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Case Study Using the Decision Analysis Process to Select a Remediation Strategy for an Upstream Oil and Gas Facility

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1.0 Abstract

Selecting the best remediation option can be a complicated task, given the relatively wide range of choices, combined with uncertainty regarding likely efficacy and cost. In this paper we provide an illustration of a probabilistic approach to assessing remediation options. The process is based on identifying desired clean-up goals, influential factors that could affect a remediation strategy, and probability ranges for each factor. In using a decision analysis process, the range of likely outcomes is estimated and illustrated. Decision makers obtain a clearer image of this range, and how variations in input parameters control those outcomes.

2.0 Introduction: Site Condition Summary

The methodology we demonstrate could be applied to any site and remediation approach. For this paper, we're using an illustrative case study with conditions often encountered at hydrocarbon-contaminated sites. There is a source area with residual free phase hydrocarbon presence, a downgradient dissolved contaminant plume that extends in the direction of groundwater flow, and an area with potential concern regarding future contamination. We assumed that the site is an actively producing facility located in central Alberta, where the near-surface zone of soil impact was excavated as soon as it was identified.

Potential environmental impacts associated with such a site range from immediate and severe (e.g., adjacent to a water course or residence with a drinking water well) to relatively minor (remote site with no nearby environmental receptors). In our case, we assumed that there is potential for receptor impact within the foreseeable future. Furthermore, we assumed that this impact could lead to a range of potential penalties to the responsible polluter.

We assumed a typical lithology commonly encountered in Alberta: sand, silt and clay layers, where sand layers near the source area represent a potential contaminant transport pathway. Groundwater is encountered below the root zone, but within a few metres of ground surface. The average groundwater flow velocity is assumed to be on the order of several metres per year.

Monitoring wells have been drilled, and sampling data help us estimate the extent of the free phase and dissolved hydrocarbon plumes. The zone of hydrocarbon impact appears to be sufficiently large that excavation is not an obvious cost-effective alternative. Free phase hydrocarbon remains in sandier layers near the original source, so some form of source control/remediation will be required. Monitoring data shows that potential environmental receptors have not yet been affected, and that natural attenuation may prevent future receptor impact. The data are not yet sufficiently compelling to make this strategy an obvious selection.

3.0 Remediation Options

The site owner would like to remediate the site to minimize future liability, but is not yet forced to remove all contamination to specific site cleanup standards. There are no specific time constraints. As a result, the owner currently has flexibility in deciding on a remediation strategy.

We developed reasonable alternatives for cleaning up the site, based on current practice, to show the benefit of using the decision analysis approach. Other technologies could also be examined. More detail regarding the application of decision analysis for remediation technology selection was described in a previous paper (Armstrong et al., 2004).

Our two main remediation alternatives are excavation and natural attenuation. Within the excavation approach, we considered two methods for treating the contaminated soil following excavation: off-site disposal and on-site treatment. The natural attenuation option includes some form of source control. Combinations of these options are possible.

3.1 Excavate and Dispose Offsite

The offsite treatment option involves excavating the contaminated soil and transporting it to an offsite treatment/disposal facility. Main factors affecting this approach are the volumes of clean and contaminated soil to be excavated and replaced. Other variables include trucking and disposal, supervisory time and confirmatory analyses.

Offsite treatment is assumed capable of meeting any remediation goal, because the option is always available to continue excavation. This approach is also likely to be quickest, because site-specific liability is assumed to leave with the excavated soil. Company liability associated with contaminated soil transport and disposal can be incorporated, but was omitted for sake of clarity. We assumed that suitable clean fill would be imported according to local land use.

3.2 Excavate and Treat Onsite

The onsite treatment option differs by requiring effort to store and turn the soil instead of trucking and tipping. This option avoids importing fill, but includes additional uncertainties around whether treatment is working fast enough, or if it meets the desired endpoint. As such, this option includes a penalty function related to failure of on-site treatment.

Off-site disposal remains a viable backup position, but it adds cost. Soil must be double-handled, and money spent in trying on-site treatment is lost. However, there is no penalty function related to failure to remove all of the contaminated soil.

The main uncertainties with excavating and treating onsite include:
- what is the probability of successfully reaching a specified endpoint;
- what is the expected time-frame to reach the endpoint;
- what is the likelihood of an unacceptable environmental impact if treatment fails;
- what is the resulting penalty that might be imposed; and,
- how accurately can these variables be estimated.

3.3 Pump Free Liquids and Treat with Natural Attenuation

Natural attenuation refers to the reduction of a contaminant mass or concentration by a series of naturally occurring physical, chemical, and biological processes. For petroleum hydrocarbons, biodegradation is the only process that destroys contaminant mass. The other processes represent either spreading the mass out over a larger area, fixation, or some form of phase change.

Monitored Natural Attenuation (MNA) refers to a strategy whereby site data are collected over regular intervals to demonstrate that natural attenuation processes are reducing the level of contamination within an acceptable time frame. Assuming source control, MNA represents an alternative approach to site remediation that could be used either as stand-alone strategy, or in combination with conventional engineered remediation techniques.

Selection of an MNA strategy is recommended only after developing an appropriate and detailed understanding of site conditions including the contaminant(s) and its distribution, transport behaviour, and attenuation characteristics. Multiple lines of evidence are needed to assess natural attenuation (refer to USEPA, 1999; ASTM, 1998 for more detail).

Application of natural attenuation to manage contaminated groundwater will typically require some form of source control/remediation. We invoked liquid pumping to recover free phase hydrocarbon present in the source area. We also assumed that dissolved hydrocarbon migrating from the source area would be amenable to natural attenuation.

We included the presence of an environmental receptor relatively near the source. Although we assumed that existing data supported the concept of natural attenuation, the receptor presence introduced uncertainty regarding risk of unacceptable impact if natural attenuation was less effective than originally interpreted. This remediation option involves additional uncertainty assessment, including:
- how effective will liquid pumping be in removing free phase hydrocarbon;
- how many pumping wells would be required, and how long would they operate;
- would natural attenuation remain effective at managing the dissolved plume;
- how long would monitoring be required to support the natural attenuation program;
- what would be the likelihood, impact and severity of penalties if the strategy failed.

4.0 Decision Metric

We assumed that lowest, discounted cost was our decision metric and we used a discount rate of 10% to account for the time value of money. We also assumed that if a remediation option failed to clean up contamination to an acceptable level within an acceptable time-frame, we would be forced to switch to an alternate remediation method.

A cost model was built for each of the remediation options and modified to allow each of the inputs to the model to be sensitized to a range of potential occurrences, P_{10}, P_{50} and P_{90}, where:

- P_{10} = unlikely to be lower (or will be lower only 10 % of the time);
- P_{50} = most likely expected value; and,
- P_{90} = unlikely to be higher (or will be higher only 10% of the time).

5.0 Discussion

5.1 Cost Comparison & Drivers

The first step in our analysis was to estimate the cost for each of the remediation options, and to sensitize those estimates to our uncertainty in the inputs. The discounted cost estimate for the Pump + NA, Onsite, and Offsite treatment alternatives is $195k, $255k, and $667k, respectively (cost above each tornado chart in Figure 1). These are the resulting cost estimates when all input values for each option are set at their most likely (P_{50}) values. These values do not include allowances for range uncertainties (the chance of getting low (P_{10}) or high (P_{90}) outcomes for any of the input variables) or chance uncertainties (the chance of the method not being successful or that we are forced to pay a penalty).

We next ran the model with the low and high values for each of the model inputs with all other inputs set at their P_{50} value. The estimated range for each input is provided in brackets beside its name (P_{10}, P_{50}, P_{90}), while the associated estimated costs are provided on either side of the tornado charts (P_{10} on the left and P_{90} on the right). Our actual analysis calculated the sensitivity based on about 20 inputs for each alternative, but for clarity we chose to display only the 4 most important uncertainties for each alternative. The inputs are ranked by the variance (displayed in brackets for each input) and plotted using the same cost scale for comparison.

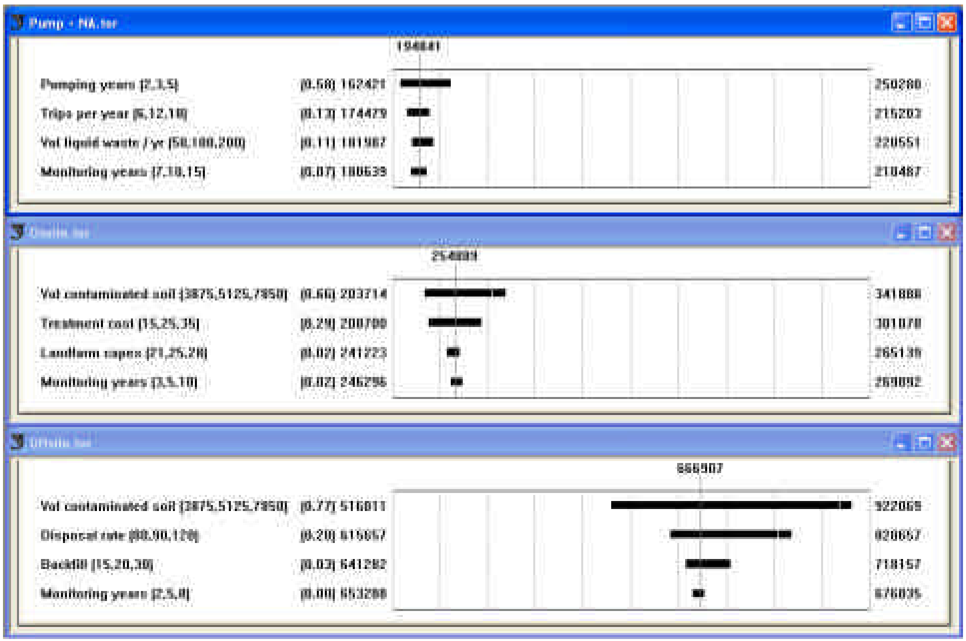

Figure 1: Sensitivity Analysis for Remediation

The following insights were gained from the sensitivity analysis:

- The Pump + NA alternative consists of two phases: pumping free product and then monitoring to ensure that the contamination dissipates. As such, the key uncertainties affecting our cost estimate involve pumping and monitoring: how long we will be required to pump, how many trips to the site are required per year, how much volume is pumped and how many years we will be required to monitor the site.
- The cost estimate of the Pump + NA alternative is most sensitive to the length of time required to pump the free product. Our estimate in the most likely case was that we would need to pump for 3 years but if we have underestimated the size of the plume and the wells continue to pump for 5 years, the estimated cost of the project increases to $250k. Similarly if the wells pump for only 2 years, the cost is likely to drop to $162k.
- The primary cost for the Onsite and Offsite treatment alternatives is in digging up and treating the contamination. Both scenarios are highly sensitive to our uncertainty in the volume of contaminated soil. In the Onsite treatment case if the volume of contaminated soil is low, the cost of the treatment drops to $204k.
- In the Onsite treatment case, because our cost estimate ranges from $204k to $342k, there may be value in getting a better estimate in the size of the plume by drilling more wells and taking more samples.
- The Offsite treatment strategy is significantly more expensive than the other two options and the uncertainties are likely to push the expected cost even higher as the high cost ranges are asymmetrically skewed to the right.

Though it seems clear that we would not likely decide on the Offsite treatment strategy, the base case results and sensitivity analysis do not tell the whole story. These results include only range uncertainties, and not chance uncertainties – which cover the potential failure outcomes, such as, the free product not pumping, contamination not decreasing naturally, or onsite treatment not reducing contamination. Chance uncertainties are incorporated through probabilistic analysis (e.g., decision trees).

5.2 Probabilistic Modeling of the Remediation Options

The structure of the decision tree for each of the remediation options is shown in Figure 2. We have opted to display only the start of the decision tree for each option, with the remaining branches hidden. At the end of each branch, we have added the P_{10}, P_{50} and P_{90} ranges for each of the key uncertainties as determined in our sensitivity analysis above. The Offsite treatment option has been expanded to show an example.

In the figure, the circular nodes represent uncertainties to model potential different outcomes over which we have no control; the square nodes represent decisions from which we select our preferred option. The arrows represent the selected decision path. For example if we chose the Pump + NA option, there is a 60% chance that the free product pumps, in which case we continue the NA strategy and a 40% chance that the free product does not pump, at which point we would be forced to decide on an alternate remediation option, either Onsite or Offsite treatment.

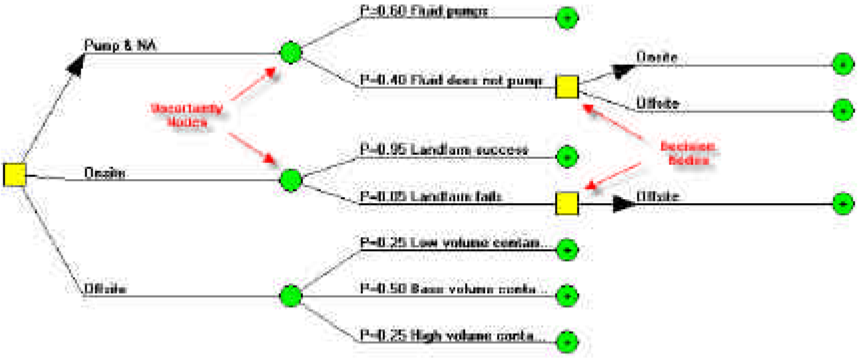

Figure 2: Structure of the Decision Tree for the Remediation Options

At the end of the branch where we opted to continue the Pump + NA option, we added a series of branches to model the situation where contamination continued to migrate to a nearby receptor (in our example, a pond). The branch structure is displayed in Figure 3. Though we felt the probability of this happening was low (2%), we considered three potential penalty outcomes:

- 10% chance of a $1,000,000 penalty;
- 50% chance of a $300,000 penalty; and,
- 40% chance of a $50,000 penalty.

In all cases, we pay the penalty and must also continue with a different remediation option, in this case, excavation with either Onsite or Offsite treatment.

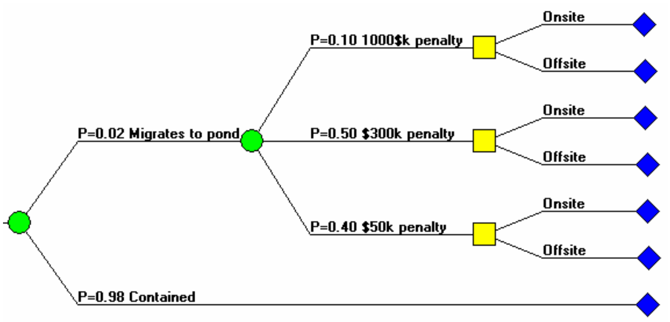

Figure 3: Decision Sub-tree Modeling the Failure of Pump +NA Alternative

5.3 Risk-weighted Expected Value Comparison

After applying the chance and range uncertainties in the decision tree and calculating the results, the Pump + NA, Onsite, and Offsite treatment options have expected costs of $299k, $311k and $727k, respectively (see Figure 4). Notice that the expected costs in all cases are higher than the "base case" costs from the tornado sensitivity analysis of $195k, $255k, and $667k, respectively (Figure 1). For the Pump + NA option, the higher expected cost is due mainly to the possibility of having to switch to a different treatment method and the possible penalty if the contaminant migrates to a receptor. The Onsite treatment case has a higher expected cost because of the possibility of having to switch to a different treatment method and asymmetrically skewed uncertainties toward higher costs. The Offsite treatment case also has a higher expected cost due to the uncertainties being asymmetrically skewed to creating higher costs.

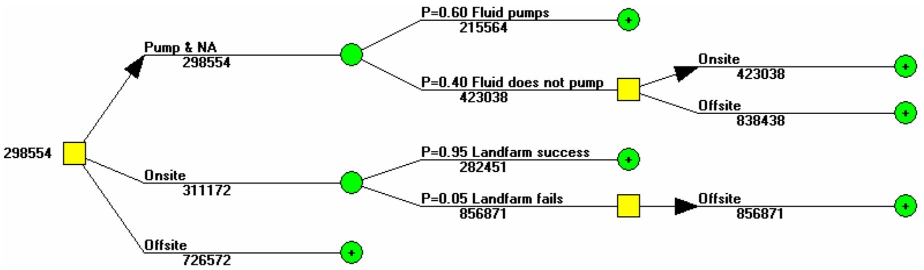

Figure 4: Expected Costs for the Remediation Options

Insights from reviewing the remediation decision tree (Figure 4) include:

- For the Pump + NA case if the free product does not pump, we would be forced to switch to either the Onsite or Offsite treatment alternatives and our expected cost would jump up to $423k. The cost increase is because we would have wasted money trying to pump the wells before giving up. If the free product does pump, the expected cost from the Pump + NA alternative drops to $216k.
- There may therefore be value in running a pilot test to first determine whether the free product will pump before selecting the Pump + NA alternative. If the pilot test indicates that the free product will not pump, we would avoid trying the Pump + NA alternative and switch to the Onsite treatment alternative.

Figure 5 displays the cumulative distribution of potential costs for each of the remediation strategies, the insights from which are listed here:

- There is almost 100% chance that the Offsite treatment alternative will cost more than the other two alternatives.
- There is about a 55% chance that the remediation cost of the Pump + NA strategy will be less than the Onsite treatment alternative.
- If we opt for the Pump + NA alternative, there is a 10% chance that the cost will be less than \$164k, a 50% chance that the cost will be less than \$250k, and a 90% chance that the cost will be less than \$457k.
- The cost of the Pump + NA alternative increases dramatically if the free product does not pump and if the contamination does not attenuate. The highest cost is about \$1,600k – though the probability of occurrence is extremely low.

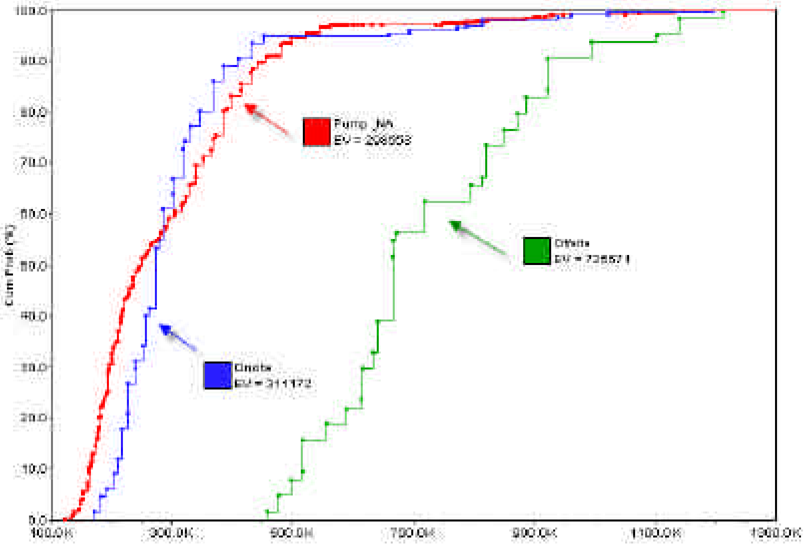

Figure 5: Range of Outcomes for Remediation Alternatives

5.4 Development of a Hybrid Alternative

We noticed in Figure 4 that there may be value in running a pilot test to first determine whether the free product will pump before selecting the Pump + NA alternative. If this new option has a lower expected cost than the original Pump + NA alternative, it will be because the pilot test informs us to switch to the Onsite treatment alternative before spending too much money on the Pump + NA alternative.

The decision tree in Figure 6 represents the new, hybrid alternative. If free product pumps in the pilot test, we opt for the Pump + NA strategy; otherwise, we opt for the Onsite treatment alternative. The expected cost for this new, hybrid alternative is \$254k. The pilot project reduces the expected cost of the Pump + NA strategy by \$45k (\$299k - \$254k), because 40% of the time it saves us from drilling wells and installing pumps when the free product is not mobile. The cost of the pilot was estimated to be \$27k.

The value that additional information adds to a project may not always be intuitive (Coopersmith and Cunningham, 2002). As the chance that the free product pumps increases, the value in running the pilot study decreases.

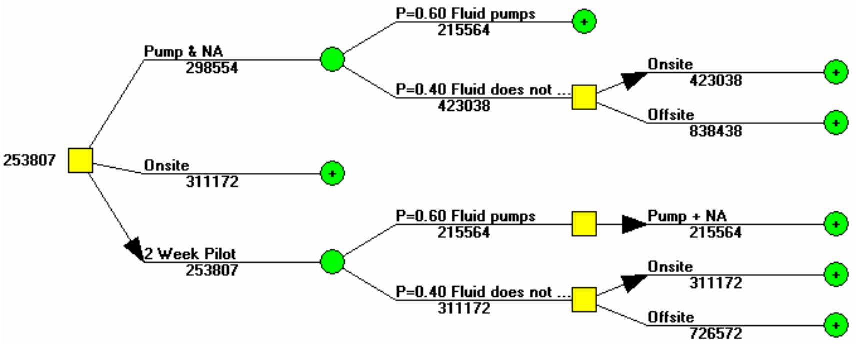

Figure 6: Decision Tree for “Pump + NA with Pilot” Alternative

The cumulative distribution of costs including the Pump + NA with Pilot alternative is displayed in Figure 7. Adding the pilot test to the Pump + NA option reduces the risk of drilling wells and installing pumps when the free product is not mobile. The new hybrid case produces a lower cost option at all probabilities and is an improvement over either of the Onsite or Pump + NA treatment options. .

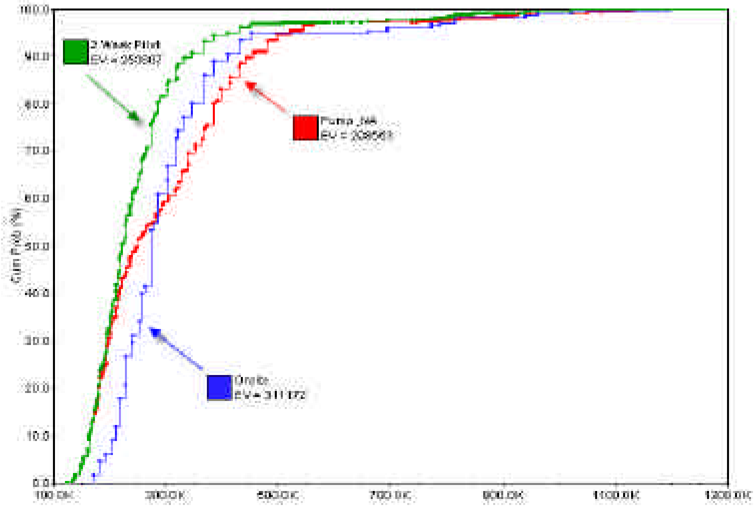

Figure 7: Range of Outcomes for Hybrid, Pump + NA with Pilot Project Alternative

6.0 Conclusions

On our example site, the decision analysis process helped us to:

1. contrast cost ranges for various remediation methods;
2. identify the value of doing a pilot study of hydrocarbon pumping; and,
3. estimate the tradeoff in cost versus confidence for offsite treatment.

The decision to do a pilot test and use MNA, based on lowest expected cost is specific to the case that we studied. Each new site should be expected to present new and/or different decisions and uncertainties regarding remediation options. However, by applying the decision analysis process to each site remediation problem, a company will be consistently improving their decisions and selecting more cost effective solutions.

7.0 Acknowledgements

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8.0 References

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