Storage and Markets: The Interaction of Inter- and Intra-temporal Water Allocation in a Changing Climate

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[1]Photo from coyotegulch.wordpress.com

1. Introduction

Water represents an important scarce natural resource in many arid parts of the world, including the Southwestern United States where 5 of the 8 fastest growing US states are located (Census, 2014). Yet most major water resource managers in this area predict shortages as large as 1,815 million acre feet over the next 100 years (MacDonald, 2010; Ackerman, 2011). In Colorado, only 80 percent of projected demand will be met by the year 2050 even if currently planned supply and conservation projects are successful, and annual expected shortfalls may exceed 500,000 acre-ft for Colorado alone (Colorado Conservation Board, 2014)[1]. Much of the Southwest will suffer similar constraints and water managers will increasingly be faced with difficult allocation and investment decisions. The solution to water scarcity has traditionally been to build more storage and increase supply, but in the 1980's this "expansionary" approach became prohibitively expensive (Booker et al., 2012). As such, solutions to water scarcity include a host of supply-side and demand-side projects, but the success of these projects depends on the institutional agreements within which they are enacted. This paper investigates the value of increased storage and optimal reservoir release under a variety of allocation institutions—namely, allocation using a competitive market and Prior Appropriation Doctrine (PAD).

In this paper, a dynamic water allocation model is used to examine the extent to which water storage capacity affects the optimal use of water over time. Next, inefficiencies are included in the model to capture the value losses associated with varying levels of restrictions in trade. The model is calibrated to the Colorado-Big Thompson water market with two user types and solved using stochastic dynamic programming to examine the additional value of water through the use of trade and storage. Two hypothetical no-trade cases represent the allocation of water through the Prior Appropriation doctrine, one where no reallocation has occurred and one with moderate reallocation. The gains from allowing trade are then evaluated under alternative storage capacity scenarios to compare the value of increased inter-temporal efficiency with the gains from trade across users. Finally, the results are applied to a climate change scenario to investigate the role of storage capacity and markets in adapting to changes in the distribution of water availability.

Currently, a large body of literature explores the optimal use of scarce water resources (Harou, 2009 provides a concise overview), but little work exists investigating the specific interactions of storage and markets. The Colorado-Big Thompson (C-BT) system, being one of the most studied water projects in the country, provides an excellent case study for analyzing storage and markets because it is highly important to the agro-economy of northern Colorado, has ownership and lease information readily available, and has

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[1] As a reference, average water use per acre of corn in Colorado is approximately 1.4 acre-feet.

low transaction costs associated with leasing or selling shares in C-BT water. This means that the baseline calibration is to a functioning market. The no-trade scenario represents the constructed counterfactual. This differs from most situations in the Southwest in which only inefficient allocations are observed and efficient allocations have to be estimated. Generally, it is difficult to determine how allocations of various efficiency will interact with storage and changes in stochastic inflow. This ambiguity occurs largely because the benefits of trade and storage strongly depend on the specific shape of each benefit function, the degree of inefficiency, and the specific parameters of the inflow distribution function. In the extreme, if it only rains once every five years it is easy to see that the benefits from storage would be large. Similarly, if it rains regularly and allocations are such that one user is flooded while another receives no water at all, it is clear that gains from trade will far outweigh those from storage. Thus, the comparison between markets and storage is largely empirical.

Our initial results indicate that trade is highly valuable whereas inter-annual storage is not in the C-BT system. The average simulated present value of water usage over the next 50 years is $707 million dollars with efficient leasing markets. Restricted trade scenarios meant to mimic Prior Appropriation Doctrine are estimate to be 96.5% and 72.9% of that value. By comparison, changes in storage have very small effects on present value estimates. In the worst case scenario, when trade is restricted such that 85% of water use is designated to agriculture (consistent with current water use in Colorado), deadweight loss is large. Our results also suggest that liberalized water markets may help ameliorate potential losses under predicted changes in climate and water availability. The same is not true for additional inter-storage, which has a small effect on value under reduced inflow scenarios.

2. Background

Allocation of water is largely determined by the institutional agreements within a region. Given ecohydrological characteristics, laws governing the use of water developed quite differently in arid regions of the world when compared to humid regions. In the West, common law was unsuitable for water allocation for two reasons. First, the quantity of available water was insufficient compared to the quantity of farmable land (Gopalakrishnan, 1973). And second, PAD avoided potential water monopolies which would be harder to restrict under common law (Schorr, 2012). Thus, western states ubiquitously adopted prior appropriation doctrine as the preferred water allocation mechanism. While each state’s specific implementation of this doctrine differs, the basic approach is to use historical consumption patterns to create a priority system of users. This system can mitigate some of the market failures associated with common goods, uncertainty, and externalities (See Robert Young's *Determining the Economic Value of Water: Concepts and Methods* for an indepth discussion). In dry years, water users with a more senior right can require that users with more junior rights stop diverting water until the senior user's right is filled. Note that this priority system does little to ensure efficient allocation since the marginal value of water to senior users is often much lower than the marginal value to junior rights holders (Howe, 1986; Brookshire, 2004). The second component of prior appropriation is the concept of "no-injury". Any change in water use or geographic location must not harm other water users. A simple example would be a historical irrigation technique which created significant runoff to other farms. The initial irrigator would have strict limitations on the portion of water, usually deemed "consumptive use" that could be sold or traded to other users. The determination of tradable water represents a significant transaction cost and barrier to water trades in practice (Linvingston, 1995; Young, 1986; Colby, 1990).

Many studies argue against these barriers to trade and use economic rationale to call for liberalized water markets (ibid). Simultaneously, economics and engineering disciplines merged to create hydro-economic models. Before hydro-economic modeling, economists introduced the concept of water 'value' in different uses, but often ignored or overly simplified physical and spatial constraints (Mukherjee, 1996). Pure engineering models historically focused on minimizing the cost of meeting fixed water 'requirements' in different locations and uses (e.g., Yeh 1985, Vedula and Mujumdar 1992). Currently, hydro-economic models account for physical capacity while incorporating the value of water in different uses (Sunding et al 2002, Cai 2008). Researchers have used hydro-economic models to explore optimal water allocation and the impacts of policy on different users (e.g., Heinz et al 2007). Such policy issues include: the impact of water markets on efficiency and equity (Ward and Pulido-Velasquez 2008), the potential impacts of weather shocks (Sunding et al 1997), and the impact of climate change on water scarcity and operational costs (Medellin-Azuara et al 2006). However, very little work investigates the interaction of the dynamic efficiencies from storage with the intra-temporal efficiencies from trade. The analysis presented here represents an attempt to fill this gap by explicitly modeling the inter-temporal use of water under different storage capacities and water allocation institutions.

Recent work has investigated the economically optimal size of storage reservoirs, but it usually takes a theoretical approach, providing qualitative guidelines, but lacking the data necessary to apply theoretical results in a real world context (Fisher and Rubio, 1997; Xie and Zilberman, 2014). Notably, Fisher and Rubio (1997) find that under logical functional forms for costs and benefits, an increase in inflow variance should increase the optimal storage capacity of a reservoir. Among other results, Xie and Zilberman (2014) find that larger water projects may be required with improved management efficiency, higher damage functions due to spills, and increases in inflows. While these results are compelling, a shortcoming of purely theoretical models is that the assumptions needed for analytical tractability restrict the applicability of results in an applied setting. On the other hand, purely numerical approaches do not shed light on general mechanisms that drive the trade-offs between water trade and storage. The current paper strikes a balance between generality and applicability by framing the dynamic water use problem in a theoretical context and using available data to quantify the benefits of storage and trade in practice.

3. Study Area

We explore the interaction of improvements in inter-annual water allocation in the context of the Colorado-Big Thompson Project. This project consists of 12 reservoirs, 35 miles of tunnels, 95 miles of canals, and seven hydroelectric plants which are managed jointly by the Northern Colorado Water Conservancy District (Northern Water) and U.S. Bureau of Reclamation (USBR). When proposed in 1938, the project was intended to deliver 310,000 acre-feet annually to the Eastern Slope, but on average it delivers only 74% of that capacity. Allottees own shares of this water that represent a fraction ($1/310000$) of the quota decision in a given year, which ranges from 50% to 100% of 310,000 acre-feet. What makes water from the C-BT so unique in the context of Colorado water law is the lack of historical use. The C-BT infrastructure delivers water from the west slope of the Rocky Mountains to the east slope and delivers it to the Colorado Front Range. Since C-BT shares have not been a historical part of in-basin water use along the Front Range, but are rather inter-basin transfers, these shares can be leased or traded without the high transaction costs associated with native water, which falls within the jurisdiction of the prior appropriation doctrine. As such, the C-BT is one of the leading water markets in the country and a useful case study in observing efficient water allocation (Griffin, 2006).

While the vast majority of Colorado’s water remains in agriculture, Municipal and Industrial (M&I) users became the majority C-BT shareholders in 1997. Although share ownership has shifted from the original allotment (85% agriculture, 15% M&I) to one in which M&I own 64% of all C-BT shares, the majority of this water is still delivered to agricultural users through leases or the Regional Pool Program, in which unused water is auctioned to the highest bidders. These trends of ownership and deliveries are illustrated in figures 1-3 in the appendix. Although average year-to-year variation is quite large, M&I owners lease over 38,000 acre-ft to agricultural irrigators each year. This can be done at a low cost and therefore efficiently allocates water between multiple uses.

The last C-BT programs which bear mentioning are the Carryover Capacity Program and the Carryover Capacity Transferability program. The former is a program which allows individual water users to store one year's allotment (minus a fee) in C-BT reservoirs to be used the following year. There are both timing and amount limitations to what individual allottees can store. Specifically, shareholders can store up to 20% of their total allotment and must make this decision by April of the following water year. In cases where individuals would like to bank more than 20%, they can participate in the Carryover Capacity Transferability program, in which they buy unused storage space from other allottees who choose to store less than the maximum allowable storage. This program is particularly unique because it allows individual allottees to make storage decisions after the quota announcement. This phenomenon is likely to push the burden of storage decisions to the individual user to increase efficiency, since they will have more information than the decision maker[2].

The Colorado-Big Thompson project contributes significantly to Colorado's economy. It is estimated that the Northern portion of the Colorado Front Range uses over 910,000 acre feet of surface water in a given year (Northern Water officials), a significant portion of which on the order of 30% is provided by C-BT. While Prior Appropriation Doctrine can seriously limit efficient water allocations along the Front Range, the supplemental supply from C-BT reduces this inefficiency. It is entirely possible, although difficult to prove, that C-BT water is a substantial enough portion of water use to achieve a relatively efficient allocation of water in Northern Colorado. Ultimately, the C-BT leasing markets are an ideal case study to estimate the gains from trade, storage, and their interaction.

4. Theoretical Model

A dynamic theoretical model is developed to investigate the interaction of trade and storage capacity in the allocation of a storable commodity. In this model, a central reservoir manager observes reservoir storage levels, s_t and inflows, I_t in a given year and decides how much water to release in that year. The inflow of water is assumed stochastic, with lognormal distribution $g(\mu, \sigma^2)$. The reservoir has a fixed capacity, C. To make the release decision, a manager aiming to maximize the expected value of water weighs the current benefit from water use today against the cost of not having the ability to use that water in the future, and in some cases the need to spill water when large inflows cause capacity to be exceeded. Stochastic inflows mean that in years of high inflows, the manager may choose to release less water in anticipation of higher value in future periods where water is scarcer. The current benefit of water is

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[2] Current work explores the gains in efficiency from disaggregated storage decisions. In the current analysis we assume that storage decisions are made by a central reservoir manager.

assumed to come from its use in agriculture (A) and in municipal and industrial sectors (MI). The benefit of water in year t in use i is defined as:

$$B_{it} = f_{it}(w_{it}) \;\; i = A, MI \quad t = 0, \dots T$$

T represents the manager's planning horizon. Note that f_{it} can vary over time with changes in the season, overall trends, or as a function of inflows. The within-year allocation of water released from the storage reservoir depends on the allocation institution in place. With markets, users allocate water in a way that is equivalent to the social planner choosing w_{it} for each user and time. On the other hand, under prior appropriation (and no trade), the planner can only choose $\overline{w}_t = w_A + w_{MI}$ and released water will be allocated according to each users' seniority. We represent this case by assuming that agricultural users receive a proportion, $\alpha \in [0,1]$ of $\overline{w}_t$. MI users receive the proportion $1 - \alpha$. Therefore, the reservoir manager's objective function depends on the water allocation institution in place. Assume that the reservoir manager discounts at rate, ρ.

4.1 Storage Management without Trade

When trade is not allowed, this is equivalent to water allocation using prior appropriation. Under prior appropriation, the manager's objective is:

$$V^{PA}(s_t; C, I_t \sim g) = \max_{\overline{w}_t} E\left(\sum_{t=0}^{T} \left(f_{At}(\alpha\overline{w}_t) + f_{MIt}\big((1-\alpha)\overline{w}_t\big)\right)(1+\rho)^{-t}\right)$$

$$s.t.\, s_{t+1} = s_t + \tilde{I}_t - \overline{w}_t$$

$$0 \le s_t \le C$$

The Bellman equation for this dynamic optimization problem can be written:

$$V^{PA}(s_t; C) = \max_{\overline{w}_t} f_{At}(\alpha\overline{w}_t) + f_{MI}\big((1-\alpha)\overline{w}_t\big) + \frac{1}{(1+\rho)} E\big(V^{PA}(s_{t+1}; C)\big)$$

$$s.t.\, s_{t+1} = s_t + \tilde{I}_t - \overline{w}_t$$

$$0 \le s_t \le C$$

After substituting the state equation into the continuation value, this can be written:

$$V^{PA}(s_t;C) = \max_{\overline{w}_t} f_{At}(\alpha\overline{w}_t) + f_{MI}\big((1-\alpha)\overline{w}_t\big) + \frac{1}{(1+\rho)}\left(E\left(V^{PA}(\min(s_t + \tilde{I}_t - \overline{w}_t, C)\,; C)\right)\right)$$

For simplicity we can define $f_{At}(\alpha\overline{w}_t) + f_{MIt}\big((1-\alpha)\overline{w}_t\big) = f_{At}\big(\alpha(s_t - s_{t+1} + I_t)\big) + f_{MIt}\big((1-\alpha)(s_t - s_{t+1} + I_t)\big) \equiv F^{PA}(s_{t+1})$ (Note that since both individual production functions are concave in s, their sum is also concave). From here we can write the Euler equation as

$$\frac{\partial F^{PA}(s_{t+1})}{\partial s_{t+1}} + \rho\left(E\big(F^{PA}_{s_{t+1}}(s_{t+1}, s_{t+2}, I_{t+1}, C)\big)\right) = 0$$

In this form, the economic intuition is straightforward; the marginal gain from shifting s_{t+1} in the current period must balance with the marginal loss of the expected continuation value. From here it is difficult to determine the magnitude of the impact of capacity changes or a free market on the optimal policy choice. In fact, such effects depend on the 3rd order derivative of the benefit function and the distribution of inflow.

4.2 Storage Management with Trade

In the presence of a water market, the manager chooses the release level and the amount allocated to each user[3]. Therefore his objective function is:

$$V^{FM}(x_t;C) = \max_{w_{it}} E\left(\sum_{t=0}^{T}\big(f_{At}(w_{At}) + f_{MI}(w_{MIt})\big)(1+\rho)^{-t}\right)$$

$$s.t.\, s_{t+1} = s_t + \tilde{I}_t - \overline{w}_t$$

$$0 \le s_t \le C$$

Following the exercise from prior appropriation, this problem is equivalent to

$$V^{FM}(x_t;C) = \max_{\overline{w}_0} f_{At}(w_{At}) + f_{MI}(w_{MIt}) + \frac{1}{1+\rho}\left(E\left(V^{FM}(\min(s_t + \tilde{I}_t - \overline{w}_t, C)\,; C)\right)\right)$$

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[3] In practice the manager chooses only the release level but the market allocates water to maximize value within the year. This is equivalent to the reservoir manager choosing individual allocations.

With the Euler Equation

$$\frac{\partial F^{FM}(s_{t+1})}{\partial s_{t+1}} + \rho\left(E\left(V^{FM}(\min(s_t + \tilde{I}_t - \overline{w}_t, C)\,;C)\right)\right) = 0$$

where:

$$F^{FM}(s_{t+1}) \equiv f_{At}(w_{At}) + f_{MIt}(w_{MIt}) = f_{At}\big(h_{At}(I_t, s_t, s_{t+1})\big) + f_{MIt}\big(h_{MIt}(I_t, s_t, s_{t+1})\big)$$

$$h_{At}, h_{MIt} \equiv \text{inverse state equation}s$$

By definition, we know that the total value of water under the free market will be higher than under PAD, but it is unclear which scenario will have a higher marginal value for increased capacity, $\frac{\partial V^{FM}}{\partial C} \lesseqgtr \frac{\partial V^{PA}}{\partial C}$. This can be seen in the Euler equations since the current marginal value needs to equal the expected continuation value, but a change in alpha affects both.

4.3 Comparison of Value from Trade and Storage Capacity

Comparing the model solutions under the alternative institutional environments allows for an evaluation of the efficiency gains from trade and how they compare to changes in the storage capacity, C. Precisely, the gain in water value from trade, conditional on a starting reservoir level equal to s_0, is equal to:

$$\Delta = V^{M}(s_0; C) - V^{PA}(s_0; C).$$

On the other hand, the gain from increased storage capacity, given prior appropriation is:

$$\nabla^{PA} = V^{PA}(s_0; C') - V^{PA}(s_0; C)$$

Where $C' > C$. Comparing the results when $C = 0$ and $C' > 0$ gives the total value of being able to store up to C' of water. A final comparison provides the combined value of increasing storage capacity while simultaneously introducing a functioning water market. This will show the interaction effect of increased inter- and intra-temporal efficiency in water use.

$$\nabla^{M} = V^{M}(s_0; C') - V^{PA}(s_0; C)$$

In general, the relative value of Δ and ∇^1 depends on the elasticities of derived demand for water and for the differences in marginal water values across uses under prior appropriation. The following stylized facts emerge from this comparison.

1. *Steeper water demand curves result in larger gains from an increased ability to smooth consumption over time.*

With a steeper demand curve, variation in water deliveries over time result in larger discrepancies in the marginal value of water within the same use across time. Therefore, there is a bigger gain from the ability to equate these marginal values across time. This result suggests that municipal water users, who have relatively inelastic demands, are more likely to push for storing across years instead of releasing water. This story is anecdotally true.

2. *A greater difference in marginal water value across the two uses under prior appropriation results in larger gains from trade.*

The deadweight loss associated with restrictions to trade increases in the difference between marginal values of water. Therefore, the gains from trade are greater if the marginal value of water differs substantially between users. In the case of the western United States, the value of water in MI uses tends to be significantly higher than the value in agriculture (Goodman 2000). Therefore, as others have argued, gains from trade are likely large (Chong, 2006; Howe, 1997).

3. *In the case of both inelastic demand and large differences in marginal benefit across uses, markets and storage capacity can combine to increase the value of water.*

With steep demand curves and inefficient use across sectors, it is likely that a combination of storage capacity and markets will be required to obtain the optimal value of water across space and time. In this case, storage can increase the ability of markets to efficiently allocate water, and vice versa.

4.4 Climate Change Impacts

While climate change models do not agree on the variability and mean precipitation changes across the intermountain west, runoff projections have been relatively consistent. The Colorado River is expected to decrease in runoff by 6 to 25% (Ray et al., 2008, Christensen et al., 2004). Additionally, snowpack is expected to melt earlier in the season, thereby increasing the need for storage. In this study, we just focus on the impact of decreased water availability and not its timing. The effects of timing will be addressed in future work.

5. Empirical Stochastic Dynamic Program

The model presented in section 4 is calibrated to the Colorado-Big Thompson (C-BT) water project to investigate the interaction of storage and trade in an applied setting. Demand curves are projected for 2 aggregate C-BT users, Agricultural and Municipal and Industrial (M&I). These functions are summed together to create the total benefit function in a stochastic dynamic program under alternative institutional and storage scenarios in order to estimate the value of water over a 50 year period. We run a total of 12 scenarios (including the base—see below for precise scenario descriptions) that differ by water allocation institution, storage capacity and climate. These model runs allow us to estimate the individual value of trade, storage, and additional storage in a context of climate change. Figure 4 in the appendix shows a schematic of the difference between the *no trade* scenario and the *perfect market* scenario, where the decision variable in the *no trade* scenario is the total release from the reservoir, and the decision variable in the *perfect market* scenario is the amount of water delivered to each user.

Both agricultural and M&I benefit functions were assumed to be quadratic with corresponding linear demand functions. Linear demand functions with negative slopes were chosen because they are theoretically consistent with what we observe. Initial water is very valuable but exhibits diminishing marginal returns. The quadratic function also implies a satiation point, beyond which users will not consume. Quadratic benefit functions allow for simple analytical demand functions. A linear inverse demand function of the form $P_i^0 = a_i - B_i w_i^0$ can be solved explicitly for a and B with given initial prices, quantities, and an elasticity estimate. Elasticity is a measure of the responsiveness of quantity to price and is mathematically represented as: $\varepsilon_i = \frac{w_i^0}{P_i^0} \frac{\partial P}{\partial w} and \ \frac{\partial P}{\partial w} = \frac{1}{B_i} \therefore B_i = \frac{P_i^0}{w_i \varepsilon_i}$ for each sector. After B is calculated from the elasticity equation, a is solved for by plugging each value into the initial demand equation. The benefit function is the integral such that the annual total value of water in a sector is: $\int_0^{w_{it}} (a_i - B_i w_{it}) dw_{it} \rightarrow a_i w_{it} - \frac{1}{2} B_i {w_{it}}^2 \rightarrow (a_i - \beta w_{it}) w_{it} \ where \ \beta_i = \frac{1}{2} B_i$. Given these functional forms and initial elasticity, quantity and price estimates, the benefit of water in each time period can be constructed. To calibrate a_i and B_i, initial prices, quantities, and elasticity estimates are required. The derivation and explanation of these estimates are presented below.

Agricultural demand functions: There are a number of ways economists have estimated the value of water in irrigation, but they are generally divided into the categories of inductive and deductive methods. The most common inductive method is residual valuation and the most common deductive method uses empirical observations in econometric analysis. There are shortcomings of both methods (See Young 2005 for a complete review) but the two most problematic issues in valuation are: 1) assigning accurate costs to all other inputs that shift with water deviations and 2) determining if water shocks should be examined under a short-run or long-run paradigm. There is little consensus on both of these issue. Acknowledging these shortfalls, the agricultural demand functions presented herein were derived from water production functions.

Agricultural production functions estimating the relationship between crop yield and water use have been used for decades. While some variations of this method exist (i.e. deficit irrigation, only including evapotranspiration, various functional forms, etc.), the estimates have remained relatively constant. Thus, the agricultural production function used in this model is from a comprehensive 1978 book by Hexem and Heady. It is a simplified econometrically calibrated function in which Nitrogen, water, and price are the only variables necessary to estimate the derived demand per acre: $W = (688 + .413N - \frac{P_w}{P_y})/20$. This production function was created based on work done in Northwest Kansas, near the Colorado border.

To produce the derived demand functions used in our DP, we incorporate current corn prices of $5 dollars a bushel and common nitrogen levels of 180kg/ha. Although alfalfa and corn are both prevalent across the front range, the idea of weighting agricultural demand functions by irrigated crop type was considered and dismissed for two reasons: first, corn is by far the most prevalent crop in Northeast Colorado-- 292,000 acres harvested compared to 99,000 of alfalfa in 2012 (NASS). Second, if farmers are suffering a water shortage, they are likely to remove water from their lowest value irrigated crop, usually corn. The benefit function for the aggregate agricultural user is $f_A = (62.05 - .00018w_A)w_A$ [4].

Municipal and Industrial Demand Curves: While there has been considerable work in deriving residential and municipal demand (Espey et al., 1997; Arbues et al, 2003; Sheierling et al., 2006: Kenney, 2008; Dalhuisen et al., 2003), the literature is very sparse when it comes to industrial demand (Booker et al. 2012). With the exception of Renzetti's work, we know of no other robust estimate of industrial demand for water (Renzetti, 1988; Renzetti, 1992). Because industrial water users often buy water from municipal sources, the M&I demand curves are calibrated to municipal demand. Municipal demand is broken into

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[4] Future versions of this model will replace this corn based demand function with one derived from the University of Nebraska's Water Optimizer tool which is, "a decision support system for agricultural producers with limited irrigation water".

both indoor and outdoor demand, both of which were derived from quadratic benefit functions. Total annual use is thus the horizontal sum of 2 indoor demand curves and one outdoor demand curve. This for was chosen in order to address the distinct difference in marginal value and elasticity between indoor and outdoor use.

Initial annual M&I water use was calculated as the average annual C-BT deliveries between 2002 and 2012. This amount was further divided into summer and winter use, where summer use includes indoor and outdoor use, and winter use only includes indoor use. The city of Fort Collins, CO estimates residential water consumption is composed of 36% outdoor and 64% indoor use. This percentage was projected across the entire C-BT so that Q_0 for summer M&I use totals 55,670 acre-ft with 26,198 acre-ft classified as indoor use and 29,472 acre-ft classified as outdoor use. Accordingly, M&I demands water in both periods, but considerably more in the summer. Its benefit function is a piecewise function meant to reflect the differing elasticities of indoor (-.8) and outdoor (-.2) use . These elasticity estimates are consistent with previous literature (Espey et al., 1997; Arbues et al, 2003; Sheierling et al., 2006: Kenney, 2008; Dalhuisen et al., 2003). An initial price of $125 per acre-foot was taken from the water strategist database[5]. Specifically it is the 3rd quartile value of lease prices to municipalities. The mean was not used due to a large number of transactions entered around zero. In fact, $125 is likely too low for initial prices since cities have paid as much as $17,000 dollars per C-BT shares which on average only delivers 74% of an acre foot of water each year (Lynn, 2012). In perpetuity this value would yield a lease price of roughly $850, much higher than the $125 used in the model.

When indoor and outdoor demand curves are horizontally summed, the annual M&I demand becomes:

$$P_{MIt} = \begin{cases} 750 - .0219 w_{MIt}, & for\ w_{MIt} \leq 39{,}296 \\ 425 - .00367 w_{MIt}, & for\ 39{,}296 < w_{MIt} \end{cases}$$

Stochastic Dynamic Model: After aggregate demand functions are calibrated, they are used in a Stochastic Dynamic Program built following Bertsekas (2005) which has been parameterized by the physical characteristics of the C-BT system. Specifically, the model is classified as a discrete state Markov decision model in which agents observe the state variable (reservoir levels), make a release decision, and realize a reward for each time period (Miranda and Fackler, 2002). Stochastic inflows are modeled as a lognormal distribution for theoretical consistency, and mean and variance values were estimated using maximum likelihood techniques to best fit ten years of historical inflows into the Western Slope

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[5] The Water Strategist is a proprietary database of Stratcon Inc. from 1987 to 2010 and includes water transactions of 17 Western States.

reservoirs[6]. The model is discretized annually over a 50-year period, by 5,000 acre-foot increments over state space, and by 5,000 and 10,000 acre-foot increments over control space for municipal and agricultural sectors, respectively. Inflow realizations are discretized from 0 to 320,000 acre-feet in 20,000 acre-foot intervals, which are appropriately sized to improve computation time without sacrificing precision.

The objective functions under each institution match the setup presented in section 4 with additional conditions for infeasible states. Under both market and prior appropriation scenarios, the reservoir manager maximizes the NPV of water by choosing an optimal release schedule (conditional on storage capacity) under a prior appropriation institution and a free market. Table 1 presents parameter values and descriptions of the discretization of control, state, and inflows.

Table1: Model Parameterization

Parameter Description	**Value (thousand acre-feet)**
Total Release (in PAD case)	$\overline{w}_t \in W \equiv \{0,5,10,\dots 495\}$
Release to Ag (in FM case)	$w_{At} \in \{0,10,20,\dots 350\}$
Release to Muni (in FM case)	$w_{MIt} \in \{0,5,10,\dots 115\}$
Spill (in both cases)	$w_{SPt} \in \{0,5,10,\dots 30\}$
Inflow	$I_t \in I \equiv \{0,20,40,\dots 320\}$
Reservoir Level	$s_t \in \{0,5,10,\dots 470\}$
Initial Reservoir Level	250
Discount Rate	$\rho =$ 0.05 (dimensionless)

With state transition probabilities, p_I, the stochastic dynamic program can be written:

$$V_t(x_t) = \max_{w_t} F(w_t) + \frac{1}{1+\rho} \sum_{I_t} p_I V_{t+1}(min(s_t + I_t - \overline{w}_t, C))$$

The precise control variable and shape of $F(w_t)$ depends on the institutional setting. This problem is solved using backward recursion for $T = 50$ years, assumed to be the representative reservoir design life following Askew (1974). At each realization of state and decision variable, the state equation and benefit function (i.e., the Bellman equation) calculate the value used in the next iteration as this process is repeated backwards in time.

This setup makes a number of assumptions that may not be directly apparent. Firstly, it allows for cost free spills, by which we mean the cost of any excess inflow beyond reservoir capacity is assumed to be

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[6] Historic inflows were taken from the Bureau of Reclamation's *Colorado-Big Thompson Project Summary of Actual Operations* Reports. http://www.usbr.gov/gp/aop/cbt/cbtintpg.html

only the opportunity cost of not using that water in subsequent periods. A number of papers penalize spills with a harm function (Xie and Zilberman, 2014; Fisher and Rubio, 1997). Although it is simple to add this component to the value function, it does not make sense in this context. Harm functions are usually meant to simulate flood damage, but such damage from large inflows would not affect the Front Range because the continental divide separates storage reservoirs from the water users (i.e., spills flow into the Colorado River), and floods are not readily congruent with an annual timestep at which scale the SDP model operates.

Another key assumption in our base model is the lack of a systematic relationship between inflows and demand functions. Benefit functions do not contain a stochastic component, which may be problematic. In years of drought, demand for supplemental C-BT water is likely to increase substantially; the inverse would be true for particularly wet summer seasons. While this limitation is of concern and may result in an underestimation of the value of storage, its consequences are small in this setting since the water collection area experiences different weather patterns than the area in which water is demanded. However, there is still a moderate correlation of .57 and a t-test suggests that the relationship is significantly different than zero (pvalue=.07) between precipitation in Fort Collins and inflows observed on the Western Slope.

Finally, we simulate the impact of climate change on the relative value of storage and markets. Under various climate scenarios, the amount and distribution of precipitation is likely to change significantly over the next hundred years. The Colorado River Basin is projected to experience a decrease in runoff by 10 to 20% under future climate scenarios (Ray et al., 2008, Christensen et al., 2004). The inflows and transition matrix of the Bellman equations are adjusted by the shift in this mean to simulate the impacts of reduced annual inflows.

Model Simulations

In order to investigate the interaction of water trade and storage, the model was run under many permutations of allocation institutions, storage, and inflows, but the main scenarios include 3 allocation institutions and 4 physical variations. The 3 allocation institutions include: Free trade, a 15-85 split meant to simulate strict PAD, and a 36-34 split meant to simulate a PAD system where water rights are more easily bought and sold but leasing is limited. The 36-64 split was chosen because it is the average use pattern of the last 10 years. These three allocation institutions are compared under 4 scenarios: 1) current inflow and storage, 2) current inflow and no storage, 3) 10% less inflow and current storage, and 4) current inflow and a 12.5% increase is storage.

Baseline: The baseline scenario to which all models will be compared is a scenario with current storage and inflow realities with a free market. This allows users to equate marginal benefits both across users and across time. This scenario is considered the baseline because it is most closely related to the realities of the C-BT system. All gains and losses of different scenarios are in comparison with this baseline.

Scenarios 1-2: These scenarios hold allocation constant at 36-64 (Scenario 1) and 15-85 (Scenario 2) with current storage capacity (500,000 acre-feet). By comparing these scenarios to the baseline we can see the current value of trade compared to two levels of inefficient PAD allocations. In this way we can subtract the NPV from scenario 2 from NPV baseline to see how large losses would be if C-BT used a prior appropriation institution.

Scenario 3-5 (No Storage): This scenario is run with current inflows but does not allow for inter annual storage. It is run under all three allocation regimes: Free Trade (Scenario 3), 36-64 (Scenario 4), and 15-85 (Scenario 5). This Scenario is meant to estimate the value of inter-annual storage. Importantly, it does not account for the value of storage and conveyance within a year.

Scenario 6-8 (10% Inflow decrease): This scenario is meant to reflect climate models which predict up to a 20% decrease in runoff in the Colorado River Basin. Again this decreased inflow was run under all three allocations: Free Trade (Scenario 6), 36-64 (Scenario 7), and 15-85 (Scenario 8).

Scenario 9-11 (12.5% Increase storage): This scenario is meant to capture the benefits of additional inter-annual storage capacity (again ignoring the value of within-year storage and conveyance). 12.5% is chosen for the storage capacity increase because it is sufficient to capture most of the gains from increasing storage. This occurs because capacity is rarely reached even with the baseline storage capacity. Increased storage is run with each allocation Free Trade (Scenario 9), 36-64 (Scenario 10), and 15-18 (Scenario 11).

6. Results

Key results will be highlighted in this section and are summarized in figure 5 and Table 1 in the appendix. As anticipated, we find that the expected value of C-BT water is sensitive to the institutional setting and inflow. However, value attributed to inter-storage is very low, meaning that the primary utility from the storage is not gained between years, but may be much more pronounced when attenuating large water use in summer and fall periods by storing water in spring and early summer.[7] It is also important to recognize that this model likely underestimates storage value because the model does not currently incorporate autocorrelation in annual inflows, it may estimate a reservoir level that is below optimal if autocorrelation is included. If droughts occur in succession, more storage would be necessary to prevent large losses. Due to these limitations, Scenario 3 (no storage) has a NPV of only 1% less than the baseline. Also note that while inter-annual storage has relatively little effect on NPV, it does have a larger effect when allocations are inefficient. While the full value of storage capacity is not captured in the model, the inter-annual value of water storage is limited.

In each of the scenarios, optimal storage levels are lower under Free Trade regimes than under proportional allocation rules; however this result doesn't imply that more efficient allocations always lead to lower storage levels. For instance our baseline scenario predicts a mean storage of 179,000 acre feet, while Scenario 1 estimates 198,000 and scenario 2 estimates 185,000. Thus, the free market optimization uses less storage compared to a proportional 36-64 split, but the most inefficient allocation, 15-85, also uses less storage. Given the ambiguity of the analytical model, this result supports the theoretical finding that the optimal storage level depends on the shape of each benefit function.

Institutional allocation has the most significant effect on NPV and mean price (or marginal value). Baseline scenario predicts a net present value of 707 million from CB-T water, while scenarios 1 and 2 predict $682 million (96.5%) and $516 million (72.9%) respectively. Decreasing inflow also has a significant effect with scenario 6, 7, and 8, predicting NPV as 97%, 92% and 68% of the baseline.

Price estimates are also informative, particularly the marginal value of water under differing institutions. In the baseline scenario, the mean, minimum, and maximum marginal value to agriculture were $41, $3, and $132 respectively. However, when trade is restricted, the mean and max prices for municipal use jump to $131 and $407 in scenario 2 and, $352 and $607 in scenario 3. In scenario 8, with decreased inflows and a 15-85 regime, the mean price increases to $392 (963% of baseline).

Ultimately the results suggest that the gains from trading water from low value users to high value users, will have a much larger positive effect than increasing the ability to smooth consumption over time with increased storage. This result is robust under each relevant scenario in the C-BT context.

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[7] We are currently expanding the model to a seasonal time-step, which is computationally demanding.

7. Data and Model Availability

For purposes of reproducing model outputs and the capability to alter parameters and change scenarios, the input data and stochastic dynamic program is placed in an online repository found at http://erams.com/sustainablewater/analytics-and-optimization/. Instructions on how to download and run the model are in the repository.

8. Discussion and Conclusions

The policy conclusion that follow from our results is clear; the allocation regime under which water infrastructure is built has significant impacts on the net present value of that infrastructure. It follows that improving the allocation of water from existing infrastructure has the potential to greatly increase the value of water across time and space. Additionally, the model predicts that losses caused by decrease flows may be quite large, and that a working market has some potential to ameliorate these damages.

Several of the results presented here are Northern Colorado and C-BT specific; specifically, storage decisions and value estimates. Water transfers from the Western slope to the Eastern slope are very valuable, but storage specific infrastructure seems relatively unimportant. Results suggest that increasing reservoir capacity for purposes of inter-annual storage is unnecessary, since capacity is only reached occasionally and it has little effect on the value of water. However, both these results should be seen as preliminary due to the current assumptions of the model, which may not accurately capture real world characteristics. Future work will explore the implications of a sub-year time step.

Another important policy implication for Northern Colorado is the need to address changes in inflow. Under a free market institution, a conservative estimate of a 10% decrease in inflow into the reservoir creates a \$1 million average annual loss; that amount jumps to \$2.1 million when inflows are decreased by 20%. However when the same decreased inflows are examined under the 15-85 rule, annual losses increase to \$1.9 million and \$4.0 million a year compared to the same baseline. The corresponding policy implication is not new, but it is worth reiterating: A working water market has potential to ameliorate a significant portion of the losses due to climate change. However, even under free market conditions, annual losses may be substantial. Thus, in addition to markets, supplemental supplies or conservation technologies may be necessary.

It is also important to recognize that the results of this model only account for impacts of storage across years, which are not necessarily the value of storage infrastructure. A large part of that value may be in conveyance throughout the year[8]. Therefore, our climate change impacts will miss any impacts that occur because of changes in demand for conveyance. We are looking only at the potential to smooth water consumption across years when some years may be droughts. Because of the yearly time step, all of the value of storage must be viewed as only the value of holding water from year to year, not the potentially bigger effect of holding it from May to August.

In addition to this problem, there are a number of other limitations to this work which we hope to address in future work. The simplification of water users into two aggregate groups obfuscates some potentially interesting distributional results. The nature of our benefit functions makes a number of assumptions about the demand for water, including a backstop price and an elasticity. Notably, the demand function for agriculture assumes only an intensive margin change; in reality, it is entirely possible that farmers will not only change the intensity of water on each acre, but also the number of acres in production. These functions do not accurately capture the extreme value assigned to water in times of great shortages. This concern is somewhat ameliorated since even under drought predictions the water supply in our model stays in the neighborhood of our initial allocations, but there are a handful of years where agriculture is allocated nothing in free market. Lastly, the model may not appropriately adjust for feedback or autocorrelative processes in its presentation of inflows or residual demand.

While the initial results are compelling, they should be viewed as preliminary since it is clear that the model needs to be expanded in a number of ways. The next steps of this research include further refining the model to include smaller time steps as well as the inclusion of evaporation. Lastly, agricultural demand functions will be adjusted to allow for farmers to optimize crop and acreage choice at different levels of water allocation. A number of areas should also be investigated analytically. Some work has been done on the optimal level of storage under uncertainty, but there is still a need to investigate these phenomena in a more realistic analytical model in order to find qualitative and systematic truths about the relationship of storage, capacity, inflows, and consumption. The analysis presented here contributes to the understanding of how inter- and intra-temporal water allocation interact to determine the value of water in a changing climate.

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[8] We are currently running the model with smaller time steps and intra-annual periods to check the sensitivity of our annual-step model

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Appendix

Figure 1)

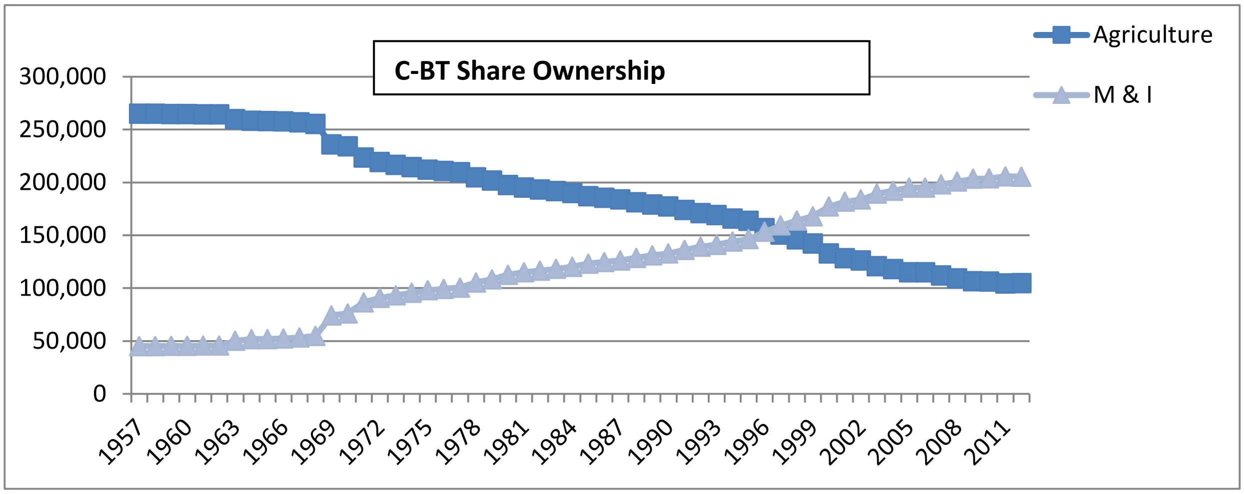


Figure 2)

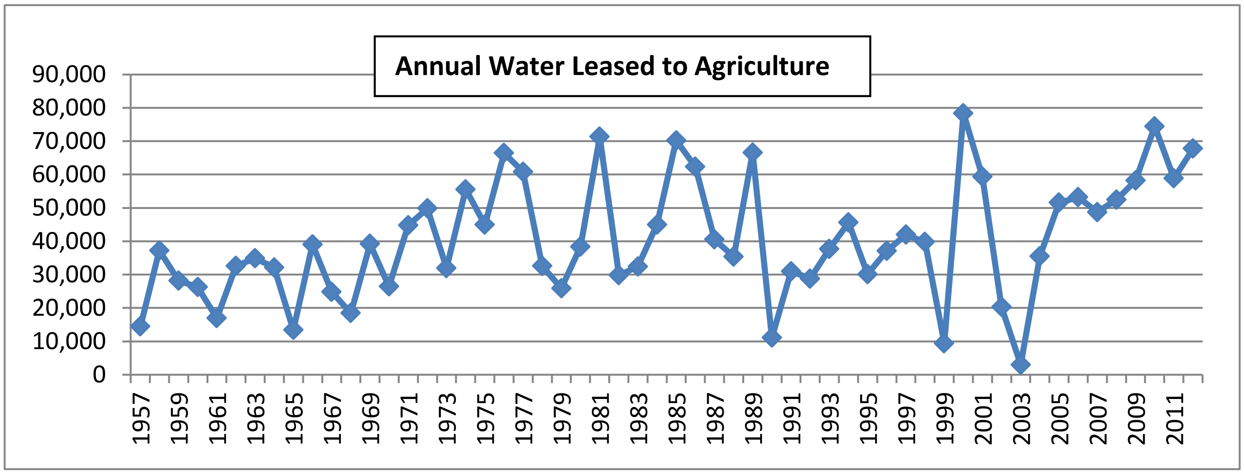


Figure 3)

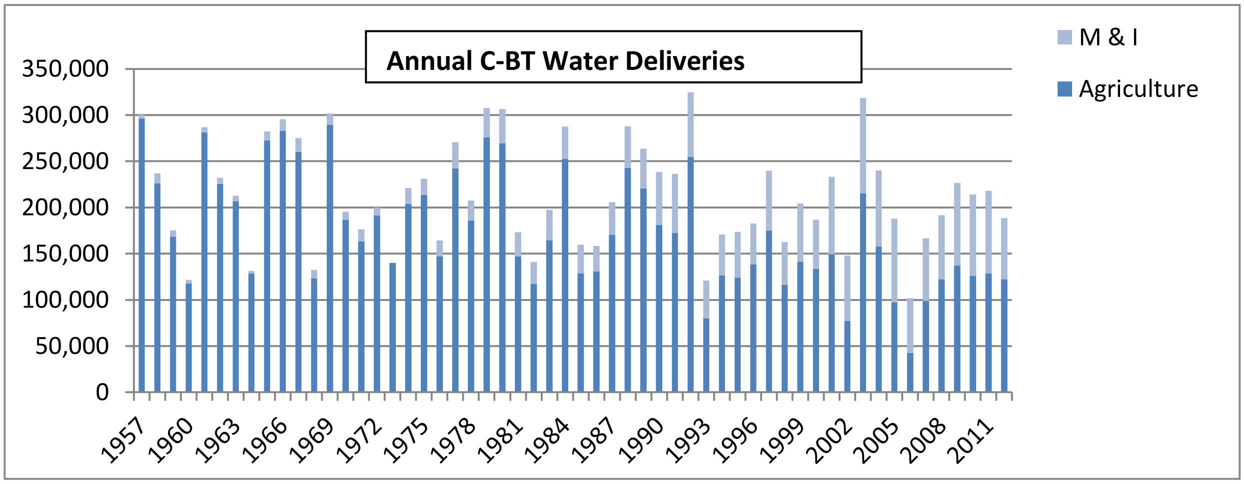


Figure 4)

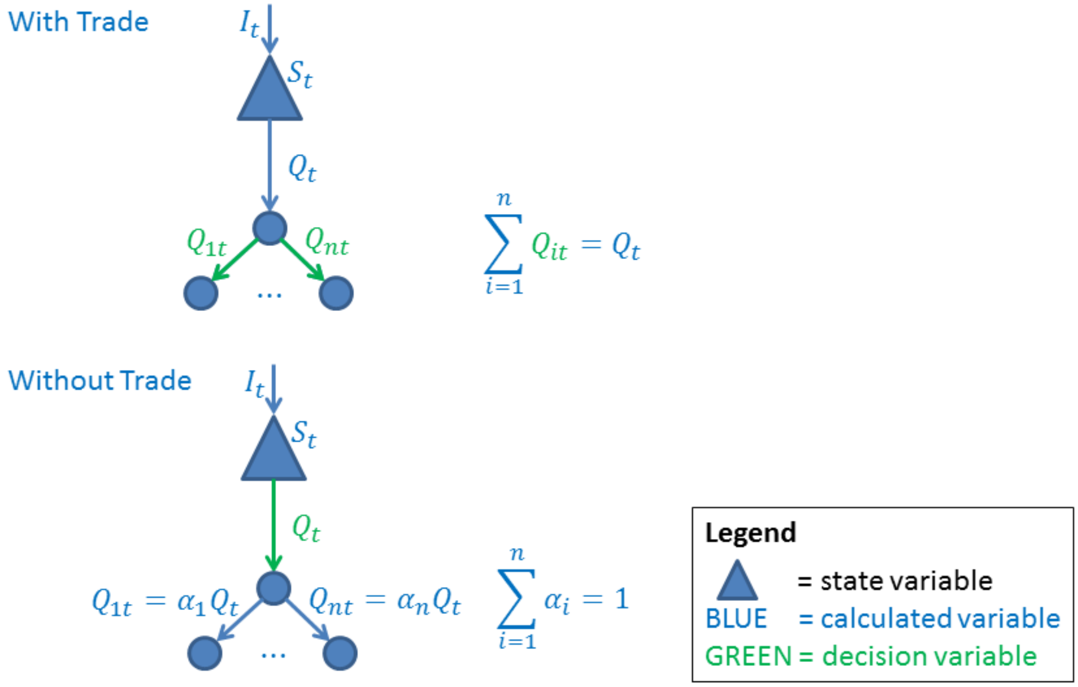
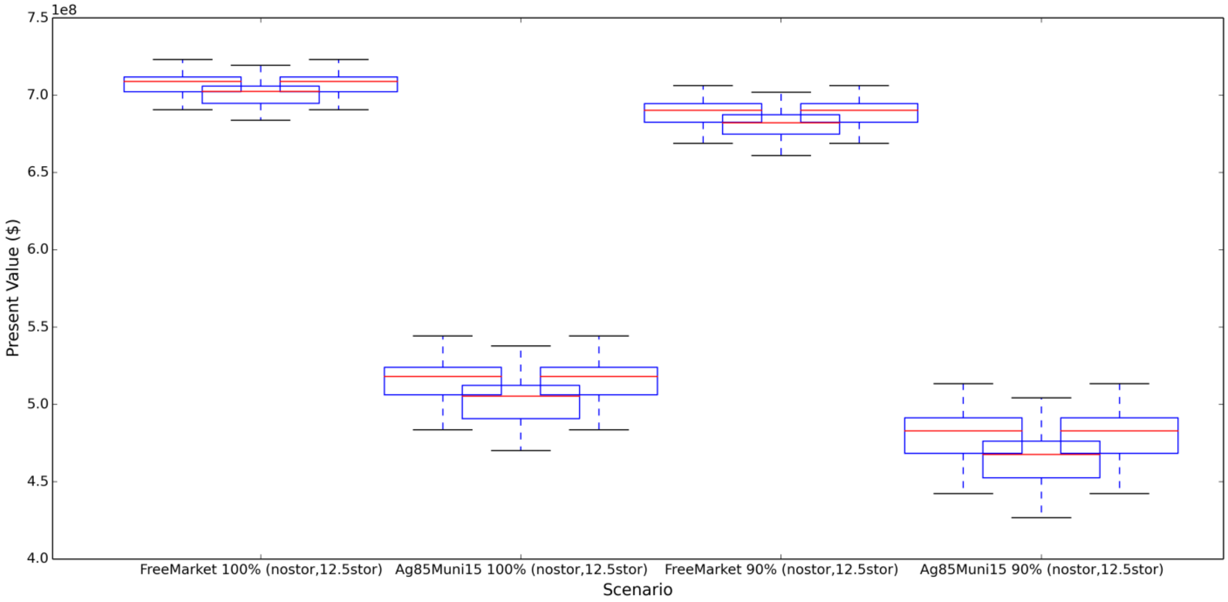


Figure 5)



Full Results

Mean NPV

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	$707,481,349	$701,012,835	$688,844,456	$707,481,349
36-64	$682,906,527	$666,232,558	$649,438,986	$682,911,729
15-85	$515,739,419	$502,767,315	$480,604,668	$515,777,742

Mean Municipal Price

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	$41	$43	$44	$42
36-64	$131	$134	$161	$131
15-85	$352	$365	$392	$352

Max Municipal Price

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	$132	$132	$205	$132
36-64	$407	$407	$493	$407
15-85	$607	$607	$643	$607

Min Municipal Price

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	$3	$24	$3	$3
36-64	$0	$3	$0	$0
15-85	$249	$249	$219	$222

Mean Agricultural Price

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	$41	$41	$45	$41
36-64	$36	$37	$39	$36
15-85	$28	$28	$31	$28

Max Agricultural Price

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	$62	$62	$62	$62
36-64	$53	$53	$55	$53
15-85	$50	$50	$53	$50

Min Agricultural Price

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	$17	$24	$45	$17
36-64	$25	$25	$25	$25

15-85	$13	$13	$5	$5

Mean Annual Value

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	$36,815,969	$36,553,200	$35,833,810	$36,815,969
36-64	$35,522,865	$34,740,651	$33,743,286	$35,525,269
15-85	$24,902,793	$26,208,991	$24,902,793	$26,765,244

Mean Storage Level

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	179,804	0	180,308	179,804
36-64	198,560	0	195,215	199,290
15-85	185,037	0	184,050	185,326

Results as a Percent of Baseline

Mean NPV

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	100.0%	99.1%	97.4%	100.0%
36-64	96.5%	94.2%	91.8%	96.5%
15-85	72.9%	71.1%	67.9%	72.9%

Mean Municipal Price

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	100.0%	106.9%	108.6%	103.5%
36-64	321.4%	329.6%	396.7%	321.4%
15-85	865.7%	897.7%	963.9%	865.6%

Max Municipal Price

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	100.0%	100.0%	155.7%	100.0%
36-64	308.8%	308.8%	373.8%	308.8%
15-85	460.4%	460.4%	487.5%	460.4%

Min Municipal Price

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	100.0%	703.6%	100.0%	100.0%
36-64	0.0%	78.6%	0.0%	0.0%
15-85	7268.8%	7268.8%	6386.1%	6466.3%

Mean Agricultural Price

	Current	No Storage	10% less inflow	12.5% more storage

Free Market	100.0%	100.8%	109.7%	100.0%
36-64	89.3%	90.0%	95.7%	89.3%
15-85	68.6%	69.4%	77.1%	68.6%

Max Agricultural Price

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	100.0%	100.0%	100.0%	100.0%
36-64	85.1%	85.1%	88.9%	85.1%
15-85	80.3%	80.3%	85.2%	80.3%

Min Agricultural Price

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	100.0%	141.6%	261.7%	100.0%
36-64	146.3%	147.7%	146.3%	146.3%
15-85	76.8%	76.8%	27.4%	31.9%

Mean Annual Value

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	100.0%	99.3%	97.3%	100.0%
36-64	96.5%	94.4%	91.7%	96.5%
15-85	67.6%	71.2%	67.6%	72.7%

Mean Storage Level

	Current	No Storage	10% less inflow	12.5% more storage
Free Market	100.0%	0.0%	100.3%	100.0%
36-64	110.4%	0.0%	108.6%	110.8%
15-85	102.9%	0.0%	102.4%	103.1%