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Confirming that Your In-Situ Remediation Monitoring Program is Designed for Success

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In-situ remediation can be a cost-efficient strategy for cleaning up impacted groundwater and saturated soil. In-situ remediation is performed using a variety of technologies, including in-situ chemical oxidation (ISCO), aerobic and anaerobic bioremediation, in-situ chemical reduction (ISCR), thermal, and air/bio sparging technologies. Implementing in-situ remediation projects requires a carefully designed monitoring program, which meets the following objectives:

- Providing a network of locations used for baseline, process, performance, and compliance monitoring;
- Assessing the effectiveness of the technology;
- Confirming the Zone of Influence, or the distribution of remediation reagents and hydrogeologic and biogeochemical effects resulting from the application of technologies;
- Capturing the temporal changes during and after remediation implementation;
- Protecting sensitive receptors (e.g. drinking water wells, surface water, and subsurface utilities);
- Including contingencies for unexpected and/or potential behaviors in the subsurface; and
- Incorporating additional regulatory permit requirements.

These in-situ remediation monitoring programs are site and technology specific, and sized based on the scale and longevity of the project.

LIFECYCLE OF A MONITORING PROGRAM

A monitoring program is planned to meet different purposes throughout the remediation project. The four major types of monitoring are: (1) Characterization & Baseline; (2) Process; (3) Performance; and (4) Compliance. These monitoring elements and their major attributes are presented below.

TIMELINE OF AN IN-SITU REMEDIATION MONITORING PROGRAM

TIME

CHARACTERIZATION & BASELINE

- Performed before remediation
- Generates data to be used as a reference condition and for remedy selection and design
- Characterizes ambient groundwater quality and plume trends
- Includes the list of parameters established for the project

PROCESS

- Conducted during remediation
- Used to monitor the progress of remediation
- Monitoring of transient behavior
- Incorporates technology-specific parameters

PERFORMANCE

- Implemented after the active phase of remediation is completed
- Produces data to gauge the effectiveness of remediation
- Monitoring the recovery and stabilization of groundwater quality
- Includes constituents of concern (COCs), biogeochemical parameters, and seasonal changes

COMPLIANCE

- Performed once the groundwater system is stabilized
- Produces data to compare the concentrations of COCs to regulatory criteria
- The list of parameters and monitoring frequency can be streamlined

BIOGEOCHEMICAL CONDITIONS AFFECTED BY IN-SITU REMEDIATION TECHNOLOGIES

The suite of technologies that can be applied to remediate soil and groundwater results in a variety of physical and biogeochemical changes in the subsurface. The chart below summarizes anticipated changes, presented by category of parameters and technology type (i.e., oxidative, reductive, and thermal). All technologies will affect local system hydraulics (i.e., groundwater flow direction and gradients) and visual observations (e.g., presence of a reagent and/or turbid groundwater). Depending on the technology, the value of geochemical parameters can increase or decrease—groundwater may become more oxidative or reductive and/or more acidic/basic. Moreover, naturally occurring metals (As, Fe, Mn) may be temporarily mobilized or precipitate out of solution. The spatial extent, magnitude and duration of the changes is a function of the dose and quantity of injected reagent, longevity of the reagents or applied technology (e.g., sparged air or heat), groundwater flow velocity, buffering capacity of site soils, and ambient geochemistry. A properly designed remediation monitoring system will be able to capture these technology and site-specific interactions.

▶ COMMON PARAMETERS TO BE MEASURED, AND THEIR ANTICIPATED CHANGES, FOR CATEGORIES OF IN-SITU REMEDIATION

Parameter		Anticipated changes during active remediation phase (i.e. injection, heating)				
		Aerobic bioremediation / Air sparging	Anaerobic bioremediation	ISCO	ISCR	Thermal remediation
Hydraulics	Water levels / pressures	↑	↑	↑	↑	↓↑
Water quality	pH	—	↓	↓↑	↓↑	↓↑ —
	ORP / DO	↑	↓	↑	↓	↓
	Spec. Cond.	↓↑	↓↑	↓↑	↓↑	↑
	Temp.	—	—	↑ —	—	↑
Visual	Reagents	↑	↑	↑	↑	—
	Precipitates / turbidity	↑	↑	↑	↑	↑ —
Chemical	COCs & breakdown products	↓↑	↓↑	↓↑	↓↑	↓↑
Reagents	Oxidants and surrogates	—	—	↑	—	—
	TOC	—	↑	—	—	↑
	Fe, reductants	↓	—	—	↑	—
Geochemical	Alk., As, Fe, Mn, TOC, CH_4, S^{2-}	↓	↑	↓	↑	↑
	SO_4	—	↓	—	—	↑ —
	Cr(VI)	—	↓	↑ —	↓	—

NOTES

— = no or little change is anticipated, ↑ = increasing value, ↓ = decreasing value
The list of parameters presented in the chart is not meant to be all-inclusive.

MONITORING PROGRAM DESIGN

The layout of a monitoring network, parameter selection, and frequency of monitoring are designed based on the conceptual site model (CSM) and site-specific application of remediation technology. Key elements of the CSM that affect monitoring program design include:

- Distribution, concentrations, and phases (i.e. NAPL, dissolved, sorbed, soil gas) of COCs;
- Three-dimensional extent of treatment zone;
- Soil type and heterogeneity (high and low permeability strata);
- Groundwater velocity and flow direction;
- Depth to groundwater;
- Groundwater geochemistry;
- Preferential flow paths such as subsurface utilities; and
- Potential receptors (e.g. surface water, drinking water wells).

The figure below presents a generalized in-situ remediation injection well and associated monitoring network for a conceptual case. For this layout, injection wells are used to distribute reagent within a contaminant source area. The zone of influence includes the area in which reagent is distributed, as well as the peripheral groundwater zone where hydraulic and shorter-lived chemical effects occur during the injection program and longer-term geochemical changes following the reagent injection. Monitoring wells are situated upgradient of the source area, in the source area, within the plume, along the plume fringe, and beyond the plume edge. Monitoring wells have been positioned to facilitate the assessment of the zone of influence and for the potential of short circuiting to the buried subsurface utility and the surface water stream. In fact, several of the monitoring locations have multi-level screened intervals so that different strata of varying permeabilities can be evaluated. With this design, baseline, process, performance, and compliance monitoring can effectively be conducted, and contingencies are provided for uncertainties during in-situ remediation.

▶ GENERALIZED IN-SITU REMEDIATION INJECTION AND MONITORING WELL NETWORK

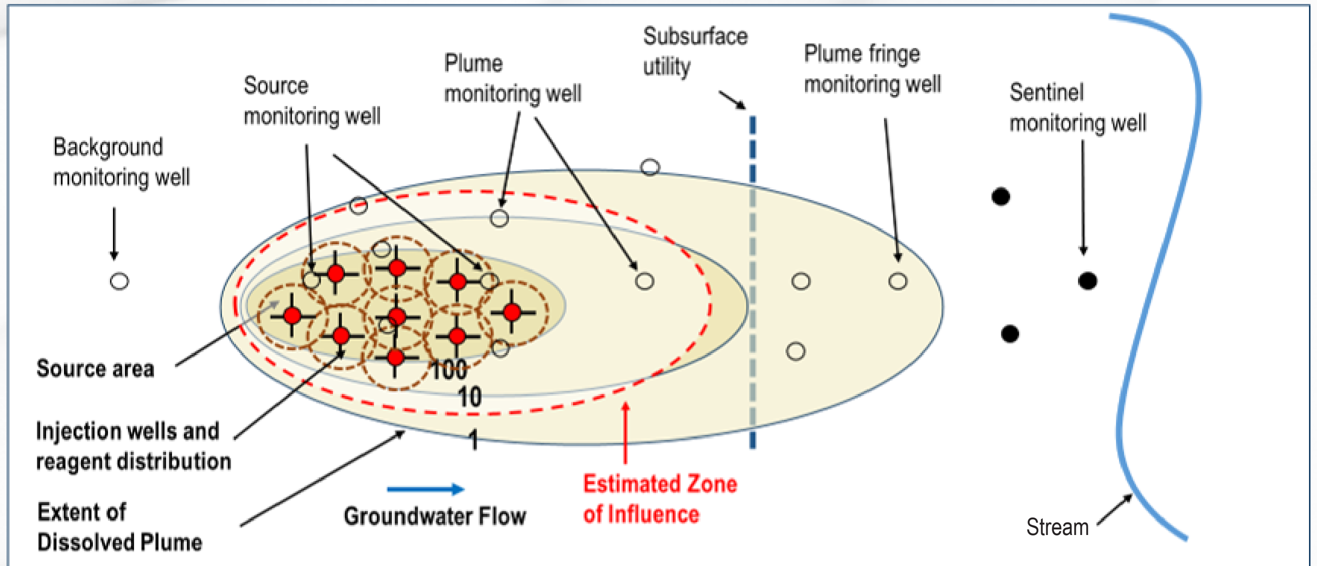


Figure adapted from NJDEP (2017)

Note: Monitoring locations are multi-level, over variable strata

Although all remedies may present special conditions that affect the sampling frequency, the following chart presents parameters commonly measured and examples of their monitoring frequencies during the life cycle of a monitoring program. The parameters are categorized by the physical, chemical, and geochemical changes that can occur during and after an in-situ remediation program. The monitoring frequency is higher during process monitoring when changes are most rapid. Following the completion of remediation, the monitoring frequency starts at a high level and decreases over time as more data is collected and the rate of change is better understood.

▶ COMMON PARAMETERS TO BE MEASURED, AND THEIR TYPICAL MONITORING FREQUENCIES

Parameters [1] (CSM and technology-specific)		Typical monitoring frequencies (with transition steps) [2]			
		Baseline monitoring	Process monitoring	Performance monitoring	Compliance monitoring
Hydraulics	Water levels / pressures Flowrates and volumes	At least once, providing representative data to design and evaluate the remedy	Daily → Weekly	Weekly → Monthly → Quarterly	Quarterly → Less frequent
Water quality	pH, ORP, DO, Spec. Cond., Temp.				
Visual	Reagents, precipitates, turbidity				
Chemical	COCs & breakdown products		Monthly → Quarterly	Monthly → Quarterly	
Reagents	Reductants/ oxidants & surrogates, TOC, Fe		Weekly → Monthly → Quarterly		
Geochemical	As, Fe, Mn, TOC, SO_4, S^{2-}, Cr(VI), CH_4		Monthly → Quarterly		

NOTES

1. The hydraulic, water quality, visual, and chemical parameters listed are common to different remediation technologies.
2. Monitoring frequencies may vary based on the technology used, duration of the active phase of remediation, and the rate of change of the parameters.

INCORPORATION OF REMOTE SENSOR TECHNOLOGIES INTO MONITORING PROGRAMS

Traditionally, field data collection consists of conducting low-flow groundwater sampling to obtain water quality parameters (pH, ORP, DO, specific conductivity, temperature, and turbidity) and samples for analytical testing. This data is collected at varying frequencies (i.e., monthly, quarterly, semi-annually, annually). The concentrations of analytically determined parameters (e.g. COCs, geochemical) can change more slowly than indicator parameters and may only need to be collected in strategic locations. Remediation technologies, such as in-situ thermal treatment and longer-term reagent delivery/pumping systems, can often benefit from more frequent collection of indicator parameter data (e.g. pH, ORP, DO, specific conductivity, temperature) to optimize processes or mitigate risk of migration of the Zone of Influence beyond desired limits.

In-well sensors (e.g., transducers, single and multi-parameter probes) can be deployed often at a lower life-cycle cost than manual collection of field data through low flow groundwater sampling. Further, in-well sensors collect higher frequency data, enabling better assessments of trends in the data. These sensors can also be coupled with remote telemetry systems such that the data is available on a near real-time basis, providing a kind of early warning system.

CASE STUDY

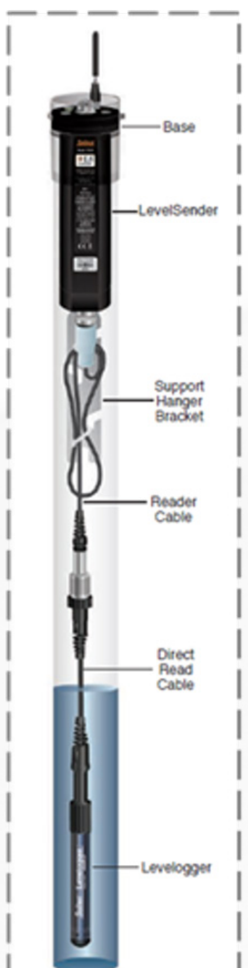
Over the last two years, we have leveraged the use of an in-well sensor network to enhance system performance and optimize the downgradient monitoring program at one of our combined remedy projects. This recent phase of the project includes: 1) groundwater migration control via extraction, treatment, and reinjection; 2) in-situ thermal remediation using steam-enhanced extraction to address chlorinated and aromatic VOCs and removal of light non-aqueous phase liquid; and 3) post-thermal remediation monitoring. The in-well sensors (transducers) were installed in nine wells at strategic locations for real-time monitoring of water elevation and temperature in downgradient groundwater and surface-water to assess the potential impact of downgradient migration of warm water from the treatment area to sensitive receptors (adjacent stream and wetland). A schematic and representative photographs of the probes and monitoring locations are shown on the following figure. The data is transmitted via a cellular connection and downloaded into a database. We then use a series of automated processes to consolidate the data and prepare time-series trend analysis, presented on a remediation dashboard to evaluate current conditions. A

> "Using the sensors and automated data management and analytics, we estimated that approximately $150,000 in cost savings, through reduced field and office labor and system operations, have been realized on the project."

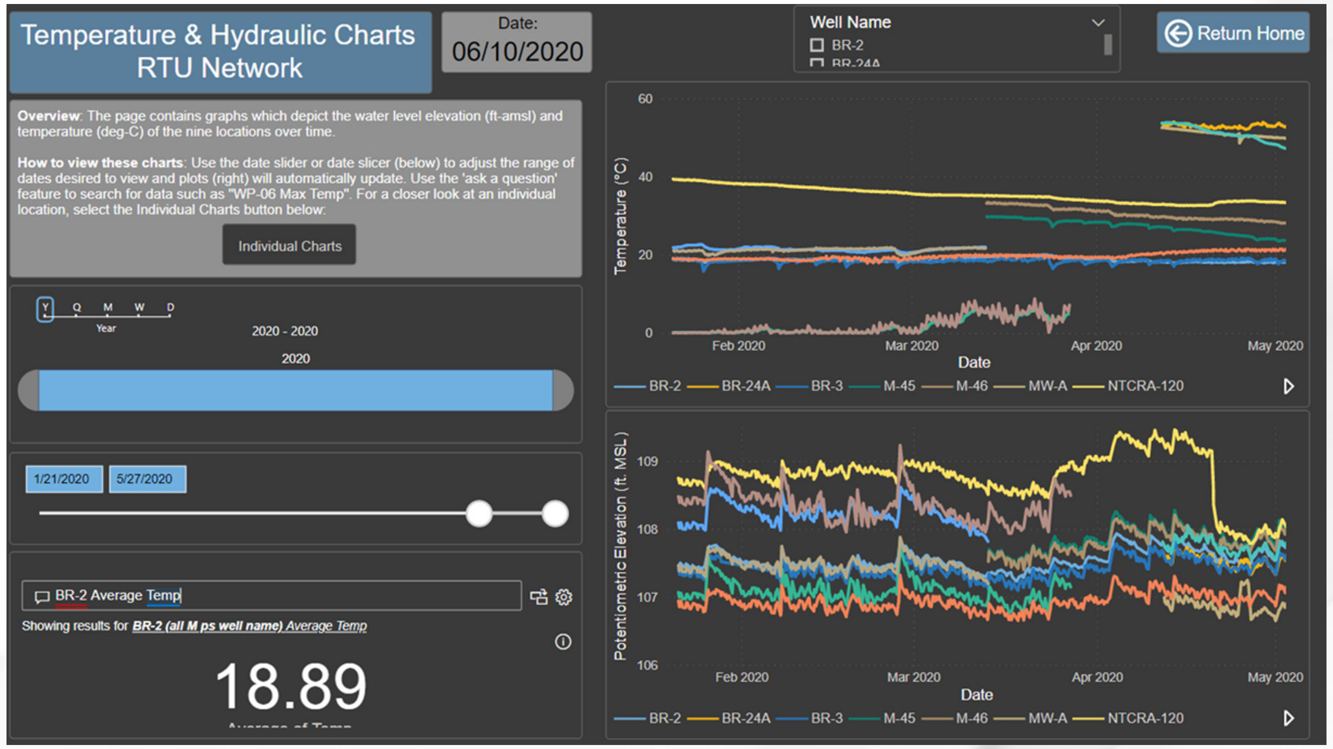
portion of the dashboard is shown in a following figure. This approach was used to identify if changes in thermal operations were warranted and is now used to track overall data trends.

Throughout the project, the sensor-based data proved invaluable. Labor hours in the field were reduced over a traditional approach based only on collecting data in the field. Office-based project team members were able to review the data in real-time, allowing for more frequent optimization of the thermal operation as conditions changed, as well as to be able to implement contingent measures as needed to address heat migration out of the treatment area and protect nearby sensitive receptors. Following attainment of remedial objectives and system shutdown, the sensor network continues to operate, allowing for post-thermal monitoring of temperature and water levels. Applying a suite of remote monitoring technologies to this remedial effort granted several benefits including a reduction in labor hours (reducing costs and providing greater protection of personnel safety) as well as faster response time to communicate site data and subsequently optimize system operations and implement mitigative measures. Using the sensors and automated data management and analytics, we estimated that approximately $150,000 in cost savings, through reduced field and office labor and system operations, have been realized on the project.

▶ REMOTE MONITORING SETUP SCHEMATIC AND PHOTOGRAPHS OF MONITORING LOCATIONS FOR IN-WELL WATER LEVEL AND TEMPERATURE TRANSDUCERS



▶ REMEDIATION DASHBOARD FOR IN-WELL WATER LEVEL AND TEMPERATURE TRANSDUCERS



CLOSING THOUGHTS

An appropriately designed monitoring program is site and technology specific and provides the ability to:

- Assess subsurface hydraulic, chemical, and geochemical conditions over the duration of an in-situ remediation project;
- Confirm the Zone of Influence, inclusive of temporal and spatial changes;
- Mitigate potential impacts to sensitive receptors;
- Account for uncertainties inherent in the subsurface and the application of in-situ remediation technologies;
- Allow for optimization over time to improve cost-effectiveness; and
- Enable the use of remote sensor technologies to minimize the collection of samples for analytical testing and to reduce the need to deploy staff in the field.

REFERENCE

NJDEP In Situ Remediation: Design Considerations and Performance Monitoring Technical Guidance Document (October 2017).

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