Valuing Investments in Water Supply Reliability

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Introduction
A common aspect of agricultural water use in the western United States is that the supply of water from government projects varies annually. While it is impossible to influence weather, governments have the capacity to alter the distribution of water supply, for example by making infrastructure investments. This study develops a method for measuring the value of marginal changes in the distribution of project water supplies.

The model captures some important aspects of water use in the western United States. In particular, we allow for the possibility that growers have access to non-project sources of water. Examples include groundwater and water purchased on local water markets. These sources of water are typically more expensive than subsidized water from deferral and stat reclamation projects. Hence, agricultural customers typically take all project water to which they are entitled and then supplement with pumping and water market purchases. This two-tiered structure is somewhat unique to water, although economists have also explored the possibility of bypass in other natural monopolies such as telecommunications, electric and natural gas industries (Laffont and Tirole).

The model distinguishes between long run capital investments that are not changeable in the short run, and temporary decisions. Short run decisions such as production levels for annual crops and the amount of groundwater pumping depend on the current level of project water allocation and on prior capital investments. Capital investments including the establishment of trees and vines and purchases of specialized farm equipment can be altered in the long run but, once selected cannot be changed from year to year. In this respect, the model is of the “putty-clay” variety (Calvo, Hochman,
and Zilberman, Johansen, Sheshinski). Because they are both long run phenomena, 
capital investment decisions are heavily influenced by the distribution of surface water 
supplies.

Theoretical results developed here show how changes in the distribution of 
project water supplies affect farm-level water use decisions and, ultimately, long run 
farm profits. For example, we consider how change in the distribution of surface water 
supplies affects the level of capital investment. We develop theoretical conditions under 
which changes in the distribution of surface water supplies will increase or decrease 
various types of capital investments. We also develop predictions about the impact of 
the surface water supply distribution on the amount of supplemental water procured by 
farmers. This result is important because it is essential that water managers know how 
changes in the surface water supply infrastructure will impact the amount of groundwater 
extration.

In a case study, the model is applied to the San Luis & Delta-Mendota Water 
Authority in California’s San Joaquin Valley to measure the willingness of growers to 
pay for arbitrary changes in the distribution of federal water supplies. We parameterize 
the distribution of surface water supplies and the cost function for supplemental water, 
and measure the willingness of growers to pay for changes in the moments of the project 
water distribution. These values can then be compared to the marginal cost of moments 
of the distribution, usually achieved through capital investments in water storage and 
conveyance infrastructure.

As an alternative to these types of investments, we also consider the impact of 
expanded water trading on the value of water supply reliability. One finding of the case 
study is that expanding the scope of water trading in the western San Joaquin Valley can
significantly lower the value of increases in water supply reliability. The basic reason for this result is that there are large differences in access to surface water supplies among growers in the areas. The value to junior rights holders of increases in water supply reliability is relatively high. However, if an expansion of the regional water market reduces the cost of supplemental water to junior rights holders, then their valuation of the increase in reliability is also lower. Empirical results show that expanded water trading reduces the value of an increase in mean project deliveries by more than 30 percent. Thus, water trading is, to some degree, a substitute for investments in new water supplies for west side agriculture.

The Model

Typically, water is not allocated among final consumers by price, but rather by rationing. In the United States, rationing rules are embodied in water laws as discussed in the seminal paper by Burness and Quirk (1978). Accordingly, suppose that an individual water user receives a stochastic annual allotment of surface water from a public water project. Let $A$ represent this allocation, and assume that water from the project is provided free of charge. The allocation $A$ has a known distribution $f(A; \theta)$ with support $[\underline{A}, \bar{A}]$ so that $F(A; \theta) = 0$ and $F(\bar{A}; \theta) = 1$. The parameter $\theta$ indexes the distribution, and is a function of public policy choices and stochastic natural precipitation.

Retail customers can supplement deliveries from the public project by procuring water from other sources, most commonly privately developed sources such as groundwater or local storage projects. Let total water use be given by $W = A + I$, where $I$ is the amount of non-project (or incremental) water obtained. The gross benefits of
water use are given as \( B(W, z) \), where \( z \) is private capital investment by the retail user.\(^1\)

Net benefits are given by \( B(W, z) - C(I) \), where \( C \) is the cost of obtaining supplemental water. Assume that \( B_w > 0, B_{ww} < 0, B_z > 0, B_{zz} < 0 \), and that \( C_I > 0 \) and \( C_{II} > 0 \).

The optimization problem consists of two stages. In the first stage, the water user chooses the level of capital investment. These expenditures have the “putty-clay” property of being malleable ex ante, but fixed in the short run. In the second stage, once the level of project water supply is realized the farmer decides the amount of total water use by selecting an amount of supplemental water to procure, if any.

As usual, we solve the model by working backwards. The second-stage or short-run maximization problem is

\[
\max_i B(A + I, \bar{z}) - C(I),
\]

where capital is denoted as \( z = \bar{z} \) since it is fixed in the short run. The first order condition is the following:

\[
B_w - C = 0 \quad \forall \, A.
\]

The second order condition for this problem is \( B_{ww} - C_{II} < 0 \), which is ensured by the assumptions on second derivatives above. The short run optimality condition states that the user will acquire supplemental water until the point at which its marginal benefit equals marginal cost, conditional on the current realization of project water supply and past capital investments. Denote the short run optimal level of incremental water as \( I(A, \bar{z}) \).

The users’ capital investment problem is

\(^1\) Alternatively, \( z \) could denote physical units of capital measured in such a way as to normalize the price at 1.
which has the following first order condition:

$$
\int_\mathcal{A} \left[ B_w \frac{dI}{dz} + B_z - C_i \frac{dI}{dz} \right] f(A) dA - 1 = 0.
$$

By the sort run first order condition (2), this expression reduces to

$$
\int_\mathcal{A} B_z f(A) dA - 1 = 0.
$$

Thus, the level of capital investment is such that the expected marginal productivity of capital equals its marginal price. At this point, we allow for the possibility that capital is either complementary to, or a substitute for, applied water.

**Comparative Statics**

The central question of the paper is to value changes in the distribution of project water supplies. That is, we wish to measure the change in the expected utility of a retail user resulting from a change in the parameter $\theta$. Define expected utility as

$$
EU = \int_\mathcal{A} B \left( A + I(A,z^*), z^* \right) - C \left( I(A,z^*) \right) f(A) dA - z^*.
$$

Taking the derivative of (5) with respect to $\theta$, it follows that

$$
\frac{dEU}{d\theta} = \int_\mathcal{A} B_w \frac{dW}{dz} \frac{dz}{d\theta} + B_z \frac{dz}{d\theta} - C_i \frac{dI}{dz} \frac{dz}{d\theta} \right] f(A) dA - \frac{dz}{d\theta} + \int_\mathcal{A} [B - C] f_\theta dA, \text{ assu}
$$
ming that the supports of the water supply distribution are invariant with respect to the policy parameter. Using equation (2) and (5), this expression reduces to

\[ \frac{dE}{d\theta} = \frac{7}{4} [B - C] f_0 dA. \]

We now consider general conditions under which (6) can be signed. The ranking theorems of Rothschild and Stiglitz provide some useful tools in this regard. To apply these theorems, it is necessary to understand how long run utility responds to changes in \( A \). First, it is straightforward to show that \( U \) is increasing in \( A \). Formally,

\[ \frac{d\Pi}{dA} = \pi_w \left( 1 + \frac{dI}{dA} \right) - C_i \frac{dI}{dA} \]

\[ = \pi_w > 0, \]

It is also necessary to establish whether \( \Pi \) is concave. Differentiating again, we see that

\[ \frac{d^2 \Pi}{dA^2} = \pi_{ww} \left( 1 + \frac{dI}{dA} \right) \]

\[ = \pi_{ww} \left( -\frac{C_i}{\pi_{ww} - C_i} \right) < 0. \]

The inequality results from the assumptions that \( \pi_{ww} < 0 \) and \( C_i > 0 \), and from the short run second order condition \( \left( \pi_{ww} - C_i < 0 \right) \). Thus at an interior equilibrium \( \Pi \) is increasing and concave in \( A \).

To see how the ranking theorems can be applied to this model, consider a special case of (6) that arises with respect to water right seniority. In the western United States, surface water is commonly allocated by a priority-based queuing system in which some users are allocated water before others. Under this “prior appropriation” rule, a marginal
increase in seniority (indexed by $\theta$) decreases the probability that the water right holder receives less than any arbitrary amount of water from the project. That is, seniority is synonymous with first order stochastic dominance: if $\theta'$ is senior to $\theta$, then $F(A; \theta') \leq F(A; \theta') \forall A$, with the inequality being strict in some region (i.e. $F_\theta \leq 0$).² Thus, in a prior appropriation system, an increase in seniority increases expected profits so long as $\Pi$ is increasing in $A$, which was verified above.

One benefit of using the stochastic dominance ranking theorems is that they permit consideration of unrestrictive changes in the distribution of project water supplies. For example, if the proposed project water distribution only second order dominates the status quo distribution, then the fact that $\Pi$ is increasing and concave in $A$ is sufficient to ensure that this change also increases expected profits. Further, if the proposed change in project deliveries simply reduces the variance of project supplies but leaves the mean unchanged (as with a simple water banking project that reallocates water from year to year), then expected profits still increase. These conclusions are quite general as they follow from assumptions about the diminishing marginal productivity of applied water and the increasing marginal cost of obtaining non-project water.

Before moving onto other parts of the analysis, it is important to spell out how the analysis can be applied for empirical work; doing so also provides intuition for the results obtained thus far. Equation (6) can be manipulated as follows to yield a convenient expression:

²This formulation is consistent with the seminal analysis of Burness and Quirk.
\[
\frac{dE \Pi}{d\theta} = \int_d^\pi \left[ B - C \right] f_\theta dA \\
= \left[ B - C \right] F_\theta |_d^\pi - \int_d^\pi \pi_w \left( 1 + \frac{dI}{dA} \right) - C_i \frac{dI}{dA} \right] F_\theta dA \\
= -\int_d^\pi B_i F_\theta dA \\
= -\int_d^\pi C_i F_\theta dA, \\
\]

(7)

where the last two steps use the short run first order condition (2). Equation (7) indicates that the marginal value of changes in the distribution of project water is related to its impact on the purchase of supplemental water. Information on the marginal cost of supplemental water is usually easy to come by since pumping depth and hence the cost of groundwater is easily known, and information on water market prices is also fairly simple to obtain. This data provides information about the function \( C_i \). As in the case study section of this paper, some parametric assumption will typically be made about the water supply distribution \( F \). We assume that this distribution is lognormal. Working with a parametric specification, it is possible to value changes in the moments of the distribution directly by using equation (7).

It is also of interest to determine how supplemental water acquisitions vary with changes in the distribution of project water supplies. Taking a long run perspective,

\[
\frac{dE[I]}{d\theta} = \int_d^\pi I(\theta, z) f(A; \theta) dA. \\
\]

Differentiating and then integrating by parts, it follows that
where SRSOC is the short-run second order condition. This last expression uses the fact that the short run first order condition implies that \( \frac{dI}{dz} = -\pi_z W_{SR} \). This expression is also of ambiguous sign, depending on the relative magnitudes of \( \pi_z W_{SR} \) and \( \frac{dz}{d\theta} \). Despite this result, equation (8) does raise the interesting possibility that a stochastically dominant increase in surface water deliveries (i.e. \( F_\theta \leq 0 \forall A \)) may actually increase the amount of groundwater pumping or water market purchases. This result occurs through the effect of the water supply distribution on capital investments. If the shift in the project water distribution induces enough investment of the type that increases the marginal productivity of water application, then even a stochastically dominant shift in project water deliveries can increase the expected amount of supplemental water purchased.

**Case Study: San Luis & Delta-Mendota Water Authority**

In this section the conceptual model is quantified using data from the San Luis & Delta-Mendota Water Authority in California’s San Joaquin Valley. We begin with a methodological point. Our primary interest is to measure the marginal value of changes in the distribution of project water supply. Equation (7) in the previous section indicates that the marginal value of changes in the distribution of project water is related to its impact on the purchase of supplemental water. This equation is most convenient if the researcher has specified a parametric distribution and knows how the policy change will alter the moments of the distribution. Often, however, one only knows how a policy
change will alter deliveries in various types of water years. That is, the researcher only has a comparison of deliveries before and after some policy change such as construction of a canal or reservoir. In this case, (7) is not convenient to work with. Fortunately, (7) expression can be rewritten to yield the following:

\[
\frac{dE}{d\theta} = -\int_A C_f F_\theta dA
\]

\[
= \int_A C_f A dA
\]

where \( \Delta A \) is the change in the amount of water available to growers at each previous level of \( A \), holding \( F \) constant. Intuitively, both expression (7) and (9) indicate that the marginal value of a change in the surface water distribution is the change in expected expenditures on supplemental water. It is significant that both (7) and (9) hold current water use patterns constant, in particular current land sue patterns and levels of investment in water use capital. This result is also important for empirical applications of the model.³

We utilize the parametric approach since our analysis does not assume any particular change in the water storage and conveyance infrastructure. That is, we wish to know how growers value general changes in the moments of the surface water supply distribution. It is most convenient to sue a parametric approach to obtain close-form solutions to the main theoretical relationships, and to measure the marginal values derived in the previous section. Suppose that \( f(A;\theta) \) is lognormal; this specification is

³ It is worth repeating, however, that this result holds only for marginal changes in \( f \).
reasonable since it constrains per-acre deliveries to be non-negative and fits the observed distribution of deliveries well.\(^4\) That is,

\[
f(A; \theta) = \frac{1}{\sqrt{2\pi\sigma(\theta)A}} \exp\left[ -\frac{(\ln A - \mu(\theta))^2}{2\sigma(\theta)^2} \right],
\]

where the moments are written as functions of policy choices. Eliminating these arguments for presentation purposes only, the moments of the distribution are

\[
\mu'_n = \exp\left( n\mu + \frac{n^2\mu^2}{2} \right)
\]

so that

\[
\bar{A} = \exp\left( \mu + \frac{\sigma^2}{2} \right)
\]

\[
Var(A) = \exp\left( 2\mu + \sigma^2 \right) \left( \exp\left( \sigma^2 \right) - 1 \right)
\]

The density \(f\) is parameterized using historical per-acre deliveries to service contractors in the SLDMWA. The U.S. Bureau of Reclamation provided these data (U.S. Bureau of Reclamation, 2007). Using historical deliveries, we find that \(\mu = 0.5286\) and \(\sigma^2 = 0.1682\). These parameters imply that

\[
\bar{A} = 1.8454\text{ and } Var(A) = 0.6238.
\]

The other function that must be parameterized is the marginal cost of supplemental water as a function of per-acre deliveries and prior investments in water-use capital. This function is measure by considering the spatial distribution of the cost of groundwater in the study area. Groundwater depths and pumping costs are taken from the inventory of groundwater wells in the central Western San Joaquin Valley compiled

\(^4\) A q-q plot of normalized log deliveries against lognormal scores is approximately linear.
by Gronberg et al., and analyzed in Gronberg and Belitz, Belitz and Phillips, and Belitz et al. An exponential function was fit through the data given in these studies to obtain the per acre cost of supplemental water. The estimated relationship between the per acre cost of supplemental water as a function of per acre project deliveries is as follows:

\[ \ln C = 4.6990 + 1.5515 \ln A. \]

For example, if project deliveries are 1.8 acre feet per acre, then the estimated function implies that growers spend $78 per acre on supplemental water; if deliveries are only 1.0 acre foot, then supplemental water cost is $228.

With this information in hand, it is possible to calculate the marginal value of the moments of the water supply distribution according to equation (7). Since we have selected a parametric representation of the density function \( f \), we will consider the marginal valuation of changes in the moments of the density (i.e., the mean and the variance, since the lognormal is a two-parameter distribution). These figures are somewhat difficult to interpret directly because if we vary only one parameter of the distribution of \( \ln A \), both moments of the distribution of \( A \) change. Thus, we calculate the parameters of the hyperplane in the

\[
\left( \text{Value}, \exp \left( \mu + \frac{\sigma^2}{2} \right), \exp \left( 2\mu + \sigma^2 \right) \left( \exp (\sigma^2) - 1 \right) \right)
\]

space to measure the marginal value of changing the mean and variance of \( A \) itself. The results are as follows:

\[
(10) \quad \text{Value} = 144.5767 \left( \bar{A}' - \bar{A} \right) - 73.9620 \left( \text{Var}A' - \text{Var}A \right).
\]

5 The form of (7) that is most convenient to estimate empirically is derived by integration by parts and cancellation:

\[
\frac{dE \Pi}{d\theta} = \int C(I(A)) \left( \frac{dI}{dA} \right)^{\gamma} f_c(A; \theta) \, dA.
\]

6 Note that “Value” is the value of a change in the distribution, so the value of the status quo mean and variance of \( \ln A \) is 0.
Thus, the per acre value to service contractors of changing the mean of project deliveries by one acre foot per acre is $144.5767. Equation (10) also defines an indifference relationship for the service contractors, and indicates that for a unit increase in the variance of deliveries, service contractors need to be compensated by increasing mean deliveries by about one-half of an acre foot per acre.

It is of interest to know how water trading would alter the value of changes in the distribution of surface water supplies. Broadly, the study area is comprised of growers with two different types of water rights. The service contractors described above have relatively junior rights, and thus have low mean deliveries. The so-called exchange contractors have much more senior rights. Not surprisingly, exchange contractors usually have cheaper supplemental water than service contractors. In part, this fact results from the large amount of deep percolation in exchange contracting areas. Also, due to their location more exchange contractors can pump groundwater form an unconfined aquifer, whereas most service contractors must pump from a deeper, confined aquifer. With an active regional water market, the cost to service contractors of supplemental water is

$$\ln C = 4.7159 + 1.0047 \ln A.$$  

These results are derived by the same procedure used to define the water cost relationship of service contractors alone. The relationship implies that if project deliveries are 1.0 acre foot, then supplemental water cost is $179, compared to $228 per acre with no trading between exchange and service contractors.

If service and exchange contractors can trade freely, the marginal cost of supplemental water to service contractors is reduced. This, in turn, lowers service contractors’ valuation of additional surface water supply. Performing the same exercise
as described in the preceding paragraph, but this time using the supplemental water cost function that results from regional trading, we find that the value hyperplane becomes the following:

\[
\text{Value} = 93.7453 \left( A' - \bar{A} \right) - 43.5448 \left( \text{Var}A' - \text{Var}A \right).
\]

Thus, trading between exchange and service contractors reduces the value of a unit change in mean deliveries from $145 per acre to $94 per acre – a decrease of over 34 percent. This analysis suggests that, to some degree, water trading within agriculture is a substitute for additional investment in water supply reliability.

**Conclusions**

The paper begins by characterizing water supply reliability. Although the term is widely used in water policy debates, it is actually quite ambiguous. In this study, reliability is couched in terms of changes in the probability of receiving various amounts of surface water. A commonly used in a policy context, the term reliability is most synonymous with the following definition: one distribution is more reliable than another if it increases the probability of receiving from the project more than any arbitrary amount of water. That is, the grower never receives less water. By this definition, reliability increases mean deliveries, perhaps substantially, and may increase or decrease the variance of deliveries. But this is not the only possible definition of reliability. In common usage, reliability implies assurance. Thus, a decrease in the variance of deliveries can also be said to increase reliability. In the context of west side agriculture, a distribution that assured growers they would always receive 1 acre foot per year would certainly be more “reliable” than the present water supply distribution, but this increase in reliability would
not be desirable. Thus, as the term is used in policy discussion, what is usually meant by reliability assumes an increase in expected deliveries.

The paper presents a model of the impact of changes in the distribution of surface water supplies on farm-level water use decision and on farm profitability. The model recognizes that farmers make both short-and long run decision that are influenced by the distribution of surface water supplies. In the long run, farmers make capital investments that are not easily altered from year to year. Investments in perennial crops, specialized farm machinery, and irrigation systems are all example. Growers make other decisions that are more temporary in nature, and that are influenced by annual project water allocations. The amount of groundwater pumped, the acres planted to annual crops, and the amount of water bought and sold on local water markets are all short run decisions. These decisions are also influenced by prior capital investments.

We consider the impact of changes in the distribution of surface water on both short and long run farm decisions. Among the conceptual results are the following:

- A first order stochastically dominant increase in the reliability of surface water deliveries increases expected farm profits. A mean-preserving decrease in the riskiness of delivery amounts also increases expected profits.
- When surface water is supplemented with water from other sources, the value of small changes in the surface water distribution is related to the avoided cost of supplemental water. This conclusion is especially important for empirical analysis since the cost of groundwater (or water purchased on local water markets) is usually easy to measure.
Changes in the distribution of surface water can increase or decrease the amount of supplemental water procured. In part, the direction of the response depends on how capital investment changes. Stabilization of surface supplies that increases the amount of capital investment and thereby increases the marginal productivity of water application increases the amount of supplemental water used by farmers. In this way, stabilization of surface water deliveries can increase the expected amount of groundwater pumping.

In this case study, the model is applied to the San Luis & Delta-Mendota Water Authority to measure the willingness of growers to pay for arbitrary changes in the distribution of Central Valley Project water supplies. Using a previous inventory of the cost of groundwater in the region, we show that the willingness to pay a one acre foot change in mean surface deliveries is $145. A one-unit increase in the variance of deliveries decreases expected profit $74 per acre.

An important finding of the case study is that expanding the scope of water trading in the west side of the San Joaquin Valley can significantly lower the value of increases in water supply reliability. The basic reason for the result is that there are large differences in access to surface water supplies among growers in the area. The value to junior rights holders of increases in water supply reliability is relatively high. However, if an expansion of the regional water market reduces the cost of supplemental water to junior rights holders, then their valuation of the increase in reliability is also lower. In the case study, if a regional water market is established in which junior rights holders can trade freely with senior rights holders, the value of a one acre foot increase in mean deliveries is $94, or a drop of over 34 percent. This finding, which is quite general,
suggests that institutional changes such as the establishment of trading zones among farmers can help forestall the need for costly investment in water infrastructure.
References


