OPERATIONS RESEARCH AND DECISION ANALYSIS

Software Tools and Applications

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Abstract: This chapter demonstrates operations research and decision and risk analysis tools and their application in the context of a hypothetical case study of groundwater cleanup at a toxic waste site [1]. The following issues are addressed:

1. Population risk assessment
2. Remediation effectiveness
3. Optimal treatment method
4. Multiple objectives
5. Reducing uncertainty
6. Linked decisions

The chapter concludes with a brief discussion integrating the six parts of the case study into a process for implementation of adaptive management.

1. Population Risk Assessment

A small community gets its water from wells that tap into an old, large aquifer. Recently, an environmental impact study found toxic contamination in the groundwater due to improperly disposed chemicals from a nearby manufacturing plant.

The environmental impact study provided estimates of the following risk factors for each chemical:

- Cancer potency factor (CPF)
- Contamination level (CL)

The study further recommended that a population risk assessment be conducted to determine if any action needs to be taken to correct the situation.

I. Linkov et al. (eds.), Real-Time and Deliberative Decision Making.

The study said that the risk assessment must account for the variability of body weights (BW) and volume of water consumed (VWC) by individuals in the community.

We will use influence diagrams [2] to frame each of the issues to be addressed. An influence diagram is a compact graphical representation of a decision scenario that shows the interactions of uncertainties and decisions to be made. The influence diagram in Figure 1 frames the population risk assessment issue using only uncertainty. We will add decisions later. The objective at this point is to determine the risk to the population due to the toxic contamination in the groundwater. The equation for this risk is given by

$$\text{Population Risk} = \frac{\left(\sum \text{CPF}_i * \text{CL}_i\right) * \text{VWC}}{\text{BW}}$$

The risk factors CPF and CL, which are inputs to this equation for each of the improperly disposed chemicals, are shown in the influence diagram as uncertainties.

The computations displayed in the influence diagram can be easily modeled in an Excel spreadsheet [2] as shown in Figure 2.

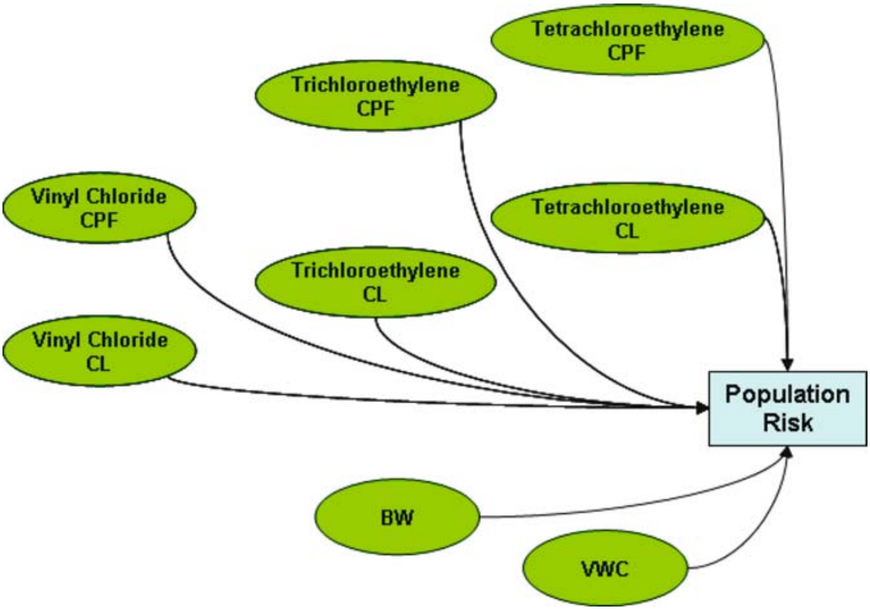
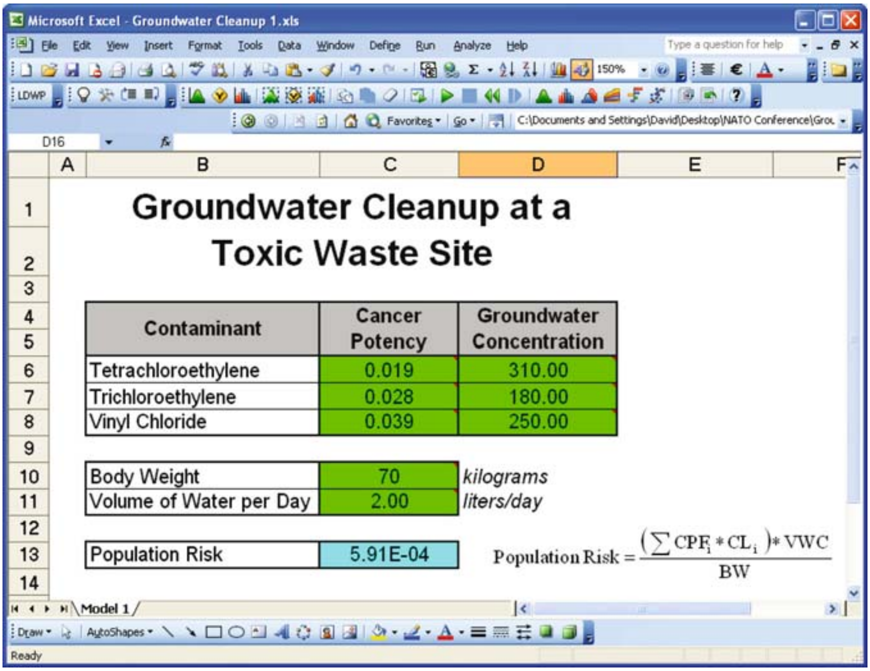


Figure 1. Population Risk Assessment Influence Diagram.



Groundwater Cleanup at a Toxic Waste Site

Contaminant	Cancer Potency	Groundwater Concentration
Tetrachloroethylene	0.019	310.00
Trichloroethylene	0.028	180.00
Vinyl Chloride	0.039	250.00

Body Weight	70	kilograms
Volume of Water per Day	2.00	liters/day

Population Risk	5.91E-04

$$\text{Population Risk} = \frac{\left(\sum \text{CPF}_i * \text{CL}_i\right) * \text{VWC}}{\text{BW}}$$

Figure 2. Excel Spreadsheet Model of Population Risk Assessment Influence Diagram.

The values of the parameters shown in the spreadsheet model are mean value estimates provided by the environmental impact study team. The study team, however, also provided distribution data. These distributions can be integrated into the spreadsheet model using the Oracle Crystal Ball [3] add-in to Excel. Crystal Ball allows the point estimates in each cell to be represented by probability distributions. For example, the means value estimates shown in the tetrachloroethylene CPF and CL cells can be replaced with their full distributions as shown in Figure 3.

These probability distributions can then be used to perform a Monte Carlo simulation to generate a complete risk profile for the population risk from toxic contamination in the groundwater. The risk profile is shown in Figure 4.

Acceptable cancer risk levels are on the order of 1 in 10,000 (0.0001) with 95% certainty. The mean value of the population risk from the toxic CL of this aquifer is approximately 0.0006 with a 25% chance that the risk could be greater than 0.0008. This is an exceptionally high population risk level for which remediation is required.

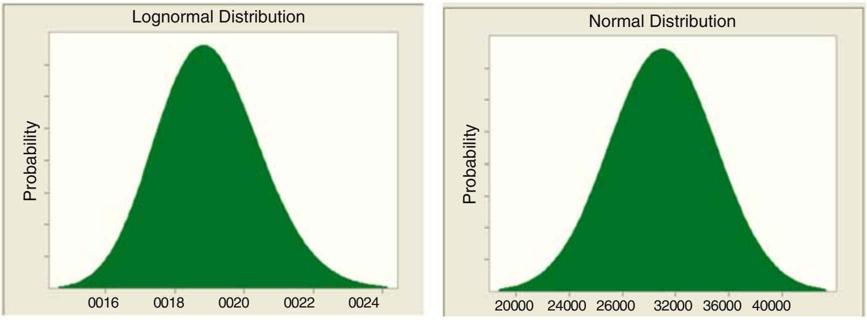


Figure 3. Probability Distributions for Tetrachloroethylene CPF and CL.

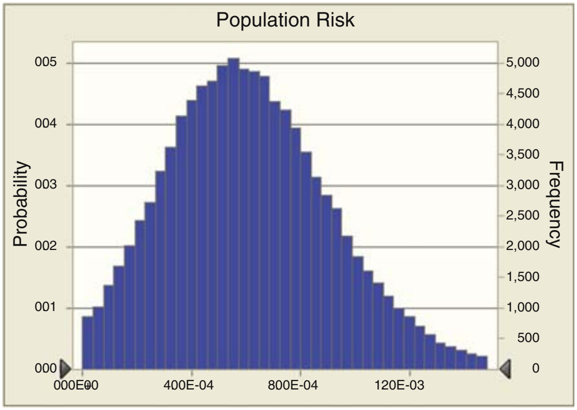


Figure 4. Risk Profile for Population Risk to Toxic Contamination in Groundwater.

2. Remediation Effectiveness

Since this is the community's only source of potable water and the population risk is unacceptable, the task force recommended the following three treatment methods:

1. Air stripping
2. Carbon filter
3. Photo-oxidation

Before proceeding, the task force wants to know the effectiveness of remediation on reduction of the population risk.

We have some limited insight into the effectiveness of the three alternatives. This insight was provided by task force experts as probability distributions of treatment cleanup efficiency. This is represented as a modification to the original influence diagram shown in Figure 5.

The task force assumed in establishing the efficiency probability for cleanup treatments that it applied equally to each alternative method. Since their knowledge of the treatment efficiency was limited, they established the uniform distribution shown in Figure 6. This uniform distribution represents the degree of uncertainty they had in treatment efficiency.

The addition of the treatment efficiency factor to the influence diagram and its associated probability distribution can be incorporated in the spreadsheet model as shown in Figure 7.

Running the Monte Carlo simulation with Crystal Ball provides the results shown in Figure 8. This figure compares the original population risk assessment without remediation with the results of remediation. It can be seen from the figure that remediation can have a significant effect on the population risk.

3. Optimal Treatment Method

Having proven the potential effectiveness of remediation, the task force wants to reduce the level of contamination to recommended standards, using one of the three remediation methods proposed.

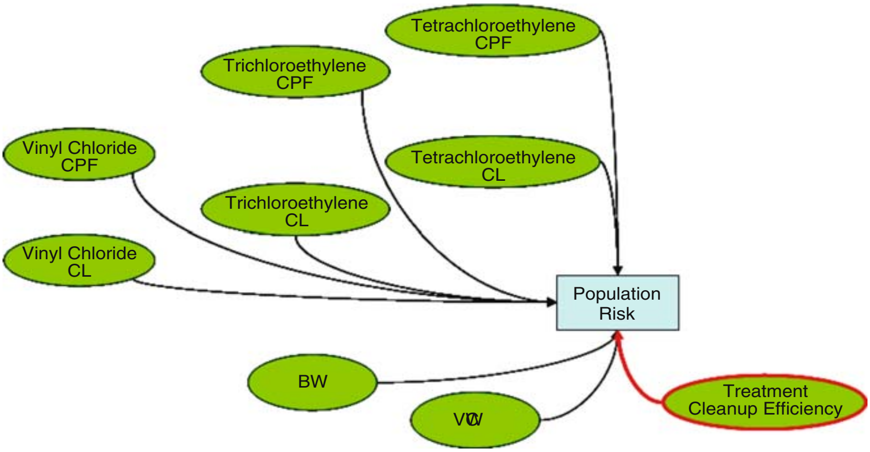


Figure 5. Influence Diagram for Remediation Effectiveness.

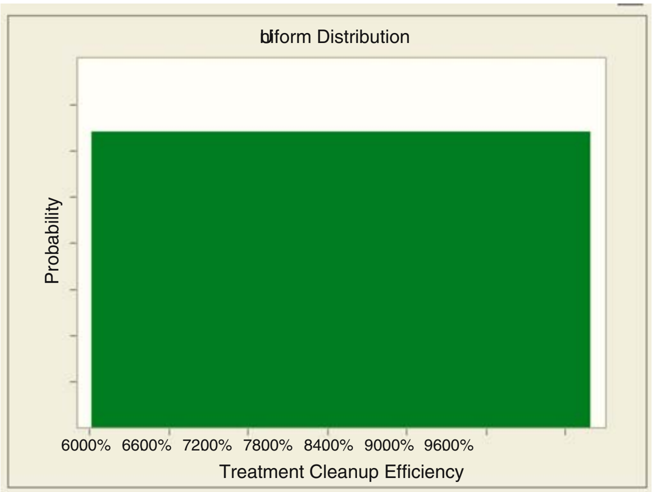
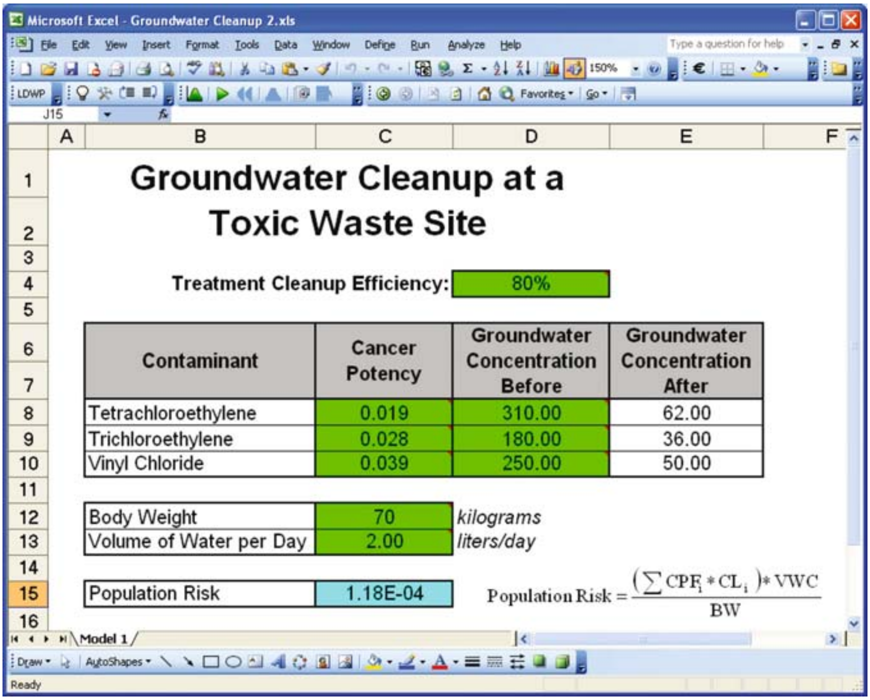


Figure 6. Uniform Distribution of Treatment Efficiency.



Groundwater Cleanup at a Toxic Waste Site

Treatment Cleanup Efficiency: 80%

Contaminant	Cancer Potency	Groundwater Concentration Before	Groundwater Concentration After
Tetrachloroethylene	0.019	310.00	62.00
Trichloroethylene	0.028	180.00	36.00
Vinyl Chloride	0.039	250.00	50.00

Body Weight	70	*kilograms*
Volume of Water per Day	2.00	*liters/day*

Population Risk	1.18E-04

$$\text{Population Risk} = \frac{\left(\sum \text{CPF}_i * \text{CL}_i\right) * \text{VWC}}{\text{BW}}$$

Figure 7. Excel Spreadsheet Model of Population Risk with Treatment Efficiency Included.

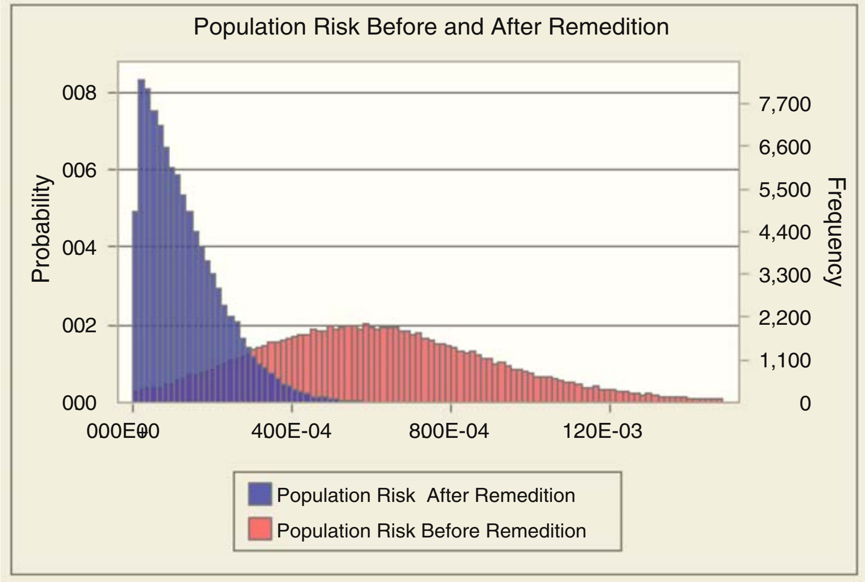


Figure 8. Effect of Remediation on Population Risk.

The costs of the different cleanup methods vary according to the resources and time required for each (cleanup efficiency). With the historical and site-specific data available, the task force wants to find the best process and efficiency level that minimizes cost and still meets the study's recommended standards with 95% certainty. Figure 9 shows the influence diagram modified to include total remediation cost as a function of fixed and variable costs for each contaminant, and two classes of decision variables. The decision variables are the things we can control; in this case, the choice of remediation method and level of cleanup efficiency.

Once again, it is an easy task to represent this influence diagram in the spreadsheet model. Figure 10 shows the modified model.

The professional version of Crystal Ball has a stochastic optimization tool called OptQuest [4] that can be used to solve this problem. The minimum cost treatment model is a mixed integer stochastic mathematical programming model with the following form (Figure 11):

The optimum solution found by OptQuest is to use the photo-oxidation remediation method at 91% cleanup efficiency. This remediation method and cleanup efficiency level costs $10,902 ± $380, and provides an average population risk level of 0.0000516 with 95% confidence (see Figure 12).

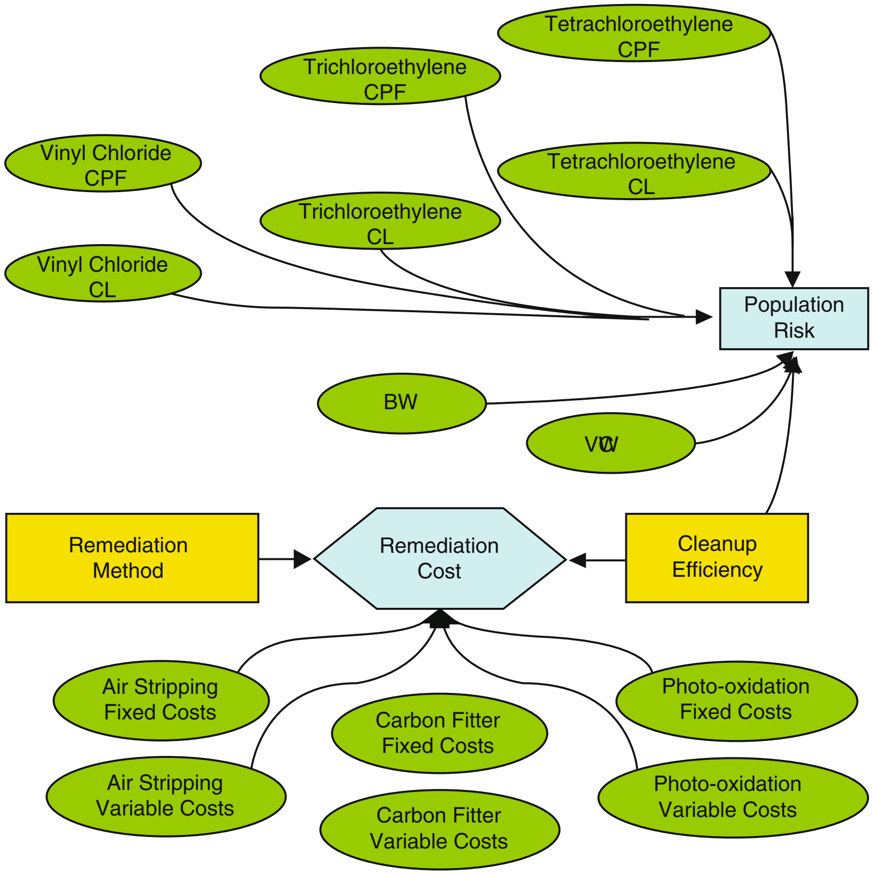
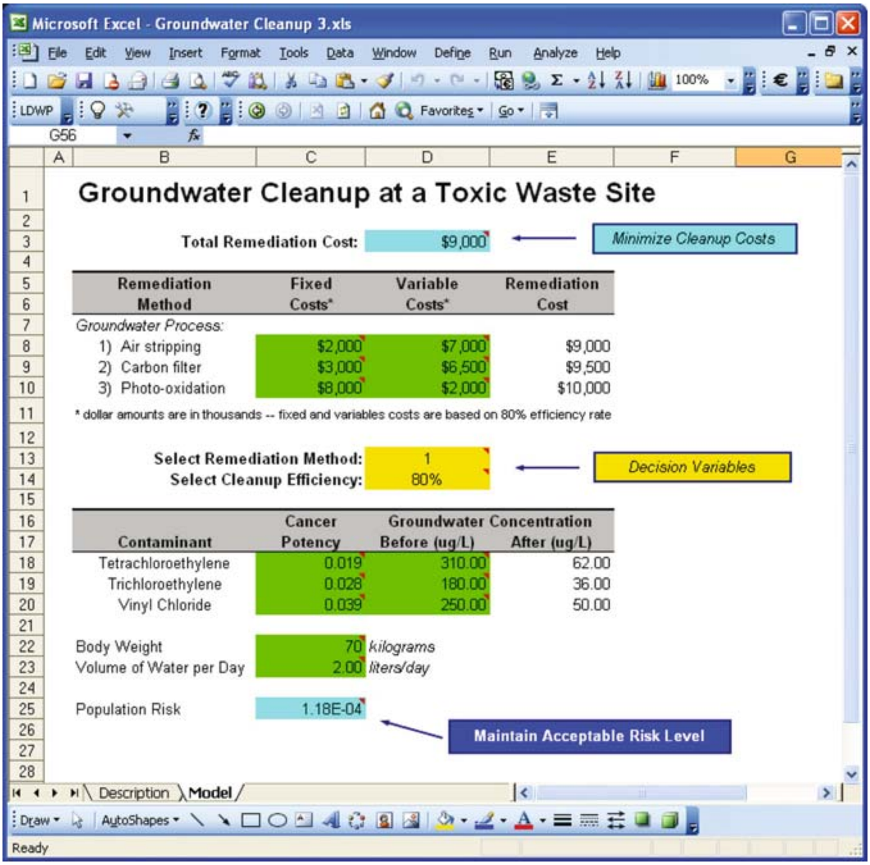


Figure 9. Influence Diagram for Determining the Minimum Cost Treatment Method.

4. Multiple Objectives

Several conservation, political, industrial, and community groups have come forward to raise issues related to their individual agendas. An extensive community consultation was conducted. All groups felt that the selection of the optimal treatment method (if remediation is done at all) must consider objectives other than just cost and population risk. The consensus was to add the following objectives:

- Incremental Health Risk
- Remediation Impacts
  - Contamination



Groundwater Cleanup at a Toxic Waste Site

Total Remediation Cost: $9,000

Minimize Cleanup Costs

Remediation Method	Fixed Costs*	Variable Costs*	Remediation Cost
Groundwater Process:			
1) Air stripping	$2,000	$7,000	$9,000
2) Carbon filter	$3,000	$6,500	$9,500
3) Photo-oxidation	$8,000	$2,000	$10,000

* dollar amounts are in thousands -- fixed and variables costs are based on 80% efficiency rate

Select Remediation Method: 1
Select Cleanup Efficiency: 80%

Decision Variables

Contaminant	Cancer Potency	Groundwater Concentration Before (ug/L)	After (ug/L)
Tetrachloroethylene	0.019	310.00	62.00
Trichloroethylene	0.028	180.00	36.00
Vinyl Chloride	0.039	250.00	50.00

Body Weight 70 *kilograms*
Volume of Water per Day 2.00 *liters/day*

Population Risk 1.18E-04

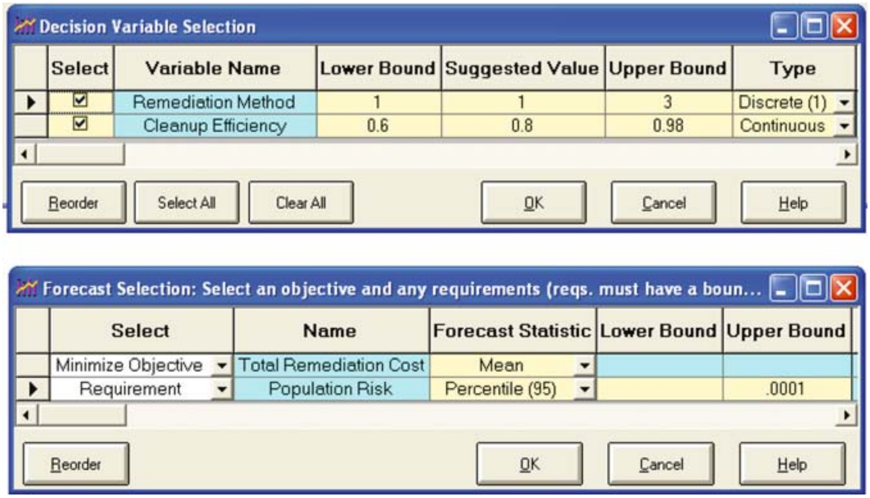
Maintain Acceptable Risk Level

Figure 10. Spreadsheet Model to Determine the Minimum Cost Treatment Method.

- Emissions
- Community
- Safety

These objectives were incorporated into the influence diagram under the category of "Remediation Impacts" as shown in Figure 13.

To incorporate the multiple objectives into the spreadsheet model, a decision analysis using value-focused thinking (VFT) [5] was conducted to assess the overall value of remediation. This analysis was conducted as a community forum where the objectives were modeled as a goals hierarchy from which value functions and objective importance weights were elicited using standard decision analysis procedures. The software package Logical



Decision Variable Selection

Select	Variable Name	Lower Bound	Suggested Value	Upper Bound	Type
☑	Remediation Method	1	1	3	Discrete (1)
☑	Cleanup Efficiency	0.6	0.8	0.98	Continuous

Forecast Selection: Select an objective and any requirements (reqs. must have a boun...

Select	Name	Forecast Statistic	Lower Bound	Upper Bound
Minimize Objective	Total Remediation Cost	Mean		
Requirement	Population Risk	Percentile (95)		.0001

Figure 11. Minimum Cost Treatment Model, Decision Variables (above) and Objective Function and Constraint (below).

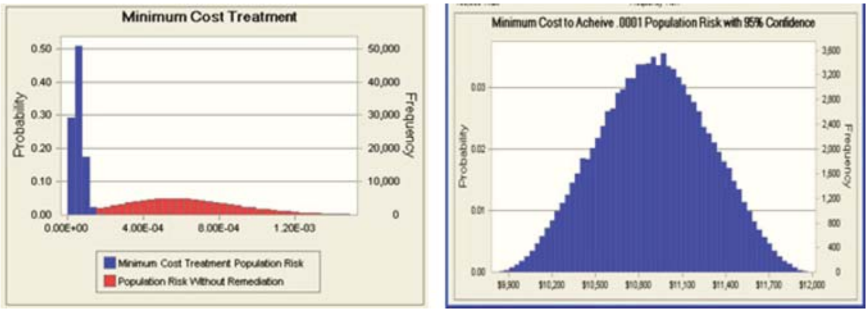


Figure 12. Optimal Treatment Method Performance and Cost Risk Profiles.

Decisions for Windows (LDW) [6] was used for the analysis. Figure 14 shows the goals hierarchy that was developed during the community forum.

Data were gathered for each of the objectives shown in the goals hierarchy. These data are shown in Figure 15.

The "Incremental Health Risk" and "Cost" data were the target population risk level and the mean of the cost data used in the previous analyses. The remediation impact objectives were all subjective estimates from the task force using qualitative scales from "Low" to "High." These data were used in the value and importance weight elicitation processes during the community forum. Value functions and importance weights are shown in Figure 16.

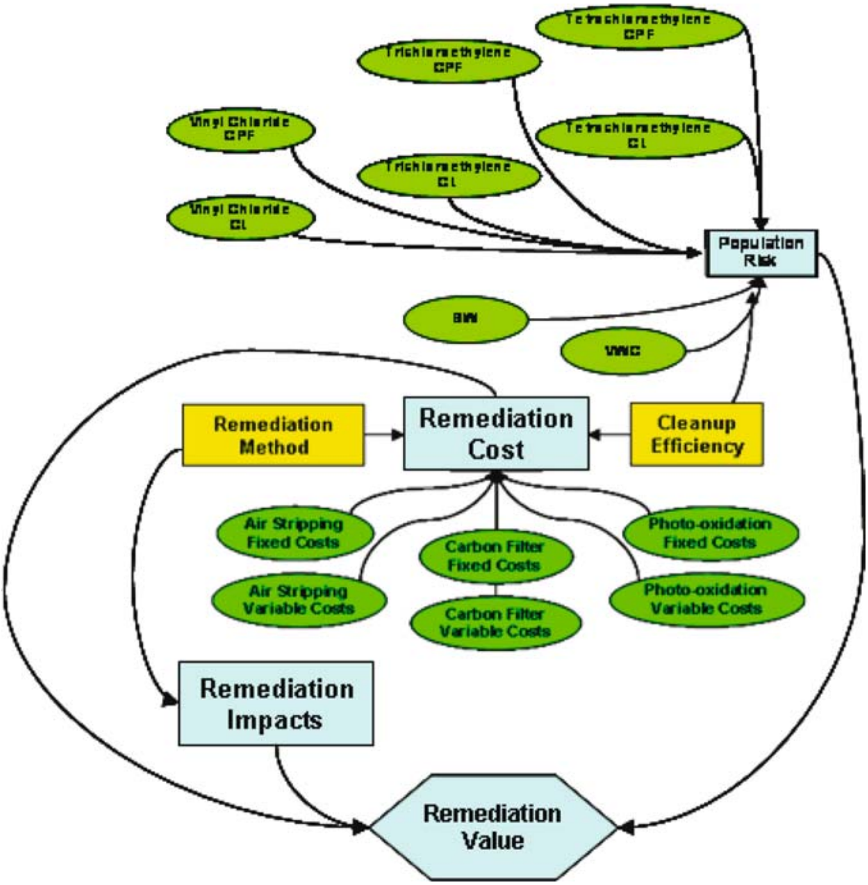


Figure 13. Multiple Objective Extension of Remediation Evaluation.

Using LDW's value function export capability, we incorporated the goals, hierarchy structure, and value functions into the spreadsheet model. The modified spreadsheet model is shown in Figure 17.

The Crystal Ball OptQuest stochastic optimization feature was then used to determine the optimum value remediation method. The result was to use carbon filter remediation at 66% cleanup efficiency with a total value of 0.908. This remediation method and cleanup efficiency level costs $6,909 ± $287, provides an average population risk level of 0.000199 with 95% confidence that the population risk level will be below 0.000392, and satisfies all of the remediation impact concerns (see Figure 18).

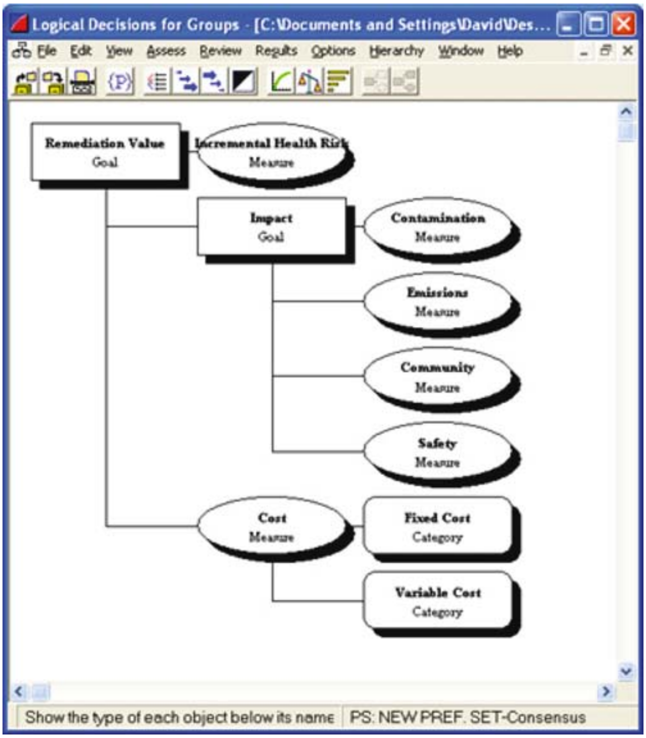
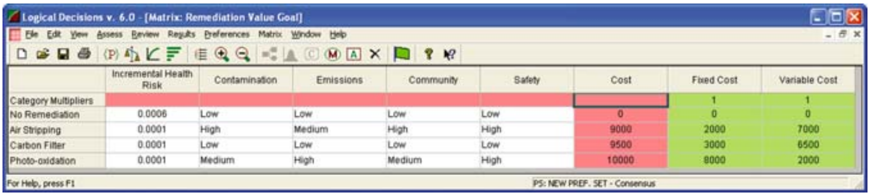


Figure 14. Community Forum Goals Hierarchy.



	Incremental Health Risk	Contamination	Emissions	Community	Safety	Cost	Fixed Cost	Variable Cost
Category Multipliers							1	1
No Remediation	0.0006	Low	Low	Low	Low	0	0	0
Air Stripping	0.0001	High	Medium	High	High	9000	2000	7000
Carbon Filter	0.0001	Low	Low	Low	Low	9500	3000	6500
Photo-oxidation	0.0001	Medium	High	Medium	High	10000	8000	2000

Figure 15. Data for Each Objective in the Goals Hierarchy.

5. Reducing Uncertainty

Having determined an optimum remediation method based on the multiple objectives of the stakeholders, the task force now wants to investigate the value of additional information so that mitigation plans can be developed to manage the population risk.

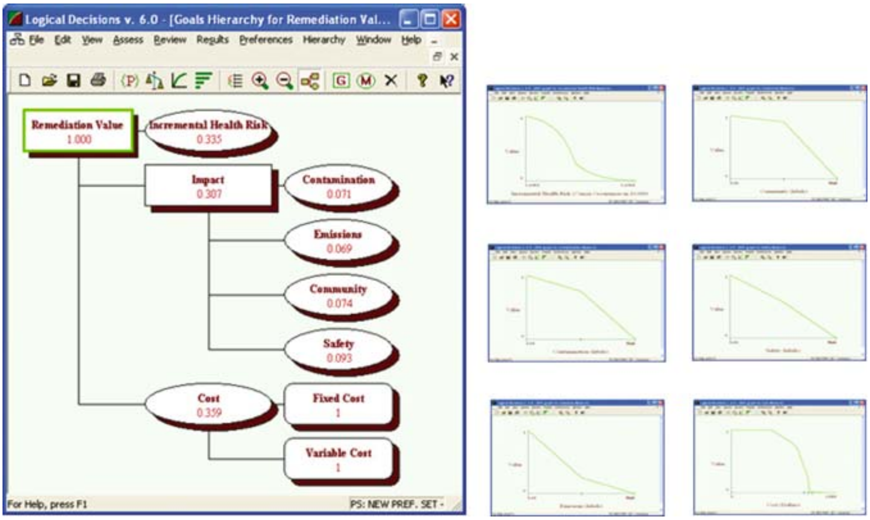
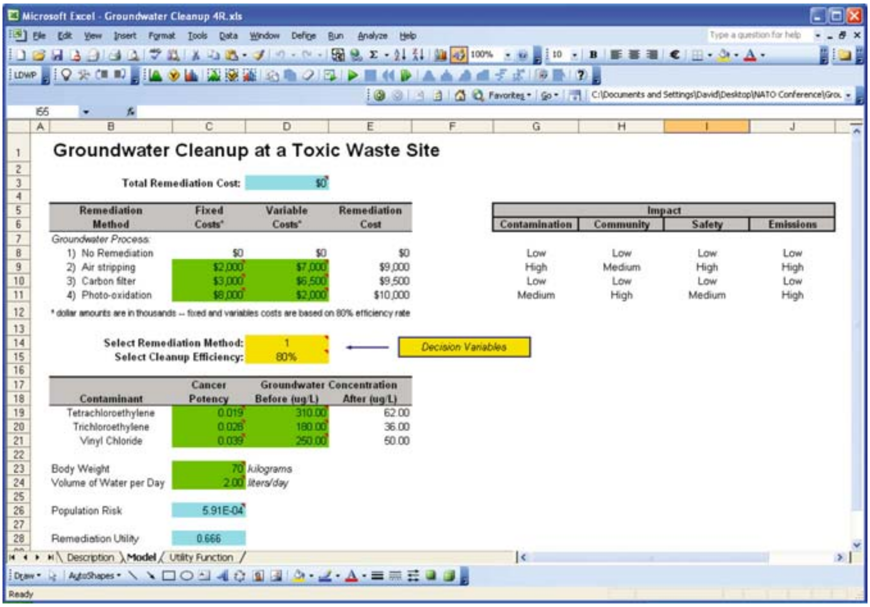


Figure 16. Importance Weights and Value Functions for Decision Criteria.



Groundwater Cleanup at a Toxic Waste Site

Total Remediation Cost: $0

Remediation Method	Fixed Costs*	Variable Costs*	Remediation Cost	Impact			
				Contamination	Community	Safety	Emissions
Groundwater Process:							
1) No Remediation	$0	$0	$0	Low	Low	Low	Low
2) Air stripping	$2,000	$7,000	$9,000	High	Medium	High	High
3) Carbon filter	$3,000	$6,500	$9,500	Low	Low	Low	Low
4) Photo-oxidation	$8,000	$2,000	$10,000	Medium	High	Medium	High

* dollar amounts are in thousands -- fixed and variables costs are based on 80% efficiency rate

Select Remediation Method: 1
Select Cleanup Efficiency: 80%

← *Decision Variables*

Contaminant	Cancer Potency	Groundwater Concentration	
		Before (ug/L)	After (ug/L)
Tetrachloroethylene	0.019	310.00	62.00
Trichloroethylene	0.028	180.00	36.00
Vinyl Chloride	0.039	250.00	50.00

Body Weight	70	*kilograms*
Volume of Water per Day	2.00	*liters/day*
Population Risk	5.91E-04	
Remediation Utility	0.666	

Figure 17. Spreadsheet Model Incorporating Multiple Objectives and Value Functions.

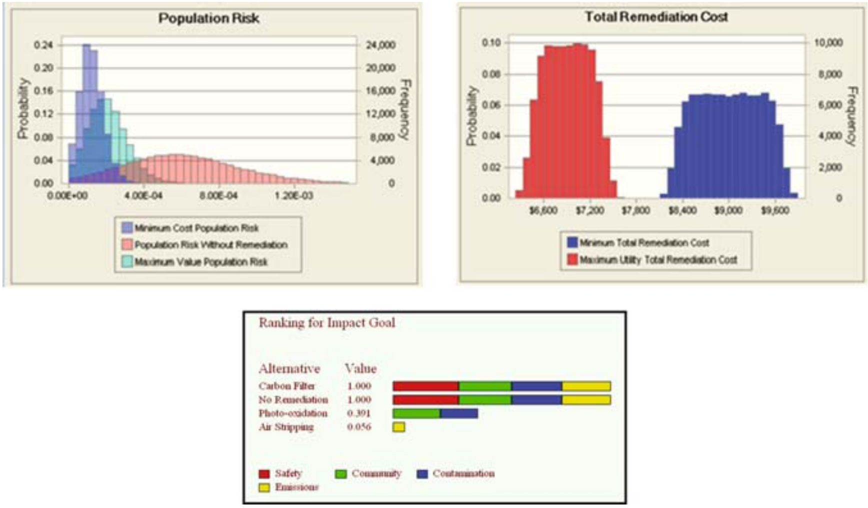


Figure 18. Maximum Value Remediation with Comparison to Minimum Cost Remediation.

Two possible cases of perfect information have been identified:

- Cancer potency and groundwater concentration
- VWC per day

The BW distribution was not considered for perfect information analysis because it represents the community population and is not an uncertainty in the same sense as the cancer potency/groundwater concentration and VWC per day.

To determine the value of perfect information for cancer potency and groundwater concentration, we remove the uncertainty and use the mean value. Figure 19 shows the modified influence diagram and spreadsheet model.

Results of the Monte Carlo simulations using the Crystal Ball are shown in Figure 20. The result shown is an overlay of the maximum-value remediation with and without perfect information for cancer potency and groundwater concentration. The overlay indicates no benefit from perfect information for cancer potency and groundwater concentration.

To determine the value of perfect information for VWC per day, we remove the uncertainty and use the mean value. Figure 21 shows the modified influence diagram and spreadsheet model.

Results of the Monte Carlo simulations using the Crystal Ball add-in to Excel are shown in Figure 22. The result shown is an overlay of the maximum-value remediation with and without perfect information for VWC. The overlay indicates a significant benefit for the perfect information about VWC.

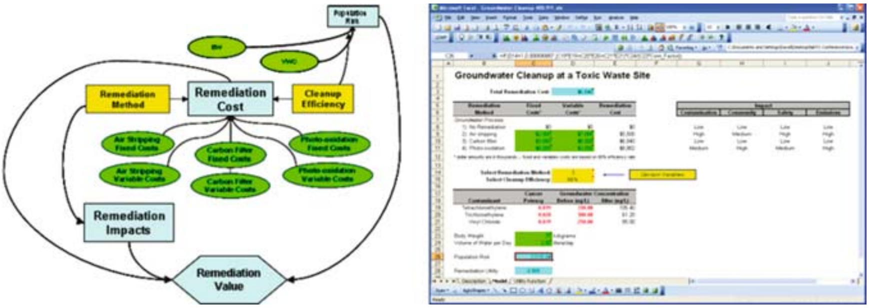


Figure 19. Influence Diagram and Modified Spreadsheet Model for Cancer Potency and Groundwater Concentration Perfect Information.

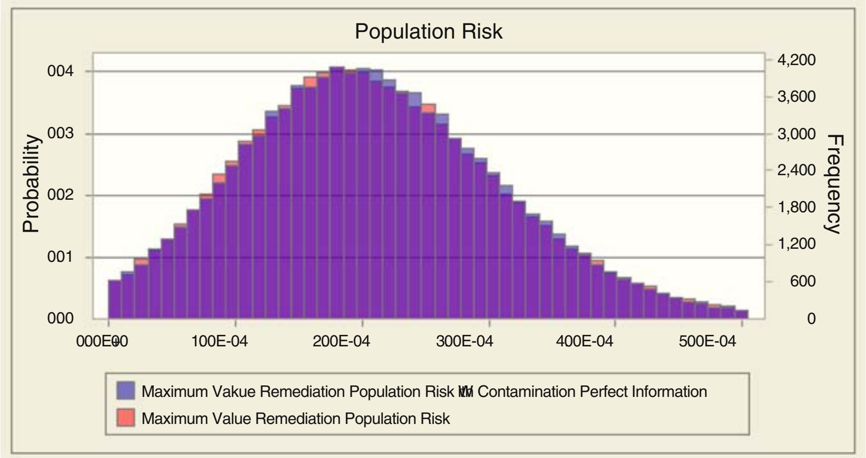


Figure 20. Overlay of Maximum Value Population Risk with and without Cancer Potency and Groundwater Concentration; Perfect Information.

6. Linked Decisions

Having done all of these analyses, the task force believes that there are so many unknowns that it would be wise to tread slowly. As a first step, they agree to proceed with the maximum-value plan to do carbon filter remediation at 66% cleanup efficiency. In addition, they agree to institute a parallel population risk mitigation plan that would supply bottled water above a daily intake of 2 L free of charge to anybody within 2 miles of the contaminated site.

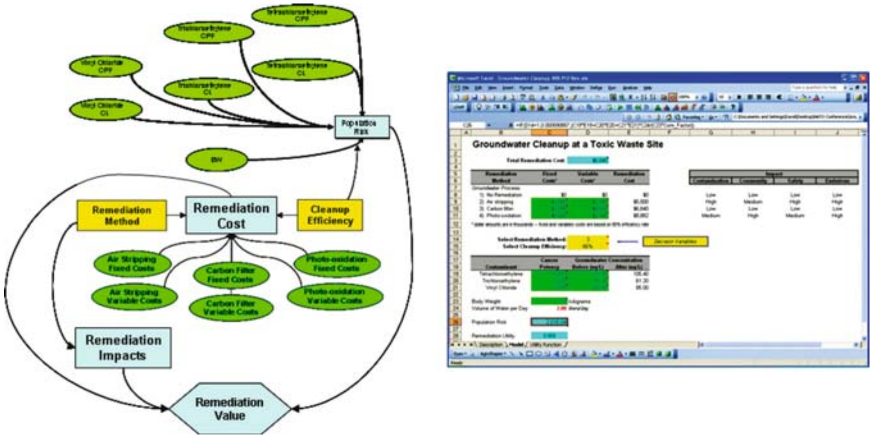


Figure 21. Influence Diagram and Modified Spreadsheet Model for VWC per Day; Perfect Information.

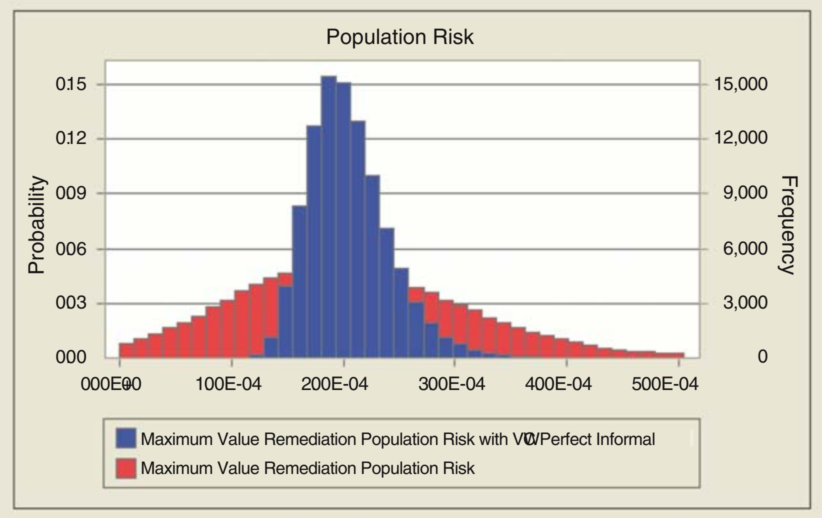


Figure 22. Overlay of Maximum Value Population Risk with and without Cancer Potency and Groundwater Concentration; Perfect Information.

Since the remediation will take many months and it would be too costly to continue this mitigation plan for a long period of time, the task force would like to periodically review the progress of the remediation to determine when to change courses of action. If during the course of the carbon filter remediation the population risk drops appreciably, the task force may decide to reduce, modify, or eliminate the bottled water mitigation plan.

The decision analysis concepts of Real Options and Options Thinking [7] provide the means for such a periodic review. Real Options provides the ability to delay and revise decisions over time as uncertainty is resolved. Options Thinking decomposes a decision into a sequence of decisions over time and reduces risk by delaying resource commitment and reducing uncertainty. Options Thinking also increases value by preserving options to proceed at lower cost, and permitting creation of new possibilities.

Figure 23 shows the flow of the Real Options process. In each phase, multiple objectives are identified together with uncertainties and decision opportunities. A maximum value decision is taken based on this "snapshot" in time, and the risks and their current levels are recorded. Risk tracking and handling plans are developed, and the project is begun.

7. Integrating the Parts: Adaptive Management

This simple case study of groundwater cleanup at a toxic waste sight has demonstrated the effective use of multiple operations research and decision analysis methods. Influence diagrams were used to frame the problem. Monte Carlo simulation was used to quantify the population risk. Stochastic optimization was used to determine a minimum cost solution at an acceptable population risk level. VFT coupled with stochastic optimization was used

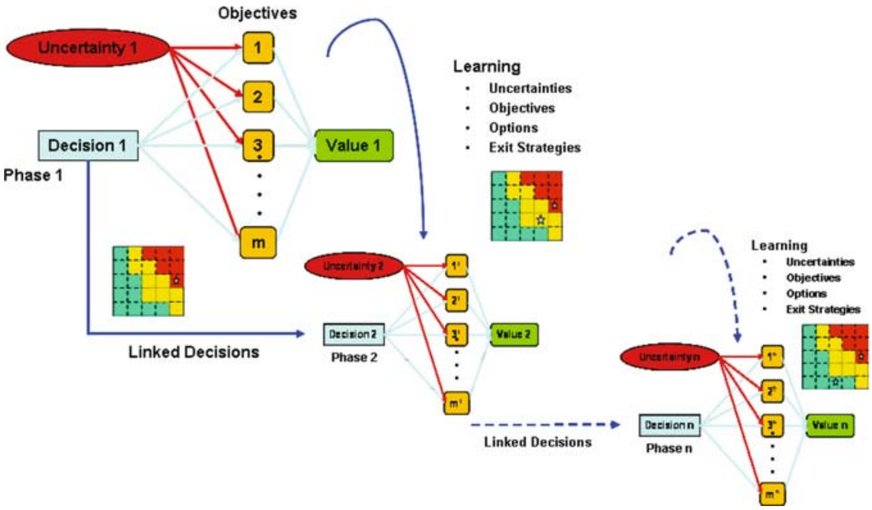


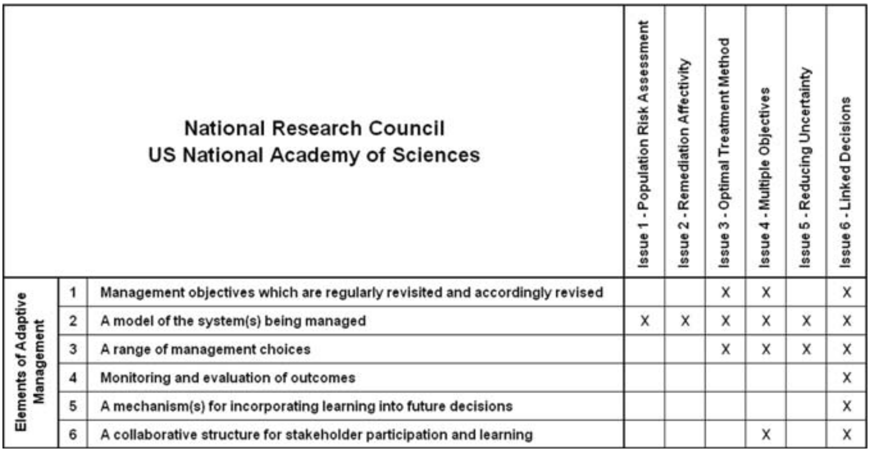
Figure 23. Flow of the Real Options Process.

to determine a maximum value solution with multiple competing objectives in addition to cost. Monte Carlo simulation was again used on the final solution to determine the value of perfect information for purposes of identifying possible mitigations plans. Finally the concept of Real Options thinking was used to provide a management procedure to insure effective completion of the remediation project. All of these operations research and decision analysis methods were implemented with available commercial software that is effective and user friendly.

The demonstrated process has all the tenets of adaptive management. It recognizes that uncertainty is inherent in any natural system, it seeks to minimize the uncertainty by learning about the system being managed over time, and it chooses a management approach and monitors the effects of that approach, making required adjustments based on the monitored results.

The benefits derived from this implementation of adaptive management are many. It provides the ability to delay and revise decisions over time as uncertainty is resolved; it reduces risk by delaying resource commitment until real progress has been made and uncertainty reduced; it increases value by preserving options to proceed more efficiently and effectively and permitting creation of new possibilities as we move from phase to phase.

Figure 24 shows a how the process demonstrated here maps to the Elements of Adaptive Management sanctioned by the National Research Council of the U.S. National Academy of Sciences.



National Research Council US National Academy of Sciences			Issue 1 - Population Risk Assessment	Issue 2 - Remediation Affectivity	Issue 3 - Optimal Treatment Method	Issue 4 - Multiple Objectives	Issue 5 - Reducing Uncertainty	Issue 6 - Linked Decisions
Elements of Adaptive Management	1	Management objectives which are regularly revisited and accordingly revised			X	X		X
	2	A model of the system(s) being managed	X	X	X	X	X	X
	3	A range of management choices			X	X	X	X
	4	Monitoring and evaluation of outcomes						X
	5	A mechanism(s) for incorporating learning into future decisions						X
	6	A collaborative structure for stakeholder participation and learning				X		X

Figure 24. Demonstrated Process Map to NRC Elements of Adaptive Management.

References

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