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Option Prices for Groundwater Protection

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This paper reports results from a contingent valuation study of households' willingness-to-pay to prevent uncertain, future nitrate contamination of a potable supply of groundwater. The functional form of the corresponding logit model is derived from utility maximization theory. Probability of future demand, change in the probability of future supply, and an attitudinal score for interests in the well-being of future generations are significant, positive determinants of option prices. Several implications of these results for aquifer management policy are highlighted. © 1988 Academic Press, Inc.

I. INTRODUCTION

In 1983, Clifford Russell, then chairman of the President's subcommittee on economic research needs relevant to improved drinking water quality, asked the pointed question, "Do prospective benefits of this or that standard justify the anticipated costs of meeting it?" [19, p. 6]. His question emphasized the need to improve our "primitive knowledge" of the benefits of potable water in order to carry out efficiency analyses of public water quality policies. Although recent benefits estimates are now available, they tend to be partial and indirect, such as health benefits derived from dose–response relationships [21, 22] and current, certain-use benefits which are assumed a priori to be at least as great as the remedial costs of mitigating groundwater contamination [17, 18]. In contrast, this paper reports on direct estimates of the total economic value of potable water, including personal use and bequest values, under conditions of supply and demand uncertainty. Specifically, the contingent valuation method was used to collect data on option prices to protect a "sole source" aquifer from uncertain, future nitrate contamination.[2]

Recently, the U.S. Geological Survey emphasized their concern about potential nitrate contamination of aquifers throughout the United States [13]. Fertilizer and sewage from human and livestock populations are the principal sources of nitrate in groundwater. Although nitrate itself is relatively nontoxic, it is reduced by intestinal bacteria to nitrite, a hazardous substance. Nitrate concentrations in drinking water above EPA's health standard of 10 parts per million (ppm) can cause infant

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[2] EPA designates a "sole source" status to aquifers which supply regional populations with their only source of drinking water and meet other criteria.

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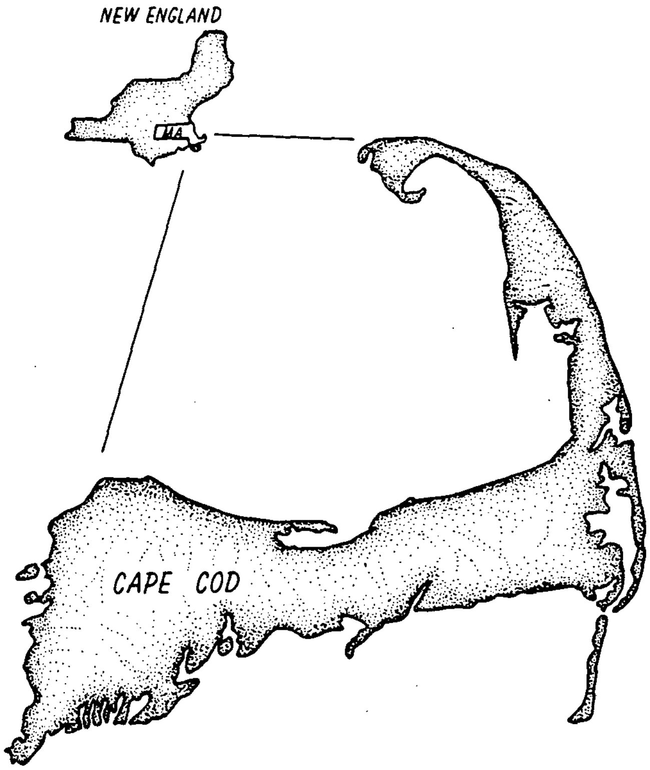

FIG. 1. Study site, Cape Cod, Massachusetts.

mortality (methemoglobinemia). In addition, long exposure to nitrate is a suspected cause of cancer.

The potential for nitrate contamination is of particular concern to coastal areas like Cape Cod, Massachusetts (Fig. 1), where the sewage of a rapidly growing population is disposed almost directly into the aquifer via septic tanks and shallow drain fields. On Cape Cod, nitrate levels are steadily increasing toward the 10 ppm health standard and will continue to increase with population size unless town and county governments alter land and water use patterns [16]. Indeed, these governments and the state recently initiated work on a regional aquifer management plan for the entire Cape, hoping to avoid problems already faced by other coastal regions such as Long Island, New York. Various options are being considered, including population growth control through down-zoning and land aquisition, sewage treatment, offshore disposal of treated sewage, on-site denitrification systems, and spray irrigation. And although the task force is only groping toward a cost assessment of specific management options it has even less knowledge of the public's total willingness-to-pay to prevent uncertain, future contamination of the aquifer.

Section II discusses and describes the contingent valuation survey which uses a binary choice format to elicit option prices from households. Section III both derives a logit model that is consistent with the binary choice format and utility maximizing choice under conditions of supply and demand uncertainties and presents results of the logit estimation. Concluding remarks are offered in Section IV.

II. SURVEY METHODOLOGY

The contingent valuation method was used to elicit a household's total maximum willingness-to-pay to prevent uncertain nitrate contamination of Cape Cod's sole source aquifer. Several years of study have established the contingent valuation method as a valid means of estimating use values of environmental resources when the contingent market is designed to control and test for various response biases [3] and when certain "reference operating conditions" are satisfied or nearly satisfied [5]. In addition, total valuations which include nonuse values such as "bequest value" cannot be ascertained from indirect methods that rely on revealed preferences. Thus, the contingent valuation method can also be one's only alternative for nonuse valuations. Finally, the contingent valuation method facilitates the collection of option price data for uncertain, future reductions in environmental resources and thereby provides an opportunity to test the effects of supply and demand uncertainties under somewhat controlled, experimental conditions. This opportunity is important because uncertainty about future contamination characterizes the nitrate problem in Cape Cod's aquifer and in many other aquifers throughout the country [13]. Also, option price is an appropriate measure of economic value for applied policy research on uncertainty [1, 4].

The contingent market section of the questionnaire consisted of several parts. First, households were asked to evaluate the importance to them of several types of benefits associated with potable groundwater. The list of benefits included wanting a cost-effective supply of water for personal use and protecting groundwater for use by future generations, but excluded direct health risks. The exclusion of health risks was appropriate in this case because the state and county systematically monitor nitrate levels in each of the public wells in order to prevent dangerous exposures to nitrate. This fact was made clear to households by stating that, "Health effects are not listed because water quality is being monitored to protect us from using contaminated water." Thus, whereas households were asked to value a potable, healthy water resource, health *risks* should not have been a consideration.[3]

Ten versions of the questionnaire posited disparate information just above the valuation question on the following factors: (a) the year of expected future contamination (5, 10, 20, and 40 years in the future); (b) the probability of nitrate contamination without a regional aquifer management plan given a 5-year time horizon (100, 75, 50, and 25%); (c) the probability of contamination with a management plan given a 5-year time horizon (0 and 25%); and (d) the price of bottled water.[4] Based on the particular time horizon received by respondents, they indicated the likelihood that they would be living on Cape Cod at the time of

[3] Of course, some households may have included the avoidance of health risks in their valuations, despite being instructed not to. In particular, the water quality of private wells is not monitored by governments, although households can have their water tested for free. (More than 2000 households on Cape Cod have had their water tested.) Still other respondents may question the reliability of the monitoring program. However, only 11% of the respondents have private wells. Furthermore, no one questioned the effectiveness of the monitoring program even though respondents were invited and given ample space to make additional comments on the last page of the questionnaire—space they used to voice other points of view. Although this evidence is admittedly circumstantial, it does not suggest that the valuation of health risks was prevalent.

[4] The price of bottled water was not a significant determinant of the probability of willingness-to-pay. Similarly, and as reported by Brookshire *et al.* [4] in regression results, the future year of expected impact was not a significant determinant either. These results are not reported in Section III.

expected contamination. Possible responses, which ranged from "yes, definitely (100 percent certain)" to "no, definitely not (0 percent chance)" with intervening answers clearly associated with 75, 50, and 25% probabilities, provided subjective information on demand uncertainty for personal use. The versions corresponding to factors (b) and (c) assigned supply uncertainties. Unfortunately, funding constraints prohibited a larger factorial design with additional information on the probability of contamination with management or on the costs of other mitigation policies. Consequently, other interesting issues concerning the effects of more detailed risk changes [23] and of mitigation costs on willingness-to-pay cannot be answered by this single study.

The valuation question was the binary choice type that Richard Bishop and his students introduced and refined (e.g., [2, 3]). This discrete, yes/no format appears to elicit more valid responses than open-ended requests or bidding games. Notably, preliminary evidence from Boyle and Bishop's [3] Wisconsin Sandhill study suggests that there is no significant difference between valuations collected from a hypothetical market using binary choice questions and from actual cash transactions. Accordingly, the contingent market in this nitrate study contained suggested annual payments to prevent future contamination that ranged from $10 to $2000. These suggested payments and their distribution were based on open-ended statements of willingness-to-pay collected from a pilot study of 200 households. Following the valuation question, respondents explained why they possibly skipped the valuation, including reasons for protests.

The pilot study also allowed testing for the potential effects of different vehicles on willingness-to-pay. Three separate questionnaires described a bond (i.e., public referendum) vehicle, a contribution vehicle, and higher water bills, while a fourth version asked for willingness-to-pay without describing a vehicle. χ^2 analyses of the number of respondents ($\chi^2 = 0.67$ with 3 degrees of freedom) and of the number of protests to the payment vehicle by respondents ($\chi^2 = 4.33$ with 3 degrees of freedom) did not reject the null hypotheses of no effects. As a result, the bond vehicle was selected as the payment mechanism in order to satisfy "reference operating conditions" [5]. Although households are familiar with the market-like experience of paying water bills, Cape Codders also have substantial experience in voting on (or choosing not to vote on) bond issues for environmental protection. This experience augments familiarity with the water resource with issues surrounding groundwater quality has discussed at length and frequently by the news media.

The design and implementation of the survey followed Dilman's [7] "total design method" for mail questionnaires, including the use of three follow-ups. One thousand households were selected at random from the telephone book using interval sampling with a random start. In turn, the households were assigned at random to the 10 versions. The telephone book was the most representative sampling frame for the target population of renters and resident and nonresident property owners. However, it was necessary to telephone each household in order to verify mailing addresses.

Seventy-eight and one-half percent of the sample returned a questionnaire, of which 585 respondents (i.e., 58.5% of the sample) provided sufficient information for analysis. The remaining respondents skipped questions pertaining to income, demand probability, attitudes, and/or valuation. Of those refusing to answer the valuation question, only 43 households (4.3% of the sample) protested the method of payment while others' reasons included needing more information before answering the question (91 respondents) and refusing to place a monetary value on groundwater (36 respondents).

III. OPTION PRICE ANALYSIS

Theoretical Model

Subsequent to Bishop *et al.*'s [2] initial work, logit models have been used increasingly to analyze binary responses to contingent valuation questions, although there is some disagreement as to how to specify the particular functional form of the model [2, 12, 20]. This study adopted Hanemann's [12] axiomatic approach whereby the logit model was derived from a utility maximizing model of household choice. Accordingly, suppose that an individual derives personal utility from a Hicksian commodity (X), water use (W), and knowledge that groundwater will remain potable for use by future generations (G) such that

$$U = b_1 \cdot \ln X + c_1 \cdot \ln W + d_1 \cdot G. \tag{1}$$

The parameters b, c, and d are functions of the individual's attitudes. To represent concern about the well-being of future generations, $G = 0$ when nitrate concentration exceeds EPA's health limit of 10 ppm, and $G = 1$ when potability is maintained for future generations.[5] The budget constraint corresponding to this utility model is

$$M = X + P \cdot W, \tag{2}$$

where X is a numeraire good and P is the relative price of water.

The bequest argument, G, is treated as a pure public good and, therefore, is not a choice variable for the individual. Hence, maximization of Eq. (1) with respect to X and W and subject to constraint (2) yields the following indirect utility function[6]:

$$V = U[M, P, G] = a_1 + b_2 \cdot \ln M + c_2 \cdot \ln P + d_1 \cdot G. \tag{3}$$

Since Hanemann [12] already explicated a practical, utility-theoretic procedure for specifying the functional form of a logit model and for deriving corresponding money measures for welfare, the presentation in this paper will be brief. The probability that an individual is willing to pay \$$A$ to protect groundwater quality corresponds to

$$\Pr = [1 + 1/\exp(\Delta V)]^{-1}, \tag{4}$$

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[5] Similar to Hanemann's [12] representation of hunting as a binary variable, this utility model uses the simplifying assumption that the bequest good either exists ($G = 1$) or does not ($G = 0$). However, it is conceivable that G could have different levels. For example, G could be indexed to nitrate concentrations in the aquifer. Nevertheless, the measurement of bequest goods is in a formative stage of development and is not explored further in this paper.

[6] The derivations for equations in this section are available from the author.

where

$$\Delta V = V[M - A, P_L, 1] - V[M, P_H, 0], \tag{5a}$$

P_L is the current, low price of muncipal water, and P_H is the higher price of drinking water when the aquifer is contaminated (e.g., bottled water). An equivalent variation measure of welfare corresponding to ΔV can then be derived by setting Eq. (5a) equal to zero and solving for A. Using Eq. (3),

$$\Delta V = b_2 \cdot \ln(1 - A/M) + c_2 \cdot \ln(P_L/P_H) + d_1 = 0 \tag{5b}$$

and equivalent variation corresponds to

$$\mathrm{EV} = M\left[1 - (P_L/P_H)^{-c_2/b_2} \cdot \exp(-d_1/b_2)\right]. \tag{6}$$

Next consider the effects of supply and demand uncertainties on the functional form of the logit model and on the equation for equivalent variation. First consider the four cases of supply uncertainty already developed by Freeman [10] and extended by Plummer [15] and assume for now that household demands for groundwater are certain.[7] Without an aquifer management plan, the probability that groundwater will not be contaminated with nitrate (i.e., that groundwater will be supplied at its present low cost) is $0 \leqslant q_2 \leqslant 1$ and expected utility is

$$E_N = (1 - q_2) \cdot V[M, P_H, 0] + q_2 \cdot V[M, P_L, 1], \tag{7a}$$

where $(1 - q_2)$ is the probability that groundwater becomes contaminated. However, with a regional aquifer management plan the probability of supply increases to $r_2 > q_2$ and the expected value of utility becomes

$$E_0 = (1 - r_2) \cdot V[M - \mathrm{OP}, P_H, 0] + r_2 \cdot V[M - \mathrm{OP}, P_L, 1], \tag{7b}$$

where OP is option price, or the constant amount that a household would be willing to pay annually for a particular management strategy, and $(1 - r_2)$ is the probability that groundwater becomes contaminated even with an aquifer management program for protection.[8]

Next introduce demand uncertainty but only for personal use value. Assume that income and prices between states of the world are known with certainty but that preferences are state-dependent. Recalling that the indirect utility function is separable in M, P, and G,

$$\begin{aligned} E_N = {} & (1 - p_2) \cdot V[M, P_L] \\ & + p_2 \cdot [(1 - q_2) \cdot V[M, P_H] + q_2 \cdot V[M, P_L]] \\ & + (1 - q_2) \cdot V[0] + q_2 \cdot V[1] \end{aligned} \tag{8a}$$

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[7] The probability that contamination will be detected is a further consideration [18]. As mentioned in Section II, however, the state monitors nitrate concentrations in the aquifer closely. Thus, it is assumed that the probability of detection is equal to 1.

[8] Gallagher and Smith [11] also studied the effect of supply uncertainty on the valuation of environmental resources. However, unlike in their study, this study adopts Freeman's [10] and Plummer's [15] assumption of no contingent claims markets.

and

$$\begin{aligned} E_0 = {} & (1 - p_2) \cdot V[M - \mathrm{OP}, P_\mathrm{L}] \\ & + p_2 \cdot [(1 - r_2) \cdot V[M - \mathrm{OP}, P_\mathrm{H}] + r_2 \cdot V[M - \mathrm{OP}, P_\mathrm{L}]] \\ & + (1 - r_2) \cdot V[0] + r_2 \cdot V[1], \end{aligned} \tag{8b}$$

where the probability of future demand is $0 \leqslant p_2 \leqslant 1$ and $(1 - p_2)$ is the probablity that demand will be zero.[9] Applying these results to Eq. (3) yields

$$\Delta V = E_0 - E_N = b_2 \cdot \ln(1 - \mathrm{OP}/M) + c_3 \cdot p_2 \cdot (r_2 - q_2) + d_1 \cdot (r_2 - q_2), \tag{9a}$$

where $c_3 = 2 \cdot c_2 \cdot \ln(P_\mathrm{L}/P_\mathrm{H})$, and $\ln(P_\mathrm{L}/P_\mathrm{H})$ are assumed to be constant for all individuals in the region.

In order to assess the effects of attitudes about groundwater protection on the probability of payment by different individuals, Eq. (9a) was modified such that

$$\Delta V = b_2 \cdot \ln(1 - \mathrm{OP}/M) + c_4 \cdot L \cdot p_2 \cdot (r_2 - q_2) + d_2 \cdot B \cdot (r_2 - q_2), \tag{9b}$$

where $c_3 = c_4 \cdot L$ and $d_1 = d_2 \cdot B$. L and B are one-dimensional Likert scales for attitudes about the importance of protecting groundwater as a cost-effective source of water for drinking and cooking (L) and the importance of bequesting clean groundwater for use by future generations (B). Although more complex scoring is possible, integer scores from 1 to 5 are generally adequate to discriminate levels of attitudes [14]. In this study, the values for L and B increase from 1 for "not important" to 5 for "very important."[10] Finally, option price can be derived by transposing Eq. (9b) for OP:

$$\mathrm{OP} = M \cdot \left(1 - 1/\exp[(r_2 - q_2) \cdot (c_4 \cdot L \cdot p_2 + d_2 \cdot B)/b_2]\right). \tag{10}$$

Results

Table I shows results from the maximum likelihood estimation of the logit model corresponding to specification (9b).[11] The coefficients have the expected sign and are statistically significant. The first regressor is the combined effect of income and the cost of groundwater protection on net benefits. The second regressor represents

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[9] The probability of future demand (p_2) and the probability that groundwater will not become contaminated with nitrate are arguably interdependent. For example, the decision to continue living on Cape Cod could be affected by whether groundwater remains potable. This complicating possibility is not treated here.

[10] Strictly speaking, the Likert scales are ordinal. Nevertheless, Likert scales have been tested by social scientists in related fields and are believed to adequately represent the strength of attitudes and beliefs [12]. Possible nonlinearities introduced by these scales were not tested due to the axiomatic way that the logit model was derived.

[11] As explained in Section II, it was not possible to vary the probability of groundwater contamination with management beyond $r_2 = 1$ and $r_2 = 0.75$. However, a model with Eq. (9b)'s specification plus a dummy variable for versions with $r_2 = 0.75$ was estimated. The results show that option price decreases when $r_2 = 0.75$, although the effect was not statistically significant. See Smith and Desvousges [23] for a broader empirical analysis of uncertainty.

TABLE I

Logit Analysis of Groundwater Protection[a]

Regressor	Coefficient	t ratio
(1) Income effect		
$\ln(1 - A/M)$	112.82	8.16[b]
(2) Bequest effect		
$(r_2 - q_2) \cdot B$	0.514	8.08[b]
(3) Personal use effect		
$p_2 \cdot (r_2 - q_2) \cdot L$	0.224	2.24[c]
$n = 585$		
$\chi^2 = 444.58$[b]		

[a] Logit model is for the probability of paying the stated amount, $\$A$. See Section III for the derivation of the model specification (Theoretical Model) and interpretation of regressors (Results).

[b] Significant at the 0.001 level of confidence.

[c] Significant at the 0.025 level of confidence.

TABLE II

Descriptive Statistics of Variables Used to Estimate Logit Model

Variable	Mean	Minimum	Maximum	Standard deviation
Income, M	55,413	7000	750,000	75,893
Scale for cost-effective supply, L	3.7	1	5	1.21
Probability of future demand, p_2	0.7	0	1	0.31
Bequest scale, B	4.6	1	5	0.59
$\ln(1 - OP/M)$	−0.009	−0.138	−0.00008	0.015
$p_2 \cdot L \cdot (r_2 - q_2)$	2.09	0	5	1.384
$B \cdot (r_2 - q_2)$	3.85	0.75	5	1.278

concern for future generations (B) weighted by the increase in the probability of future groundwater supply ($r_2 - q_2$). Finally, the third regressor represents personal interest in minimizing the cost of potable water (L) weighted by both the increase in probability of future supply ($r_2 - q_2$) and the probability of future demand (p_2). The data used to estimate the logit model are described in Table II.

Unlike in other studies of natural resource benefits where income was either an insignificant regressor in the logit model [2] or its coefficient had an unexpected sign [6], income had a strong and positive effect on the probability of paying for groundwater protection in this study.[12] For this particular functional structure,

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[12] In a separate, linear model where income, the suggested payment, uncertainties, and attitudes were specified additively, the coefficient on income was positive, significant, and robust. The coefficient on the suggested payment was negative and also significant and robust. However, the additive model predicts implausibly that option price is greater than zero when the probability of future demand is zero ($p_2 = 0$) *and* the increase in the probability of future supply is zero ($r_2 - q_2 = 0$). Thus, in addition to the possible advantage of deriving utility-theoretic measures of surplus, Hanemann's [12] recommended procedure for contingent valuation experiments with binary response questions avoids this counterintuitive result.

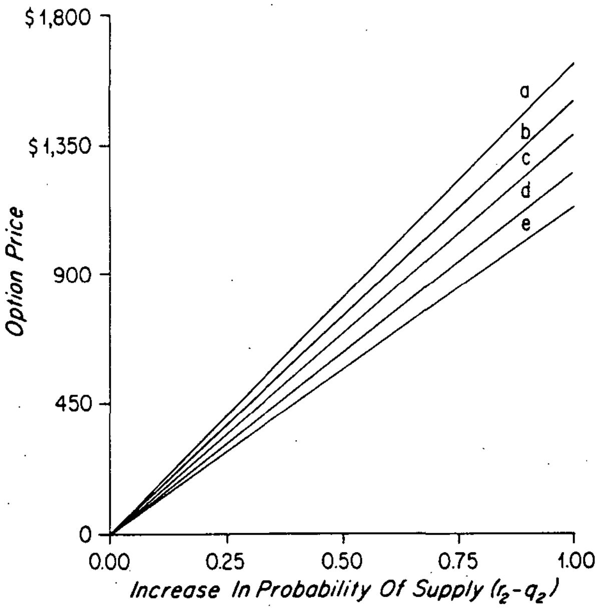

FIG. 2. Option prices for groundwater protection. Probability of future demand (p_2) is (a) 1, (b) 0.75, (c) 0.50, (d) 0.25, and (e) 0.00.

option price is predicted to increase linearly with income. The percentage increase ranges from 0% of income when either groundwater will remain potable without management (i.e., $q_2 = 1$) or there is no increase in the probability of supply to about 3.5% of income when the aquifer management plan will avert certain contamination ($r_2 - q_2 = 1$) for an individual with certain future use ($p_2 = 1$) and with attitudinal scales at their highest values.

The effects of the demand and supply uncertainties and of the bequest motivation on estimates of option price are illustrated in Figs. 2 and 3 for a hypothetical household with average respondent traits described in Table II. Each curve in Fig. 2 shows the strong effect of a net increase in the probability of supply on option price. In these examples, option price ranges from $0 when a management plan does not increase the probability of supply to $1623 when the probability of supply is increased from 0.0 to 1.0. These curves also illustrate how option price declines when the probability of future demand for groundwater on Cape Cod decreases. This decrease applies to households who are uncertain about how long they will live on Cape Cod and, therefore, possibly use groundwater from the aquifer. For example, a reduction in the probability of demand (p_2) from 1.0 (curve a) to 0.5 (curve c) is predicted to reduce option price by about 15%, ceteris paribus.

Also of special interest is the relative influence of the bequest attitude on option price. The change in the probability of future supply is held constant along each curve in Fig. 3. Along a single curve, option prices predicted by model (10) almost triple as the bequest scale increases from the value 1 ("not important") to the value 5 ("very important"). The influence of the bequest attitude on option price also increases as the change in the probability of supply increases. For example, the range in option prices along curve d in Fig. 3 where the increase in the probability of future supply is only 0.25 is \$248 whereas the range in option prices along curve a where the increase in the probability of future supply is 1.0 is \$975.

Even households with a zero probability of future demand for groundwater on Cape Cod have positive option prices. This benefit is attributable exclusively to the bequest motivation. Curve e in Fig. 2 illustrates one example for a household with average respondent traits. As described by Eq. (10) for option price, curves a, b, c, and d comprise bequest value that is traced by curve e, plus the combined effect of wanting a cost-effective supply of water and of the probability of future demand (i.e., $c_4 \cdot p_2 \cdot L$). Based on this comparison alone, 70% (curve a) to 90% (curve d) of total option price is attributable to bequest value, the remainder being due to personal use values. Of course, these percentages would change for different values of the attitudinal scales.

Figure 2 reveals another interesting and possibly surprising result concerning the components of option prices for groundwater protection. Although probably not apparent to the reader's naked eye, the curves in Fig. 2 are slightly concave with respect to the $(r_2 - q_2)$ axis. This relationship suggests that option values are positive. That is, option price is by definition the sum of the expected value of consumer surplus and option value. Graphically, the expected value of consumer surplus increases linearly from \$0 to its maximum where the increase in the probability of future supply $(r_2 - q_2)$ is equal to 1 (i.e., where the probabilities of future supply both with and without the management plan are not uncertain). Thus, the slightly concave option price curves that lie above the lines for the expected value of consumer surplus suggest positive but very small option values. In relative terms, option values associated with Fig. 2 are 1% or less of option price depending on the increase in the probability of supply.[13]

As mentioned previously, the aquifer management plan for Cape Cod is in its formative stages. Unfortunately, the county government has not contracted a cost analysis of possible management options, nor have the probabilities of nitrate contamination for recharge areas surrounding public wells (q_2) been determined by hydrogeologists. Consequently, it is impossible at this time to estimate the efficiency of aquifer management for Cape Cod. Nevertheless, the range of possible aggregate benefits is of interest. Two cases should come close to bounding the range of possible values. In Case I, nonrespondents to the survey (21.5% of the sample) are assumed to place zero value on the potability of the aquifer. In contrast, nonrespondents are assumed to have preferences similar to respondents in Case II.[14] In both cases, the average values of traits characterizing the respondents are used to describe those who value potable groundwater.

The present value of aggregate benefits per 1000 households is reported in Table III. The projections, which correspond to a 30-year time series of option prices

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[13] For comparison, option values derived from an identically specified probit model

$$\begin{array}{lll} \Pr\{\text{individual willing to pay}\} & = & 61.31 \cdot \ln(1 - A/M) \\ (t \text{ statistic}) & & (9.16) \\ & & + \underset{(8.89)}{0.299} \cdot (r_2 - q_2) \cdot B + \underset{(2.30)}{0.121} \cdot p_2 \cdot (r_2 - q_2) \cdot L \end{array}$$

were larger than those derived from logit but still less than 2% of option price.

[14] These assumptions ignore possible nonrespondent and selection biases [8]. The calculations only serve as likely bounds for aggregate benefits.

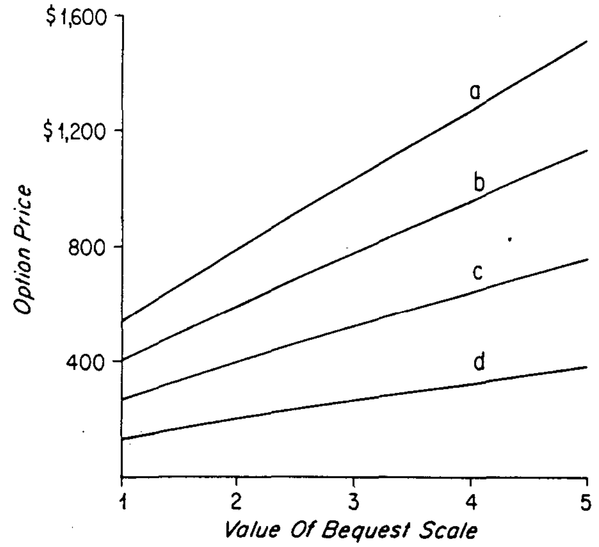

FIG. 3. Option prices for groundwater protection. Values for the increase in probability of supply ($r_2 - q_2$) are (a) 1, (b) 0.75, (c) 0.5, and (d) 0.25.

TABLE III

Present Value of Aggregate Benefits per 1000 Households[a]

Increase in probability of supply ($r_2 - q_2$)	Case I: Nonrespondents do not value the aquifer ($ million)	Case II: Nonrespondents and respondents are identical ($ million)
(1.00 − 0.75) = 0.25	4.93	6.28
(1.00 − 0.50) = 0.50	9.81	12.50
(1.00 − 0.25) = 0.75	14.67	18.69
(1.00 − 0.00) = 1.00	19.51	24.85

[a] Present value = n OP$[1 - (1 + 0.04)^{-30}]/0.04$ where n = 1000 households; OP is option price for the representative household, 0.04 is the discount rate, and 30 years is the time horizon.

discounted at 4%, increase from nearly $5 million under Case I when the probability of supply increases by only 0.25 from $q_2 = 0.75$ to $r_2 = 1.0$ to nearly $25 million under Case II when the probability of supply increases from 0.0 to 1.0 with a management plan.

IV. CONCLUDING REMARKS

This paper tested for the effects of demand and supply uncertainties and the strength of a bequest attitude on household willingness-to-pay to protect groundwater quality from uncertain, future nitrate contamination. These results complement recent cost analyses of aquifer contamination [17, 18] with estimates of option prices and provide insights into option and bequests values associated with potable groundwater. A logical extension to this research would be to explore the effects of other factors on willingness-to-pay which vary depending on the pollutant and environmental conditions. These factors include toxicity of the pollutant, the probability that contamination is detected, health risks, and the costs of options to mitigate groundwater contamination.

Several implications of these results are worth emphasizing in the context of efficient aquifer management. First, the sensitivity of option prices to a change in the probability of supply indicates that in at least this case the benefits of an aquifer management project should not be calculated from only certain changes in the availability of the resource [i.e., $(r_2 - q_2) = 1.0$]. Planners and resource managers who work only with certain, worse case scenarios are likely to substantially overestimate the benefits of averting uncertain, future contamination. As illustrated by Figs. 2 and 3, the probability of supply without management (q_2) and, therefore, the increase in the probability of supply have a strong effect on option price. Emotional arguments for groundwater protection which ignore this effect could promote gross misallocations of public monies for groundwater protection.

A second, surprising result is the small size of option value relative to option price (1–2% or less). In contrast, water quality studies summarized by Fisher and Raucher [9] report nontrivial option values—often greater than 50% of option price. Naturally, the comparison is imperfect because of differences in methods and in resource values (recreation versus potable groundwater). Without more studies for comparison it is impossible to discern the empirical effects of methods and the effects of irreversibility and the availability of close substitutes. Nevertheless, the small size of option value in this study suggests that the benefits of aquifer management can be measured nearly completely as the increase in the expected value of benefits. This result, if accurate, simplifies benefit measurement to eliciting the total value of certain changes in the availability of the resource ($r_2 - q_2 = 1$) and multiplying this value by the actual net increase in the probability of supply (i.e., the net reduction in the probability of contamination).

A third interesting result is the strong influence of bequest motives on total willingness-to-pay. Equity issues not withstanding, individuals appear to be willing to pay substantial amounts of money annually to protect groundwater for use by future generations. Therefore, this benefit category cannot be ignored when evaluating the efficiency of a groundwater management policy, including a decision whether to avert contamination or wait until contamination is realized. Economists' recent interest in explaining and ascertaining bequest value [3] should be extended to groundwater issues soon.

Finally, these results further illustrate that benefit–cost analysis of groundwater problems are inherently site specific. In addition to the effect of hydrogeologic setting on the probability of contaminating an aquifer and its combined effect with various planning and engineering alternatives for groundwater management on the effectiveness of protection, frequency distributions of socioeconomic factors related to income levels, the probability of future demand, and attitudes about bequests are likely to vary from site to site. Furthermore, the bequest motive will be irrelevant when groundwater contamination is reversible and future generations do not incur any mitigation costs. Each of these effects on option price—including factors affecting the increase in the probability of supply—should be evaluated separately for homogeneous units.

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