Full scale results from Australia are summarized in Table 1 and demonstrate >99.99 percent removal of PFAS using fractionation using ozone and nanofiltration polishing treatment.

PFAS	Influent (ppt)	Ozofraction removal	Filtration % removal	Treated water (ppt)	Total % removed
PFOS+PFHxS	535	98.13%	-	<2	99.63%
PFOA	341	97.07%	-	<2	99.41%
6:2 FtS	18,400	99.14%	96.84%	<5	99.97%
PFPeA	1,140	82.46%	99.00%	<2	99.82%
PFHxA	1,050	95.19%	95.00%	<2	99.81%
Sum PFAS	7,480	96.87%	99.15%	<2	99.97%
Total PFAS, TOP Assay	**28,800**	**98.58%**	**99.51%**	**<2**	**99.99%**

Table 1: *Full-scale ozofractionation system performance data.*

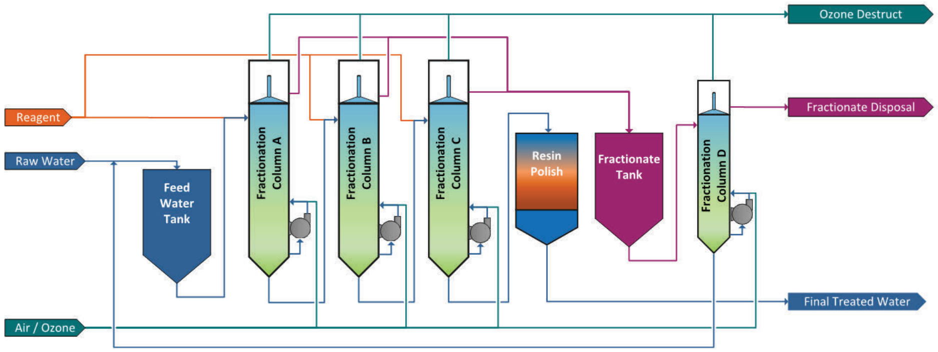
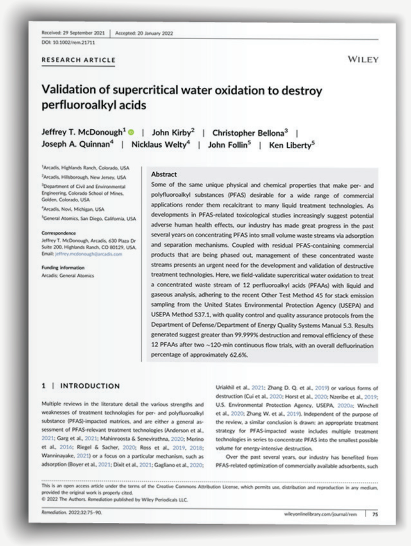


Figure 7: *Fractionalization process flow diagram. Image courtsey of EVOCRA Pty Ldt.*

After either adsorption-based or separation-based removal technologies have created a smaller volume, higher-concentration PFAS waste stream, the next step in the treatment process is destroying the concentrated PFAS waste. SCWO is a technology that has come out of the nuclear industry and involves exposing liquid to heat under high pressure and thereby lead to super critical conductance and enhancing heat conductance of steam and allowing for mineralization (destruction) of PFAS, including PFOS and PFOA. Arcadis collaborated with General Atomics to demonstrate the efficiency of SCWO for PFAS destruction (Figure 8). The supercritical water oxidation demonstration objective was to treat a concentrated waste stream of 12 perfluoroalkyl acids (PFAA) with liquid and gaseous analysis, adhering to the recent Other Test Method 45 for stack emission sampling from the United States Environmental Protection Agency (USEPA) and USEPA Method 537.1, with quality control and quality assurance protocols from the Department of Defense/Department of Energy Quality Systems Manual 5.3. Results generated suggest greater than 99.999% destruction and removal efficiency of these 12 PFAAs after two ~120-min continuous flow trials, with an overall defluorination percentage of approximately 62.6% and supporting the utility of the destruction method.

Other destruction mechanisms being explored include chemical reduction and defluorination of PFAS via direct electron transfer to PFAS that have affixed themselves to an anode in an electrochemical cell. Some challenges associated with electrochemical treatment include high energy demand; long treatment residence times; secondary water-quality concerns such as the formation of perchlorate,



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RESEARCH ARTICLE

WILEY

Validation of supercritical water oxidation to destroy perfluoroalkyl acids

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Funding information
Arcadis; General Atomics

Abstract

Some of the same unique physical and chemical properties that make per- and polyfluoroalkyl substances (PFAS) desirable for a wide range of commercial applications render them recalcitrant to many liquid treatment technologies. As developments in PFAS-related toxicological studies increasingly suggest potential adverse human health effects, our industry has made great progress in the past several years on concentrating PFAS into small volume waste streams via adsorption and separation mechanisms. Coupled with residual PFAS-containing commercial products that are being phased out, management of these concentrated waste streams presents an urgent need for the development and validation of destructive treatment technologies. Here, we field-validate supercritical water oxidation to treat a concentrated waste stream of 12 perfluoroalkyl acids (PFAAs) with liquid and gaseous analysis, adhering to the recent Other Test Method 45 for stack emission sampling from the United States Environmental Protection Agency (USEPA) and USEPA Method 537.1, with quality control and quality assurance protocols from the Department of Defense/Department of Energy Quality Systems Manual 5.3. Results generated suggest greater than 99.999% destruction and removal efficiency of these 12 PFAAs after two ~120-min continuous flow trials, with an overall defluorination percentage of approximately 62.6%.

1 | INTRODUCTION

Multiple reviews in the literature detail the various strengths and weaknesses of treatment technologies for per- and polyfluoroalkyl substance (PFAS)-impacted matrices, and are either a general assessment of PFAS-relevant treatment technologies (Anderson et al., 2021; Garg et al., 2021; Mahinroosta & Senevirathna, 2020; Merino et al., 2016; Riegel & Sacher, 2020; Ross et al., 2019, 2018; Wanninayake, 2021) or a focus on a particular mechanism, such as adsorption (Boyer et al., 2021; Dixit et al., 2021; Gagliano et al., 2020; Uriakhil et al., 2021; Zhang D. Q. et al., 2019) or various forms of destruction (Cui et al., 2020; Horst et al., 2020; Nzeribe et al., 2019; U.S. Environmental Protection Agency, USEPA, 2020a; Winchell et al., 2020; Zhang W. et al., 2019). Independent of the purpose of the review, a similar conclusion is drawn: an appropriate treatment strategy for PFAS-impacted waste includes multiple treatment technologies in series to concentrate PFAS into the smallest possible volume for energy-intensive destruction.

Over the past several years, our industry has benefited from PFAS-related optimization of commercially available adsorbents, such

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Remediation. 2022;32:75–90. wileyonlinelibrary.com/journal/rem | 75

Validation of supercritical water oxidation to destroy perfluoroalkyl acids

In this research article, we field-validate supercritical water oxidation to treat a concentrated waste stream of 12 perfluoroalkyl acids (PFAAs) with liquid and gaseous analysis. Results generated suggest greater than 99.999% destruction and removal efficiency of these 12 PFAAs.

Download the article for the full results.

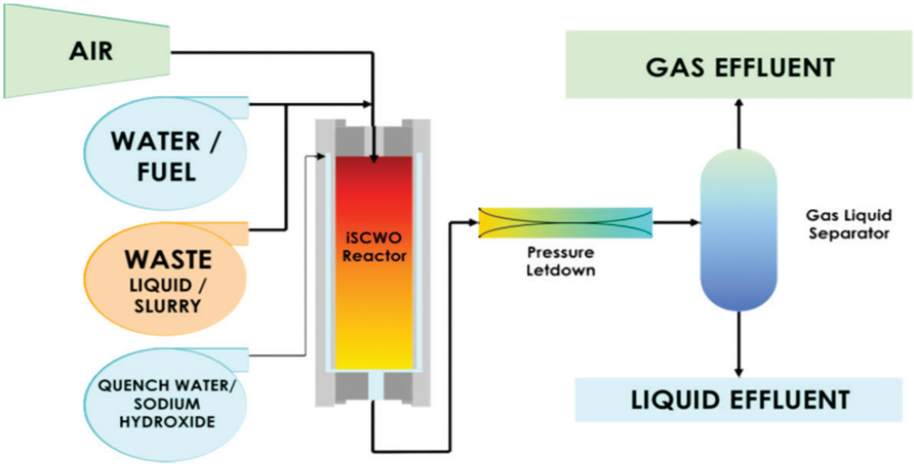

Figure 8: *Arcadis collaborated with General Atomics to demonstrate the efficiency of SCWO for PFAS destruction. Graphic used with permission from General Atomics.*

hexavalent chromium and bromate, acid based adsorption of PFAA to the anode masking true destruction, and reduced effectiveness on partially defluorinated daughter products.

Sonolysis is another form of destruction-based treatment. Sonolysis, as it relates to PFAS treatment, is the creationof microbubbles generated through ultrasound application to water. The successful rarefaction and compression of the microbubbles leads to cavitation, which can facilitate generation of point sources of plasma at temperatures over 5,000 degrees Kelvin, as the bubbles collapse. The heat generated is not transmitted efficiently to the aqueous matrix, so the system can be maintained at 35 degrees Celsius, with little energy needed for cooling. PFAS partition to the gas-liquid interface of the microbubbles and, upon the plasma- associated bubble collapse, are destroyed through pyrolysis. Some challenges associated with sonolysis include high energy demand, long treatment residence times, interferences from co-contaminants and dissolved ions, and the complexities of reactor scale- up using multiple transducers. While destruction-based technologies exist for handling the low-volume concentrated PFAS wastes, it is clear their field-scale practicality is still under development.

Degradation of PFAS using biological and conventional chemical treatments is very challenging due to the strength of C–F bonds.

Soil Remediation

PFAS-impacted soil remediation options are expensive due to restrictions on landfilling, which often requires significant transport cost to specialized Sub-Title C facilities, zero-net-discharge landfills in arid climates, or specialized Sub-Title D facilities with PFAS leachate treatment. The Congressional moratorium on incineration, resulting from the National Defense Authorization Act (NDAA) 2020, prohibits DoD from incinerating PFAS-containing materials until the USEPA certifies these facilities, further limits options for stakeholders. However, emerging technologies offer stakeholders cost-effective options for managing PFAS-impacted soils.

In-situ Stabilization (ISS)

Arcadis demonstrated soil stabilization using chemical fixants, which limit leaching in soils and enable stakeholders to manage treated soils on-site. The technical approach was validated through AFCEC's broad agency announcement (BAA) research program that tests ISS using commercially available fixants (Rembind™ or FluoroSorb™). Testing compared various mixtures of fixants with a Portland cement control. The results indicate that the fixant process results in stable conditions, with PFOA and PFOS leaching values less than groundwater screening levels after two years of monitoring; however, minimal reduction in leaching was observed in the cement control plot. The results are documented in the ACS Omega Journal article. With USEPA's consideration of hazardous substance designation for PFOS and PFOA, and concerns about incineration, on-site stabilization provides a cost-effective management alternative. Additional testing is ongoing at Air Force facilities to verify the cost and performance of in-situ stabilization.

Soil washing treatment steps:

1. Feed soil into plant, add process water
2. Gravel separated, dewatered and stockpiled
3. Soil flows through to mixing tanks for PFAS desorption
4. Cyclone separates the sand and fines
5. Sand dewatered and stockpiled
6. Fines sent to thickener, dewatered and stockpiled
7. Process water treated using GAC and IXR and recycled

Soil Washing

Soil washing has been used for volume reduction since the 1980s and 1990s, when USEPA demonstrations applied variations of the technology to treat PCBs, metals, pesticides and radioactive materials. The basic idea is to use a combination of physical separation (size, density, and magnetics) and chemical leaching to treat the coarse fractions and separate the fines and organics, for alternative treatment. Arcadis ESTCP ER20-5258 demonstration applied CleanEarth Technologies' soil washing approach to optimize treatment of PFAS-impacted soils. Soils from an AFFF source containing 3 mg/kg PFOS and two construction-related stockpiles with approximately 100 ug/kg and 30 ug/kg were treated at the bench. Results demonstrated that a simple physical separation with water-based attrition scrubbing was sufficient to meet Alaska DEC's soil-migrating-to-groundwater standard of 3 ug/kg for PFOS and 1.7 ug/kg for PFOA. The AFFF source required application of additional chemical reaqents and physical treatment; however, the soil met ADEC's standard and reduced leaching below the USEPA groundwater screening value of 40 ng/L for PFOA and PFOS.

The results of the soil washing demonstration are summarized in the upcoming Remediation Journal article in press and will be detailed in the final demonstration report, which will be published in September. Soil washing provides stakeholders a waste minimization approach that will be competitive with landfilling and thermal desorption. Varying degrees of PFAS impacts can be treated by tailoring the soil washing process to address low concentrations using a simple process or by adding additional reagents and physical processes to address AFFF sources. Depending on the stakeholder's objectives, the fines and organics can be landfilled, stabilized and managed on-site, or treated using a variety of thermal desorption approaches, if absolute minimization of waste is a priority.

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Joseph Quinnan, PE, PG, is the Global Director of the Arcadis Site Investigation Community of Practice and is co-author of Remediation Hydraulics. Joe has over 30 years' experience in site characterization, hydrogeology and remediation. He is Arcadis' DoD PFAS lead, supporting the Air Force, Army and Army National Guard programs. Joe is also principal investigator for several ESTCP demonstration projects including Validation of a PFAS Mobile lab and stratigraphic flux to visualize migration pathways, application of superfine poswered activated carbon and ceramic membrane filter to treat PFAS-impacted groundwater, and soil washing to treat PFAS adsorbed to AFFF source soils.

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1,4-Dioxane: An increasing number of innovative treatment technologies

Caitlin Bell and Monica Heintz

1,4-Dioxane

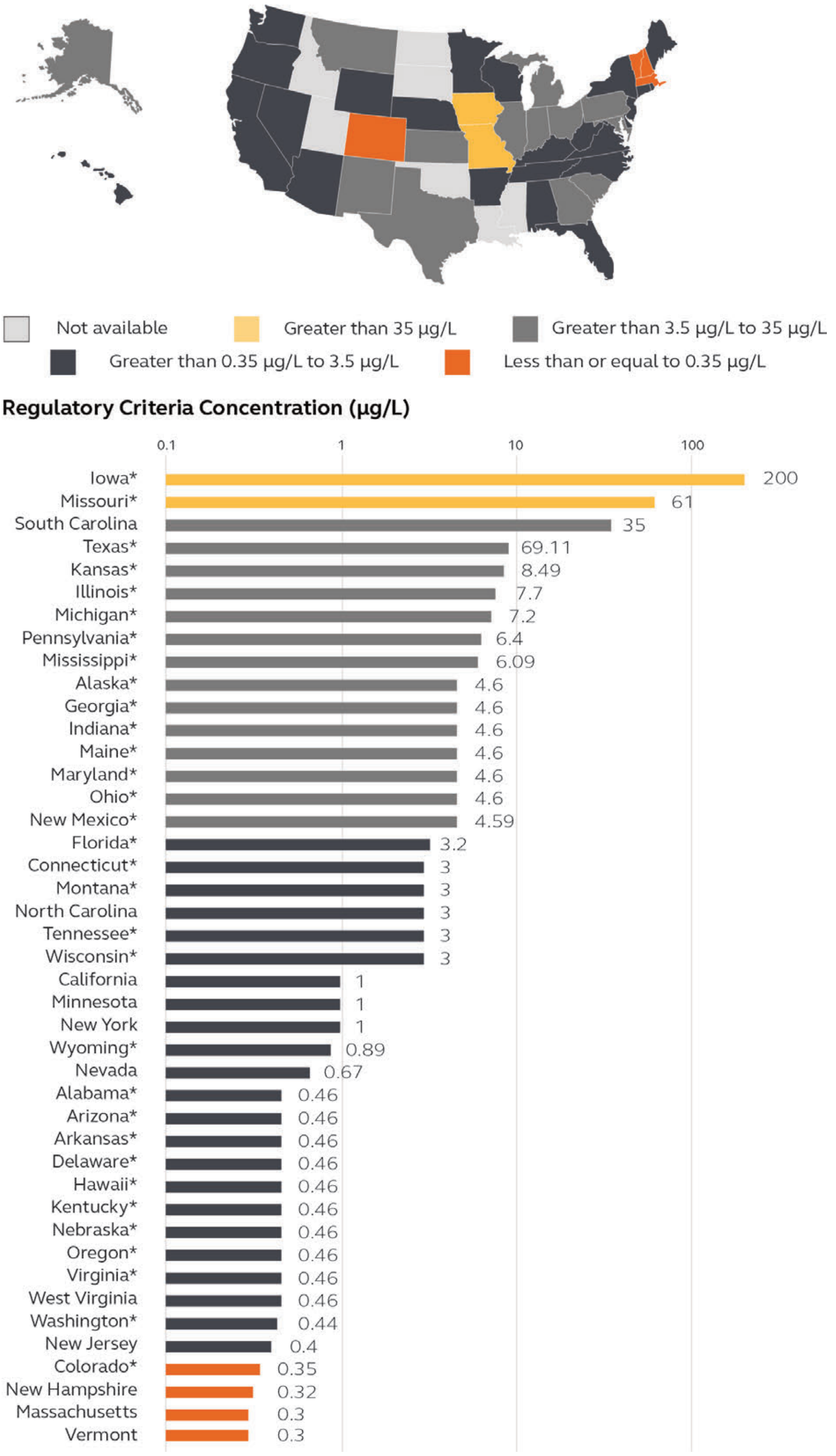
Caitlin Bell and Monica Heintz discuss treatment options for 1,4-dioxane and highlight Arcadis' recent advancements into bioremediation treatment technologies.

6 minute podcast

1,4-Dioxane is an emerging contaminant that is a growing concern. It is present in a substantial number of water supply sources and has entered groundwater aquifers. Concern over the presence of 1,4-dioxane in drinking water has led to increased scrutiny, regulation, and legal action. Historically, advanced oxidation processes (AOPs) have been the presumptive ex situ treatment strategy, but they come with significant capital and operational costs. Bioremediation is quickly becoming an attractive, sustainable, and economical alternative. Arcadis is leading the industry in attaining site closure under natural attenuation strategies, application of advanced analytical tools to demonstrate 1,4-dioxane treatment, implementation of in situ bioremediation approaches, and innovating with ex situ bioreactors that are expected to become attractive retrofit options for existing groundwater treatment systems. A changing regulatory landscape and liability uncertainties have prompted many Arcadis clients to consider assessing 1,4-dioxane risk across their site portfolios – a proactive management strategy that saves both money and corporate reputation.

1,4-Dioxane occurrence and regulation

Most 1,4-dioxane has historically been used as a stabilizer in chlorinated solvents (specifically 1,1,1-trichloroethane). Increased awareness has revealed that 1,4-dioxane is also a byproduct of many manufacturing processes and is present in a variety of personal care products, detergents, and other commercial items. Its prevalence in industry and consumer products — and release into the environment — has led to its presence in nearly 20% of the large-scale public water supply systems tested by the United States Environmental Protection Agency. While a federal maximum contaminant level (MCL) has not been established for 1,4-dioxane, more than 40 states have developed drinking water or groundwater guidelines and promulgated standards (Figure 1). Additionally, states like New York passed a state MCL with New Jersey following suit. Unfortunately, these standards vary by over three orders of magnitude, complicating remediation and liability management decisions. Nevertheless, increased focus has resulted in regulatory mandates for investigation, remediation, or legal action against potentially responsible parties.



** Drinking water value not available; groundwater value provided for reference.*
For illustrative purposes; please verify local requirements.

Figure 1: *Illustrative examples of drinking water and groundwater 1,4-dioxane values.*

Increasing legal and regulatory drivers for 1,4-dioxane treatment have also been amplified by public concern, sometimes resulting in both fiscal and reputational consequences for responsible parties. This can be mitigated by combining an awareness of the regulatory climate, familiarity with potential liabilities within a portfolio, and adoption of a proactive management strategy.

1,4-Dioxane treatment options

Conventional drinking water and wastewater treatment processes often only remove a portion of the 1,4-dioxane present – typically less than 50%. Likewise, traditional groundwater treatment systems historically designed to remove chlorinated solvents via sorptive processes (e.g., granular activated carbon) and stripping processes (e.g., air strippers) are generally not effective at removing 1,4-dioxane. AOP has therefore been the most dependable and widely used 1,4-dioxane treatment technology, which entails a combination of powerful chemical oxidants and/or ultraviolet light that results in complete destruction of 1,4-dioxane. AOP implementation requires harsh chemicals, significant energy input, and can come with substantial capital and annual operational costs. While AOP has been the historical gold standard, other treatment methods are emerging – with bioremediation serving as a reliable, safer, sustainable, and economical alternative to AOPs.

Biodegradation of 1,4-dioxane occurs naturally and can be enhanced in engineered systems. 1,4-Dioxane biodegradation occurs metabolically and cometabolically. Understanding which mechanism is most applicable to a given site setting is critical to understanding how natural attenuation may be occurring and how best to deploy an engineered application.

Lines of evidence for natural attenuation

Plume stability

- Stable or decreasing 1,4-dioxane concentration trends over time
- Stable or shrinking plume size or plume mass

Geochemical evaluation

- Generally oxidizing geochemical conditions in groundwater
- Circumneutral pH
- Potential presence of primary substrates that could facilitate cometabolic biodegradation

Environmental molecular diagnostics and microcosms

- Presence/abundance of biomarkers for metabolic or cometabolic biodegradation
- Isotopic shift in ^{13}C and ^{2}H identified via compound specific isotope analysis
- Biotransformation of 1,4-dioxane to end products via ^{14}C assays
- Microcosms with site-specific media that show 1,4-dioxane biodegradation

***Figure 2:** Lines of evidence to consider when evaluating natural attenuation of 1,4-dioxane.*

Fundamentally, successful natural and enhanced bioremediation requires that microorganisms have what they need to mediate the biodegradation reactions of interest and that the co-residence times of the microorganisms, their substrates, nutrients, and the targeted contaminants are balanced.

This may occur naturally in some subsurface environments, and natural attenuation has been approved or utilized to achieve site closure at multiple sites. At some of these, a proactive management strategy provided enough historical data to demonstrate stable and decreasing 1,4-dioxane trends in groundwater and achieve closure.

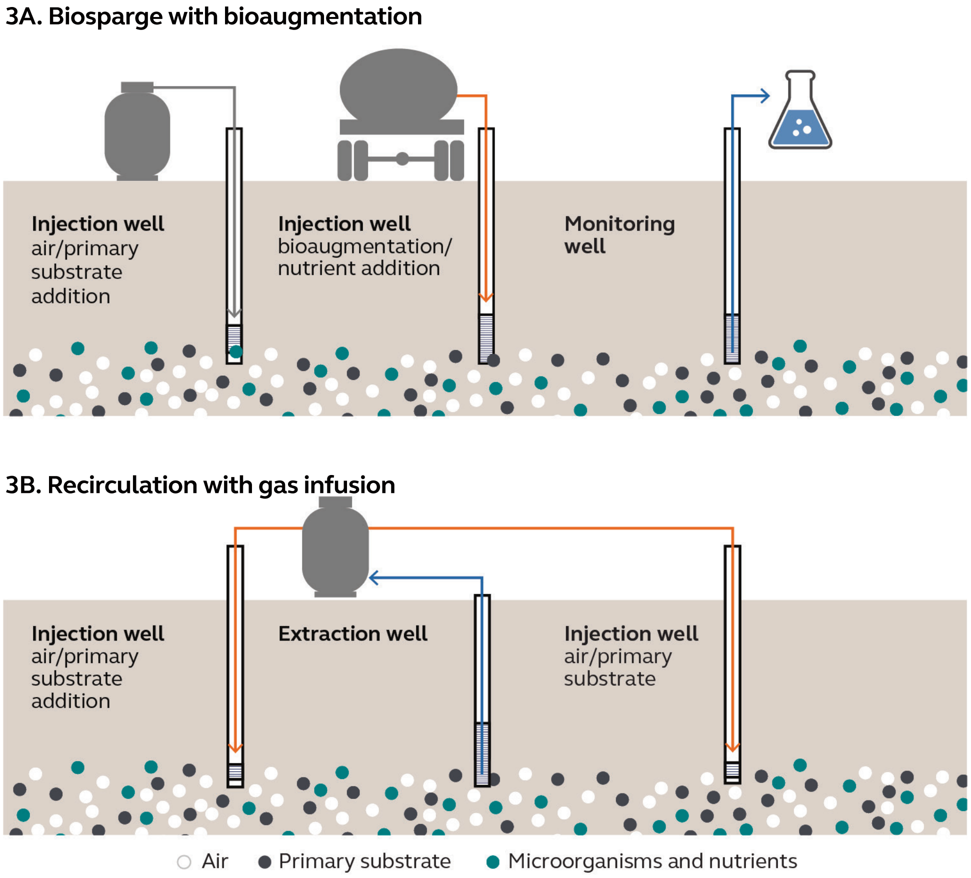


***Figure 3:** Conceptual depictions of multiple ways to deliver gaseous substrates to facilitate cometabolic biodegradation of 1,4-dioxane. Figure 3A depicts a gas sparging approach while Figure 3B depicts a groundwater recirculation approach.*

Beyond conventional geochemical methods to assess 1,4-dioxane biodegradation, emergent molecular diagnostic techniques now provide stakeholders with improved, low-cost sampling capability to provide supplemental lines of evidence and boost the case for natural attenuation (Figure 2). Recently, Arcadis partnered with the British Geological Survey to pioneer and apply a monooxygenase gene sequencing assay (EBNET project POC202029). This assay has been applied to samples collected at a variety of sites with 1,4-dioxane in groundwater to evaluate the abundance and types of these genes, providing an additional line of evidence for evaluating 1,4-dioxane biodegradation potential and insight into the microorganisms that may play an important role under different environmental conditions.

Where conditions are not favorable for natural attenuation of 1,4-dioxane, innovative in situ and ex situ engineered bioremediation systems may be cost-effective alternatives to conventional AOP.

For in situ bioremediation systems, the necessary microbial support components may be delivered directly to the subsurface (Figure 3A), or groundwater may be extracted, and the necessary components added before reinjection (Figure 3B). Because one (oxygen) or more (light hydrocarbon gasses for cometabolism) of the necessary substrates for 1,4-dioxane biodegradation is a gas, the most effective mechanism for in situ delivery must carefully consider site hydraulics and facility constraints.

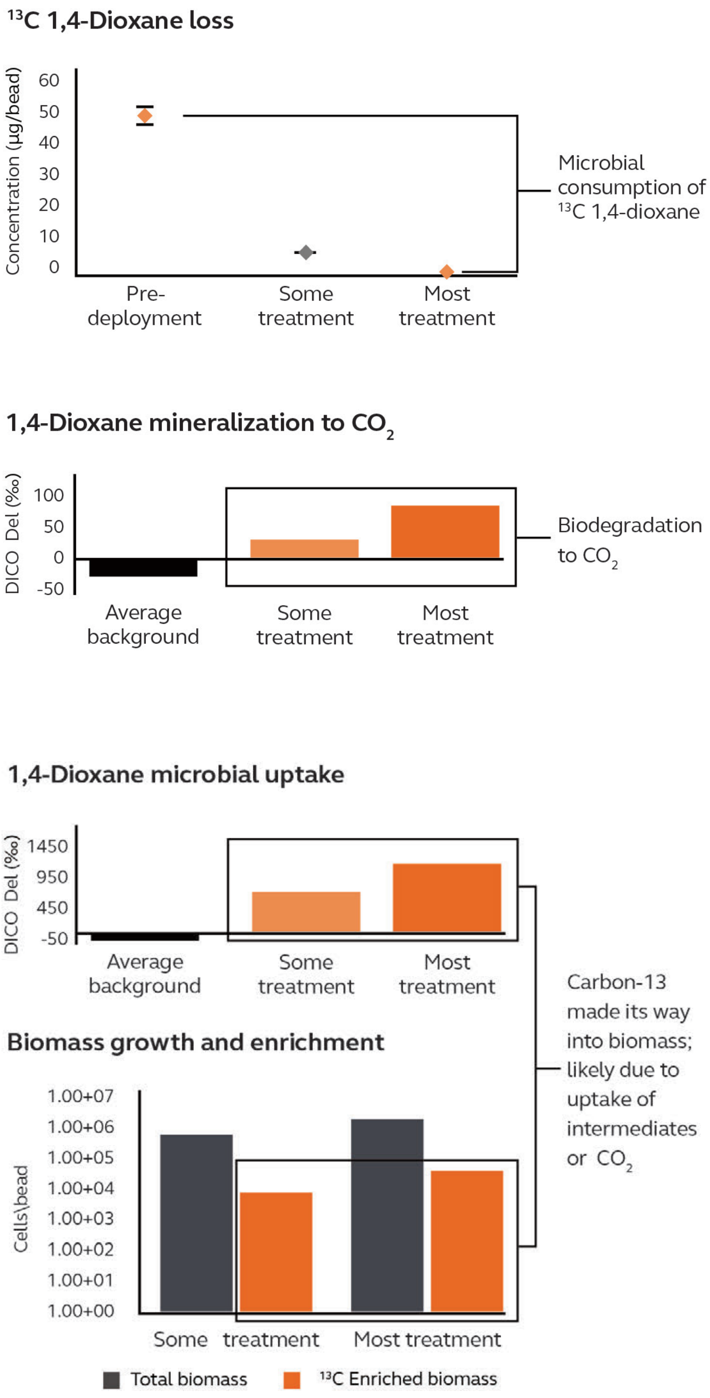


Figure 4: *Summary of stable isotope probing results during in situ propane biosparging. The location marked as "Most Treatment" was close to the biosparge point and saw ~83% reduction in 1,4-dioxane over the 2-month treatment period. The location marked as "Some Treatment" was further from the biosparge point and saw ~45% reduction in 1,4-dioxane over the 2-month treatment period. (Graphics adapted from those provided by Microbial Insights Inc.)*

At a site in California, Arcadis took the direct-delivery approach and sparged air, propane, nutrients, and a bioaugmentation culture into the subsurface treatment area to facilitate biodegradation of 1,4-dioxane, as illustrated in Figure 3A. This was the first full-scale application of in situ propane biosparging for biodegradation of 1,4-dioxane (Bell et al. 2022). For that project, Arcadis used stable isotope probing to confirm that biodegradation was a dominant treatment mechanism for 1,4-dioxane concentration decreases (Figure 4 and Bell et al. 2016).

At another direct-delivery site in Michigan, Arcadis treated 1,4-dioxane in a weathered, interbedded bedrock aquifer with biosparge points installed with emplaced sand lenses within bedrock fractures (Horst et al. 2019). Additionally, bench-scale studies with partners from UCLA explored the microbial community involved with the biodegradation of 1,4-dioxane at this site (Miao et al. 2021).

At many chlorinated solvent sites, existing ex situ treatment systems are already actively treating contamination that was historically identified, but often these systems were not designed with 1,4-dioxane in mind. Retrofitting existing ex situ treatment systems with AOPs is a typical reactionary response at sites where 1,4-dioxane was recently identified after years of system operation.

Other end-of-pipe treatment options include bioreactors, which may prove more cost effective than AOPs at certain flow rates and 1,4-dioxane mass loading. Additionally, conventional pump and treat systems can be reconfigured to become dynamic groundwater recirculation systems and effectively shorten remedial timeframes.

While there are fewer examples of ex situ bioreactors than in situ treatment systems, it is a technology that is rapidly developing (Cordone et al. 2016). The longest-running 1,4-dioxane cometabolic bioreactor is located at the Lowry Landfill and has been successfully operating since 2003.

Arcadis pilot tested two bioreactor configurations at a site in Michigan (Horst et al. 2019): one that relied on metabolic biodegradation of 1,4-dioxane, and one that relied on propane-mediated cometabolic biodegradation of 1,4-dioxane. Additionally, Arcadis has teamed up with Arizona State University and APTwater to develop and field-test a membrane biofilm reactor (MBfR) that provides both oxygen and propane for cometabolic biodegradation of 1,4-dioxane (ESTCP project ER22-7226). This work is expected to provide a stable bioreactor configuration that consistently and efficiently removes 1,4-dioxane from water.

Concluding thoughts

1,4-Dioxane is a growing concern for clients across multiple market sectors. Anywhere chlorinated solvents were historically used may have an uncharacterized 1,4-dioxane problem – but potential liability risk cannot be assessed based solely on sites where chlorinated solvents were used.

The widespread presence of 1,4-dioxane in a variety of products and commercial applications has created an abundance of mechanisms through which 1,4-dioxane can be released to the environment. Its detection in municipal water supplies has also increased public scrutiny and concern, increasing attention and demand for management and remediation solutions.

Proactive management steps can be taken to understand applicable regulatory requirements and mitigate risk. Where necessary, proactive strategies also allow early identification of more innovative techniques to support natural attenuation demonstration, cost-effective remedy implementation, or system retrofitting and optimization to offset long-term cost.

About the authors

Caitlin H. Bell, PE, is a Technical Expert and 1,4-Dioxane Lead for Arcadis North America. She focuses on subsurface treatment of soil and groundwater using in situ techniques. Specifically, she focuses on in situ bioremediation applications for a variety of chemicals of concern, including emerging contaminants. She serves as a technical resource to clients on topics such as molecular biology tools, bioaugmentation, compound-specific isotope analysis, and challenging bioremediation approaches for compounds like 1,4-dioxane. Ms. Bell was author/editor of the 2019 Emerging Contaminants Handbook and a member of the team that authored the Interstate Technology & Regulatory Council's 2021 1,4-Dioxane Technical Guidance Document.

Dr. Monica Heintz has more than 15 years of academic and environmental consulting experience. She works at the nexus of groundwater hydrology, geochemistry, and microbiology to understand, manage, and mitigate environmental impacts. She specializes in application of environmental molecular diagnostic and statistical tools to understand, describe, and predict contaminant fate and distribution. She excels at conceptual site model and remediation strategy development for sites with complex constituent mixtures. Dr. Heintz was a member of the team that authored the Interstate Technology & Regulatory Council's 2021 1,4-Dioxane Technical Guidance Document. She currently leads 1,4-dioxane biodegradation research and development efforts for Arcadis North America.

Sweating the small stuff…and it's all small stuff

Connecting the dots for large plume restoration Part 1: The three-compartment model, *Smart* Characterization (HRSC) and DGR™ treatment

Scott Potter, PhD, PE and Marc Killingstad, PE

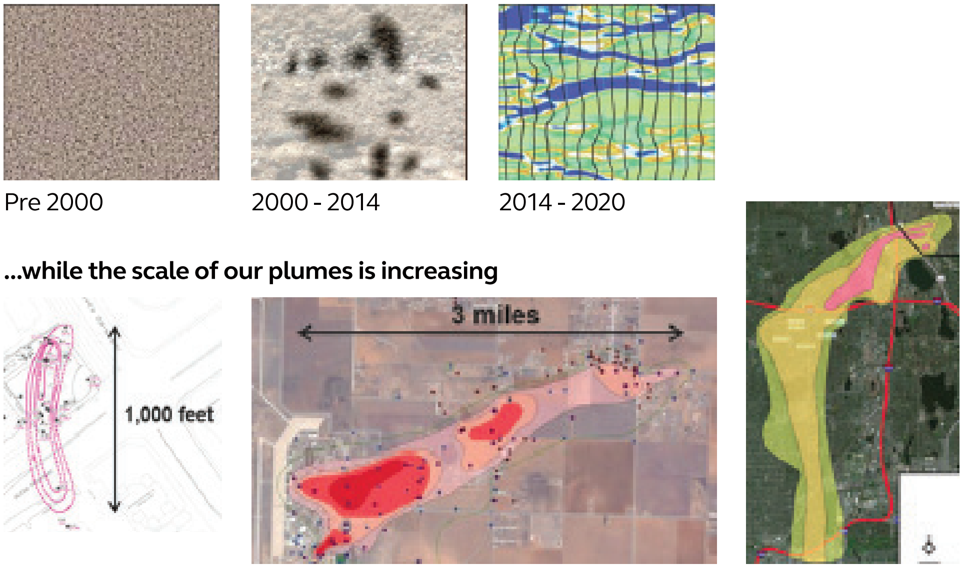
Contaminant transport in the subsurface is controlled by hydrological, microbiological, and geochemical processes that occur over scales ranging from the microscopic (sub-nanometer) to macroscopic (kilometer). The remediation industry has historically focused on the macroscopic impacts of these processes while 'blackboxing' the finer details that are essential to reducing treatment time, achieving remedy objectives, and reducing costs.

Successful (i.e., effective and efficient) remediation of an impacted aquifer requires an understanding of each of these processes and the ability to characterize the spatial variability of complex subsurface properties that control groundwater flow and contaminant transport. This knowledge, along with the application of predictive models that can assimilate the relevant processes over a range of scales, is needed to forecast the potential effectiveness of various remedial strategies. While this sounds intuitive, the ability to accurately predict finite remedial timeframes has been a great challenge for remediation professionals.

Subsurface behavior has typically been investigated using a reductionist approach where the details of small-scale processes (e.g., soil gradation or site depositional features derived from a soil boring) are generalized and then scaled up using simplifying assumptions to match field-scale behaviors (i.e., prediction scale). These simplified, lumped parameters can be conveniently incorporated into predictive tools (e.g., groundwater models),which were originally developed for regional potable water supply aquifer systems. While this approach has had some success, it lacks the nuance necessary to reliably simulate contaminant transport and predicting treatment response. Until recently, it has been impractical to obtain the multi-scale characterization data needed to adequately and objectively represent the subsurface environment to improve this approach.

We have seen significant advancements over the last 10 years in site investigation and characterization methods i.e., *Smart* Characterization/high resolution site characterization [HRSC]) as well as advective transport and storage zone concepts (i.e., development of an effective framework of the conceptual site model [CSM] for groundwater remediation). We have also seen a shift towards flux-oriented remediation techniques. When combined, these developments have provided a more realistic and detailed approach to mapping a contaminant's fate and transport in the subsurface, and more importantly, have increased the efficiency and reliability of our remedial strategies.

The data and information we collect is decreasing…



Pre 2000

2000 - 2014

2014 - 2020

…while the scale of our plumes is increasing

Figure 1: *The scale of site-specific investigations has decreased with evolving advanced technologies and at the same time the scale of the plumes we focus on has increased.*

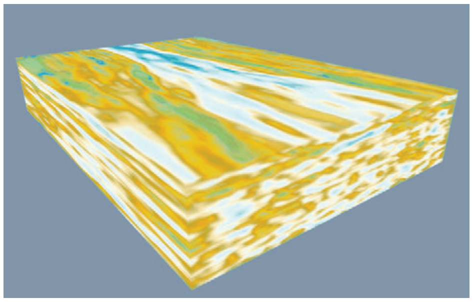


Figure 2A: *Three-dimensional depiction of variations in hydraulic conductivity and heterogeneous conditions within an alluvial aquifer. Blues and whites represent sands and gravels, and greens represent silts and clays.*

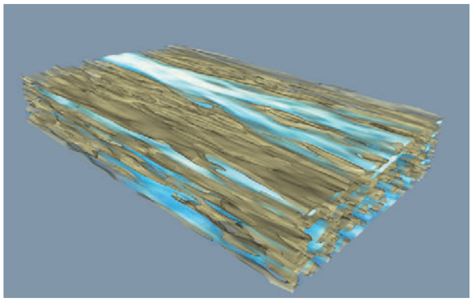


Figure 2B: *Highlights primary groundwater flow pathways (blue and white zones) and primary storage zones (brown and green zones) through the aquifer.*

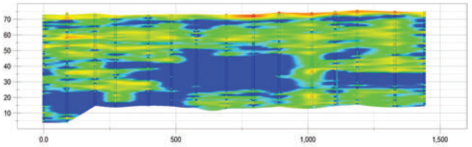
The three-compartment model: A new framework for focused

Over the last few decades, the scale of contaminant plumes has increased, while the scale at which we collect our subsurface data has decreased (Figure 1). We have evolved from applying simplified bulk averages and steady-state assumptions, to where we now collect high resolution data and consider transient behavior. We recognized that our CSMs and predictive tools needed to improve to better understand and explain the nuances and increased level of detail in the data being collected. More importantly, we realized that to develop appropriate remedial strategies and accurately predict their associated cleanup times, we needed to do a better job conceptualizing our sites and predicting contaminant transport behavior.

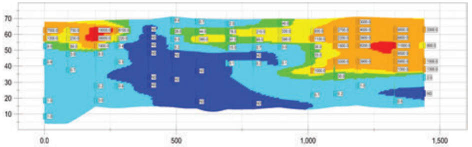
Before the start of the new millennium, practitioners believed that by reducing the complexity observed in soil borings into a simplified, but equivalent, homogenized model (representative elemental volume [REV]), we could adequately describe groundwater flow dynamics and make accurate predictions. Limitations with the REV were obvious (e.g., where projected treatment times for conventional pump and treat [P&T] remedies were exceeded by decades, accumulating ongoing annualized costs).

A clue to the solution was revealed in the early 2000s via advances in site characterization methods (e.g., tracer studies and high-resolution aquifer profiling), where we found that: (1) plumes were moving much faster than we initially thought; and (2) plumes do not get homogenized across the aquifer with distance. Instead, we saw that plumes move through networks of small-scale pathways of higher permeability consistent with the geologic processes that created the aquifer (Figure 2). It was obvious that the subsurface needed to be assessed at a scale smaller than the REV to incorporate these heterogeneities that control groundwater flow and contaminant transport.

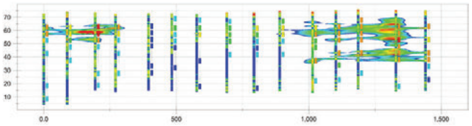
The dual-domain model (DDM), originally developed in the early 1960s but not fully embraced until the early 2000s, advanced our ability to represent heterogeneities in transport models by dividing the aquifer matrix into two compartments: one immobile and the other mobile with mass exchanged between the two via a transfer coefficient. While the DDM improved our ability to represent the fast- and slow-moving flow and transport processes and created a clearer distinction between the "bulk average" concepts of the REV and site-specific contaminant transport, it still simplified subsurface heterogeneity by lumping together a broad range of aquifer permeabilities.



Hydraulic conductivity



Concentration profile



Relative mass flux

Figure 3: *High-resolution mass flux profile through an alluvial aquifer showing the variations in mass flux across the cross section influenced by the networks and small-scale pathways within the transport zone (adapted from Suthersan et al., 2016).*

When we consider the findings of *Smart* Characterization/HRSC studies, though, this simplification becomes even more evident and has repeatedly shown that much of the transport occurs in only a small fraction of the cross-sectional area: typically, we find that over 80% of the contaminant flux occurs in less than 20% of the cross section. If the DDM held, that would mean upwards of 20% of the contaminant remains in storage (i.e., silts and clays) and accessible only via matrix diffusion occurring over a very long time or by implementing costly "brute force" measures to recover or destroy mass.

This view of the subsurface as a binary system of either transport or storage does not reflect the insights gained from *Smart* Characterization/HRSC: that the true range of permeability in the subsurface cannot be adequately represented by the DDM (or two-compartment model) (Figure 3). While high permeability sands and gravels acting as pure transport zones and low permeability silts and clays acting as pure storage zones is consistent with the two-compartment DDM model, we also know that intermediate permeability zones (interbedded sands/silts/clays) are prevalent in natural depositions. Some portions of these intermediate zones may be static; however, most of the groundwater is slowly moving but at rates far faster than the velocity of diffusion.

In other words, these intermediate zones do not act as pure storage zones. This small but important distinction offers an improved framework for developing more effective remedial systems and provides meaningful progress at sites where it was previously not thought possible.

These concepts form the foundation of our three-compartment model in which we divide the aquifer based on order of magnitude contrasts in groundwater flux (Figure 4):

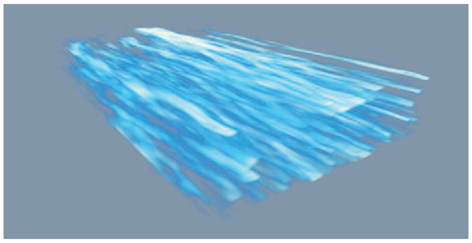
Compartment 1 (C1 or Q_{90}): where advection is the predominant transport mechanism and 90% of groundwater flux occurs (i.e., coarse-grained sediments/sands and gravels);

- Compartment 2 (C2 or Q_9): where slow advection is dominant, but diffusion has observable effects and 9% of groundwater flux occurs (i.e., mix of coarse-grained and fine-grained sediments/sands with silts and clays); and
- Compartment 3 (C3 or Q1): where transport is dominated by both diffusion and storage and 1% of groundwater flux occurs (i.e., fine-grained sediments/silts and clays).

In this framework, what we refer to as compartment 1 (C1) is the pure advection or transport zone and this is akin to the mobile domain in the DDM. This is where most of the groundwater flux occurs, about 90% (Q90). Realizing that what was previously considered the immobile domain in the DDM is not a 'pure' storage zone but that there is a portion participating in the advective process, we've defined that as compartment 2 (C2) which is our slow advection zone where both advection and diffusion processes participate in contaminant transport. This zone accounts for about 9% of the groundwater flux (Q9). Finally, we have what we'll call the 'pure' storage zone or compartment 3 (C3) – where diffusion rules. This accounts for about 1% of the groundwater flux through the aquifer (Q1).

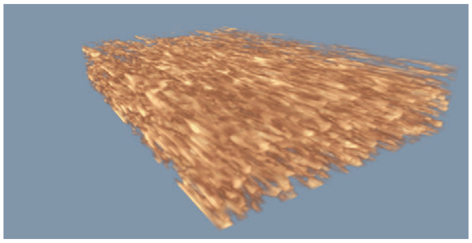
Because of contrasts in permeability, we see this model present in all aquifers.

Compartment 1 (C1or Q_{90})



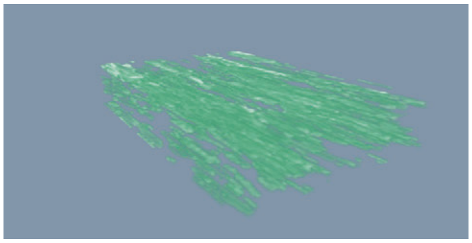
90% of groundwater flux; 55% of aquifer volume

Compartment 2 (C2 or Q_9)



9% of groundwater flux; 39% of aquifer volume

Compartment 3 (C3 or Q_1)



1% of groundwater flux; 6% of aquifer volume

Figure 4: *Separation of the aquifer depicted in Figure 2 demonstrating the three-compartment model of the subsurface aquifer architecture representing a realistic conceptual model of solute transport based on order-of-magnitude contrasts in groundwater flux: (C1/Q_{90}) pure advective/transport zones [sands and gravels] (C2 /Q_9) slow advective/storage zones [sands mixed with silts and clays], and (C3 /Q_1) pure storage zones [silts and clays].*

Dynamic Groundwater Recirculation (DGR™): A more focused remedial strategy

The three-compartment model helps explain what a monitoring well observes during remediation (Figure 5): initial improvements in water quality are due to flushing of C1 (pure advection), the tail is due to slow advection (mix of advection with diffusion) from C2, and the remaining portion of the curve is due to the slow diffusion of mass from C3. This tells us that if we can increase the flux through C2 (i.e., enhance flushing of slow advection zones), we can reduce the time to access impacted groundwater and achieve shorter cleanup times. But how can we leverage this knowledge?

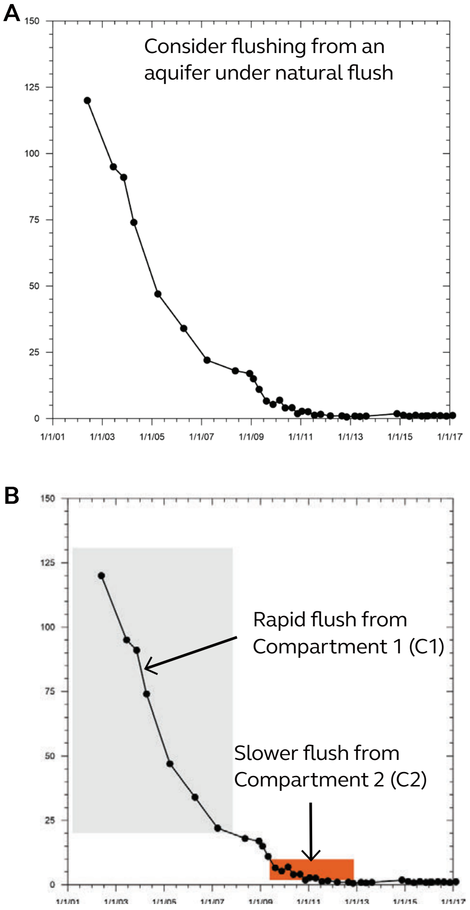


Figure 5: *Concentration declines in monitoring wells as contaminants are flushed from an aquifer (A) can be explained using individual segments to represent the sequential flushing of compartments over time (B).*

One solution has been found in looking at improving conventional pump and treat (P&T) systems. P&T is arguably the original groundwater remediation technology and continues to be widely used—particularly with the recent focus on emerging contaminants like 1,4-dioxane and per- and polyfluoroalkyl substances (PFAS) that aren't particularly amenable to in situ treatment technologies. However, P&T is really a strategy that works primarily to control rather than restore, and the central weakness of conventional P&T is that it tends to create fixed hydraulic conditions. This leads to development of stagnation zones and limits aquifer flushing to the primary transport zones (C1) while isolating other zones containing contaminant mass (C2), ultimately resulting in extended remedial timeframes.

However, by applying the three-compartment model, we believe that to successfully restore an aquifer, it is necessary to create dynamic conditions that mimic, even exaggerate, the natural variability that initially created the plume. In truth, aquifers are dynamic systems with groundwater levels rising and falling, transient shifts in groundwater flow patterns, and varying groundwater demands over time, all of which work to collectively spread contaminants within an aquifer. By strategically manipulating a combination of injection and extraction volumes and patterns in the subsurface, we can induce dynamic conditions and create differential hydraulic gradients between transport zones that will flush contaminant mass from the adjacent slow-advection zones (C2) to the advection zones (C1) where it can then be easily recovered (Figure 4). This is the basis for the enhanced flushing technology known as dynamic groundwater recirculation (DGR™).

The underlying concept is relatively simple: accelerate the influx of clean groundwater to enhance hydraulic and concentration gradients that, in turn, drive contaminant mass out of the aquifer via all advective pathways and diffusive gradients. Faster cleanup times can be achieved by strategically moving more pore volumes and manipulating gradients to increase mass flux/advective transport through C1 and C2 (transport and slow-advection zones, respectively). Furthermore, the clean water flushing through these two compartments works to enhance the mass transfer/diffusive transport of stored massed across C3 (storage zones), providing a means to overcome aquifer heterogeneities and the effects of matrix-controlled back diffusion.

To that end, the primary distinction between DGR™ and conventional P&T is this: DGR™ leverages site data to develop (1) an appropriate flushing framework, (2) a dynamic operation plan, and (3) an approach for continuous adaption based on remedial performance (i.e., data-driven adaptive management). The key to a successful DGR™ strategy is frequent system optimization by varying pumping/injection rates and locations in response to changes in performance data to accelerate the removal of contaminant mass while maintaining hydraulic control

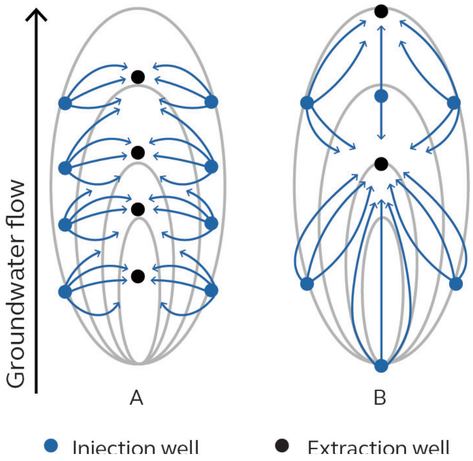


Figure 6: *Conceptual layouts of DGR with groundwater flow vectors. (A) 2:1 ratio of injection and extraction wells with injection along plume periphery and extraction in the core. (B) 3:1 ratio with injection within and along periphery and extraction within and downgradient.*

of the plume. Put simply, the goal of DGR™ system design and operation is to maximize contaminant mass removal by extracting within the most impacted portions of the plume while strategically injecting clean water to enhance flushing and drive contaminants toward extraction wells (Figure 6).

When properly designed and operated, DGR™ can be a highly effective remedial technology that significantly advances conventional P&T applications of the past—in some cases, existing P&T systems can even be re-engineered to a more effective DGR™ remedy. It provides an efficient way to manage treated water while maintaining water levels, reduces time required for remediation through enhanced flushing, and, most importantly, can achieve endpoints that were previously considered virtually impossible to reach—particularly for large, diffuse plumes.

Large plume restoration: Success where remediation was once considered impossible

Large plume is a term that covers a wide range of contaminated aquifer scenarios but, in our definition, a large plume can be characterized as one that:

- Occurs in a reasonably productive aquifer with the potential to transport dissolved contaminants over large distances;
- Consists of contaminants that do not sorb to the aquifer matrix and are not quickly degraded (chemically or biologically) under natural aquifer conditions; and
- Develops from a large enough source mass (or multiple sources) to generate a large volume of impacted groundwater that exceeds regulatory criteria.

While there has been steady progress moving small plume sites to closure through improved technology (e.g., transition to in situ reagent-injection programs) and institution of risk-based regulatory standards over the last 20 years, there has been little advancement for large plumes, and the total inventory has increased with establishment of regulatory guidance for emerging contaminants (e.g., PFAS). The remedial approach to large plumes has historically been conventional P&T and, as we have outlined in this article, this strategy can contain large plumes but often does not accelerate aquifer restoration. In fact, conventional P&T can extend remedial timeframes in costly ways.

In the late 1990s, as part of a performance-based contracting program, we committed to achieving closure for several large plume sites, and we recognized early on that to meet these commitments, the traditional approach to large plumes had to be abandoned.

First, we re-examined our understanding of contaminant transport and storage in aquifers. Next, we needed to develop and apply cost-effective characterization strategies and tools to support the improved science of remediation hydrogeology (i.e., introduction of *Smart* Characterization/HRSC). Finally, we needed to create and test technologies that could remediate large plumes cost-effectively.

Through this process we learned that, because of the wide range of soil permeabilities found in even the simplest geologic settings, groundwater flow (and contaminant flux) occurs in a very small fraction of the total aquifer volume (Figures 3 and 4). By improving our understanding of and ability to define the relevant contaminant transport zones, we can reduce the scope of remedial action to a fraction of what was needed historically under the old conceptual models of contaminant flow and transport (i.e., REV and DDM). We have also translated this new interpretation of contaminant flow pathways and aquifer matrix storage processes into more effective remedial technologies, such as DGR™.

The enhanced flushing approach employed by DGR™ has been and is currently being applied to numerous contaminated sites in various settings with great results. To date, we have applied DGR™ technology to over 30 contaminated aquifers in a variety of geologic settings (unconsolidated and fractured bedrock) and for a wide variety of contaminants (e.g., chlorinated volatile organic compounds [CVOCs], hydrocarbons, chromium, pesticides, chlorides, 1,4-dioxane and PFAS). We have also combined DGR™ with other technologies where appropriate (e.g., thermal, in situ bioremediation, NAPL recovery, etc.) and have used both vertical and horizontal wells.

While this strategy may not work for every project site, the primary elements of large plume CSM and performance optimization allow realization of project cost savings regardless of whether the goal is to improve annual remedy efficiency or to advance plume cleanup to clean closure. These flux-based and data-driven operational elements are also especially favorable for successful application of DGR™, allowing achievement of what was previously unthinkable for many large and/or complex contaminant plumes – within relatively shorter time frames and with reduced costs.

So you're saying there's a chance…a reason for optimism

Connecting the dots for large plume restoration Part 2: The three-Compartment Model, *Smart Characterization* (HRSC), DGR™ *and flux-informed remedy optimization*

Environmental restoration has always been a judicious balance of three fundamental steps:

1. site characterization;
2. remedy design/application (engineering); and
3. remedy operation and maintenance (O&M).

Too much or too little emphasis placed on any of these components will often result in reduced efficiency, increased scope, escalated life cycle costs, and, in extreme cases, may lead to complete remedy failure. When the balance is optimized, though, it will lead to more effective and sustainable outcomes (Figure 1).

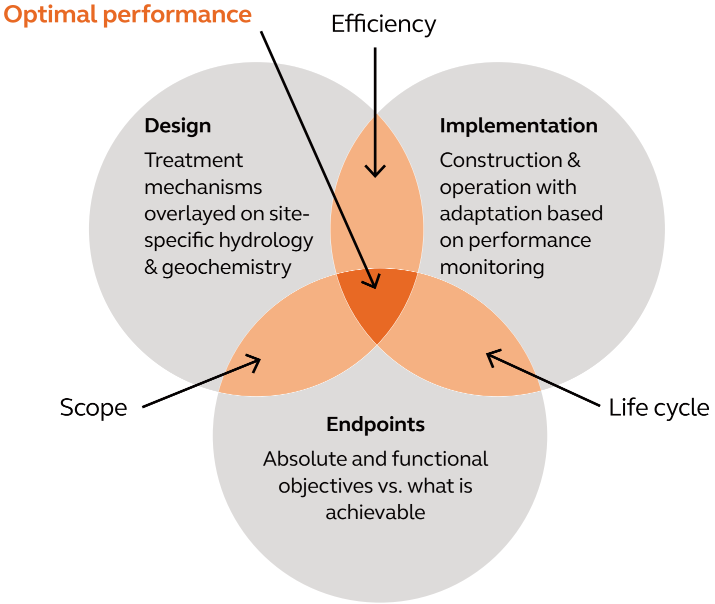


Figure 1: *Elements of successful in situ remedies. (Adapted from Suthersan et al., 2010)*

In 2010 we introduced an approach for remediation decision making that focused on weighing these three phases along with remedial endpoints against the constraints of the natural system within a mass flux/mass discharge framework (Suthersan et al., 2010). Concepts and examples were presented that highlighted some of the potential challenges and opportunities practitioners may face in pursuing a remedial strategy that focuses on the "mass that moves" or a flux-informed approach.

Over the past 10 years we have also seen the continued advancement of:

1. Site investigation and characterization methods (i.e., *Smart* Characterization/high resolution site characterization [HRSC]),
2. The framework of the conceptual site model (CSM) for groundwater remediation (i.e., the three-compartment model), and
3. Flux-oriented remediation techniques (i.e., dynamic groundwater recirculation [DGR™]).

These concepts and technologies have improved our understanding of how contaminants move through and interact with the aquifer matrix, allowing for development of better remedial strategies and system designs.

While the scale at which we collect our subsurface data has been decreasing, though, the scale of our plumes has been increasing. And, with the ever-changing establishment of regulatory guidance for emerging contaminants (e.g., *1,4-dioxane and per- and polyfluoroalkyl substances [PFAS]*), the total inventory of large plumes has increased correspondingly. While there has been steady progress moving small plume sites to closure through our improved technology and institution of risk-based regulatory standards, there has been little advancement for addressing large plumes.

The traditional approach to large plume remediation has been (and continues to be particularly with the recent focus on emerging contaminants, like PFAS, that are ubiquitous and not particularly responsive to in situ treatment technologies) conventional pump and treat (P&T). And, as we have discussed elsewhere, this strategy often falls short when it comes to advancing aquifer restoration in any meaningful way and may, in fact, extend remedial time frames resulting in significant cost overruns. This is where DGR™ comes in… when properly designed and operated, DGR™ can be a highly effective remedial technology, particularly for large, diffuse plumes. The key to successful DGR™ implementation/operation (or any hydraulic-based remedy) is frequent system optimization in response to changes in performance data. This typically involves varying pumping/injection rates and locations to create dynamic conditions that accelerate the removal of contaminant mass while maintaining hydraulic control of the plume.

Traditionally, we often focused our optimization efforts on the ‘above ground’ components (e.g., treatment system methods/technologies, construction/infrastructure, operation, and maintenance relative to costs) rather than the ‘below ground’ components (e.g., well locations, screened interval, flow rates, gradients/flow directions, and mass removal rates). Adaptive management of the ‘below ground’ components, though, can ultimately drive the remedy to a more efficient completion—this presents a “blue-sky” opportunity to develop fresh approaches.

Here, by considering and applying lessons learned over the last decade, we present an alternative optimization framework that incorporates a mass flux-based metric. One that merges the hydraulics of a remedy with the predicted rate of contaminant mass removed or mass flux ‘captured’. Mass flux is generally defined as the mass moving across a unit area of aquifer over a given time (mass/time/area). Because the approach presented here attempts to couple the contaminant mass flux within the aquifer to the rate of mass removed from the aquifer, we use the term mass flux to also describe the rate of mass removed per well (i.e., flow rate multiplied by concentration).

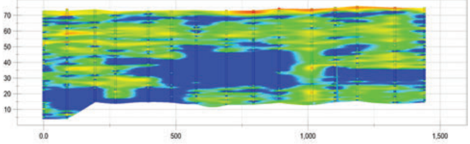
The relatively simple optimization framework allows us to answer a key lingering question: “Based on the known data, where and how much do we need to extract and/or inject to ensure that contaminant mass/mass flux at a site is efficiently removed/captured?” To date, the answer to this question has typically been approached computationally by playing dice, exploring all possibilities to define the probability of success. This approach is technically unsatisfying as it does not often result in clear recommendations. With the framework presented below, we are suggesting an approach that not only evaluates the possibilities, but also provides clear recommendations to achieve success.

Why optimize?

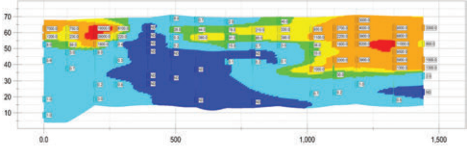
In 2017 the United States Environmental Protection Agency (USEPA) *Superfund Remedy Report* stated that for the 160 groundwater decision documents signed between 2012 to 2014, groundwater remedies continue to be primarily a mix of in situ treatment, P&T, and monitored natural attenuation. In other words, hydraulic-based remedies still comprise a large portion of the remediation technologies applied at contaminated groundwater sites and, when appropriately implemented, can be a very effective treatment for aquifer restoration. Also, as outlined in their *National Strategy to Expand Superfund Optimization Practices from Site Assessment to Site Completion* (USEPA, 2012), USEPA has implemented a comprehensive optimization program *“to take advantage of newer tools and strategies that promote more effective and efficient cleanups” and “to achieve verifiably protective site cleanups faster, cleaner, greener and cheaper.”*

This optimization initiative aligns well with the data-driven conceptual site model development, adaptive design process, and overall remedial philosophy that we initially presented in *Remediation Hydraulics* (Payne et al., 2008). Under this approach, the understanding of site conditions (i.e., the conceptual site model) continues to evolve throughout the entire site remediation process, helping to adapt the remedy to arrive at the most efficient/optimal completion. This optimization strategy is employed by the U.S. Navy and for 233 sites that have undergone an optimization review, they have reported a return on investment (ratio of avoidance cost to cost of review and implementation) of greater than 6:1 (NAVFAC, 2010).

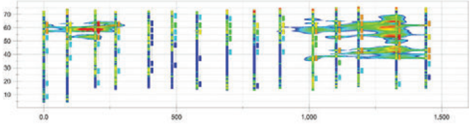
Optimizing the effectiveness of hydraulic-based groundwater remedies is often constrained by well placement and their capacity to support adequate pumping or injection rates. The application of high-resolution characterization tools, though, has allowed us to see and understand groundwater contaminant plumes in ways that we were not previously able to. We can now more effectively map mass transport zones and mass storage zones which, in turn, enables more accurate selection and placement of well infrastructure and ultimately realization of better performance at a much lower cost. An example of this is depicted on Figure 2.



Hydraulic conductivity



Concentration profile



Relative mass flux

Figure 2: *High-resolution mass flux profile through an alluvial aquifer, helping show where pumping can be most effective. (adapted from Suthersan et al., 2016).*

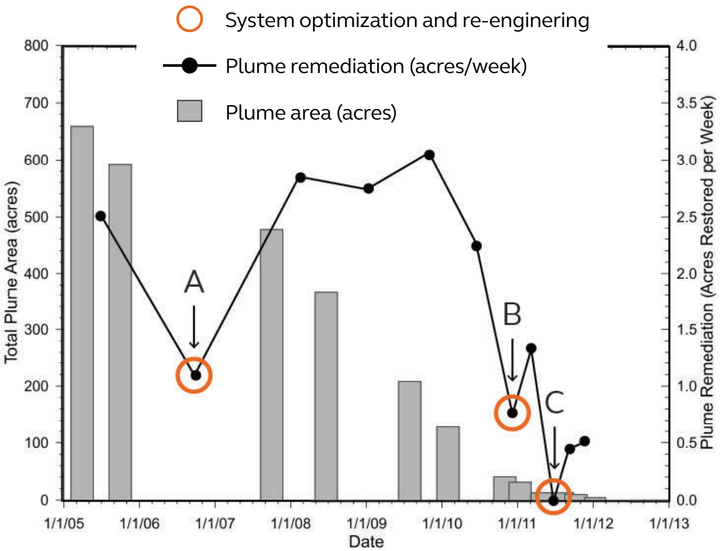


Figure 3: *Plume area in acres at the former Reese Air Force Base during remediation. The pace of performance (represented by the line) shows the number of acres cleaned up per week. The red circles represent major system optimization events (Adapted from Suthersan et al., 2015).*

Traditional approach to remedy optimization

Historically, a sound understanding of groundwater flow conditions along with some form of groundwater modeling (analytical or numerical) were applied to not only design a hydraulic-based remedy and estimate the corresponding flow conditions but also to support remedy optimization. Solute transport modeling analyses were often performed to better understand and/or predict the likely performance of the system configuration. A tedious, brute force trial-and-error approach was often undertaken to align the system hydraulics with the contaminant plume dynamics to effectively contain the plume (i.e., capture zones), maximize contaminant mass recovery over time which, based upon best practices and a little luck, would minimize the expected period of performance.

Over the period of operation, additional modeling may be carried out to reassess remedy performance, predict remedial timeframes, and revisit/support decisions related to system operation (i.e., refine pumping estimates and/or rudimentary system optimization as depicted on Figure 3). In some cases, though, nothing more than simple flow/capture calculations are performed for a contaminated site to estimate the overall flow rate required for hydraulic containment. In either case, though, the professional judgement of the analyst (or the design team) weighs heavily in developing the final configuration of remediation wells.

To improve this type of approach, many numerical modeling schemes aimed at remedy optimization have been developed and presented in the literature with corresponding studies demonstrating the potential cost savings that could be realized for hydraulic-based remedies. Usually, groundwater modeling codes coupled with numerical optimization schemes have been used to perform remedy optimization analyses (as well as developing the design basis) for hydraulic-based groundwater remedies. These optimization schemes often require the integration and execution of separate groundwater flow and solute transport models, leading to very long simulation times with the output often biased by the subjective judgment of the practitioner.

Many of the existing numerical global optimization methods either solve linear algebraic equations, use differential evolution methods, or apply probabilistic algorithms. Most of these tools typically evaluate the remedy hydraulics (e.g., hydraulic capture zones) by defining hydraulic gradient constraints (water-level differences between locations) while contaminant mass removal is a secondary metric assessed by performing contemporaneous solute transport model simulations. Both approaches have limitations as the optimal hydraulics for individual wells can be difficult to determine using hydraulic gradient constraints alone and the corresponding solute transport simulations tend to be either under- or over-parameterized as well as computationally arduous, particularly if multiple contaminants need to be considered.

A better approach to hydraulic-based remedy optimization

As a practical and effective alternative, we offer a new combined objective function or metric that merges the hydraulic potential (i.e., hydraulic capture zone) of the remediation wells with the predicted contaminant mass removed from the aquifer. The resulting framework is a mass flux-based approach to remedy design and optimization without requiring corresponding solute transport modeling simulations.

The volumetric-tracking code MODALL, initially developed by Arcadis in 1992 to support design and optimization of P&T systems, offers an improved method over particle-tracking codes (MODPATH) as it allows the practitioner to determine hydraulic capture zones directly and quantitatively by computing the fraction of flow in each individual model grid cell that will eventually contribute to the volume removed by specific pumping wells. MODALL has been modified over the last decade to incorporate pore flushing and mass flux components that are key elements of our DGR™

$$\wp = \frac{\text{Plume mass captured}}{\text{Total plume mass}} = \frac{\sum_{i=1}^{\text{grid cells}} V_i \times C_i \times Ƒ_i}{\sum_{i=1}^{\text{grid cells}} V_i \times C_i}$$

The plume capture function

technology. The current version of MODALL can be applied to help evaluate the remedy period of performance by combining the capture fraction (Ƒ) (i.e., portion of the flow in a model grid cell contributing to a specific remediation well) with the observed concentration data to compute relative pore volume flushes (i.e., complete mix theory) necessary to reach certain concentration levels (e.g., closure criteria), the ratio of plume mass captured, the mass flux distribution (both lateral and vertical), and even the ratio of mass flux captured. By incorporating these additional flux-based metrics, application of MODALL now provides further support for the effective design, evaluation, and optimization of hydraulic-based remedies.

The capture fraction (Ƒ) is coupled with the interpolated dissolved-phase contaminant concentration distribution to generate a new metric for each remediation well that represents the mass capture fraction of the plumes within the model. Optimization simulations can work towards maximizing this metric while minimizing pumping rates and costs to achieve optimal performance. MODALL also calculates the overall pore water exchange rate within the plumes for each simulation relating the flow rates/aquifer flushing to estimate a remedial time frame (i.e., tracking the time required for aquifer restoration). These calculations provide additional metrics to rank alternatives without having to develop and execute corresponding solute transport model simulations.

We refer to this combined metric as the plume capture function (PCF; ℘) and is represented by the expression above.

Where V_i is the volume of groundwater in model grid cell i, C_i is the interpolated contaminant concentration in model grid cell i, and Ƒi is the capture fraction in model grid cell i for a given extraction well or network of extraction wells. This provides a normalized performance metric varying from 0.0 to 1.0. Mathematically, this metric meets the necessary conditions to serve as the objective function for all varieties of numerical global optimization tools available for groundwater evaluations—the function is continuous, differentiable, and bounded between limits. Like the capture fraction, Ƒ, the PCF (℘) is a function of time increasing asymptotically to a maximum value at steady state.

Illustrative examples

The usefulness of the PCF to optimize a remedy can be explained using a simple example for the hypothetical site presented on Figure 4. This hypothetical site represents a manufacturing facility underlain by a sand and gravel aquifer with groundwater flow from north to south, sourced from recharge and discharges naturally via streams in the south. A dissolved contaminant was released from the site resulting in a large solute plume. Two existing extraction wells located in the plume are available to recover the solute mass. The treatment plant can only receive 20 gpm, but each well can pump at operate at 20 gpm. What are the optimal rates to extract from each well to maximize the mass recovery?

Following a more traditional approach, we would likely develop a steady-state MODFLOW model for the site and then run some particle-tracking simulations to see what pumping distribution makes the most sense. Figure 5 depicts two cases where the objectives are met. But which is better? A qualitative assessment may suggest that Case B is better since pathlines indicate that less 'clean' water is captured. That may be a fair argument, but is it really the better option?

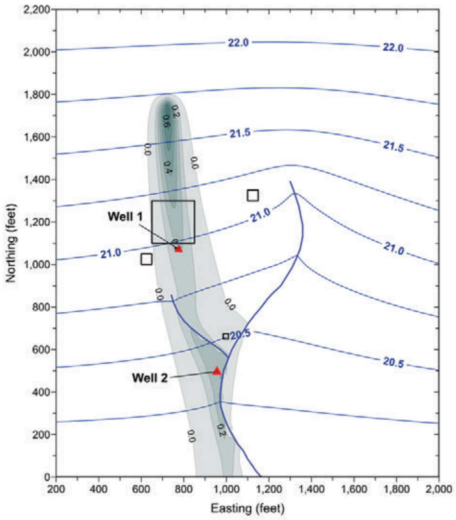


Figure 4*: A hypothetical site with a branched stream to the south (blue line). Groundwater elevation contours depict ambient groundwater flow direction. A dissolved contaminant was released from the Site resulting in a large solute plume (filled contours). Two extraction wells within the plume (red triangles) are available to recover solutes.*

MODALL runs were also performed to compute the mass recovery from each well. Results presented in Figure 6A show the mass recovery curve for each well operated individually at various rates (i.e., Well 2 is off when Well 1 is operating and vice versa). The curves show a logical relationship of increasing mass recovery asymptotically approaching a maximum value. Figure 6B shows the integrated response when both wells are operating illustrating the usefulness of an unbiased optimization approach. The x- and y-axis represent the flow rates of each well, while curves on the plot correspond to the PCF values for each combination of rates. The resulting plot is a contour map of the possible options. The diagonal lines are uniform total pumping at both wells. As noted above the, the goal is to achieve the maximum mass flux from

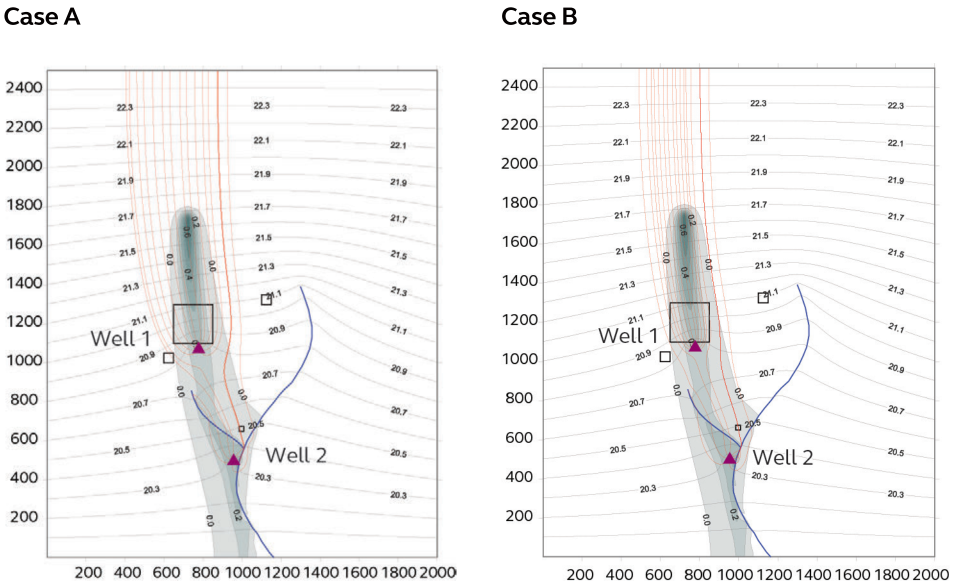


Figure 5: *Two potential pumping configurations (Case A and Case B) that meet the objectives and constraints outlined for the hypothetical problem shown in Figure 4. Red lines depict the reverse particle tracks generated from each extraction well.*

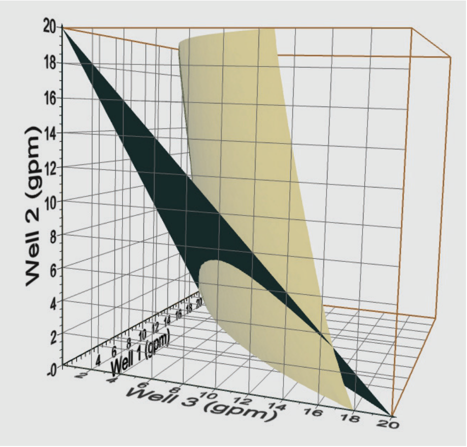


Figure 7: *Three well optimization solution. The optimal solution for the three wells at a total flow rate of 20 gpm (represented by the red circle) is found along the line made by the intersection of the face of a plane (shown in black) and the maximum transecting value of the PCF function (shown in brown) on the plane.*

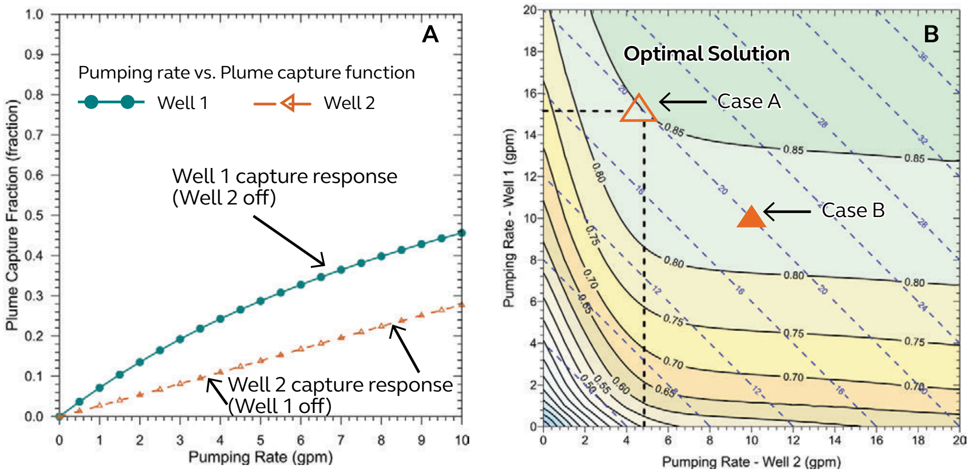


Figure 6: *Two well optimization assessment of the problem in Figure 4. A) shows the relationship of increasing PCF to increasing pumping at each well when each well is operated individually (e.g., Well 2 is operating when Well 1 is off). B) the curves shows the PCF relationship when both wells are operating simultaneously, while the dashed lines are uniform total pumping at both wells. The optimal solution is the triangle, the maximum PCF while pumping at 20 gpm.*

the extraction wells (i.e., mass recovery) while pumping no more than 20 gpm. The solution can be identified by inspection at the identified point on the plot—85% of the mass in the plume can be recovered if Well 1 operates at 15.1 gpm and Well 2 pumps at 4.9 gpm, which is Case A (Figure 5). The pumping distribution in Case B (a 10 gpm/10 gpm split) is a valid solution, but the distribution in Case A is incrementally better.

An optimal solution for this seemingly simple problem was solved via brute force—1,600 MODFLOW and MODALL simulations were performed (all combinations of pumping from 0 to 20 gpm by 0.5 gpm increments) to develop the underlying PCF values to understand the problem and identify the solution—but it does illustrate that an optimal distribution can be determined in this manner. Clearly, a more efficient approach needs to be applied to solve this problem.

In fact, this problem becomes nearly impossible to illustrate graphically as extraction wells are incrementally added to the decision process: if a third well were added to the existing problem, the optimum solution space becomes three-dimensional and feasible solutions are found on the line made by the intersection of the surface of a plane (total flow = 20 gpm) and the maximum PCF value on the plane (Figure 7). Put simply, this intersection provides the "Goldilocks" point: not too hot and not too cold, but just right. With more than 3 wells, the problem can't be shown graphically, and we need different tools to explore the possibilities. Mathematically, the optimal solution for a remedy with N remediation wells is defined by the intersection of a N dimension function and a N-1 dimension function.

This mathematical intricacy is why optimization schemes need to be used in conjunction with groundwater models to unravel the complexity of finding the optimal solution which, in turn, provides a basis for remedy optimization.

One of the optimization tools available is very fast simulated reannealing (VFSR). VFSR is a probabilistic technique for approximating the global optimum (or limits) of a given objective function. Combining the dynamic numerical technique of VFSR with MODFLOW and MODALL using the PCF ($\wp$) as the objective function, provides a relatively simple but effective optimization framework for hydraulic-based remedies, allowing the practitioner to answer key questions such as, where do we need to place extraction and/or injection wells and at what flow rates to ensure that impacted groundwater/contaminant mass flux is optimally contained and/or removed?

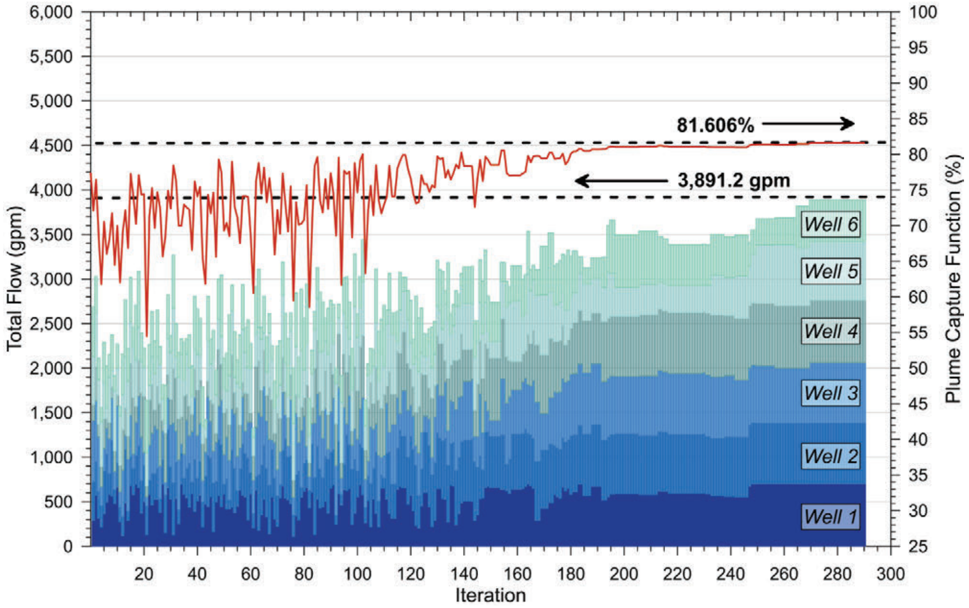


Figure 8: *Convergence process of pumping rates and the plume capture function (PCF) during the iteration process. The estimate of the PCF for each iteration is the solid line at top. The underlying colored fill are a stacked plot of the pumping rates at each well.*

While different numerical optimization schemes can be applied with this approach, for the purposes of demonstrating the efficacy of utilizing our PCF as the objective function,we have developed an illustrative example that employs VFSR as our numerical algorithm.

For this example, the goal is to maximize the contaminant mass recovery from a large solute plume site using a maximum of six (6) groundwater extraction wells pumping at a maximum combined pumping rate of 4,500 gpm. Extraction well locations and initial flow rates were determined using a calibrated MODFLOW model and supported by analyses using MODPATH and MT3DMS. The design basis started with placement of a few wells based on mass flux, groundwater concentrations, and ambient groundwater flow, but as with most real-world designs, final choices were limited—access limitations due to various site-specific conditions and constraints dictated where wells could be located rather than strategic placement based on reasonable assumptions, groundwater concentrations, and mass flux estimates. Additional wells were located within the plume footprint until simulated hydraulic interference between wells defined the maximum possible capture.

This trial-and-error process yielded the "optimum" number of recovery wells (6) for recovery of contaminated groundwater. Each well was assumed to have a pumping capacity of 750 gpm, and the trial-and-error modeling analysis indicated there was an incremental increase in mass recovery by pumping more groundwater (i.e., mass recovery would be greatest when the wells operated at their maximum rates, or 4,500 gpm total). This configuration resulted in a total mass recovery or a combined PCF of slightly over 81.6%. While this configuration or distribution of pumping resulted in maximizing mass recovery, intuitively, there are likely more efficient pumping configurations with reduced pumping rates rather than having each well operating at capacity. The question was then posed: Are there combinations of pumping rates (other than maximum rates) that would be expected to have similar mass recovery rates?

VFSR (along with MODFLOW and MODALL) was used to reassess this problem to determine whether a more optimized remedy exists. VFSR begins with a valid guess of a possible alternative (i.e., any combination of flow rates that produce a result is sufficient to serve as a starting point/valid guess). We started the analysis with each well pumping at 500 gpm for a total of 3,000 gpm, with the results from this calculation producing the first estimate of the optimal PCF function. Using the PCF computed from this guess, VFSR makes random estimates or "walks" equal to the number of parameters to be adjusted. For this example, VFSR needs to generate six (6) different combinations of pumping rates at each well (36 values bounded from 0 to 750 gpm and totaling less than 4,500 gpm). The combined PCF from the initial guess and the six (6) additional estimates of the PCF from each walk form the basis of a second guess at the optimal value. This process repeats until the difference between successive estimates of the PCF are less than predefined limits of convergence or change.

The results of this analysis are shown on Figure 8. As noted above, each iteration represents a guess or the current estimate of the optimal solution, plus six (6) walks. The red line on Figure 8 illustrates the convergence process of pumping rates and PCF during the iteration process, while the color fills are a stacked plot of the pumping rates at each well. Early in the solution process, little is known regarding the distribution of possibilities, so there is significant variability between consecutive estimates. As the algorithm "learns" more about the underlying variability of the PCF distribution, the algorithm asymptotically approaches the solution of the problem. Convergence is defined when the change in the PCF is less than a predetermined value (0.001% for this example). The optimal solution had a PCF of 81.606% with a total pumping rate of approximately 3,890 gpm. While the optimal solution is essentially the same PCF as the initial design, the total flow rate is approximately 15% less, which translates to reduced costs/use of resources and improved sustainability.

An important consequence of applying a well-formulated probabilistic approach is that the solution is typically not only optimal but also the most robust option, which we define as the option having a greater likelihood for success. A histogram of the total pumping rate of all estimates, including the walks, is presented on Figure 9. The overlying curves are a normal distribution with the respective 99% confidence interval. The estimated maximum pumping rate of 3,890 gpm is at the upper limits of the distribution; therefore, quantitatively, there is less than a 1% chance that there is a combination of pumping rates that would produce a better outcome (i.e., recover more mass from the plume).

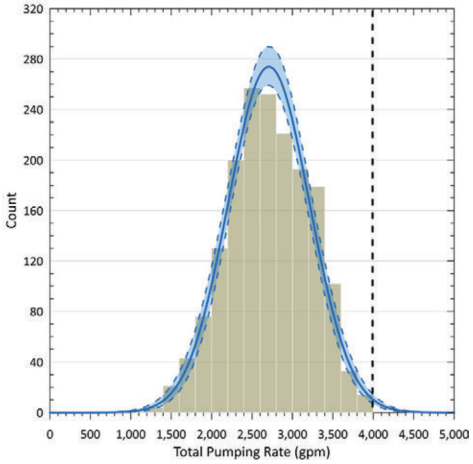


Figure 9: *Histogram of the total pumping rate of all optimization estimates, including walks. The overlying curves are a normal distribution with the respective 99% confidence interval. The vertical dashed line represents the estimated optimal pumping rate of 3,890 gpm.*

Another critical outcome of this approach is that it shows there are other viable options, while less robust, that have similar levels of estimated performance. A scatter plot of all estimates of total flow versus the computed PCF value is presented on Figure 10. Considering the area of the plot inside the dashed box. Each point represents a pumping configuration with less than a 2% difference in the mass capture (between 80 and 81.6%); however, the pumping rate varies by more than 30% (from approximately 2,700 gpm to 3,890 gpm).

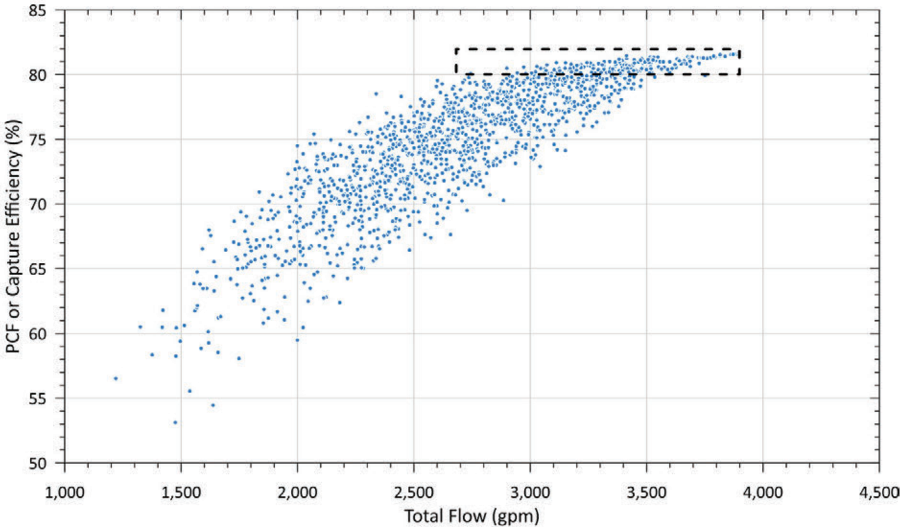


Figure 10: *A scatter plot of all estimated PCF values versus total flow. The dashed box represents all pumping configuration with greater than 80% capture efficiency (i.e., Performance Shell).*

This limited difference in remedy performance contrasted by the wide range in total pumping rate further highlights the usefulness of applying objective (unbiased) optimization methods: the value of this procedure rests not only with the ability to efficiently find the most optimal simulation, but also in identifying a range of viable options from the large number of simulations evaluating complex distributions that achieve similar results—we call this area of the plot the Performance Shell (PS). Because these alternatives can be easily identified, the best actual remedy for the site can be better evaluated and understood by the analyst.

This range of viable options (PS) can then be used to actively manage a DGR™ system and/or pulsed/dynamic P&T system. For example, an operational schedule can be established based on an acceptable percentage of the maximum PCF (i.e., defining the CSP). Flow distributions between wells can then be varied based on the possible flow distributions contained within the CSP. This phase of operation would then be monitored for performance. Once a pre-defined quantitative metric based on specific project objectives has been met (e.g., time to achieve a weighted pore volume based on the plume concentrations), the plume would be reinterpreted, and the process would be started again.

This process is simpler and more efficient than it may appear, taking less than 100 lines of computer code to generate the flows for each walk and eliminating the need to perform concurrent (and computationally time-consuming) solute transport modeling analysis required by most traditional numerical optimization schemes.

This process can be further enhanced by accounting for uncertainties associated with the underlying geologic structure/ hydraulic conductivity field and plume distribution by considering multiple viable realizations to develop an overall probability density function for the PCF. This can be particularly important since application of professional judgment can show up at many steps throughout this process.

For example, the CSM, which forms the foundation for development of quantitative models, is based on site data and professional judgement. Groundwater models are developed with numerous objectives that sometimes affect the estimation of parameters and delineation of constituent distributions. Detailed uncertainty analyses should be performed on both the groundwater model as well as the subsequent optimization process, thereby affording an opportunity for the analyst to acknowledge and weigh uncertainties as part of the remedy design and optimization decision-making process. In this systematic approach, the practitioner can focus on the design of better remedy, identifying the mass that matters, while further constraining inherent user biases.

While professional judgment will likely never be fully eliminated (nor should it be) from the remedy design and optimization process, by relying on a mass flux-based (i.e., mass removal) metric that merges the hydraulics of a remedy with the predicted contaminant mass captured, this framework attempts to balance the historically subjective nature of this process with more objective and informative remedy performance metrics.

Using our accumulated knowledge combined with off-the-shelf numerical modeling tools, we introduce a practical and relatively simple framework for hydraulic-based remedy design and optimization.

About the authors

Scott Potter, PhD, PE, is the Chief Hydrogeologist for Arcadis North America. He has more than 30 years of experience in groundwater hydrology and remediation. Mr. Potter has project experience developing site-wide remedial strategies, groundwater flow and contaminant transport, surface-water flow and transport, and quantitative analysis of hydrogeologic systems.

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New horizontal well applications for monitoring and remediation

Jesse Wright, PE, PG and Craig Divine, PhD, PG

HRX Wells®

Craig Divine describes the HRX Well system and explains two new horizontal well applications for monitoring and remediation.

11 minute podcast

How HRX Wells® work

A simple explanation of Arcadis' patented award-winning HRX Well, a new in situ remediation technology for PFAS, chlorinated solvents, 1,4-dioxane, perchlorate, metals, and other contaminants.

3 minute video

This article discusses two new horizontal well applications for monitoring and remediation that are being developed and field-demonstrated by Arcadis. The primary benefit of horizontal wells is they can be readily installed and operated under buildings, roads, flight lines, and other surface infrastructure that may have been previously inaccessible via vertical boreholes. Additionally, advances in directional drilling methods have increased well design options while lowering overall installation costs. The first application is the Horizontal Reactive Media Treatment well (HRX Well®), which utilizes large-diameter horizontal wells for in situ treatment of chlorinated solvents, per- and polyfluoroalkyl substances (PFAS), and other contaminants.

The HRX Well concept is particularly well-suited for sites where long-term mass discharge control is a primary performance objective. Comparable remedial technologies include PRBs and groundwater pump and treat systems.

The second application is the Vertebrae™ system, which is a segmented multi-screen horizontal well technology that allows up to 20 separately plumbed screen zones to be installed in a single boring. This allows for targeted mass flux monitoring. The Vertebrae system can also be used for targeted injection of remediation amendments.

It is increasingly recognized that contaminant mass flux/discharge provides the most representative measure of plume dynamics and risk to receptors. Consequently, remedial technologies focusing on long-term mass flux/discharge reduction will be increasingly favored, and new strategies that can accurately measure changes in mass flux/discharge over time will be more frequently implemented. Flux-focused remediation and monitoring approaches are relevant for any type of contaminant source zone, but will be particularly important in the future for assessing the risk and benefits of mitigation activities for per- and polyfluoroalkyl substances (PFAS) discharging from fire training areas and other source area types.

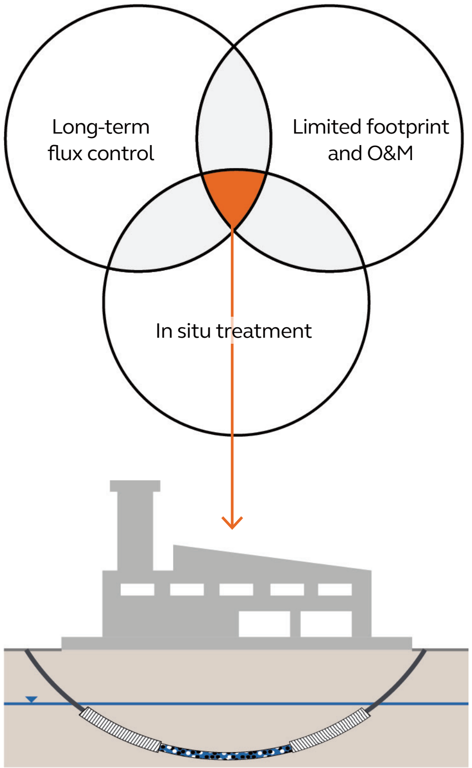

Figure 1: HRX Well applicability
The HRX Well is well-suited for sites where long-term mass discharge control is a primary performance objective, site access is restricted, and in situ treatment is preferred over above ground management and ex situ treatment of impacted groundwater.

Horizontal reactive media treatment well (HRX Well®) for in situ treatment and mass discharge control

The HRX Well, a new in situ remediation approach, uses directionally drilled horizontal wells installed in the direction of groundwater flow that are then filled with treatment media such as granular activated carbon (GAC) or zero valent iron (ZVI) (Figure 1). The basic HRX Well concept requires no above-ground treatment, has limited ongoing maintenance, and doesn't require a surface footprint. For GAC, ZVI and other treatment media, the in situ units are designed for easy removal and regeneration or replacement when exhausted. The HRX Well concept is well-suited for sites where long-term mass discharge control is a primary performance objective (Figure 2) and is particularly appropriate for recalcitrant and difficult-to-treat constituents, including chlorinated solvents, PFASs, 1,4-dioxane, and metals. Contaminant mass discharge can be dramatically reduced, and can be cost-effectively sustained over many years. By greatly reducing/eliminating source zone discharge via implementation of the HRX Well, downgradient plumes can be more effectively treated, possibly even achieving low water quality standards in a relatively short period of time. The HRX Well concept has been field validated using granular treatment media. Arcadis is also actively developing an alternative configuration for destructive treatment of PFAS within an HRX Well. Arcadis is teaming with Clarkson University and the U.S. Army Corps of Engineers on an upcoming project where the goal will be to demonstrate the effectiveness of a compact sonolytic reactor, termed the in situ reactor technology (InSRT), specifically designed for deployment within an HRX Well.

The HRX Well (Figure 2) is oriented in the general direction of groundwater flow and is filled with treatment media to treat captured groundwater within the well. Flow-focusing, resulting from a high in-well hydraulic conductivity relative to the aquifer hydraulic conductivity, passively directs a capture zone of impacted groundwater into the well through the screen at the upgradient portion of the well. Because the well is filled with a treatment medium, impacted groundwater is treated in-situ as it flows through the HRX Well, before discharging through the screen on the downgradient side of the well. For some applications, the flow through the HRX Well and size of the capture zone can be increased through pumping (i.e., active configuration), where the pump intake is placed in the upgradient screen and groundwater is pumped through a packer into the treatment media. In this configuration, no groundwater is brought to the surface for treatment.

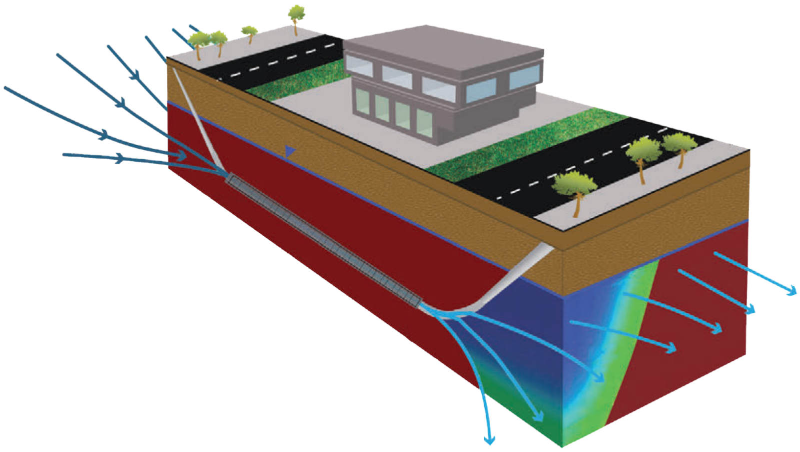

Figure 2: Conceptual depiction of an HRX Well. *Groundwater (indicated by blue flowlines) is focused and flows into the upgradient screen section of the HRX Well (grey cylinder) where it is treated as it passes through granular reactive media before exiting the downgradient screen section back into the aquifer. The color flood indicates contaminant concentrations, where hot colors represent high concentrations and cool colors indicate treated groundwater. Some flowlines are outside the treatment zone and do not enter the well; therefore, groundwater along these flow paths remains untreated.*

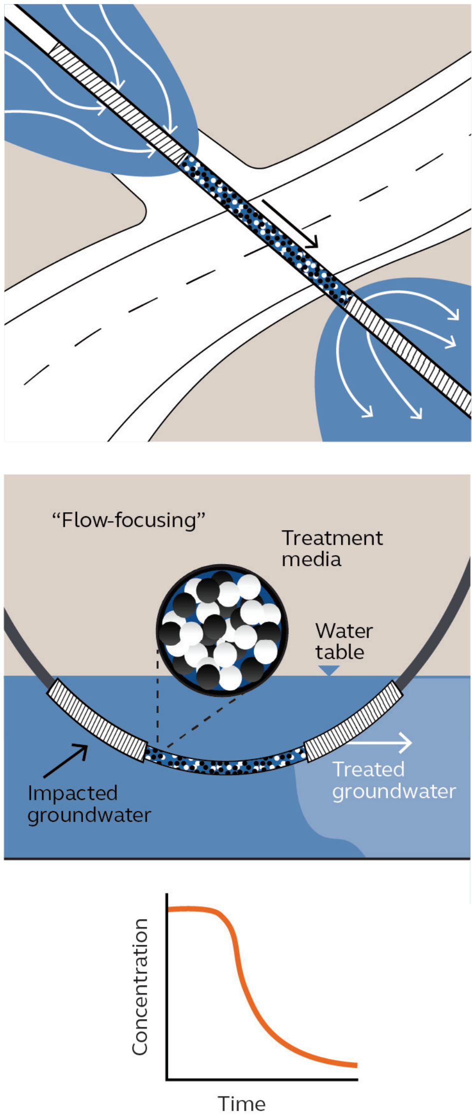

Figure 3: *Conceptual depiction of the HRX Well treatment process.* *Watch the video* *to learn more.*

The HRX Well controls contaminant mass discharge to downgradient aquifer zones, and these zones will clean up over time through flushing and contaminant elution. As indicated in the conceptual treatment process above (Figure 3), water exiting the HRX Well screen is clean nearly immediately, while concentrations at downgradient monitoring locations will decline as treated groundwater moves with ambient groundwater flow.

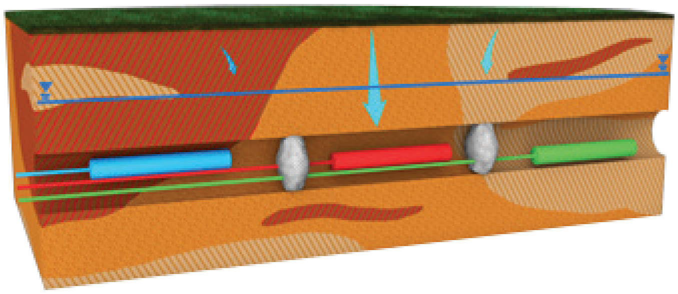

Figure 4: Vertebrae Well System. *The Vertebrae Well System contains multiple screen segments separated by grout seals with independent connections to the surface. It can be thought of as a nested well installed horizontally. (Source: EN Rx, Inc.)*

The HRX Well technology was initially tested and verified through extensive numerical and physical modeling (i.e., laboratory tank testing) completed as part of Strategic Environmental Research and Development Program Project ER-2423. The concept was then first field validated at Vandenberg Space Force Base (formerly Vandenberg Air Force Base) in California as part of Environmental Security Technology Certification Program (ESTCP) Project ER 201631. Further details have been published in the scientific literature (Divine et al. 2018a, b; Horst et al. 2019, Divine et al. 2020). The project validated the HRX Well as an in situ remediation approach with an average mass discharge reduction of approximately 1.8 g/day for over 1,200 days. HRX Well systems have been installed at additional sites to treat chlorinated solvents and PFAS, demonstrating successful installation under active infrastructure and in a wide range of hydrogeologic conditions.

Based on the results of the field validation at Vandenberg Space Force Base, the HRX Well technology was awarded the National Groundwater Association's 2019 Technology Award, ESTCP's 2020 Project of the Year, and the 2021 Environmental Business Journal Project Merit Award.

Vertebrae™ Segmented Horizontal Wells for mass flux monitoring

The Vertebrae system is a single, small diameter horizontal well that contains multiple isolated screen segments; an engineered multi-port well that is installed horizontally instead of vertically (Figure 4). The Vertebrae system is unique with many discrete screen zones running horizontally along its length with separate, small diameter tubing plumbed from each screen to the surface. Grout is tremied in to isolate the individual screen intervals which can be tailored to specific site conditions.

Vertebrae wells result in minimal impact to facility operations during installation and sampling. These wells can be designed to target precise elevations and laterally continuous high-permeability zones in the horizontal plane (e.g., sand layers). The Vertebrae approach is novel and advantageous because multiple, closely spaced measuring points across a transect can be easily installed from a single boring (reducing costs) and contaminant zones that may have been previously inaccessible via vertical boreholes can be characterized. Based on reasonable assumptions for common site conditions, a single Vertebrae system may be more cost effective than installing multiple conventional vertical wells when the total number of targeted sampling intervals is more than about seven.

Pre-built Vertebrae well materials are shown in the photo on the left. The directional drilling rig and support equipment are shown in the photo on the right.

Arcadis is leading a current ESTCP project (ER20-5026), where the objective is to field validate the use of the horizontal multi-port Vertebrae well system for monitoring contaminant mass flux/discharge in groundwater systems (Figure 5). This project applies mass flux/discharge methods proven for conventional vertical transect approaches to the Vertebrae system. The patented Vertebrae system (by EN Rx, Inc.), was first implemented in a field application for remediation agent injection purposes in 2014, and the first system used to collect groundwater quality data as a monitoring system was completed in 2015. To date, more than 170 Vertebrae systems have been deployed at more than 60 sites in a wide range of geologic settings in which more than 925 individual wells (separate screen intervals) have been installed to characterize contaminant distribution and support remediation. Project ER20-5026 aims to leverage this technology to improve mass flux/discharge quantification methods.

As part of ESTCP project ER20-5026, three Vertebrae well systems were installed during 2021 at a DoD installation where there is a well characterized PFAS groundwater plume (Figure 6). Previous site characterization activities were completed as part of ESTCP project ER19-5203, which validated the application of real-time mobile laboratory methods for characterization of PFAS source areas and associated groundwater plumes.

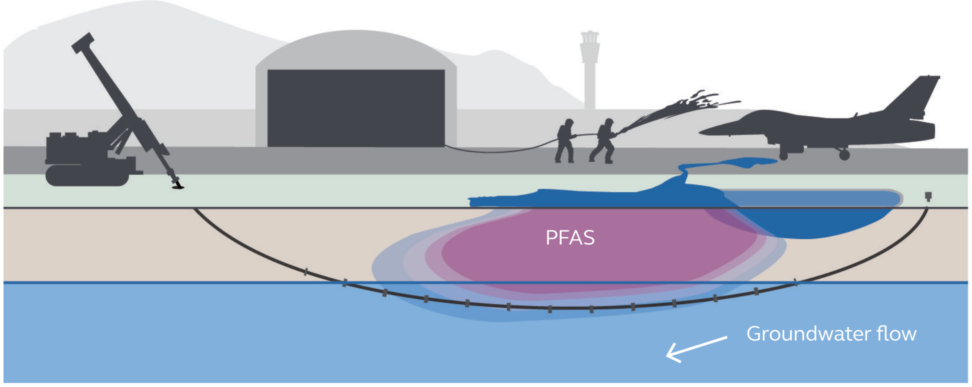

Figure 5. Conceptual depiction of a Vertebrae Well System measuring PFAS mass flux/discharge. *The overall goal of ESTCP Project ER20-5026 is to demonstrate and validate the Vertebrae horizontal well system as a technology for reliable long-term monitoring of contaminant mass flux/discharge from PFAS source zones.*

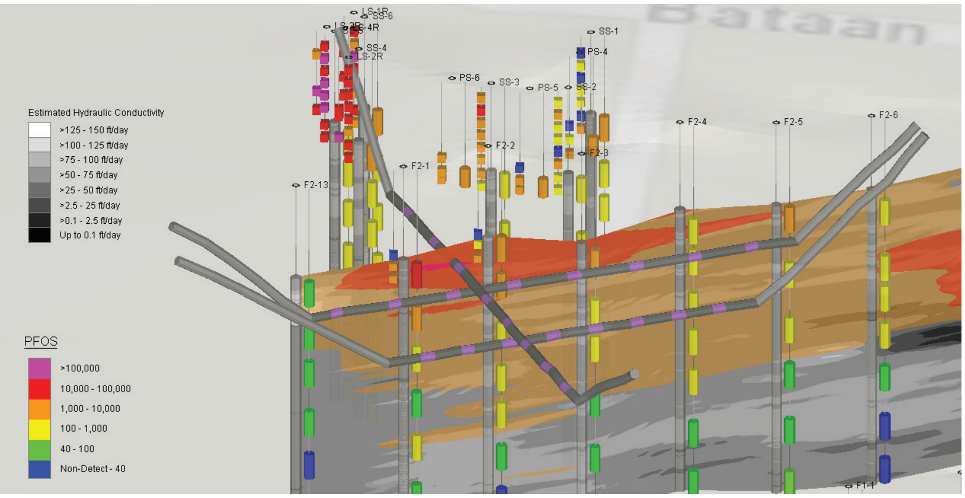

Figure 6: 3D Model Showing design of the Vertebrae Systems based on data from a vertical transect. *Groundwater analytical results are shown as tubes with units of ng/L. Soil analytical results are shown as cubes with units of ng/kg.*

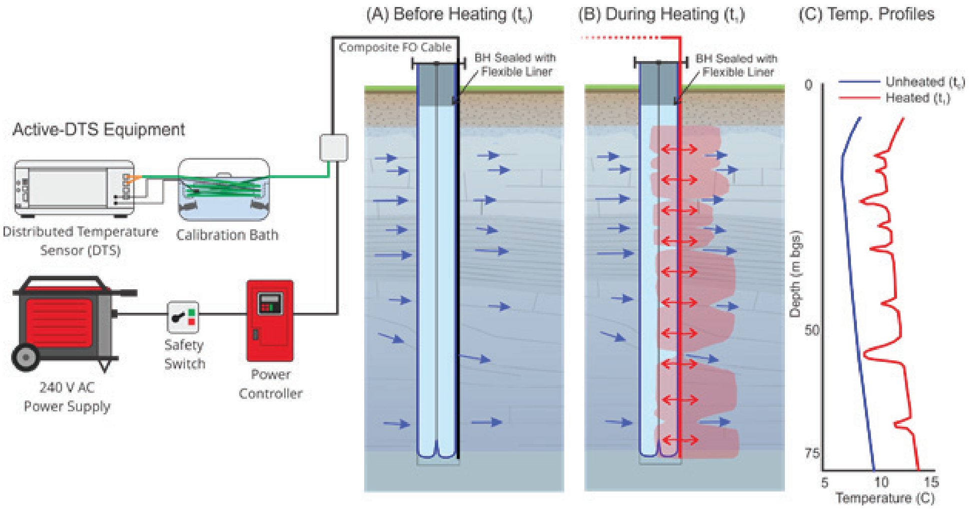

Figure 7: Schematic of Active Distributed Temperature Sensing (A-DTS) *in a fractured rock borehole with the composite Fiber Optic and heating cable sealed behind a blank FLUTe™ liner. Active groundwater flow causes preferential cooling at those depths (modified from Maldaner et al. 2019). The A-DTS system will be used with cables installed with the Vertebrae systems to verify the integrity of the grout seals. (Source: Jonathan Munn, University of Guelph).*

Two Vertebrae systems were installed transverse to groundwater flow (i.e., transects) downgradient of a source area. These transverse alignments were placed at two different depth intervals. An additional application that is being tested is the orientation of the Vertebrae systems parallel to groundwater flow (i.e., “longsect”) to measure changes in contaminant characteristics along the contaminant flow path (i.e., plume centerline) within a continuous hydrostratigraphic zone. Each of the Vertebrae systems that were installed as a part of this project are approximately 500 feet long, for a total length of approximately 1,500 linear feet.

The University of Guelph G360 Institute for Groundwater Research has developed an Active Distributed Temperature Sensing (A-DTS) method applicable to both bedrock and unconsolidated aquifers. This method involves installing a composite fiber optic cable containing both optical fibers and heating wires in a borehole and heating the cable at a constant rate (Figure 7). Groundwater flow increases heat dissipation, with the magnitude of the shift proportional to the groundwater flow rate (Maldaner et al. 2019). This allows depth-discrete groundwater flow rates to be estimated using A-DTS tests. Fiber optic cables have been integrated with the Vertebrae wells, to allow A-DTS testing to quantify groundwater flux. An additional application of the A-DTS method includes assessment of the grout seals between well screens in the Vertebrae system. EN Rx has developed a proprietary grout seal mixture to increase elasticity, longevity, and sealing efficiency to isolate the intervals in each horizontal boring. A-DTS testing and data evaluation will continue during 2022.

The first sampling event was completed during December 2021. The PFOS results are shown on Figure 8, along with vertical aquifer profile sample results from October-November 2019 and September 2021. Comparison of the results indicates general agreement between the vertical aquifer profile samples and samples from the Vertebrae well screens. Additional performance monitoring events will be completed during 2022 to assess changes in PFAS groundwater concentrations over time and validate Vertebrae methods for measuring groundwater flux.

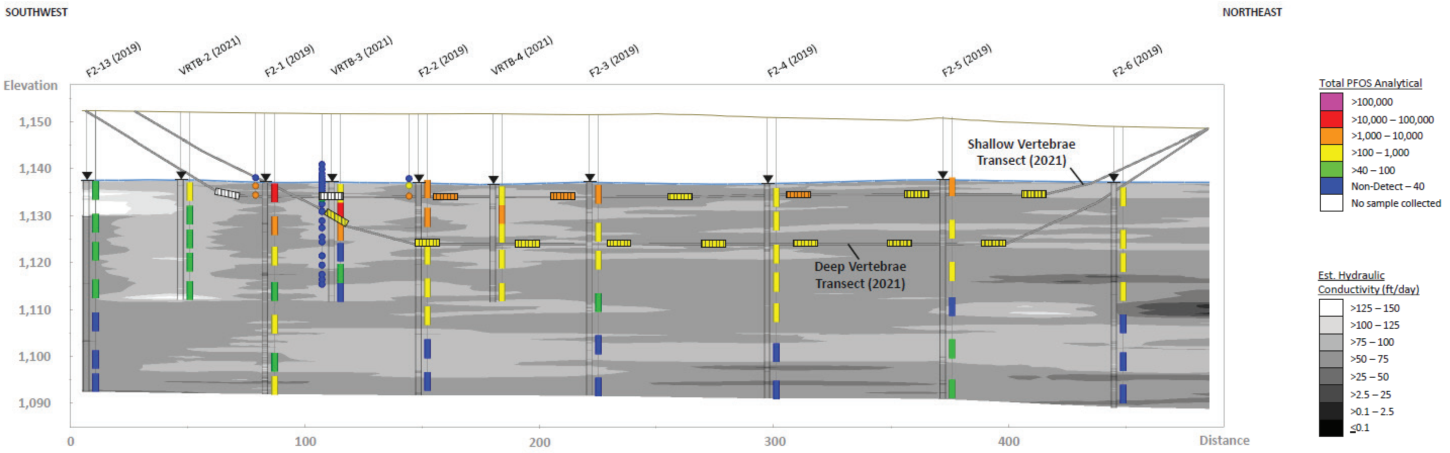

Figure 8: Cross Section Showing initial sampling results from the Vertebrae Systems compared to data from a vertical transect. *PFOS groundwater analytical results are shown as tubes with units of ng/L. PFOS soil analytical results are shown as cubes with units of ng/kg.*

Publications:

Divine, C.E., Roth, T., Crimi, M., DiMarco, A.C., Spurlin, M., Gillow, J. and Leone, G. 2018. The Horizontal Reactive Media Treatment Well (HRX Well®) for Passive In-Situ Remediation. Groundwater Monitoring & Remediation, 38(1), 56-65. DOI: 10.1111/gwmr.12252

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Koenigsberg SS, Piatt ER, Robinson LI. 2018. New perspectives in the use of horizontal wells for assessment and remediation. Remediation, 28:45–50. https://doi.org/10.1002/rem.21575.

Maldaner, C., Munn, J., Coleman, T., Molson, J., Parker, B.L. 2019. Groundwater flow quantification in fractured rock boreholes using active distributed temperature sensing under natural gradient conditions. Water Resources Research, 55(4), 3285-3306.

About the authors

Jesse Wright, PE, PG, is a Senior Engineer at Arcadis with over 20 years of environmental consulting experience. He has extensive experience utilizing the latest high-resolution site characterization (HRSC) techniques to design horizontal remediation wells for a variety of remedial technologies. Mr. Wright has considerable experience with all aspects of horizontal well design and has recently focused on research and development of new horizontal well applications.

Craig Divine, PhD, PG, is a Technical Expert and Senior Vice President at Arcadis with over 25 years of experience in subsurface investigation and remediation at oil and gas facilities, military installations, smelters and mines, power generation facilities, chemical and manufacturing plants, landfills, steel mills, and aerospace facilities. He has extensive experience developing and field-testing innovative technologies, including Arcadis' Min-Trap® sampler, Horizontal Reactive Treatment Well®, and passive PFAS sampler Sentinel™.

Sustainable resilient remediation

Jessica Gattenby and Stephanie Fiorenza, PhD

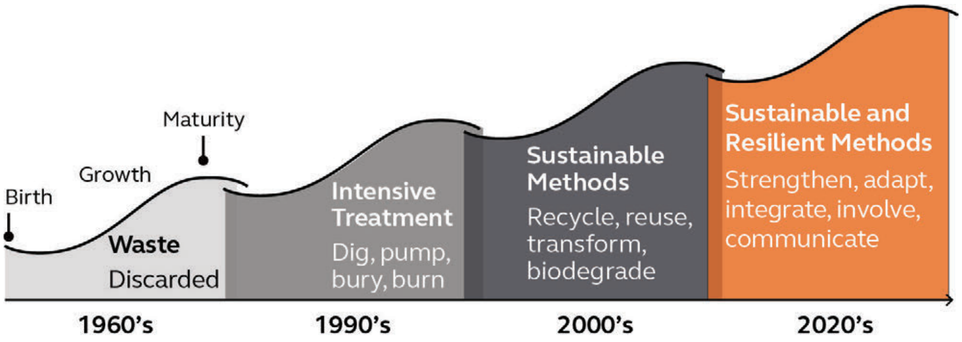

Figure 1: *Evolution of thinking in waste cleanups.*

Globally, we're feeling the effects climate change, rapid urbanization, and loss of biodiversity. The rate at which we're seeing devastating large-scale events such as droughts, floods, and wildfires is becoming more frequent. The demand has never been greater to help our cities and communities create healthier lives and become better stewards of our natural resources and a more resilient future.

Evaluation and implementation of remedial solutions for contaminant treatment at impacted sites has long been a balance of cost efficiency, technical effectiveness, and community acceptance. Many phases of evolution have taken place within the remediation industry (Figure 1) due to technological developments, higher focus on emerging contaminants and new contaminant types, regulatory changes, economic factors, and, most recently, sustainability and resiliency considerations.

Generally, sustainability is defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland Definition; 1987 Report of the World Commission on Environment and Development). Within sustainability is resilience, or the capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimal damage to social wellbeing, the economy, and the environment (ASTM). Inherently built into the practice of remediation is the process of improving environmental conditions for future generations and responding to hazards to human health and the environment. While this implies that all remediation practices are aligned with general sustainability objectives, incorporating sustainability and resiliency into our remedial practices should be considerably more deliberate and purposeful to maximize the benefit.

The sustainability benefits of a cleanup remedy are best evaluated at the outset of design with a focus on five primary elements: 1) total energy and renewable energy use, 2) air pollutants and greenhouse gas emissions, 3) water use and impacts to water resources, 4) materials management and waste reduction, and 5) land management, biodiversity and ecosystems protection. This evaluation is commonly referred to as green remediation.

> Truly sustainable remedies integrate both social and economic sustainability components with the environmental analysis

These three major factors are commonly referred to in sustainable remediation as the triple bottom line (Figure2). Social sustainability components inherently address. the issue of environmental justice and are only sustainable if they address all components of the local communities they affect. The economic sustainability of a project is not only considered in the context of the cost of implementation, but considers local labor and suppliers, the local economy, and the project's environmental footprint.

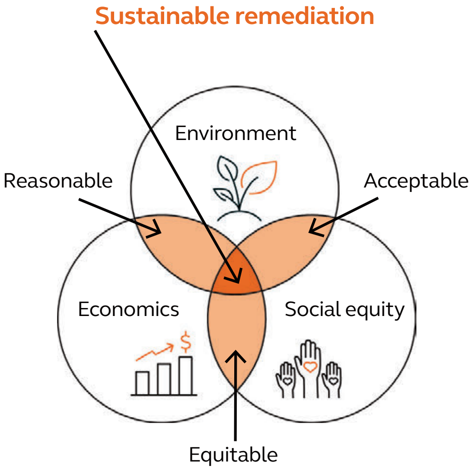

Figure 2: *The confluence of three major factors consisting of the triple bottom line - economic, environment, and social equity. Truly sustainable remedies integrate both social and economic sustainability components with the environmental analysis.*

Group	Mission	Publications
ITRC	Implementation of GSR through educating state environmental regulators and other environmental professionals	• Green and Sustainble Remediation (GSR): A Practical Framework (2011) • Sustainable Resilient Remediation (SRR) (2021)
SURF (US, UK, Nicole Latin America)	Maximize the overall environmental, societal, and economic benefits from the site cleanup process by advancing the science and application of sustainable remediation	• Numerous guidance documents, frameworks and tools have been developed through SURF US and SURF UK
ASTM	Forum for the development and publication of voluntary consensus standards	• Integrating Sustainable Objectives into Cleanup (2013) • Standard Guide for Greener Cleanups (2016) • Climate Resiliency Planning and strategy (2015)

Table 1: *Major Sustainable Resilient Remediation organizations publishing guidance documents and tools.*

The remediation industry has also recognized that as our climate changes, so does the potential risk profile for longer-term remedial plans. For example, sea level rise can result in the surfacing and uncontrolled discharge of impacted groundwater plumes or can compromise the integrity of landfills and other hazardous waste controls. Vulnerability evaluations can be conducted for remediation projects to identify site-, community-, and region-specific risks. With the vulnerabilities assessed, mitigation measures can be identified, prioritized, and implemented to improve the resilience of the remedy. Integrating resilience with sustainability planning and management is expected to minimize conflicts and maximize synergies when compared with separate implementation strategies (ITRC 2021)[1]. This integrated approach to planning is now commonly referred to as Sustainable Resilient Remediation (SRR)

In this article we explore how to integrate SRR into remediation projects to add value and ensure a successful project outcome. We also highlight some innovative remediation technologies that offer a more sustainable approach to achieve project goals. With renewed focus from scientific, regulatory, and stakeholder interests, there is significant momentum to unlock new opportunities to realize the triple bottom line.

Building momentum

Multiparty, government, and nonprofit organizations have developed frameworks to implement sustainable practices based on value judgements that are process-based and scalable. The three most prominent organizations involved in this effort are the Interstate Technology and Regulatory Council (ITRC), the Sustainable Remediation Forum (SURF), and the American Society of Testing and Materials International (ASTM), each with slightly varying roles. Arcadis is an active member of these organizations and has contributed to the frameworks and guidelines that continue to shape how our industry achieves SRR in practice.

Establish SRR goals

Sustainability policy, metrics, goals and targets

Resiliency guidelines

Stakeholder engagement

Ongoing throughout the process

Evaluate / update CSM

Environmental footprint

Climate risk

Community sensitivities

Evaluation level(s) & measure

Prioritize measures: highest impact & lowest effort

Synergy opportunities

Implement & execute project

Limit resource consumption

Optimize approach

Integrate in project plans and OMM manuals

Measure & communicate impact

Measure (quantify) the sustainable impact

Report in the dashboard

Share the success of the project!

Figure 3: *Integrating Sustainability, Arcadis programmatic approach for site evaluation and remediation.*

Sustainability considerations and green remediation practices (GSR) have been supported by the remediation industry at all stages in the remedy lifecycle since the early 2010s, however they have not always been strongly embraced. More recent remediation sustainability publications have evolved the topic to incorporate resilience as a consideration under sustainability creating SRR. Publicly available resources include guidance documents, frameworks and methodology for conducting GSR assessments, best management practices, software programs and other assessment tools, case studies and GSR initiatives – most of which we have helped develop. These have been published by the EPA Superfund program, EPA regions, various state environmental agencies, the ITRC, SURF, SURF UK, ASTM, the Association of State and Territorial Solid Waste Management Officials (ASTSWMO), US Department of Defense (DoD) and its branches (Army, Air Force and Navy), and private industry. This continued focus on sustainability and resiliency by the industry has resulted in a strong, well-defined understanding of how SRR principles can be incorporated into projects and, as a result, is gaining increased support.

UN Sustainable Development Goals

Primary focused SDGs

Secondary SDG's

***Figure 4:** Arcadis focused sustainable development goals.*

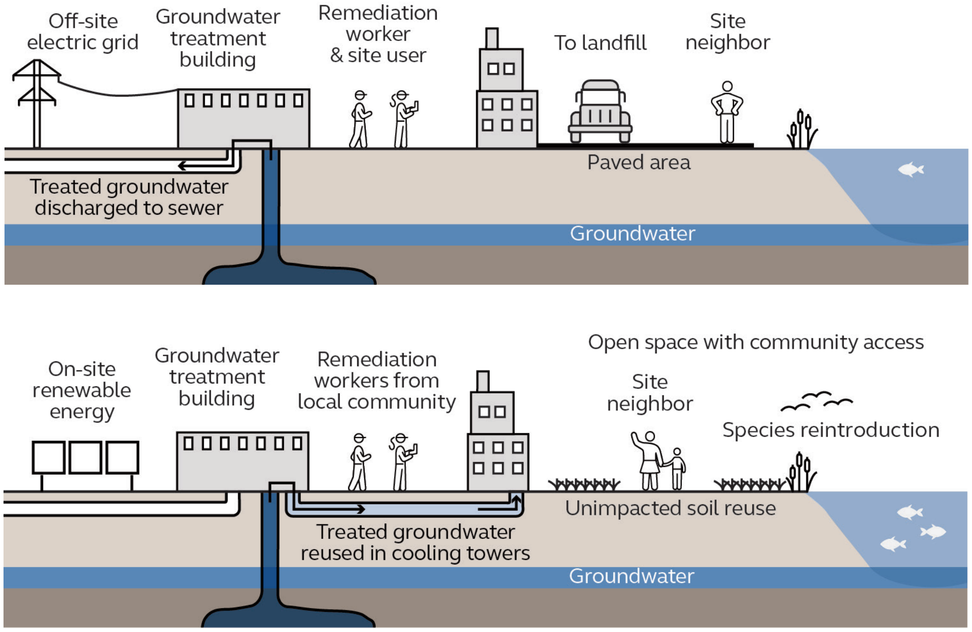

***Figure 5:** A whole systems approach.*

Concurrent with the efforts of the organizations outlined above, Arcadis developed a programmatic approach to integrate sustainability into remediation projects and portfolios. (Figure 3) This process-based approach aligns client objectives with available policy, regulations and Arcadis' own SRR objectives, translating the holistic approach of sustainability into concrete measures for more resilient project solutions.

Arcadis' identified five of the 17 United Nations (UN) sustainable development goals (SDGs) that we are able to directly affect through our project planning and implementation (Figure 4). Additionally, 3 SDGs were identified as outcomes we can encourage through project decisions. These goals can be scaled or applied based on the scope of a given remediation effort and client objectives and serve as a target for influence and measure across Arcadis projects and solutions. Additionally, concrete measures are evaluated to reduce energy and carbon, integrate climate adaptation, promote nature and biodiversity, increase circularity, and improve societal impact during project implementation.

The specific geographic location of the project(s) is also important, as local, regional, or Federal guidance documents, policies, and regulations are all used to tailor the SRR approach. These include a focus on the five elements of green remediation: total energy use and renewable energy use, air pollutants and greenhouse gas emissions, water use and impacts to water resources, materials management and waste reduction, and land management and ecosystems protection balanced with holistic sustainability metrics.

A whole systems approach

SRR integration into remediation projects is refined based on overall project objectives using a whole-systems approach. (Figure 5) Using sustainability frameworks in the project planning facilitates segmentation evaluations to identify opportunities for combining the remedy with broader considerations of property use and the surrounding communities. The planning process can be used to engage with stakeholders, better define the conceptual site model (CSM), select the evaluation metrics, and determine the plan for documentation.

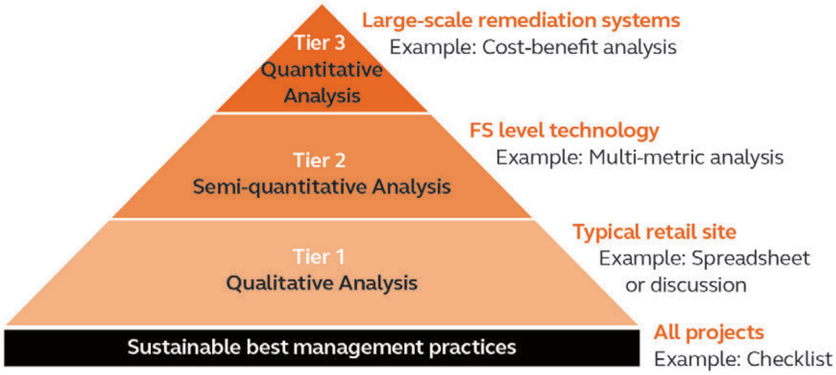

Figure 6: *Using tiered evaluation to guide integration for SRR projects.*

While refining the CSM for remediation sites has traditionally focused on delineation, understanding contaminant distribution, and assessing mass flux, an SRR approach challenges the team to look through a wider lens. Extending the site understanding to include vulnerability analysis, supply chain positioning and societal setting creates a foundation that can be built upon throughout the project life cycle. Performing these evaluations is increasingly more streamlined as digital resources have evolved. This enables management of sites at the portfolio level, with greater ease in segmenting sites based on status, outlining the required processes, and identifying reoccurring activities that can be improved for greater impact on the larger whole.

Setting evaluation metrics, levels, and boundaries for sustainability can be challenging. Metrics may be objective or subjective. A recommended approach adheres to business process reengineering (Trimble n.d.) and defines metrics that are specific, measurable, actionable, relevant, and timely (SMART). As available SRR and digital tools have evolved, our ability to measure and benchmark these metrics has improved. Most commonly, metrics are selected that align with corporate goals, green remediation core elements, SDGs and/or regional or stakeholder concerns (i.e., water, air pollution)

Within a sustainability program, it is common to have multiple levels of evaluation (Figure 6-Tiered Evaluation). These levels can be based on site-specific criteria or based on where the project is in the remediation life cycle. Sustainable remediation core elements are complex and interconnected, with varied and distinct units of measure (e.g., kilowatt-hours for energy, tons for air emissions, gallons for water). This can make development of an aggregate analysis and comparison of different remedies extremely challenging. For complex cleanup sites with various stakeholders involved in the decision-making process, a structured approach and aggregate analysis that integrates the remedial evaluation with stakeholder goals is essential.

Sustainable best management practices (SBMPs) are now strongly embraced and supported by the remediation industry. SBMPs promote resource conservation and process efficiency, which generally results in cost savings. While the evaluation of applicable SBMPs is relatively straightforward, the largest challenge is tracking improvements based on sustainability metrics. To aid in this process, we have developed a digital questionnaire platform that allows for rapid assessment of applicable SBMPs. The SBMP list used is a compilation of publicly available guidelines (EPA, NAVFAC, ASTM, ITRC, and CLAIRE) and includes a focus on regional considerations. Using preset characteristics, the SBMPs can be used to benchmark common metrics and boundary conditions with a semi-quantitative model. This connection has overcome the common hurdles of SBMPs and enables the users to “get credit” for considering and implementing sustainable project improvements. Prioritization of potential measures and the need for a full quantitative model for specific technologies or actions can be accessed at the portfolio level based on the outcome of the semi-quantitative model.

There may still be scenarios where a qualitative analysis is warranted. Many states and EPA regions have policies that require the consideration of GSR at the remedy evaluation stage. EPA also requires an evaluation of resiliency for remedy evaluation and as part of five-year reviews. With the recent issuance of the ITRC SRR guidance, it is expected that many states will gradually adopt and issue similar policies. SRR evaluations can be completed qualitatively for simple projects and most standard remedial approaches, as sustainability tradeoffs tend to be straightforward and allow for easy ranking. In cases of more complex or combined remedies, or in areas where public interest is high, it is harder to determine if the sustainability tradeoffs are balanced, and a quantitative assessment provides a more defensible analysis.

Guidance on appropriate levels of evaluation based on the remedial phase of a project is included in guidelines from ASTM (Figure 7 Project and Site continuum) and expanded in the recent ITRC SRR guidance.

Arcadis performs quantitative analysis using SiteWise^{TM}, a publicly available life-cycle assessment (LCA) tool maintained by SURF. SiteWise^{TM} assesses the remedy footprint of a remedial alternative/ technology in terms of a consistent set of metrics, including GHG emissions, energy use, air emissions of criteria pollutants, including NOx, SOx, and PM, water consumption, resource consumption, and worker safety (Figure 8). LCA is a well-established quantification framework for understanding the environmental impacts at every stage of a product or process life (creation, transport, use, and disposal), commonly referred to as cradle-to-grave analysis. We also support the emerging perspective on life-cycle assessments which states that they should be viewed from cradle-to-cradle. In other words, the waste of one product/process feeds the input of another product/process and essentially, there is no true waste. Processes therefore become a feedback loop of creating economic, social, and environmental value – creating the foundation of improved circularity.

An overarching issue during remedial comparisons is determining whether and to what degree the implementation of a particular remedy is advantageous or detrimental to one or multiple metrics. For example, selecting in situ treatment over pump-and-treat may address concerns of intensive energy use but may also result in much larger material consumption and one-time energy use to install the well network necessary to achieve acceptable treatment. Understanding, quantifying, and balancing these tradeoffs is critical to achieving net environmental benefit.

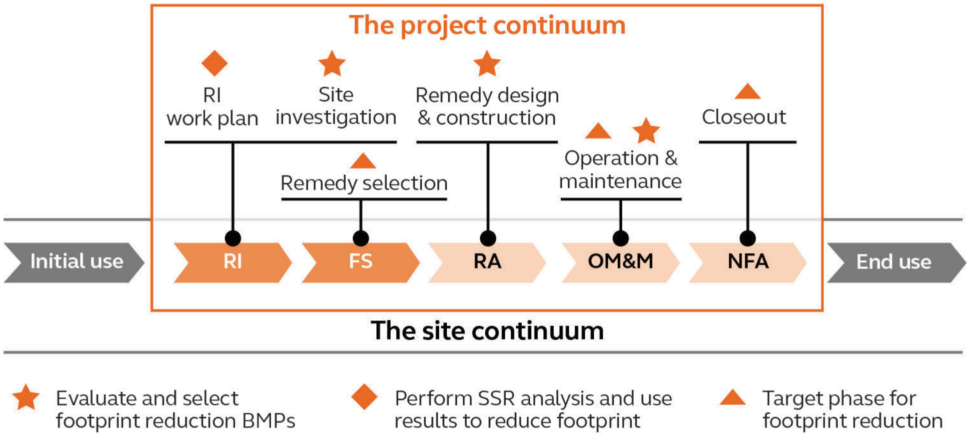

Figure 7: *Integrating SRR throughout the project and site continuum.*

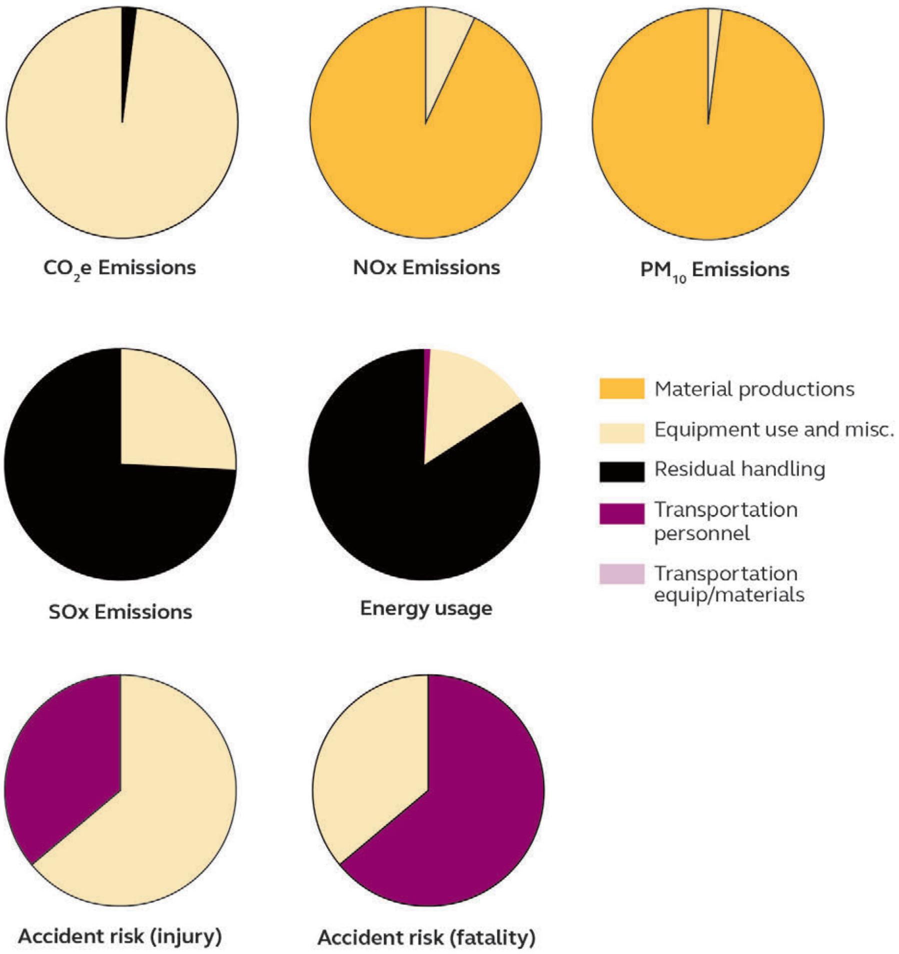

Figure 8: *Example results from SiteWise^{TM} excavation analysis.*

Triple bottom line of sustainable remediation

Truly sustainable remedies integrate both social and economic sustainability components. Often it is possible to implement a sustainable remedy that addresses both the wants and needs of a community while also benefiting the local economy or environment. For example, a desire for more green space may align with a nature-based solution that also benefits the environment (e.g., vegetated soil covers, phytoremediation), or the need for a community meeting space may be fulfilled by repurposing a vacant building, thus eliminating the cost and material needed to create a new structure. Further, economic improvements to the community can be fostered by using local vendors for such projects. Often, remediation coupled with redevelopment can lead to improved economic and social benefits. Sources of the benefits that can be pursued while planning remediation are detailed in ITRC's Sustainable Resilient Remediation (2021) and in CLAIRE 2020. When applying social and economic practices, there are several approaches that can be used to assess benefits and potential impacts: best management practices, such as ASTM's Standard Guide for Integrating Sustainable Objectives into Cleanup (ASTM E2876, 2013), BMPs coupled with a simple scoring system, or Multi-Criteria Decision Analysis (Harclerode et al. 2015).

Environmental and climate justice

The social dimension of sustainability naturally leads to the concept of environmental justice. In many cases, environmental stressors such as municipal landfills, abandoned industrial sites and wastes, and operating industrial sites, which actively produce emissions, are situated in disadvantaged areas, placing undue health burdens on the people who live in those communities. Two publicly available tools can be leveraged to understand where vulnerable populations might be impacted by environmental stress.

Economic, health and climate change factors help to identify vulnerable communities. Photo: Louisiana coastline after Hurricane Delta.

The US EPA developed EJ Screen and recently updated it as EJ Screen 2.0. EJ Screen 2.0 is a web-based digital tool that combines national environmental and population data with information on climate change risks, service gaps and the Underground storage tank database in a GIS application. Using this data, eight demographic indicators and 12 environmental indicators, three health disparities (life expectancy, asthma, heart disease), five climate change risks (wildfire, drought, coastal flood, 100-year flood plain, sea level rise) and three critical service gaps (lack of broadband, fresh foods, medical services) were identified, indicating where there may be pollution burdens and vulnerable communities.

The Council on Environmental Quality has released a 2022 beta version of its Climate and Economic Justice Screening Tool (CEJST) to identify communities at a disproportionate risk of climate change and pollution impacts. CEJST is part of the Justice40 Initiative. Both tools use publicly available, consistent, national datasets, which allows for nationwide comparisons to be made.

More than half of the U.S. lives within three miles of a Superfund, RCRA, abandoned Underground Storage Tank, or Brownfield site; the applicability of the tools is multifaceted because there is likely to be an affected community in any situation. The national tools are valuable as a starting point for sustainable remediation of contaminated properties because they can quickly identify key issues that will be critical to a stakeholder group, thereby addressing one of the three aspects of sustainability. The national mapping tools are also important to include when planning the redevelopment of properties to ensure critical community involvement and when considering the resilience of a site.

These national datasets are valuable for setting a national baseline, but they are unable to capture locally significant issues. It is still important to identify site-specific environmental and climate justice problems to capture both large scale trends and local and regional data. Some states are developing their own screening tools (e.g., Maryland's MD EJ Screen, that have richer local data and input from local communities and community groups.) While screening tools have been valuable for education, there remain challenges in connecting awareness of EJ issues with improvements in conditions. New Jersey's Administrative Order No. 2021-25, issued on September 22, 2021, develops this relationship by requiring public hearings and extending comment periods for all permit requests from facilities in overburdened communities. New Jersey's order is really the beginning of codifying community involvement in environmental decisions that impact a community.

Sustainable innovation – an Arcadis best practice

To be more deliberate and purposeful in achieving more sustainable outcomes, Arcadis seeks out, invests in, and develops SRR approaches for implementation on complex restoration projects. These approaches include patented technologies developed solely by Arcadis or in partnership with other vendors to leverage opportunities identified at project sites.

Remediation technologies

Thermal in-situ remediation (TISR$^{\text{TM}}$) (Figure 9) is a practical method for modest heating of contaminant treatment zones utilizing a sustainable heat source (generally solar or waste heat), closed loop fluid circulation system, and borehole heat exchangers (BHEs) (GWMR 2018). Thermal conduction and advection are applied in heating the subsurface by approximately 10-20°C above ambient. Elevated temperatures lead to the enhancement of existing treatment mechanisms including both biotic (i.e., biodegradation) and abiotic (i.e., hydrolysis) processes. TISR is applicable in a broad range of hydrogeologic settings, requires low capital and operational costs, and has a minimal carbon footprint that will shorten remedial timeframes and lower lifecycle impacts and costs. Use of this technology contributes to achievement of multiple target UN SDGs, with the following renewable energy sources or infrastructure innovations leveraged:

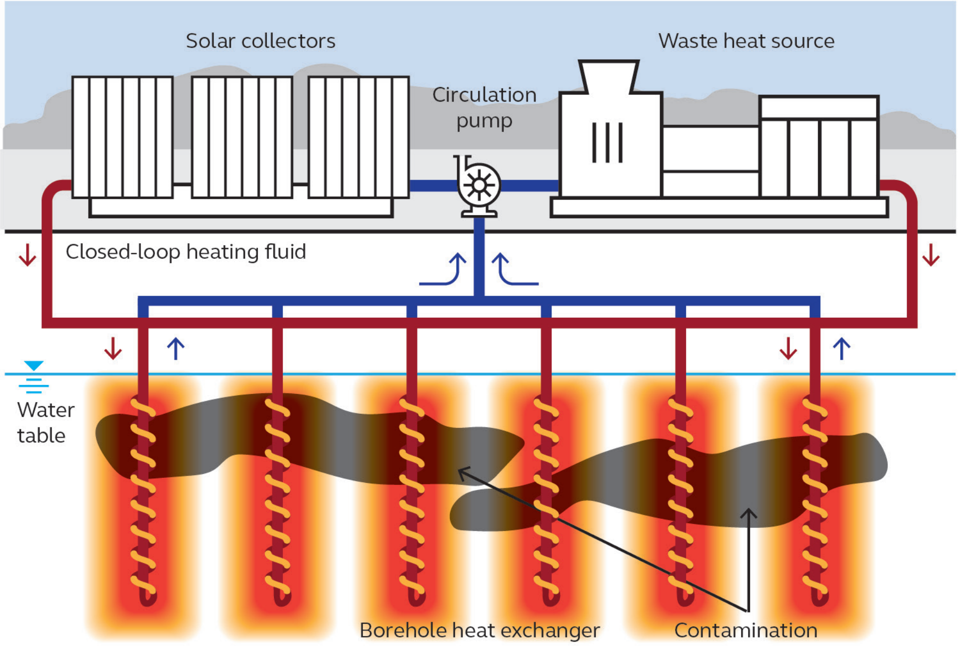

__Figure 9:__ Thermal in-situ remediation (TISR$^{\text{TM}}$) is a practical method for modest heating of contaminant treatment zones.

- **Solar Energy:** TISR has been implemented using solar collectors at 16 sites worldwide including in the United States, Mexico, Brazil, and the Netherlands. The scale and magnitude of these systems has expanded, while best practices and guidance continue to be refined for greater efficiencies and optimization of heat transfer and energy use.
- **Waste Heat**: A TISR system utilizing waste steam from an active manufacturing facility is currently underway to integrate production and remediation in a symbiotic manner. Leveraging waste heat to enhance conventional biosparge or air sparge systems provides an opportunity to reduce carbon footprint while enhancing microbial kinetics, shortening remediation time.
- **Reduced Raw Materials, Leveraging Existing Infrastructure:** TISR can be incorporated into existing infrastructure to reduce environmental restoration time, life cycle costs, and carbon footprint.

Innovative horizontal well applications for monitoring and remediation have also been developed and/or field-demonstrated by Arcadis. These wells offer a solution that results in smaller land disturbance footprints, reduced wastes and materials and reduced emissions compared with traditional installation of multiple wells to achieve the same goal. Developed through the DOD ESTCP and SERDP programs, the Horizontal Reactive Media Treatment Well (HRX) well (Figure 10) is a large diameter horizontal well oriented in the general direction of groundwater flow and filled with reactive media. Flow-focusing, resulting from the high in-well hydraulic conductivity of the engineered reactive media relative to the aquifer hydraulic conductivity, it passively directs a large capture zone of impacted groundwater into the well through the screen at the upgradient portion of the well. Because the well is filled with a reactive media, impacted groundwater is treated in situ as it flows through the HRX Well. The treated groundwater then exits the well through the screen along the downgradient section. More information on the development and use of these wells can be found on the ESTCP website.

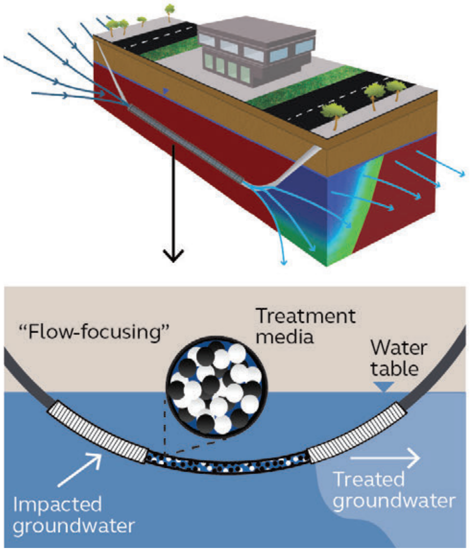

***Figure 10:** Conceptual depiction of HRX well treatment process.*

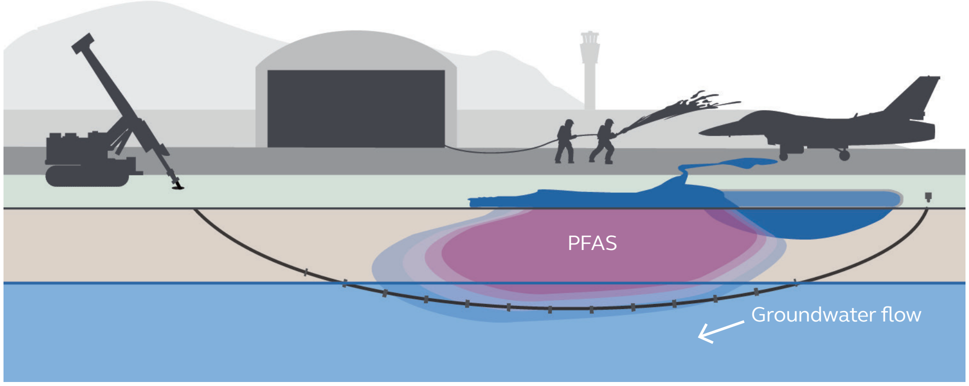

Figure 11: *Conceptual depiction of the Vertebrae™ segmented wall.*

Figure 13: *Example application of poplars for treatment of petroleum hydrocarbons.*

Another horizontal well application is the Vertebrae™ Segmented Horizontal Wells for mass flux monitoring. The VertebraeTM system is a single, small-diameter horizontal well that contains multiple isolated screen segments to serve as an engineered multi-port well that is installed horizontally instead of vertically (Figure 11). The VertebraeTM system is unique with many discrete screen zones running horizontally along its length with separate, small diameter tubing plumbed from each screen to the surface. Grout is tremied in to isolate the individual tailor-designed screen intervals which can be tailored to specific site conditions. Additional information on the demonstration testing can be found on the ESTCP website.

Similar to the HRX well, an in-situ treatment approach was developed using conventional techniques modified to leverage the benefits of an artesian aquifer impacted with VOCs. Flux from a historical source area traveled 1,500 feet downhill towards a receiving stream. At the base of the hill, artesian groundwater conditions exist which created upward plume transport and VOC discharge into the stream and surrounding flood zone (Figure 12).

The remote nature of the site, combined with a mature native forest overlying the groundwater plume and sensitive ecological receptors (endangered red cockaded woodpecker, wild turkeys, and deer) meant there were significant access limitations to mitigate the TCE impacts. Additionally, the low permeability of the native soils at the site made most traditional remedial approaches technically impractical. Balancing the overall treatment objectives and the ecosystem considerations, a sustainable, cost-effective remediation strategy was developed that leveraged the natural hydraulic conditions to achieve remedial objectives in collaboration with all stakeholders involved.

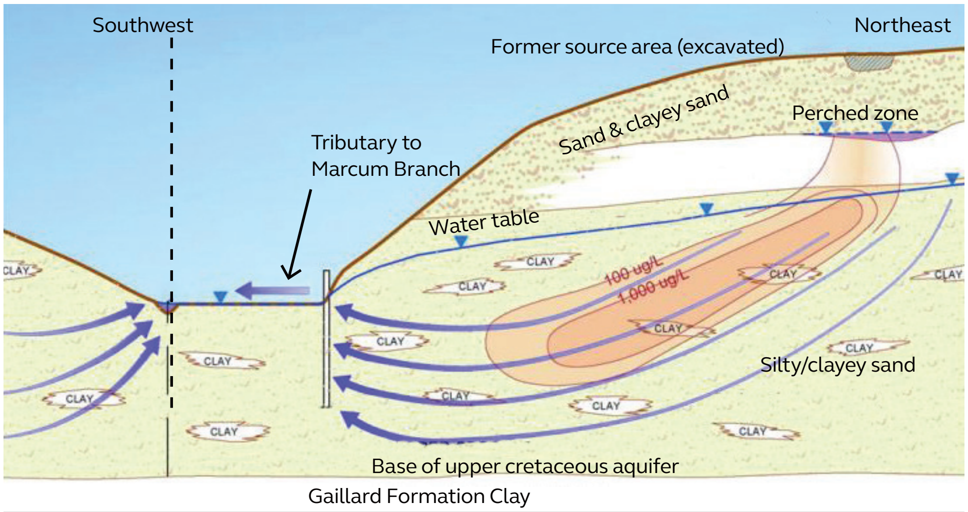

Figure 12: *Cross section showing artisanal conditions and contaminant plume migration.*

Using the natural groundwater dynamics, the Artesian Treatment Vessels were installed to facilitate passive groundwater extraction and carbon adsorption treatment. The vessels were installed below land surface and the differential upward pressure between the aquifer and the land surface to convey the impacted water through the vessels where it undergoes treatment prior to surface discharge over a gravel apron into the flood plain. Reliance on natural pressure gradients and gravity resulted in a remediation system with no moving mechanical parts, no external power source, no direct air emissions, and a minimal impact on the environment while providing sensitive riparian protection (GWMR, 2012).

The trees shown in Figure 13 are just another example of leveraging the natural site conditions to promote remediation or achieve sustainable contamination controls and is like a host of phytoremediation or phytohydraulic remedies installed to achieve passive, sustainable treatment (GWMR 2020). These methods include combinations of woody plants, native grass species, arbuscular mycorrhizal fungi, and cultured microbial strains in high moisture level areas (e.g., coastlines or stormwater collection areas) to passively control and attenuate contamination.

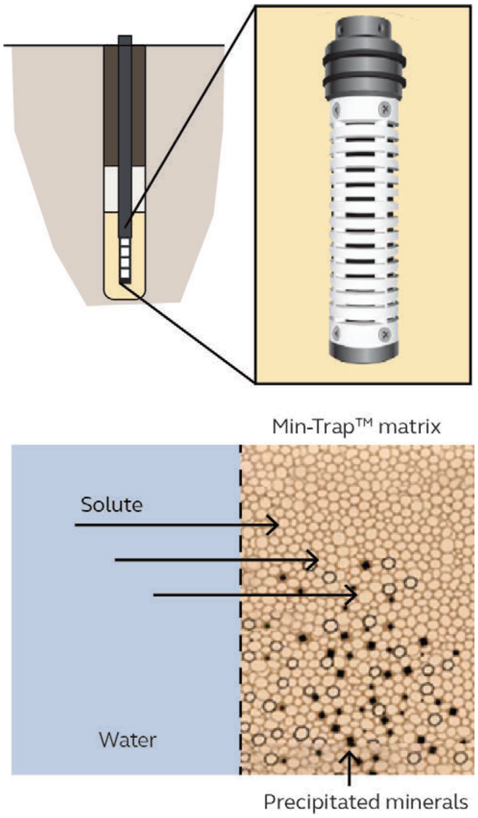

***Figure 14:** Min-Trap™ sampling device functional application.*

Sustainable sampling methodologies

Another technology developed to meet unique challenges is the Min-Trap™ (GWMR 2019). Arcadis developed this technology and then worked with Microbial Insights to bring a direct measurement device for reactive mineral quantification to scale. This approach makes it possible to directly observe the formation of reactive minerals in situ, either passively or within engineered reactive zones. The technology is used to confirm metal precipitation reactions and evaluate abiotic chlorinated volatile organic carbon (CVOC) transformation and determine decay rates.

These specialized sampling devices can be installed in conventional monitoring wells and consist of a solid porous medium contained within a permeable mesh, housed within a slotted PVC casing (Figure 14). The porous medium provides a carrier substrate upon which minerals can form passively. A nonreactive medium (e.g., silica sand), reactive medium (e.g., iron oxide sand or site soil), or a combination can be used. The use of reactive media within the Min-Trap provides a "mineral" matrix for transformation processes that would normally occur in aquifer soil. Ambient groundwater flow across the Min-Trap permeable matrix results in capture of mineral precipitates or transformation of minerals in the trap. Minerals formed within the Min-Trap can be directly characterized using any of the analytical methods described above. Min-Trap samples effectively concentrate the fraction of interest within a uniform matrix, tempering background "noise" in the data during analysis (when compared to analysis of native soil from core samples). By the nature of their design, Min-Traps only measure minerals that are actively forming in an aquifer system.

Arcadis was an early user and promoter of passive sampling devices, and to date has deployed more of these samplers than all other firms combined.

Compared to the Min-Trap sampling methods, traditional means for obtaining similar data require drilling to collect whole undisturbed samples for analysis. Instead, the Min-Trap device can be deployed repeatedly in the same location, without drilling, to obtain a time series of data and gain repeatability. In addition to the improved data quality, the Min-Traps reduce the emissions footprint previously required for drilling, reduce health and safety risks associated with the sampling activity and improve stakeholder and regulatory agency engagement.

The development of the Min-Trap sampling device was preceded by an extensive history in implementation of more sustainable sampling tools and equipment. As a firm, Arcadis purchases and deploys more passive sampling devices on our project sites that all other environmental firms, combined.

***Figure 15:** Hydrosleeve™ Passive sampling device.*

Passive sampling devices are designed to sample groundwater within a screened interval of a permanent monitoring well without pumping or purging. Given that the screened interval is in dynamic equilibrium with the adjacent formation groundwater, passive samplers can obtain representative groundwater samples when used appropriately. Several passive sampling devices have been developed, and testing has shown that passive samplers can replace traditional purge-based sampling and low flow purge methods without loss of data quality (ESTCP). Whether it entailed PDBs, Hydrasleeves™ (Figure 15) or Snap Samplers™, the transition to these methods shortens the duration of field activities, reduces emissions associated with travel, and eliminates purge water created during the sampling events, often eliminating the need for off-site waste disposal.

Digital innovations, as described elsewhere in this eBook, provide entirely new platforms from which to improve sustainability. Arcadis' remote expert services is a solution to provide expertise and access at a site without having to physically travel to the site. Interactive tools allow teams to record significantly more data, view shared maps and images, and collaborate via interactive onscreen video in real-time. The ability to see field conditions and interact with on-site personnel to make rapid decisions provides value to project schedules, costs, and safety.

These innovations are already translating to improvements in passive monitoring. Currently in development via ESTCP funding are novel, in-field-scale demonstrations of Real-Time Sensors for PFAS (ESTCP). This project aims to field-validate the use of a portable electrochemical sensor technology for rapid assessment of per-and polyfluoroalkyl substances (PFAS) at DoD sites. Comparatively low regulatory screening levels for PFAS have created a need for faster, reliable, and cost-effective measurement. The PFAS electrochemical sensor is an adaptable technology that will be integrated into a broad range of applications, such as initial characterization and remedy evaluation.

Integrated approach

Arcadis' programmatic approach to SRR integration provides a framework to go beyond industry standards to leverage digital tools, identify site-specific needs, and develop innovative methods to outline a tailored approach to meet project objectives. We support this framework through a culture of innovation, a whole systems view, and continuous stakeholder dialogue to incorporate and meet rising social considerations. These frameworks facilitate effective management of sustainability by clearly identifying ambition levels, prioritizing goals in decision making processes, outlining implementation benchmarks, and communicating the results in user-friendly dashboards as part of the regular reporting process. Through this, we will continue to unlock sustainable opportunities from scientific, regulatory, and stakeholder perspectives to fully realize the triple bottom line.

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1. *ITRC (Interstate Technology & Regulatory Council). 2021. Sustainable Resilient Remediation SRR-1. Washington, D.C.: Interstate Technology & Regulatory Council, SRR Team.*

About the authors

Jessica Gattenby leads the Sustainable Resilient Remediation Focus Area within Arcadis Technical Knowledge and Innovation Group and has more than 18 years of experience in environmental consulting and sustainable management. Specifically, she focuses on sustainable environmental management program development and implementation, integrating sustainability into remediation projects, sustainability training, developing remedial site strategies, and performing feasibility assessments and costing. Ms. Gattenby has led the use of sustainability assessments to support client decision making, gaining support of project stakeholders and reducing life cycle costs. As a member of ASTM Jessica participated in the working groups to create the ASTM guidelines for green, sustainable and resilient remediation. Most recently Ms. Gattenby was a member of the team that authored the ITRC Sustainable Resilient Remediation guideline.

Stephanie Fiorenza, PhD, is a Principal Scientist and Technical Lead for the Oil & Gas sector at Arcadis U.S., Inc. She also supports PFAS site assessment, remediation, and research projects across the organization. In her previous employment in BP's Remediation Engineering and Technology group in Houston, TX, she was the focal point for sustainable remediation efforts within BP. Dr Fiorenza was a founding member of the Sustainable Remediation Forum (SURF) in 2006, a member of ITRC's Green and Sustainable Remediation work group and internet trainer and is currently the Task Group Leader for ASTM's Climate and Community Mapping standard guidance, which focuses on environmental justice and climate change issues. She has presented on sustainability and sustainable remediation topics in the U.S. and overseas over the last 10+ years.

Plastic in the environment

Shannon Dunn

Plastic in the environment

Shannon Dunn examines the impact plastic pellets have on the environment and discusses how we can address this emerging concern.

11 minute podcast

Plastic pellets (including plastic polymer such as powder, flake, and fluff) are manufactured as base products for the plastic industry. Releases of plastic pellets into the environment are persistent, highly visible and pose a mitigation challenge. The easily recognizable nature of plastic pellets has recently led to several high-profile settlements in the United States based on violation of the Clean Water Act. These settlements — and the associated public responses — have led to enhanced regulatory scrutiny that presents a rapidly emerging liability and requires a proactive, thoughtful management approach.

Addressing liability related to the release of plastic pellets is challenging due to the convergence of several factors:

- **Lack of regulatory guidance:** The regulatory landscape is evolving with inconsistencies across states as new regulations are proposed and implemented.
- **Lack of standardized analytical methods:** Unlike other contaminants, there are no standardized analytical methods and no contaminant level thresholds to measure against.
- **Risk perception:** The mobile and highly visible nature of plastic pellets leads to a perception of greater harm, which contributes to a growing global ecological concern about plastics in the environment.
- **Comingling of released pellets:** Multiple sources of released pellets pose a challenge to differentiating between sources.
- **Mitigation challenges:** The physical properties of plastic pellets lead to widespread dispersion into aquatic environments that make it difficult to access and remove pellets without doing damage to the area that is targeted for cleanup.

Despite these challenges surrounding plastic pellets in the environment there are strategies to position your organization to address this emerging concern in a proactive, risk-based, and informed manner.

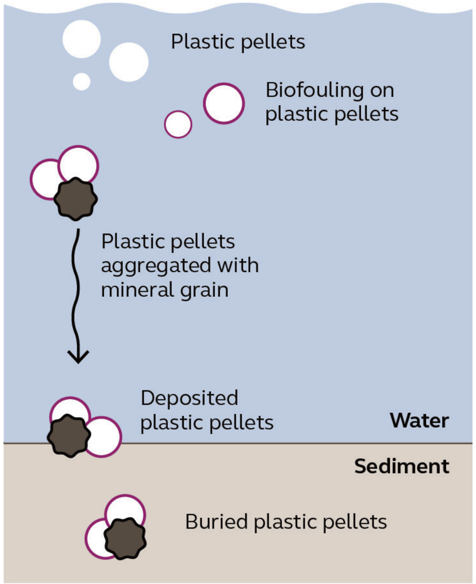


***Figure 1:** How pellets are deposited in sediment.*

Risk from plastic pellets

Pellets often enter the environment from spills through stormwater. Accidental single or long-term loss of pellets at manufacturing facilities or during transport can be carried into the environment via stormwater that discharges to waterbodies, including wetlands. Once in waterbodies, pellets may accumulate on the water surface, the shoreline, and in the sediment. Many plastics have densities less than water and are therefore buoyant. Biofilms commonly form on the plastics, leading to agglomeration of pellets and denser particles that may settle. This results in pellets being deposited in sediment (Figure 1).

Plastic pellets alone are not inherently toxic or dangerous to human health. Ecological risk assessment on plastic pellets is a developing science. Two primary concerns are being evaluated for ecological risk from plastic pellets: risk from the physical pellets and risk from chemicals that may be released during digestion of the pellets.

The physical risk of pellets is being studied, but initial assessment of the risk from chemicals leaching from pellets indicate it is an insignificant risk. As the risk assessment science develops, the current focus is the aesthetic impact of pellets in the environment.

Source control

The first step of any cleanup action is to control the source of pellet release. Then, pellet cleanup can be cost-effectively planned, permitted, and performed. If the source is not controlled, cleanup efforts become a routine housekeeping action — not the remediation of a liability. Source control should include a facility evaluation to identify where and how pellets are released. The plastic industry proactively developed an effective template for multifaceted source control leveraging a combination of engineering controls and routine housekeeping practices to prevent the release of pellets, contain pellets that are released, and clean up the released pellets.

A key element of any source control program starts with stormwater best management practices (BMPs) to capture pellets that are not controlled by the facility's prevention, containment, and cleanup program. Stormwater BMPs can be implemented to prevent pellets from entering the stormwater system and contain the pellets in the stormwater system. A hierarchy of BMPs balances the infrastructure needs for the BMPs and the amount of pellet capture (Figure 2). Routine maintenance of the stormwater system includes cleaning out the accumulated pellets to avoid discharge of the pellets with the stormwater.

Addressing pellets in the environment

Cleanup of historically released plastic pellets, whether on- or off-site, is a challenging undertaking given several factors: the potential for plastic pellet transport in waterbodies, the dispersed spatial extent of pellet distribution, and the comingling of pellets with environmental media. Cleanup techniques are well proven, commonly available, and widely delivered, but matching the technique to site-specific conditions is integral for successful cleanup. Although there may be urgency for action, thoughtful consideration of the overall cleanup strategy confirms that the cleanup response is commensurate with the risk. This includes tackling the fundamental and often difficult question: "how clean is clean?" Establishing cleanup criteria and project success metrics are critical in the planning stages. Each cleanup area should be defined, and a response developed that is scaled to the extent of impact and best

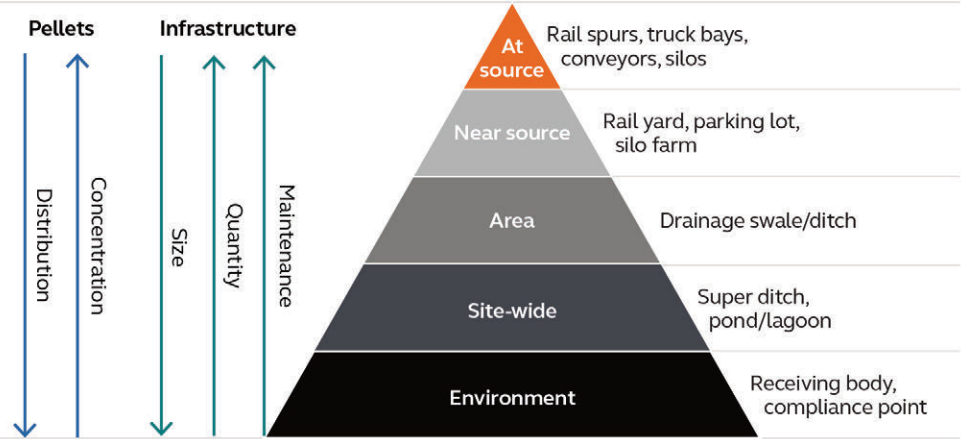


***Figure 2:** Stormwater BMP hierarchy of control.*

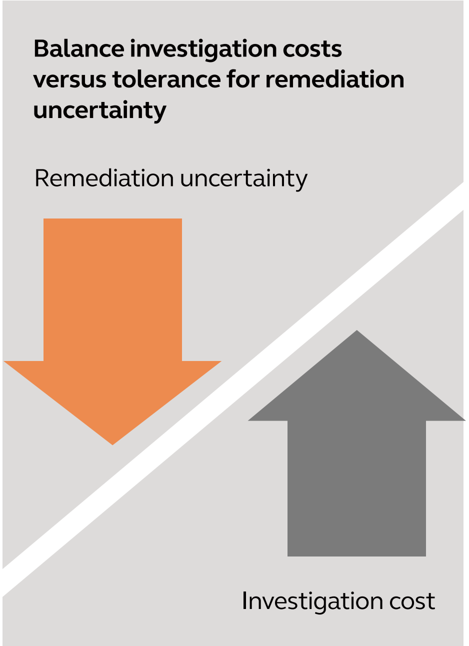
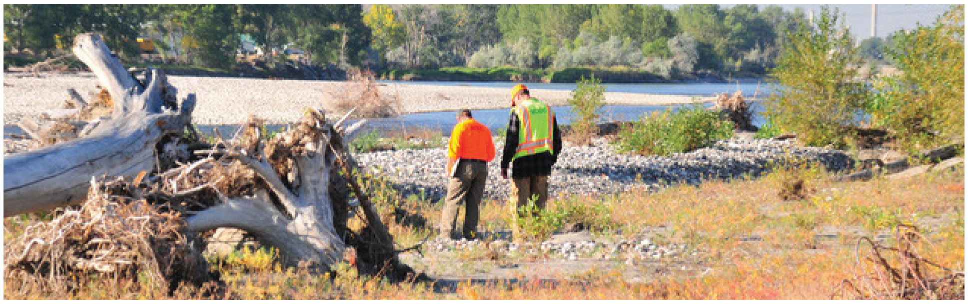


Figure 3: *How to address data gaps.*

methods of removal. A tiered remedial approach may be applicable when site characteristics and pellet density vary. Obtaining stakeholder and regulatory buy-in is important given the absence of promulgated criteria which creates a risk for re-openers on completed remediation.

It might be tempting to launch a cleanup effort quickly to show your organization is tackling this challenge head-on. However, without a proper risk-based site investigation a cleanup will always struggle to establish and meet a "how clean is clean" expectation. Similarly, as research and regulations evolve, you may find out your cleanup was done incorrectly and resulted in undo harm to the environment. Rushed cleanup responses could very well complicate or even increase overall liability.



So how clean is clean?

The cleanup of plastic pellets in the environment presents several challenges. First, the risk reduction benefit of removing all pellets is questionable when compared to the impact of the cleanup on the environment. Second, in the absence of a defined chemical concentration that serves as a cleanup level for remediation, cleanup goals are considered qualitative rather than quantitative. Finally, establishing a qualitative goal for removal of all pellets presents its own significant compliance and contracting challenges – as this is often infeasible and cost prohibitive.

To address the challenges above, we have modified the oil spill remediation approach, which uses visual objectives to define cleanup, to instead describe pellet cleanup goals. This approach defines cleanup goals, based on the physical attributes of affected areas, to determine when sufficient remediation has been performed. This method acknowledges the value of existing habitat and public space. In turn, this balances pellet removal with minimization of the removal action on the natural environment. Defining meaningful, measurable, and achievable cleanup goals will assist in stakeholder agreement on project endpoints and in reducing construction costs and disputes.

Tips to address pellets in the environment

Site investigation is usually needed to evaluate the extent of pellets in the environment, the extent of which is often driven by the performing party's risk management approach. More investigation has increased field work costs but reduces uncertainty in design and remediation (Figure 3). Less investigation increases remediation planning uncertainty and then needs to be managed during cleanup contracting. In our experience, the site investigation usually includes a visual survey at a minimum and may include soil and sediment sampling to evaluate if buried pellets are present. If microplastics are of interest, surface water and biota tissue sampling may be performed.

In the face of future regulatory and public scrutiny uncertainty, the remediation plan should revolve around your unique risk profile, site conditions, stakeholders, and resources. Addressing plastic pellets in the environment warrants a site-specific risk-based approach (Figure 4). One size will not fit all. The process starts with on-site source control, which can then be coupled with adaptive plastic pellet site investigation and delineation. On-site source control can include hydrodynamic modeling to estimate transport of pellets

Source control and cleanup levels	Delineation	Cleanup method & permitting	Removal	Post-construction management
• BMPs • Remedial action objectives	• Survey	• Technology evaluation • Contracting • Permitting	• Removal • Construction management • Completion report	• Monitoring • Liability management

Figure 4: *Site-specific pellet management process.*

in the environment. The modeling informs the extent of the site investigation. Next, define the cleanup levels based on the delineation. Defining the cleanup goals will set the basis for design and the benchmark for remediation oversight. This effort is followed by an informed evaluation of cleanup methods and permitting requirements, removal action implementation, and post-cleanup monitoring. In our experience, remediation often requires permits, particularly if the remediation is in a wetland or waterbody. Stop gates can be included in the process to allow for senior management engagement, risk review, options analysis, stakeholder engagement, and data-driven decision-making as the plan progresses.

Pellet removal techniques range from manual collection to heavy yellow-iron excavation and dredging. The appropriate cleanup method will depend on site conditions and cleanup goals. For example, vacuum trucks can be effective for accumulations of pellets on soil and skimming pellets off the surface of the water can be performed with mobile or stationary systems and automated or manual methods. Any method of pellet collection often also collects other media including non-plastic waste, vegetation, and soil. Whether to separate plastic from other media prior to reuse or disposal is a project-specific decision that depends on regulations (some jurisdictions have bans on disposing of plastic in landfills), the suitability of the plastic for and if there is a market for reuse of the plastic, and cost. Multiple separation technologies used in soil remediation or industries in theory would work for plastics but there are not many full-scale project examples to confirm this.

Investments in source control and remediation need to be future-proofed. Long-term monitoring and maintenance of facility pellet control and stormwater BMPs are essential tools to verify that pellet management remains effective. These ongoing processes confirm elimination, or reduction, of continued pellet release and document that the remediated areas remain protected.

Conclusion

Addressing plastic pellets in the environment is a challenging endeavor. With stakeholder commitment and deliberate consideration, development of a site-specific, risk-based approach is achievable. Develop a strategy for pellet management. Perform source control within the facility and in the stormwater system. Identify cleanup goals. Proactively addressing current risks and future-proofing liability creates a position that is resilient to growing public scrutiny and regulatory oversight.

About the author

Shannon Dunn, PG, leads Arcadis' Sediment Community of Practice. She works on aquatic sites, including investigating and remediating plastic in aquatic systems. She manages multidisciplinary teams to meet clients' objectives on sediment management sites. She is participating in ITRC's development of microplastic guidance.

Multiple lines of evidence approach for evaluating mining-related impacts at abandoned uranium mines

Paul Knightly, Monica Heintz and Richard Murphy

Evaluating Mining-related Impacts at AUMs

Paul Knightly discusses the multiple lines of evidence approach he and his team are using to identify and evaluate abandoned uranium mines.

12 minute podcast

Introduction

A multiple lines of evidence approach has been developed and applied to the characterization of abandoned uranium mines. This approach allows for a robust, data-based assessment of mining-related impacts and sets the framework for future evaluations of potential site risk and remedial actions for these mines. Though developed specifically for these mines, the approach or process can be adjusted and leveraged for use at other unique impacted sites.

Abundant uranium deposits at and near ground surface are a characteristic feature of many areas of the Colorado Plateau, including in the Navajo Nation in northern Arizona. A series of geological events including sedimentation, lithification, roll-front and humate-type uranium mineralization, and erosion from the Colorado and Little Colorado River basins resulted in the development of an economic source of uranium[1, 2, 3] that was heavily mined in open-pits during the Cold War arms race in the 1950s and 1960s[3, 4, 5]. There are over 4,000 abandoned uranium mines (AUMs) in the United States, with approximately 500 in the Navajo Nation[6]. These AUMs are subject to ongoing reclamation and remediation efforts. Due to the presence of naturally occurring radioactive material (NORM) at the surface, there are challenges associated with defining disturbance feature boundaries, assessing potential offsite transport, and comparing site and background conditions for meaningful assessments of risk and necessary remediation. These challenges reflect the difference in conceptualization of impacts from surface AUMs relative to the conceptualization of more "traditional" remedial investigations.

Typically, such as in the case of a surface release of chemicals at an industrial facility, "contamination" is characterized by a localized area of elevated concentrations and decreasing concentrations with distance from the source area in the direction of transport. In these typical cases, the nature and extent of contamination can be defined by the detection and characterization of the constituents of concern. In contrast, at surface AUMs, NORM at ground surface was mined with the objective of recovering maximum-grade ore. In most cases, NORM is heterogeneously distributed both within mine site boundaries and adjacent areas. Because the material that was altered and disturbed is also naturally and heterogeneously distributed across the areas of potential impact, it is difficult to accurately distinguish the effects of mining.

Mining-related activities occurred over three phases: exploration, production, and reclamation. The exploration phase was focused on locating economically viable ore deposits and often involved using bulldozers to remove overburden to determine the lateral extent of ore bodies. The production phase involved extracting ore from shallow bulldozer cuts and pits that were up to 40 meters deep[5] and transporting mined ore to nearby mills for further processing. The reclamation phase consisted of initial efforts to reduce hazards present at AUMs by consolidating mining-related materials into the pits, and then covering the pits with locally sourced borrow material. In some cases, mining resulted in an overall decrease in radioactive material in areas where the most mining activity occurred, while in other cases, exploration and production mining activities resulted in disturbances that may alter and even potentially enhance exposure to harmful constituents, including uranium, radium-226, and associated metals.

Mining-related features present two types of hazards: physical hazards and radiological and/or chemical hazards. Physical hazards primarily include issues related to landform stability while radiological and chemical hazards include exposure to constituents of concern by a variety of potential pathways. Identifying features related to each of the phases of mining related activities using multiple lines of evidence provides a framework for determining where radiological and chemical hazards are the result of site disturbance, where this type of hazard is attributable to undisturbed NORM, and where there may be physical hazards associated with mining-related features that do not currently present a radiological or chemical hazard. In some cases, a feature may present both types of hazard (e.g., a bulldozer cut that exposed material with higher radioactivity than the overburden that was removed and is also experiencing active physical erosion). In other cases, a reclamation feature (such as a cap) may not currently present radiological or chemical hazards, but if it is physically unstable and left unaddressed there may be a radiological and/or chemical hazard in the future. These hazards are evaluated in the context of mapped site features, geology, and transport mechanisms and characteristics.

The multiple lines of evidence-based mining forensics approach presented herein includes a detailed review of historical records and aerial imagery[7], geological/geomorphological and mining-related disturbance mapping, collection of high-resolution gamma data by walkover scans using sodium iodide scintillation detectors, and soil sampling with vertical delineation (drilling) to verify mine pit depths. The integration of these lines of evidence enables the delineation of mining and non-mining features on and near the site. This distinguishes undisturbed naturally radioactive areas (i.e., NORM) from radioactive areas disturbed by mining-related activities. This approach allows for a robust, data-based assessment of mining-related impacts and provides a framework for future evaluations of potential site risk and remedial actions for these AUMs.

Methods

Prior to the start of field work, a cultural resource survey was performed by a Navajo-owned company and a biological survey was performed by Arcadis. The purpose of the surveys was to identify cultural artifacts or sensitive species that would otherwise be impacted by site characterization activities and any subsequent restoration activities at the site. When identified, care was taken to not disturb or adversely impact any cultural artifacts or sensitive species on-site.

Following the cultural resources survey, site investigation activities included the following:

Surface walkover gamma scanning

Gamma scanning helps assess the surficial distribution of radium-226 at AUMs. Because gamma radiation is not attributable solely to radium-226, but to all radionuclides that emit gamma rays during radioactive decay, soil samples are used to correlate gamma scanning results with actual radium-226 activity concentrations. To assess the surface gamma radiation levels within and outside of AUM boundaries, a series of surface gamma scans were conducted.

Gamma measurements were collected using multiple Ludlum Model 2221 ratemeters with Ludlum Model 44-10 NaI(Tl) 2- by 2-inch probes (2x2 systems), coupled with global positioning system (GPS) connectivity. The response in terms of counts per minute (cpm) varies for each detector based on instrument-specific factors (e.g., instrument efficiency, operating voltage). Additionally, the response of each detector may change between field events due to adjustments during calibration and maturation of the instrument. Therefore, the data were normalized per field event.

Daily operational checks were performed prior to and after collecting field measurements at AUM sites, with and without a cesium-137 check source in a consistent configuration to verify instrument operability. Daily operational checks were conducted to document detector response for each instrument used during the field events to develop normalization factors for each detector.

Geology, hydrology, and geomorphology mapping

Geologic maps[8, 9] and descriptions[3, 10] were consulted prior to conducting field work to gain an understanding of the regional geology. The geological units that are present onsite were classified during initial site visits and the gamma walkover surveys. Site geology and geomorphology were mapped using the same backpack-mounted GPS and tablet systems used for the walkover gamma surveys.

Onsite watershed boundaries and surface water features (channels and ponds) were mapped using the GPS and tablet systems. Onsite watershed boundaries were mapped by starting at the onsite point of maximum elevation and then walking downgradient along the high ground between channels. Surface channels were mapped to delineate potential preferential pathways, and gamma measurements were used to assess for potential transport of disturbed material. A total of five separate transects were mapped for each channel: the primary channel thalweg (1), each channel bank (2), and each channel overbank (2).

Delineation of mining-related disturbance features

Mapping mining-related disturbance features is a critical step towards achieving the primary objective of distinguishing between disturbed and undisturbed areas. This is accomplished by delineating features spanning the exploration, production, and reclamation phases of each site's history. Associating mapped features with known exploration, production, and reclamation practices provides a distinction between mining-related and non-mining related features that may be present on each site. This mining forensics approach incorporates other factors, such as site geology, that help to place features in context with areas of mineralization (e.g., a mine pit or exploration-related features are not likely to be located in areas with low-grade ore or low to no mineralization present).

A desktop review of historical and modern aerial photos, aerial radioactivity survey results[11, 12], historical mining documents and references[3, 5], and Navajo Abandoned Mine Lands (NAML) reports and reclamation maps was conducted prior to field mapping of mining-related disturbance features. These historical reports were used to understand potential disturbance areas before arriving at each site.

In the field, conservative mapping methods were used to minimize the possibility of overlooked features. These techniques involved mapping areas slightly larger than the observed footprint

Figure 1*: Examples of commonly identified mining-related disturbance features. A) Exploration-related bulldozer cuts with overburden. B) Drill roads along a Petrified Forest Member hillslope. C) NAML reclamation cap adjacent to local geology. NAML cap comoposed of bentonite sourced from the Petrified Forest Member and native geology is Shinarump Member sandstone subcrop.*

and mapping features that resembled but were not positively identified as mining-related disturbances. In addition, historical information was provided in the field by a former NAML employee, community liaison, and resident.

Disturbance features were identified and are classified into three main types:

- Exploration features include bulldozer cuts, boreholes, drill roads, overburden (push-off), pick and shovel work.
- Production features include bulldozer cuts, mine pits, haul roads, overburden (push-off), stockpile areas, visible remaining waste, and waste piles.
- Reclamation features include borrow areas, reclamation caps, reclamation-related roads, reclamation staging areas, scarified roads, and water bars.

In addition to these types of disturbance features, potential transport pathways (e.g., erosion of material from each site into channels) were evaluated, as described in the following section.

Standardized methodologies were used to delineate mining-related features in the field. For brevity, the process involved with mapping bulldozer cuts and overburden are described here, however the methods for delineating other exploration, production, and reclamation features adhere to similar mapping principles.

Bulldozer cuts may be related to the exploration and/or production phase of mining. Exploration bulldozer cuts (Figure 1) removed overlying material to explore for potential mineralized materials. Production bulldozer cuts were made to remove mineralized material for subsequent transport and processing. Exploration and production bulldozer cuts are mapped, including windrows and terminal berms, by conservatively walking along the outer extent of the disturbance.

Exploration and production bulldozer cuts are identified and distinguished by evaluating lines of evidence in the field based on the following:

- Both exploration and production bulldozer cuts are usually linear features that are devoid of vegetation.
- Both exploration and production bulldozer cuts have characteristic windrows and/or terminal berms, allowing these disturbances to be distinguished from other linear features (e.g., roads).
- Exploration bulldozer cuts may be hundreds of meters, while production bulldozer cuts are typically shorter (tens of meters).
- Exploration bulldozer cuts can vary in size depending on the bulldozer used. Some exploration bulldozer cuts can be up to 5.5 meters wide, while others are smaller (generally 1.2 to 1.8 meters wide). Production bulldozer cuts are typically 1.2 to 1.8 meters wide.

- Production bulldozer cuts are typically in a focused area and often overlap, whereas exploration bulldozer cuts of similar width are typically longer and often form radial or linear patterns that were part of a systematic prospecting effort.
- Exploration bulldozer cuts most often run straight downhill/uphill; rarely, they track along a geologic contact. Production bulldozer cuts are often grouped and/or overlapping in localized areas with exposed mineralization, often near a mine pit area.
- Erosion features such as rills may form within or at the edges of exploration bulldozer cuts. These erosion features are not as commonly associated with production bulldozer cuts or other linear features such as drill roads or trails.
- Exploration bulldozer cuts may be cross-cut by more recently created disturbance features.

Overburden material that was removed to access potential higher-grade ore was often pushed over a slope or cliff and is often associated with bulldozer cuts (Figure 1). This material can be identified based on the following observations:

- Piles of rock that are unnaturally broken up (more so than from natural erosional forces), out of place stratigraphically, and/or contain rocks positioned at unnatural angles on slopes.
- Crushed or broken pieces of normally coherent rock that would be expected to be intact in the absence of mechanical disaggregation.
- If the overburden was pushed over the edge of a slope or cliff, bulldozer cuts or pick and shovel work can often be seen in the area above.
- Disturbed overburden is mapped by walking the perimeter of the area identified. If the edges of the area are inaccessible, overburden may be mapped by digitally drawing the feature in the field using the best approximation of the physical location and shape, which may be refined later using aerial photos.
- Evaluation of potential transport of radiological materials

In addition to evaluating mapped mining-related disturbances, assessment of potential enhanced downgradient transport of radiological material in channels as a result of mining activities is necessary to fully distinguish the extent of mining impact. Three types of material could be transported in the channels: naturally eroded material from undisturbed areas (may include NORM), NAML cap material, and material from exploration or production disturbance areas. NAML cap material is frequently sourced from offsite borrow areas or from onsite borrow sources (frequently Petrified Forest bentonite) that are visually distinct from adjacent geology. Potential for enhanced transport was evaluated using visual, sedimentological, geomorphic, and radiological lines of evidence in conjunction with observations of interpreted exploration, production, and reclamation features. During channel surveys, channel sediments and loose rocks were continuously compared to the geology of the banks and overbanks along the length of the channel to determine if the material is consistent with expected geology or was potentially transported from onsite areas.

Locally elevated gamma readings can be due to transported eroded NORM, in-place NORM (i.e., undisturbed bedrock), or transported material from disturbed areas onsite. Gamma scanning along the bank and overbank helps to distinguish in-place NORM from transported material (naturally eroded NORM or disturbed sediments) by establishing the in-place radiological conditions along the channel. NORM is interpreted to be present in areas where radiologically elevated measurements are uniformly observed between the bank/overbank and within the channel. In areas where gamma measurements in the channel are greater than those made on the bank/overbank, the sediments could be influenced by transported material from disturbed areas upgradient. In a situation where potential transported disturbed material is present in channels alongside NORM, the appearance and composition of the potential transported disturbed material relative to the in-place NORM and the known composition of transported disturbed material onsite can be used to distinguish material origin.

Vertical delineation

At sites with former mine pits that were subsequently backfilled during reclamation, vertical delineation is needed to distinguish between disturbed material and NORM at depth. Drilling was conducted using a hollow-stem auger rig to delineate pit depths and to locate the interface between the pit (mining disturbance) and undisturbed bedrock (NORM). This also enabled the calculation of more accurate estimates of the volume of consolidated material in the former mine pits. Boreholes were drilled until undisturbed geology was identified in the drill cores, indicating that the base of the pit had been reached. Soil cores were logged and screened using a “pancake” frisker probe. In addition, a Ludlum Model 44-2 probe was used to collect down-hole static gamma measurements every 15 centimeters. Soil samples were collected and analyzed at discrete intervals.

Discussion

The methods described in the preceding section have been implemented at approximately 30 AUM sites. For brevity and clarity, the results from one site are discussed here. Figure 2 displays the distinct exploration (A.), production (B.), and reclamation (C.) feature boundaries mapped at the site.

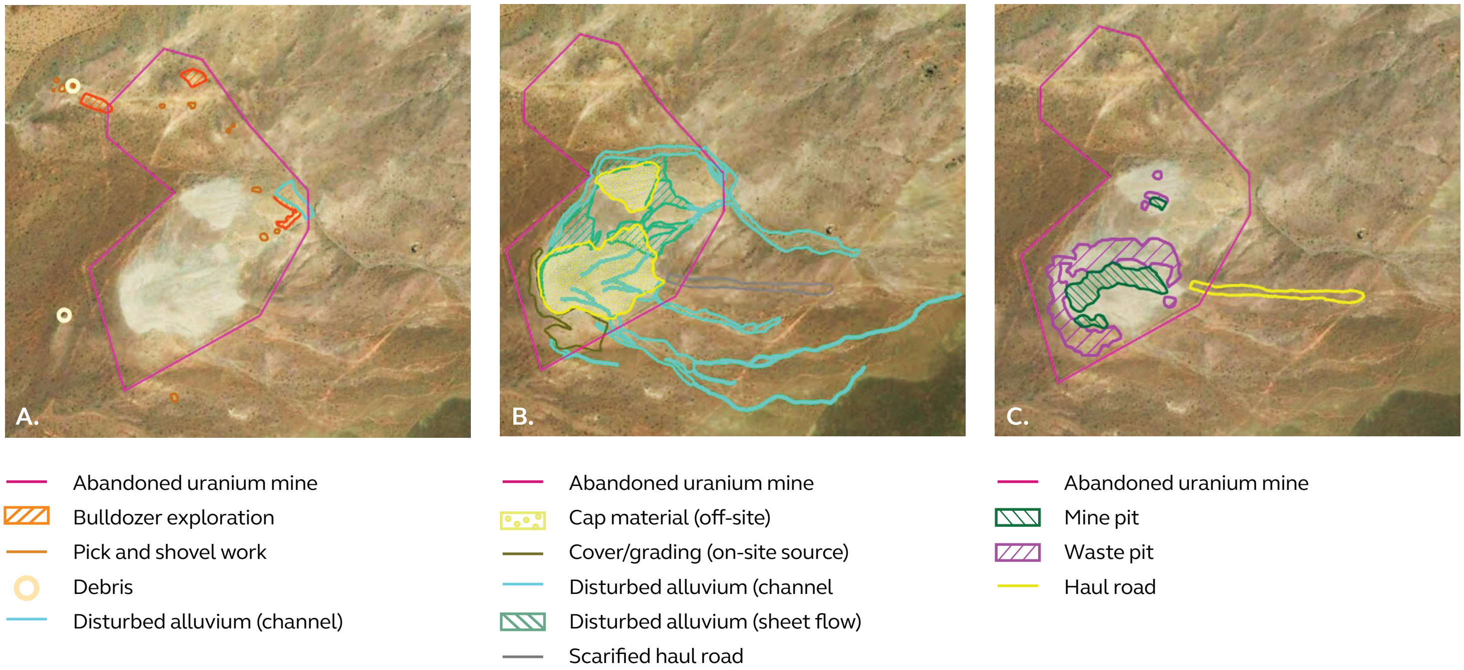


Figure 2: *Example of mapped mining-related disturbance features relative to the USEPA site boundary (pink).*

A. Exploration disturbances include bulldozer cuts and pick and shovel work. Bulldozer cuts at the site are attributed to exploration only as the cuts were not disturbed further through removal of mineralized material (production). Exploration bulldozer cuts (orange) at the site range from tens to hundreds of meters in length. Pick and shovel work (tan) was conducted for smaller scale exploration and is identifiable in rock as potholes and down-cut areas generally following a mineralized layer; individual pick marks are sometimes visible in these small depressions.

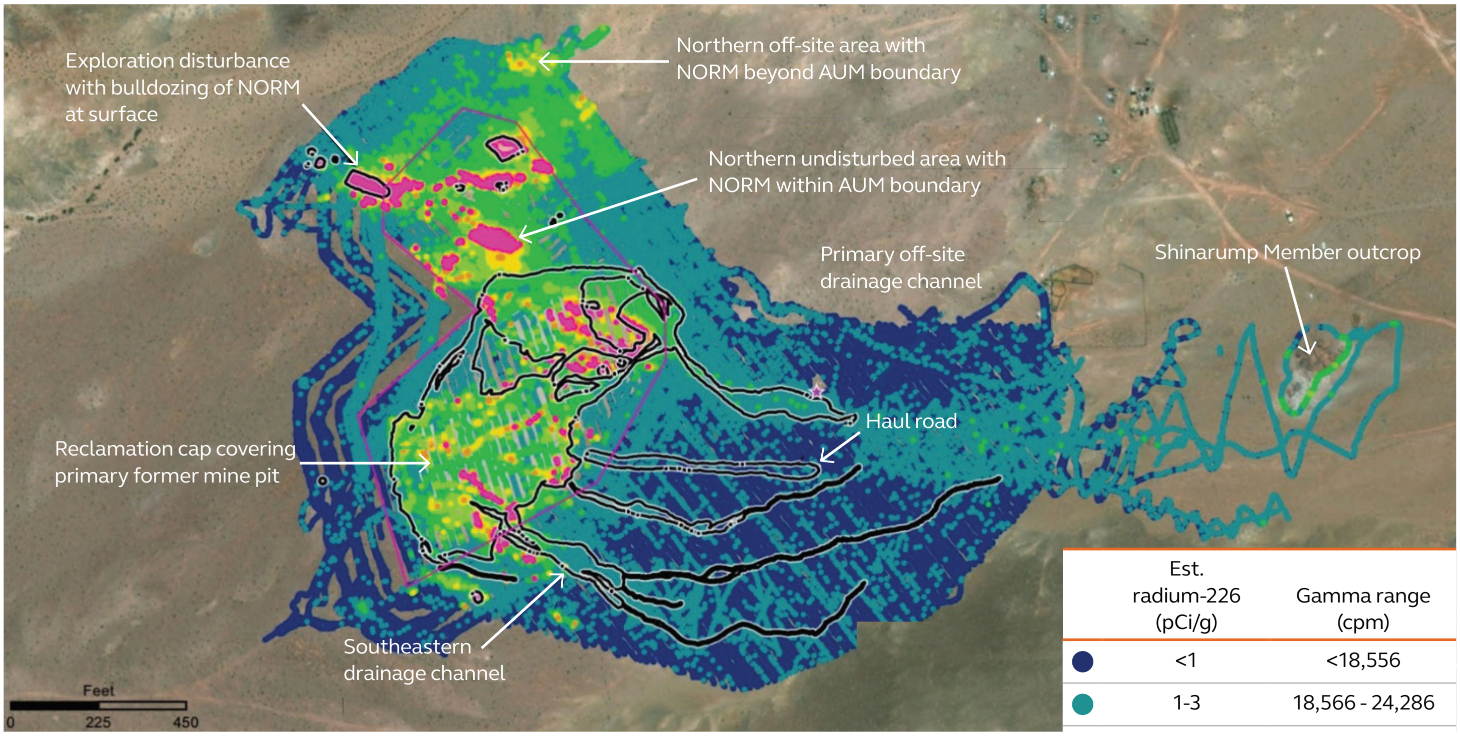
B. Production disturbances at the site include mine pits (green), a haul road (yellow), and waste piles (purple). Vertical delineation by drilling verified the depth of the mine pit and the interface between disturbed and undisturbed bedrock. Verifying the depth of the pit enabled volume calculations to estimate the total volume of material that would either need to be removed under a dig-and-haul remediation scenario or under a cap stabilization scenario.

C. During reclamation, NAML filled and covered the mine pits. As a component of this work, waste piles were consolidated into the pits. Also, during reclamation, the haul road was scarified (ripped) to restrict site access. Reclamation activities produced site features that are visible in the field and were generally accurately documented on NAML reclamation maps. These features include NAML cap (yellow/dot fill) and cap/grading of onsite material (olive green). NAML cap was placed on top of consolidated material in the mine pits and on other areas with elevated gamma to minimize potential exposure. The NAML cap was determined to be from an offsite borrow source based on its compositional similarity to bentonite and gravels sourced from near the contact between the Petrified Forest Member and overlying Quaternary gravels.

Figure 3 displays the total disturbance footprint and channels as well as the total mapped gamma, including transect walkover gamma measurements and additional gamma measurements collected in focused areas surrounding individual features identified during the lateral delineation process. Walkover gamma measurements are also presented in terms of estimated radium-226 concentrations derived from a site-specific correlation between normalized static uncollimated gamma measurements and laboratory measured radium-226 concentrations.

The site depicted in Figure 3 illustrates the contrast between mapped features and gamma measurements, as follows:

- Elevated gamma ranges not associated with disturbance features: There is an area with gamma measurements in the maximum range (>20 pCi/g; pink) within and adjacent to the northern AUM site boundary where there is no evidence of mining related disturbance. There is also an area of somewhat elevated gamma measurements (up to ~10 pCi/g; green) associated with a Shinarump Member outcrop east of the site, downgradient of channels that extend offsite, which demonstrates a challenge associated with identifying offsite transport based on radioactivity measurements in the context of local NORM that is not associated with mining-related disturbances.
- Disturbance features with elevated gamma ranges: As would be expected in the context of prospecting for maximum grade ore, exploration features in the northern area of the site are associated with gamma



	Est. radium-226 (pCi/g)	Gamma range (cpm)
●	<1	<18,556
●	1-3	18,566 - 24,286
●	3-6	24,286 - 32,881
●	6-10	32,881 - 44,341
●	10-15	44,341 - 58,666
●	15-20	58,666 - 72,991
●	>20	>72,991

Figure 3: *Total mapped mining-related disturbances and channels emanating from the site. Note that while some of the most radiologically elevated areas are contained within mining-related disturbance features, there are several areas where elevated estimated radium-226 concentrations (>20 pCi/g) are present in areas of NORM. NORM is also present in outcrop along channels near the site, attributable to halo mineralization surrounding the ore body.*

measurements in the maximum range (>20 pCi/g; pink). The lines of evidence method was used to delineate the extent of disturbance associated with each of these features.

- Disturbance features with variable gamma ranges: Prior to mining, maximum concentrations of radium-226 were presumably located in the mine pit area. However, as a result of removal of material during the production phase and backfilling and placement of cap material during the reclamation phase, this area is now characterized by estimated radium-226 concentrations that are generally intermediate, but variable. The NAML reclamation cap is covering the primary former mine pit and shielding underlying material including a combination of consolidated waste pile material with elevated gamma levels and borrow material with lower gamma levels. Higher gamma measurements at the surface in the NAML cap area are reflective of thinning of the cap due to erosion, radiologically elevated material located close to the cap interface, or both.
- Disturbance features with low gamma ranges: In cases such as the haul road, relatively homogenous and low gamma measurements in a disturbance feature may be indistinguishable from the surrounding area and the feature is only revealed through lateral delineation field mapping. While there are not radiological or chemical hazards associated with this type of feature, physical stability needs to be evaluated to assure that the mining-related disturbance is not and will not in the future result in enhanced transport away from the site.
- Potential transport: Some transport of intermediate gamma range material is apparent near the southeastern drainage channel as evidenced by measurements within the channel thalweg that are greater than those along the channel banks and overbanks. In contrast, although NAML cap material is visually apparent in the primary offsite drainage, the distribution of gamma measurements is generally homogeneous and the magnitude is generally low and indistinguishable from the surrounding area. This observation emphasizes the need to assess physical hazards associated with stability in cases where there may not be current evidence for transport of material posing a radiological or chemical hazard.

Conclusions

We have successfully applied a multiple lines of evidence and mining forensics approach to characterize approximately 30 AUM sites in a manner that overcomes challenges associated with defining disturbance feature boundaries, assessing potential offsite transport, and comparing site and background conditions for meaningful assessments of risk and necessary remediation. This approach includes a detailed review of historical records and aerial imagery, geological/geomorphological and mining-related disturbance mapping, collection of high-resolution gamma data by walkover scans using sodium iodide scintillation detectors, volume calculations derived from the vertical delineation of mine pits, and compilation of these lines of evidence. The integration of these lines of evidence enables the lateral delineation of mining and non-mining features on and near the site to constrain disturbance feature boundaries. This creates a clear distinction between undisturbed NORM and areas that were disturbed by mining-related activities, with only the latter needing to be addressed in the current regulatory context. If a traditional gamma walkover gamma investigation was performed and interpreted without consideration of additional lines of evidence, a different conclusion would have been reached with the extent of mining-related impacts encompassing large areas of NORM on and near the site while potentially missing mining-related features associated with lower gamma measurements and radium-226 activities on and near the site. This multiple lines of evidence approach allows for a robust, data-based assessment of mining-related impacts and sets the framework for future evaluations of potential site risk and remedial actions for these AUMs. Though developed specifically for these mines, the approach or process can be adjusted and leveraged for use at other unique impacted sites.

About the authors

Paul Knightly is a geologist and PhD candidate with over 10 years of environmental consulting experience and has spent the past seven years working on radiological projects, including abandoned uranium mines.

Richard Murphy, PhD, has over 40 years of experience in radiological site investigation and remediation, geochemistry, environmental science and engineering, and analytical chemistry. He has led multidisciplinary teams performing field work, routine and advanced laboratory analyses, method development, site investigations, data evaluation, remedy development and site remediation.

Dr. Monica Heintz has more than 15 years of academic and environmental consulting experience. She works at the nexus of groundwater hydrology, geochemistry and microbiology to understand, manage and mitigate environmental impacts. She specializes in application of environmental molecular diagnostic and statistical tools to understand, describe and predict contaminant fate and distribution. She excels at conceptual site model and remediation strategy development for sites with complex constituent mixtures.

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Controlling the unpredictable: Innovations in incident and disaster response

Andrew McManus

Impacts and trends

Emergencies and disasters can create hazardous conditions, impact entire communities, disrupt business operations, and pose threats to public health and the environment – all impacts to Quality of Life. Effective incident management can help build community and regulatory trust, support lesson learning and process improvements, reduce risk, and expedite business restoration. Conversely, inefficient or ineffective incident management can increase risk exposure, elicit increased regulatory oversight, and generate negative public attention. Emergencies often bring other complicating factors including multi-jurisdictional agency involvement, conflicting or vague regulatory guidance, and public awareness campaigns. Despite these complexities, incident management solutions are proven methods to organize the chaos and distill critical project data into actionable information.

By implementing incident management solution tools and processes before, during, and after emergencies, multiple industrial and municipal clients have achieved successful outcomes despite headwinds presented by complex emergencies. Practical benefits derived from applying comprehensive, programmatic, incident management strategies have included:

- Shortening the length of emergency phase operations,
- Identifying and achieving cleanup endpoints during emergency phase,
- Understand and manage risks and liabilities,
- Support community and stakeholder outreach and engagement, and
- Drive efficiency through comprehensive resource management.

Successful emergency response begins with effective planning and there are more considerations than ever when evaluating risks to your business. Short- and long-term effects of climate change, environmental, cultural, and socio-economic permitting requirements, and incorporating sustainability related business objectives must be considered during emergency response planning and implementation. The identification and management of emerging contaminants, such as the common use of per- and polyfluoroalkyl substances (PFAS) as an ingredient in aqueous film forming foam (AFFF), is also a core component of a comprehensive emergency planning strategy. A focus on emerging contaminants, like PFAS in firefighting foams, is one of five key considerations for controlling the unpredictable. These considerations include:

Incident management solutions

- Release modeling
- Remote sensing and digital innovation
- Natural resource damage management
- Emerging contaminants

Despite the uncertainty surrounding comprehensive emergency planning and implementation; there are strategies and tools which can be used to identify and manage your risks proactively and comprehensively.

Incident management solutions

Widespread adoption of National Incident Management System (NIMS) and Incident Command System (ICS) frameworks for all levels of incidents is occurring nationwide, with some jurisdictions mandating certification for Spill Management Teams (SMTs) and select ICS positions. Using ICS as the basis for Incident Management Solutions allows organizations to seamlessly integrate response partners into all levels of their pre-established response hierarchies and facilitates the development of client-specific digital solutions in support of comprehensive resource management, financial tracking, operations, planning, and NIMS/ICS training.

There is a critical need for at-risk industry partners to maintain appropriate incident response capabilities, including incident management and training solutions consistent with the National Response Framework (NRF), National Incident Management System NIMS and ICS and various state and federal planning requirements including the ability to developing and implement a full range of training and exercises including tabletop and full- scale exercises consistent with PREP guidelines.

It is important to prioritize the development of an accurate common operating picture by utilizing best-available technology, like unmanned aerial systems (UAS), multi-spectral photography, and integrated topographic-subsurface 3D modeling coupled with *Smart* characterization techniques to accelerate decision making and build consensus around response priorities.

Incident Management Solutions can help organize a variety of response related services, including environmental cleanup, construction oversight, regulatory negotiations, financial tracking, data collection, management, and visualization. A centralized approach brings clarity and efficiency to the incident management process and allows for deeper insights into process improvement opportunities. Examples of program-specific improvements include barcode scanning for large disposal projects to enhance accountability, reduce demurrage, and improve invoicing efficiency. Other examples include the development of client-specific ICS forms including 214 Activity Logs and 218 Equipment Inventory Logs, pre-populated with consultant and OSRO equipment based on MSA rates.

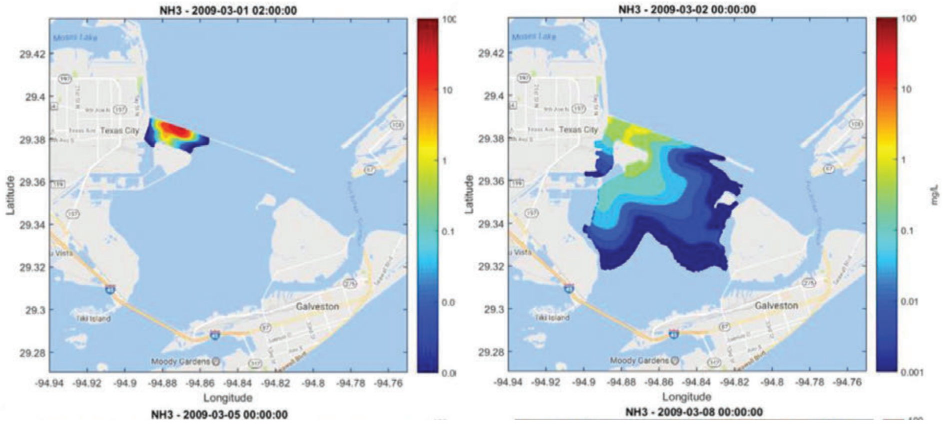


Figure 1: *Hydrodynamic model illustrating fate and distribution of ammonia following a hypothetical pipeline release.*

This integrated approach is flexible and supports adaptation to changing conditions. A recent example is the adaptation of emergency response management to the COVID-19 pandemic. Industry adaptations included the adoption of touch-free sign-in/out practices, daily temperature screening, and enhanced social distancing efforts including the use of digital command posts.

Integrate your planning

Holistic approaches to emergency planning offer a variety of benefits from managing compliance cycles to evaluating and preparing for worst-case scenarios at your facilities. Proactive modeling of petroleum and non-petroleum releases in onshore, nearshore, and offshore environments can provide critical insights into response plan deficiencies. We recommend utilizing flexible and integrated modeling tools, capable of simulating two- and three-dimensional flow, sediment transport and morphology, waves, water quality, ecology, and the complex interactions between these processes. These models not only allow for response decision making and trajectory predictions related to product recovery efforts, but the results can be used to estimate the ecotoxicological or ecological risk of the released chemicals or products. Multiple scenarios can be modelled, time slice analysis provide, and the efficacy of specific risk mitigation measures evaluated (e.g. placement of booms, construction of engineered barriers). This work can be completed once a spill has occurred but is also powerful when applied as a precautionary measure to identify and manage the potential for off-site migration of materials once released.

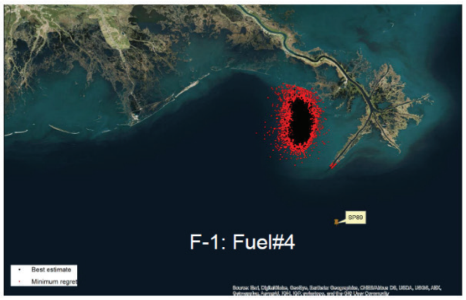


Figure 2: *Oil spill trajectory analysis used for shoreline impact analysis and emergency planning purposes.*

When integrated into an Incident Management Solutions program, proactive modeling, such as the hydrodynamic model output shown on Figure 1 above, can be directly utilized to prepare specific Geographic Response Strategies (GRS) for sensitive receptors and at-risk resources identified within

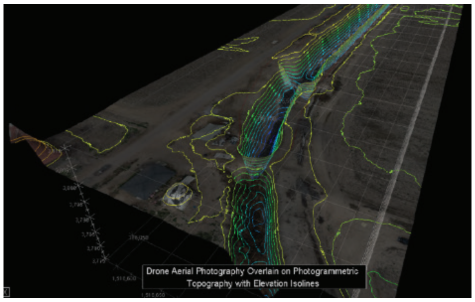


***Figure 3:** UAS collected aerial imagery overlaying topographic elevation isocontours generated using photogrammetric methods.*

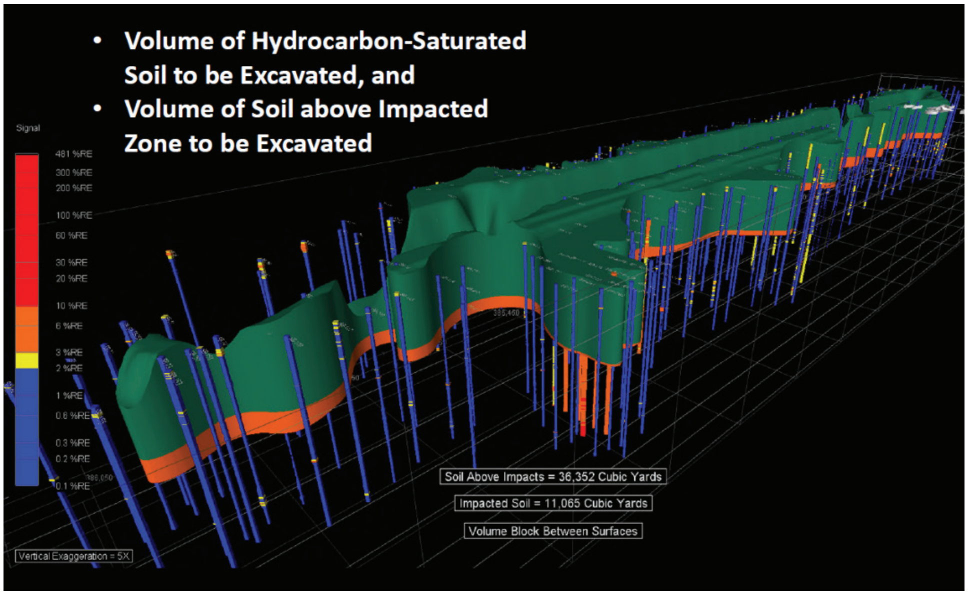


***Figure 4:** 3D model of subsurface hydrocarbon impacts resulting from a pipeline release. High-resolution site characterization allowed for informed and effective decision-making during emergency response.*

the modeled release trajectory. Other examples of preemptive modeling include impact analysis for offshore releases (Figure 3). Impact analyses may be performed on a variety of products under a variety of conditions to calculate the potential length of affected shorelines or waterways. Beaching, dispersion, evaporation rates, and travel time estimates are also model outputs which may be used during integrated planning processes. When incorporated into contingency planning and during actual responses, where models can be validated in near-real time with remote sensing technologies, release modeling can be an impactful tool for protecting sensitive receptors and effectively deploying mitigation measures.

Integrating your response

Outside of the widespread adoption of NIMS/ICS, the most significant improvements in our ability to respond to emergencies and disasters in the last 20 years are, arguably, all technological or digital innovations. Technical innovations continue to increase the resolution at which we can see and interpret where contamination exists, its transport mechanisms, and our ability to interpret the relationship between the two. Digital innovations are driving our ability to collect and analyze dramatically larger data sets with significantly reduced labor or opportunity for human error. These advances come with risks, including challenges with maintaining data discipline, data security, and ensuring collected information is actionable. We do not believe that all technology is created equal, and in emergency response situations, proven effectiveness and reliability are important characteristics for success. However, we also believe that emergencies provide the best opportunities for innovation as no two incidents are the same regardless of shared characteristics and unique needs are solved by unique solutions. That is why Arcadis believes that technical knowledge and experience must form the basis of our clients' successes and that we must leverage technology as a tool and not a strategy. Further synergies can be recognized when the organization and structure of Incident Management Solutions combine with the rapid insights enabled by emerging technologies as demonstrated in the following case study.

Smart characterization case study

Multiple high-resolution site characterization techniques and data sources were available to a corporate response team while supporting a large petroleum pipeline release in a remote desert setting. *Smart* characterization is a process for collecting and translating high-resolution data into contaminant behavior and relating that behavior to remedy selection and performance monitoring. This deliberate approach to was utilized to collect large amounts of actionable data very quickly - a valuable addition to an emergency response toolkit.

Aerial photography was collected autonomously using UAS and a high-resolution, site-specific digital topographic surface was generated using cloud-based photogrammetry (see below). This baseline topographic surface was combined with Smart subsurface characterization results from a high-resolution geophysical and laser induced fluorescence investigations to create a 3Dl model of the site. This model visually represented the nature, extent, and predicted behavior of the plume and identified a thin high-permeability source zone containing the majority of the hydrocarbon impacts. The *Smart* characterization approach resulted in the collection of actionable data – an excavation plan that was approved within 24 hours of data visualization where the high-resolution mapping of impacted versus non-impacted materials resulting in reducing excavation volumes by 78%.

The deliberate approach of integrating technical knowledge, digital proficiency, and incident management solutions provides material benefits related to reductions in the overall cost and duration of the incident, increased stakeholder confidence, and cost-avoidance including measurable reductions in the overall carbon footprint of the response.

PFAS containing forms have been widely used around the world for firefighting and training purposes. While most firefighting foams are no longer manufactured using PFOS or PFOA, older foams are still occasionally used and long serving firefighting equipment may still contain residual PFAS, negating some benefit of transitioning to fluorine free foam (F3). However, complete transitions to F3 are possible and can reduce ongoing risk of contamination.

Integrating emerging trends

A holistic and integrated emergency planning process must consider emerging trends including upcoming regulatory changes. One noteworthy trend within the emergency response community and those charged with infrastructure protection is the identification of poly- and perfluoroalkyl substances, or PFAS, in firefighting foams. PFAS are a group of engineered compounds, comprised of thousands of manmade chemicals, and have been bulk-manufactured for use in a variety of other manufacturing processes or in commercial products themselves. PFAS' thermal stability, surfactant, and chemical-, oil-, and water-resistant properties which made it an ideal component of aqueous film forming foam (AFFF) and fluoroprotein foams.

PFAS present some unique challenges as a result of their extreme persistence and high mobility. Their high use and recalcitrant nature have led to increased regulatory scrutiny, as well as introducing uncertainty surrounding sustainable PFAS management solutions. Best practices include taking a proactive and progressive approach to identifying PFAS risk and developing foam management and changeout solutions. Global partnerships are critical to leverage best practices from around the world and provide insight into emerging regulatory frameworks. It is important to recognize that integrating PFAS management solutions with emergency planning can help minimize risks from fluorinated foam use at future incidents as well as utilize emergency planning tools to manage legacy foam and firefighting equipment changeout.

Firefighting foam replacement and transition services

PFAS-containing AFFF have been widely used around the world for both firefighting (in fixed systems and incident response) and fire training purposes. Historically, AFFF contained high concentrations of PFOS, PFOA, and their precursors. Current AFFF products may still contain short chain PFAS compounds, including precursors that are difficult to measure with routine methods. Arcadis offers foam changeout – and cleanout – services and sustainable fire training area design to help minimize future potential risk related to PFAS.

Firefighting foam chemistry and regulations

AFFF chemistry has evolved over time and varies by manufacturer. Arcadis has a detailed longitudinal understanding of AFFF PFAS content, how to assess foams for PFAS content that may be difficult to detect with standard methods, and how historical and current foam ingredients may be subject to regulations across many jurisdictions globally.

Firefighting foam transition

While most firefighting foams no longer contain PFOS or PFOA, a complete transition to fluorine-free foams (F3) may be feasible and appropriate to reduce ongoing risks of contamination from other PFAS compounds and residual contamination. Foam transition requires a thorough cleanout of the previous foam material to avoid cross-contamination of the F3 material. F3 foams are becoming more common in Europe, Asia, and the United States as they are an effective, biodegradable and reduce the possibility of future environmental liabilities associated with PFAS. This, in turn, can provide a net cost benefit to a foam replacement program.

Assessment and remediation of firefighting foam impacted environments

PFAS impacts to soils, sediments, surface or groundwater may occur as a result of legacy or ongoing use of PFAS-containing products, including AFFF, and may be a driver of environmental risk. This widespread usage of PFAS in commercial and industrial processes is making PFAS increasingly ubiquitous in the environment. Additional potential sources of PFAS include landfills, water-treatment biosolid waste, and industrial effluents related to a wide variety of processes. These factors often complicate contamination assessment, source differentiation, and ultimately cleanup apportionment. Arcadis' understanding of current analytical method

An excavator removing contaminated soil during a redevelopment program. Disposal of PFAS contaminated soil remains largely unregulated in the United States.

capabilities and limitations, PFAS forensic evaluation tools, and fingerprinting capabilities can limit liabilities created by historic or emergency AFFF use.

Arcadis has significant global experience in the assessment and remediation of PFAS-impacted soil, groundwater, drinking water, and infrastructure. Our global community of experts has supported more than 400 PFAS projects and has designed and installed approximately 30 large-scale water treatment systems in six countries using a variety of technologies, including absorption, fractionation, and conventional source removal techniques. This experience, and our knowledge sharing culture, provide us with unparalleled insight for driving PFAS cleanup solutions.

PFAS disposal considerations

Despite an increase in regulatory scrutiny, there is a notable absence of PFAS related disposal regulations in the United States. This lack of regulatory guidance creates uncertainty related to the treatment or disposal of PFAS containing wastes. The persistence of PFAS in the environment makes it challenging to identify appropriate disposal methods and the identification of landfills as a potential primary source of PFAS to the environment makes risk and liability management difficult. In the absence of regulatory guidance, many PFAS waste generators are electing to manage their waste via incineration. A costly, and often overly conservative approach that is not without inherent liabilities (e.g. toxic air emissions from insufficient incineration temperatures). Conversely, some of our clients are also electing to temporarily store and contain PFAS containing wastes until further regulatory guidance is issued. Disposal at landfills is becoming increasingly less viable as an option as tipping fees become more expensive as PFAS face a hazardous substance designation and is increasingly recognized as a long-term liability.

Conclusion

Emergency planning integrates is inherently flexible and scalable. It provides a simplified platform to manage compliance related planning, training, and exercise requirements. It can serve as a planning tool to develop facility or resource-specific mitigation strategies. Integrating technology as a tool that is guided by a base of technical knowledge into emergency planning and incident response is an effective way to enhance safety, build consensus, manage risk, identify effective and efficient mitigation and remediation strategies, and shorten actual emergency response timeframes.

About the author

Andy McManus, PG leads Arcadis' Incident Response and Recovery (IRR) Program. Andy has 17 years of site characterization and remediation experience in addition to having provided on-site and remote support for hundreds of client emergencies and incidents while at Arcadis. As IRR program lead, he is responsible for program development while continuing to lead multi-disciplinary teams to respond to the wide range of challenges presented by environmental, industrial, and natural disasters. He has developed innovative mass balance techniques to assess flammable liquid consumption during terrestrial fires as well as defensible methods for product recovery tracking.

Preferential pathways: Responding to changes in the vapor intrusion CSM

Megan Hamilton, Sarah Jonker, Adam Richmond and Robert Uppencamp

Introduction

While vapor Intrusion (VI) has been characterized and evaluated for approximately 30 years, this exposure pathway is still in its scientific and regulatory infancy. Over the past decade, significant scientific advancements and an improved understanding of subsurface vapor transport have resulted in a cascade of most State and Federal regulatory VI guidance documents. One of these advancements is the growing recognition of preferential pathways and their importance in managing sites affected by VI. Guidance documents now recognize that preferential pathways need to be understood and adequately characterized but provide little information about how this can be achieved. Much of this is attributed to site-specific conditions that govern when preferential pathways may exist. As a result, many regulatory frameworks require preferential pathway assessment based on suspected site conditions that may not manifest in risk.

Arcadis is a leader in the industry for attaining site closure where the VI pathway is a concern, applying innovative site characterization and sampling methods, real time analytical tools, and mitigation strategies that navigate the uncertainty and maintain pace with the ever-changing regulatory climate and science surrounding VI.

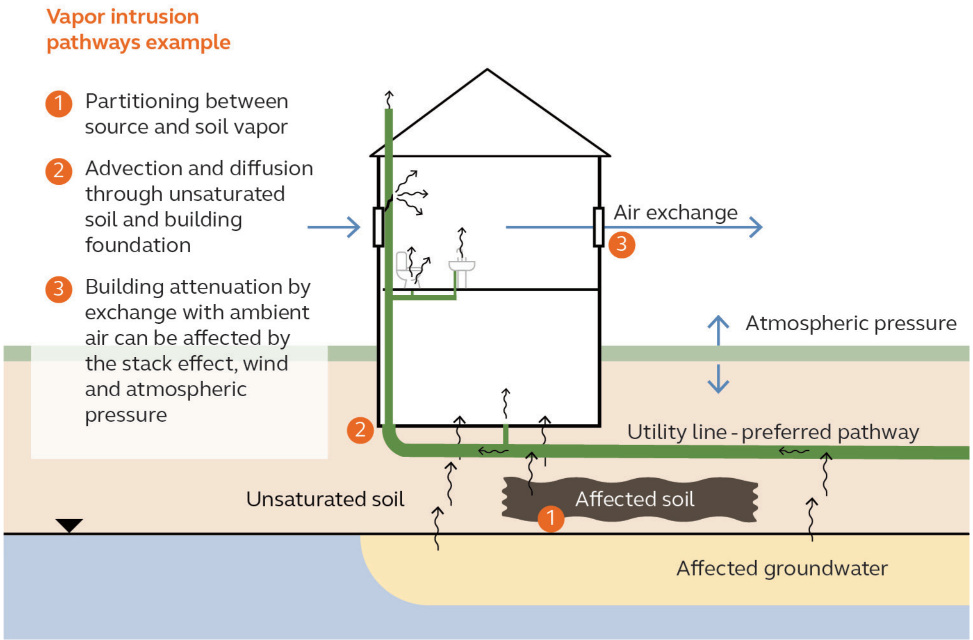


***Figure 1**: Standard conceptual site model of the vapor intrusion pathway.*

These methods are critical to understanding the evolving science around preferential pathways and successfully managing them as part of the site closure process.

The changing VI conceptual model

Standard VI transport models assume volatilization of compounds from a steady state subsurface source (groundwater and/or soil). Vapor transport is affected by a variety of variables (Figure 1) reliant on applicable industry assumptions that have been investigated via standard investigation practices over the past 30 years. Preferential pathway vapor transport adheres to very different assumptions, ultimately negating the usefulness and validity of standard VI models and screening methods.

A preferential pathway is typically defined as a high permeability conduit that can serve as a high-capacity transport pathway for volatile organic compound

(VOC) vapors from the source area to or into a building. Preferential pathways may transport vapors farther or faster than what would be predicted by vapor migration models or assumptions. Typical preferential pathways potentially include sewer and utility corridors, cracks and holes in building foundations, sump pits, and/or natural geologic pathways (e.g., karst or fractured bedrock). Of these, subsurface utility corridor backfill material is often an initial focus early in the preferential pathway evaluation process. These arise when a utility corridor within backfill material extends through an area of impacted soil and/or groundwater and a building footprint (Figure 2) serving as a potential conduit between source and receptor.

Examples of VOC migration through backfill have not been documented or published in peer-reviewed literature, suggesting that vapor transport through backfill material is not a high-risk pathway. More recent research has instead indicated that vapor transport occurs more readily through a sewer pipe or utility tunnel ("pipe" pathway) (Figures 3 & 4) as the most prevalent preferential pathway (McHugh, T., Beckley, L., 2018).

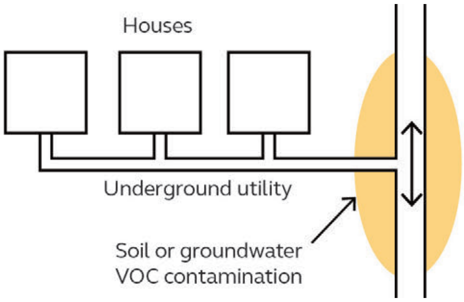


Figure 2: *Significant preferential pathway.*

In the absence of regulatory guidance for the investigation and mitigation of preferential pathways, moving sites through the closure process in a consistent manner has become a significant challenge for projects across the United States. We have found that successful navigation of the ever-changing scientific and regulatory climate relies on several key elements. The first includes direct involvement with the regulatory community as part of the guidance development process and is a critical step to ensure that regulatory specifications rely on the current state of the science and best practices. The second element then includes working within this guidance framework to leverage best practices and innovative investigation and mitigation methods to move from the initial desktop review through the preferential pathway investigation process.

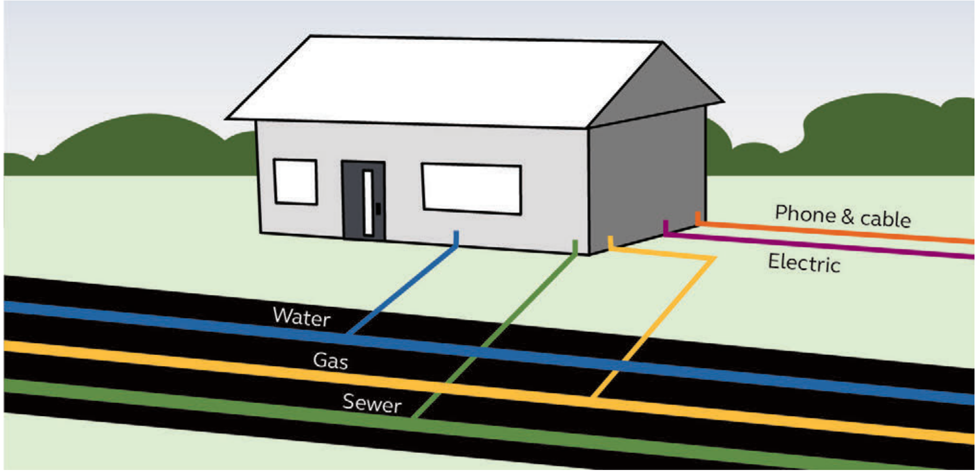


Figure 3: *Common utility tunnels*

There are a variety of applicable tools for use in understanding the sewer preferential pathway and alleviating client and regulatory concerns, particularly under complex site conditions. These include grab and time-integrated sewer vapor samples using canister sampling methods via United States Environmental Protection Agency (USEPA) Compendium Method TO-15 or passive samplers, such as the Beacon Chlorosorber™, Radiello®, and Waterloo Membrane Sampler™ (WMS™). Real-time screening instruments such as the Frog-5000™, VOCAM™, HAPSITE®, and AROMA have also gained significant traction in providing adaptive sampling capability in the field to overcome transient sewer conditions and allow for the efficient collection of vapor data over a relatively continuous and/or more frequent timeframe.

In some cases, initial desktop review activities or screening phases of the VI investigation have enabled us to rule out the sanitary sewer as a preferential pathway, alleviating the need for extensive and lengthy investigations. Still, while new sampling methods have improved the overall quality and efficiency of our VI investigations, knowing when and how specific tools should be employed is a key decision step. Depending on the complexity of the site, investigation programs are initiated with a simple desktop evaluation to guide investigation decisions. Then, a combination of real-time monitoring, passive sampling, VI tracing, smoke testing, and/or pipe camera videography could all be employed, as applicable.

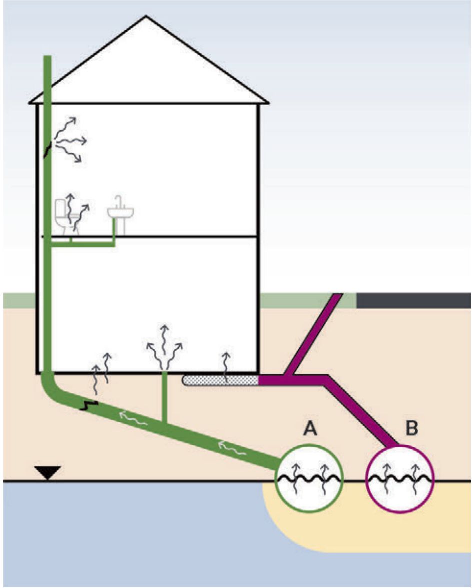


Figure 4: *Examples of vapor migration through a sanitary sewer pipe (A) and land drain (B).*

Desktop evaluations guide innovative screening methods

Conducting a desktop evaluation should always be the first step in any VI preferential pathway investigation. Desktop evaluations start with reviewing available data to provide a wealth of information to conserve time and resources potentially spent on mobilization and sampling costs. Desktop evaluations aid in conceptual site model (CSM) development, identify initial data gaps, provide a starting point for investigation activities, and determine the best tools for the work.

Desktop evaluations can also eliminate the need for preferential pathway investigations entirely. In one example, a desktop evaluation of sanitary and storm sewer construction records for a residential neighborhood underlain by a groundwater plume found no direct sewer connections to occupied buildings within the area of groundwater impact. The review included records of sanitary and storm sewer locations and depths, groundwater elevations, and groundwater VOC concentrations. Septic systems throughout the area were identified at elevations well above the water table and therefore were not acting as a direct “pipe” preferential pathway. Demonstrating the lack of preferential pathways in the area allowed a more straightforward VI approach to proceed and offset the need for a large-scale preferential pathway investigation.

In this same example, a desktop evaluation was used in conjunction with real-time air monitoring to rule out off-site preferential pathway investigations at the commercial properties located north of the site. A review of sanitary and storm sewer locations and depths, groundwater elevations, and groundwater VOC concentrations identified on-site storm sewers discharged to a lined detention basin on the northeastern part of the site and therefore, were determined to not be a concern for off-site vapor migration The evaluation also identified one on-site sanitary line that discharged into the public sanitary sewer north of the site and required further investigation as a potential preferential pathway.

The real-time air monitoring device FROG-5000™ was utilized to sample the three on-site sanitary manholes along the northern property boundary closest to the public sanitary sewer to determine if off-site preferential pathway investigations were warranted at the commercial properties located north of the site. The FROG-5000™ is a hand-held gas chromatograph (GC) system used for detecting VOCs and can be calibrated for the analysis of up to five individual compounds during one sampling event. The typical sample collection duration is approximately eight to 10 minutes, which allows for the collection of multiple samples throughout the day and produces quantitative results in real-time, allowing for adjustments and decisions to be made in the field.

Best management practices were employed during sampling to allow for potential vapors to equilibrate within the sewer and ensure the samples were collected from the appropriate depth. Three samples were collected from each manhole to confirm sample results and characterize potential variability. Due to the lack of detected site-related compounds, the sanitary sewer was ruled out as a preferential pathway for vapor migration to buildings located north of the site. Utilization of the innovative technology provided by the FROG-5000™ allowed for this portion of the preferential pathway investigation to be completed within one business day which saved time and resources that could have been spent on multiple mobilizations and sampling costs.

A similar combination of desktop evaluation in conjunction with passive sewer sampling was used at a separate project site to rule out further VI preferential pathway investigations at off-site properties. For this project, the sanitary sewer was submerged below the water table, creating a higher risk for the sanitary sewer pipe to act as a preferential pathway for both impacted groundwater and vapor transport. Based on the desktop evaluation, it was determined that storm water at the site discharged to the adjacent creek and further evaluation was not required, however, off-site properties located to the north, south, and east of the site were determined to be connected to the potentially affected sanitary sewer line. These properties represented data gaps in the CSM for VI risk evaluation. A scope of work was developed and approved by the regulatory agency to address these data gaps in a stepwise approach, eliminating the immediate need to access private property and inconvenience third party property owners. The scope of work consisted of deploying seven-day duration passive samplers in a total of five manholes along the sanitary sewer line in the direction of potentially affected properties during two sampling events in October of 2020 and 2021.

It is important to understand sewer conditions as some passive samplers perform better in humid and/or wet conditions. Three different types of passive samplers, ChloroSorber™, Radiello®, and the Waterloo Membrane Sampler™ (WMS™) were deployed in the sewer during the two sampling events. Both the Radiello® and the WMS™ were used as an additional quality control measure for both sampling events. Passive samplers were deployed for a sampling duration of seven days at two

The three different types of passive samplers, ChloroSorber™, Radiello®, and the Waterloo Membrane Sampler™ that were deployed in the sewer during two different sampling events.

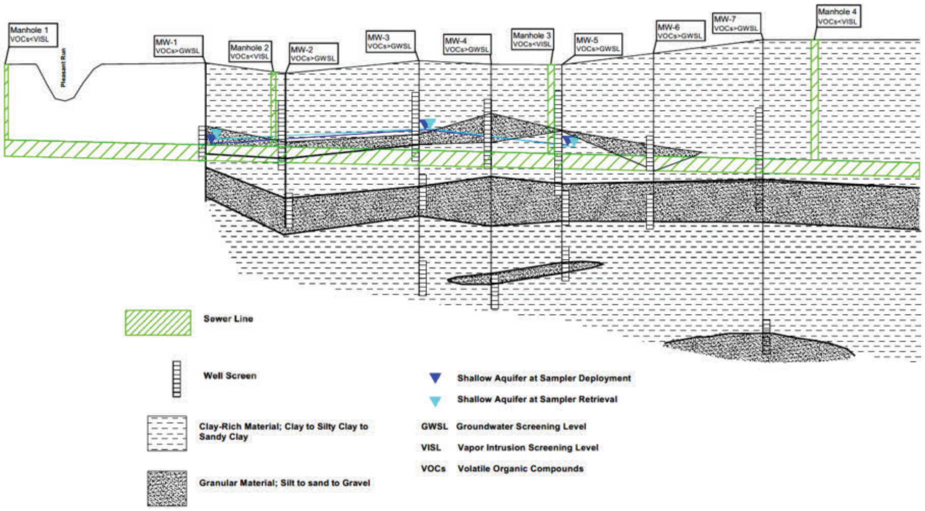


Figure 5: *Sanitary sewer cross section with sewer vapor and groundwater results.*

different depths to assess time-averaged sewer gas concentrations and to account for potential moisture interference and high-level liquid. The extended sampling duration was chosen to limit the number of sampling events required, while still accounting for variations in sewer liquid volume and flow.

Sanitary sewer passive sampler results were all below the applicable screening levels during both sampling events (Figure 5). By implementing a stepwise approach utilizing innovative sampling methods that accounted for inherent variability within sewer liquid and vapor, a VI preferential pathway investigation was completed in two sampling events, without involving third party property owners.

Preferential pathway case study

A desktop evaluation was conducted at a site in response to building occupants complaining of a petroleum odor inside an on-site office building. The slab-on-grade construction office building was built on a former petroleum filling and service station site. The initial CSM, groundwater sample results, groundwater elevations, previous remedial activities, vapor intrusion investigations, and the proposed mitigation system design were reviewed as part of the desktop evaluation.

The petroleum odors were sporadically observed during heavy rain events over a 25-year period. The initial CSM concluded that impacted soil vapor trapped beneath the building was pushed into the building during or directly after heavy rain as groundwater rose. Several paired indoor air and sub-slab sampling events had been completed and limited remedial measures implemented over the years. Only low levels of petroleum volatile organic compounds (pVOCs) had been detected in the indoor air and sub-slab vapor. Petroleum odors sporadically persisted inside the building and the final suggested remedy was to install a vapor mitigation system. After initial review of the mitigation system design, several discrepancies were discovered indicating that the vapor mitigation system would not mitigate the problem:

- Historic groundwater results were at sufficient concentrations to yield detections of pVOCs in soil vapor. However, several paired indoor air and sub-slab soil vapor sampling events did not reveal elevated pVOC concentrations in the indoor air or soil vapor below the building footprint.
- Shallow groundwater ranged from two feet below ground surface (ft bgs) to 11 ft bgs. The sump in the elevator was located at 5 ft bgs with groundwater seasonally connected to the sump pit. However, pVOC odors were only reported during heavy rain events and it is unlikely that groundwater could rise quickly enough to push soil vapor into the building in such a short timeframe. Further, the site and surrounding areas were covered by impervious surfaces with building roof drains discharging to the street.
- Reportedly, pVOC odors only originated from rooms with floor drains.
- Residual impacts from several historic businesses adjacent to the site could potentially contribute to pVOC vapors in the sanitary sewer system via infiltration.
- It was therefore theorized that the odors were originating from the municipal sanitary sewer and entering the building through dry floor drain p-traps in the plumbing system. This was tested by completing a preferential pathway investigation at the former petroleum site and the adjacent sanitary sewer to determine if the source of petroleum odors was originating from the sanitary sewer.

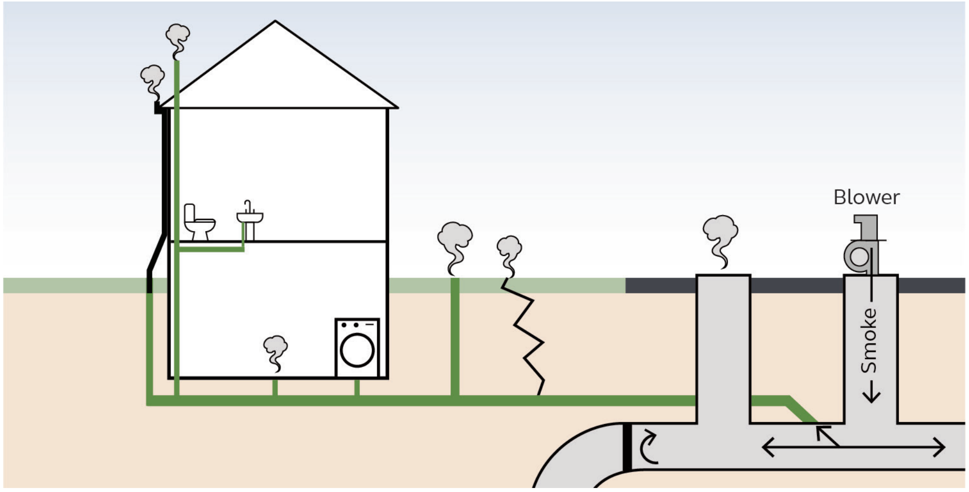


Figure 6: *Typical smoke test*

Smoke coming from a floor drain during testing.

An extendable backflow preventer valve was installed in the sewers lateral sewer to limit the potential for a siphoning effect.

Sewer information was gathered from the local city sewer department with approval to sample the vapor inside the sewer. The site building's sanitary sewer lateral was connected to an 80-year-old eight-inch public sanitary sewer line that was undersized for the current area population.

Indoor air samples were collected first inside the on-site office building to establish current indoor air pVOC concentrations. A passive sampler was then deployed in the manholes directly upgradient and downgradient of the site to measure potential pVOC vapors for a seven-day period. Benzene was detected in both manholes at concentrations two to four times greater than benzene levels detected in indoor air samples.

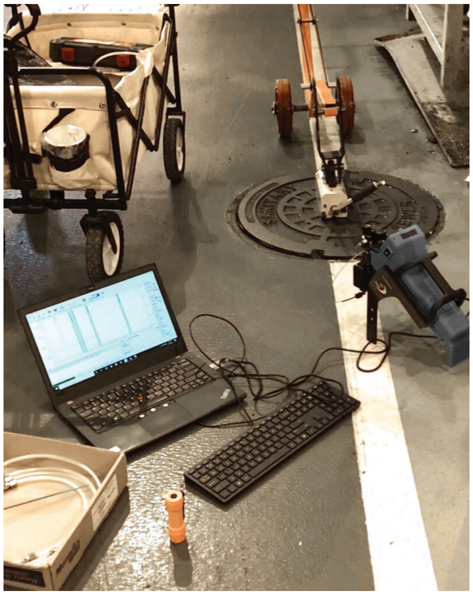
A local plumbing company was employed to evaluate the plumbing venting system, floor drains, and p-traps for the on-site office building by completing a smoke test. Figure 6 shows a typical plumbing system smoke test with a fan blowing smoke into a manhole adjacent to a building to evaluate the migration of vapors between the manhole and the sanitary sewer system connected to a building. The upper right photo shows smoke emanating from a floor drain indicating an improper connection or a dry floor drain p-trap. The smoke test at the site revealed multiple issues with the plumbing system as smoke was observed emanating from four of the five floor drains and one improperly connected plumbing vent.

A potential reason the floor drain p-traps were dry is the siphon effect. Siphoning can occur when the public sanitary sewer line fills to capacity and sewage backs up into a building's lateral line. The pressure gradient can pull water from the building's p-traps as the sewage level in the sewer recedes allowing sewer gas to enter the building.

The licensed plumber installed floor drain trap seals in all of the floor drains and repaired the plumbing vent. To further limit the potential for the siphoning effect to occur, an extendable backflow preventer valve system was installed in the building's sewer lateral. A backflow preventer valve (photo right) is a simple one-way spring flap that is closed until sewage from the building pushes open the flap and then returns to the closed position.

To install the backflow preventer, the sewer lateral was uncovered and cut to make room for the backflow preventer and to allow for an inline camera to inspect the lateral for breaks, damage, and quality of connections. The backflow preventer is incorporated with a standpipe from the lateral to the surface for access. This solution corrected the odor issue and allowed for site closure without the need for long-term mitigation operation and maintenance.

Grab liquid and vapor sampling from a sanitary sewer manhole.



Screening of sanitary sewer manhole using the Frog-5000™.

Complex preferential pathway case study

Multiple evaluation tools including desktop evaluation, private utility locating, camera inspections, visual inspection and real-time data collection were critical to investigating the sanitary sewer preferential pathway at a large industrial facility. An initial desktop evaluation showed that the on-site facility contains a substantial, complex sanitary sewer network that ultimately discharges to an off-site municipal sewer main that services many homes and businesses surrounding the facility. The evaluation showed that the on and off-site sanitary sewer network transects chlorinated hydrocarbon (cVOC) impacted soil, and that portions of the sanitary sewer network are in contact with cVOC contaminated groundwater.

The initial evaluation of the on- and off-site sanitary sewer system consisted of collecting liquid, sediment, and grab vapor samples from a select number of manholes. It was determined that a combination of inflow and infiltration of cVOC constituents were impacting the sewer network and traveling off-site. Initial remedies included rehabilitating and/or lining portions of the on-site and off-site sanitary sewer.

Follow up routine sanitary sewer grab liquid and vapor sampling (above left) revealed that these remedies significantly reduced cVOC concentrations in the sewer network on- and off-site. However, concentrations of cVOCs in sanitary sewer vapor continued to be above site-specific screening levels, particularly at on-site sanitary sewer manhole locations.

To further pinpoint the cVOC source that appeared to be located on-site, multiple Frog-5000™ units were used daily for three weeks to screen several primary manholes on-site that previously had the highest cVOCs concentrations (above right). Concentrations in primary manholes were followed to secondary screening locations on-site and beyond to sewer cleanouts inside the facility. In doing this exercise, trends in the analytical data were developed. The source was traced to a specific portion of the sanitary sewer network on-site that may require cleaning or rehabilitation. Other relevant observations potentially influencing the vapor data consisted of precipitation, the amount of activity in the facility, and other factors that influenced flow through the sewers.

The presence of preferential pathways can be a challenge in addressing the VI risk at a site as typical VI models and screening methods cannot be used. Arcadis has been able to effectively evaluate the VI risk through preferential pathways using a combination of innovative technical methods and multiple lines of evidence to pinpoint the location of preferential pathways, alleviate client and regulatory concerns, and effectively mitigate potential exposures to workers and residences. These tools alleviate the need for extensive and lengthy investigations and aid in expediting the site closure process.

About the authors

Megan Hamilton has over 20 years of experience in environmental regulatory oversight and consulting, with a focus on risk assessment and vapor intrusion (VI) expertise. Ms. Hamilton is a Principal Environmental Scientist, one of Arcadis' VI technical leaders, and member of the Arcadis VI Community of Practice (CoP). She remains heavily involved with research into the developing science of VI and presents on a national level. Work experience includes design and implementation of numerous VI investigations and mitigation for commercial, industrial, and residential properties; participation in public outreach and public meetings for large neighborhoods potentially affected by exposure through the VI pathway; and evaluation of conceptual site models and remediation work plans at sites ranging from retail gas stations and dry cleaners to large manufacturing facilities.

Sarah Jonker has over 15 years of experience in the environmental field to include field operations, technical lead, task management, and regulatory experience. Since joining Arcadis, she has specialized in vapor intrusion investigations, community outreach, mitigation, task management, plume stability assessments, human health risk assessments, and most recently sewer investigations. Ms. Jonker is well versed in various vapor intrusion sampling methods to include USEPA Methods TO-15, TO-17, TO-13A, TO-4A, and many types of passive sampling methods.

Adam Richmond has 10 years of experience working on the execution of environmental assessment project tasks related to groundwater and soil remediation projects and vapor intrusion studies. Mr. Richmond specializes in vapor intrusion studies and is the technical lead for vapor intrusion investigations for multiple client portfolios across the country, including multiple automotive, oil and gas, pest control, railroad, medical, and manufacturing clients, and former manufactured gas facilities. As a technical lead, he is responsible for the assessment and monitoring of large-scale, complex vapor plumes, leading project teams and clients through the challenges associated with the vapor intrusion pathway and navigating sites to closure.

Robert Uppencamp is a vapor intrusion (VI) technical expert and human health risk assessor with over 26 years of environmental consulting experience. He has experience with VI project management and oversight in multiple states, EPA regions, countries, and under multiple regulatory programs. Mr. Uppencamp's intimate knowledge of VI science allows him to apply the most current science to projects regardless of location. His ability to understand and interpret VI guidance under any regulatory jurisdiction allows him to assist clients from multiple business sectors with the design and implementation of the most straightforward and cost effective VI evaluation and remedy. He has also managed VI research and development projects for the USEPA and has participated in VI guidance development. Mr. Uppencamp has also served as the subject matter expert on multiple civil and class action lawsuits and has participated in public relations meetings. He also has significant experience in design and installation oversight of multiple VI mitigation technologies.

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About Arcadis

Arcadis is the leading global Design & Consultancy firm for natural and built assets. Applying our deep market sector insights and collective design, consultancy, engineering, project and management services we work in partnership with our clients to deliver exceptional and sustainable outcomes throughout the lifecycle of their natural and built assets. We are 29,000 people, active in over 70 countries that generate $4.2 billion in revenues. We support UN-Habitat with knowledge and expertise to improve the quality of life in rapidly growing cities around the world.

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