Special Series

# Integrated Risk and Recovery Monitoring of Ecosystem Restorations on Contaminated Sites

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## EDITOR'S NOTE:

This article represents 1 of 6 articles in the special series "Restoration of Impaired Ecosystems: An Ounce of Prevention or a Pound of Cure?" The articles result from a Technical Workshop organized by SETAC and the Society for Ecological Restoration, held June 2014 in Jackson, Wyoming, that focused on advancing the practice of restoring ecosystems that have been contaminated or impaired from industrial activities.

## ABSTRACT

Ecological restorations of contaminated sites balance the human and ecological risks of residual contamination with the benefits of ecological recovery and the return of lost ecological function and ecosystem services. Risk and recovery are interrelated dynamic conditions, changing as remediation and restoration activities progress through implementation into long-term management and ecosystem maturation. Monitoring restoration progress provides data critical to minimizing residual contaminant risk and uncertainty, while measuring ecological advancement toward recovery goals. Effective monitoring plans are designed concurrently with restoration plan development and implementation and are focused on assessing the effectiveness of activities performed in support of restoration goals for the site. Physical, chemical, and biotic measures characterize progress toward desired structural and functional ecosystem components of the goals. Structural metrics, linked to ecosystem functions and services, inform restoration practitioners of work plan modifications or more substantial adaptive management actions necessary to maintain desired recovery. Monitoring frequency, duration, and scale depend on specific attributes and goals of the restoration project. Often tied to restoration milestones, critical assessment of monitoring metrics ensures attainment of risk minimization and ecosystem recovery. Finally, interpretation and communication of monitoring findings inform and engage regulators, other stakeholders, the scientific community, and the public. Because restoration activities will likely cease before full ecosystem recovery, monitoring endpoints should demonstrate risk reduction and a successional trajectory toward the condition established in the restoration goals. A detailed assessment of the completed project's achievements, as well as unrealized objectives, attained through project monitoring, will determine if contaminant risk has been minimized, if injured resources have recovered, and if ecosystem services have been returned. Such retrospective analysis will allow better planning for future restoration goals and strengthen the evidence base for quantifying injuries and damages at other sites in the future. *Integr Environ Assess Manag* 2016;12:284–295. © 2015 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals, Inc. on behalf of SETAC.

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## INTRODUCTION

When implementing ecological restoration actions on contaminated lands, ecological recovery ideally proceeds concurrently with the reduction of contaminant risk. Their integration should progress consistently along all steps of the restoration process- from preliminary goal setting through postrestoration management. Restoration monitoring plays a critical role in this integration.

As with any restoration, a well developed monitoring plan keeps the restoration on track, using relevant metrics collected from the site to assess progress and guide corrective actions. Concurrent measurements of contaminant occurrence, availability, and effects provide feedback on risk reduction and removal goals and prevent the occurrence of unanticipated impacts that might occur with restoration-associated manipulation of the site. Successful integration results in restoration of desirable ecological structure, function, and services, while minimizing contaminant risk in the recovered ecosystem.

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### *Restoration approaches and need for remediation*

Restoration scenarios on contaminated sites differ in the degree of action taken to address contamination. In the simplest of these, ecosystem modification restores ecological attributes for purposes independent of resident contamination. Monitoring focuses on restored attributes but also includes assessment of residual contaminant movement within site trophic pathways and potential effects on organisms that use the site. Unanticipated monitoring findings could change both the regulatory status of the contaminant and the trajectory of the restoration, particularly with the demonstration of unacceptable risk or injury to resources. When contaminant risk is sufficient to require site remediation, methods used for remediation can severely alter site geography, including soil structure and surface water features, and lead to loss of plant and animal resources. Such landscape alterations can push back the starting point, or baseline, of habitat development, and monitoring would document the rebuilding of depleted habitats.

Concurrent integration of remediation and restoration practices offers benefits beyond their sequential implementation through time (Kapustka et al. this issue; Farag et al. this issue). Understanding the desired future condition of a site can direct levels of remediation and help design restoration site characteristics. For example, efficiencies in the engineering of the site are obtained if remediation and restoration are performed using the same equipment, and if seed banks can be returned using conserved and reused surface soils. Integrated monitoring could also benefit from combined efforts of contaminant exposure and effect monitoring carried out as part of the remediation, which could inform baseline monitoring for long-term restoration assessments.

### *The role for monitoring*

Independent of the specific mix of a site's remediation and restoration drivers, monitoring assesses and enables management of the progress of site activities and defines the degree of success at the cessation of those activities (Figure 1). During early site assessments, before remediation and restoration, data collected on the site define pretreatment or baseline conditions. If remediation proceeds separately from restoration, the postremediation site assessment will define the prerestoration condition.

Monitoring following restoration implementation documents attainment of desired site modification and ensures that, with time, the site condition progresses toward the desired ecological characteristics defined in the project goals. In response to monitoring findings, corrective actions can modify methods or objectives to redirect the ecological successional progress of the restored site, should it stray from the desired ecological trajectory. In more complex restorations with a variety of active stakeholders, such modifications of restoration activities progress through a more formal adaptive management approach. Because postimplementation recovery times often entail many years, monitoring findings at multiple

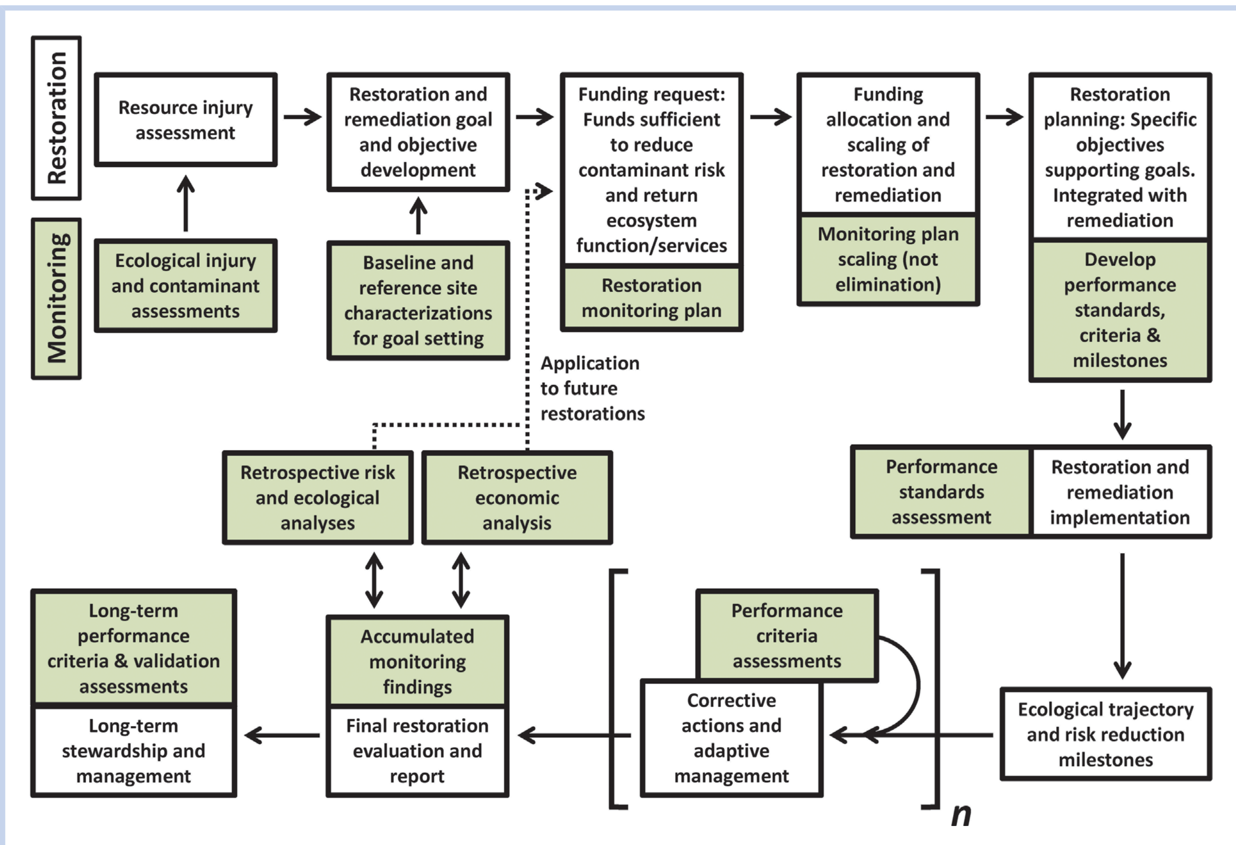


**Figure 1.** Application of monitoring to the ecological restoration of contaminated sites. Monitoring provides inputs into planning (separate monitoring boxes) and then integrates into the restoration and/or remediation process (fused boxes). When not specifically noted, remedial actions continue concurrently with restoration. "n" is the number of iterations necessary to maintain restoration trajectory toward restoration and remediation goals, and varies with project complexity, duration, and resources.

successional benchmarks may lead to multiple corrective actions to ensure the project attains the desired immediate and long-term goals.

Given its importance, restoration monitoring needs to be an integral component in project planning, proceeding hand-in-hand with the development and implementation of the restoration plan. The monitoring plan should clearly describe specific assessment details prior to initiating fieldwork, allowing implementation in a manner that makes its findings most applicable to each stage of the restoration process. At the completion of a restoration, findings from monitoring studies and the responses to them should provide documentation for the restoration outcome, whether it is the successful attainment of restoration goals or incomplete realization due to design miscalculations or extenuating circumstances.

Findings from monitoring studies also provide learning opportunities. Retrospective evaluation of planning and implementation methods can lead to important insights for future restorations. Overly optimistic projections of biotic production or succession can be adjusted to allow for more realistic planning of restorations. When project funding depends on anticipated time to recovery of the damaged resource, more realistic inputs into resource models will result in better estimates of time and funding necessary to attain resource recovery.

## DESIGNING AND IMPLEMENTING A MONITORING PLAN

A "monitoring plan" specifies information required for collection and evaluation over time. All ecological restoration plans should have a monitoring component to assess project goal attainment. Without monitoring, it is impossible to evaluate the progress or success of risk reduction and restoration activities. Monitoring helps ensure that a restoration plan based in science does not devolve into "faith-based restoration," where the project is implemented and the hope is that the outcome will be positive, that Mother Nature will allow it to succeed or ". . .if you build it, they will come" (Hilderbrand et al. 2005). Scientific monitoring of the restoration process is essential in determining that each step of the restoration is proceeding toward the goals established in the restoration plan.

The rigor and level of detail contained in the monitoring plan are defined by the scope and scale of the restoration plan itself. Regardless of complexity or scale of the restoration actions, the monitoring plan needs to address a variety of basic questions: What components of the restored system will be measured and over what spatial scale? How will components be measured? Using what metrics and benchmarks? How will the data be stored, managed, modeled, and evaluated? Who will conduct the studies and analyze the data? When will those elements be measured, at what frequency, and for what duration? How will monitoring findings affect management of the remediation and restoration? Who will communicate the results and to what audiences? Who will pay for monitoring costs? All these questions are linked by the critical question: How does the monitoring relate to the goals and objectives that drive the restoration?

### *What should be monitored?*

Throughout the course of a restoration project, different types of monitoring yield data and information needed to evaluate the effectiveness of particular restoration activities. Although terminology differs and there can be subtle differences among the various types, there are generally 4 basic categories of monitoring: baseline, implementation, effectiveness, and validation. Baseline monitoring of the ecologically degraded site characterizes existing (prerestoration) biotic and abiotic conditions and is therefore essential to help define needed restoration actions and provide for comparisons following restoration implementation. Low to moderate contaminant levels may allow for baseline development using site conditions at the beginning of concurrent site remediation and restoration. However, high levels of contamination can lead to remedial actions that modify the site and redefine the baseline before actual restoration can commence.

Note that the term "baseline" can also describe the condition of the impacted site, were it not for the contamination event that led to its disturbance (Burger et al. 2007; Alagoana et al. 2012). Here, we differentiate such sites as "reference" conditions, which are often the target habitat conditions for restoration (Wagner et al. this issue). Reference conditions, when applied to targeted restoration efforts, rarely mean "pristine." Impaired and contaminated ecosystems, particularly in urban environments, are often subject to a multitude of environmental and external stressors, including chemical (such as the ubiquity of numerous chemical contaminants), physical (e.g., storm damage, sedimentation, fragmentation, bulkheads), and biological (e.g., invasive species, extinction of local endemics, high herbivory) impediments that will limit the extent of recovery in a restoration. It is important to be clear when describing site recovery, defining whether restoration "recovery" is an improvement above the prerestoration baseline or progress in returning to reference conditions. The latter of these is a more conservative measure and provides a better assessment of restoration progress (Rey Benayas et al. 2009).

Implementation of restoration activities generally progresses through the completion of discrete objectives, such as removal or sequestration of chemical contaminants, removal of roads and invasive species, soil improvement, native species planting, or performing prescribed burns. Such actions proceed according to specific performance standards: methodologies and materials deemed appropriate to meet the project objectives. Implementation or compliance monitoring evaluates whether those actions meet the project performance standards, with the level of effort reflecting the complexity of the restoration. At its simplest, and in the absence of remediation or restoration actions on a site, monitored natural recovery may require only initial documentation of existing baseline conditions without implementation monitoring (Magar et al. 2009). Alternatively, with closely integrated restoration and remedial activities, extensive soil excavation or sediment dredging may require detailed contaminant monitoring concurrent with monitoring of restoration implementation.

Following implementation, performance criteria describe the desired observable and/or measurable results of the restoration actions and tie back to project objectives. Effectiveness monitoring evaluates whether the plan, as implemented, had the intended effect on the habitat and meets performance criteria. Near-term criteria can include such measures as percent survival of transplants, percent coverage of vegetated areas over discrete times, or occurrence of specific wildlife species with a particular frequency. Biogeochemical or physical processes that affect contaminant forms, concentrations, and corresponding toxicities can require continued chemical monitoring until sufficient evidence demonstrates that the site is effectively remediated, through removal or stabilization, to require only periodic follow-up monitoring. Because ecological systems are not static, chemical, physical, and biological conditions will continue to change over space and time. Ecological habitats follow a successional trajectory where species and community composition as well as physical and hydrogeochemical features change. Over time, longer-term performance criteria form the basis of assessments of progress toward desired site conditions, with focus turned to measures such as closure of forest canopy, community development, and ecosystem resilience. Their assessment through effectiveness monitoring can identify when corrective actions and site management may be necessary to attain or maintain the functioning ecological community defined in the goals of the restoration.

As restored ecological systems mature and become more complex, validation monitoring can enhance the evaluation of causal relationships between a restoration action and a response, allowing better understanding of restoration results (MacDonald et al. 1991; USDA USDI 1994; Roni 2005). A good example is provided by postimplementation monitoring programs of agricultural land retirement (Christensen and Kieta 2014) and wetland restoration (Kreiling et al. 2013) efforts in the upper Mississippi basin, which have demonstrated reductions in sediment and associated nutrient loading in adjacent waterways. Validation monitoring using isotopic and elemental tracers in suspended sediments demonstrated that cropland and stream bank soils accounted for a far greater proportion of sediments in streams lacking adjacent conservation actions (Williamson et al. 2014). As sediment-bound nutrient drainage and runoff into streams and rivers contribute to harmful algae blooms and hypoxic dead zones in receiving waters, validation of these conservation practices strengthens the case for their use to reduce agricultural runoff and its adverse effects.

### *Restoration scale and functional metrics*

Spatial and temporal scales are key factors in monitoring program design. Scale affects the statistical design needed to detect significant results, the type of monitoring methods that are applied, and the ecological functions and ecosystem services used to evaluate restoration success. Ultimately, the ability to assess the achievement of restoration goals depends on appropriate consideration of scale (Block et al. 2001).

Restoration monitoring can capture the range of necessary assessment criteria, including the complexity of food webs, habitat heterogeneity, and the dynamic processes that occur or have the potential to occur on the site (Temperton et al. 2004). The size and complexity of the restoration project and its context within the larger environment determine the spatial scale of a monitoring program (Block et al. 2001), from narrow (e.g., a stream reach habitat) to broad (e.g., a watershed ecosystem) contexts (Bestelmeyer et al. 2006).

Although practicality and budget often dictate that the majority of monitoring occurs at the habitat level, ideally, the data collected from these efforts infer knowledge at the ecosystem and landscape levels, allowing comparisons with ecologically similar sites within that region. For example, regional monitoring networks (e.g., the Coastwide Reference Monitoring System in Louisiana, USA) (Steyer et al. 2003) collect standardized data at regular intervals that allow for comparability across the region. By collecting similar types of data at similar temporal and spatial scales, restoration projects can be evaluated against regional reference conditions, thus providing insights into regional stochasticity or constraints on habitat development (Lewis et al. 1996). Landscape level context can define a site's interconnectedness with the surrounding landscape (e.g., providing wildlife corridors) and how a restored site can play a role in providing regional benefit beyond the site boundaries (such as migration corridors or stopover sites) (Rohr et al. this issue).

Scale is also inherent in the restoration goals and the ecological functions and ecosystem services measured as part of a monitoring program (Kapustka et al. this issue; Wagner et al. this issue). Ecological functions are the dynamic attributes of ecosystems, including interactions among organisms and between organisms and their environment, that provide the basis for self-maintenance in an ecosystem (SER 2004). Ecosystem services, on the other hand, are the benefits provided by ecosystems that support, enrich, and sustain human life. The 2 are often reliant on the same underlying biotic and abiotic processes, but the manner of measuring them, or monitoring their recovery, is dependent on their scale and can be very different.

Restoration objectives frequently include achieving a specific standard of ecological function and/or ecosystem service, often making these standards key indicators of restoration success (Palmer and Filoso 2009; Harris 2012). However, it is difficult and costly to directly measure ecosystem services and ecological functions (SER 2004; Tulloch et al. 2011), especially those that accrue over long time scales or large spatial extents. Therefore, in the context of monitoring habitats, structural metrics are selected as proxies for ecological functions (Rohr et al. this issue). A robust monitoring program establishes a strong connection between the metrics measured and the ecological functions and ecosystem services desired as part of the restoration goals and objectives.

Even when using proxy metrics, the scale of a monitoring plan should be directly relevant to the intended goal or goals of the restoration. For example, restoration of vegetative cover on a denuded area of a watershed, with a goal of restoring a functional ecosystem for target species, will require local monitoring over a defined successional time scale focused on species composition and habitat quality. On the other hand, if the goal of that restoration is to enhance a viable water supply to downstream users by reducing off-site flow of sediments and nutrients, spatial and temporal scales for monitoring will be much larger. Moreover, the recovery may not follow a linear trajectory. Vegetation communities with high evapotranspiration rates may actually reduce stream flow in the early stages of restoration (Springer et al. 2006). In this case, monitoring the target ecosystem service over too short a timescale may lead to the wrong conclusions about the ultimate effect of the restoration on the ecosystem service.

### *Metrics driven by restoration goals and objectives*

Selecting the proper metrics to accurately assess the achievement of specific restoration goals is critical for effective monitoring. Metrics selected should be indicative of progress toward, and success in, remediating and restoring contaminated sites. The level of sampling effort should be consistent with that required for statistical comparisons with reference areas or temporal demonstrations of habitat recovery. Metrics should thus be primarily quantitative in nature, but can include qualitative criteria such as timescale and historical photography (Jackson and Hobbs 2009; Woodward and Hollar 2011).

The level of detail in the objectives and goals of the restoration project will determine the effort expended and the number and type of metrics used for monitoring. Although data from multiple metrics would best depict the condition of a restoration project, monitoring metrics must also reflect available funding. Selection should rely on the literature and knowledge of reference areas with an additional eye toward critical species, their habitats, and biotic and abiotic criteria such as organism abundance and water and/or soil chemistry (Meador et al. 2002; Cacela et al. 2005; Gouguet 2005; Wang et al. 2013). As the restoration matures, monitoring efforts concentrate on metrics that help define limiting factors and instruct ongoing restoration activities.

Studies of prairie recovery monitored over time on the Nachusa Grasslands in Illinois, USA, provide a good example of multiple metrics used in postrestoration monitoring. Although soil bulk density remained elevated and total soil C and N were low throughout the 20 y following restoration, above-ground net primary productivity (ANPP) and floristic quality were within remnant prairie benchmark ranges for the first 5 y after reseeding (Hansen and Gibson 2013), which is important due to the difficulty in recovering critical native prairie species in restorations. Older restorations, however, showed time-dependent decreases in floristic quality and an increase in ANPP variability, likely due to expansion of C4 grasses and their negative effects on native forbs over time. The greater initial floristic quality correlated with seed mixes with greater richness in desirable native species. It is yet to be determined how increased seed density at planting, overseeding, mowing, and burning might extend floristic quality beyond the short-term. Although the recovery of desirable soil characteristics is slow following prairie restoration, it appears that with some methodological experimentation, the local ecosystem could benefit from returned primary production and floristic quality in the meantime.

In contaminated environments, the impaired status of functional groups or specific taxa can range from reductions in abundance, to rare occurrence or entire absence of species on a site (Beketov et al. 2013). Contaminants and habitat perturbation can affect microbial, algal, plant, invertebrate, and animal communities, as well as physical habitat attributes. Metrics that can identify species assemblage, species abundance and physical habitat attributes provide measurable data for comparison with reference or historical areas. Selected metrics should allow for the evaluation of trophic interactions, and should follow the pathways of contaminants through the food web (Stewart et al. 2004; Farag et al. 2007). Of course, the contaminants of concern are generally required to meet predetermined goals established during the initial study design or values designated by regulatory agencies. It may be further necessary to integrate contaminant data into risk- or hazard-based models or defined regulatory assessments.

Habitat assessment to describe physical characteristics of impacted sites can provide evidence to differentiate effects on biota caused by habitat limitations from those due to contaminants. In the Boulder River, Montana, USA, salmonid abundance and habitat quality were assessed at a site with historic hard rock mining activity. Stream habitat models then determined expected fish biomass based on habitat alone, which was compared with actual biomass to estimate the loss of biomass from metal exposure (Farag et al. 2003). Similar approaches used in the monitoring process could differentiate recovery due to habitat improvement versus contaminant removal.

Because disturbed habitats create ideal conditions for the proliferation of invasive species (Hierro et al. 2006), monitoring the presence and abundance of invasive species identifies any needs for their management. Invasive species can alter restoration trajectories and succession through direct predation, competition, alteration of soils, and altered fire regimes (Krueger-Mangold et al. 2006), and unless accommodated as part of a novel ecosystem approach, will need to be identified through monitoring and controlled.

Monitoring should also document the benefits of restoration for surrounding communities, particularly when restorations include development intended to directly benefit people. Metrics can include aesthetic or infrastructure improvements that make restored lands and waterways more attractive for recreational use, economic indicators such as improved land values, and changes in economic activity provided by increased recreational use (USDOI 2012).

### *Study design, statistical power, and data quality*

Because monitoring activities generate data, it is important in all stages of monitoring, planning, and implementation to understand and elucidate clearly how the data will be validated, managed, and used to assess restoration goals. Establishment of appropriate data management and quality assurance/quality control (QA/QC) measures is central to any data collection effort, instilling a higher degree of utility and confidence in data analysis. Data management and QA/QC measures will be unique to the project and specific to the various types of data to be collected (e.g., field duplicates and matrix spikes for chemical analysis; replicate community counts for ecological analysis). Regulatory agencies may require formalized QA/QC and data management project plans. Managing evolving sets of monitoring data over the multiyear course of active restoration, and the subsequent ecological recovery is a key to the success of any monitoring plan, although it can become a daunting task when monitoring activities can last for decades.

The monitoring plan should include a data analysis plan that specifies the types of quantitative, semiquantitative, and qualitative analyses conducted to evaluate restoration success. For quantitative analyses, ensure that study design includes an adequate sample population to provide robust statistical power, thereby reducing variability and other uncertainties in the data set. The level of data collection efforts should be scaled and more rigorous with increasing complexity of the restoration and with greater relative funding levels. In addition, critical to statistical evaluation is the consideration of whether tests are effects-based (i.e., is there a significant difference?) or effect size-based (i.e., what is the magnitude of this difference?) (Osenberg et al. 2006).

Last, there is an important role in monitoring for graphic visualization of data coupled with observational analysis. Geographic information systems (GIS) that allow the user to visualize georeferenced data can be very useful in evaluating spatial effects, especially for large-scale projects and particularly when used within time-series analysis to look either retrospectively at ecosystem changes over time, or to use in predictive modeling of future trajectories.

Using a multiple lines-of-evidence approach to evaluate changes over space and time, rather than reliance on only statistical significance (or lack thereof), can provide a "reality check" that may avoid erroneous conclusions. In summary, different types of data (e.g., chemical, biological) may require different methods of evaluation. It is thus beneficial prior to data collection to understand characteristics of the data (such as variability) to be collected and how those data will be used to evaluate restoration effectiveness.

### *Monitoring frequency*

Following restoration implementation, the frequency of monitoring necessary to provide confidence that regulatory compliance and ecological function will be achieved will be both context and metric driven. The context will include the overarching goals and objectives for the restoration site and the broader landscape, the specifics of the restoration plan as implemented, and the regulatory requirements and stakeholder expectations of what should be achieved within a certain timeframe. The metrics will be those chosen to reflect the desired ecological function and services at an intensity appropriate for the scale and funding levels of the restoration.

Monitoring of structural components of the restoration often requires multiple site assessments during the year to capture particular life history stages necessary to fully document their presence and condition. Vegetation assessments may begin following germination, in the case of programs employing direct seeding and/or relying on emergence from soil seed banks. Such early assessments, although useful, will reflect the capacity of the surface or near-surface substrate conditions to support initial vegetation establishment and land cover before external factors such as variable weather conditions, soil moisture and nutrient availability, or herbivorous predation have a significant impact. The inability to identify to species at such an early stage limits the amount of information on species richness and biodiversity. For this reason, vegetation monitoring is appropriate during flowering and fruiting seasons. Given the typical growth curves of perennial vegetation, monitoring will tend to be longer than a single growing season to document establishment of hardy individuals.

Multiple-season monitoring assessments may also be necessary for animal species on restored sites. Resident species on sites, such as invertebrates or amphibians, have annual cycles of life forms (eggs, larvae or tadpoles, adults) with optimal seasonal monitoring periods. Highly mobile species, such as birds, vary their occupancy during the year, with local residents present in the winter, migrants making an appearance in spring and fall, and summer residents joining local residents breeding on the site in spring and summer. Depending on the restoration goals, the monitoring focus could be on a single critical species, stopover use by migrants and/or nesting habitat for residents and migrants, each requiring differing frequency of monitoring through the year.

In a program that has the opportunity for progressive restoration over time, the initial programs can essentially be established as an "experiment," with potential oversampling and assessment being tolerated for the greater gain in creating a more refined and efficient program and to inform future monitoring parameters and frequency. If corrective management actions (or unexpected perturbations, such as fire, extreme weather events) are imposed on the restored ecosystems, the frequency of monitoring may revert to that established for an earlier successional stage commensurate with the degree of impact and level of regression.

Monitoring metrics will likely extend to many biotic and abiotic components of the system. Although the temporal alignment of monitoring various parameters is necessary in order to examine relationships and interactions between components of the system, measuring all components on all occasions will be an unnecessary and inefficient strategy. Monitoring frequency of individual metrics is determined by the preset or qualitative and/or observational rate of change in that particular metric, and the criticality of the data points in attaining monitoring goals.

When deleterious contaminants pose potential risks to site biota, changes in contaminant presence, availability, and effects are often assessed based on regulatory guidelines. Seasonal changes in contaminant presence with changing hydrological conditions will make focused monitoring necessary to catch periods of highest risk to life forms on the site. With less stable materials exposed in the early stages of restoration, early precipitation can result in pulses of high aquatic contaminant levels. Extreme weather events can similarly exacerbate contaminant flow in and away from the site. The monitoring frequency of restored ecosystems at risk will thus develop from the outcomes of the first-flush and other preliminary assessments of the chemical (and physical) loads that regularly or irregularly leave a restoration site, the dilution factor as a consequence of discharge, and the impact on recovery rates of restored ecosystems and the organisms therein. As the restoration site matures, the propensity for contaminants leaving a site by surface flows diminishes, although groundwater flows and subsequent surface expression may still pose an ongoing risk.

### *How long should we monitor?*

Measurement duration will generally vary with the metric, with structural measures such as plant species composition or plant primary productivity being useful at frequent intervals throughout the site recovery. More integrative functional endpoints, such as soil C and N, and plant or wildlife community development will require longer-term, less frequent monitoring (Herrick et al. 2006; Hansen and Gibson 2013). Furthermore, not all metrics will peak or asymptote at the same time. Some may become redundant and some may require minimal and less frequent attention, whereas new metrics may become relevant as the restoration matures and stabilizes. Monitoring should continue while the site matures, undergoes corrective actions that keep it on course, or until structural and functional metrics suggest arrival at, or a solid trajectory toward, the final restoration goals.

In general, measurement of absolute metric values at a point in time is of less value than sufficiently regular measures that define and account for variation and allow assessment of whether the ecological trends are in a direction desired for the restoration. Studies of ecosystem recovery following natural or anthropogenic disturbances provide insight into the dynamics of natural recovery (Russell and Hageseth Michels 2011). Similar studies following restoration can provide insight into the anticipated recovery timeline, dynamics, and the benefits of specific interventions to ecosystem recovery (Hansen and Gibson 2013). Chronosequences such as this can be particularly useful when fully incorporated within the planning and monitoring of the postrestoration recovery process. Some site characteristics may be very slow in recovery, requiring decades to over a century to approach full recovery. Monitoring a profile of structural and functional site metrics over time can provide a means to determine if the restoration is on track to reach long-term goals.

Multidecadal or centurial timescale remediation and/or restoration projects are often associated with large-scale mining or chemical contamination sites where hazardous waste materials are deposited in surface, subsurface, or aquatic impoundments. Toxic soils or tailings piles, uncontrollable groundwater intrusion, or extensive river or lake sediment loads can be present in massive volumes and present a high risk. These sites, such as the Rocky Mountain Arsenal, Colorado, USA (buried chemically contaminated soils) and the Anaconda Smelter Site, Montana, USA (stockpiled tailings and sediment deposits) are often treated or monitored "in perpetuity" or "contained for 10,000 years" (Edson et al. 2011). Where such temporal realities make achievement of restoration goals an intergenerational effort, monitoring duration does not project a completion date, but rather assures confidence that the stabilizing characteristics of the restoration are maintained. It is particularly important that restoration construction be sufficiently resilient to stand up to any planned or unplanned perturbations on the site that would interrupt restoration progression, which could be catastrophic at sites with this magnitude of contamination. Substantial trust funds can ensure that such monitoring continues and does not default to the responsibility of government regulatory bodies or, ultimately, the taxpayers.

Ideally, monitoring is required up to the point of restoration goal achievement; although funding realities more than likely substitute proxy measures indicative of progress toward long-term restoration success. In many cases, the implementation of the restoration, assurance of performance standards and short-term monitoring of performance criteria may be all that the budget will allow. In these cases, local or regional governments or NGO entities often become the "stewards" of restored sites, assuming responsibility for site management. When previous chemical contamination requires continued long-term monitoring, regulations will establish the frequency and intensity. The progress of the restoration, however, generally folds into the site management where it is rare for the monitoring and adaptive management paradigm to continue. More likely, unless the site is incorporated into a larger managed park or preserve, management will center on maintenance for local use as a park, open space, fishing access, or other community asset. Allocation of funding for post-closeout monitoring or the development of citizen science programs that can continue the more critical long-term monitoring can help assure that the restoration goals will be reached in the long-run. Such programs may be scaled back from the formal monitoring program, but focus on critical site indicators that could herald the eventual achievement of restoration goals or catch aberrant patterns of succession on the site before they become uncontrollable.

## RESPONSE TO MONITORING FINDINGS

### *Milestones, corrective actions, and adaptive management*

A set of time- or event-driven milestones along a restoration trajectory can be developed from knowledge of the biotic and abiotic components and conditions present on a site, combined with habitat-specific chronosequences or professional experiences that provide informed performance criteria. Milestones can be set, based on time after completion or significant steps of the implementation (e.g., monitoring bouts at 1, 2, 5, and 10 y postconstruction) or based on events within the restoration trajectory. The latter might entail contaminant concentrations falling above or below critical values or biological events such as forest canopy closure or species abundance or diversity criteria, all generally tied to anticipated performance timelines. In this context, monitoring provides insight on restoration progress and identifies reasonable delays or unanticipated intrinsic or external impediments in the attainment of milestones along the restoration trajectory. In a worst-case scenario, without correction, such delays or impediments may create a trajectory departure that leads to an alternative endpoint or, at worst, system failure. Flexibility in site management (and budget) will allow monitoring findings to drive the decisions on whether natural successional recovery through time will rectify temporary departures or more intensive monitoring and management are required to return to a scheduled trajectory toward restoration goals (Block et al. 2001).

Adaptive management in a natural resource management setting (Walters and Holling 1990) employs an iterative approach rooted in flexibility and learning by doing, or learning from "mistakes." Its implementation occurs throughout the duration of restoration action as the results of monitoring activities reveal the progress and nature of the recovering ecosystem. Monitoring is thus critical to site managers throughout the implementation and recovery phases of the project, allowing for "mid-course corrections" or "corrective actions" that fine-tune the objectives and management activities so that they are more likely to meet the original goals of the project (Hilderbrand et al. 2005). More serious modifications may require re-evaluation of the milestones and objectives to meet remediation and restoration goals, implementing adaptive management plans, and possibly, after having exhausted all feasible alternative approaches, revisiting the goals to re-evaluate their feasibility (Efroymson et al. 1997; LoSchiavo et al. 2013).

The application of adaptive management is a recognition of uncertainty in our understanding of future events and interactions between abiotic and biotic drivers of restoration (Linkov et al. 2006). Thus, it is an iterative approach, where performance measures or thresholds are set for restoration progress to achieve or avoid. Although adaptive management allows for midcourse corrections, it is not an "on-the-fly" approach to changing methods. Rather, it is an approach to site management in which relationships between monitoring metrics and the variables influencing them were anticipated during the goal-setting and planning phases. Outcomes that deviate from the expected targets trigger a change in methods based on known factors influencing the system. In some cases, adaptive management may be a hypothesis-driven approach in which multiple strategies are used in parallel, varying only the factor that is hypothesized to be the major determinant in the outcome (Linkov et al. 2006). Thus, learning can occur as the project progresses, and once found, a successful strategy can be efficiently scaled up throughout the project.

Adaptive management can play an important role in restoration progress when there is uncertainty associated with residual contaminant risk on restored sites. Ongoing restorations of marsh tidelands in the South San Francisco Bay estuary (California, USA) seek to reclaim more than 60 $km^2$ of industrial salt evaporation ponds (USFWS CDFG 2007). The process is hampered by Hg-contaminated sediments in the ponds, the result of effluents from 150 years of Hg mining in the mountains south of the Bay. A 50 y adaptive management program for this restoration is weighing data from studies of wintering and nesting bird site use and foraging patterns, fish communities, and sediment dynamics to guide site modifications in an informed, incremental manner (Appendix D; USFWS CDFG 2007). A detailed series of studies has evaluated Hg exposure and effects in birds using the site and, based on findings to date, focuses on methylmercury concentrations in Forester's tern and American avocet eggs as integrating bioindicators of Hg risk to birds (Ackerman et al. 2013, 2014). As controlled breaching of levees surrounding contaminated evaporation ponds occurs in stages, avian egg and fish monitoring studies have demonstrated transient pulses in methylmercury bioavailability in the local fauna as sediments redistribute in the Bay (Amato and Valoppi 2015). The adaptive management of these ponds will determine the eventual proportions of marshland and managed pond habitat restored in the South Bay. Concurrent monitoring of Hg concentrations in sentinel species reflects the risk associated with the restoration activities and provides the ability to respond to unreasonable or sustained Hg mobilization and bioavailability above local background.

Adaptive management can be a useful tool in realigning project results with restoration goals as efficiently as possible, but it is a planning process as much as a late stage management process, and requires a strong understanding of the interactions between management actions and metric outcomes. Problems can arise in applying adaptive management with the inertia of large, complex restoration projects. With larger projects, it is particularly critical to set thresholds that trigger adaptive management actions early in the design process to obtain stakeholder buy-in and agreement and link the metrics collected during monitoring to those collected during site evaluation and design.

A discussion of milestones would not be complete without considering the case where an ecosystem's successional trajectory requires tempering to maintain a community that has attained the ecological functions and ecosystem services established as its goals (Prach et al. 2007). For example, under unmanaged conditions, many freshwater wetlands eventually transition to upland systems through the successional processes of debris accumulation, soil formation, and changes in vegetation communities (Maitland and Morgan 1997). The objectives of a restored wetland, meant to remain intact in perpetuity, may not be feasible without continued management that interrupts the natural successional trajectory. Here again, monitoring includes metrics that trigger the management actions needed to arrest successional change toward a climax system and maintain the desired seral state.

### *Communication of restoration activities*

The need to communicate monitoring results to diverse audiences over the course of any restoration cannot be overstated. Technical reports, publications, and presentations at scientific meetings inform the scientific community of scientific results of the monitoring studies. That, however, is only the start of communicating monitoring results. To ensure long-term public support, restoration practitioners benefit by conveying monitoring results outside the scientific community to interested public groups and to government officials at many levels. This often requires "translating" complex scientific findings into plain language, with scientists working hand-in-hand with communications and outreach specialists, presenting results in terms that are relevant and comprehensible to nonscientists. Simple conceptual models, indicator or surrogate metrics, and report cards are examples of tools that have proven useful in such communications. Public engagement throughout active restoration and subsequent monitoring provides the best assurance for continued support and the potential for long-term stewardship of the restoration site. Appropriately designed citizen science can often provide additional technical results at a low cost to supplement traditional approaches using academic or contract support to collect and analyze more complex data (Cohn 2008).

A communications plan, accompanying and integrated with the major elements of the restoration and monitoring plans, lays out the specifics of planned communication with the public. Because these communications strive to reach multiple varied audiences, communications plans should include a variety of venues and media, potentially including web-based communications and new electronic media. Outside the scientific community, especially among the general public and political office-holders and their staff, anecdotal evidence (especially when combined with strong visual images) can be a powerful mode of communications. Before and after pictures showing degraded and restored habitats can be much more effective when communicating with nontechnical audiences than busy graphs or tables filled with endless numbers and Latin names of species. For example, outreach efforts communicating success of bald eagle restoration and recovery from Montrose Chemical DDT contamination in coastal southern California included web cameras in their nests, documenting successful natural reproduction on the Channel Islands (USNPS 2015). When incorporated into classroom curricula, these webcams inspire youth to care about the results of the restoration and may foster some students to become the next generation of restoration professionals.

## WHEN ARE WE DONE?

When does the need for monitoring end? Have we met our monitoring objectives and achieved our restoration goals? If not, why not? Are the collected monitoring data adequate for decision making or are additional parameters needed? Have data generated from the monitoring program facilitated a decision to modify any of these goals and/or employ adaptive management procedures? Are monitoring parameters still relevant and significant for evaluation of goals? Ideally, consideration of these questions occurs throughout the monitoring process, to ensure progress toward project goals and avoid critical failures.

Different types of monitoring programs will have individual timeframes. For example, whereas implementation and baseline monitoring may proceed for only the duration of active implementation, effectiveness and validation monitoring will occur over a longer time period. Thus, as certain levels of monitoring may end, other components of the monitoring program continue into the future. Some types of remediation, such as monitored natural recovery, capping, or chemical amendments may need to be monitored for an extended period of time, or even in perpetuity, to affirm that the remedial strategy remains effective at maintaining residual risk at or below an acceptable level. Though many contaminant levels may decrease over time once remediation attenuates the input source, restoration actions on the site may serve to increase contaminant availability (see *Monitoring Frequency*, above). Stochastic events, such as major storms, flooding, oil spills, and geological events can undo any advances in ecological restoration of an area, essentially resetting the clock. Thus, long-term, "disturbance-based" monitoring may be necessary when unacceptable risk would result from failure of the remedy to remain protective in the face of events that could cause changes in site conditions (Magar et al. 2009). On sites where contaminants pose a bioaccumulation threat, contaminant monitoring in upper trophic level biota can serve as an integrative measure of movement of such compounds through food webs. On the Rocky Mountain Arsenal, postremediation monitoring for dieldrin, the principal contaminant of concern on the site, is focused on Kestrels and European starlings inhabiting nest boxes distributed across the restored site for this purpose (RMABAS 2006).

In light of these considerations, should we ever truly be finished monitoring? Clearly, it is not practical or feasible to fund monitoring for an indefinite amount of time, particularly if future funding may not be available to fix problems that arise from future, unforeseen events. This stark fact nevertheless highlights the need for, and importance of, more robust monitoring, data evaluation, and problem solving, particularly in the initial and intermediate stages postimplementation where funding might allow adjustments to set the site on the right trajectory toward restoration success.

### *Measures of success*

Success measures in ecological restoration generally focus on goals set during restoration planning, goals that are generally a site-specific collection of conditions and values that once attained should return the impaired resource or resources to a functioning independent ecosystem. Thus, success can be measured as a function of the ability to achieve performance criteria for activities and objectives necessary to reach those goals. Given reasonable goals and objectives, unlimited resources, and a commitment to corrective action and adaptive management, restoration projects should usually be capable of reaching their goals. In most cases, attainment of actual target ecosystems during the monitoring period is not likely, due to the realities of extremely long-term recovery periods following restoration implementation (Russell and Hageseth Michels 2011; Hansen and Gibson 2013). When adequate data are available from natural or similar previously restored habitats, monitoring findings demonstrating a condition at a known point in the successional recovery trajectory may serve as a surrogate for complete restoration recovery (Berkowitz 2013).

An important question to ask at the completion of restoration monitoring is "Have the degraded resources been restored, replaced, or rehabilitated?" For ease in answering this question, a subset of monitoring metrics should be the same as those used in the risk analysis phase that occurred with, or leading up to, restoration goal-setting. Recovery should be evident in the improvement in the condition of those metrics. Employing different endpoints and metrics may yield important information but will require intermediary interpretive steps to connect the dots between those data and data on the prerestoration status.

A common scenario plays out with monitoring activities continuing until restoration funding runs out, with the success of the restoration judged on the adequacy of the work performed up to the point where activities ceased. Considerations include how well the objectives were completed, unanticipated impediments that may have delayed or obstructed progress, and whether goals were actually realistic based on funding levels in the first place. In any case, progression toward restoration goals should be documented with sufficient detail to allow assessment of the project's success as well as consideration of what additional resources might be required should decision makers decide that further work on the restoration is worthy of future support.

Restorations driven by regulations, for example, when those responsible for the contamination perform the restoration themselves as part of a settlement or litigation outcome, require budgets adequate to continue restoration monitoring until goals are attained. This is in contrast to outcomes where those parties might provide a set dollar amount for restoration, leaving the logistical details to the limitations of the negotiated budget. In this latter case, as in all cases where restoration of impaired resources depends on completion within a set budget, "...the immediate loss is certain, whereas future gain is uncertain" (Moilanen et al. 2009).

## WHAT HAVE WE LEARNED?

As we have demonstrated, monitoring is essential to determine progress and success of restorations. Monitoring results can inform future actions at the site or influence restoration activities at other sites. Recovery curves or chronosequences, compiled from the results of multiple restoration experiences on a common ecosystem type, can place the recovery into a temporal framework so that estimates of site maturation are based on realistic recovery curves and not simply on convenient near-term estimates (Steyer et al. 2003; Berkowitz 2013). In some cases, negative results can be even more informative than positive results. George Santayana's maxim, "Those who cannot learn from history are doomed to repeat it," applies to restoration monitoring as well as to history. Insights regarding restoration actions that do not meet objectives, and retrospective discussions of why objectives were not attained, should be shared so restoration practitioners can avoid repeating past mistakes. Researchers and restoration managers can often be hesitant to report negative results, but failure to do so runs the risk of missed opportunities to improve the state of practice of restoration. The journal, *Restoration Ecology*, includes the section, "Set-backs and Surprises," for publishing such information (Hobbs 2009).

One of the more useful applications of restoration monitoring data is their role in evaluating the restoration planning process. Scaling of restorations often involves calculating the activities and resources necessary to achieve particular species, community, or habitat recovery. Models, such as resource or habitat equivalency analyses, calculate the scale of restorations necessary to compensate for lost services that occur due to contaminant or oil releases (Munns et al. 2009). Many inputs go into these models, often only best estimates, so data from on-site monitoring can reduce uncertainty in model outputs. When used early in the restoration, such checks on the accuracy of site models may benefit adaptive management for the current restoration, whereas retrospective assessments at project's end help inform future restoration planning.

As compensation for contaminant injury often has its basis in the costs estimated for restoration of those resources, the more accurate the cost estimates, the greater the ability to accomplish the restoration. An alternative situation often faces practitioners: a set budget with a need to scale the restoration to available funds. Planning for the scale of the restoration will be more accurate when realistic data are available from the monitoring findings of previous restoration experiences. In both of these cases, restoration activities can be more dependably optimized based on scale or budget, leading to better chances that restoration goals will be reached for the project.

The use of restoration monitoring is not universal among practitioners (Bernhardt et al. 2005) and retrospective analyses are demonstrating that restoration goals often remain unattained, or worse, unassessed. Monitoring, when it does occur, is usually of limited duration and ends many years short of attainment of restoration goals. Much of what we will learn has yet to be seen, as the numbers of restorations performed on contaminated sites is generally small, with most still in progress and few with long-term definitive stories. As commitments and funding for restoration continue to increase, it has been suggested that a core of basic principles should drive restorations, emphasizing ecological integrity, long-term sustainability, grounding in historical and future site context, and linkages to societal benefits and engagement (Suding et al. 2015). Although these qualities may be easy to claim during restoration planning, it will require monitoring to document their attainment. Use of approaches discussed herein could likely provide the data necessary to show progress in attaining these principles.

The design of monitoring programs, the techniques used, and the measurement, analysis, and interpretation of results from such programs can demonstrate the utility of new and established methods in meeting the breadth of needs for restoration and remediation monitoring. Because a monitoring plan is established essentially as an experiment, with research questions, hypotheses, objectives, and methodologies, lessons learned from monitoring "experiments" can identify successes and drive improvements in the science. To ensure sufficient rigor and cost-effectiveness in monitoring, metrics have emerged to maximize accuracy in detecting changes in ecological structure and function. When applied in a manner that accounts for the inherent heterogeneity and variance in reconstructed ecosystems, these approaches have contributed to the understanding of restoration science and methodologies used in the restoration process itself.

Following the 1989 Exxon Valdez oil spill in Alaska's Prince William Sound, long-term monitoring documented the effects of high pressure, hot seawater washing on oiled intertidal zone habitats (Shigenaka 2014). Hot water treatment was initially detrimental to intertidal life relative to areas where oil dissipated naturally. However, postremediation monitoring of washed and nonwashed shoreline showed those differences were not significant after 1 to 2 y, and that within 3 to 4 y, treated and untreated sites recovered back to nonoiled conditions. Abundance measures were, however, highly variable. Subsequent controlled recovery studies that eradicated all lifeforms on nonoiled intertidal zone plots put the monitoring findings in context, confirming a 2-y recovery period for this highly resilient component of the ecosystem. A surprising and important finding over the next 15 y of monitoring was that the highly variable abundance measures of mussels, limpets, and rockweed were closely tied to the warming and cooling seawater trends of the large-scale Pacific Decadal Oscillation (PDO). These postremediation and controlled validation investigations not only provided guidance for future remedial actions but also demonstrated the mechanistic basis of much baseline habitat variability (i.e., the PDO). Understanding how water temperature patterns acted as a stochastic influence on habitat provides insight into influences of today's climate change-induced ocean warming on baseline habitat variability.

## SYNOPSIS—PUTTING RESTORATION MONITORING TO WORK

Ecological restorations focus on reestablishing injured species, habitats, and ecosystems, each with focal biotic and abiotic features, and its own prescribed structures, functions, and services that reflect the goals established for success. Chemical contaminants complicate the restoration, sometimes leading to a bewildering array of possible restoration scenarios. Crafting a suitable restoration monitoring plan comes down to accommodating the specifics of the planned restoration, integrating appropriate measures of potential chemical risk, and assuring that mechanisms are in place to allow managers to act on the findings to optimize ecological recovery and minimize residual chemical risk. As each monitoring plan will differ based on variability in restoration design, so will the applicability of the topics described in this synthesis. The reader is encouraged to incorporate the approaches and considerations that will benefit their specific remediation and/or restoration scenario.

Should funding constraints threaten to reduce the scope of a restoration, it is best not to eliminate the monitoring plan, but to downscale, shifting the focus to less expensive, less labor-intensive and more integrative measures (Woodward and Hollar 2011). It may be true that the cost of monitoring can decrease the extent of a restoration, diverting resources that might have funded a larger restoration. However, monitoring ensures that should the restoration falter or move off-course, an opportunity exists to make corrections and continue toward success. Some may feel that "a bad restoration is better than no restoration," although what may be left is a failed restoration seriously underperforming its intended function. A slightly smaller restoration, visibly delivering desired ecological function and ecosystem service goals, guarantees that a portion of lost resources are recovered and creates the confidence in the restoration process that can be the foundation for future projects.

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