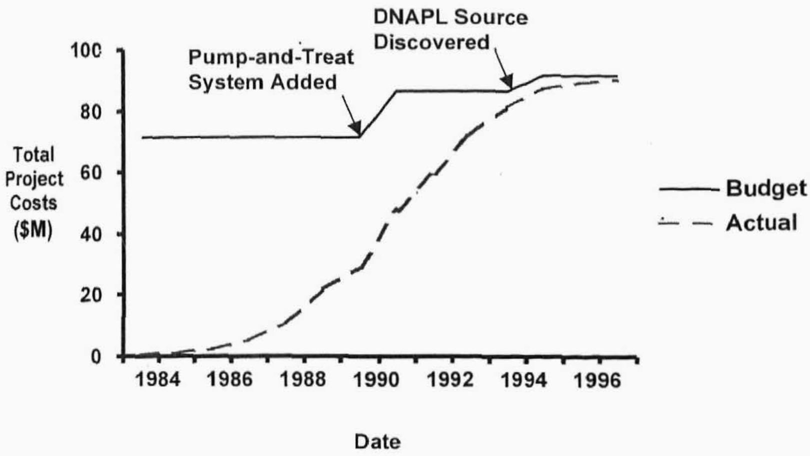


Figure 4. Total project costs for French Ltd.

*Uncertainty in Source Locations*

Uncertainty in the locations of sources at Sikes was not properly recognized in the design and implementation of remedial action. The remedial-action objective was to reduce groundwater concentrations by removing all sources of contamination. In order to accomplish this objective, the locations of sources were estimated based on available information about the waste disposal practices and characteristics, and a soil boring program at the site. However, this information was by no means definitive in identifying source locations. First, the waste disposal practice was described as "indiscriminate," making the source distribution across the site difficult to estimate. Second, industrial wastes were accepted, similar to French Ltd. where DNAPLs were discovered, introducing uncertainty in the vertical extent of the separate-phase sources. Third, when waste was placed, lifts of clean soil of varying thickness were apparently placed between the waste, eliminating any trends in the vertical source distribution, e.g., concentrations decreasing with depth.

Data from soil borings support this conclusion that there was significant uncertainty in the location of sources prior to the excavation and incineration of contaminated soil and sludge. The design excavation depth was set at an average depth of approximately 3 m below the ground surface based on these boring data. Data from two soil borings, one located in the main waste pit and the second in the overflow area, are shown in Figures 5 and 6, respectively.

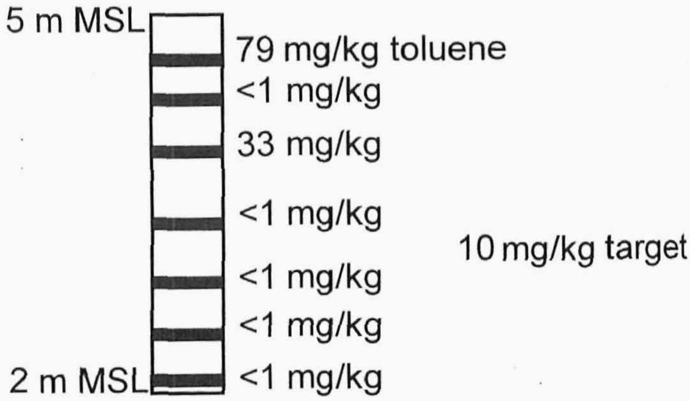


Figure 5. Toluene concentrations in soil for boring B-1 at Sikes

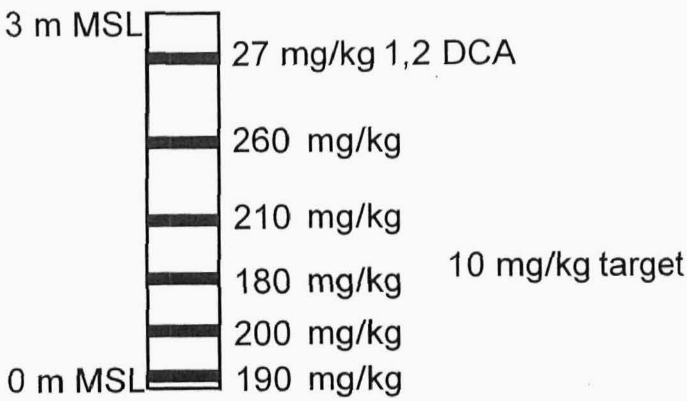


Figure 6. 1,2 DCA concentrations in soil for boring B-2 at Sikes

As can be seen in Figure 5 from a boring in the main waste pit, the COC concentrations oscillate around the regulatory-prescribed limit. However, the design excavation depth was apparently appropriate at this location. Conversely, the data on Figure 6 from a boring in the overflow area, show a COC concentration well in excess of the regulatory-prescribed limit of 10 mg/kg at the design depth for the excavation. In addition, even at the base of this boring, the COC concentrations exceeded the target value. Therefore, the vertical extent of the source at this location could not have been clearly defined from this boring.

There were two major consequences of not recognizing uncertainty in the location of sources during the remedial design. First, additional contaminated soil was found during excavation and incineration. Most of this additional soil was below the design excavation depth in the overflow area. This result should not have been a surprise based on the data in Figure 6. However it was not expected and it led to an additional Remedial Investigation and Feasibility Study after remedial action had begun. Ultimately, this additional soil was also incinerated, increasing the total project cost by more than 35 percent. Second, sources of groundwater contamination were likely missed. The concentrations of 1,2 DCA in MW-28 (Figure 2), a well screened in the upper alluvium, have exceeded the regulatory limit of 9.4 µg/L since site closure (Figure 7). Due to the relative insolubility of DNAPLs such as 1,2 DCA and the small allowable concentration, a small source has the potential to impact groundwater for a very long period. The persistence and level of these 1,2 DCA concentrations in groundwater indicate a source of 1,2 DCA very likely still exists in the ground. This conclusion is consistent with the results from French Ltd. where DNAPL sources were identified outside of the main waste lagoon.

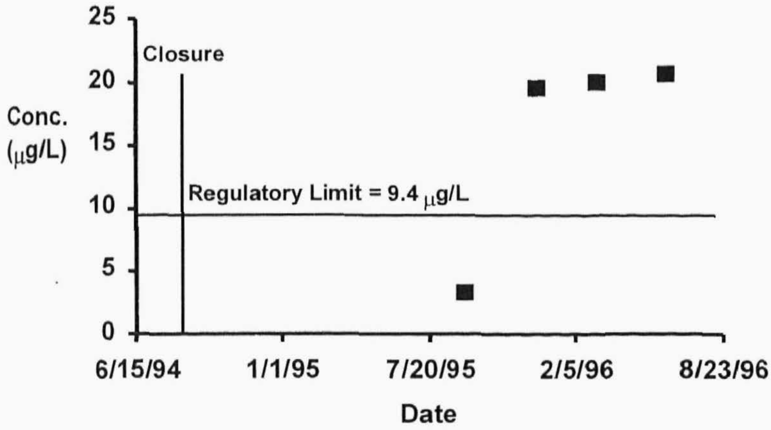


Figure 7. 1,2 DCA concentrations in groundwater data from MW-28 at Sikes

*Uncertainty in Soil-Fill Volumes*

Uncertainty in soil-fill volumes led to cost overruns at the Belvidere site. The final cover design for the landfill included compacted clay and vegetative cover layers underlain by a leveling layer. The leveling layer consisted of a compacted fill placed directly on top of the existing, flat landfill surface. Its purpose was to provide three-percent drainage grades sloping toward the perimeter of the landfill. The volume of fill in the leveling layer was estimated to be 100,000 $m^3$, and the design called for it to be obtained from an on-site borrow area.

When the leveling layer was constructed, the actual volume of fill required was 40,000 $m^3$ more than the estimated volume. This additional fill volume had a significant impact on cost because the on-site borrow area could not supply it and soil had to be hauled from an off-site borrow source. In the end, the actual cost of the final cover was nearly 20 percent greater than the estimated cost of $3 million due to the additional volume in the leveling layer.

The discrepancy between estimated and actual volumes for the leveling layer was due to errors in the base grade elevations used to develop the volume estimates. The actual landfill surface was one to two feet lower than was indicated by the base grades. These base grades had been established during the remedial investigation from aerial photographs and a ground survey. Possible sources of error were (1) vegetation on the landfill surface masked the actual elevation in the aerial photographs; (2) the ground survey used to supplement the aerial photography was tied to a benchmark that had moved; or (3) the landfill surface had settled in the three years between when the base grades were established and the cover was constructed.

The assumption in design that there was little uncertainty in base grade elevations was problematic, although consistent with standard practice. While a 10 percent contingency had been included in the $3 million cost estimate to accommodate uncertainties in factors such as fill volumes, the actual cost was 20 percent greater than the cost estimate including contingencies. Several steps could have been taken to reduce this cost increase if this source of uncertainty had been recognized. First, a ground survey could have been conducted to improve the accuracy of the base grades. Second, an additional on-site borrow area could have been established during the design stage to accommodate the possibility that the original area would not supply enough fill volume. Third, when problems with the design base grades became evident during construction, the design elevations for the leveling layer could have been lowered to reflect the actual base grades. Fourth, a larger contingency could have been used in estimating the project cost.

## Flexibility in Design and Implementation

As discussed in the previous section, decisions in remediation projects are made under uncertainty. Therefore, flexibility to adjust to unexpected conditions in design and implementation is important to manage this uncertainty. The following examples illustrate the need for and importance of flexibility during remediation.

### *Flexibility Required in Source Removal Objective*

At French Ltd., the remediation approach was focused on source removal. However, data obtained during implementation of remedial action indicated that complete removal of the source was not feasible and that source control was also necessary. During remediation of the main waste lagoon, a pump-and-treat system was installed to remediate groundwater flowing toward the housing development (Figure 1). Within the first weeks of operation, free-phase DNAPL was pumped from one of the wells located outside the main lagoon (the "source"). In addition, at least three other areas were identified as potential DNAPL sources from the groundwater concentration data.

A separate investigation was performed once the DNAPL was discovered in order to locate the sources and remove them. Time and money were subsequently spent trying to locate all the DNAPL pools in the subsurface. However, the only source that was confirmed to exist was at the location where free-phase DNAPL was originally pumped. Even still at this location, the extent of the DNAPL source was never determined. Therefore, source removal was not technically feasible. A sheet-pile containment wall was subsequently installed in several areas with suspected DNAPL sources instead of trying to remove or treat these sources. In addition, all areas with suspected DNAPL sources are being monitored during the post-closure period.

The economic impact of the discovery of DNAPL outside the main waste lagoon is shown on Figure 4. However, this impact could have been much greater if there had not been flexibility in the objective of source removal.

*Inability to Modify Design Grades During Construction*

Flexibility in design grade elevations could have reduced or eliminated cost overruns at the Belvidere site. As discussed previously in "Impacts of Uncertainty," the volume of fill required for the final cover at the site was underestimated due to errors in base grade elevations. This underestimation led to significant cost overruns because the additional soil had to be hauled in from a distant off-site borrow source.

The error in the base grades became evident early in construction when the contractor conducted a ground survey for the purpose of fill control. The design grade elevations could have easily been modified to reflect the actual base grade elevations, and little if any additional fill would have been required. However, at that point in the Superfund process, the Remedial Design had already been approved and modifying design grade elevations was considered a significant design change. Therefore, design modifications submitted to and approved by both the Illinois EPA and the USEPA would have been required. It was estimated that this approval process would have taken at least two months.

A delay of several months in construction of the cover could have delayed closure of the site by as much as 6 to 9 months. Construction of the cover was scheduled to be completed in two construction seasons: the leveling layer would be placed during the first season and the clay and vegetative cover layers would be placed during the second. There was little flexibility in this schedule considering that the clay could not be placed during winter months and the final cover surface could only be seeded in certain weeks during the spring or fall. A delay of several months would have possibly extended the construction schedule over three instead of two construction seasons.

There are two possible ways in which greater flexibility could have been incorporated into this design. First, notes on the design drawings indicating that design grade elevations were subject to change if base grade elevations changed would have facilitated the design modification process. Second, a streamlined, regulatory-approval process for major design changes during construction would have reduced the impact of this problem.

## Value of Information

Information from a site investigation is only valuable if it helps in making remediation decisions. The case histories illustrate several instances where money and time were spent collecting data that were never used. Two examples of site investigation programs with limited value are described below.

### *Limited Value in Searching for DNAPL Sources*

An extensive search for DNAPL sources was conducted at the French Ltd. site when they were discovered during remedial action. After this discovery (see "Flexibility Required in Source Removal Objective"), a site investigation was conducted in an attempt to determine the location, nature, and extent of DNAPL sources with 19 cone penetrometer tests, 15 monitoring wells and four cored borings.

At the end of this effort, the data were still insufficient to positively conclude the presence of DNAPL sources in any of the areas where it was suspected. Even in the area where DNAPL was pumped, the extent of the source was not defined. Therefore, in situ containment versus source removal was selected to address these sources of groundwater contamination.

The information obtained in the attempt to determine the nature and extent of DNAPL sources at this site was of limited value. Without collecting this information, the adopted approach of in situ containment and monitoring could have been implemented because the potential locations of DNAPL sources were identified with groundwater monitoring data from existing wells. In fact, no new locations were identified by the DNAPL investigation. Furthermore, it is very unlikely that enough information to successfully implement source removal could have been obtained from the additional site investigation, even if significantly greater effort had been put forth (e.g., McGrath et al. 1996). The decision to control versus remove the DNAPL sources could have been made when they were initially discovered based on the available data at that time. Since an additional site investigation attempting to better characterize these sources could not (and did not) change this decision, the time and money spent on this investigation was not used effectively.

### *Limited Value from Additional Site Investigation*

An additional site investigation was performed at Sikes even though there was essentially only one appropriate remediation alternative. As discussed in "Uncertainty in Source Locations," additional soil with elevated COC concentrations was discovered below the planned excavation depth. It was determined that an additional three-step Remedial Investigation and Feasibility Study was needed to decide how to deal with the additional volume. One objective of this investigation was to identify the remediation alternatives available. The soil under examination however, was very similar to the soil already excavated and incinerated. The conclusion of the additional RI/FS was therefore that the additional soil should be excavated and incinerated.

The primary reason the additional soil volume would have required a different remediation method would have been if it affected the incinerator operations, i.e., the volume was too large or the thermodynamic properties were out of specification. The issue of volume was not problematic as the incinerator used at this site was the largest mobile incinerator ever operated in the United States. The additional volume would therefore not have lead to any problems with the incinerator operations had excavation continued at the time contamination was discovered below the planned excavation depth. As for the thermodynamic properties of the soil, the soils across the site were already being combined to maintain a constant mixture through the incinerator. Had variations in this soil been encountered, the mixing process would have minimized any effects. It was therefore highly unlikely that a different remediation alternative would have been more cost effective. Conducting the additional RI/FS cost time and money, but provided little value to the final remedial action.

## Ongoing Remedial Action

Remedial action is an ongoing process that continues beyond "closure." The following examples illustrate that even at sites where the corrective-action approach was to remove contaminant sources, additional remedial action during the post-closure period has or will be required in the future. In addition, the examples demonstrate that performance changes with time and requires constant attention even after closure.

### *Continued Remedial Action during Post-Closure Period*

The approach at the French Ltd. Site was to remove and control the source of groundwater contamination and to remediate contaminated groundwater with a pump-and-treat system by enhancing biodegradation of organic chemicals. Both of these efforts were considered to be successful. The implementation of in-situ bioremediation to remediate the main waste lagoon (the main source of groundwater contamination) was the first large-scale project of this type with wastes containing chlorinated solvents. A significant effort was therefore made to use this new technology and demonstrate its effectiveness. Three different pilot studies were conducted: a laboratory study, an on-site tank study, and a small scale in-situ study. Significant sampling of the lagoon sludge was conducted during implementation of in-situ bioremediation at the field scale, and these results indicated that the treatment was successful in reducing chemical concentrations in the sludge to below target levels (e.g., Powers and Rubin 1996). In addition, the efforts to reduce concentrations of organic chemicals by injecting nutrients and oxygen into the alluvial aquifer were considered to be successful based on reductions in concentrations of these chemicals. For example, Figure 8 shows how concentrations of 1,2 DCA decreased at one monitoring well after the pump-and-treat system was started. The system was shut off when analyses indicated that natural biodegradation during the post-closure period would be sufficient to meet performance criteria.

While performance of the remedial action at the time of closure was considered a success, post-closure monitoring data have indicated that chemical concentrations in the groundwater have increased since the pump and treat system was terminated (e.g., Figure 8). In addition, concentrations for benzene and 1,2 DCA have generally been above those predicted when the decision was made to shut off the pump and treat system. Additional groundwater modeling has therefore been conducted and continually updated during the post-closure period. Also, additional pumping and treating of groundwater has been conducted in several areas of the site during the post-closure period.

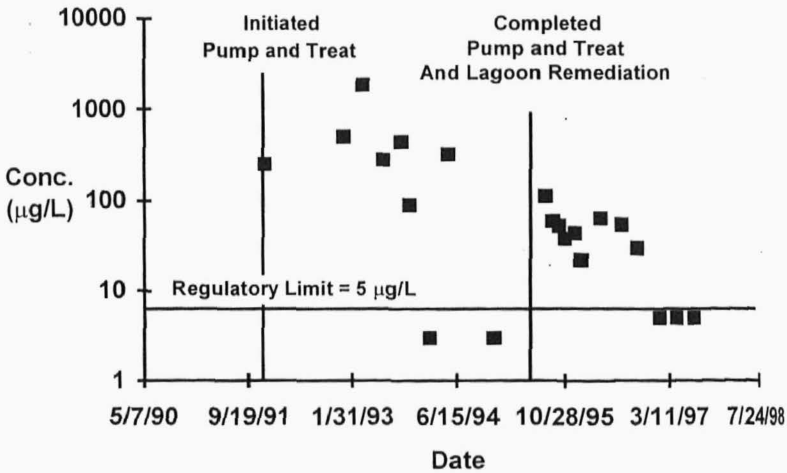


Figure 8. 1,2 DCA concentrations in groundwater data from INT-106 at French Ltd.

The continuation of remedial action after closure at this site brings into question the value of source removal for remediating contaminated groundwater. A large percentage of the source was apparently removed through in situ biodegradation of the sludges in the main waste lagoon. However, for chemicals such as 1,2 DCA and benzene, even a small percentage remaining in the ground has the potential to cause groundwater concentrations in excess of regulatory-prescribed limits for many years in the future (e.g., Pankow and Cherry 1996). In fact, Figure 8 indicates that source removal may have had little impact on the concentration of 1,2 DCA at this monitoring well. In situ containment of the lagoon sludge, say by covering, would have been significantly less expensive than in situ biodegradation and may have performed as well with respect to groundwater.

*Potential Need for Future Remedial Action*

The remedial-action approach at the Sikes site was to remove the source of groundwater contamination. Post-closure monitoring data for groundwater indicate however that future remedial action may be required. Unfortunately, the post-closure plan at Sikes included only vague performance criteria to trigger additional remedial action, and the effect of source.removal on groundwater concentrations was never predicted. Furthermore, the groundwater data prior to the remediation are very limited and were gathered at wells that were not used in post-closure monitoring. For example, Figure 7 shows the available data for MW-28, a monitoring well located south of the main waste pit (Figure 2). In this case, data have only been collected during post closure and it is not clear what the effects of the remediation were. The data do show however, that the concentrations are in excess of the regulatory-prescribed limits. Because the performance criteria are vague, the time at which additional remedial action is required is difficult to determine and the recent groundwater concentration data have not yet been addressed.

*Pump and Treat Shut-Off and Possible Re-Start*

The pump-and-treat system at the Belvidere site was shut-off several years into post-closure monitoring when performance criteria for the groundwater were satisfied. In contrast to the Sikes site, the criteria established for shut down of the pump and treat system at the Belvidere site illustrate the advantages of having specific performance criteria. Two compliance wells for groundwater monitoring were established near the pump and treat system, MW-6 and MW-7 (Figure 3). Next, allowable concentration levels were set for each of six target chemicals. These allowable concentrations were established considering a maximum excess, lifetime cancer risk of $10^{-6}$; Safe Drinking Water Act Maximum Contaminant Levels (MCLs) or proposed MCLs; and method detection limits. A sampling frequency of quarterly for the first year and semi-annually thereafter if concentration levels were constant or declining was established. A specific statistical test was provided to make the decision about whether the sampling frequency could be reduced after the first year. Finally, criteria for shut down of the pump and treat system were provided: the system could be shut down if the concentrations for the six target chemicals were below their respective allowable concentrations in three consecutive monitoring rounds.

After the first several years of operation, the shut-off criteria were satisfied, as shown on Figure 9 for MW-7 (Figure 3). However, continued monitoring has indicated increased concentrations (Figure 9), and re-starting the pump-and-treat system is presently under consideration.

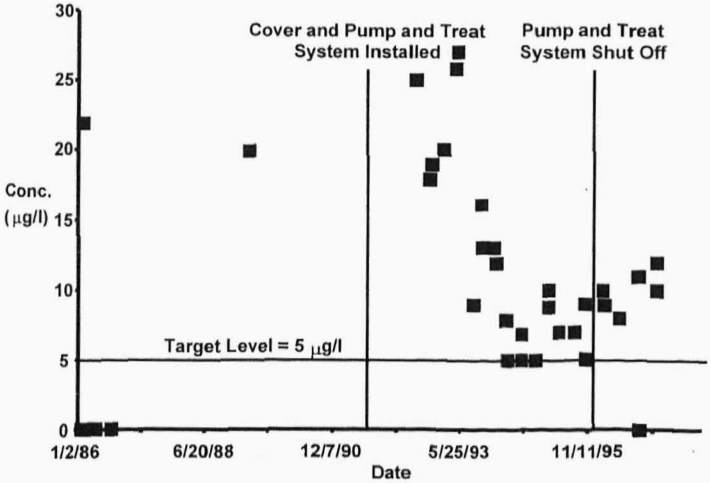


Figure 9. Benzene concentrations in groundwater from MW-7 at Belvidere

## CONCLUSIONS

The topics presented in this paper are the key aspects we identified that impacted the technical and economic performance of three case-study remediation projects. We have presented these topics in the form of "lessons learned," which are summarized below.

- Uncertainty exists, such as in source location and hydrogeologic conditions, and should be accounted for in remediation decisions.
- Flexibility in design and implementation of remedial action is necessary to accommodate unexpected discoveries during the remediation.
- The value of programs to collect information about a site should be evaluated on the basis of whether they will help in making remediation decisions. If the data will not be helpful in decision making, they are of limited value.
- Remedial action should be viewed as an ongoing process, even throughout the post-closure care period. Performance changes with time, and requires constant attention even after closure.

It is important to recognize that these lessons were arrived at by evaluating actual performance after completion of remedial action, an advantage that was not available to the regulators and project managers on these projects. Therefore, these case histories are not intended to reflect poorly on the regulators or the project managers. Our goal is to summarize lessons learned by everyone working on these projects to provide decision makers with useful information for future projects.

## ACKNOWLEDGMENTS

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The contents of this paper reflect the opinions of the authors.

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