Valuing Water Supply Reliability with Sensitivity Analysis

Steven Buck* Mehdi Nemati†

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Abstract

The purpose of this paper is to calculate the expected reliability benefits of alternative water supplies that are less vulnerable to disruption than the current composition of supplies, especially those regions which rely on imported surface water. Expected reliability benefits are measured using estimates of welfare losses under various levels of supply disruption, the probability of each level disruption, and on consumption forecasts over the life of proposed alternative supplies. To consider uncertainty in reliability benefits, we run sensitivity analyses to value reliability under different discount rates, the elasticities of demand, water supply disruption levels, and corresponding probability distributions of disruption.

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*University of Kentucky, email: steven.buck@uky.edu

†University of Kentucky, email: mehdi.nemati@uky.edu

1 Introduction

California's water system is vulnerable to supply fluctuations. Natural variation in precipitation and runoff leads to changes in water supply that pose challenges to urban water purveyors who seek to meet target levels of demand. In recent years, environmental protections for endangered fish and aquatic habitats have increasingly impinged on the ability of water managers to reliably divert water towards urban uses. A prime example is the pumping restrictions placed on diversions from the southern Delta to the California Aqueduct to protect the delta smelt under the "Wanger decision" in December, 2010. Yet, despite these challenges to urban water supplies, urban water demand in many parts of the California continues to grow, and is projected to do so for decades to come.

Taken together, the natural variation in water supply coupled with continued and often unabated growth in water demand highlight the importance of understanding the value that results from investments in reliable water supplies. In this paper ratepayer welfare losses in the Municipal and Industrial (M&I) sector are measured under different magnitude reductions in annual water supplies in Southern California. The goal of the research is to measure the losses that will actually occur in California under various levels of shortage and combine this information on the likelihood of shortage to estimate expected welfare losses under existing infrastructure and supplies. Calculation of the ratepayer welfare losses in the M&I sector during a water supply shortage requires information on (i) end-user demands for water and (ii) the financial structure of municipal water purveyors.

(i) End-user water demands are estimated to calculate the additional premium that end-users in the M&I sector are willing to pay above the prevailing water rate for water units displaced during a shortage. The demand estimates, are refined to the local retailer level in Southern California and build upon the methods for estimating end-user demand employed by Renwick and Green (2000). Other studies measuring the value of water supply reliability have employed contingent valuation methods (Griffin, 2000; Howe, 1994), which rely on self-reported valuations as opposed to valuations based on actual market transactions. The results presented in this paper are based on the market prices for water and consumption levels reported in water utility administrative records. In this respect, the analysis has the advantage of being based on actual valuations of water units by end-users as opposed to stated preferences or the results of hypothetical scenarios. Information on end-user demands enables the calculation of lost consumer surplus experienced by ratepayers during a shortage relative to baseline consumption.

(ii) The financial structure of a water utility (public or private) is that of a natural monopoly, which is characterized by high fixed costs and approximately constant marginal costs that are small. Further, for investor-owned, publicly regulated water utilities, most are regulated under a profit or net revenue (revenue minus the marginal costs of service delivery) constraint that limits their ability to set water prices. As a result, for both public and investor-owned water utilities, a substantial share-often the largest share-of end-user water rates are set to recover fixed costs via average cost pricing rather than marginal cost pricing. Fixed costs, which are sunk in advance of a water supply disruption, must be paid despite the fact that the net revenues associated with shorted units of water are lost and, thus, unavailable for fixed costs recovery. Due to the net revenue constraint, ratepayers bear the burden of lost net revenues in the form of higher rates.

Ratepayer welfare losses under a given level of shortage are equivalent to the sum of lost consumer surplus and lost net revenues. This paper estimates these ratepayer welfare losses over the likely range of shortage levels and combines them with information about the likelihood of such shortages occurring. One of the main contributions of this paper is a translation of the resulting probabilistic ratepayer welfare losses into a reliability premium representing the amount of money ratepayers would be willing to pay to fully mitigate the adverse effects of future shortages.

2 Economic Framework

We measure welfare losses in the residential sector using a measure of ratepayers' Willingness-To-Pay (WTP) to avoid water supply disruption, which is similar to other recent works

(Brozović et al., 2007; Buck et al., 2016, 2015). Notably, among water utilities in California, and the United States more broadly, volumetric water rates reflect both variable and fixed costs. Often the fixed cost component of price is considerable; thus, the consumer surplus triangle can be a gross underestimate of losses experienced by ratepayers. (Buck et al., 2015) provide evidence of average cost pricing among public water utilities in California. Consistent with this, we measure ratepayer welfare losses as the area under the demand curve and above the marginal costs curve. We assume a constant elasticity of demand and estimate the single family residential water demand elasticities using the following equation:

$$P = AQ^{1/(\epsilon)} \tag{1}$$

where, A is a constant and ϵ is the elasticity of water demand. We denote price and quantity of water consumption by households, before the supply disruption as P^* and Q^*, respectively. Assuming water supply disruption at time t is given by $Q(r_t) < Q^*$ we can define a water supply disruption with:

$$Q_(r_t) = (1 - r_t)Q^* \tag{2}$$

Using equations Equation 1 and Equation 2, we can estimate consumer willingness to pay to avoid a supply disruption r_t by integrating under the isoelastic demand curve between baseline consumption Q^* and consumption under the disruption $Q(r_t)$. This is demonstrated with the equalities below:

$$W(r_t) = \int_{Q(r_t)}^{Q^*} P(Q)dQ = \int_{Q(r_t)}^{Q^*} AQ^{1/\epsilon_i}dQ = \epsilon/(1+\epsilon)P^*Q^*[1 - (1-r_t)^{1+\epsilon/\epsilon}] \tag{3}$$

Note that an urban water utility's total cost of service is the sum of fixed cost (e.g., infrastructure costs, repair, and maintenance, administrative expenses, etc.) and variable cost (e.g., energy and chemical costs of treating water); the latter depends on the amount of water delivered to the customers. Disruptions reduce variable costs simply because the urban water utilities supply $Q(r_t) < Q^*$. The measure of WTP to avoid a disruption indicated in Equation 3 does not account for the avoided costs of service delivery when there is a supply disruption, therefore, Equation 3 is not a correct measure of welfare losses.

Assuming the marginal cost of service delivery is C, Equation 3 becomes as follows:

$$W(r_t) = \epsilon/(1+\epsilon)P^*Q^*[1-(1-r_t)^{1+\epsilon)/\epsilon}] - \int_{Q(r_t)}^{Q^*} C(x)dx \tag{4}$$

Assuming a flat marginal rate curve, we can re-write the welfare loss function as follows:

$$W(r_t) = \epsilon/(1+\epsilon)P^*Q^*[1-(1-r)^{((1+\epsilon)/\epsilon)}] - r_tQ^*C \tag{5}$$

Based on Equation 5, the welfare loss resulting from a supply disruption is a function of initial water price prior to the supply disruption at time t, the variable cost of service, and the elasticity of demand.

Using Equation 5 we can calculate welfare conditional on a given supply disruption in a given year. However, for the value of reliability, we need to calculate net present value of welfare loss for the project lifetime. Project reliability benefits are assumed to be equal to expected present value ratepayer welfare loss due to supply disruption in water use. For this purpose, we can calculate welfare loss for each year and then calculate the present value of welfare loss. Also, note that supply disruption is not given for each year. Ratepayer welfare losses are calculated for multiple supply disruption scenarios. The probability of each reduction scenario was estimated, enabling reliability benefit for year t to be calculated as follows:

$$B_t = \int_{t=1}^{n} (W_r dr) \tag{6}$$

Where: B_t is the reliability benefit for year t, W_r is ratepayer welfare loss for supply disruption r. The annual benefits were discounted and summed over the project lifetime to give the net present reliability benefit for a project lifetime.

3 Baseline Assumptions for Reliability Benefits Calculation

In calculating reliability benefits of the residential water supply, several assumptions have been made. Limitations posed by these assumptions will be discussed later in the paper.

3.1 Project Lifetime

We assumed 35 years as a timespan in calculations of reliable water supply benefits (what are the benefits if we have a reliable water supply until 2050). 35 years is an average lifetime of a reliable urban water supply project. For example, lifespan for a typical seawater desalination project based on the project characteristics such as project size is between 20 to 30 years (Association et al., 2012; Dore, 2005).The lifespan of reuse water project is approximately 50 years (WHO, 2015; Estevez-Olea, 2015).

3.2 Discount Rate

The discount rate is another factor which can effect the present value of water supply reliability benefits. Discount and interest rates are commonly controversial in economic and financial analyses. Therefore, a sensitivity analysis using different discount rates is appropriate. United States Environmental Protection Agency (USEPA) suggests displaying the time paths of benefits and costs projected over the project lifetime without discounting, discounting using the consumptive rate of interest (3%) and the rate of return on private capital (7%). The USEPA defines the extent of the results to the feasible range of discount rates (De Souza et al., 2011). Real discount rate between 3% and 7% is consistent with suggested discount rate in other reports and studies in this area. For example, California Urban Water Conservation Council (CUWCC) suggested using 5% to 6% real discount rate in calculating the present value of water projects text[2]. Based on the United States government regulations analysis of federal water projects in the United States must use a time-constant discount rate announced by the government each year. Most recent published discount rate to be used for federal water project planning is 3.4%. However, water agencies also can regulate their discount rate. For example water agencies in California are using 6% discount rate for planning water projects (DWR, 2008; Griffin, 2016). Taking all together, we will use 3% to 7% real discount rate to calculate water supply reliability benefits.

3.3 Elasticity of Water Demand

The elasticity of water demand, in this paper, is assumed to be vary between -0.1 and -0.4 (Buck et al., 2016). Assuming price elasticity of residential water demand in California between -0.1 and -0.4 is consistent with findings in other studies (Nataraj and Hanemann, 2011; Buck et al., 2015; Klaiber et al., 2014; Olmstead et al., 2007).

3.4 Water Price

Another factor in calculations of benefits of water supply reliability is residential water price. Based on the (Hanak, 2011) study water rates in different parts of the California state ranges from 545 to 1,857 ($/AF). Based on the recent water rate survey result in (Buck et al., 2015, 2016) average water rate in California for the Single Family Residential sector is 1300 ($/AF). This result is consistent with 2013 and 2014 American Water Workers Association water rate survey in California[3][4]. Based on these studies we assumed 1300 ($/AF) as a baseline water rate in our analysis.

Another concern is water rate growth over time. Based on the American Water Workers Association water rate survey (2014), from 2004 to 2014 water rate have annually increased

[2]http://www.cuwcc.org/Research-Portal/Discount-rates

[3]http://www.sweetwater.org/Modules/ShowDocument.aspx?documentid=5333

[4]http://www.awwa.org/portals/0/files/publications/documents

on average by 5.4%. Taking inflation rate into account (average of 2.3%), the real increase in water rate is 3.1% (aww, 2014). Based on the Metropolitan Water District of Southern California 2015 financial report[5] 4.5% increase in water rate is proposed for the future water planning. In this paper, we assumed water price growth rate is between 0% to 5%.

3.5 Water Supply Disruption Distribution

In the last step, we need to define assumptions about the water supply disruption distribution. In doing this, zero disruption (zero- benefit of supply reliability) is defined as occurring at the currently forecasted residential demand levels (maximum or target demand). Benefits associated with the reliable water supply due to the residential deliveries less than the maximum demand are found by integrating the demand curve from the 2050 maximum residential demand left-wards to the delivery. This process is done for disruption levels up to a 50% residential water disruption.

In this paper, we assumed disruption probabilities in the future will be between zero to fifty percent which is distributed using generalized beta distribution. However, Gamma distribution is used widely in the literature to explain drought distribution (Shiau, 2006; Nadarajah and Gupta, 2007; Husak et al., 2007; Nadarajah, 2009) but generalized beta distribution is more appropriate for the purpose of our analysis. Given that disruption in residential water delivery at any moment may vary from 0 to the maximum disruption (in this paper 50% of the target demand), we chose a beta distribution which is bounded both below and above. Also, Beta distribution is similar to the Gamma distribution regarding flexibility in the representation of a variety of distribution shapes with only using two parameters (Wilks, 1990).

The beta distribution is a good choice for describing disruption in residential water delivery because of a variety of reasons. The first advantage of beta distribution as mentioned above is bounded between zero and one. Bonding between zero and one is important for

[5]for more information see: http://www.mwdh2o.com/PDF_NewsRoom/Budget_LeaveBehind.pdf

disruption in residential water deliveries because negative and more than 100% disruption is impossible. Another advantage of beta distribution is that it can take on many different shapes (Mielke and Johnson, 1974). This feature of the beta distribution is especially important in this study because we want to calculate expected reliability benefits for cases that there is a high probability of low disruptions in the future and also for cases that we assume a high probability of high disruption in the future. In fact, this flexibility of beta distribution allows us to fit any disruption assumption regime.

Equation 7 is a general equation for the probability density function of the beta distribution.

$$f(x) = (x-a)^{p-1}(b-x)^{q-1}/B(q,p)(b-a)^{p+q-1} \tag{7}$$

where $a \leq x \leq b; p, q > 0$ where p and q are the shape parameters, a and b are the lower and upper bounds, respectively, of the distribution, and $B(p,q)$ is the beta function. We can write beta function as the following formula:

$$B(\alpha, \beta) = \int_a^b t^{\alpha-1}(1-t)^{\beta-1}\,dt \tag{8}$$

Figure 1 presents disruption probability distribution function under generalized beta distribution with α between 0 to 0.75 and β equal to 2. In this figure, blue colors are representative of the low probability of high disruption in the future (optimistic cases), and red colors are representative of the high probability of high disruption (pessimistic case).

We observe probability distribution of disruptions more clearly by plotting average disruption probabilities as intervals. For the purpose of Figure 2, we used five different distributions then we calculate the probability of each disruption intervals under these distributions. Reflecting the pattern observed in Figure 1, we see that there is a significant increase in the probability of higher disruptions (30% to 50%) as we move from distribution 1 to distribution 5.

4 Sensitivity Analysis Results

4.1 Sensitivity to Probability Distribution of Supply Disruption

Nine scenarios are used for the probability of disruption distribution to calculate expected benefits of water supply reliability. In distribution one, assumptions about the future disruptions in the water supply are optimistic in which we assumed, 0% disruption is most likely to happen, and 50% disruption is least likely to occur. The assumption about the future disruptions probability gets more pessimistic as we move from distribution one to distribution nine. In the last distribution, we assumed extreme disruptions like 30% to 50% are more likely to occur. Also, we assumed discount rate could vary between 3% to 7%. Reliability benefits sensitivity to disruption probability distribution under different discount rates (holding everything else constant) are calculated and presented in Figure 3.

Based on expected reliability benefits calculations, which is presented in Figure 3, we can conclude that: (i) comparing lower discount rates (3%) to higher discount rates (7%) result indicates that the lower discount rate results higher EPRB which is unassociated with disruption distribution and (ii) moving from first disruption probability distribution (optimistic case) to distribution nine (pessimistic case) the EPRB increases from approximately [$6-$11] billion dollars to [$17-$28] billion dollars depending on the discount rate. These results indicate that higher expectations of disruption (e.g. extreme droughts) in the future increase the EPRB. Also, sensitivity of the EPRB to discount rate increases as the probability of disruption distribution moves from distribution one to five (less dry versus more dry future).

4.2 Sensitivity to Elasticity of Demand

In this section, the effect of elasticity of demand on the ERPB is calculated. The elasticity of demand is assumed to vary from the low elasticity of demand (-0.1) to high elasticity of demand (-0.4). Similar to the previous section, we assumed discount rate varies between 3% to 7%. Also, for this section we assumed only one beta distribution in which α is equal to 0.4 and β is equal to 2. Figure 4 presents results for this section. Results indicate that the ERPB is less sensitive when demand is less inelastic (in this paper -0.4), and it is more sensitive as demand gets more inelastic (-0.1). Also, ERPB sensitivity to elasticity is nonlinear. Similar to the previous results, ERPB is lower when we use low discount rates and also is less sensitive. Results indicate that moving from high elasticity of demand (-0.4) to low elasticity of demand (-0.1) the EPRB increases from approximately [$7-$21] billion dollars to [$24-$67] billion dollars depending on the discount rate.

4.3 Sensitivity to Water Price

Most of the water agencies, increase water price every year and is not constant. To incorporate dynamic price assumption in the ERPB calculations, we assumed water price growth rate is between 0% to 5% depending on the scenario. As mentioned earlier, we assumed 1300 ($/AF) as a baseline water price in our analysis. Calculating ERPB using zero growth rate in water price generates baseline ERPB numbers for comparison purposes. Next, we assumed price grows in more than zero rates up to 5%. Figure 5 presents results for this calculations. Results indicate that the ERPB is less sensitive when price growth rate is close to zero, and it is more sensitive as price growth rate gets close to 5%. Also, ERPB sensitivity to changes in price growth rate is nonlinear. Similar to the previous results, ERPB is lower when we use low discount rates. Results indicate that moving from lower price growth rate (closer to zero) to higher growth rates (closer to 5%) the EPRB increases from approximately [$10-$36] billion dollars to [$14-$94] billion dollars depending on the discount rate.

5 Concluding Remarks

This study provides insight how we can incorporate uncertainty into calculations of the value of water supply reliability. Specifically, we calculate the welfare loss under water supply disruption for the project lifetime and then calculate the expected present value of reliability. Next we analyse the sensitivity of the value of reliability to the distribution of water supply disruption, the elasticity of water demand, and water price.

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6 Figures and Tables

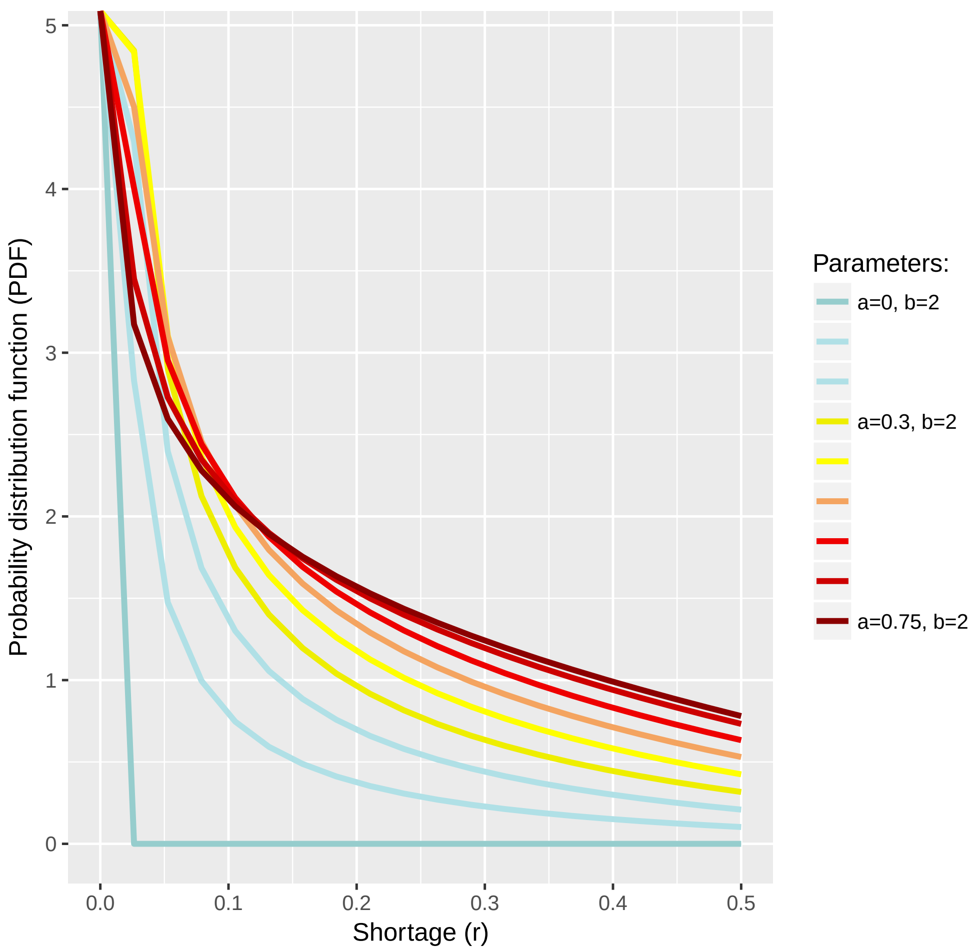

Figure 1: Probability of disruption distribution function using generalized beta distribution function.

Notes: Probability of a disruption higher than 50% is assumed to be zero. Read line shows lowest probability of disruption and pink line (α= 0.75, β=2) shows high probability of disruption.

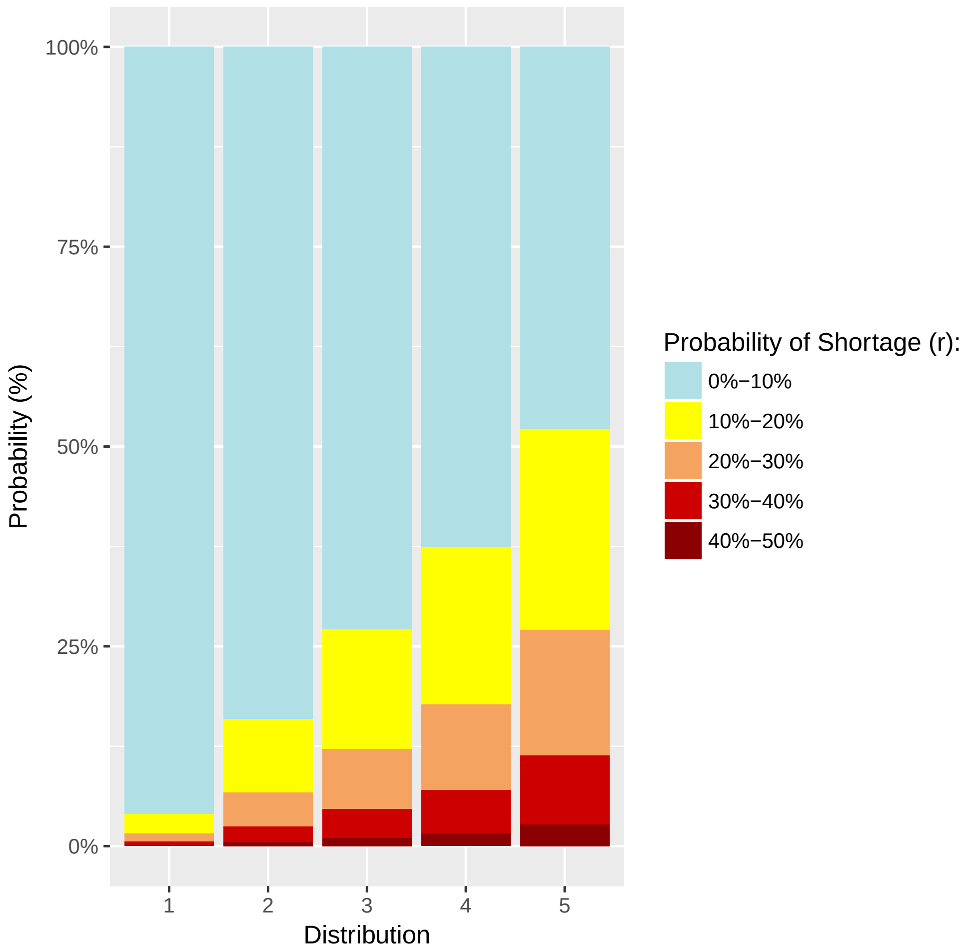

Figure 2: Changes in Probability of disruption by Changing Distribution

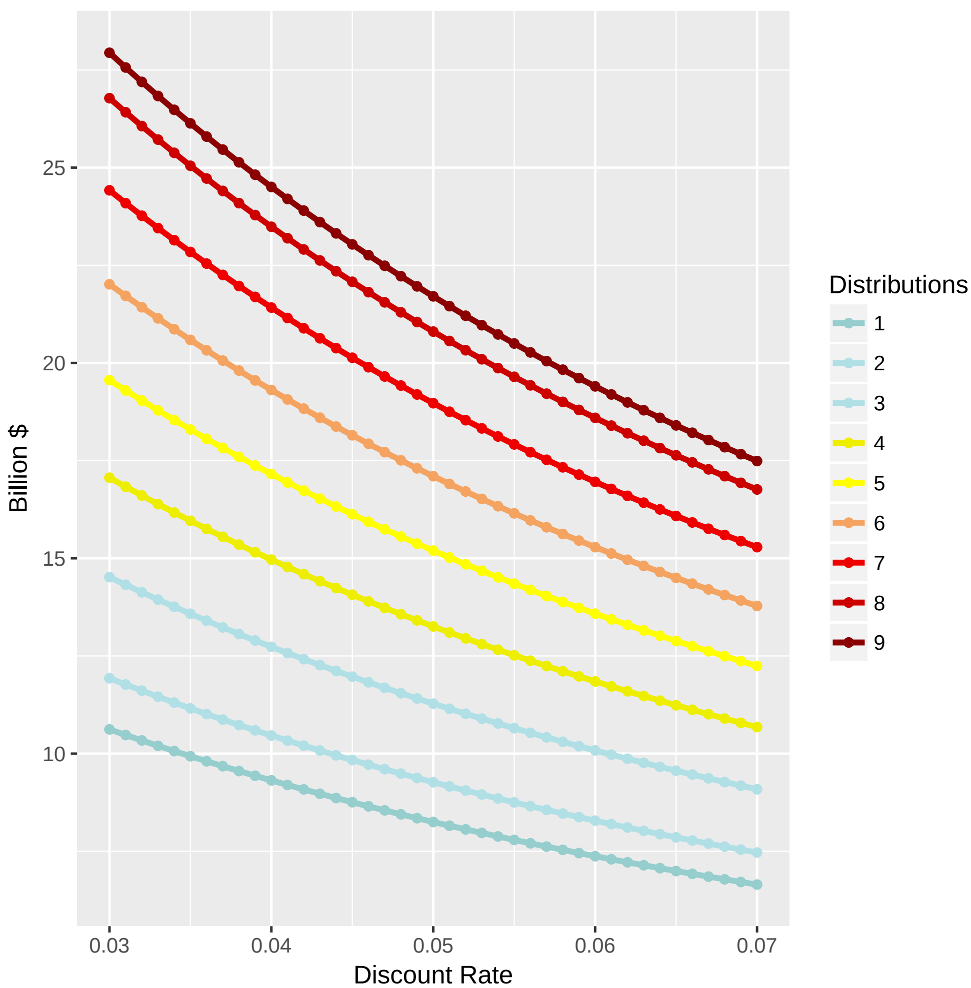

Figure 3: Expected Present Reliability Benefits Sensitivity to Probability of disruption Distributions.

Notes: For these calculations, we assumed only probability of disruption distribution and discount rate varies and everything else is constant. Discount rate varies between 0% and 7%. Specifically, we assumed demand stays constant at 2,154,967 (AF), water rate is constant at \$1, 300 (per AF), elasticity of demand is assumed to be equal to -0.2, marginal cost of water delivery is \$196 (per AF), and project lifetime is 35 years.

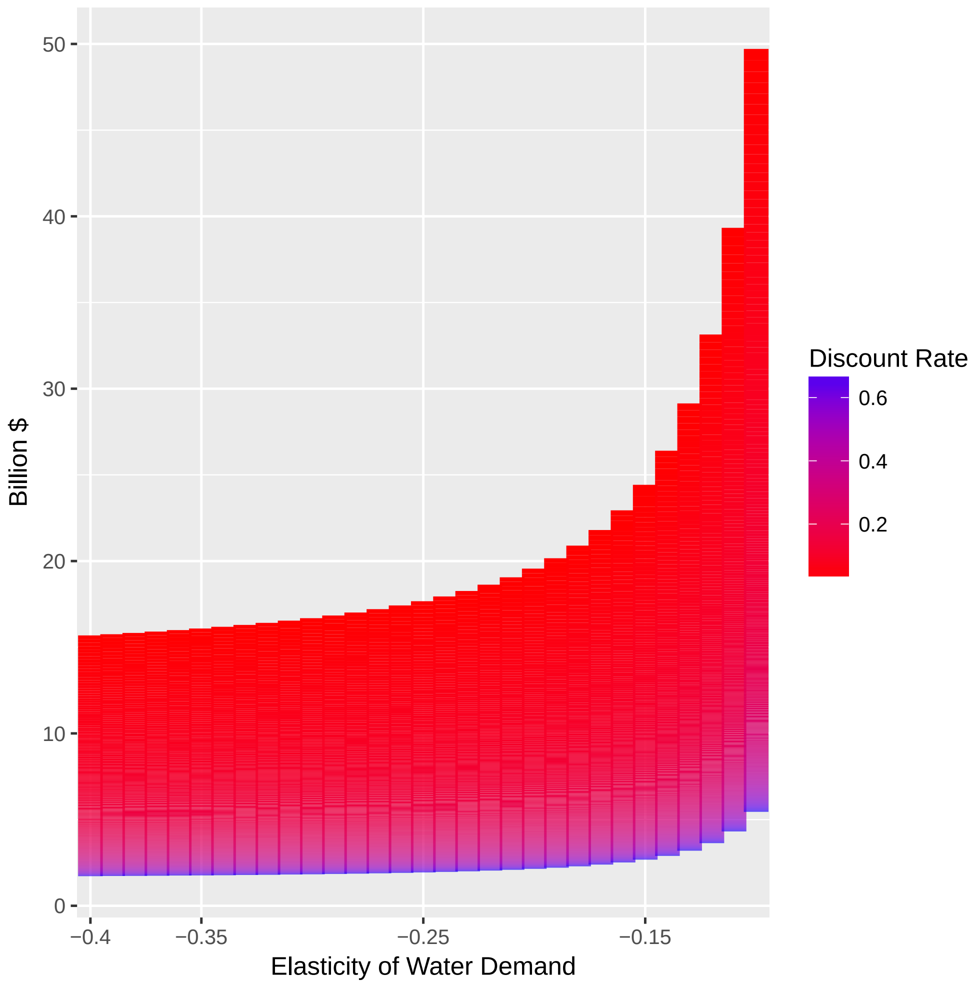

Figure 4: Expected Present Reliability Benefits Sensitivity to Elasticity of Water Demand.

Notes: Elasticity of water demand is assumed to be vary between -0.1 and -0.4 and discount rate varies between 0% and 7%. Additionally, for these calculations, we assumed only one probability of disruption distribution (α= 0.4 and β=2). Also, we assumed demand stays constant at 2,154,967 (AF), water rate is constant at $1, 300 (per AF), marginal cost of water delivery is $196 (per AF), and project lifetime is 35 years.

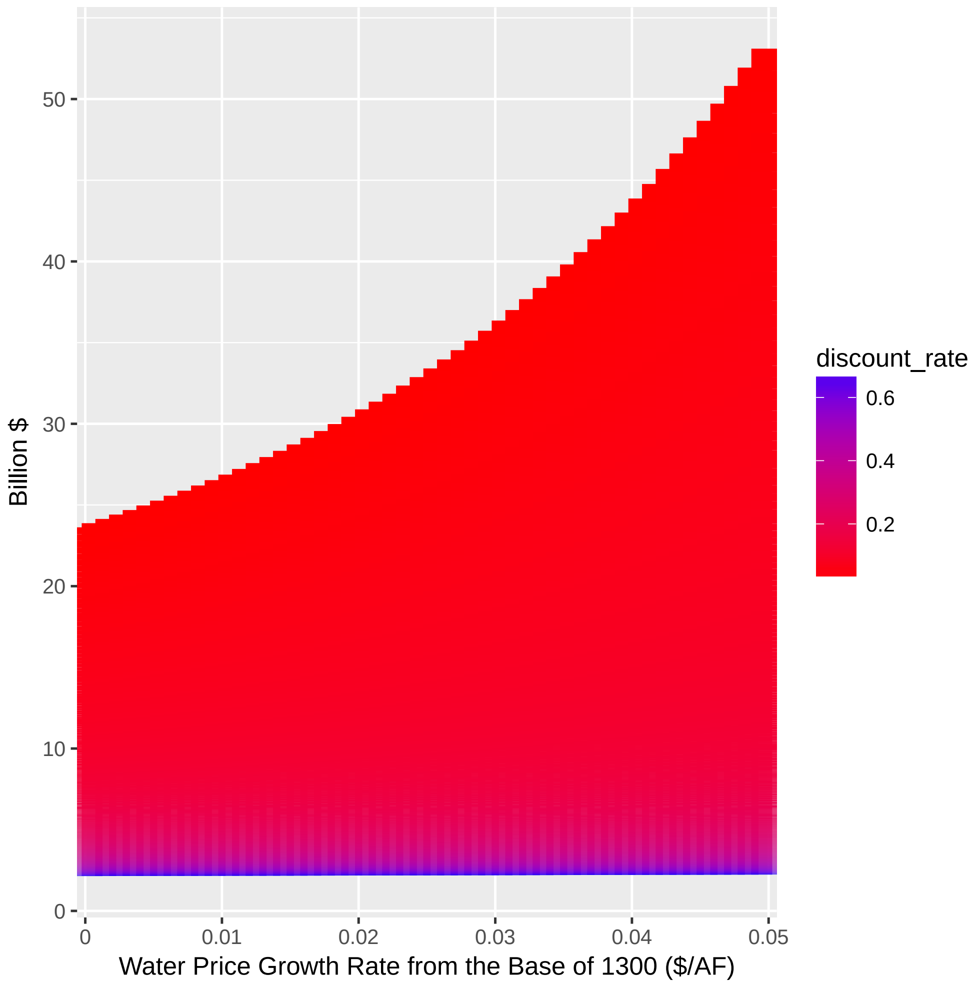

Figure 5: Expected Present Reliability Benefits Sensitivity to Water Price and Price Growth Rate

Notes: Depending on calculation scenario, price growth rate is assumed to vary between 0% and 5% and discount rate varies between 0% and 7%. Additionally, for these calculations, we assumed only one probability of disruption distribution (α= 0.4 and β=2). Also, we assumed demand stays constant at 2,154,967 (AF), price elasticity of water demand is constant at -0.2, marginal cost of water delivery is $196 (per AF), and project lifetime is 35 years.