Choosing Alternatives to Contaminated Ground water Supplies: A Sequential Decision Framework Under Uncertainty

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In increasing numbers, communities that rely on ground water for drinking supplies have discovered contamination from agricultural pesticides and herbicides, road salt, underground fuel storage, and septic systems. A variety of short- and long-run remedies are available with highly uncertain outcomes. An appropriate technique for solving a benefit-cost problem of this type is a sequential decision framework using stochastic dynamic programming procedures for solution. The approach is illustrated here by means of an application to the problem of the recent contamination of the groundwater of Whately, Massachusetts by the agricultural fumigant EDB and the pesticide aldicarb.

Groundwater is the primary source of drinking water for approximately one-half of the nation's population and 90 percent of all rural households. Once considered a pristine source, groundwater is today an endangered natural resource in many areas. A recent water quality survey by the Environmental Protection Agency (EPA) indicates that non-point source pollution of ground and surface water is the most serious environmental problem in three quarters of the states. Public attention is turning increasingly to strategies for protecting aquifers from various sources of contamination, including agricultural pesticides and herbicides, underground fuel storage, road salt, and septic systems.

In many localities, however, it is too late for preventive measures since contamination has already occurred. In Massachusetts, for example, more than 110 public wells have been closed to date. That number is expected to double in the immediate future under new provisions of the federal Safe Drinking Water Act which set standards and require testing for many additional toxic substances. Pollution of private wells is similarly widespread, and in at least one respect may be considered a more serious problem than contamination of public wells: since regular testing of private wells is expensive and is generally not required, contamination may remain undetected for long periods of time.

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A community which discovers that its groundwater is contaminated faces complex decisions in which a number of possible strategies must be compared. Development of new and safe water sources and decontamination of existing aquifers are long-term projects with costs which are difficult to estimate accurately, because many of the necessary technologies are relatively unknown. Stop-gap measures for treating contaminated water are available, but are not considered fully adequate. The seriousness and frequency of health effects which may result from consumption of the tainted water are difficult to predict accurately, and are a source of justifiable anxiety. For these reasons community decisions must be made under conditions of very great uncertainty regarding both the costs and benefits of alternative courses of action.

We suggest that an appropriate technique for addressing benefit-cost problems of this type is a sequential decision framework using stochastic dynamic programming procedures for solution. This method is not often used, perhaps because of a fear that the solution would be too difficult or expensive. In many cases, however, such fears are groundless. The sequential decision method of analysis is illustrated here by means of an application to the problem faced by the town of Whately, Massachusetts. The approach indicates optimal first period decisions, and provides a road map for later period decisions given earlier period information. It readily permits examination of sensitivity to model coefficients, and in the process directs attention to the most promising areas for future research to reduce uncertainties about these values.

The recent experience of Whately resembles that of hundreds of other communities across the country. The groundwater supply was discovered almost accid ;ntally to be contaminated by leachate and runoff from pesticide and fertilizer applications on agricultural lands. In 1984, following inquiries by a local citizen, state authoritites tested private wells in Whately for the agricultural fumigant ethylene dibromide (EDB) and the pesticide aldicarb (known under the tradename Temik). More than thirty percent of the wells sampled tested positive for EDB or Temik contamination and two-thirds of these were shut down because the levels exceed state safety limits.

Town selectmen commissioned an Engineering Study to develop a hydrogeological report of the surrounding area and to recommend an alternative water supply. The study cited four possible actions, which could be taken alone or in combination: use of bottled water, installation of carbon-activated filters, development of a municipal water system, and hookup to neighboring town water supplies.

The recommended long-term plan called for the development of a central municipal water system to replace the contaminated private wells, at an estimated cost of $3.4 million, and adoption of regulations to protect the new water supply: protection zones would be set up which would restrict land use and technological practices in areas linked hydraulically to the new aquifer.

In the interim period, it was recommended that households install carbon-activated filters. Such niters eliminate Temik and EDB, but are ineffective in removing nitrates and sodium, which were also found in sampled wells. In addition, carbon-activated filters are prone to mechanical failure and bacterial buildup, and require periodic monitoring. Installation of filters could be expected to alleviate the immediate water supply problem for households with contaminated wells, but not to provide a long-term solution.

The Engineering Study estimated costs for both the long-term plan and the interim plan, but failed to evaluate benefits. As a result no comparison was made or could be made between the recommended strategy and alternative strategies for dealing with the water crisis. The reasons for not evaluating benefits presumably involve the great uncertainties about their magnitude, the difficulty of assigning a value to non-market effects such as illness and death, and the long planning horizon which is under consideration. A proper policy analysis cannot be undertaken, however, without a comparison of alternative strategies. The conditions of the problem and many others like it suggest sequential decision analysis as an appropriate methodology.

Sequential Decision Analysis

Sequential decision analysis can help decision-makers to project net benefits from various decision strategies when faced with uncertainty about future conditions and relevant program parameters such as costs. The main feature of sequential analysis is to incorporate probabilities about unknown parameters into the decision procedure. Within this framework, information gained at every stage in the planning horizon is used to reduce uncertainties about future stages, thus improving the quality of decisions in remaining periods. At the beginning, there is no single best action for the entire horizon, but rather a flexible strategy which incorporates chance events and knowledge gains into future decisions. Works by Rausser and Dean and Willis have demonstrated the utility of sequential decision analysis in evaluating new technologies.

The simplified decision tree in Figure 1 conveys the essence of the present decision problem. Assume that a rural community discovers contamination of its water supply and must initially decide whether to take remedial action or to let the pollution continue. A planning horizon of 20 years is considered, with decision points at ten year intervals, so that there are only two decision points. Suppose there are two possible actions at each decision point:

Action A1: delay treatment of the contaminated aquifer and install household filters, in hopes that the aquifer will cleanse itself within ten years

Action A2: attempt to rehabilitate the aquifer by indirect remedial methods such as withdrawal, treatment, and reinjection.

The major sources of uncertainty associated with action Al are the cost of filter maintenance and operation, and the rate at which natural processes will cleanse the aquifer. The outcome of action A2 is also subject to great uncertainty since attempting to cleanse an aquifer is a costly, complicated, and long-term undertaking.

If treatment of the aquifer is attempted and fails, the town will incur a large financial loss and still have to adopt other measures. If on the other hand the town waits for the aquifer to cleanse itself and it does not, then additional expenses must be incurred to continue use of filters or attempt direct treatment. Of course in the event that either course

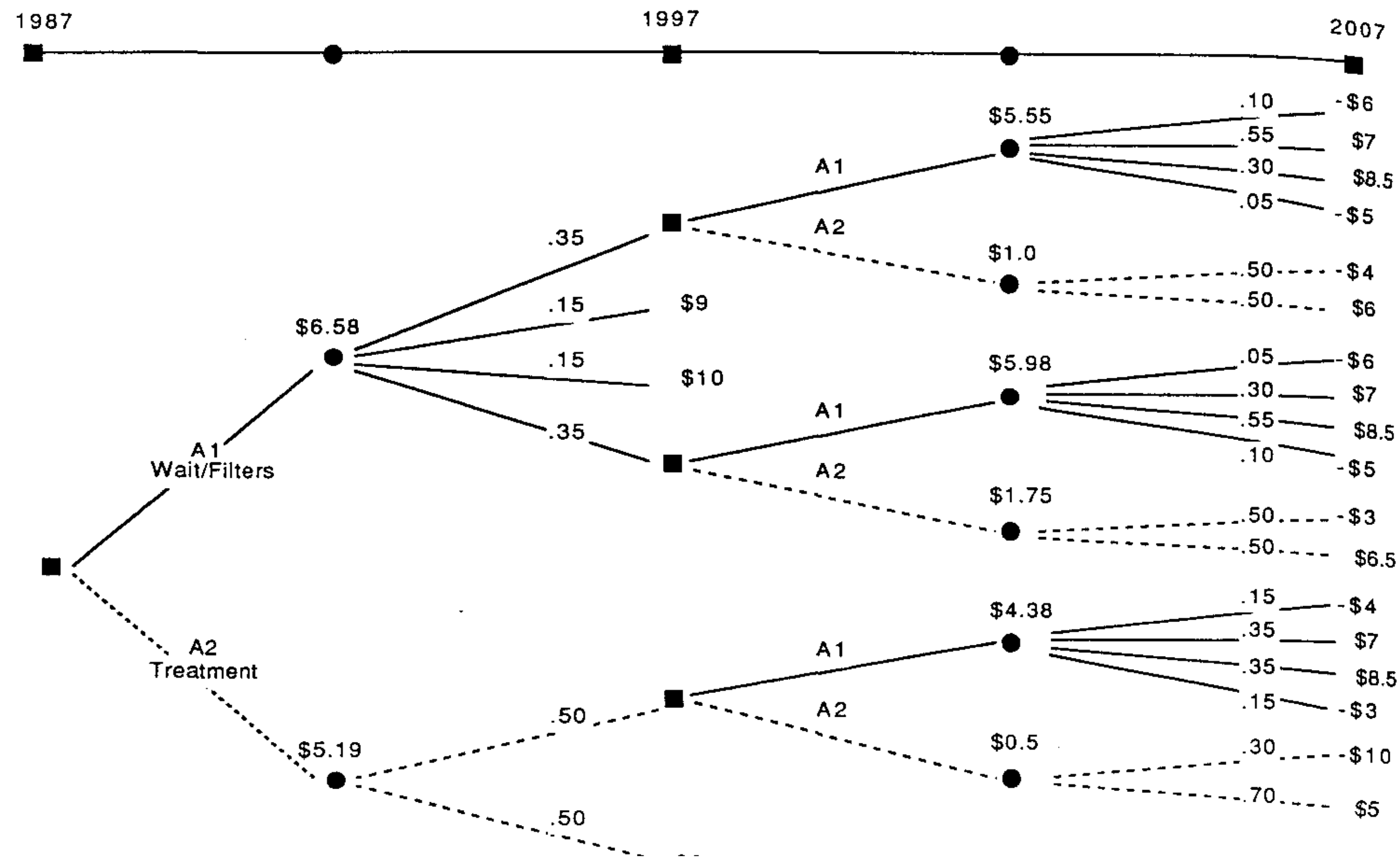

Figure 1. An Example Illustrating the Use of Sequential Decision Analysis for Evaluating Groundwater Supply Alternatives

of action is adopted and succeeds before the second decision point is reached, no further action is necessary.

Sequential decision analysis explicitly recognizes these uncertainties and deals with them by assigning probabilities to the various situations ('states of nature') which may occur. For action Al (wait/install filters), possible states of nature are:

State S1 = Contamination of the aquifer con tinues and filters are found to be costly

State S2 = The aquifer cleanses itself and filters are found to be costly

State S3 = The aquifer cleanses itself and filters are found to be inexpensive

State S4 = Contamination continues and filters are found to be inexpensive.

For action A2 (treatment), the relevant states of nature are:

State S5 = Treatment process fails—contami-

State S6 — Treatment process succeeds—aquifer becomes potable.

A probability must be assigned to each outcome based on the best available evidence. If action Al is adopted, we assume that states SI and S4 are believed to have probability .35, and states S2 and S3 probability .15. For action A2, success and failure are believed equally likely to occur, and each is assigned probability .5. In addition, dollar values are assigned to each outcome (i.e. action plus state of nature) which reflect its net benefits. The difficult problem of valuing life and health is addressed later.

As seen in Figure 1, the effects of action Al or A2, selected in 1987, will prevail until 1997. At the end of that initial period, decision-makers know which state of nature has occurred, and have an opportunity to revise their strategy. If outcomes S2, S3 or S6 have occurred, the contamination problem is solved, no uncertainty remains and no further action is necessary. If SI, S4, or S5 has occurred, the probability and net benefit estimates on the remaining branches will be revised, in order to

In this example, neither action Al nor A2 precludes revision of the strategy after the first period. l_t should be noted that this need not always be the case: sometimes the best strategy consists of taking an irreversible action at the beginning of the time horizon.

The value of each action is defined to be its expected monetary net benefits, defined as the weighted sum of present valued net benefits under each action and state of nature, where the weights are probabilities of the states of nature. The most favorable outcome in the example occurs if decision-makers choose action Al and if state S3 occurs during 1987-97. In this case, potable water is obtained without a costly treatment expense, since by good luck natural cleansing has occurred and filters have turned out to be inexpensive. Unfortunately, the probability associated with state S3 during this period is rather low, .15, so that the potential net benefit to the community of $10 million translates into an expected net benefit of only $1.5 million. The most unfavorable outcome occurs if treatment is chosen and fails, i.e. action A2 combined with state S5, in both decision periods. In this case large costs are incurred without any positive result, and net benefits equal —$10 million.

The analysis of a problem of this type leads to a "backward solution," as explained for example in Willis. Because the value of any decision depends on the probabilities and net benefits associated with all possible subsequent outcomes, the valuation of expected net benefits starts from the 'tips' of the decision tree, and works backward in time toward the initial decision point.

In the present example, we begin at the top branch of the decision tree for 1997. It is necessary to evaluate expected net benefits from both Al and A2. If we take action A1, the ensuing state of nature may turn out to be SI, S2, S3, or S4. The values assigned to these outcomes (in millions) are -$6, $7, $8.5, and -$5, with probabilities .10, .55, .30, and .05, respectively. The expected net value of action Al taken in 1997 is therefore:

$$.10 \times (-\$.6) + .55 \times \$7 + .30 \times \$8.5 + .05 \times (-\$5) = \$5.55.$$

Similarly, the expected value of action A2 in 1997 is:

$$.50 \times (-\$4) + .50 \times \$6 = \$1.0.$$

Expected net benefits for the lower branches of the tree are calculated in the same manner.

Having obtained a complete set of values for the 1997 decision nodes we are in a position to consider the optimal decision for the initial period, 1987. We have concluded that action A1 would be chosen in 1997 if the events described by the top branch come to pass (i.e. Al is chosen and SI occurs in the first period). The calculated composite value of $5.5 is therefore the relevant one to use in evaluatinga 1987 choice of action Al if state SI occurs. Complete expected net benefits from Al in 1987 are:

$$.35 \times \$5.55 + .15 \times \$9\ 4\text{-}\ .15 \times \$10 + .35 \times \$5.98 - \$6.88.$$

Similarly, the expected value of action A2 in 1987 is calculated as:

$$.50 \times \$4.38 + .50 \times \$6 = \$5.19.$$

Action A2 is dominated and Al is selected as the optimal first-period decision.

The completed decision tree provides a flexible framework for making sequential choices over time. The optimal decision for the next period depends on the unfolding of events, the "states of nature." If S2 or S3 occurs in the first period, no additional action will be necessary. If state Si or S4 occurs, 1987 information would suggest continuation of action Al in 1997, since it has higher expected value than A2. If however new information is obtained in the interim, probabilities and value estimates will be adjusted before a second period decision is made.

Far more complex problems can be solved using essentially the same technique. The decision tree will grow with the number of choices at each node and with the number of decision points over time.

Empirical Application

The full set of strategies which have been proposed to deal with contamination of the Whately aquifer consist of combinations of the following actions:

(A1) development of a municipal water supply system
(A2) use of bottled water (A3) installation of household carbon-activated
filters (A4) hookup to neighboring water supplies.

As in the example, expected net benefits of each action will be calculated from probabilities assigned to various states of nature and the net benefits associated with each action/state of nature combination. Before a comparison of actual decision strategies can be made, these values, which in the example were assigned arbitrarily, must be defined realistically.

Net benefits are comprised of project benefits, capital costs, and operation and maintenance expenses. Project benefits in this case consist primarily of reductions in health risks due to improvements in the quality of water. There are additional benefits from some of the above actions which must also be taken into account, such as gains in consumer surplus if the unit cost of obtaining water is reduced, and savings on fire insurance premiums when water mains are installed.

A full description of variables, states of nature, and the four basic actions can be found in Sarnat, Willis and Alien. For present purposes, only the features essential to understanding the structure of the decision problem are provided.

Human Health Valuation. Contaminant concentrations in sampled wells and a cancer risk coefficient generated by the Environmental Protection Agency have been used to estimate the mortality and morbidity risk from drinking contaminated water. A useful conceptual framework for working with non-market benefits of this kind is provided by Raucher. Excess cancer risk, the increase in probability of contracting cancer due to drinking water contaminated by a pollutant (j), is represented as:

(1) $$r_j(dj) = a_j d_j, a_j \geq 0,$$

where TJ is the additional risk due to contaminant j, dj is the daily intake of the pollutant in milligrams/kilogram body weight, and aj is the potency of the contaminant (Schechter). In the absence of synergistic effects (i.e. assuming carcinogenic substances operate independently), excess risk of contracting a disease S from drinking water contaminated by J chemicals may be approximated by the sum of individual risks:

(2) $$R(d) = \Sigma r_j, \text{ where } d = (d_1, d_2, \ldots, dn).$$

Mortality risk (Mr) is then the probability of becoming sick from the received dose times the conditional probability that death M occurs once the disease S has been contracted:

(3) $$Mr(d) = R(d) \times prob(M \mid S).$$

Those individuals who do not die from the disease experience a decrease in the quality of life due to illness. Their morbidity rate (Md) is similarly expressed as:

(4) $$Md(d) = R(d) \times (1 - prob(M \mid S)).$$

Unfortunately the risk factors TJ for carcinogens are almost never known with any degree of assurance. The application of quantitative risk assessment techniques to laboratory animal data often results in human risk estimates which differ by 10^4 or more in the relevant dose range. In the present case the EPA has generated a risk factor of .0015 for EDB. Since there are no adequate data con cerning the health effects of aldicarb and nitrates the present health damage estimates reflect only the lifetime cancer risk for EDB. Calculated damage estimates must therefore be considered lower bound estimates.

One way in which health damage may be incorporated into a quantitative decision model is bv assigning monetary values to death and illness (or to risks of death and illness). The total valuation of health damage (Hd) is then given by:

(5) $$Hd - (Mr \times Pop \times V_1) + (Md \times Pop \times V_1)$$

where Pop is the number of persons exposed, and Vi and Vj are the monetary values assigned to loss of a statistical life or a statistical illness respectively.

A range of estimates for the dollar valuation of a statistical life are presented in Sharefkin, Shechter, and Kneese, with values from \$57,000 (Frankel) to \$10,120,000 (Jones-Lee), refiectina[b] differences in estimation procedures—human-capital valuation, contingent valuation, and implicit valuation—and model assumptions. The median value (\$600,000 in 1985 dollars) has been used here. The economic cost of morbidity has been estimated at 72 percent of the dollar value of mortality, following Berk, Paringer, and Mushkin. Total illness or morbidity costs include direct payment costs (i.e., medical expenses) and indirect costs represented by loss in earnings due to mortality.

It should be noted that the value-of-life treatment of human death and illness, although often used by economists to make problems tractable, is controversial and in some situations may be unacceptable to decision makers. In addition to the obvious moral difficulties which it raises, the value of life technique is incapable of distinguishing between very small risks spread over large populations , which may often be acceptable to a community, and larger risks to a few individuals, which may not be acceptable.

Consumer's Surplus. Development of a municipal water system or providing hookup to neighboring water supplies is expected, once the fixed hookup costs have been paid, to lower the unit cost of water to households in comparison with the pumping and maintenance costs of household wells. Consumer's surplus provides a good approximation for welfare changes due to price changes of this kind. Per capita consumption of water in rural households is estimated at sixty gallons per person per day (Coffin & Richardson and BSC Engineering, 1985). Since the amount of water consumed is the same for rural households with metered municipal systems as for homes with household wells, the demand for water is assumed to be perfectly inelastic with respect to price.

Insurance Premiums. The Massachusetts Insurance Service Office classifies all towns according to their fire suppression capability. Since the rate criteria include the number, distance and flow rates of hydrants and the distance of each dwelling from the nearest fire station, development of a municipal water system or hookup to neighboring water supplies would decrease fire insurance premium rates for households and commercial businesses. These savings are estimated at $50.00 per year per household, for a total of $11,650, and at $2,330 per year for businesses. Project benefits for actions Al and A4 therefore include decreases in the cost of water and fire insurance in addition to health risk reductions.

The Alternatives. Action A1, development of a water supply system, is a complex undertaking which is divided here into three separate sub-actions. Action Ala represents the early phases of the proposed water supply system detailed in the Engineering Study, including installation of a water distribution network to serve 200 households, development of a deeper aquifer water supply source, and con-strruction of water storage facilities. Action A1b represents a later phase of the same proposal, consisting of installation of water pipe to supply additional households in southeast Whately. Action Ale represents an alternative possibility available to decision-makers: to plan from the beginning for a more limited distribution network, capable of supplying only those households already affected by groundwater contamination. This plan avoids the additional expense of a larger distribution system. If contamination spreads to southeast Whately, however, a loss in terms of human health may be experienced in the town.

The other long-term solution suggested to the town (action A4) was to hook up to water supplies in two neighboring towns which previously developed lower aquifer wells. This could offer a less costly long-term solution, but would require the cooperation of several towns.

Short-term solutions include the use of bottled water (A2) and installation of carbon-activated filters (A3). Such actions are reversible, and therefore provide an opportunity to delay development of any central distribution system, in hopes that the shallow aquifer would cleanse itself naturally over time. Bottled water is the least costly action, but is not recommended for more than 1-2 years, since only 20 percent of total daily exposure to organic chemicals is assumed to come from oral consumption of polluted water. The remaining 80 percent derive from inhalation and skin absorption. In the model, use of bottled water was restricted to one period, since many households were known to have used bottled water for some time.

States of Nature. Table 1 summarizes the states-of-nature associated with each possible action, and probabilities which reflect an initial best guess about their relative likelihood. The probabilities are subject to reevaluation at each decision node as new information becomes available. For actions A1a and A1b, the major sources of uncertainty are the capital, operation and maintenance expenses to develop and operate a central water distribution system. In the first period, based on present knowledge, high cost and low cost are considered equally likely, and are assigned probabilities of .5. For action A1e, the unknown factor is whether contamination will spread. Since adverse levels of EDB and al-dicarb have not been detected in southeast Whately wells to date, states S5 and S6 are also assumed equally likely events in 1989. If contaminant concentrations have not appeared by 1989, the probability of contamination thereafter is assumed to be .05.

For action A2 there is no uncertainty, but health risk reduction is only partial. For A3, high cost and low cost states of nature reflect the efficiency rate of filters in removing contaminant residues. Filter efficiency can be increased by replacing the carbon medium more frequently, for example at 75 percent of its projected lifetime. High cost, S8, assumes that premature breakthrough occurs more frequently than the predicted level and that operation and maintenance costs are increased in an attempt to improve filter efficiency. Low cost, state S9, assumes the carbon medium is recharged every 60,000 gallons (the suggested carbon lifetime) and is 90 percent efficient. In the initial decision period, states S8 and S9 are considered equally likely to occur. If the high cost situation (S8) occurs in the first decision period, use of filters will be discontinued due to escalating operation and maintenance costs. If the low cost event (S9) occurs in the first period, the probability of low cost occurring in the second year increases by . 1.

To model the value of delaying a decision, in the hope that the shallow aquifer may cleanse itself naturally over time, A3 is repeated for the entire decision horizon (seven years). At the end of the seventh year, if cleansing has not occurred, an additional expense is required, either to continue using filters or to develop a water distribution system at that time. Contaminant persistence and mobility depend upon oxidation-reduction potential, contaminant characteristics, and the soil structure. The oxygen-poor nature and slow laminar movement

Table 1 Possible Actions, States of Nature, and Assigned Probabilities

Action		Probability
Ala:	Development of a Municipal Water System — Early Phases	
	STATE S1: High capital, operation and maintenance costs	.5
	STATE S2: Low capital, operation and maintenance costs	.5
Alb:	Development of a Municipal System — Later Phase	
	STATE S3: High capital, operation and maintenance costs	*
	STATE S4: Low capital, operation and maintenance costs	*
Ale:	Stop after Early Phase of Municpal System	
	STATE S5: Contamination spreads to Southeast Whately	.5
	STATE S6: Southeast Whately wells remain potable	.5
A2:	Bottled Water	
	STATE S7: Incomplete Health Risk Reduction	1.0
A3:	Installation of Carbon-activated Filters	
	STATE S8: High capital, operation and maintenance costs	*
	STATE S9: Low capital, operation and maintenance costs	*
	STATE S10: The shallow aquifer has cleansed itself	.01
	STATE SI 1: Contamination levels have not decreased	.99
A4:	Hookup to Neighboring Water Supply	
	STATE 12: High capital cost and purchasing price	.5
	STATE 13: Low capital cost and purchasing price	.5

*Probability is adjusted according to previous year's costs

of groundwater contributes to the persistence of contaminants in groundwater. The half-life of EDB under neutral conditions is estimated 24 years (Brown and Rowan). Given the hydrogeological attributes of the aquifer, and the fact that natural processes are expected to take between 20 and 50 years to cleanse the aquifer, the probability associated with state S10 (natural cleansing in seven years) is set at .01.

For action A4, unknown elements include capital costs and the price which will be charged per unit of water. If this action, hookup to neighboring water supplies, is chosen, states S12 and S13, high and low costs respectively of capital and water, are considered equally likely events.

Consequences. The consequences of any given action will depend on the state of nature that occurs. There are 156 terminal positions in the model, representing all possible action/state combinations. Details of the capital costs, operating and maintenance expenses, and benefits used to calculate the expected net benefits for each action/state pair are presented in the Appendix to Sarnat, Willis, and Alien.

All actions offer some reduction in health risk, though the degree of health improvement will differ from one ation to another, with bottled water and carbon-activated filters providing only partial protection. In addition to health benefits, actions Al and A4 provide economic gains in the form of consumer surplus for water and savings on fire insurance. The costs of each action may be divided into capital costs and operating expenses of various types. Net benefits from any action consist of the sum of costs and benefits of various types, under a particular state of nature.

Consequences of undertaking action Al (development of a municipal water system) are the health benefits from the project, consumer's surplus for water, and savings on insurance premiums; and the costs, which include both capital expenditures and operation and maintenance costs. Consequences of action Al under states of nature SI (high cost) and S2 (low cost) are estimated to be ten percent above and ten percent below projected capital and operation expenses for the municipal system.

The consequence of choosing action A2 (bottled water) is the health benefit less the capital cost. This choice is completely reversible, since any of the remaining alternatives—Al (development of a municipal system), A3 (installation of carbon filters), and A4 (hookup to neighboring water supplies) is possible in the subsequent decision period.

If action A3 (installation of carbon filters) is r-en, the consequences are health benefits associated with the use of filters less capital and operating expenses. Again, high cost and low cost states of nature are estimated at ten percent above i apd below projected costs.

The consequences of undertaking action A4 (hookup to neighboring water supplies) are the project benefits including health benefits, consumer's surplus and savings on insurance premiums, less capital expenses. (Operation and maintenance costs are incurred by the neighboring town.) The high and low cost states of nature do not restrict alternative actions in subsequent decision periods. If state of nature S12 occurs, the distribution network could easily be converted to a municipal system by developing a water pumping facility within the town. It should be noted, however, that once action A4 is undertaken it cannot be interrupted until the end of the decision horizon—in this case, a period of seven years.

i Results

Expected present value of net benefits for each first period action were found to be as follows, when a human life is valued at $600,000 as discussed previously, and the discount rate is taken to be seven percent per year:

Al Municipal System —$1.41 million A2 Bottled Water -$1.24 million A3 Carbon Filters —$1.34 million A4 Neighboring Water Supplies —$1.22 million.

All results are negative, indicating that when human life and health are valued at this rate, the optimal action is to do nothing, and to incur the level of health risk which is believed to result from groundwater contamination. Such a conclusion may or may not be acceptable to the community. Dollar measures of mortality and morbidity may be found inappropriate on a number of grounds. The absolute risk to individuals in the community, and the number of individuals exposed to the risk, may be considered to be more relevant criteria for social decision-making. For the at-risk population in Whately, the mortality rate for exposure to EDB in drinking water is estimated at .213 over a 70 year lifespan. This is equivalent to a one-in-five chance that a life will be lost over a 70 year period from the EDB levels currently recorded.

Some evidence for the value residents place on their health safety may be gathered from purchases of bottled water. Current use of bottled water suggests that individuals" value of life is greater than that assumed in the base case—in excess of $5 million rather than $600,000. This value has been calculated as seventy times the annual cost of bottled water, divided by the sum of the mortality and morbidity rates.

On the assumption that inaction is not socially acceptable, and that some type of action must be taken, we proceed to compare the relative expected benefits of actions Al through A4 in the first period. Of the actions considered, A4 (hookup to neighboring water supplies) represents the minimum expected net present value loss ($1.2 million). Action Al (development of a municipal water system) shows the greatest loss ($1.4 million). Although A4 yields lower benefits than Al due to lower consumer's surplus, it represents a considerable savings in capital costs and therefore is economically superior to Al. The net benefit associated with actions A2 (bottled water) and A3 (filters) is insufficient to warrant delaying development of a water distribution network.

It should be noted that it may be necessary to engage in a long-term contract in order to purchase water from neighboring communities. If this is the case action A4 once initiated cannot be revised until the end of the seven year contractual period. Following expiration of the water contract, however, Whately could develop its own municipal well—i.e., take action A1. Another timing feature of the initial period decision is that benefits attributable to A2 and A3 are received immediately, whereas benefits from Al or A4 are delayed one year prior to completion of the water distribution network. The use of bottled water results in only 20 percent of total health benefits, but they are available in the first year.

Sensitivity Analysis. A partial sensitivity analysis of probabilities of the relevant states of nature was conducted. The optimal solution sequence was found to be insensitive to a change in the probability (.01 to .001) of the aquifer cleansing itself over a seven year period and to a change in the probabilities associated with filter cost and efficiency. Other pairs of states are considered equally likely because the "best estimate" consequence was used. Sensitivity here was done by varying the assumed consequence. In an effort to test the sensitivity of expected net benefits to other changes in model parameters, scenarios were examined which had varying discount rates, values of life, estimated costs, and number of prospective consumers.

Discount Rate. The results summarized in Table 2 suggest that the expected net benefits of the alternative actions are relatively sensitive to changes in the discount rate. At a discount rate of .10 or ,09, the optimal solution sequence is action A2

Table 2. Sensitivity of Expected Present Value of Net Benefits to a Change in the Discount Rate (R) and Value of Life*

		Expected Present Value of Net Benefits to First Period Action ($thousands)			
		A,	A_n	A_3	A_4
Discount	.10	- 1,383	- 1,239	- 1,299	-1,262
Rate	.09	- 1,395	- 1,242	- 1,326	-1-254
R	.08	- 1,405	- 1 ,242	- 1,341	-1.241
	.07	- 1.412	- 1.237	- 1.343	-1.223
	.05	- 1,413	- 1,211	- 1,331	-1,171
Value	$0.6	- 1,412	- 1,237	- 1,343	- 1 ,233
of	$1.0	- 1,377	- 1 ,200	- 1,304	-1,184
Life	$3.0	-1,199	- 1,018	- 1,109	- 993
($ million)	$5.0	- 1 ,022	- 835	- 914	- 800

*Other **parameters** at baseline values

(bottled water) followed by A3 (installation of carbon-activated filters) in the subsequent planning period. At a discount rate of .08 or below, action A4 (hookup to neighboring water supplies) is the optimal solution.

Value of Life. Table 2 also summarizes the sensitivity of the expected present value of net benefits to changes in the valuation of life. If a statistical human life is valued at $5 million or less, inaction is found to be optimal according to conventional measures of economic efficiency, since any reallocation of resources to develop a water distribution system represents a net loss in the general welfare of the community when measured in those terms.

Distribution Cost. The possibility has been raised that a municipal water system could be developed at a lower cost to the town than the estimated $2.4 million (plus $1.0 million granted by the state), for example by scaling down the proposed system. Since the primary cost of developing a water distribution system is in water main installation, the cost of either action Al (municipal system) or action A4 (hookup) would be reduced if such a scaled down plan were found to be feasible.

Table 3 indicates that expected net benefits are relatively sensitive to the cost of developing a municipal water system. If the cost to Whately of developing the system is reduced from $2.4 million to $1.7 or $1.5 million, then action A4 (hookup) remains the optimal (least negative) action. However, if the cost of the system turns out to be $1.3 million, development of the municipal water system becomes optimal. Action Al (development of the municipal system) is the least attractive option at a price of $2.4 million and the second best alternative at $1.5 million. At $1.3 million it becomes the optimal action, with an expected net benefit of —$0.4 million, and A4 falls to second best.

These results indicate that projected distribution costs are crucial in determining the optimal groundwater supply alternative. Efforts to develop more precise cost estimates would therefore improve the analytic capability of such models.

Number of Prospective Customers. Based on recent experiences in nearby communities, the Engineering Study predicted an increase in population growth following development of a water distribution system. In order to simulate the impact of increased population density in Whately, the number of households to be connected to the proposed system has been doubled and then tripled. It is assumed that the only additional cost of increasing the number of prospective consumers is the $1,000 hookup fee to extend pipe from the main and do necessary plumbing alterations. Operation and maintenance costs are also increased proportionately.

Table 3 shows these results. If the number of households connected to the system is increased from 233 to 466, action Al (development of the municipal system) becomes the optimal water supply alternative. Action A4 (hookup to neighboring towns) is then second best. Similar results are obtained when the number of prospective consumers is tripled. In this case, however, the economic advantage in developing a municipal system over hooking up to existing supplies in other towns is much stronger.

Although they suggest the nature of potential benefits from additional consumers, these two cases are not definitive measures of an expanded distribution system. In order to evaluate an expanded system, additional data would be required, since

Table 3. Sensitivity of Expected Present Value of Net Benefits to a Change in the Cost of Municipal Water System and the Number of Prospective Consumers*

		Expected Presnet Value Of Net Benefits of First Period Action ($ thousands)			
		A!	A_2	A_3	A_4
Cost of System To Whatlev** ($\$10^6$)	2.4	-1,412	- 1,237	-1,343	- 1,223
	1.7	- 879	- 850	- 968	- 809
	1.5	- 721	- 735	- 851	- 686
	1.3	- 504	- 547	- 666	- 517
Number of Households	233	-1.412	- 1.237	-1.343	- 1.223
	466	- 1 ,076	- 1,161	-1,399	-1,132
	699	- 738	- 941	-1.308	- 1 ,037

***Other parameters at baseline** values
****The total cost** of developing **a public water distribution system was reduced by one million** dollars, **the size** of **the grant** received **by** the **town** of Whately.

for example the network of water pipe for an expanded system might vary significantly from estimates presented in the Engineering Study.

Conclusions

Results of the base case analysis reveal that if the median estimate is used from the existing literature on the value of a statistical human life ($600,000), then any action to alleviate groundwater contamination in Whately represents a net social loss. Based on this definition of economic efficiency, the optimal action would be to suffer the risk of ill health from contaminated groundwater.

A number of considerations point to the desirability of taking action, however. Health effects from EDB alone were taken into account, since health effects due to other contaminants were largely unknown and hence unquantifiable. Even for EDB the use of a single point estimate to predict numbers of cancers is questionable, since quantitative risk assessment procedures are not considered reliable. Moreover, increased risks to certain groups within the community, notably children and those families whose wells have higher than average contamination, have not been taken into account. The community may also feel strongly averse to cancer risks, and expected net benefit analysis will not capture such effects.

Purchases of bottled water by town residents indicate a willingness to pay for health safety which is consistent with a much higher value per statistical life than the $600,000 used in the base case analysis. The economic comparisons among alternative actions must therefore be considered more meaningful than the comparisons between action and inaction.

Expected net benefits from the four water supply alternatives were seen to be relatively sensitive to changes in the discount rate. At or below eight percent, the use of interim actions such as bottled water and carbon-activated filters is not an efficient strategy.

Under most scenarios considered, the development of a municipal water system is economically inferior to hooking up to existing systems in order to purchase water from nearby towns. This situation reverses, however, if the number of prospective consumers increases substantially above the current number of households.

Development of an expanded water distribution system appears to be the most promising solution to groundwater contamination in Whately if the number of prospective consumers within the town is increased or if efforts can be coordinated with neighboring communities desiring centralized water systems. In this case economies of size are likely to yield project benefits which offset the estimated costs, and hence represent a net social gain to the community.

Because groundwater contamination is a relatively new phenomenon, the technology for rehabilitating aquifers is still emerging and the costs are extremely uncertain. Sequential decision analysis permits the incorporation of probabilities about future states of nature, including the cost and effectiveness of new technologies. Moreover the sequential framework allows for the reassessment of remaining choices over time as learning occurs. The ability to learn from experience and to benefit from new technologies is thus embodied in the decision calculus and ultimately in the optimal solution.

To be sure, not all uncertainties were dealt with in this application. More extensive sensitivity analysis could be accomplished and objectives beyond expected present values may be appropriate. The application neglects asymmetries and skewness of risk aversion. But it does go well beyond the usual "'cost effective" decision criterion that neglects a variety of monetary and non-monetary benefits and ignores the sequential possibilities for decision analysis. All results shown here were obtained on a very ordinary Kaypro II microcomputer. The primary point is that far from being an esoteric concept, sequential analysis is readily available to local decision makers.

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