Valuing Water Supply Reliability

Ronald C. Griffin and James W. Mjelde

Instead of creating water supply systems that fully insulate mankind from climate-imposed water deficiencies, it is possible that for municipal water systems a nonzero probability of water supply shortfall is efficient. Perfect water supply reliability, meaning no chance of future shortfall, is not optimal when water development costs are high. Designing an efficient strategy requires an assessment of consumer preferences pertaining to the reliability of water supply. Contingent valuations of both current and future shortfalls are reported. The consistency of these measures is gauged using an expected utility model.

Key words: reliability, water demand, water policy.

An important dimension of the water scarcity problem is the management of water supply risk, especially as it relates to drought. The traditional management practice for controlling urban water supply risk has been one of avoidance, that is, to develop a sufficiently large water supply that the probability of any tangible shortfall is very small. In light of the high and growing costs of water development, it may be sensible to revise the water planning paradigm, so that periodic shortfalls are regarded as acceptable, even planned, events.

In the municipal water use sector, there is an innate tendency to size the water supply system for severe droughts of low probability (Howe and Smith). Water is usually supplied by an entity that faces no competition and has the legal ability to pass all reasonable costs to consumers. Moreover, water supply systems are operated by people whose performance is gauged by their ability to deliver a dependable, steady, and problem-free water supply. They are not judged by their ability to deliver water that has value in excess of its costs. Consequently, the reliability[1] of water systems may be too high, water supplies dedicated to municipal use may be too great, and infrastructure costs may be too large.

Given that available water is physically limited in many regions, when municipalities increase water system reliability, they are shifting risk to nonmunicipal sectors. Obviously, some water users must incur the shortfall during drought situations. Traditionally, risk has been progressively shifted to the riparian and estuary habitat systems. These natural resource systems have become the residual claimants, possessing only what is left after man has diverted water to satisfy his wants. Recently, public policy emphasis on streamflow protection has begun to reverse this tradition (MacDonnell and Rice). One result may be the redistribution of water supply risk back toward municipalities, thereby increasing the importance of risk-attentive water supply planning.

Three dimensions of reliability analysis are addressed here. First, policy options and consumer behavior relevant to water system reliability are discussed. Second, the theory of optimizing water system reliability is briefly restated and refined. This basic theory outlines a method for optimizing reliability and identifies informational needs. Finally and primarily, contingent valuation analyses of modified reliability are presented.

Reliability Policy and Consumer Behavior

To affect water system reliability, managers can (*a*) adjust the long-run supply of water, (*b*) enhance the short-run supply of water during a shortfall event, (*c*) influence the long-run demand for water by consumers, and (*d*) lessen water demand during a shortfall. Rather than being viewed as substitute approaches, the appropriate planning goal is to develop an efficient package of all options.

The authors are professors in the Department of Agricultural Economics at Texas A&M University.

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[1] The reliability of a water supply system is commonly regarded as inversely related to the probability of a system shortfall (demand > supply).

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On the supply side, both physical and paper components of a water supply can be adjusted. While the physical components are generally well acknowledged, various paper components (such as water rights, storage permits, contracts with other water suppliers, and dry-year options) represent an increasingly important dimension of planning tools. Either physical or paper components can be modified to adjust long-run water supply reliability, but these supply-side tools are limited for short-run water supply adjustments. Only rapidly executable leases with water right holders or contracts with other water suppliers are practical short-run tools.

Demand management tools have substantial relevance as both long- and short-term measures. Long-run policy options include regulations (e.g., plumbing codes requiring the installation of water-conserving fixtures), education programs, and water pricing. Short-run demand tools involve contingency policies such as water use regulations (e.g., alternate day watering), prohibitions, and pricing. Because of the relative impracticality of most supply policies during shortfall events, demand-based options have enhanced relevance in the short run.

In response to both long-run and short-run policies, consumers make decisions that are broader than merely how much water to consume. Households choose additions to and replacements of their water-using durables. The major durables of consequence are plumbing fixtures, appliances, pools, sprinklers, and lawn/landscaping. These durables are available in different sizes, models, and properties that influence water use and the ability of consumers to continue using durables during water supply shortfalls. Water use associated with a given durable is largely a fixed multiple of its operating time, so important determinants of household water use become less flexible when the household commits to the purchase/installation of each water-using durable. Long-run demand management policies influence these commitments (Dubin, Wirl).

Lawns and landscape plants are unique with respect to their interrelationship with water supply reliability. Lawns and landscaping are durables established for visual and aesthetic satisfaction. This satisfaction flows to residents continually, rising or falling according to the condition of the lawn/landscape. Long water supply shortfalls can depreciate or extinguish lawns and landscaping, thereby lowering their future net benefits. This implies that there may be instances in which consumers attach high value to avoiding a severe, yet transitory shortfall, because they wish to avoid diminished present and future net benefits.

These simple observations disclose important interrelationships among water supply reliability, the value of reliability, water-using durables, and the value of these durables. When making commitments to specific durables, the consumer is implicitly mindful of water price and supply policy. Consumers likely form expectations of future price and reliability based on recent experience and, perhaps, trends. Once a set of durables is acquired by the household, prospective increases in reliability offer little short-run value because the durable base is fixed. On the other hand, decreased reliability constrains the satisfaction available from the accumulated durable base. Thus, consumers have asymmetric attitudes toward increases and decreases in reliability. The change in value for an increase in reliability can be expected to be less, in absolute value, than the change in value for an equivalently measured reliability fall. This asymmetry is likely to be more pronounced in the short run where, by definition, the durable base is fixed. For this reason, as well as the wealth effect, it should be expected that equivalent surplus exceeds compensating surplus for reliability improvements.

Optimizing Reliability

Although interest in water supply reliability is increasing (Lund), there are few empirical studies of the value households associate with the reliability of their water supply. Using a mailed survey in three Colorado cities, Howe et al. asked open-ended willingness-to-pay (WTP) and willingness-to-accept (WTA) questions about modifications to the frequency of a standard annual shortage event (SASE). They define a SASE to be a supply shortfall sufficient to cause the temporary use of a specific lawn watering restriction. An advantage of this approach is that the SASE offers a very tangible and known situation for the surveyed population.

Barakat & Chamberlin, Inc. report a WTP analysis of increased reliability performed for ten California water utilities. This contingent valuation study uses a combination mail–telephone survey to obtain double-bounded dichotomous choice data. Households are asked if they would pay a specified amount per month to eliminate future shortfalls of a specified strength and frequency. Because the elimination of shortfalls is not a realistic planning scenario, the Barakat & Chamberlin, Inc. findings should be interpreted as upper bounds for consumer valuations pertaining to modified shortfall scenarios.

Howe and Smith et al. present some basic theory outlining the optimal selection of water supply level. A noteworthy observation about their theory, which distinguishes it from leading theory regarding optimal energy supply reliability, is that it sets aside the potential role of price in managing excess demand during shortfall events (Crew and Kleindorfer 1976, 1978, Marino, Meyer). The energy research on optimal reliability addresses the collaborative role of pricing and investment for achieving an optimal policy. The absence of price control in the Howe and Smith et al. theory can be criticized, but water managers remain far more concerned about appropriate concrete and pipe solutions than they are about establishing proper prices. Moreover, for stochastic settings, resource allocation by price may be economically inferior to quantity-based policy such as rationing rules (Weitzman).

A theoretical model offered by Howe and Smith et al. focuses on the concept of SASE. This model posits that the probability of occurrence for the SASE in period t is a decreasing function of supply-side investment I:

$$(1)\quad \text{Prob}\{\text{SASE}_t\} = P_t(I).$$

The objective is to determine a level of investment that minimizes investment costs plus the expected losses caused by the occurrence of the SASE. Let $A(I)$ denote annualized investment costs and let $E[L(P_t)]$ be the expected loss due to excess demand in period t. The expected value of L is an increasing function of $P_t(I)$. The optimization problem is then

$$(2)\quad \min_I [A(I) + E[L(P_t(I))]].$$

This problem yields the first order condition

$$(3)\quad \frac{dA}{dI} = -\frac{dE[L]}{dI}$$

indicating that the marginal cost of investment should equal the negative of the marginal expected losses. Howe and Smith et al. do not optimize I, but they do compare changes in A and in $E[L]$ where the changes are accomplished by sales or purchases of surface water rights.

A deficiency of this theory is its emphasis of a single type of shortage, the SASE (Lund). Nothing is conveyed about the selection of water supply capacity for addressing more moderate or extreme shortage events. Because supply investments alter the frequencies of all degrees of shortage, not just the SASE, this omission is important. To obtain a more broadly applicable theory (also initiated by Howe and Smith et al.), suppose that aggregate water demand D is an increasing function of some short-term climate index which we will call aridity "a." Water supply S is a decreasing function of aridity and an increasing function of investment I. Water price is assumed to be fixed.

When demand exceeds supply for a given aridity level in period t, the loss suffered is $\ell_t(D_t - S_t)$. Otherwise, the loss is zero. The overall loss function can be stated as

$$(4)\quad L_t(I, a_t) = \begin{cases} 0 & \text{if } D_t(a_t) \le S_t(I, a_t) \\ \ell_t\big(D_t(a_t) - S_t(I, a_t)\big) & \\ & \text{if } D_t(a_t) > S_t(I, a_t). \end{cases}$$

If f_t is the probability distribution function for the random variable a_t, then expected losses are

$$(5)\quad E[L_t(I, a_t)] = \int_{a_t^0}^{\infty} L_t(I, a_t) f_t(a_t)\, da_t$$

where a_t^0 is the level of aridity for which $D_t(a_t) = S_t(I, a_t)$.

Assuming the social problem is to minimize the sum of investment costs and the expected welfare loss due to water supply shortfall, the following criterion for investment choice is obtained:

$$(6)\quad \min_I \left[I + \sum_t \int_{a_t^0}^{\infty} L_t(I, a_t) f_t(a_t)\, da_t \right].$$

Discounting may be added explicitly to this model or it may be viewed as implicit in the definition of L_t. After differentiating the objective function with respect to I and simplifying, the first order condition becomes

$$(7)\quad 1 = \sum_t \int_{a_t^0}^{\infty} \ell_t'(\cdots) \frac{\partial S_t}{\partial I} f_t(a_t)\, da_t.$$

The left hand side of this condition is the marginal cost of investment. The right hand side is investment's marginal benefit.

This basic theory has four informational requirements that must be met prior to application. First, an aridity index must be constructed for which a probability distribution function can be determined and which can be used as an argument of demand and supply functions. Second and third, $D(a)$ and $S(I, a)$ are needed. Finally, the function giving the value of loss due to shortfall, $\ell_t(D_t - S_t)$, must be obtained. The latter requirement is the focus of the research reported here.

Survey Design and Procedures

Two lines of inquiry are pursued here using contingent valuation methods. First, the value of current water supply shortfalls—existing shortages of known strength and duration—is addressed. Second, an inquiry into the value of future shortfalls is presented. The latter are probabilistic shortages of differing frequency, strength, and duration.

A questionnaire was mailed to 4,856 households in seven Texas cities.[2] For two of the seven surveyed cities, there were a priori indications of experience with water supply shortfalls. There may be some bias in reliability valuation if assessments are sought solely from shortfall-inexperienced households. Experienced households may attach lower values to reliability for three general reasons. First, inexperience with water supply shortfalls may support an artificially high, physiological objection to an unfamiliar event. Once this unknown is removed, the consumer may have a "that wasn't so bad" reaction. Second, the learning of new water use behaviors is likely to be pronounced during shortfalls. As the consumer becomes more proficient with coping strategies, the value of shortfall-created inconveniences may decline. Third, as discussed previously, if households are accustomed to a highly dependable water supply, they are more likely to have assembled a water-intensive set of water-using durables.

Each questionnaire includes two contingent valuation questions. Paired with each of these questions is a question designed to ferret out protest responses. The first contingent valuation question is a closed-ended WTP question concerning a hypothetical current shortfall. This question establishes an "immediate and known" water supply shortfall of $X\%$ of the community's water demand expected to have a duration of Y summer days. The respondent is then asked if he/she would pay a one-time fee of $\$Z$ to be exempt from the outdoor water use restrictions the city would impose during this shortfall. Thirty-six different X-Y-Z combinations are used, and a logit model is fitted with the resulting data.

The second contingent valuation question is an open-ended WTP or WTA question concerning a hypothetical increase or decrease in future water supply reliability. This question poses an initial situation in which approximately once every U years a shortfall of $V\%$ would occur with a duration of W days. The question then poses a potential improvement or decline in one of the U or V parameters with the other being unchanged. Shortfall duration W varies among questionnaires, but it is constant in a given questionnaire. In the case of reliability improvements, the respondent is asked for a maximum WTP where this amount is expressed as a permanent increase in monthly water bills. In the case of reliability declines, the respondent is asked for a similarly expressed minimum WTA. Thirty-six distinct before and after regimes (U-V-W combinations) are used. Thus, there are thirty-six WTP questions and, by reversing the before and after components, thirty-six WTA questions. Each survey contains only one of these seventy-two variants. Respondents therefore answer either a WTP or WTA question concerning future shortfalls, but not both. Resulting data are used to estimate two tobit models, one for WTP and one for WTA.

Because there are thirty-six different constructions for the current shortfall question and seventy-two different constructions for the future shortfall questions, each of the current shortfall question variants are employed with two of the future shortfall question's scenarios. These assignments were made randomly.

The future shortfall question is more definitive in that it incorporates frequency information regarding prospective supply shortfalls, and it involves both WTP and WTA formats. However, it also presents a more perplexing proposition to respondents,

[2] Each mailing included a preaddressed and postage-paid return envelope. After two weeks, nonrespondents were mailed a reminder postcard. After three to four additional weeks, individualized surveys were again prepared for nonrespondents and were mailed with a new cover letter and a return envelope.

and there is justifiable concern that this question might overwhelm people. In the health risk valuation literature, it has been observed that probabilistic risk information is difficult to communicate to respondents and that many people may have difficulty processing this information (Loomis and duVair, Smith and Desvousges). The survey's current shortfall question poses a simpler, more comprehensible, and less challenging query for surveyed households. Inclusion of two general question styles offers the possibility of checking the consistency of survey results with expected utility theory.

A WTA version of the current shortfall question is not investigated because of the reduced information provided by close-ended questions (thereby necessitating larger datasets to achieve a given level of explanatory power). Moreover, the normative, status quo foundation of the reliability issue is closer to one where consumers do not possess entitlements to particular reliability positions.

Because water supply reliability is an unusual item for individuals to value, it is important to provide households with a solid informational context. Therefore, the individual questionnaire relayed summary information about the household's own water use patterns and bills. Because water supply shortfalls generally occur during summer months, the survey also includes information regarding the cyclical nature of the household's water use. To accomplish this, monthly 1995 information from city utilities was obtained for every household in the survey sample, and these data were used to calculate personalized information provided on each survey. The calculated information could have been electronically merged into the survey instrument prior to printing, but hand writing of this information into surveys was selected to emphasize the customized nature of the entries.[3] On the questionnaire the customized personal information is preceded and followed by additional contextual information regarding the importance and meaning of water supply reliability. The contextual information is replicated in the Appendix of this paper.

Overall, 30% of the survey recipients had responded prior to remailing of the survey. The overall survey response is 43%. Across the seven cities, the response rate varies from a low of 32% to a high of 45.8%. These percentages include all surveys returned with at least one question answered. Respondent and nonrespondent water use characteristics are similar, and none of the differences in the water use characteristics are statistically significant.

WTP to Avoid a Current Shortfall

A representative sample of the thirty-six editions of the current shortfall WTP question is as follows:

> Suppose that a community in which you live is facing an immediate and known shortfall of 10% that is expected to last for the next 14 *summer* days. This means that water supply is 10% less than demand. To correct this shortfall, the community is planning to restrict outdoor water use until the problem has passed. The Survey Residence can get a one-time exception from these water-use restrictions if you pay a one-time fee of $10.00.

Would you pay this one-time fee for this one-time exemption at the Survey Residence?

☐ Yes ☐ No ☐ Don't Know

Over all thirty-six scenarios, 437 respondents indicated they would be willing to pay the fee, whereas 1,595 indicated they would not be willing to pay the additional fee or did not know. Of these 1,595 respondents, 171 constituted nonprotest bids. Nonprotest bids are defined to be those meeting one of the following criteria: (*a*) any respondent answering yes to this question, or (*b*) any respondent answering no or don't know to the question *and* indicating the fee was too high to justify the payment in the subsequent protest filtering question. More than one-fourth of the 1,595 selected "Don't Know." The large number of protest bids appears to be partly a consequence of the good being valued. Some respondents indicated in hand-written notes something to the effect that "water

[3] The personalized information includes: total 1995 water use (gallons), peak water use month, water use in peak month (gallons), water and wastewater bill for peak month ($), low water use month, water use in low month (gallons), water and wastewater bill for low month ($), total bill for 1995 water use ($), total bill for 1995 wastewater service ($), and average monthly water and wastewater bill ($).

is a god-given right and should not be valued economically." Such public perspectives often confound water policy research because "access to water is regarded as a moral right, and discriminating among claimants to water on the basis of wealth or position is in many places regarded as immoral" (Martin et al., p. 28).

Current Shortfall Model

Because of the structure of the current shortfall question, the following logistic model is estimated using maximum likelihood techniques:

$$(8)\quad F[\beta'\mathbf{x}] = \frac{e^{\beta'\mathbf{x}}}{1 + e^{\beta'\mathbf{x}}}$$

where $F[\beta'\mathbf{x}]$ is the cumulative density function associated with the logistic function, $\mathbf{x}$ is a matrix of explanatory variables, and β is a vector of associated coefficients to be estimated (Judge et al., p. 591). Explanatory variables are:

- rain — mean annual rainfall by city (National Climatic Data Center),
- summer — mean July plus August rainfall divided by the mean annual rainfall for each city,
- price — respondent's total annual water bill divided by total water use,
- fee — fee the respondent must pay to avoid the water use restrictions,
- shortfall — percent shortfall the respondent's community is facing,
- duration — number of days the shortfall will last,
- income — income level of the respondent (five categorical levels correspond to the categories on the survey; the first level is dropped to avoid a singular matrix),
- activities — respondent's preferences toward water use activities[4] (this variable is the sum of a linear index of the importance attached by the respondent to lawn and landscaping, fruit and vegetable gardening, and car washing),
- people — total number of people living at the residence,
- rent — 0/1 dummy variable with a 1 indicating the respondent rents the survey residence from another person or business,
- live — 0/1 dummy variable with a 1 indicating the respondent lives at the survey residence, and
- experience — 0/1 dummy variable with a 1 indicating the respondent has experienced water use restrictions in the past five years.

Surveys from all cities are combined into a single dataset for estimation purposes. City-by-city examinations of the data are available in an expanded report (Griffin and Mjelde). Estimation of the logit model with dummy variables for each city indicated no statistical differences in the probabilities of paying the fee between respondents in different cities. Further, simple correlation coefficients and auxiliary regression equations indicate multicollinearity is not a problem in the dataset.

Estimated coefficients for the logit model are presented in table 1. A chi-squared value of 161 is obtained for the statistical test that

Table 1. Current Shortfall Value Logit Model Coefficients, 508 Observations

Variable	Estimated Coefficient	Standard Error	p-value
Intercept	−2.12	2.36	0.37
Summer	5.99	7.34	0.41
Rain	0.0325	0.0382	0.39
Price	−0.132	0.0594	0.03
Fee	−0.104	0.0135	< 0.01
Shortfall	0.0221	0.0168	0.19
Duration	0.0358	0.0237	0.13
Inc2	0.997	0.325	< 0.01
Inc3	1.81	0.347	< 0.01
Inc4	1.80	0.443	< 0.01
Inc5	2.80	0.567	< 0.01
Activities	0.0126	0.0494	0.80
People	−0.0626	0.0679	0.36
Rent	0.201	0.408	0.62
Live	1.07	0.729	0.14
Experience	0.255	0.323	0.43

[4] Instead of asking respondents for an inventory of their water-using durables, they were asked to select one of five levels of "importance" for each of three water activity categories. This preference-based approach avoids the impracticality of obtaining water consumption features of individual durables (e.g., area, condition, species of grass lawns), but it does not enable a testing of the role of durables in determining reliability values.

all coefficients are equal to zero. For this level, the null hypothesis is rejected at a p-value < 0.01, indicating the variables help to explain the probability of choosing to pay the fee to avoid water use restrictions. As the fee increases, respondents are less likely to pay to avoid the restrictions. Respondents are more likely to pay to avoid the restrictions as the duration and/or strength increases. All three coefficients associated with these variables are significant at p-values of 0.20 or less with fee being significant at the 0.01 level. As the respondent's average water price increases, the respondent is less likely to pay to avoid the restrictions. The coefficient associated with water price is significant at the 0.03 level.

Of the variables associated with the respondent's individual characteristics, income is highly significant with respondents in higher income categories generally more likely to pay the fee than respondents with lower incomes. The one exception to this observation is that the fourth income category's estimated coefficient is slightly less than the third income category's coefficient. Respondents who live at the survey residences are more likely to pay the fee than respondent landlords who do not live at the residence. The remaining variables are insignificant at the 0.20 level of significance.

Current Shortfall Valuation

The typical approach to obtaining valuations from such models is to determine the fee amount corresponding to a Prob[Yes] = 0.5, that is, the fee level that the average respondent would find agreeable (Hanemann). Here, this fee level is the value the average household is willing to pay to avoid a current shortfall. Using mean levels of exogenous variables, a low income household would be willing to pay a one-time fee of $17.19 to avoid a current shortfall, and a high income household would be willing to pay $44.04. If shortfall parameters are varied across the questionnaire scenarios and income is varied across the five groupings, the predicted WTPs range from $12.99 to $48.88.

WTPs to avoid current shortfalls of various strengths and durations are presented in table 2. All other variables, including income class binary variables, are set at their means in the calculation of these values. As indicated earlier, WTP to avoid current water supply shortfalls increases with the anticipated strength and duration of the shortfall. For the average respondent, $29.86 is the avoidance value for a three-week current shortfall of 20%. Changes in shortfall parameters affect this value as follows. A one-week increase (decrease) in shortfall duration increases (decreases) this value by $2.41. Every 10% increase (decrease) in shortfall strength increases (decreases) this value by $2.12.

Table 2. Current Shortfall Values (WTP)

		Shortfall Duration		
		14 days	21 days	28 days
	10%	$25.34	$27.75	$30.15
Shortfall	20%	$27.46	$29.86	$32.27
strength	30%	$29.58	$31.98	$34.39

WTP/WTA to Modify Future Reliability

An example of the thirty-six future shortfall WTP questions is as follows:

Current: For your community, suppose that water demand will exceed supply once every 10 years. This shortfall will have an average length of 14 days. Typically, water restrictions will be used in the years of shortfall to decrease demand 20% as needed to manage this shortfall.

Future: Suppose that your community is considering an expansion of its water supply system to improve reliability. Subsequently, water demand will exceed supply once every 15 years. This shortfall will have an average length of 14 days. Typically, water restrictions will be used in times of shortfall to decrease demand 20% as needed to manage this shortfall.

To Summarize:	*Current*	*Future*	
Shortfall Frequency is once every	*10*	*15*	years.
Shortfall Length will average	*14*	*14*	days.
Shortfall Amount is	*20*	*20*	% of the city's demand.

Please consider the next questions carefully.

What is the largest increase in your average water bill of $ ___ per month that you would be willing to pay each and every month to obtain this reliability improvement at the Survey Residence?

$___ per month

The first blank was precompleted with the respondent's average monthly water bill, so the respondent only needed to state WTP. Bids of \$0 for this question may be protests. A nonprotest \$0 bid is defined here as one in which the respondent either (*a*) checked "the reliability improvement wouldn't help me much" in the accompanying protest filter question or (*b*) did not provide any responses to the protest filter.

Households receiving a future shortfall WTA survey encountered a boxed summary nearly identical to that above followed by this question:

What reduction in your average water bill of \$___ per month is the minimum you would be willing to accept each and every month in exchange for this reliability reduction at the Survey Residence?

\$___ per month

Nonprotest bids are defined to be those who selected the following response to the paired protest filtering question: "My answer is about right for the added inconvenience."

Future Shortfall Estimation Procedures

Both the WTP and WTA open-ended questions result in a censored sample; that is "... some observations on the dependent variable corresponding to known sets of independent variables are not observed" (Judge et al., p. 609). In the WTP and WTA samples, the observable range of WTP and WTA range from zero to the highest bid. In such cases, ordinary least squares estimators are biased and inconsistent (Judge et al., p. 615). Consequently, tobit analysis is used here.

The underlying tobit model for this study is

$$(9)\quad y_i^* = \beta'\mathbf{x}_i + \varepsilon_i$$

where $\mathbf{x}_i$ are the independent variables for observation i, y_i is the dependent variable, β's are coefficients to be estimated, and ε_i is an error term. Also, $\varepsilon_i \sim N[0, \sigma^2]$; if $y_i^* \leq 0$, then $y_i = 0$; and if $y_i^* > 0$, then, $y_i = \beta'\mathbf{x}_i + \varepsilon_i$. This model is estimated using maximum likelihood techniques (Greene). Conditional means (prediction) from the tobit model are

$$(10)\quad E[y|\mathbf{x}_i] = \Phi(\hat{\beta}'\mathbf{x}_i/\hat{\sigma})\hat{\beta}'\mathbf{x}_i + \hat{\sigma}\phi(\hat{\beta}'\mathbf{x}_i/\hat{\sigma})$$

where Φ represents the cumulative standard normal distribution function, ϕ represents the standard normal density function, $\hat{\sigma}$ is the estimated standard error for the error term, and $\hat{\beta}$ is the vector of estimated coefficients.

Independent variables used in the estimation procedure for both the WTP and WTA models are the same. These variables are defined equivalently to those used in the current shortfall logit model previously presented with the exception of new variables defining water reliability. The two new variables are:

- severity — the initial severity of the water shortfall, defined as probability of shortfall occurring in any given year times shortfall strength, and
- shortype — a binary variable which equals zero if the proposed change affects the probability of a shortfall occurring and equals one if the proposed change affects shortfall strength.

By design, the number of usable responses for the WTP and WTA questions will be less than the value of current shortfall question. Four hundred and sixty-six usable observations are available for estimation of the WTP model, whereas 240 observations are usable from the WTA surveys. The difference between WTP and WTA usable responses may pertain to two factors. First, water is better understood as a good for which one pays rather than as a good for which one might receive a payment. The unfamiliar WTA perspective may have caused some confusion. Second, the wording of the WTA question is more confusing than the WTP question. A large number of respondents checked "I don't understand the question" in the protest filter.

Of the 466 usable responses in the WTP data set, 21.4% (100/466) of the respondents indicated a monthly WTP equal to zero. Using dollar intervals of 0.01–1, 1–5, 5–10, 10–15, and 15 +, the percent of responses in each interval are 1.7%, 22.1%, 21.7%, 17.8%, and 15.2%. The WTA sample is less censored, with only 5.4% (13/240) of the respondents indicating a WTA equal to zero. Also, 0%, 12.9%, 25.4%, 23.8%, and 32.5% of the respondents lie in the dollar intervals 0.01–1, 1–5, 5–10, 10–15, and 15+.

WTP for Reliability Enhancements

Presented in table 3 are the estimated coefficients and statistics for the WTP model.

Table 3. Future Shortfall Value Tobit Model Coefficients

	WTP Model 466 Observations		WTA Model 240 Observations	
Variable	Estimated Coefficient	p-value	Estimated Coefficient	p-value
Intercept	47.8	0.00	27.3	0.08
Summer	−42.5	0.32	5.97	0.90
Rain	−0.751	< 0.01	−0.643	0.01
Price	−0.113	0.78	−1.09	0.09
Severity	−0.527	0.23	−0.178	0.83
Shortype	0.618	0.67	2.18	0.13
Duration	−0.0711	0.57	0.0222	0.86
Inc2	5.03	0.01	−2.50	0.22
Inc3	3.70	0.10	−4.79	0.02
Inc4	4.17	0.11	−2.76	0.34
Inc5	8.45	< 0.01	0.207	0.94
People	1.22	0.05	0.716	0.19
Activities	−0.104	0.73	0.946	< 0.01
Rent	2.23	0.37	−0.684	0.78
Live	−8.28	0.03	3.08	0.49
Experience	−6.18	< 0.01	−0.882	0.65
σ	14.7		10.8	

The Wald chi-squared test that all coefficients are jointly significantly different from zero is rejected at a p-value below 0.01. The water reliability variables are all insignificant at p-values less than 0.23. Insignificance of the severity variable suggests that consumer valuations are unaffected by dimensions of the initially posed shortfall. The insignificance of the shortype variable indicates respondents did not value improvements in shortfall frequency or shortfall strength differently. These results corroborate the "threshold" nature of valuations suggested by Barakat & Chamberlin, Inc.:

> ... respondents regard even a mild shortage scenario as an inconvenience that they want to avoid. They may make a greater distinction between "shortage" and "no shortage" than between different sizes or frequencies of shortages (p. 15).

Individual income levels are significant at p-values of 0.11 or less. Respondents in income categories two through five (inc2–inc5) are willing to pay more for reliability increases than respondents in income category one (inc1—the base which is omitted from the model). Rain is significant at the 0.01 level with respondents in cities with higher rainfall willing to pay less than respondents in drier cities.

In contrast to the value of a current shortfall, individual characteristics appear to help explain WTP bid levels. Live, experience, and people are highly significant. As the number of people living at a residence increases, the respondent is willing to pay more for the reliability enhancement. Respondents who have experienced water shortfalls in the last five years are on average willing to pay less for the reliability increase than those who have not experienced a shortfall. The signs associated with the live variable are different than prior expectations. It was expected that respondents who do not live at the survey residence would be willing to pay less than respondents who do. One possible explanation for this discrepancy is that the variables are not picking up the desired impact. By far the majority of respondents live at and own the survey residence. In the usable dataset only sixteen observations fall into the "don't live at the residence" category; mean WTP for these sixteen is \$14.56, whereas the mean WTP for the remaining observations is \$8.25. Remaining variables are insignificant at p-values below 0.20.

WTA for Reliability Declines

Also presented in table 3 are the estimated coefficients and standard errors from the WTA estimation. The Wald chi-squared test that all coefficients are jointly equal to zero is rejected. The magnitudes, signs, and significance of the estimated coefficients differ between the WTA and WTP models. As in the WTP model, rain's impact is negative and significant at the 0.01 level. Summer and rent are insignificant in both the WTP and WTA models. In contrast to the WTP model, both water price and water activities are significant in the WTA model. The signs and significance of the income categories change, weakening results relative to the WTP model. Similarly, variables for experience and live are insignificant in the WTA model.

As with the WTP model, the coefficients associated with initial severity and duration are insignificant. The coefficient associated with shortype is, however, significant at a p-value of 0.13. The coefficient implies that mean WTA is approximately $2.00 higher for an increase in shortfall strength than an increase in shortfall frequency.

Future Shortfall Valuations

WTP and WTA measures can be obtained as means from survey responses, or they can be calculated as means of the in-sample predicted values from the tobit models using the conditional means equation presented earlier. Both methods are employed here. Presented in table 4 are summary statistics associated with the monthly WTP and WTA measures. Mean data WTP is $8.47, whereas the predicted WTP is $9.76. These WTP measures constitute 22.2% and 25.6% of the respondents' mean monthly water bills. These values compare with means of $11.63 to $16.92 (depending on initial shortfall frequency) reported by Barakat & Chamberlin, Inc. for the complete elimination of future Californian shortfalls. Consistent with earlier discussion regarding consumer behavior, both the predicted and data mean WTA are larger than the WTP mean values. Mean WTA is $12.66 and $13.20 for the raw data and predicted values, respectively. These mean WTAs are 32.4% and 33.8% of mean monthly water bills.

Consistency of Results

A useful inquiry pertains to whether obtained future shortfall valuations are consistent with the current shortfall valuations reported earlier. That is, are consumer valuations of modified shortfall probabilities compatible with the values they assign to avoiding current shortfalls?

The future shortfall WTP question asks respondents to state a payment p to accompany a lowered shortfall frequency such that the new state would be viewed indifferently to the initial state. Adopting the expected utility model, this means that initial expected utility must equal subsequent expected utility. Therefore,

$$(11) \quad b \cdot U(y - v) + (1 - b) \cdot U(y) = c \cdot U(y - v - p) + (1 - c) \cdot U(y - p)$$

where b is initial shortfall probability, c is subsequent shortfall probability, $U()$ is the utility function, y is income, and v is the value of a known (current) shortfall. This equality implicitly relates future shortfall value p to current shortfall value v.

The utility function is assumed to be locally given by the constant absolute risk aversion form $U(w) = n - me^{-rw}$, where n, m, and r are constant preference parameters. With this assumption, an explicit function can be obtained for p:

$$(12) \quad p = \frac{1}{r} \ln \left[\frac{be^{rv} + 1 - b}{ce^{rv} + 1 - c} \right]$$

where r is the Arrow–Pratt risk aversion coefficient. For demonstrative purposes, we employ two coefficients, $r = 0.01$ and $r = 0.05$. Both of these values lie at the high end

Table 4. Summary Statistics on Willingness-to-Pay and Willingness-to-Accept Using Individual Observations ($/Month).

	Data				Predicted			
	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
WTP	8.47	12.90	0.00	100.00	9.76	2.90	2.77	28.41
WTA	12.66	11.12	0.00	60.00	13.20	3.53	2.20	24.19

of empirically estimated ranges—indicative of a high degree of risk aversion (Raskin and Cochran). For before and after shortfall probabilities, we use the two scenarios posed in the WTP versions of the survey: $\langle b = 1/10, c = 1/5\rangle$ and $\langle b = 1/5, c = 1/10\rangle$.

Table 5 contains the results of calculating future shortfall values based on current shortfall values and the above methodology. For example, a household willing to pay \$30 to avoid a current shortfall and having a risk aversion coefficient of 0.05 should be willing to pay a one-time fee of \$1.80 to support a project that alters shortfall frequency from 1/10 to 1/15. The same household should be willing to pay \$4.59 for a project that alters shortfall frequency from 1/5 to 1/10. Our respondents provided average indications of being willing to pay larger amounts than these each and every month. Consequently, the future shortfall values reported here appear inconsistent with the reported current shortfall values.

One is inclined to look to the future shortfall valuation work for the source of the discrepancy because (*a*) the context of the current shortfall valuation offers a firm and well understood platform for respondents, (*b*) this platform is not confused by the added dimension of frequencies or probabilities, and (*c*) the resulting logit model performs well. Several potential reasons for the incompatible current and future shortfall valuations can be hypothesized. First, respondents may not have understood the future shortfall query well. Even though only one parameter was altered, we may have parameterized shortfalls beyond common comprehension. Second, using frequency to convey probabilistic information may be a bad idea because of scaling problems. When shortfall frequency is altered from one out of ten years to one out of fifteen, the change in probability is quite minor (0.033). In retrospect, we wonder whether respondents could grasp the smallness of this change. Third, perhaps respondents place some value on the convenience or social fairness of regular payments to achieve high system reliability as opposed to one-time payments to sidestep temporary shortfall policies. These hypotheses may be useful suggestions for the conduct of future research in this arena.

Conclusions

If economists are to contribute policy advice concerning water system reliability, we must establish and refine a guiding theory, understand the behavior and reactions of managers and consumers, and investigate the values associated with probabilistic shortfalls. The research reported here builds upon prior contributions in each of these areas.

The theoretical development offers modest improvements and questions the use of a "standardized shortage event" in theoretical or applied research. Given the range of potential water shortfalls, in terms of probability, strength, and duration, it is important to examine empirical options for obtaining shortfall values as a function of shortfall parameters. Such pursuits promise to be a challenging departure from the valuation of a standardized shortfall.

Whereas prior research has acknowledged the attitudes of water managers toward system shortfall, important features of consumer behavior have not been examined. When consumers are considered, it becomes evident that their accumulated bundles of water-using durables influence their actions as well as the values they assign to shortfalls. There is noteworthy feedback here too. The potential for shortfalls affects the selection of durables

Table 5. Consistent Future Shortfall Values (p).

	Δ Frequency: $b \to c \equiv \frac{1}{10} \to \frac{1}{15}$		Δ Frequency: $b \to c \equiv \frac{1}{5} \to \frac{1}{10}$	
Current Value (v)	$r = 0.01$	$r = 0.05$	$r = 0.01$	$r = 0.05$
\$10	\$0.35	\$0.41	\$1.04	\$1.18
\$20	\$0.72	\$1.00	\$2.14	\$2.74
\$30	\$1.14	\$1.80	\$3.32	\$4.59
\$40	\$1.57	\$2.78	\$4.58	\$6.58
\$50	\$2.05	\$3.87	\$5.91	\$8.48

by consumers. Another crucial observation is that durable fixity in the short run gives rise to asymmetric values for reliability improvements and reliability declines.

When contingent valuation methods are employed to assess consumer losses due to shortfall, the contingent valuation analysis can address either the value of avoiding a current shortfall or the value of changing the character of probabilistically defined future shortfalls. The probabilistic information necessary for future shortfall surveys confounds respondents and reduces data quantity and quality. A demonstrated option is to employ expected utility theory in conjunction with assessments of current shortfalls to calculate implied future shortfall values. This alternative eliminates the need to convey probabilistic information to respondents but requires additional assumptions regarding consumer risk preferences. Moreover, current shortfall values can be directly used to specify the loss function, $l_t(D_t - S_t)$, needed to ascertain optimal water supply. Given these findings, future research should concentrate on refining the value of current shortfalls rather than pursuing contingent valuation of probabilistically specified future shortfalls.

Even in the absence of probabilistically defined contingent valuation scenarios, there are pitfalls for the nonmarket valuation of shortfall losses. Two such pitfalls can be encountered in other arenas, but they are certainly pronounced for water issues. These are the "birthright" perspective and consumers' lack of personal consumption information. With respect to birthright, water is popularly thought of as a public good to which people have some inalienable entitlement. Many see water bills as a tax rather than as an invoice for the on-demand delivery of treated, pressurized tap water. Consequently, there is a strong tendency for respondents to protest proposed WTP scenarios. Overcoming this pitfall appears extremely difficult at this time, but some redress may be achieved through very carefully worded survey prefaces. The analyst's burden is high here.

With respect to the second pitfall, most households are not aware of their actual water use or their water bills. Not only is water a low budget share item for most households, thus failing to motivate much attention, but water bills are lumped into utility bills that may include electricity, natural gas, and solid waste components. This lack of consumer information also raises the burden for survey instruments. Our instrument's inclusion of consumer-specific data is a novel approach worthy of use, and perhaps testing, by future research.

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Appendix: Background Information

The questionnaire's introduction included contextual information highlighting four key points:

- A temporary water supply shortfall is when water supply is less than water demand. During a temporary water supply shortfall, households usually experience a drop in water pressure, NOT the loss of all water.
- A water pressure drop causes water to flow more slowly through pipes. Sinks and bathtubs take longer to fill. Water-using appliances such as washing machines take longer to operate. Outdoor sprinklers operate more slowly, and the sprinklers will not spray as far.
- Usually, water supply shortfalls occur during the summer months. Average Texas households use 40% less water in December/January than in July/August.
- During a shortfall, your community may employ voluntary or mandatory outdoor water use restrictions (such as restrictions on lawn watering or car washing) to reduce use.

After the customized household data, the questionnaire includes two short paragraphs containing basic details about why shortages tend to occur during the summer and about the important tradeoffs this creates.

> In Texas, water use and water supply change seasonally. Water demand is highest during the summer because of outdoor uses like lawn watering. This is also the season when water supply may be the lowest.
>
> Texas water utilities have traditionally designed their water supply systems to reliably provide peak summertime needs. The full capacity of these systems may be utilized only a few days a year. A portion of water supply systems costs and the rates you pay are therefore for capacity which is used only part of the year. On the other hand, this service capacity also offers Texas communities some insurance against short-term droughts and unexpected water system failures.