Water Storage Capacities versus Water Use Efficiency: Substitutes or Complements?

Yang Xie David Zilberman

Department of Agricultural and Resource Economics
University of California, Berkeley
phd.yang.xie@gmail.com zilber11@berkeley.edu

Selected Paper prepared for presentation for the 2015 Agricultural & Applied Economics Association and Western Agricultural Economics Association Annual Meeting, San Francisco, CA, July 26–28.

Water Storage Capacities versus Water Use Efficiency: Substitutes or Complements?

Yang Xie* David Zilberman†

July 12, 2015

Abstract

We investigate the economic relation between two common approaches to tackling water scarcity and adapting to climate change, namely expanding water-storage capacities and improving water-use efficiency. We build, analyze, and extend a simple model for capacity choices of dams, incorporating stochastic, dynamic control of water inventories and efficiency in water use. We show that expanding water-storage capacities could encourage water users to improve water-use efficiency and improving water-use efficiency could increase optimal dam sizes even if water-use efficiency improvement decreases the water demand. This possibility of complementarity is numerically illustrated by an empirical example of the California State Water Project. Our analysis suggests that, if complementarity holds, resources should be distributed in a balanced way between water-storage expansions and water-use efficiency improvement instead of being invested on one activity while the other being ignored. Implications of this paper are applicable to the storage demand and consumption efficiency of other resources, for example, energy and food.

Keywords: Dam; reservoir; technology adoption; drip irrigation; drought; cost-benefit analysis; stochastic control; climate change; California State Water Project

*Corresponding author. Affiliation: Department of Agricultural and Resource Economics, University of California at Berkeley. Address: 207 Giannini Hall, University of California, Berkeley, CA 94720-3310, U.S. Email: phd.yang.xie@gmail.com.

†Affiliation: Department of Agricultural and Resource Economics, University of California at Berkeley.

Acknowledgements and Disclosure

We thank Julio Berbel, Peter Berck, Ujjayant Chakravorty, Yazhen Gong, Joshua Graff Zivin, Ernesto Guerra, Larry Karp, Mechel Paggi, Jeffrey Peterson, Andrew Stevens, Rebecca Taylor, Christian Traeger, Daniel Tregeagle, Russell Tronstad, Min Wang, Brian Wright, Lunyu Xie, Jintao Xu, and participants in seminars at the University of California, Berkeley and Peking University, the 2014 Western Agricultural Economics Association Annual Meeting, the 2014 Giannini Agricultural and Resource Economics Student Conference, the 4th Association of Environmental and Resource Economists Annual Conference, the 2015 Agricultural and Applied Economics Association and Western Agricultural Economics Association Joint Annual Meeting, and the 29th International Conference of Agricultural Economists for their valuable comments. We thank Angie Erickson for her help in editing.

An earlier version of this paper won the Second Place in the Graduate Student Paper Competition at the 2014 Western Agricultural Economics Association Annual Meeting. Another earlier version was posted as the University of California, Berkeley, Department of Agricultural and Resource Economics Working Paper 1138. The title of these earlier versions was *The Economics of Water Project Capacities under Optimal Water Inventory Management.* From these earlier versions to the current version, there are important changes in models and results.

1 Introduction

Water scarcity is among the most important constraints limiting social and economic development throughout the world. Climate change will make the constraint even tighter: As reported by the Intergovernmental Panel on Climate Change (Jiménez Cisneros et al., 2014, p. 251), "water resources are projected to decrease in many mid-latitude and dry subtropical regions, and ... even where increases are projected, there can be short-term shortages due to more variable streamflow (because of greater variability of precipitation) and seasonal reductions of water supply due to reduced snow and ice storage."

Two technological approaches are frequently considered to tackle water scarcity and adapt to climate change: One is to build dams, reservoirs, and other water projects to move water intertemporally (e.g., surveys by Yeh, 1985; Simonovic, 1992). The other is to improve water-use efficiency, for example, adopting conservation technologies like drip irrigation instead of flood irrigation in agriculture (e.g. surveys by Caswell, 1991; Sunding and Zilberman, 2001; Schoengold and Zilberman, 2007) and reducing the leaking and evaporation loss in water conveyance (e.g., Chakravorty et al., 1995). An important policy question then emerges: How should limited resources be allocated between the policies that provide incentives of the two approaches? The answer to this question is about the economic relation between water-storage capacities and water-use efficiency: Are they substitutes or complements?

This paper investigates this relation theoretically with empirical illustrations. More specifically, we focus on two questions:

1. Will improvement in water-use efficiency increase or decrease optimal dam capacities?

2. Will larger dam capacities encourage or discourage water users to improve efficiency?

People might intuitively believe that larger dams should discourage water-use efficiency improvement and that this improvement should make larger dams less desirable (e.g., the World Wide Fund for Nature, 2014; Beard, 2015). In other words, water-use efficiency and water-storage capacities should be substitutes. In this paper, we shall prove, however, that complementarity is possible: Water-use efficiency improvement could lead to more investment in water-storage capacities (and larger dams could encourage water-use efficiency improvement), *even if this improvement does decrease the water demand.* Sufficient conditions for this possibility are identified from the following sequence of logic and results:

1. We start by building a minimalistic two-period, stochastic model for capacity choices of dams, incorporating stochastic, dynamic control of water inventories and efficiency in water use, while holding constant site selection (e.g., Bıçak et al., 2002; the International Commission on Large Dams, 2007) and other important issues in dam design

(e.g., Hall, 1984; the International Union for Conservation of Nature and World Bank, 1997; Hurwitz, 2014). In this model, we recognize two primary purposes of dams: a *water-catchment* purpose to capture and transfer water from wet seasons or water-abundant areas to dry seasons or water-scarce areas, and a *stochastic-control* purpose to store water now for the possibility of droughts in the future.

2. We then prove, as Lemma 1, that the two questions we have asked are two sides of the same coin: Water-use efficiency improvement will increase optimal dam capacities, if and only if larger dams encourage water-use efficiency improvement. This lemma allows us to focus on either one between the two questions, knowing that the answer to the other question will follow. We choose to focus on Question 1—the impact of water-use efficiency on the optimal choice of dam capacities.

3. To answer Question 1, we investigate the marginal benefit of dam capacities. In Lemma 2, we prove that the marginal benefit of dam capacities depends on, first, the marginal benefit of water release once the dam is full and, second, the likelihood that the dam will be full. Therefore, the impact of water-use efficiency improvement on the marginal benefit of dam capacities have two channels—the *marginal-water-benefit* channel and the *full-dam-probability* channel. Since the marginal benefit of water release when the dam is full measures the value of additional water catchment, the *marginal-water-benefit* channel will be prominent if the dams's *water-catchment* purpose is important. Because the probability that the dam will be full in the future depends on how much water is stored now, the *full-dam-probability* channel would never exist if the dam did not managed water inventories, and this channel will be crucial if the dam carries a significant *stochastic-control* purpose.

4. We then analyze the two channels separately, and find that both of them are determined by the properties of the production function that uses water as input. Although these properties could be difficult to be directly observed, we can infer them from the properties of the water demand that is derived from the production function under profit maximization:

    - We prove, as Proposition 1, that the *marginal-water-benefit* channel will be positive if and only if water-use efficiency improvement will increase the water demand. This condition means that the marginal productivity of water declines rather slow as water use increases. This property can be quantified in Corollary 1 as the elasticity of the marginal productivity (EMP) of effective water being smaller than one.

- For the *full-dam-probability* channel, we prove, as Proposition 2, that, water-use efficiency improvement will increase the optimal amount of water stored for the future and, therefore, the probability that the dam will be full in the future, if water-use efficiency improvement does decrease the water demand but the decrease is larger at larger amounts of water. This condition is equivalent to having the marginal productivity of water declining fast and the decline not getting much slower as water use increases. Corollary 2 quantify these properties as the EMP being larger than one and the second-order elasticity of the marginal productivity (SEMP) being smaller than two.

5. Finally, we collect these two channels in Proposition 3: If any of these two channels is positive, complementarity between dam capacities and water-use efficiency will be possible. In particular, even if water-use efficiency improvement does decrease the water demand and, therefore, does make the *marginal-water-benefit* channel negative, a positive *full-dam-probability* channel could still create complementarity.

After discussing the implications of these results for economic analysis and policy issues, we analytically confirm these results in an extension with an infinite planning horizon. To illustrate all of the analyses, we specify this extended model to the irrigation water-inventory management problem of the California State Water Project. According to the California Department of Water Resources (1963–2013), in 2010, the Project is "the largest state-built, multipurpose, user-financed water project" in the United States and its water benefits "approximately 25 million of California's estimated 37 million residents" and "irrigates about 750000 acres of farmland." The significance of the Project in American and global agriculture establishes the practical significance of our analysis. Illustrations confirm the empirical relevance of our theoretical results and the existence of complementarity between dam capacities and water-use efficiency in the particular case. In the illustrations, the complementarity is more prominent in the positive impact of water-use efficiency improvement on water-storage expansions, but not the other way around.

Contribution to policy debates and literature. Our analysis directly contributes to a lasting and important debate about water-infrastructure investment in water-resource management. Dams, reservoirs, and other water-storage facilities have been an important contributor to human civilizations. They have been providing huge benefits in the agricultural, energy, and urban sectors, but frequently accompanied with huge environmental, ecological, social, and economic cost.[1] Without fully recognizing these costs, dams have been

[1]Dams have turned deserts in California's Central Valley into one of the most productive agricultural regions in the world, have survived large cities in Northern China like Beijing through the periodic droughts

overbuilt, causing major struggles across the world, e.g., in the western United States, as depicted in Reisner (1993)'s *Cadillac Desert*.[2] Improving water-use efficiency is then increasingly perceived as an important alternative to dam building (e.g., the World Commission on Dams, 2000; Schwabe and Connor, 2012; Olen et al., Forthcoming). The cost-benefit analysis method and the symbol of its success in practice, the United States Water Resources Council (1983)'s *Principles and Guidelines* for the United States Army Corps of Engineers, have also been criticized as often overemphasizing structural measures but overlooking the alternative approach (e.g., Zilberman et al., 1994; the World Commission on Dams, 2000). Some scholars further advise policymakers not to build large dams (e.g., Ansar et al., 2014). Our analysis suggests that dam building and water-use efficiency improvement could be mutually inclusive and that the relation between these two approaches varies in different circumstances.

Our paper would provide implications for many major water-policy debates about competition between these two approaches for limited resource. For example, in response to the devastating drought since 2012 in the western United States and, especially, California, lawmakers have been working at both federal and state levels to authorize and fund expansions of water infrastructures, as many studies have documented huge benefit from water projects in reducing the drought impact in this area (e.g., Hansen et al., 2011, 2014; Howitt et al., 2011; Zilberman et al., 2011).[3] Opponents of infrastructure expansions, however, think that money should be spent only to subsidize recycling projects and conservation-technology adoption, as they believe that the efficiency improvement will lead to smaller and fewer dams demanded and that dam expansions would severely discourage conservation effort.[4] Our analysis implies, however, that resources should be distributed in a balanced way between dam expansions and water-use efficiency improvement, instead of being concentrated

in the area, and, in Reisner (1993, p. 162–164)'s words, have produced "American hydroelectric capacity that could turn out sixty thousand aircraft in four years," which "simply outproduced" the Axis and helped the Allies win the Second World War. The benefits are not costless. For example, when dams are built, the natural environment is seriously altered, in many cases irreversibly, and the salmon and other aquatic species are endangered. Sometimes numerous families are displaced and historic and cultural sites are covered. Huge potential loss associated with the dam failure risk is also created. For the recent debate on the cost-benefit accounting about large dams, see Ansar et al. (2014), Nombre (2014).

[2]For the politics about the United States Central Valley Project Improvement Act of 1992, see Fischhendler and Zilberman (2005). For the controversy about China's Three Gorges Dam, see Jackson and Sleigh (2000). For the disappointment of dams in India, see McCully (2001) and Duflo and Pande (2007).

[3]Goodhue and Martin (2014) and Howitt et al. (2014, 2015) present estimates of the loss caused by the drought. As a result of the drought, in January 2014, the California Department of Water Resources announced the first zero water allocation from the California State Water Project in the Project's 54-year history. In April 2015, the Governor of California, Jerry Brown, directed the first ever statewide mandatory water reductions. For an example of media coverage on the severeness of the drought, see Serna (2014) and Walton (2015).

[4]For examples of the debate, see Calefati (2014), Dunning and Machtinger (2014), and Hanson (2015).

on either side.

This paper connects three threads of literature: on water-infrastructure investment, inventory management of water and other storable commodities, and irrigation-technology adoption. In particular, to our knowledge, our simple and extended models are the first in the literature on capacity choices of water projects (e.g., Miltz and White, 1987; Tsur, 1990; Fisher and Rubio, 1997; Schoengold and Zilberman, 2007; Haddad, 2011; Houba et al., 2014; Xie and Zilberman, 2014a) to incorporate water-use efficiency and stochastically, dynamic control of water inventories. This effort is necessary for us to answer the two questions. We are therefore the first to identify water-use efficiency as a potential factor affecting water-storage investment.

Second, the literature on optimal inventory management of water generally focuses on the optimal management of existing storage systems (e.g., Burt, 1964; Riley and Scherer, 1979; Gisser and Sánchez, 1980; Dudley and Musgrave, 1988; Tsur and Graham-Tomasi, 1991; Chatterjee et al., 1998; Freebairn and Quiggin, 2006; Brennan, 2008; Hughes and Goesch, 2009; Truong, 2012; Truong and Drynan, 2013). Our paper, however, has an additional focus on the optimal adjustment of existing storage systems or optimal design of new storage systems. Fisher and Rubio (1997) have made an admirable attempt in this direction on dam renovations, but their analysis is restricted to the mean level of the equilibrium. In this paper, we provide the first analytical comparative statics about the marginal benefit of water-storage capacities in the whole equilibrium. Our extended model can also be regarded as an extension of the competitive storage model for commodity markets (e.g., Working, 1933; Gustafson, 1958; Samuelson, 1971; Gardner, 1979; Newbery and Stiglitz, 1981; Scheinkman and Schechtman, 1983; Williams and Wright, 1991; Deaton and Laroque, 1992; Chambers and Bailey, 1996; Bobenrieth et al., 2002), where Truong (2012) and Asche et al. (2014) are among the first to discuss the impact of storage capacities on the equilibrium of the model. Our model extends this literature by analyzing the impact of other parameters on choices of storage capacities. This effort is technically not trivial, as the comparative statics about long-run behaviors of the competitive storage model is analytically so difficult that only few exceptions have attempted (e.g., Deaton and Laroque, 1992; Truong, 2012).

Third, the rich literature on irrigation-technology adoption considers the impacts of many factors on the adoption and water conservation (e.g., Caswell and Zilberman, 1986; Caswell et al., 1990; Dinar and Yaron, 1992; Dinar et al., 1992; Shah et al., 1995; Green et al., 1996; Khanna and Zilberman, 1997; Carey and Zilberman, 2002; Koundouri et al., 2006; Baerenklau and Knapp, 2007; Schoengold and Sunding, 2014; Olen et al., Forthcoming), but not the impact of changes in water-storage capacities. Our analysis adds water-storage capacities to the list of potential factors affecting irrigation-technology adoption and water conservation. This contribution is important given that large dams and reservoirs usually affect a large number of water users.

Both sides of our complementarity result are further related to resource economics in a broader perspective. The positive impact of water-storage capacities on water-use efficiency improvement is linked to the literature on underinvestment in efficiency improvement of energy and other resource use (e.g., surveys by Jaffe and Stavins, 1994; Jaffe et al., 2004; Gillingham et al., 2009; Linares and Labandeira, 2010; Allcott and Greenstone, 2012; Gerarden et al., 2015a,b). Our result adds underinvestment in storage of resources to the list of potential factors inducing underinvestment in resource-use efficiency. Furthermore, the positive impact of water-use efficiency on optimal water-storage capacities is also related to the rebound effect, also named the Jevons (1865) paradox and the Khazzoom (1980)–Brookes (1992) postulate. In the literature, a positive rebound effect on energy or water use could offset the resource-saving effect of efficiency improvement in the use of resources (e.g., Scheierling et al., 2006b; Ward and Pulido-Velazquez, 2008; the European Commission, 2012; Berbel and Mateos, 2014; Pfeiffer and Lin, 2014; Chan and Gillingham, 2015; Cobourn, 2015; surveys by Greening et al., 2000; Alcott, 2005; Hertwich, 2005; Sorrell, 2009; Berbel et al., 2015). We extend the literature by showing that efficiency improvement could still increase the demand for storage investment even if it decreases the temporary demand for resource use.

Last, but not least, our results have some counterintuitive implications for the rich body of literature on the relation between infrastructure investment and resource conservation (e.g., on roads and deforestation, Chomitz and Gray, 1996; Nelson and Hellerstein, 1997; Pfaff, 1999; Cropper et al., 2001; Deng et al., 2011; on roads and groundwater depletion, Chakravorty et al., 2015). In particular, increasing concerns about environmental externality that lead to smaller dams could also lead to less conservation effort like adoption of more-efficient irrigation technologies. At the same time, the huge progress and potential of this adoption across the world (e.g., Postel, 2013) could increase the demand for water-storage investment and will eventually increase consumptive use of water and environmental damage, even though both of the outcomes are optimal from the efficiency perspective that takes market and environment considerations into account. This implication is consistent with and more than the emerging agreement among water economists that adoption of efficient irrigation technologies often leads to higher consumptive use of water (e.g., the International Water Resource Economics Consortium, 2014).

The paper is unfolded as follows. Section 2 builds the two-period, stochastic model. Section 3 analyzes this model and derives the results. Section 4 discusses the implications of these results. Section 5 extends the planning horizon to infinity. Section 6 shows the numerical illustrations and Section 7 concludes the paper.

2 The Two-Period, Stochastic Model

The model has two stages. The second stage is a problem of stochastic, dynamic control of water inventories, given the two key parameters for our purpose—the dam capacity, $\bar{a}$, and water-use efficiency, α. As illustrated by Figure 1, we assume that there are two periods, 0 and 1, and that, in each period, a wet season proceeds and a dry season follows. In period 0, given the amount of water availability in the wet season, $a_0 > 0$, the dam captures water as much as its capacity allows, $\min\{a_0, \bar{a}\}$. In the dry season, there is no water added to the dam, and the dam chooses how much water to release, $w_0 \in [0, \min\{a_0, \bar{a}\}]$, and how much to store and carry to period 1, $s_0 \equiv \min\{a_0, \bar{a}\} - w_0$. For clarification, we call s_0 the *water storage* and $\bar{a}$ the *dam* or *water-storage capacities*. In period 1, there is a stochastic inflow to the dam in the wet season, $e_1 \in [\underline{e}, \bar{e}]$, where $\underline{e} > 0$. The water availability is then

$$a_1 \equiv e_1 + (1 - d)s_0, \tag{1}$$

where d is the rate of evaporation between the periods. The dam still captures water of $\min\{a_1, \bar{a}\} \geq 0$. In the dry season, there is still no water added to the dam, and the dam just releases all it has, $w_1 \equiv \min\{a_1, \bar{a}\}$. In each period, the water release, w_t with $t \in \{0, 1\}$, generates the benefit of $B(w_t, \alpha)$.

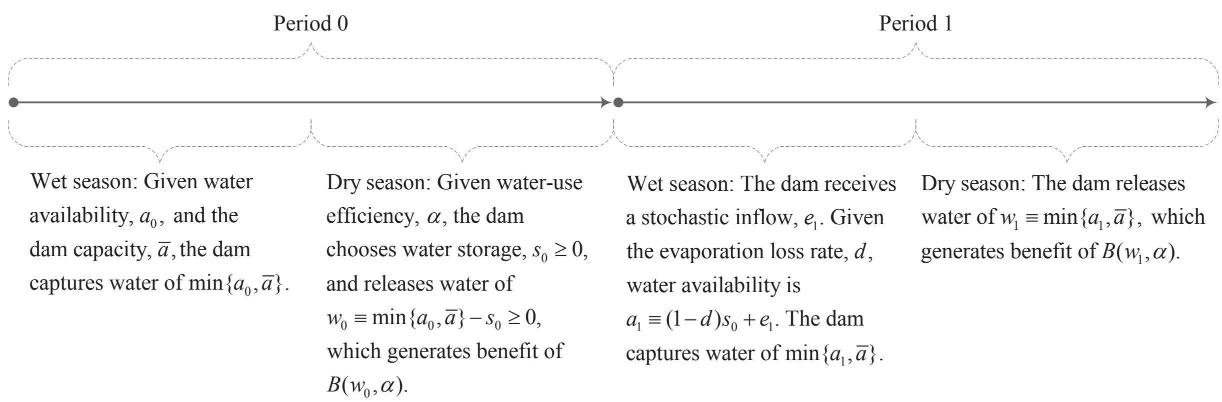


Figure 1: Operation of the dam in the two-period, stochastic model

It is important to note that, in this model, the dam capacity has two purposes:

1. The water-catchment purpose: It sets the maximum amount of water that human use deprives from the natural environment and moves between seasons or areas.[5]

[5]The wet season and the dry season can also be interpreted as a water-abundant area and a water-scarce

2. The stochastic-control purpose: It gives room to control water inventories dynamically and stochastically.

In literature there are alternative ways to model purposes of dam capacities. For example, Fisher and Rubio (1997) and Hughes and Goesch (2009) assume that dams only have the stochastic-control purpose and that spills generate irrigation benefit as regulated water release does. Considering highly seasonal inflows, in our model, we recognize the water-catchment purpose of dams and assume that spills in wet seasons are not captured so it cannot be utilized to generate benefit. This approach is consistent with some economic models (e.g., Truong, 2012) and most dam models in applied probability theory (e.g., Moran, 1959).

Following the idea of Caswell and Zilberman (1986), we further assume that the function of water benefit, $B(w_t, \alpha)$, is the benefit generated by effective water, $\mathcal{B}(\alpha w_t)$. In other words, α measures input efficiency—the proportion of applied water that is effectively used. Adopting more-efficient irrigation technologies, improving conveyance, and reducing evaporation between wet and dry seasons would then increase $\alpha \in [0, 1]$.[6] We assume that regular assumptions, such as $\mathcal{B}''(\cdot) < 0$, $\mathcal{B}''(\cdot)$ is continuous almost everywhere, and $0 < \mathcal{B}'(\cdot) < \infty$, also apply here. It is also important to recall that the marginal benefit of or inverse demand for water is $B_1(w_t, \alpha) \equiv \alpha\mathcal{B}'(\alpha w_t)$, and the impact of higher water-use efficiency on it is $B_{12}(w_t, \alpha) \equiv \mathcal{B}'(\alpha w_t) + \alpha w_t \mathcal{B}''(\alpha w_t)$. Therefore, higher water-use efficiency will decrease the (inverse) demand for water if and only if the marginal productivity of effective water, $\mathcal{B}'(\alpha w_t)$, declines sufficiently fast. Also, if the decline does not get much slower as effective water increases, the negative impact of higher water-use efficiency on the (inverse) demand for water will be larger for larger water use.

Under the stochastic, dynamic control of water inventories, the (gross) value that is generated by the dam is

$$V^*(\bar{a}, a_0, \alpha) \equiv \max_{w_0, s_0} \{B(w_0, \alpha) + \rho \mathbf{E}_0 [B(w_1, \alpha)]\} \qquad \text{s.t.} \tag{2}$$

$$s_0 \geq 0,\ w_0 = \min\{a_0, \bar{a}\} - s_0 \geq 0,\ a_1 = (1-d)s_0 + e_1,\ w_1 = \min\{a_1, \bar{a}\}, \tag{3}$$

area.

[6]Chakravorty et al. (1995, 2009) have discussed the optimal design of the distribution and allocation system. As the economics of the distribution and allocation system is not our paper's main focus, we leave the functioning of the system out of the model. The function $B(\cdot, \cdot)$ can include agricultural, industrial, and environmental benefit and any other outcomes of the dams that depend on water storage or release, e.g., drought relief and flood control. For a general description of the various benefit generated by dams, see the World Commission on Dams (2000). The function of the benefit of water release has already accounted for any downstream economic distortions.

where ρ is the discount factor. The problem is equivalent to

$$V^*(\bar{a}, a_0, \alpha) \equiv \max_{s_0} \{B(\min\{a_0, \bar{a}\} - s_0, \alpha) + \rho \mathbf{E}_0 [B(\min\{(1-d)s_0 + e_1, \bar{a}\}, \alpha)]\} \text{ s.t.} \quad (4)$$

$$s_0 \geq 0, \ \min\{a_0, \bar{a}\} - s_0 \geq 0. \quad (5)$$

The first stage of the model is about the choice of the dam capacity. Taking the initial water availability, a_0, and water-use efficiency, α, as given, the dam designer maximizes the dam generated value, $V^*(\bar{a}, a_0, \alpha)$, net of the construction, maintenance, and environmental-damage cost, $C(\bar{a})$, by choosing the dam capacity, $\bar{a}$:

$$\max_{\bar{a} \geq 0} \qquad V^*(\bar{a}, a_0, \alpha) - C(\bar{a}). \quad (6)$$

This decision can also be interpreted as how much to adjust the total water-storage capacity of a huge water system by introducing a new dam or removing an old dam.[7] Especially for large dams, the dam cost should also include social cost, for example, displacement of residents and demolishing of historical and cultural sites. The environmental-damage cost should also include the opportunity cost of the water that is captured by the dam and would be used instead for other environmental and ecological purposes, for example, surviving aquatic species, in the form of overflows. The marginal-cost function is assumed positive and increasing, which means that $C'(\cdot) > 0$ and $C''(\cdot) > 0$.[8]

3 Analysis and Results

3.1 Equivalence between the Two Questions

Recall the two questions:

1. Will water-use efficiency improvement increase the optimal dam capacity?

2. Will larger dam capacities encourage water users to improve the efficiency?

The first result from the model is that these two questions are two sides of the same coin:

[7] Readers might want to think $a_0 \equiv 0$ as there is no water in the dam when the dam is built. Readers can also think $a_0 \equiv e_0$, the inflow into the dam in the first season. The difference between the interpretations is minor in our analysis. For simplicity, we leave a_0 in the dam generated value function without specifying it.

[8] The assumption is not too unrealistic, since the resource for dam building and maintenance is always limited. As larger dams make the ecological system more vulnerable to further human actions, it is also fair to assume an increasing marginal environmental-damage cost. Furthermore, the assumption makes the dam-capacity problem have solutions.

Lemma 1 (Two sides of the same coin). *Water-use efficiency improvement will lead to larger/smaller optimal dam capacities, if and only if larger dams will increase/decrease the incentive for water users to improve water-use efficiency. This complementarity/substitution holds, if and only if the cross elasticities of the marginal value (CEMV) of dam capacities and water-use efficiency,* $\frac{\alpha \cdot dV_1^*(\bar{a}^*, a_0, \alpha)}{V_1^*(\bar{a}^*, a_0, \alpha) \cdot d\alpha}$ *and* $\frac{\bar{a} \cdot dV_3^*(\bar{a}^*, a_0, \alpha)}{V_3^*(\bar{a}^*, a_0, \alpha) \cdot d\bar{a}}$*, are positive/negative. Equivalently, this complementarity/substitution holds, if and only if the cross-partial derivative (CPD) of the dam generated value with respect to dam capacities and water-use efficiency,* $V_{13}^*(\bar{a}^*, a_0, \alpha)$*, is positive/negative.*

Appendix A.1 proves Lemma 1. The main idea is that, as the dam generated value is well-behaved (almost everywhere), the impact of water-use efficiency on the marginal benefit of dam capacities, $V_{13}^*(\bar{a}^*, a_0, \alpha)$, and the impact of dam capacities on the marginal contribution of water-use efficiency to the dam generated value, $V_{31}^*(\bar{a}^*, a_0, \alpha)$, should be equivalent (almost everywhere). Since changes in the marginal benefit of dam capacities will change the optimal choice of dam capacities and changes in the marginal contribution of water-use efficiency will change the optimal investment in water-use efficiency, the equivalence between the two questions is derived.

Lemma 1 implies that, once we answer either question, we will straightly know the answer to the other question. We then choose to focus on Question 1—whether water-use efficiency will lead to larger or smaller dams—in our analysis hereafter.

3.2 Two Channels in the Impact of Water-Use Efficiency on Optimal Choices of Dam Capacities

To answer Question 1, we need to investigate the marginal benefit of dam capacities and the impact of water-use efficiency improvement on it. This investigation starts from the problem of stochastic, dynamic control of water inventories. There could be three scenarios of storage–release decisions in period 0:

1. Zero release: $w_0^* = 0$, $s_0^* = \min\{a_0, \bar{a}\}$;

2. Positive storage (and positive release): $w_0^* = \min\{a_0, \bar{a}\} - s_0^* \in (0, \min\{a_0, \bar{a}\})$;

3. Zero storage: $w_0^* = \min\{a_0, \bar{a}\} > 0$, $s_0^* = 0$.

About the three scenarios, first, note that optimal management of water inventories will not allow the zero-release scenario: If all of the captured water in period 0 is stored, the marginal benefit of water release in period 0 will be so high that releasing even a tiny bit of water will be beneficial.[9]

Second, if the positive-storage scenario happens under optimal management of water inventories, the dam generated value will be

$$V^*(\bar{a}, a_0, \alpha) = B(\min\{a_0, \bar{a}\} - s_0^*, \alpha) + \rho \mathbf{E}_0 \left[B(\min\{(1-d)s_0^* + e_1, \bar{a}\}, \alpha) \right] \tag{7}$$

with an Euler equation,

$$B_1(\min\{a_0, \bar{a}\} - s_0^*, \alpha) = \rho(1-d)\mathbf{E}_0 \left[I_{(1-d)s_0^* + e_1 \leq \bar{a}} \cdot B_1((1-d)s_0^* + e_1, \alpha) \right]. \tag{8}$$

The left-hand side of the equation is the cost that a marginal increase in the water storage will incur, which is the current marginal benefit of water. The right-hand side is the benefit that the marginal water storage will generate. Note that the marginal water storage will not generate any benefit if the dam is full in the future: In this case, the dam will not be able to capture the additional water. The equation implies that the optimal water storage, s_0^*, should make the marginal cost and benefit equal, because, otherwise, the dam operator would be able to improve the dam generated value by adjusting the storage-release decision.

Third, if the zero-storage scenario happens under optimal management of water inventories, the dam generated value will be

$$V^*(\bar{a}, a_0, \alpha) = B(\min\{a_0, \bar{a}\}, \alpha) + \rho \mathbf{E}_0 \left[B(\min\{e_1, \bar{a}\}, \alpha) \right] \tag{9}$$

with an Euler inequation,

$$B_1(\min\{a_0, \bar{a}\}, \alpha) \geq \rho(1-d)\mathbf{E}_0 \left[I_{e_1 \leq \bar{a}} \cdot B_1(e_1, \alpha) \right], \tag{10}$$

which means that it is not beneficial to store even a tiny bit of water.

In the positive-storage and the zero-storage scenarios, the marginal benefit of dam capacities is

$$V_1^*(\bar{a}, a_0, \alpha) = I_{a_0 > \bar{a}} \cdot B_1(\bar{a} - s_0^*, \alpha) + \rho B_1(\bar{a}, \alpha) \mathbf{P}_0 \left[(1-d)s_0^* + e_1 > \bar{a} \right]. \tag{11}$$

[9] To see this point, suppose that it is optimal to store all of the captured water in period 0 for period 1. An Euler inequation, $B_1(0, \alpha) \leq \rho(1-d)\mathbf{E}_0 \left[I_{(1-d)\min\{a_0, \bar{a}\} + e_1 \leq \bar{a}} \cdot B_1\left((1-d)\min\{a_0, \bar{a}\} + e_1, \alpha\right) \right]$, must hold. This is impossible, however, because $\rho(1-d)\mathbf{E}_0 \left[I_{(1-d)\min\{a_0, \bar{a}\} + e_1 \leq \bar{a}} \cdot B_1\left((1-d)\min\{a_0, \bar{a}\} + e_1, \alpha\right) \right] \leq B_1(\min\{\underline{e}, \bar{a}\}, \alpha) < B_1(0, \alpha)$.

This expression carries important intuition: If and only if the dam is currently full, which corresponds to $a_0 > \bar{a}$, or is full in the future, which corresponds to $(1-d)s_0^* + e_1 > \bar{a}$, a marginal increase in dam capacities will help to capture some additional water, generating the marginal benefit of water release, which is $B_1(\bar{a} - s_0^*, \alpha)$ or $B_1(\bar{a}, \alpha)$.

Most importantly, this expression implies that the impact of water-use efficiency on the marginal benefit of dam capacities is

$$\begin{aligned} V_{13}^*(\bar{a}, a_0, \alpha) = I_{a_0 > \bar{a}} \cdot & \left(B_{12}(\bar{a} - s_0^*, \alpha) - B_{11}(\bar{a} - s_0^*, \alpha) \frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha} \right) \\ & + \rho B_{12}(\bar{a}, \alpha) \left[1 - F_{e_1}\left(\bar{a} - (1-d)s_0^* \right) \right] \\ & + \rho (1-d) B_1(\bar{a}, \alpha) f_{e_1}\left(\bar{a} - (1-d)s_0^* \right) \frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha}, \end{aligned} \tag{12}$$

where $s_0^* \equiv s_0^*(\bar{a}, a_0, \alpha)$ is the optimal water storage given the dam capacity, the initial water availability, and water-use efficiency, $F_{e_1}(\cdot)$ is the cumulative distribution function of the future inflow, and $f_{e_1}(\cdot)$ is the probability density function of the future inflow. We then see the two channels through which water-use efficiency can affect the marginal benefit of dam capacities and the optimal choice of dam capacities:

Lemma 2 (Two channels)**.** *Water-use efficiency, α, affects the marginal benefit of dam capacities, $V_1^*(\bar{a}, a_0, \alpha)$, and the optimal dam capacity, $\bar{a}^*$, through two channels:*

1. *The marginal-water-benefit channel: It can change s_0^*, the optimal water storage, and can change $B_1(w, \alpha)$, the inverse function of the water demand (or inverse demand for water), given any w. These two changes will collectively alter the marginal benefits of water release when the dam is full, $B_1(\bar{a} - s_0^*, \alpha)$ and $B_1(\bar{a}, \alpha)$. This channel is represented by the first two terms in Equation (12).*

2. *The full-dam-probability channel: It can change the optimal water storage, s_0^*. This change will individually alter the probability that the dam will be full in the future, $\mathbf{P}_0\left[(1-d)s_0^* + e_1 > \bar{a}\right]$. This channel is represented by the third term in Equation (12).*

It is important to see that the full-dam-probability channel would never be recovered if there were no *stochastic, dynamic* control of water inventories: The channel depends on the probability that the dam is full in the future, which would become meaningless if inflows were not stochastic. The channel also relies on the storage-release decision, which would be assumed away if the dam did not control water inventories dynamically.

Guided by Lemma 2, we shall analyze the determinants of the directions of the two channels and, eventually, identify conditions under which water-storage capacities and water-use efficiency are complements or substitutes.

3.3 The Marginal-Water-Benefit Channel

Proposition 1 (The marginal-water-benefit channel)**.** *The impact of water-use efficiency on the optimal choice of dam capacities through the marginal-water-benefit channel will be positive if and only if water-use efficiency improvement will increase the inverse demand for water. Mathematically, the sum of the first two terms in Equation (12) will be positive/negative if* $B_{12}(w, \alpha)$ *is positive/negative for any* $w \in [(1-d)\bar{s} + \underline{e}, \bar{a}]$*, where* $\bar{s}$ *denotes* $s_0^*(\bar{a}, a_0, \alpha)$ *for* $a_0 \geq \bar{a}$*.*

Appendix A.2 proves Proposition 1. The main intuition is that the direct effect through the shift in the inverse demand for water caused by water-use efficiency improvement will always dominate any indirect effect through the change in the optimal water storage.

Proposition 1 emphasizes the impact of water-use efficiency improvement on the marginal benefit of or inverse demand for water. As mentioned in Section 2, if the marginal productivity of effective water declines slow as effective water increases, then water-use efficiency improvement will increase the inverse demand for water. In other words, the slope of the downward-sloping marginal productivity is flat. Mathematically, we have

$$B_{12}(w, \alpha) = \frac{d^2\mathcal{B}(\alpha w)}{d\alpha dw} = \mathcal{B}'(\alpha w) + \alpha w \mathcal{B}''(\alpha w). \tag{13}$$

Therefore, $B_{12}(w, \alpha) \geq 0$ is equivalent to

$$\text{EMP} \equiv -\frac{\alpha w \mathcal{B}''(\alpha w)}{\mathcal{B}'(\alpha w)} \leq 1, \tag{14}$$

where EMP represents the elasticity of the marginal productivity of effective water. We document this result as a corollary:

Corollary 1 (EMP in the marginal-water-benefit channel)**.** *The impact of water-use efficiency on the optimal choice of dam capacities through the marginal-water-benefit channel will be positive if and only if the marginal productivity of effective water declines sufficiently slow. Equivalently, the elasticity of the marginal productivity (EMP) of effective water is smaller than one.*

Proposition 1 and Corollary 1 follow the established literature on the importance of the EMP in the relation between the water demand and water-use efficiency, which starts with

Caswell and Zilberman (1986) and is well noted in other studies (e.g., surveys by Feder and Umali, 1993; Lichtenberg, 2002). Xie and Zilberman (2014a) apply this idea to the demand for water projects without inventory management. Proposition 1 and Corollary 1 extend the application to the demand for water-storage capacities.

This extension is intuitive from the perspective of economic theory. The marginal-water-benefit channel is the direct reflection of the water-catchment purpose of dam capacities. An increase in water-use efficiency actually increases effective water given the total water use, so whether more water and larger water-catchment capacities will be demanded should depend on the change in the marginal productivity of effective water—the second-order property of the benefit of effective water. The EMP is just a measure about the second-order property.

3.4 The Full-Dam-Probability Channel

It is first obvious that, in the zero-storage scenario, the impact of water-use efficiency on the optimal choice of dam capacities through the full-dam-probability channel does not exist. In the positive-storage scenario, we have the following result:

Proposition 2 (The full-dam-probability channel)**.** *In the positive-storage scenario, the impact of water-use efficiency on the optimal choice of dam capacities through the full-dam-probability channel will be positive, if water-use efficiency improvement decreases the inverse demand for water and the decrease is larger with larger water use. Mathematically, the third term in Equation (12) will be positive if* $B_{12}(w, \alpha) \leq 0$*,* $B_{121}(w, \alpha) \leq 0$*,* $B_{111}(w, \alpha) \leq 0$*, and* $B_{1211}(w, \alpha) \geq 0$ *for any* $w \in [\underline{e}, (1-d)\bar{s} + \bar{e}]$*.*

Appendix A.3 proves Proposition 2. Figure 2 illustrates the intuition. The figure plots the decision of the optimal water storage, which is determined by the Euler equation,

$$B_1(\min\{a_0, \bar{a}\} - s_0^*, \alpha) = \rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq\bar{a}} \cdot B_1((1-d)s_0^* + e_1, \alpha)\right], \tag{15}$$

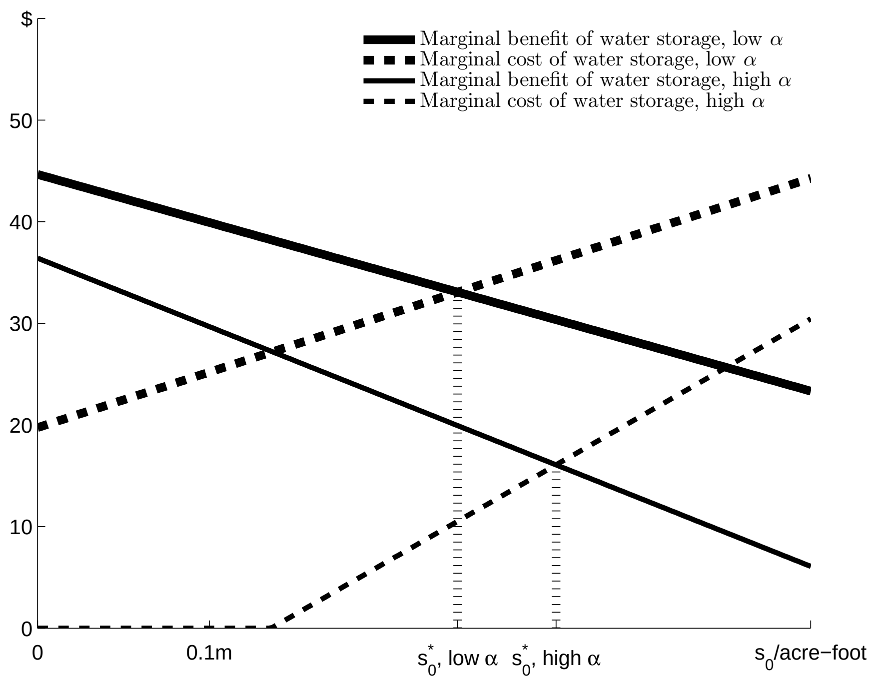
which is the same as Equation (8). The solid lines are the right-hand side, the benefit of a marginal increase in the water storage, s_0. The dashed lines are the left-hand side, the marginal cost of water storage. The optimal water storage, s_0^*, should make the marginal benefit and marginal cost intersect. If water-use efficiency improvement decreases the inverse demand for water, both sides of the Euler equation will be shifted down, so the impact on the optimal water storage will depend on the relative magnitudes of the shifts. For an intuitive interpretation, we can roughly consider

$$\mathbf{E}_0\left[B_1((1-d)s_0 + e_1, \alpha)\right] \approx B_1((1-d)s_0 + \mathbf{E}_0\left[e_1\right], \alpha) \tag{16}$$

and approximate the Euler equation as

$$B_1(\min\{a_0, \bar{a}\} - s_0^*, \alpha) \approx \rho(1-d)B_1((1-d)s_0 + \mathbf{E}_0\left[e_1\right], \alpha). \tag{17}$$

This approximation suggests that the current water release, $\min\{a_0, \bar{a}\} - s_0^*$, should roughly be larger than the mean of the future water release, $(1-d)s_0 + \mathbf{E}[e_1]$, because, otherwise, the marginal benefit of water in the future would be lower than that now and it would not be beneficial to store any water. Given this observation, if the decrease in the inverse demand for water caused by water-use efficiency improvement is larger with larger water use, then the shift in the marginal cost of water storage will be larger than that in the marginal benefit of water storage. Therefore, the optimal water storage will increase.[10] This increase will increase the probability that the dam will be full in the future.



With $B_{12}(w, \alpha) \leq 0$, $B_{121}(w, \alpha) \leq 0$, $B_{111}(w, \alpha) \leq 0$, and $B_{1211}(w, \alpha) \geq 0$, water-use efficiency improvement will increase the optimal water storage, s_0^*, and the likelihood of the dam reaching the full capacity in the future, $\mathbf{P}[(1-d)s_0^* + e_1 \geq \bar{a}]$. The direction of the full-dam-probability channel is then positive. Specification: $B(w, \alpha) = 181.0 \cdot \alpha x - \frac{1.5\times10^{-4}}{2} \cdot (\alpha x)^2$, where $x \equiv \min\left\{w, \frac{181.0}{1.5\times10^{-4}\cdot\alpha}\right\}$, low $\alpha = 0.6$, high $\alpha = 0.8$, $\bar{a} = 2038052$, $a_0 = 0.8\bar{a}$, $d = 0.04$, $\rho = 0.9434$, the probability of $e_1 = 975785$ is 0.8, and the probability of $e_1 = 1536597$ is 0.2

Figure 2: An example of water-use efficiency increasing the optimal water storage

It is also important to observe that this intuition will hold even if $\rho(1-d)$ is close to one.

[10]Conditions such as $B_{111}(w, \alpha) \leq 0$ and $B_{1211}(w, \alpha) \geq 0$ polish the argument with technical details.

This observation implies that the different magnitudes of the shifts in the marginal benefit and the marginal cost of water storage comes from not only the regular "discount-factor effect" but also the properties of the marginal productivity of effective water.

Proposition 2 emphasizes the monotonicity of the impact of water-use efficiency improvement on the marginal benefit of water with respect to water use. Which characteristic of the water benefit is determining the monotonicity? As mentioned above, if the decline of the marginal productivity of effective water does not get much slower as effective water increases, then $B_{121}(w, \alpha) \leq 0$. In other words, the marginal productivity of effective water is not extremely convex. Mathematically, we have

$$B_{121}(w, \alpha) = 2\alpha\mathcal{B}''(\alpha w) + \alpha^2 w\mathcal{B}'''(\alpha w). \tag{18}$$

Therefore, $B_{121}(w, \alpha) \leq 0$ is equivalent to

$$\text{SEMP} \equiv -\frac{\alpha w\mathcal{B}'''(\alpha w)}{\mathcal{B}''(\alpha w)} \leq 2, \tag{19}$$

where SEMP represents the second-order elasticity of the marginal productivity of effective water. We document this result as a corollary.

Corollary 2 (EMP and SEMP in the full-dam-probability channel)**.** *In the positive-storage scenario, the impact of water-use efficiency on the optimal choice of dam capacities through the full-dam-probability channel will be positive, if the marginal productivity of effective water declines fast and the decline does not get much slower as effective water increases. Equivalently, the elasticity of the marginal productivity (EMP) of effective water is larger than one and the second-order elasticity of the marginal productivity (SEMP) is smaller than two.*

Proposition 2 and Corollary 2 extend the literature's focus on the EMP to the SEMP. This extension is also intuitive from the perspective of economic theory. The full-dam-probability channel corresponds to the stochastic-control purpose of dam capacities. An increase in water-use efficiency actually increases the variation of effective water given the variation of total water use, so whether storing more water will be desirable and whether more room for dynamic control will be demanded should depend on the third-order property of the benefit of effective water. The SEMP is just a measure about the third-order property.

3.5 Possibility of Complementarity

Assembling Lemmas 1 and 2 and Propositions 1 and 2, we can identify the conditions under which complementarity between water-storage capacities and water-use efficiency is possible:

Proposition 3 (Possibility of complementarity)**.** *Dam capacities and water-use efficiency could be complements:*

- *If the marginal-water-benefit channel is positive: Water-use efficiency improvement will increase the inverse demand for water;*

- *Or, if the full-dam-capacity channel is positive: Water-use efficiency improvement will decrease the inverse demand for water and the decrease is larger with larger water use.*

Mathematically, the CEMV and Equation (12) could be positive:

- *If the sum of the first two terms in Equation (12) is positive:* $B_{12}(w, \alpha) \geq 0$ *for any* $w \in [(1-d)\bar{s} + \underline{e}, \bar{a}]$*;*

- *Or, if the third term in Equation (12) is positive:* $B_{12}(w, \alpha) \leq 0$, $B_{121}(w, \alpha) \leq 0$, $B_{111}(w, \alpha) \leq 0$, *and* $B_{1211}(w, \alpha) \geq 0$ *for any* $w \in [\underline{e}, (1-d)\bar{s} + \bar{e}]$.

Proposition 3 is the main result of this paper. Not only showing the possibility of complementarity, it also shows that the possibility exists even if water-use efficiency improvement decreases the water demand. As discussed above, this probably counterintuitive result comes from the full-dam-probability channel, which relies on stochastic, dynamic control of water inventories.

We can also write Proposition 3 in terms of the marginal productivity of effective water:

Corollary 3. *Dam capacities and water-use efficiency could be complements:*

- *If the marginal productivity of effective water declines sufficiently slow;*

- *Or, if it declines fast and the decline does not get much slower as effective water increases.*

Equivalently, dam capacities and water-use efficiency could be complements:

- *If the EMP is smaller than one;*

- *Or, if the EMP is larger than one but the SEMP is smaller than two.*

As Vaux et al. (1981) recognize, the isoelastic and the linear water demands are convenient in econometric studies and influential in policy related researches. We then apply Proposition 3 and Corollary 3 to the two important specifications of the water demand:

Corollary 4 (Isoelastic water demand)**.** *When the water demand is isoelastic, dam capacities and water-use efficiency will be complements, if and only if the water demand is elastic.*

The intuition of Corollary 4 is as follows: A classic result in water-resource economics states that, for isoelastic water demands, water-use efficiency improvement will shift up the marginal benefit of water if and only if the demand is elastic. More importantly, this shift will be proportional, so it will not change the optimal storage-release decision. Therefore, the full-dam-probability channel will not work. We can then fully identify complementarity through the marginal-water-benefit channel.

Corollary 5 (Linear water demand)**.** *When the water demand is linear, dam capacities and water-use efficiency could be complements:*

- *If the initial dam capacity is sufficiently small;*
- *Or, if the mean of the inflow is sufficiently large.*

Mathematically, when $\mathcal{B}'''(\cdot) = 0$*, the CEMV and Equation (12) could be positive:*

- *If* $\bar{a} \leq \hat{w}$*, where* $\hat{w}$ *solves* $-\frac{\alpha\hat{w}\mathcal{B}''(\alpha\hat{w})}{\mathcal{B}'(\alpha\hat{w})} = 1$*;*
- *Or, if* $\underline{e} \geq \hat{w}$*.*

The intuition of Corollary 5 is as follows: Another classic result in water-resource economics states that, for linear water demands, first, water-use efficiency improvement will increase the inverse demand for water if and only if the initial water use is small, which will be guaranteed by a sufficiently small initial dam capacity. Second, along the same logic, a sufficiently large minimum of the inflow will guarantee that water-use efficiency improvement will decrease the inverse demand for water. Third, note that, for linear water demands, the SEMP is always zero, which is smaller than two.

4 Implications

4.1 Land Constraints and Water Development

Our results imply, first, that the marginal-water-benefit channel is important in determining the relation between water-storage capacities and water-use efficiency. This channel is governed by the first-order impact of water-use efficiency on the inverse demand for water, or, more deeply, whether the marginal productivity of effective water declines slow or fast. Two factors deserve special attentions. The first is land constraints—it is natural to expect and has already been observed that the marginal productivity of effective water should decline much slower, when irrigable land is not constrained and irrigators can expand planted areas, than it does when irrigators have to exploit the constrained irrigable land (e.g., Scheierling et al., 2006b; Berbel and Mateos, 2014; Dinar, 2014; the survey by Berbel et al., 2015). This factor could be important in both of the developed and developing worlds (e.g., the European Commission, 2012; the International Water Resource Economics Consortium, 2014).

The second factor is the stage of the development of water resources. In areas like Western Europe and India where water resources have already been exploited by infrastructure investments (e.g., Shah and Kumar, 2008; Hasanain et al., 2013), it is likely that water-use efficiency improvement will decrease the inverse demand for water use. For areas like sub-Saharan Africa where agriculture is still mainly fed by rain (e.g., Kadigi et al., 2013), the opposite is more likely to hold. Actually, some scholars have already been seeing that, given unconstrained irrigable areas and small initial water-catchment capacities, adoption of more-efficient irrigation technologies is increasing the demand for water and the demand for water-storage projects (e.g., about Xinjiang, a major area of irrigated agriculture in China, Xu, 2015).

4.2 Water Produced Commodities and Trade Policies

Our results also suggest that the elasticity of the water demand is important in determining the complementarity or substitution, especially when the water demand is considered to be isoelastic. It is well noted that the elasticity of the water demand is highly correlated with the economic properties of the water produced commodity, e.g., irrigated agricultural products or hydropower (e.g., Scheierling et al., 2006a). As an example, the elasticity of the demand for the commodity and the elasticity of the water demand could be positively correlated as long as the production function of the commodity is increasing in water.[11]

This observation carries important policy implications. On the one hand, many small, developing countries are exporting agricultural commodities, and the sector is important for the economy. When their production is small in the world market, they face an almost perfectly elastic demand for the commodity, so the irrigation demand for water could be elastic. In this case, improvements in water-use efficiency, which could result from international aid, could optimally lead to larger dams for the irrigation needed for the commodity production. This point suggests that the aid tackling water challenges in developing countries should have a joint perspective about international trade, conservation, and water infrastructures.

On the other hand, in cases of dams used to produce nonexported commodities or commodities with low demand elasticities, e.g., electricity and staple food for domestic consumption, the derived demand for water could be inelastic, so dam capacities and water-use

[11] This argument follows the assumption that the benefit of effective water, $\mathcal{B}(x)$, is equal to the production function of the water produced commodity in effective water, multiplied by the inverse demand for the commodity—the revenue of the commodity production.

efficiency could be substitutes. This point suggests that the joint policy about conservation and water infrastructures should critically depend on the property of the water produced commodity.

4.3 Specifications of the Demand for Water

Our results also imply that the functional form of the water demand is critical in determining the complementarity or substitution. Studies find that the irrigation-water demand is usually inelastic (e.g., Moore et al., 1994; Schoengold et al., 2006; Hendricks and Peterson, 2012). An isoelastic, inelastic specification of the water demand suggests that irrigation-dam expansions and conservation-technology adoption should be substitutes. Water-demand elasticities do vary with respect to water use, however, and it is possible for the linear specification that has the same elasticity as the isoelastic, inelastic specification when the water price is at its mean level to suggest complementarity. The difference in functional forms could then lead to opposite answers to the two questions.

As Caswell and Zilberman (1986) recognize, the linear water demand is more consistent than the isoelastic demand with the classic three-stage model of the marginal productivity of water in irrigation. Therefore, about water-storage capacities for agricultural use, the linear water demand is empirically more relevant. It is also important to note that both conditions in Corollary 5 are eventually about the amount of water use (or release): If the initial dam capacity is small, then the amount of water catchment and water use could not be large. If the minimum of the inflow is large, then the amount of water catchment and water release will not be small, as long as the dam capacity is not extremely small. Therefore, complementarity between irrigation efficiency and irrigation dams is possible, in the case where the initial water-storage capacity is small, and in the case where water is abundant in the source area and the constructed water-storage capacity is large.

4.4 Policy Implications given Complementarity or Substitution

When dam capacities and water-use efficiency are complements, first, public water-storage capacities could be expanded without discouraging improvement in water-use efficiency, e.g., adopting more-efficient irrigation technologies and better conveyance technologies. Second, policymakers might believe that subsidizing water users to improve water-use efficiency could make expanding water storage unnecessary, but the subsidies could backfire by increasing the demand for investment in water storage. Third, probably not obviously, complementarity also implies that more intensive evaporation within each water year (from the wet season to the dry season), which could be caused by climate warming, will lead to downward adjustment in water-storage capacities. When dam capacities and water-use efficiency are substitutes, some opposite policy implications would follow.

Last but not least, in the case of complementarity, assuming a policymaker maximizing the social welfare that is related to water-storage capacities, limited resources should be distributed in a balanced way between dam building and water-use efficiency improvement, instead of being concentrated on either side with the other side being ignored. Only extreme substitution could make investing in a single approach an optimal allocation of resources. Appendix A.4 formalizes this implication.

5 Extension with an Infinite Horizon

In this section we extend the simple two-period, stochastic model by incorporating an infinite horizon of the dam operator. The extension is for two purposes. First, as the simple model assumes only two periods in the dam operation, we shall use the extended model to show that the insight and results from the simple model are robust if a longer horizon is introduced. Second, as the horizon of dam operators is usually long in reality (e.g., Reilly, 1995), the extended model can help us in empirical illustrations.

The extension then turns the water-inventory management problem into

$$V^*(\bar{a}, a_0, \alpha) \equiv \max_{\{w_t\}_{t=0}^{\infty}, \{s_t\}_{t=0}^{\infty}} \mathbf{E}_0 \left[\sum_{t=0}^{\infty} \rho^t B(w_t, \alpha) \right] \qquad \text{s.t.} \tag{20}$$

$$\begin{aligned} & s_t \geq 0, w_t \geq 0, w_t + s_t = \min\{a_t, \bar{a}\} \text{ for any } t \geq 0; \\ & a_0 \text{ is given; } \; a_t = (1-d)s_{t-1} + e_t \text{ for any } t \geq 1, \end{aligned} \tag{21}$$

where $e_t \in [\underline{e}, \bar{e}] \sim e$, i.i.d., and all the variables have the same meaning.[12]

Appendix A.5 solves the inventory-management problem. The marginal benefit of dam capacities in the extend model turns out to be

$$V_1^*(\bar{a}, a_0, \alpha) = B_1(\bar{a} - \bar{s}, \alpha) \left[I_{a_0 > \bar{a}} + \sum_{t=1}^{\infty} \rho^t \mathbf{P} \left[a_t^* > \bar{a} | \bar{a}, a_0, \alpha \right] \right], \tag{22}$$

where $\bar{s}$ is the optimal water storage when the dam is full and a_t^* is the water availability at t under optimal storage-release decisions. This expression has exactly the same intuition as in the simple model: The marginal benefit of dam capacities depends on the marginal benefit of water release when the dam is full and the probability that the dam will be full in

[12]The Office of Management and Budget (2011) recommends a constant but not declining discount factor for project evaluation.

the future. Therefore, the marginal-water-benefit and the full-dam-probability channels will still exist. Appendix A.5 then derives parallel results to the simple model.

6 An Empirical Example with Numerical Illustrations

In this section, we present numerical illustrations of our results by simulating the extended model. The simulation is based on the irrigation water-inventory management problem of the California State Water Project. We use three specifications of the water demand in the illustrations: 1) isoelastic, elastic with the elasticity being -1.21 as estimated by Frank and Beattie (1979); 2) isoelastic, inelastic with the elasticity being -0.79 as estimated by Schoengold et al. (2006); and 3) linear with the same elasticity as the second isoelastic, inelastic demand when the demand is equal to the 1975–2010 mean of the annual water deliveries from the Project to agricultural use. The three specifications help to confirm our theoretical results and show their empirical relevance. Table 1 summarizes the three demand functions, while Table 2 summarizes the specification of the whole simulation. For more details about the specification, see Appendix A.6.

Table 1: Specifications of the benefit of water release in the empirical example

Benefit of water release	Demand for water release
$B(w,\alpha) = 3.0 \times 10^7 \cdot (\alpha w)^{1-\frac{1}{1.21}}$	Isoelastic, elastic, $\mu = -1.21$
$B(w,\alpha) = -7.1 \times 10^9 \cdot (\alpha w)^{1-\frac{1}{0.79}}$	Isoelastic, inelastic, $\mu = -0.79$
$B(w,\alpha) = 181.0 \cdot \alpha x - \frac{1.5\times10^{-4}}{2} \cdot (\alpha x)^2$, where $x \equiv \min\left\{w, \frac{181.0}{1.5\times10^{-4}\cdot\alpha}\right\}$	Linear, equivalent to $\mu = -0.79$

The price elasticity of the water demand is denoted as μ.

For each of the three water demands, we focus on two questions—whether more-efficient technology adoption in irrigation, which induces higher water-use efficiency (larger α), will increase or decrease the marginal benefit of dam capacities, $V_1^*(\bar{a}, a_0, \alpha)$, and whether water-storage expansions, which induce larger dam capacities (larger $\bar{a}$), will increase or decrease the marginal contribution of water-use efficiency to the dam generated value, $V_3^*(\bar{a}, a_0, \alpha)$. The two questions are equivalent to the two questions we have asked.

Table 3 shows results with the benchmark level of storage capacities, 2025335 acre-feet, zero initial water availability, and the benchmark level of water-use efficiency, 0.7135. Panel A is for the isoelastic, elastic demand. A 1% improvement in water-use efficiency from 0.7135 to 0.7206 will increase the marginal benefit of dam capacities by 0.17%. This positive impact confirms the prediction of complementarity in Corollary 4 for isoelastic, elastic water

Table 2: Specification of the empirical example

Inflow in acre-feet	$e_t \sim$ Adjusted, estimated historical inflows, i.i.d.
Evaporation-loss rate	$d = 0.04$
Discount factor	$\rho = 0.9434$
Benefit of water release in \$	$B(w,\alpha) = 3.0 \times 10^7 \cdot (\alpha w)^{1-\frac{1}{1.21}}$
(one in each illustration)	$B(w,\alpha) = -7.1 \times 10^9 \cdot (\alpha w)^{1-\frac{1}{0.79}}$
	$B(w,\alpha) = 181.0 \cdot \alpha x - \frac{1.5\times 10^{-4}}{2} \cdot (\alpha x)^2$, where $x \equiv \min\left\{w, \frac{181.0}{1.5\times 10^{-4}\cdot\alpha}\right\}$
Baseline water-use efficiency	$\alpha = 0.7135$
Baseline dam capacity in acre-feet	$\bar{a} = 2025335$

For the irrigation water-inventory management problem of the California State Water Project. Based on the California Department of Water Resources (1963–2013, 1976–2014, 1990–2014, 1998–2005, 2008) and Schoengold et al. (2006). Details in Appendix A.6.

demands. Moreover, the 0.17% increase in the marginal benefit of dam capacities is solely caused by a 0.17% increase in the marginal benefit of water release when the dam reaches the full capacity, while the net present frequency of the dam reaching the full capacity in the future does not change. This observation confirms the logic of Corollary 4.

How will the 0.17% increase in the marginal benefit of dam capacities be reflected on the optimal choice of storage capacities? Without information about the marginal cost of dam capacities, the most we can do is to estimate the range of the impact: It is obvious that if the marginal cost of dam capacities are perfectly vertical, then the optimal choice of storage capacities will not change. If the marginal cost of dam capacities are assumed perfectly horizontal, then we can derive the upper bound of the increase in optimal storage capacities caused by the 1% improvement in water-use efficiency.[13] In this case, the upper bound will be $-0.17/(-20.27) \approx 8.39 \times 10^{-3}$. In other words, the 1% improvement in water-use efficiency will generate at most a negligible but still positive increase in the optimal storage capacity from the benchmark level if we assume the water demand is isoelastic and elastic.

How will a 1% increase in dam capacities change the optimal water-use efficiency? A similar exercise shows that the upper bound of the elasticity of the optimal choice of use efficiency with respect to dam capacities will be a small but still positive number, 6.83×10^{-3}.

[13] A little bit algebra can express the upper bound of the elasticity of the optimal choice of storage capacities with respect to water-use efficiency, $\frac{d\bar{a}^*}{d\alpha} \cdot \frac{\alpha}{\bar{a}^*}$, as the elasticity of the marginal benefit of dam capacities with respect to water-use efficiency, $\epsilon_\alpha^{V_1^*(\bar{a},a_0,\alpha)}$, divided by the elasticity of the marginal benefit with respect to dam capacities, $\epsilon_{\bar{a}}^{V_1^*(\bar{a},a_0,\alpha)}$. Mathematically, totally differentiating both side of the first-order condition of the dam-capacity choice gives $V_{11}^*(\bar{a}^*, a_0, \alpha)d\bar{a}^* + V_{13}^*(\bar{a}^*, a_0, \alpha)d\alpha = C''(\bar{a})d\bar{a}^*$, which derives $0 < \frac{d\bar{a}^*}{d\alpha} = \frac{V_{13}^*(\bar{a}^*,a_0,\alpha)}{-V_{11}^*(\bar{a}^*,a_0,\alpha)+C''(\bar{a})} < -\frac{V_{13}^*(\bar{a}^*,a_0,\alpha)}{V_{11}^*(\bar{a}^*,a_0,\alpha)}$. Also, $0 < \frac{d\bar{a}^*}{d\alpha} \cdot \frac{\alpha}{\bar{a}^*} < -\frac{V_{13}^*(\bar{a}^*,a_0,\alpha)}{V_{11}^*(\bar{a}^*,a_0,\alpha)} \cdot \frac{\alpha}{\bar{a}^*} = -\frac{\alpha V_{13}^*(\bar{a}^*,a_0,\alpha)}{V_1^*(\bar{a}^*,a_0,\alpha)} \cdot \left(\frac{\bar{a}^* V_{11}^*(\bar{a}^*,a_0,\alpha)}{V_1^*(\bar{a}^*,a_0,\alpha)}\right)^{-1} \equiv -\epsilon_\alpha^{V_1^*(\bar{a},a_0,\alpha)} \Big/ \epsilon_{\bar{a}}^{V_1^*(\bar{a},a_0,\alpha)}$.

Table 3: The empirical example: Responses to a 1% increase in water-use efficiency or water-storage capacities

Variable	Elasticity w.r.t. α	Elasticity w.r.t. $\bar{a}$
Panel A: Isoelastic, elastic demand		
Marginal benefit of water release with a full dam, $B_1(\bar{a}-\bar{s},\alpha)$	0.17	
Net present frequency of a full dam, $\sum_{t=0}^{\infty}\rho^t\mathbf{P}_0\left[a_t^*>\bar{a}\right]$	0.00	
Marginal benefit of dam capacities, $V_1^*\left(\bar{a},a_0,\alpha\right)$	0.17	-20.27
Optimal dam capacity, $\bar{a}^*$	$(0,0.01]$	
Marginal contribution of water use efficiency, $V_3^*\left(\bar{a},a_0,\alpha\right)$	-0.82	0.01
Optimal water-use efficiency, α^*		$(0,0.01]$
Panel B: Isoelastic, inelastic demand		
Marginal benefit of water release with a full dam, $B_1(\bar{a}-\bar{s},\alpha)$	-0.26	
Net present frequency of a full dam, $\sum_{t=0}^{\infty}\rho^t\mathbf{P}_0\left[a_t^*>\bar{a}\right]$	0.00	
Marginal benefit of dam capacities, $V_1^*\left(\bar{a},a_0,\alpha\right)$	-0.26	-13.88
Optimal dam capacity, $\bar{a}^*$	$[-0.02,0)$	
Marginal contribution of water use efficiency, $V_3^*\left(\bar{a},a_0,\alpha\right)$	-1.25	-0.01
Optimal water-use efficiency, α^*		$[-0.01,0)$
Panel C: Linear demand, inelastic at the mean of water deliveries		
Marginal benefit of water release with a full dam, $B_1(\bar{a}-\bar{s},\alpha)$	-3.02	
Net present frequency of a full dam, $\sum_{t=0}^{\infty}\rho^t\mathbf{P}_0\left[a_t^*>\bar{a}\right]$	4.13	
Marginal benefit of dam capacities, $V_1^*\left(\bar{a},a_0,\alpha\right)$	0.99	-5.86
Optimal dam capacity, $\bar{a}^*$	$(0,0.17]$	
Marginal contribution of water use efficiency, $V_3^*\left(\bar{a},a_0,\alpha\right)$	-1.72	0.05
Optimal water-use efficiency, α^*		$(0,0.03]$

Initial conditions: $\bar{a}=2025335$, $a_0=0$, and $\alpha=0.7135$. The optimal water storage when the dam reaches the full capacity is denoted by $\bar{s}$. Specification follows Tables 1 and 2.

In other words, a 1% increase in dam capacities will generate at most a 0.007% improvement in water-use efficiency if we assume the water demand is isoelastic and elastic.

Panel B reports results for the isoelastic, inelastic water demand. They confirm the prediction and the logic of Corollary 4, again: For isoelastic, inelastic demands, dam capacities and water-use efficiency are substitutes, and water-use efficiency improvement decreases the marginal benefit of dam capacities without changing the frequency of the dam reaching the full capacity in the future.

Panel C reports results for the linear water demand. Because around 72.2% of the inflow distribution in the empirical example is larger than the critical level of water release beyond which water-use efficiency improvement will decrease the linear inverse demand for water, 845597 acre-feet, the second condition for linear demands in Corollary 5 is almost satisfied. Consistent with theoretical predictions, water-use efficiency improvement will decrease the marginal benefit of water release when the dam reaches the full capacity but will also increase the frequency of the dam reaching the full capacity in the future. Moreover, the full-dam-probability channel does dominate and a 1% improvement in water-use efficiency will increase the marginal benefit of dam capacities by 0.99%. The positive impact suggests complementarity between dam capacities and water-use efficiency if we assume the water demand is linear.

Comparing Panels B and C now confirms the importance of the specification of water demands. The underlying water demands of the two panels both have a price elasticity of -0.79 if the demand is equal to the mean of the 1975–2010 annual water deliveries from the California State Water Project to agricultural use, but differ in their functional forms: The water demand of Panel B is isoelastic while the demand of Panel C is linear. The difference in functional forms leads to different predictions about the economic relation between dam capacities and water-use efficiency. The reason for the difference in predictions is just that water-use efficiency improvement could increase the frequency of the dam reaching the full capacity in the future by optimally increasing water storage, and we can only recognize this impact by recognizing stochastic, dynamic control of water inventories and the full-dam-probability channel.

As we have discussed earlier, irrigation demand for water is usually inelastic, and a linear water demand is empirically more relevant to irrigation. The two points suggest that, for the irrigation water-inventory management problem of the California State Water Project, the linear water demand and Panel C should be empirically more relevant than the other two isoelastic specifications and Panels A and B. Panel C does suggest complementarity between dam capacities and water-use efficiency, which implies balanced distribution of limited resources on water-storage expansions and water-use efficiency improvement.

Table 4: The empirical example: Responses to a 5% increase in water-use efficiency or water-storage capacities

Variable	Response to $\Delta\alpha$ (%)	Response to $\Delta\bar{a}$ (%)
Panel A: Isoelastic, elastic demand		
Marginal benefit of water release with a full dam, $B_1(\bar{a}-\bar{s},\alpha)$	0.85	
Net present frequency of a full dam, $\sum_{t=0}^{\infty}\rho^t\mathbf{P}_0\left[a_t^*>\bar{a}\right]$	0.00	
Marginal benefit of dam capacities, $V_1^*\left(\bar{a},a_0,\alpha\right)$	0.85	-43.86
Optimal dam capacity, $\bar{a}^*$	$(0, 0.10]$	
Marginal contribution of water use efficiency, $V_3^*\left(\bar{a},a_0,\alpha\right)$	-3.95	0.03
Optimal water-use efficiency, α^*		$(0, 0.04]$
Panel B: Isoelastic, inelastic demand		
Marginal benefit of water release with a full dam, $B_1(\bar{a}-\bar{s},\alpha)$	-1.29	
Net present frequency of a full dam, $\sum_{t=0}^{\infty}\rho^t\mathbf{P}_0\left[a_t^*>\bar{a}\right]$	0.00	
Marginal benefit of dam capacities, $V_1^*\left(\bar{a},a_0,\alpha\right)$	-1.29	-46.56
Optimal dam capacity, $\bar{a}^*$	$[-0.14, 0)$	
Marginal contribution of water use efficiency, $V_3^*\left(\bar{a},a_0,\alpha\right)$	-5.99	-0.06
Optimal water-use efficiency, α^*		$[-0.05, 0)$
Panel C: Linear demand, inelastic at the mean of water deliveries		
Marginal benefit of water release with a full dam, $B_1(\bar{a}-\bar{s},\alpha)$	-7.07	
Net present frequency of a full dam, $\sum_{t=0}^{\infty}\rho^t\mathbf{P}_0\left[a_t^*>\bar{a}\right]$	12.84	
Marginal benefit of dam capacities, $V_1^*\left(\bar{a},a_0,\alpha\right)$	4.87	-25.18
Optimal dam capacity, $\bar{a}^*$	$(0, 0.97]$	
Marginal contribution of water use efficiency, $V_3^*\left(\bar{a},a_0,\alpha\right)$	-8.57	0.31
Optimal water-use efficiency, α^*		$(0, 0.18]$

Initial conditions: $\bar{a} = 2025335$, $a_0 = 0$, and $\alpha = 0.7135$. The optimal water storage when the dam reaches the full capacity is denoted by $\bar{s}$. Specification follows Tables 1 and 2.

Table 4 tests the robustness of Table 3 by calculating responses of the variables of interest to a 5% increase in water-use efficiency or water-storage capacities. All the results in Table 3 qualitatively hold and their magnitude becomes larger in Table 4. Panel C in Table 4 shows that a 5% increase, a reasonable improvement, in water-use efficiency will at most increase the optimal dam capacity by around 1%, while a 5% increase in water-storage capacities will at most increase the optimal water-use efficiency by around 0.2%.

Both Panel Cs in Tables 3 and 4 show asymmetry in the complementarity between water-storage capacities and water-use efficiency: The impact of dam capacities on optimal water-use efficiency is always quite small. It is because that the existing dam capacity is large: First, the contribution of water-use efficiency to the dam generated value depends on the amount of water release in the long run, and so does the marginal contribution—the incentive of water-use efficiency improvement. Second, when the existing dam capacity is large, the amount of water release is large, so the relative increase in the amount of water release by additional dam capacities will be small. Therefore, the impact of the small increase in dam capacities on the incentive of water-use efficiency improvement and the optimal water-use efficiency will be weak. The complementarity between dam capacities and water-use efficiency is then more prominent in the impact of water-use efficiency improvement on water-storage expansions, but not the other way around.

Using the linear demand for water, we finally illustrate the comparison between the value-maximization logic of economists and the cost-minimization logic in the engineering literature (e.g., surveys by Yeh, 1985; Simonovic, 1992). Along the cost-minimization logic, dam designers are choosing the minimal dam capacity, which will incur the minimal cost, to satisfy specific policy objectives. For example, if there is a 5% increase in water-use efficiency, the minimal dam capacity to reach the (gross) value that is generated by the benchmark dam capacity with the benchmark water-use efficiency will be 29.59% smaller than the benchmark dam capacity. This result confirms the intuition that, since the function of the benefit from effective water is increasing, higher water-use efficiency means a higher dam generated value given any dam capacity, so the cost-minimization logic will lead to a smaller capacity choice. In contrast, weighing the marginal benefit and the marginal cost of dam capacities, the optimal dam capacity with the same water-use efficiency improvement, as shown in Table 4, will be larger than the benchmark dam capacity by at most 0.97%.

7 Conclusion

In this paper, we analyze the relation between two technological approaches in water-resource management, namely, expanding water-storage capacities and enhancing water-use efficiency, under stochastic, dynamic control of water inventories. This relation is the key to the policy design to tackle water scarcity and adapt to climate change. Recognizing the water-catchment and the stochastic-control purposes of dams, we show that water-storage capacities and water-use efficiency could be complements even if water-use efficiency improvement decreases the water demand. This result comes from the full-dam-probability channel.

Our analysis shows that the properties of the marginal productivity of effective water determines the directions of this full-dam-probability channel and the other marginal-water-benefit channel. Precise information about the marginal productivity of effective water, however, is sometimes difficult to be known. That said, we can still identify the direction of these two channels, as long as we know the properties of the water demand, which is much easier to be estimated in practice.

There are also dams in areas where the peaks of the water endowment and the water demand generally overlap. The water-catchment purpose of these dams are then not important. For these water-storage facilities, our analysis about the stochastic-control purpose and the full-dam-probability channel is still applicable.[14]

Our results imply that the policies encouraging public or private water storage could encourage water users to improve water-use efficiency, e.g., adopt more-efficient technologies in irrigation or invest in conveyance systems, and the policies subsidizing the improvement could also increase the demand for water-storage capacities. After all, policymakers should not separately design the two categories of policies—expanding water storage and improving water-use efficiency. In the case of complementarity, resources should not be concentrated only on one category with the other being ignored. This implication is especially important for the countries with small initial water-storage capacities, by which water-use efficiency improvement will increase the demand for water, and the countries with generally abundant inflows and large initial water-storage capacities, by which water-use efficiency improvement will increase the likelihood that dams reach their full capacities.

As the relation between the policies is important in policy debates and could be counterintuitive, it deserves more serious theoretical modeling and empirical investigations. Further effort could be made to specify the improvement in water-use efficiency, e.g., model conservation-technology adoption with heterogeneous water users and specific land constraints. The cost of dams that will be correlated with water-use efficiency improvement, for example, displacement or introduction of specific water users, should also be considered. Our model can also serve as a starting point for a research agenda on the relation between water-storage expansions and other approaches in water-resource management, e.g., introducing water markets to existing systems of water rights and adopting drought-tolerant varieties in

[14]Some results are presented in Xie and Zilberman (2014b).

agriculture. In a more general perspective, our analysis on the marginal benefit of storage capacities can be applied and extended to investigate investment decisions in other contexts, such as the joint management of water and food inventories. Ultimately, introducing political economy into the discussion between water infrastructure and conservation effort would be necessary.

References

Alcott B. 2005. Jevons' paradox. *Ecological Economics* **54**: 9–21.

Allcott H, Greenstone M. 2012. Is there an energy efficiency gap? *Journal of Economic Perspectives* **26**: 3–28.

Ansar A, Flyvbjerg B, Budzier A, Lunn D. 2014. Should we build more large dams? The actual costs of hydropower megaproject development. *Energy Policy* **69**: 43–56.

Asche F, Oglend A, Zhang D. 2014. Hoarding the herd: The convenience of productive stocks. *Journal of Futures Markets* .

Baerenklau KA, Knapp KC. 2007. Dynamics of agricultural technology adoption: Age structure, reversibility, and uncertainty. *American Journal of Agricultural Economics* **89**: 190–201.

Beard DP. 2015. Should the Bureau of Reclamation be abolished? High Country News, March 19, 2015.

Bellman RE. 1957. *Dynamic Programming.* Princeton, New Jersey: Princeton University Press.

Berbel J, Gutiérrez-Martín C, Rodríguez-Díaz JA, Camacho E, Montesinos P. 2015. Literature review on rebound effect of water saving measures and analysis of a Spanish case study. *Water Resources Management* **29**: 663–678.

Berbel J, Mateos L. 2014. Does investment in irrigation technology necessarily generate rebound effects? A simulation analysis based on an agro-economic model. *Agricultural Systems* **128**: 25–34.

Bıçak HA, Jenkins GP, Özdemirağ A. 2002. Water flow risks and stakeholder impacts on the choice of a dam site. *Australian Journal of Agricultural and Resource Economics* **46**: 257–277.

Bobenrieth ESA, Bobenrieth JRA, Wright BD. 2002. A commodity price process with a unique continuous invariant distribution having infinite mean. *Econometrica* **70**: 1213–1219.

Brennan D. 2008. Missing markets for storage and the potential economic cost of expanding the spatial scope of water trade. *Australian Journal of Agricultural and Resource Economics* **52**: 471–485.

Brookes LG. 1992. Energy efficiency and economic fallacies: A reply. *Energy Policy* **20**: 390–392.

Burt OR. 1964. Optimal resource use over time with an application to ground water. *Management Science* **11**: 80–93.

Calefati J. 2014. California drought: So many water bonds, so little time. San Jose Mercury News, March 22, 2014.

California Department of Water Resources. 1963–2013. *Bulletins 132-63–99 and 132-00–11: Management of the California State Water Project*. Accessible at `http://www.water.ca.gov/swpao/bulletin_home.cfm` on November 21, 2014.

California Department of Water Resources. 1976–2014. *State Water Project Annual Report of Operations, 1975–2009*. Accessible at `http://www.water.ca.gov/swp/operationscontrol/annual.cfm` on November 21, 2014.

California Department of Water Resources. 1990–2014. *State Water Project Monthly Operations Data, 1990–2014*. Accessible at `http://www.water.ca.gov/swp/operationscontrol/monthly.cfm` on March 12, 2015.

California Department of Water Resources. 1998–2005. *Annual Land and Water Use Estimates, 1998–2005*. Accessible at `http://www.water.ca.gov/landwateruse/anaglwu.cfm` on January 21, 2015.

California Department of Water Resources. 2008. *California Department of Water Resources Economic Analysis Guidebook*. Accessible at `http://www.water.ca.gov/economics/guidance.cfm` on November 21, 2014.

Carey JM, Zilberman D. 2002. A model of investment under uncertainty: Modern irrigation technology and emerging markets in water. *American Journal of Agricultural Economics* **84**: 171–183.

Caswell MF. 1991. Irrigation technology adoption decisions: Empirical evidence. In Dinar A, Zilberman D (eds.) *The Economics and Management of Water and Drainage in Agriculture*. New York: Springer Verlag, 295–312.

Caswell MF, Lichtenberg E, Zilberman D. 1990. The effects of pricing policies on water conservation and drainage. *American Journal of Agricultural Economics* **72**: 883–890.

Caswell MF, Zilberman D. 1986. The effects of well depth and land quality on the choice of irrigation technology. *American Journal of Agricultural Economics* **68**: 798–811.

Chakravorty U, Deng X, Gong Y, Pelli M, Zhang Q. 2015. Roads and resources: Groundwater depletion in Lankao County in the North China Plain. Tufts University Working Paper.

Chakravorty U, Hochman E, Umetsu C, Zilberman D. 2009. Water allocation under distribution losses: Comparing alternative institutions. *Journal of Economic Dynamics and Control* **33**: 463–476.

Chakravorty U, Hochman E, Zilberman D. 1995. A spatial model of optimal water conveyance. *Journal of Environmental Economics and Management* **29**: 25–41.

Chambers MJ, Bailey RE. 1996. A theory of commodity price fluctuations. *Journal of Political Economy* **104**: 924–957.

Chan NW, Gillingham K. 2015. The microeconomic theory of the rebound effect and its welfare implications. *Journal of the Association of Environmental and Resource Economists* **2**: 133–159.

Chatterjee B, Howitt RE, Sexton RJ. 1998. The optimal joint provision of water for irrigation and hydropower. *Journal of Environmental Economics and Management* **36**: 295–313.

Chomitz KM, Gray DA. 1996. Roads, land use, and deforestation: A spatial model applied to Belize. *World Bank Economic Review* **10**: 487–512.

Cobourn KM. 2015. Externalities and simultaneity in surface water-groundwater systems: Challenges for water rights institutions. *American Journal of Agricultural Economics* .

Cropper M, Puri J, Griffiths C. 2001. Predicting the location of deforestation: The role of roads and protected areas in North Thailand. *Land Economics* **77**: 172–186.

Deaton A, Laroque G. 1992. On the behaviour of commodity prices. *Review of Economic Studies* **59**: 1–23.

Deng X, Huang J, Uchida E, Rozelle S, Gibson J. 2011. Pressure cookers or pressure valves: Do roads lead to deforestation in China? *Journal of Environmental Economics and Management* **61**: 79–94.

Dinar A. 2014. Personal conversation. World Bank Headquarters, Washington, D.C., September 9, 2014.

Dinar A, Campbell MB, Zilberman D. 1992. Adoption of improved irrigation and drainage reduction technologies under limiting environmental conditions. *Environmental and Resource Economics* **2**: 373–398.

Dinar A, Yaron D. 1992. Adoption and abandonment of irrigation technologies. *Agricultural Economics* **6**: 315–332.

Dudley NJ, Musgrave WF. 1988. Capacity sharing of water reservoirs. *Water Resources Research* **24**: 649–658.

Duflo E, Pande R. 2007. Dams. *Quarterly Journal of Economics* **122**: 601–646.

Dunning H, Machtinger S. 2014. Feinstein water legislation will weaken Delta conservation efforts. San Jose Mercury News, May 30, 2014.

European Commission. 2012. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Blueprint to Safeguard Europe's Water Resources*. Brussels, Belgium: European Commission.

Feder G, Umali DL. 1993. The adoption of agricultural innovations: A review. *Technological Forecasting and Social Change* **43**: 215–239.

Fischhendler I, Zilberman D. 2005. Packaging policies to reform the water sector: The case of the Central Valley Project Improvement Act. *Water Resources Research* **41**.

Fisher AC, Rubio SJ. 1997. Adjusting to climate change: Implications of increased variability and asymmetric adjustment costs for investment in water reserves. *Journal of Environmental Economics and Management* **34**: 207–227.

Frank MD, Beattie BR. 1979. The economic value of irrigation water in the Western United States: An application of ridge regression. Technical Report No. 99, Texas Water Resources Institute, Texas A&M University.

Freebairn J, Quiggin J. 2006. Water rights for variable supplies. *Australian Journal of Agricultural and Resource Economics* **50**: 295–312.

Gardner BL. 1979. *Optimal Stockpiling of Grain*. Lexington, Massachusetts: Lexington Books.

Gerarden TD, Newell RG, Stavins RN. 2015a. Assessing the energy-efficiency gap. National Bureau of Economic Research Working Paper No. 20904.

Gerarden TD, Newell RG, Stavins RN, Stowe RC. 2015b. An assessment of the energy-efficiency gap and its implications for climate-change policy. National Bureau of Economic Research Working Paper No. 20905.

Gillingham K, Newell RG, Palmer KL. 2009. Energy efficiency economics and policy. *Annual Review of Resource Economics* **1**: 597–620.

Gisser M, Sánchez DA. 1980. Competition versus optimal control in groundwater pumping. *Water Resources Research* **16**: 638–642.

Goodhue R, Martin P. 2014. Labor, water, and California agriculture in 2014. *Agricultural and Resource Economics Update* **17**: 5–8.

Green G, Sunding D, Zilberman D, Parker DD. 1996. Explaining irrigation technology choices: A microparameter approach. *American Journal of Agricultural Economics* **78**: 1064–1072.

Greening LA, Greene DL, Difiglio C. 2000. Energy efficiency and consumption—the rebound effect—a survey. *Energy Policy* **28**: 389–401.

Gustafson RL. 1958. Implications of recent research on optimal storage rules. *Journal of Farm Economics* **40**: 290–300.

Haddad MS. 2011. Capacity choice and water management in hydroelectricity systems? *Energy Economics* **33**: 168–177.

Hall JF. 1984. Dams and earthquake safety. *Engineering and Science* **47**: 17–20.

Hansen ZK, Libecap GD, Lowe SE. 2011. Climate variability and water infrastructure: Historical experience in the western United States. In Libecap GD, Steckel RH (eds.) *The Economics of Climate Change: Adaptations Past and Present*. Chicago, Illinois: University of Chicago Press, 253–280.

Hansen ZK, Lowe SE, Xu W. 2014. Long-term impacts of major water storage facilities on agriculture and the natural environment: Evidence from Idaho (U.S.). *Ecological Economics* **100**: 106–118.

Hanson VD. 2015. Why California's drought was completely preventable. National Review, April 30, 2015.

Hasanain A, Ahmad S, Mehmood MZ, Majeed S, Zinabou G. 2013. Irrigation and water use efficiency in South Asia. Global Development Network Working Paper Series No. 68.

Hendricks NP, Peterson JM. 2012. Fixed effects estimation of the intensive and extensive margins of irrigation water demand. *Journal of Agricultural and Resource Economics* **37**: 1–19.

Hertwich EG. 2005. Consumption and the rebound effect: An industrial ecology perspective. *Journal of Industrial Ecology* **9**: 85–98.

Houba H, Pham-Do KH, Zhu X. 2014. Capacity choice of dams under rivalry use and externalities. Tinbergen Institute Discussion Paper 2014-143/II.

Howitt R, MacEwan D, Medellín-Azuara J, Lund J, Sumner D. 2015. Preliminary analysis: 2015 drought economic impact study. Center for Watershed Sciences, University of California, Davis.

Howitt R, Medellín-Azuara J, MacEwan D, Lund J, Sumner D. 2014. Economic analysis of the 2014 drought for California agriculture. Center for Watershed Sciences, University of California, Davis.

Howitt RE, MacEwan D, Medellín-Azuara J. 2011. Drought, jobs, and controversy: Revisiting 2009. *Agricultural and Resource Economics Update* **14**: 1–4.

Hughes N, Goesch T. 2009. Management of irrigation water storages: Carryover rights and capacity sharing. Australian Bureau of Agricultural and Resource Economics Research Report 09.10.

Hurwitz Z. 2014. *Dam Standards: A Rights-Based Approach: A Guidebook for Civil Society*. Berkeley, California: International Rivers.

International Commission on Large Dams. 2007. *Dams and the World's Water*. Levallois-Perret, France: Vlady France Conseil.

International Union for Conservation of Nature, World Bank. 1997. *Large Dams: Learning from the Past, Looking at the Future*. Washington, D.C.: World Bank.

International Water Resource Economics Consortium. 2014. The Eleventh Annual Meeting of the International Water Resource Economics Consortium. World Bank Headquarters, Washington, D.C., September 7–9, 2014.

Jackson S, Sleigh A. 2000. Resettlement for China's Three Gorges Dam: Socio-economic impact and institutional tensions. *Communist and Post-Communist Studies* **33**: 223–241.

Jaffe AB, Newell RG, Stavins RN. 2004. Economics of energy efficiency. *Encyclopedia of Energy* **2**: 79–90.

Jaffe AB, Stavins RN. 1994. Energy-efficiency investments and public policy. *Energy Journal* **15**: 43–65.

Jensen JLWV. 1903. Sur les fonctions convexes et les inégalités entre les valeurs moyennes. *Acta Mathematica* **30**: 175–193.

Jevons WS. 1865. *The Coal Question; An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal Mines*. London: Macmillan & Co.

Jiménez Cisneros BE, Oki T, Arnell NW, Benito G, Cogley JG, Döll P, Jiang T, Mwakalila SS. 2014. Freshwater resources. In Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. New York: Cambridge University Press, 229–269.

Kadigi RMJ, Tesfay G, Bizoza A, Zinabou G. 2013. Irrigation and water use efficiency in Sub-Saharan Africa. Global Development Network Working Paper Series No. 63.

Khanna M, Zilberman D. 1997. Incentives, precision technology and environmental protection. *Ecological Economics* **23**: 25–43.

Khazzoom JD. 1980. Economic implications of mandated efficiency in standards for household appliances. *Energy Journal* **1**: 21–40.

Koundouri P, Nauges C, Tzouvelekas V. 2006. Technology adoption under production uncertainty: Theory and application to irrigation technology. *American Journal of Agricultural Economics* **88**: 657–670.

Lichtenberg E. 2002. Agriculture and the environment. *Handbook of Agricultural Economics* **2**: 1249–1313.

Linares P, Labandeira X. 2010. Energy efficiency: Economics and policy. *Journal of Economic Surveys* **24**: 573–592.

McCully P. 2001. *Silenced Rivers: The Ecology and Politics of Large Dams*. London: Zed Books.

Miltz D, White DC. 1987. Sedimentation and the economics of selecting an optimum reservoir size. *Water Resources Research* **23**: 1443–1448.

Moore MR, Gollehon NR, Carey MB. 1994. Multicrop production decisions in western irrigated agriculture: The role of water price. *American Journal of Agricultural Economics* **76**: 859–874.

Moran PAP. 1959. *The Theory of Storage*. London: Methuen Publishing.

Nelson GC, Hellerstein D. 1997. Do roads cause deforestation? Using satellite images in econometric analysis of land use. *American Journal of Agricultural Economics* **79**: 80–88.

Newbery DMG, Stiglitz JE. 1981. *The Theory of Commodity Price Stabilization: A Study in the Economics of Risk*. New York: Oxford University Press.

Nombre A. 2014. International Commission on Large Dams President answers Oxford misleading study. Accessible at `http://www.icold-cigb.org/share/article/0/icold-president-answers-oxford-misleading-study` on January 18, 2015.

Office of Management and Budget. 2011. *Regulatory Impact Analysis: A Primer*. Accessible at `http://www.whitehouse.gov/sites/default/files/omb/inforeg/regpol/circular-a-4_regulatory-impact-analysis-a-primer.pdf` on November 22, 2014.

Olen B, Wu J, Langpap C. Forthcoming. Irrigation decisions for major West Coast crops: Water scarcity and climatic determinants. *American Journal of Agricultural Economics* .

Pfaff ASP. 1999. What drives deforestation in the Brazilian Amazon?: Evidence from satellite and socioeconomic data. *Journal of Environmental Economics and Management* **37**: 26–43.

Pfeiffer L, Lin CYC. 2014. Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence. *Journal of Environmental Economics and Management* **67**: 189–208.

Postel S. 2013. Sustaining freshwater and its dependents. In Worldwatch Institute (ed.) *State of the World 2013*. Washington, D.C.: Island Press, 51–62.

Reilly J. 1995. Climate change and global agriculture: Recent findings and issues. *American Journal of Agricultural Economics* **77**: 727–733.

Reisner M. 1993. *Cadillac Desert: The American West and Its Disappearing Water*. New York: Penguin Books, revised and updated edition.

Riley JG, Scherer CR. 1979. Optimal water pricing and storage with cyclical supply and demand. *Water Resources Research* **15**: 233–239.

Samuelson PA. 1971. Stochastic speculative price. *Proceedings of the National Academy of Sciences of the United States of America* **68**: 335–337.

Scheierling SM, Loomis JB, Young RA. 2006a. Irrigation water demand: A meta-analysis of price elasticities. *Water Resources Research* **42**.

Scheierling SM, Young RA, Cardon GE. 2006b. Public subsidies for water-conserving irrigation investments: Hydrologic, agronomic, and economic assessment. *Water Resources Research* **42**.

Scheinkman JA, Schechtman J. 1983. A simple competitive model with production and storage. *Review of Economic Studies* **50**: 427–441.

Schoengold K, Sunding DL. 2014. The impact of water price uncertainty on the adoption of precision irrigation systems. *Agricultural Economics* **45**: 729–743.

Schoengold K, Sunding DL, Moreno G. 2006. Price elasticity reconsidered: Panel estimation of an agricultural water demand function. *Water Resources Research* **42**.

Schoengold K, Zilberman D. 2007. The economics of water, irrigation, and development. *Handbook of Agricultural Economics* **3**: 2933–2977.

Schwabe KA, Connor JD. 2012. Drought issues in semi-arid and arid environments. *Choices* **27**.

Serna J. 2014. California breaks drought record as 58% of state hits driest level. Los Angeles Times, July 31, 2014.

Shah FA, Zilberman D, Chakravorty U. 1995. Technology adoption in the presence of an exhaustible resource: The case of groundwater extraction. *American Journal of Agricultural Economics* **77**: 291–299.

Shah Z, Kumar MD. 2008. In the midst of the large dam controversy: Objectives, criteria for assessing large water storages in the developing world. *Water Resources Management* **22**: 1799–1824.

Simonovic SP. 1992. Reservoir systems analysis: Closing gap between theory and practice. *Journal of Water Resources Planning and Management* **118**: 262–280.

Sorrell S. 2009. Jevons' Paradox revisited: The evidence for backfire from improved energy efficiency. *Energy Policy* **37**: 1456–1469.

Sunding D, Zilberman D. 2001. The agricultural innovation process: Research and technology adoption in a changing agricultural sector. *Handbook of Agricultural Economics* **1**: 207–261.

Truong CH. 2012. An analysis of storage capacity reallocation impacts on the irrigation sector. *Environmental and Resource Economics* **51**: 141–159.

Truong CH, Drynan RG. 2013. Capacity sharing enhances efficiency in water markets involving storage. *Agricultural Water Management* **122**: 46–52.

Tsur Y. 1990. The stabilization role of groundwater when surface water supplies are uncertain: The implications for groundwater development. *Water Resources Research* **26**: 811–818.

Tsur Y, Graham-Tomasi T. 1991. The buffer value of groundwater with stochastic surface water supplies. *Journal of Environmental Economics and Management* **21**: 201–224.

United States Water Resources Council. 1983. *Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies*. Washington, D.C.: United States Government Printing Office.

Vaux HJ Jr, Pruit WO, Hatchett SA, de Souza F. 1981. Optimization of water use with respect to crop production. Technical completion report prepared for the California Department of Water Resources.

Walton B. 2015. California drought: A dry January closes and dread mounts. Circle of Blue, January 29, 2015.

Ward FA, Pulido-Velazquez M. 2008. Water conservation in irrigation can increase water use. *Proceedings of the National Academy of Sciences* **105**: 18215–18220.

Williams JC, Wright BD. 1991. *Storage and Commodity Markets*. New York: Cambridge University Press.

Working H. 1933. Price relations between July and September wheat futures at Chicago since 1885. *Wheat Studies of the Food Research Institute* **9**: 187–238.

World Commission on Dams. 2000. *Dams and Development: A New Framework for Decision-Making*. London: Earthscan Publications Ltd.

World Wide Fund for Nature. 2014. Dam solutions: Easing agricultural pressure. Accessible at `http://wwf.panda.org/what_we_do/footprint/water/dams_initiative/dams/agriculture/` on November 22, 2014.

Xie Y, Zilberman D. 2014a. The economics of water project capacities and conservation technologies. Agricultural and Applied Economics Association 2014 Annual Meeting.

Xie Y, Zilberman D. 2014b. Water-storage capacities versus water-use efficiency: Substitutes or complements? University of California, Berkeley Department of Agricultural and Resource Economics (CUDARE) Working Paper 1138.

Xu J. 2015. Personal conversation. National School of Development, Peking University, Beijing, May 15, 2015.

Yeh WWG. 1985. Reservoir management and operations models: A state-of-the-art review. *Water Resources Research* **21**: 1797–1818.

Young WH. 1910. *The Fundamental Theorems of the Differential Calculus.* Number 11 in Cambridge Tracts in Mathematics and Mathematical Physics. London: Cambridge University Press.

Zilberman D, Dinar A, MacDougall N, Khanna M, Brown C, Castillo F. 2011. Individual and institutional responses to the drought: The case of California agriculture. *Journal of Contemporary Water Research and Education* **121**: 17–23.

Zilberman D, Griffin RC, Parker DD, Mazzotta MJ, Opaluch JJ, Hyde WF, Larson DM, Fisher AC. 1994. Review of *Principles and Guidelines.* Department of Agricultural and Resource Economics, University of California.

A Appendices

A.1 Proof of Lemma 1

Proof. About Question 1, the first-order condition to the capacity-choice problem is

$$V_1^*(\bar{a}^*, a_0, \alpha) = C'(\bar{a}^*). \tag{23}$$

The left-hand side of the condition is the marginal benefit of dam capacities, while the right-hand side is the marginal cost of dam capacities. Assuming interior solutions, the optimal dam capacity, $\bar{a}^*$, should make the marginal benefit and the marginal cost of dam capacities intersect with each other. Any shifts, rotations, or other changes in the marginal benefit, $V_1^*(\bar{a}^*, a_0, \alpha)$, will move the intersection between the marginal benefit and the marginal cost, which means that the optimal dam capacity changes. The sign of $V_{13}^*(\bar{a}^*, a_0, \alpha)$ and also the CEMV, $\frac{\alpha \cdot dV_1^*(\bar{a}^*, a_0, \alpha)}{V_1^*(\bar{a}^*, a_0, \alpha) \cdot d\alpha}$, tells whether an increase in water-use efficiency will shift the marginal benefit of dam capacities up or down and, therefore, answers whether the dam designer should choose larger or smaller dam capacities.

About Question 2, given a dam capacity, if the representative water user can choose whether to improve water-use efficiency, the program will be

$$\max_{\alpha \in [0,1]} \qquad V^*(\bar{a}, a_0, \alpha) - G(\alpha), \tag{24}$$

where $G(\alpha)$ is an increasing, convex function, representing the cost at which the water user can make water-use efficiency reach α. The first-order condition of the program is then

$$V_3^*(\bar{a}, a_0, \alpha^*) = G'(\alpha^*). \tag{25}$$

The left-hand side is the marginal contribution of water-use efficiency to the dam generated value, and the right-hand side is the marginal cost of water-use efficiency improvement. Assuming interior solutions, the water user's optimal choice of water-use efficiency, α^*, should make the marginal contribution and the marginal cost intersect with each other. Therefore, the sign of $V_{31}^*(\bar{a}, a_0, \alpha)$ and also the CEMV, $\frac{\bar{a} \cdot dV_3^*(\bar{a}^*, a_0, \alpha)}{V_3^*(\bar{a}^*, a_0, \alpha) \cdot d\bar{a}}$, tells whether a larger dam capacity will shift the marginal contribution of water-use efficiency up or down and whether the water user should choose higher or lower water-use efficiency.

Now we want to establish the equivalence between $V_{13}^*(\bar{a}, a_0, \alpha)$ and $V_{31}^*(\bar{a}, a_0, \alpha)$. With some algebra, we can show that

$$
\begin{aligned}
V_{13}^*(\bar{a}, a_0, \alpha) = I_{a_0 > \bar{a}} \cdot & \left(B_{12}(\bar{a} - s_0^*, \alpha) - B_{11}(\bar{a} - s_0^*, \alpha) \frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha} \right) \\
& + \rho B_{12}(\bar{a}, \alpha) \left[1 - F_{e_1}\left(\bar{a} - (1-d)s_0^*\right) \right] \\
& + \rho(1-d) B_1(\bar{a}, \alpha) f_{e_1}\left(\bar{a} - (1-d)s_0^*\right) \frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha}
\end{aligned} \tag{26}
$$

and

$$
\begin{aligned}
V_{31}^*(\bar{a}, a_0, \alpha) = I_{a_0 > \bar{a}} \cdot B_{21}(\bar{a} - s_0^*, \alpha) & - B_{21}(\min\{a_0, \bar{a}\} - s_0^*, \alpha) \frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \bar{a}} \\
& + \rho B_{21}(\bar{a}, \alpha) \left[1 - F_{e_1}\left(\bar{a} - (1-d)s_0^*\right) \right] \\
& + \rho(1-d) \frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \bar{a}} \int_{-\infty}^{\bar{a}-(1-d)s_0^*} f_{e_1}(e_1) B_{21}((1-d)s_0^* + e_1, \alpha) de_1.
\end{aligned} \tag{27}
$$

Observe that the derivatives, $V_{13}^*(\bar{a}, a_0, \alpha)$ and $V_{31}^*(\bar{a}, a_0, \alpha)$, are continuous almost everywhere. Therefore, by Young (1910)'s Theorem, $V_{13}^*(\bar{a}, a_0, \alpha) = V_{31}^*(\bar{a}, a_0, \alpha)$ almost everywhere. The Lemma is then proved. □

A.2 Proof of Proposition 1

Proof. In the zero-storage scenario, $s_0^* = 0$, so $\frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha} = 0$. The proof is then trivial.

In the positive-storage scenario, we need to look at $\frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha}$. By the Euler equation,

$$
\begin{aligned}
B_1(\min\{a_0, \bar{a}\} - s_0^*, \alpha) &= \rho(1-d) \mathbf{E}_0 \left[I_{(1-d)s_0^* + e_1 \leq \bar{a}} \cdot B_1((1-d)s_0^* + e_1, \alpha) \right] \\
&= \rho(1-d) \int_{-\infty}^{\bar{a}-(1-d)s_0^*} f_{e_1}(x) B_1((1-d)s_0^* + x, \alpha) dx,
\end{aligned} \tag{28}
$$

we have

$$
\begin{aligned}
&- B_{11}(\min\{a_0, \bar{a}\} - s_0^*, \alpha) ds_0^* + B_{12}(\min\{a_0, \bar{a}\} - s_0^*, \alpha) d\alpha \\
=\ &\rho(1-d)^2 \mathbf{E}_0 \left[I_{(1-d)s_0^*+e_1 \le \bar{a}} \cdot B_{11}((1-d)s_0^* + e_1, \alpha) \right] ds_0^* \\
&- \rho(1-d)^2 f_{e_1}(\bar{a} - (1-d)s_0^*) B_1(\bar{a}, \alpha) ds_0^* \\
&+ \rho(1-d) \mathbf{E}_0 \left[I_{(1-d)s_0^*+e_1 \le \bar{a}} \cdot B_{12}((1-d)s_0^* + e_1, \alpha) \right] d\alpha, \qquad (29)
\end{aligned}
$$

so

$$
\begin{aligned}
&\frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha} \\
=\ &\left(B_{12}(\min\{a_0, \bar{a}\} - s_0^*, \alpha) - \rho(1-d) \mathbf{E}_0 \left[I_{(1-d)s_0^*+e_1 \le \bar{a}} \cdot B_{12}((1-d)s_0^* + e_1, \alpha) \right] \right) \\
&\cdot \Big[B_{11}(\min\{a_0, \bar{a}\} - s_0^*, \alpha) + \rho(1-d)^2 \mathbf{E}_0 \left[I_{(1-d)s_0^*+e_1 \le \bar{a}} \cdot B_{11}((1-d)s_0^* + e_1, \alpha) \right] \\
&- \rho(1-d)^2 f_{e_1}(\bar{a} - (1-d)s_0^*) B_1(\bar{a}, \alpha) \Big]^{-1}. \qquad (30)
\end{aligned}
$$

We then know

$$
\begin{aligned}
&I_{a_0 > \bar{a}} \cdot \left(B_{12}(\bar{a} - s_0^*, \alpha) - B_{11}(\bar{a} - s_0^*, \alpha) \frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha} \right) \\
=\ &I_{a_0 > \bar{a}} \cdot \Bigg\{ B_{12}(\bar{a} - s_0^*, \alpha) - B_{11}(\bar{a} - s_0^*, \alpha) \\
&\cdot \left(B_{12}(\bar{a} - s_0^*, \alpha) - \rho(1-d) \mathbf{E}_0 \left[I_{(1-d)s_0^*+e_1 \le \bar{a}} \cdot B_{12}((1-d)s_0^* + e_1, \alpha) \right] \right) \\
&\cdot \Big[B_{11}(\bar{a} - s_0^*, \alpha) + \rho(1-d)^2 \mathbf{E}_0 \left[I_{(1-d)s_0^*+e_1 \le \bar{a}} \cdot B_{11}((1-d)s_0^* + e_1, \alpha) \right] \\
&- \rho(1-d)^2 f_{e_1}(\bar{a} - (1-d)s_0^*) B_1(\bar{a}, \alpha) \Big]^{-1} \Bigg\} \\
=\ &I_{a_0 > \bar{a}} \cdot \Bigg\{ \Big[\rho(1-d)^2 B_{12}(\bar{a} - s_0^*, \alpha) \mathbf{E}_0 \left[I_{(1-d)s_0^*+e_1 \le \bar{a}} \cdot B_{11}((1-d)s_0^* + e_1, \alpha) \right] \\
&- \rho(1-d)^2 B_{12}(\bar{a} - s_0^*, \alpha) f_{e_1}(\bar{a} - (1-d)s_0^*) B_1(\bar{a}, \alpha) \\
&+ \rho(1-d) B_{11}(\bar{a} - s_0^*, \alpha) \mathbf{E}_0 \left[I_{(1-d)s_0^*+e_1 \le \bar{a}} \cdot B_{12}((1-d)s_0^* + e_1, \alpha) \right] \Big] \\
&\cdot \Big[B_{11}(\bar{a} - s_0^*, \alpha) + \rho(1-d)^2 \mathbf{E}_0 \left[I_{(1-d)s_0^*+e_1 \le \bar{a}} \cdot B_{11}((1-d)s_0^* + e_1, \alpha) \right] \\
&- \rho(1-d)^2 f_{e_1}(\bar{a} - (1-d)s_0^*) B_1(\bar{a}, \alpha) \Big]^{-1} \Bigg\}. \qquad (31)
\end{aligned}
$$

Denote $s_0^*(\bar{a}, a_0, \alpha) \equiv \bar{s}(\bar{a}, \alpha)$ or just $\bar{s}$ when $a_0 \geq \bar{a}$. Then we have

$$
\begin{aligned}
& I_{a_0 > \bar{a}} \cdot \left(B_{12}(\bar{a} - s_0^*, \alpha) - B_{11}(\bar{a} - s_0^*, \alpha) \frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha} \right) \\
= & I_{a_0 > \bar{a}} \cdot \Bigg\{ \Big[\rho(1-d)^2 B_{12}(\bar{a} - \bar{s}, \alpha) \mathbf{E}_0 \left[I_{(1-d)\bar{s} + e_1 \leq \bar{a}} \cdot B_{11}((1-d)\bar{s} + e_1, \alpha) \right] \\
& \quad - \rho(1-d)^2 B_{12}(\bar{a} - \bar{s}, \alpha) f_{e_1}(\bar{a} - (1-d)\bar{s}) B_1(\bar{a}, \alpha) \\
& \quad + \rho(1-d) B_{11}(\bar{a} - \bar{s}, \alpha) \mathbf{E}_0 \left[I_{(1-d)\bar{s} + e_1 \leq \bar{a}} \cdot B_{12}((1-d)\bar{s} + e_1, \alpha) \right] \Big] \\
& \quad \cdot \Big[B_{11}(\bar{a} - \bar{s}, \alpha) + \rho(1-d)^2 \mathbf{E}_0 \left[I_{(1-d)\bar{s} + e_1 \leq \bar{a}} \cdot B_{11}((1-d)\bar{s} + e_1, \alpha) \right] \\
& \quad - \rho(1-d)^2 f_{e_1}(\bar{a} - (1-d)\bar{s}) B_1(\bar{a}, \alpha) \Big]^{-1} \Bigg\}. \qquad (32)
\end{aligned}
$$

By the Euler equation we know

$$
B_1(\bar{a} - \bar{s}, \alpha) = \rho(1-d) \mathbf{E}_0 \left[I_{(1-d)\bar{s} + e_1 \leq \bar{a}} \cdot B_1((1-d)\bar{s} + e_1, \alpha) \right] \leq B_1((1-d)\bar{s} + \underline{e}, \alpha), \quad (33)
$$

so $\bar{a} - \bar{s} \geq (1-d)\bar{s} + \underline{e}$. Note $B_1(w, \alpha) > 0$ and $B_1(w, \alpha) < 0$ by $\mathcal{B}'(\cdot) > 0$ and $\mathcal{B}''(\cdot) < 0$. Therefore, we can sign the first term in Equation (12):

$$
I_{a_0 > \bar{a}} \cdot \left(B_{12}(\bar{a} - s_0^*, \alpha) - B_{11}(\bar{a} - s_0^*, \alpha) \frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha} \right) \geq 0 \quad (34)
$$

if $B_{12}(w, \alpha) \geq 0$ for any $w \in [(1-d)\bar{s} + \underline{e}, \bar{a}]$;

$$
I_{a_0 > \bar{a}} \cdot \left(B_{12}(\bar{a} - s_0^*, \alpha) - B_{11}(\bar{a} - s_0^*, \alpha) \frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha} \right) \leq 0 \quad (35)
$$

if $B_{12}(w, \alpha) \leq 0$ for any $w \in [(1-d)\bar{s} + \underline{e}, \bar{a}]$. We also know that the second term in Equation (12) will be positive if and only if $B_{12}(\bar{a}, \alpha) \geq 0$. Therefore, we can sign the sum of the first two terms in Equation (12): It will be positive if $B_{12}(w, \alpha) \geq 0$ for any $w \in [(1-d)\bar{s} + \underline{e}, \bar{a}]$. It will be negative if $B_{12}(w, \alpha) \leq 0$ for any $w \in [(1-d)\bar{s} + \underline{e}, \bar{a}]$. □

A.3 Proof of Proposition 2

Proof. Follow Appendix A.2's expression of $\frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha}$ to sign the third term in Equation (12).

When $B_{12}(w,\alpha) \leq 0$ for $w \in [\underline{e}, (1-d)\bar{s}+\bar{e}]$,

$$\begin{aligned}
&B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha) - \rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq\bar{a}}\cdot B_{12}((1-d)s_0^*+e_1,\alpha)\right] \\
&\leq B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha) - \mathbf{E}_0\left[B_{12}((1-d)s_0^*+e_1,\alpha)\right]. \qquad (36)
\end{aligned}$$

When $B_{12}(w,\alpha) \leq 0$ and $B_{1211}(w,\alpha) \geq 0$ for $w \in [\underline{e}, (1-d)\bar{s}+\bar{e}]$, by Jensen (1903)'s inequality,

$$\begin{aligned}
&B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha) - \rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq\bar{a}}\cdot B_{12}((1-d)s_0^*+e_1,\alpha)\right] \\
&\leq B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha) - \mathbf{E}_0\left[B_{12}((1-d)s_0^*+e_1,\alpha)\right] \\
&\leq B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha) - B_{12}((1-d)s_0^*+\mathbf{E}_0\left[e_1\right],\alpha). \qquad (37)
\end{aligned}$$

When $B_{111}(w,\alpha) \leq 0$ for any $w \in [\underline{e}, (1-d)\bar{s}+\bar{e}]$, by the Euler equation and Jensen (1903)'s inequality,

$$\begin{aligned}
B_1(\min\{a_0,\bar{a}\}-s_0^*,\alpha) &= \rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq\bar{a}}\cdot B_1((1-d)s_0^*+e_1,\alpha)\right] \\
&\leq \mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq\bar{a}}\cdot B_1((1-d)s_0^*+e_1,\alpha)\right] \\
&\leq \mathbf{E}_0\left[B_1((1-d)s_0^*+e_1,\alpha)\right] \\
&\leq B_1((1-d)s_0^*+\mathbf{E}_0\left[e_1\right],\alpha), \qquad (38)
\end{aligned}$$

so $\min\{a_0,\bar{a}\}-s_0^* \geq (1-d)s_0^*+\mathbf{E}_0\left[e_1\right]$.

When $B_{12}(w,\alpha) \leq 0$, $B_{1211}(w,\alpha) \geq 0$, and $B_{111}(w,\alpha) \leq 0$ for $w \in [\underline{e}, (1-d)\bar{s}+\bar{e}]$ and $B_{121}(w,\alpha) \leq 0$ for any $[(1-d)s_0^*+\mathbf{E}_0\left[e_1\right], \min\{a_0,\bar{a}\}-s_0^*]$,

$$\begin{aligned}
&B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha) - \rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq\bar{a}}\cdot B_{12}((1-d)s_0^*+e_1,\alpha)\right] \\
&\leq B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha) - B_{12}((1-d)s_0^*+\mathbf{E}_0\left[e_1\right],\alpha) \\
&\leq 0. \qquad (39)
\end{aligned}$$

Note that $\min\{a_0,\bar{a}\}-s_0^* \leq (1-d)\bar{s}+\bar{e}$ and $(1-d)s_0^*+\mathbf{E}_0\left[e_1\right] \geq \underline{e}$. We can then state that, when $B_{12}(w,\alpha) \leq 0$, $B_{121}(w,\alpha) \leq 0$, $B_{1211}(w,\alpha) \geq 0$, and $B_{111}(w,\alpha) \leq 0$ for any $w \in [\underline{e}, (1-d)\bar{s}+\bar{e}]$,

$$B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha) - \rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq\bar{a}}\cdot B_{12}((1-d)s_0^*+e_1,\alpha)\right] \leq 0, \qquad (40)$$

which means $\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha} \geq 0$. The third term in Equation (12) is then positive. □

A.4 Resource Allocation between Water-Storage Expansions and Water-Use Efficiency Improvement

Consider the problem of resource allocation between increasing dam capacities by $\Delta\bar{a}$ and improving water-use efficiency by $\Delta\alpha$:

$$\max_{\Delta\bar{a}\geq 0, \Delta\alpha\geq 0} \quad V^*(\bar{a}+\Delta\bar{a}, a_0, \alpha+\Delta\alpha) \quad \text{s.t.} \quad p_{\bar{a}}\cdot\Delta\bar{a}+p_\alpha\cdot\Delta\alpha\leq b, \tag{41}$$

where $p_{\bar{a}} \equiv C'(\bar{a}) + D'(\bar{a})$ is the price for dam expansion, $p_\alpha \equiv G'(\alpha)$ is the price for water-use efficiency improvement, and b is the policy budget. An interior solution with $\Delta\bar{a} > 0$ and $\Delta\alpha > 0$ corresponds to a balanced distribution of the budget, while a corner solution with $\Delta\bar{a} = 0$ or $\Delta\alpha = 0$ corresponds to concentrating the budget on either dam expansion or water-use efficiency improvement with the other being ignored. An interior solution will be reached as long as the isovalue curve, $V^*(\bar{a}+\Delta\bar{a}, a_0, \alpha+\Delta\alpha) = v$, is tangent with the budget-constraint line, $p_{\bar{a}}\cdot\Delta\bar{a}+p_\alpha\cdot\Delta\alpha = b$, at a point with $\Delta\bar{a} > 0$ and $\Delta\alpha > 0$, in a $\Delta\bar{a}$-$\Delta\alpha$ span. It is equivalent to say that the slope of the isovalue curve in $\Delta\bar{a}$, $-\frac{V_1^*(\bar{a}+\Delta\bar{a},a_0,\alpha+\Delta\alpha)}{V_3^*(\bar{a}+\Delta\bar{a},a_0,\alpha+\Delta\alpha)}$, increases and becomes less negative as $\Delta\bar{a}$ increases. Mathematically, it is equivalent to

$$\frac{d\left(-\frac{V_1^*(\bar{a}+\Delta\bar{a},a_0,\alpha+\Delta\alpha)}{V_3^*(\bar{a}+\Delta\bar{a},a_0,\alpha+\Delta\alpha)}\right)}{d\Delta\bar{a}} = \underbrace{-\frac{V_{11}^*(\bar{a}+\Delta\bar{a},a_0,\alpha+\Delta\alpha)}{V_3^*(\bar{a}+\Delta\bar{a},a_0,\alpha+\Delta\alpha)}}_{(+)} + \underbrace{\frac{V_1^*(\bar{a}+\Delta\bar{a},a_0,\alpha+\Delta\alpha)}{V_3^*(\bar{a}+\Delta\bar{a},a_0,\alpha+\Delta\alpha)^2}}_{(+)} \cdot V_{13}^*(\bar{a}+\Delta\bar{a},a_0,\alpha+\Delta\alpha) > 0. \tag{42}$$

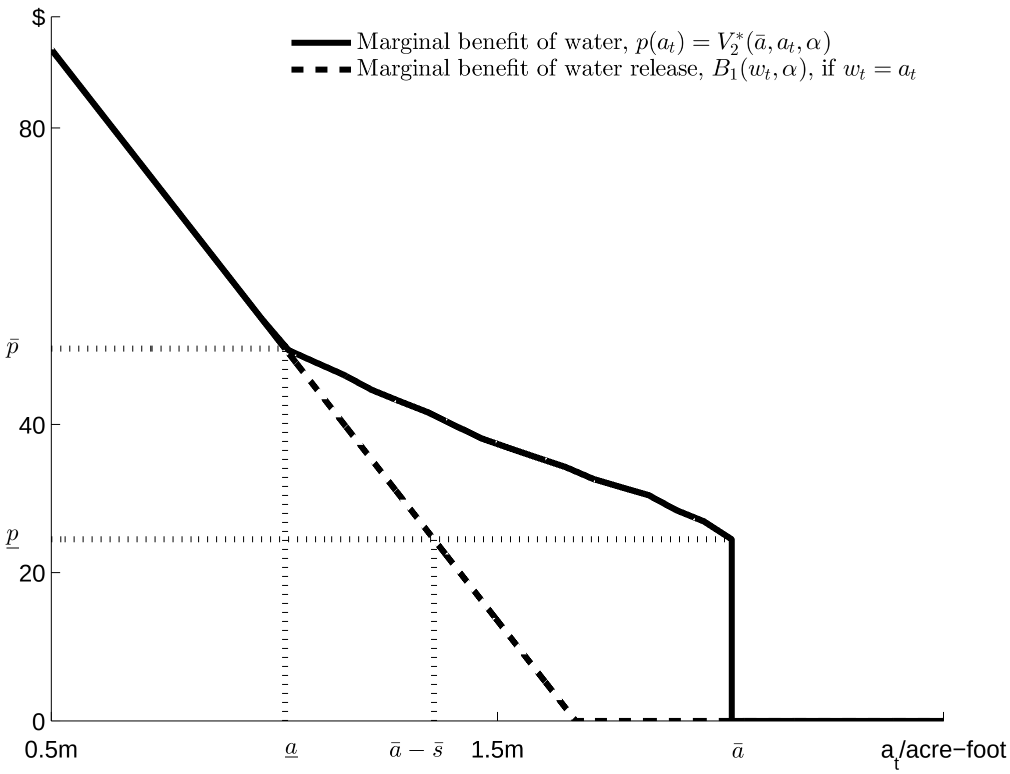
Note that complementarity between dam expansion and water-use efficiency improvement is equivalent to $V_{13}^*(\bar{a}+\Delta\bar{a}, a_0, \alpha+\Delta\alpha) > 0$, so the complementarity will guarantee an interior solution to the resource allocation problem, which means that balanced distribution between the policies will be optimal. Only extremely strong substitution with $V_{13}^*(\bar{a}+\Delta\bar{a}, a_0, \alpha+\Delta\alpha) \ll 0$ could make ignoring either dam expansions or water-use efficiency improvement optimal.

A.5 Analysis and Results for the Extended Model

The extended model carries the same logic as in the simple model. The Euler (in)equations of the water-inventory management problem are

$$\begin{aligned} &B_1(w_t^*, \alpha) \geq \rho(1-d)\mathbf{E}_t\left[V_2^*(\bar{a}, (1-d)s_t^* + e_{t+1}, \alpha)\right] \text{ if } s_t^* = 0; \\ &B_1(w_t^*, \alpha) = \rho(1-d)\mathbf{E}_t\left[V_2^*(\bar{a}, (1-d)s_t^* + e_{t+1}, \alpha)\right] \text{ if } s_t^* > 0 \text{ and } w_t^* > 0, \end{aligned} \tag{43}$$

where w_t^* and s_t^* are the optimal water release and water storage at t given the water availability, a_t, respectively, and $w_t^* + s_t^* \equiv \min\{a_t, \bar{a}\}$, the amount of water that is captured at t. The left-hand sides of the (in)equations are the marginal cost of water storage and the right-hand sides are the marginal benefit of water storage. The equation holds when the optimal water release and the optimal water storage are both positive.



The marginal benefit of water release when the dam reaches the full capacity is $\underline{p} \equiv B_1(\bar{a} - \bar{s}, \alpha)$, where $\bar{s}$ is the optimal water storage when $a_t \geq \bar{a}$. Specification follows Table 2 in Section 6.

Figure 3: Example of the solution to the water-inventory management problem in the extended model

Figure 3 shows an example of the solution to the water-inventory management problem. The dashed line is the marginal benefit of water release if the dam releases all of the captured water, which could be suboptimal. The solid line shows the marginal benefit of water under optimal water-inventory management as a function in the current water availability, a_t. When $a_t < \underline{a} < \bar{a}$, the zero-storage scenario happens: The marginal benefit of water release will be higher than the marginal benefit of water storage even if the dam does not store any water. Therefore, it is optimal to release all of the captured water. The marginal benefit of water, $V_2^*(\bar{a}, a_t, \alpha)$, then goes exactly the same as the marginal benefit of water release valued at the level of the current water availability, $B_1(a_t, \alpha)$, so the dashed line and the solid line overlap. When $\underline{a} < a_t < \bar{a}$, we move into the positive-storage scenario: A positive amount of water storage, $s_t^* > 0$, will make the marginal benefit of water release and the marginal benefit of water storage break even. The marginal benefit of water, $V_2^*(\bar{a}, a_t, \alpha) = B_1(w_t^*, \alpha)$, is then higher than the marginal benefit of water release valued at the level of the current water availability, $B_1(a_t, \alpha)$, because $w_t^* \equiv a_t - s_t^* < a_t$. When $a_t > \bar{a}$, the dam reaches the full capacity and can capture no more than $\bar{a}$. Therefore, any additional water will spill and the marginal benefit of water is zero. We still denote the optimal water storage in this case as $\bar{s}$. The marginal benefit of water release when the dam reaches the full capacity is then $\underline{p} \equiv B_1(\bar{a} - \bar{s}, \alpha)$.

Proposition 4 (Possibility of complementarity in the extended model)**.** *Dam capacities and water-use efficiency could be complements:*

- *If the marginal-water-benefit channel is positive: Water-use efficiency improvement will increase the inverse demand for water;*
- *Or, if the full-dam-capacity channel is positive: Water-use efficiency improvement will decrease the inverse demand for water and the decrease is larger with larger water use.*

Mathematically, the CEMV could be positive:

- *If* $B_{12}(w, \alpha) \geq 0$ *for any* $w \in [\underline{e}, \bar{a} - \bar{s}]$*;*
- *Or, if* $B_{12}(w, \alpha) \leq 0$*,* $B_{121}(w, \alpha) \leq 0$*,* $B_{111}(w, \alpha) \leq 0$*, and* $B_{1211}(w, \alpha) \geq 0$ *for any* $w \in [\underline{e}, (1-d)\bar{s} + \bar{e}]$*.*

Parallel corollaries then follow.

Proof. The Bellman (1957) equation is

$$V^*(\bar{a}, a_0, \alpha) \equiv \max_{s_0} \{B(\min\{a_0, \bar{a}\} - s_0, \alpha) + \rho \mathbf{E}_0 [V^*(\bar{a}, (1-d)s_0 + e_1, \alpha)]\} \quad \text{s.t.} \tag{44}$$

$$s_0 \geq 0, \min\{a_0, \bar{a}\} - s_0 \geq 0, a_0 \text{ is given.} \tag{45}$$

The marginal benefit of dam capacities is

$$\begin{aligned} V_1^*(\bar{a}, a_0, \alpha) = &\, I_{a_0 > \bar{a}} \cdot B_1(\bar{a} - s_0^*, \alpha) - B_1(\min\{a_0, \bar{a}\} - s_0^*, \alpha) \frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \bar{a}} \\ &+ \rho \mathbf{E}_0 [V_1^*(\bar{a}, (1-d)s_0^* + e_1, \alpha)] \\ &+ \rho(1-d)\mathbf{E}_0 [V_2^*(\bar{a}, (1-d)s_0^* + e_1, \alpha)] \frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \bar{a}} \end{aligned} \tag{46}$$

Suppose $s_0^* = \min\{a_0, \bar{a}\}$. Then an Euler inequation,

$$\begin{aligned} B_1(0,\alpha) &\le \rho(1-d)\mathbf{E}_0\left[V_2^*(\bar{a},(1-d)\min\{a_0,\bar{a}\}+e_1,\alpha)\right] \\ &= \rho(1-d)\mathbf{E}_0\left[I_{(1-d)\min\{a_0,\bar{a}\}+e_1\le\bar{a}}\cdot B_1(w_1^*,\alpha)\right], \end{aligned} \tag{47}$$

must hold, but it is impossible, because

$$B_1(0,\alpha) \le \rho(1-d)\mathbf{E}_0\left[I_{(1-d)\min\{a_0,\bar{a}\}+e_1\le\bar{a}}\cdot B_1(w_1^*,\alpha)\right] < B_1(0,\alpha) \tag{48}$$

makes a contradiction. Therefore, $s_0^* \in [0, \min\{a_0, \bar{a}\})$.

Suppose $s_0^* = 0$. Then the marginal benefit of dam capacities is

$$V_1^*(\bar{a},a_0,\alpha) = I_{a_0>\bar{a}}\cdot B_1(\bar{a},\alpha) + \rho\mathbf{E}_0\left[V_1^*(\bar{a},e_1,\alpha)\right]. \tag{49}$$

Suppose $s_0^* \in (0, \min\{a_0, \bar{a}\})$, an Euler equation,

$$B_1(\min\{a_0,\bar{a}\}-s_0^*,\alpha) = \rho(1-d)\mathbf{E}_0\left[V_2^*(\bar{a},(1-d)s_0^*+e_1,\alpha)\right], \tag{50}$$

must hold. Then the marginal benefit of dam capacities is

$$V_1^*(\bar{a},a_0,\alpha) = I_{a_0>\bar{a}}\cdot B_1(\bar{a}-s_0^*,\alpha) + \rho\mathbf{E}_0\left[V_1^*(\bar{a},(1-d)s_0^*+e_1,\alpha)\right]. \tag{51}$$

Collecting the two cases of $s_0^* \in [0, \min\{a_0, \bar{a}\})$, the marginal benefit of dam capacities is

$$\begin{aligned} V_1^*(\bar{a},a_0,\alpha) &= I_{a_0>\bar{a}}\cdot B_1(\bar{a}-s_0^*,\alpha) + \rho\mathbf{E}_0\left[V_1^*(\bar{a},(1-d)s_0^*+e_1,\alpha)\right] \\ &\equiv I_{a_0>\bar{a}}\cdot B_1(\bar{a}-\bar{s},\alpha) + \rho\mathbf{E}_0\left[V_1^*(\bar{a},(1-d)s_0^*+e_1,\alpha)\right], \end{aligned} \tag{52}$$

where we denote the optimal storage when the dam reaches the full capacity as $\bar{s}(\bar{a}, \alpha)$ or simply $\bar{s}$. By iteration,

$$
\begin{aligned}
V_1^*(\bar{a}, a_0, \alpha) &= I_{a_0>\bar{a}} \cdot B_1(\bar{a}-\bar{s}, \alpha) + \rho \mathbf{E}_0 \left[V_1^*(\bar{a}, (1-d)s_0^* + e_1, \alpha)\right] \\
&= I_{a_0>\bar{a}} \cdot B_1(\bar{a}-\bar{s}, \alpha) + \sum_{t=1}^{\infty} \rho^t \mathbf{E}_0 \left[I_{a_t^*>\bar{a}} \cdot B_1(\bar{a}-\bar{s}, \alpha)\right] \\
&= I_{a_0>\bar{a}} \cdot B_1(\bar{a}-\bar{s}, \alpha) + B_1(\bar{a}-\bar{s}, \alpha) \sum_{t=1}^{\infty} \rho^t \mathbf{E}_0 \left[I_{a_t^*>\bar{a}}\right] \\
&= I_{a_0>\bar{a}} \cdot B_1(\bar{a}-\bar{s}, \alpha) + B_1(\bar{a}-\bar{s}, \alpha) \sum_{t=1}^{\infty} \rho^t \left(1 - F_{a_t^*|\bar{a},a_0,\alpha}(\bar{a}; \bar{a}, a_0, \alpha)\right) \\
&= B_1(\bar{a}-\bar{s}, \alpha) \left[I_{a_0>\bar{a}} + \sum_{t=1}^{\infty} \rho^t \left(1 - F_{a_t^*|\bar{a},a_0,\alpha}(\bar{a}; \bar{a}, a_0, \alpha)\right)\right] \qquad (53)
\end{aligned}
$$

The cross-partial derivative (CPD) of the dam generated value with respect to dam capacities and water-use efficiency is then

$$
\begin{aligned}
V_{13}^*(\bar{a}, a_0, \alpha) = &\left(B_{12}(\bar{a}-\bar{s}, \alpha) - B_{11}(\bar{a}-\bar{s}, \alpha)\frac{\partial \bar{s}(\bar{a}, \alpha)}{\partial \alpha}\right) \\
&\cdot \left[I_{a_0>\bar{a}} + \sum_{t=1}^{\infty} \rho^t \left(1 - F_{a_t^*|\bar{a},a_0,\alpha}(\bar{a}; \bar{a}, a_0, \alpha)\right)\right] \\
&- B_1(\bar{a}-\bar{s}, \alpha) \sum_{t=1}^{\infty} \rho^t \frac{\partial F_{a_t^*|\bar{a},a_0,\alpha}(\bar{a}; \bar{a}, a_0, \alpha)}{\partial \alpha}. \qquad (54)
\end{aligned}
$$

The first term is the marginal-water-benefit channel. The second term is the full-dam-probability channel.

We have known that $\bar{s}(\bar{a}, \alpha) \in [0, \bar{a})$. Suppose $\bar{s}(\bar{a}, \alpha) = 0$. Then the optimal storage will always be zero. Therefore, the CPD becomes

$$
V_{13}^*(\bar{a}, a_0, \alpha) = B_{12}(\bar{a}, \alpha) \cdot \left[I_{a_0>\bar{a}} + \sum_{t=1}^{\infty} \rho^t \left(1 - F_{e_t}(\bar{a})\right)\right], \qquad (55)
$$

whose sign is determined by the sign of $B_{12}(\bar{a}, \alpha)$.

Now consider the case in which $\bar{s}(\bar{a}, \alpha) \in (0, \bar{a})$. First focus on $\frac{\partial \bar{s}(\bar{a},\alpha)}{\partial \alpha}$. By the Euler equation,

$$
\begin{aligned}
B_1(\bar{a}-\bar{s}, \alpha) &= \rho(1-d)\mathbf{E}_0 \left[V_2^*(\bar{a}, (1-d)\bar{s} + e_1, \alpha)\right] \\
&= \rho(1-d) \int_{-\infty}^{\bar{a}-(1-d)\bar{s}} f_{e_1}(x) V_2^*(\bar{a}, (1-d)\bar{s} + x, \alpha) dx, \qquad (56)
\end{aligned}
$$

we have

$$
\begin{aligned}
& B_{12}(\bar{a}-\bar{s},\alpha)d\alpha - B_{11}(\bar{a}-\bar{s},\alpha)d\bar{s} \\
= \; & -\rho(1-d)^2 f_{e_1}(\bar{a}-(1-d)\bar{s})V_2^*(\bar{a},\bar{a},\alpha)d\bar{s} \\
& + \rho(1-d)^2\left[\int_{-\infty}^{\bar{a}-(1-d)\bar{s}} f_{e_1}(x)V_{22}^*(\bar{a},(1-d)\bar{s}+x,\alpha)dx\right]d\bar{s} \\
& + \rho(1-d)\left[\int_{-\infty}^{\bar{a}-(1-d)\bar{s}} f_{e_1}(x)V_{23}^*(\bar{a},(1-d)\bar{s}+x,\alpha)dx\right]d\alpha \\
= \; & -\rho(1-d)^2 f_{e_1}(\bar{a}-(1-d)\bar{s})V_2^*(\bar{a},\bar{a},\alpha)d\bar{s} \\
& + \rho(1-d)^2\mathbf{E}_0\left[I_{(1-d)\bar{s}+e_1\le\bar{a}}\cdot V_{22}^*(\bar{a},(1-d)\bar{s}+e_1,\alpha)\right]d\bar{s} \\
& + \rho(1-d)\mathbf{E}_0\left[I_{(1-d)\bar{s}+e_1\le\bar{a}}\cdot V_{23}^*(\bar{a},(1-d)\bar{s}+e_1,\alpha)\right]d\alpha
\end{aligned} \tag{57}
$$

Therefore, we know

$$
\begin{aligned}
\frac{\partial\bar{s}(\bar{a},\alpha)}{\partial\alpha} = & \left[B_{12}(\bar{a}-\bar{s},\alpha) - \rho(1-d)\mathbf{E}_0\left[I_{(1-d)\bar{s}+e_1\le\bar{a}}\cdot V_{23}^*(\bar{a},(1-d)\bar{s}+e_1,\alpha)\right]\right] \\
& \cdot\Big[B_{11}(\bar{a}-\bar{s},\alpha) + \rho(1-d)^2\mathbf{E}_0\left[I_{(1-d)\bar{s}+e_1\le\bar{a}}\cdot V_{22}^*(\bar{a},(1-d)\bar{s}+e_1,\alpha)\right] \\
& \quad - \rho(1-d)^2 f_{e_1}(\bar{a}-(1-d)\bar{s})V_2^*(\bar{a},\bar{a},\alpha)\Big]^{-1},
\end{aligned} \tag{58}
$$

so

$$
\begin{aligned}
& B_{12}(\bar{a}-\bar{s},\alpha) - B_{11}(\bar{a}-\bar{s},\alpha)\frac{\partial\bar{s}(\bar{a},\alpha)}{\partial\alpha} \\
= & B_{12}(\bar{a}-\bar{s},\alpha) - B_{11}(\bar{a}-\bar{s},\alpha) \\
& \cdot\left[B_{12}(\bar{a}-\bar{s},\alpha) - \rho(1-d)\mathbf{E}_0\left[I_{(1-d)\bar{s}+e_1\le\bar{a}}\cdot V_{23}^*(\bar{a},(1-d)\bar{s}+e_1,\alpha)\right]\right] \\
& \cdot\Big[B_{11}(\bar{a}-\bar{s},\alpha) + \rho(1-d)^2\mathbf{E}_0\left[I_{(1-d)\bar{s}+e_1\le\bar{a}}\cdot V_{22}^*(\bar{a},(1-d)\bar{s}+e_1,\alpha)\right] \\
& \quad - \rho(1-d)^2 f_{e_1}(\bar{a}-(1-d)\bar{s})V_2^*(\bar{a},\bar{a},\alpha)\Big]^{-1} \\
= & \Big[\rho(1-d)^2 B_{12}(\bar{a}-\bar{s},\alpha)\mathbf{E}_0\left[I_{(1-d)\bar{s}+e_1\le\bar{a}}\cdot V_{22}^*(\bar{a},(1-d)\bar{s}+e_1,\alpha)\right] \\
& - \rho(1-d)^2 B_{12}(\bar{a}-\bar{s},\alpha) f_{e_1}(\bar{a}-(1-d)\bar{s})V_2^*(\bar{a},\bar{a},\alpha) \\
& + \rho(1-d)B_{11}(\bar{a}-\bar{s},\alpha)\mathbf{E}_0\left[I_{(1-d)\bar{s}+e_1\le\bar{a}}\cdot V_{23}^*(\bar{a},(1-d)\bar{s}+e_1,\alpha)\right]\Big] \\
& \cdot\Big[B_{11}(\bar{a}-\bar{s},\alpha) + \rho(1-d)^2\mathbf{E}_0\left[I_{(1-d)\bar{s}+e_1\le\bar{a}}\cdot V_{22}^*(\bar{a},(1-d)\bar{s}+e_1,\alpha)\right] \\
& \quad - \rho(1-d)^2 f_{e_1}(\bar{a}-(1-d)\bar{s})V_2^*(\bar{a},\bar{a},\alpha)\Big]^{-1}.
\end{aligned} \tag{59}
$$

Note $V_2^*(\bar{a},a_t,\alpha) = I_{a_t\le\bar{a}}\cdot B_1(w^*(\bar{a},a_t,\alpha),\alpha)$, where $w^*(\bar{a},a_t,\alpha)$ is the optimal current water release when the current water availability is a_t. Therefore,

$$\begin{aligned}
&\mathbf{E}_0\left[I_{(1-d)\bar{s}+e_1\leq\bar{a}}\cdot V_{23}^*(\bar{a},(1-d)\bar{s}+e_1,\alpha)\right]\\
=&\,\mathbf{E}_0\left[I_{(1-d)\bar{s}+e_1\leq\bar{a}}\cdot B_{12}(w^*(\bar{a},(1-d)\bar{s}+e_1,\alpha),\alpha)\right] \qquad (60)
\end{aligned}$$

and

$$\begin{aligned}
&\mathbf{E}_0\left[I_{(1-d)\bar{s}+e_1\leq\bar{a}}\cdot V_{22}^*(\bar{a},(1-d)\bar{s}+e_1,\alpha)\right]\\
=&\,\mathbf{E}_0\left[I_{(1-d)\bar{s}+e_1\leq\bar{a}}\cdot B_{11}(w^*(\bar{a},(1-d)\bar{s}+e_1,\alpha),\alpha)\right]\\
\leq&\, 0. \qquad (61)
\end{aligned}$$

We then can sign $B_{12}(\bar{a}-\bar{s},\alpha)-B_{11}(\bar{a}-\bar{s},\alpha)\frac{\partial\bar{s}(\bar{a},\alpha)}{\partial\alpha}$ and the first term of the CPD: They are positive if $B_{12}(w,\alpha)\geq 0$ for any $w\in[\underline{e},\bar{a}-\bar{s}]$. They are negative if $B_{12}(w,\alpha)\leq 0$ for any $w\in[\underline{e},\bar{a}-\bar{s}]$.

Now focus on the second term of the CPD and, equivalently, $\frac{\partial F_{a_t^*|\bar{a},a_0,\alpha}(\bar{a};\bar{a},a_0,\alpha)}{\partial\alpha}$. First consider $\frac{\partial F_{a_1^*|\bar{a},a_0,\alpha}(\bar{a};\bar{a},a_0,\alpha)}{\partial\alpha}=\frac{dF_{e_1}(\bar{a}-(1-d)s_0^*(\bar{a},a_0,\alpha))}{d\alpha}=-(1-d)f_{e_1}(\bar{a}-(1-d)s_0^*)\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha}$. We have already known that $s_0^*(\bar{a},a_0,\alpha)\in[0,\min\{\bar{a},a_0\})$.

Suppose $s_0^*=0$. Then $\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha}=0$.

Suppose $s_0^*\in(0,\min\{\bar{a},a_0\})$. By the Euler equation,

$$\begin{aligned}
B_1(\min\{a_0,\bar{a}\}-s_0^*,\alpha)&=\rho(1-d)\mathbf{E}_0\left[V_2^*(\bar{a},(1-d)s_0^*+e_1,\alpha)\right]\\
&=\rho(1-d)\int_{-\infty}^{\bar{a}-(1-d)s_0^*}f_{e_1}(x)V_2^*(\bar{a},(1-d)s_0^*+x,\alpha)dx, \qquad (62)
\end{aligned}$$

we know

$$\begin{aligned}
&B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)d\alpha-B_{11}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)ds_0^*\\
=&-\rho(1-d)^2f_{e_1}(\bar{a}-(1-d)s_0^*)V_2^*(\bar{a},\bar{a},\alpha)ds_0^*\\
&+\rho(1-d)^2\left[\int_{-\infty}^{\bar{a}-(1-d)s_0^*}f_{e_1}(x)V_{22}^*(\bar{a},(1-d)s_0^*+x,\alpha)dx\right]ds_0^*\\
&+\rho(1-d)\left[\int_{-\infty}^{\bar{a}-(1-d)s_0^*}f_{e_1}(x)V_{23}^*(\bar{a},(1-d)s_0^*+x,\alpha)dx\right]d\alpha\\
=&-\rho(1-d)^2f_{e_1}(\bar{a}-(1-d)s_0^*)V_2^*(\bar{a},\bar{a},\alpha)ds_0^*\\
&+\rho(1-d)^2\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq\bar{a}}\cdot V_{22}^*(\bar{a},(1-d)s_0^*+e_1,\alpha)\right]ds_0^*\\
&+\rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq\bar{a}}\cdot V_{23}^*(\bar{a},(1-d)s_0^*+e_1,\alpha)\right]d\alpha, \qquad (63)
\end{aligned}$$

so

$$\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha} = \left[B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)-\rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}}\cdot V_{23}^*(\bar{a},(1-d)s_0^*+e_1,\alpha)\right]\right] \cdot\Big[B_{11}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)+\rho(1-d)^2\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}}\cdot V_{22}^*(\bar{a},(1-d)s_0^*+e_1,\alpha)\right] -\rho(1-d)^2 f_{e_1}(\bar{a}-(1-d)s_0^*)V_2^*(\bar{a},\bar{a},\alpha)\Big]^{-1}, \tag{64}$$

Note again $V_2^*(\bar{a},a_t,\alpha)=I_{a_t\le\bar{a}}\cdot B_1(w^*(\bar{a},a_t,\alpha),\alpha)$. Therefore,

$$\begin{aligned}&\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}}\cdot V_{23}^*(\bar{a},(1-d)s_0^*+e_1,\alpha)\right]\\ =&\,\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}}\cdot B_{12}(w^*(\bar{a},(1-d)s_0^*+e_1,\alpha),\alpha)\right]\end{aligned} \tag{65}$$

and

$$\begin{aligned}&\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}}\cdot V_{22}^*(\bar{a},(1-d)s_0^*+e_1,\alpha)\right]\\ =&\,\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}}\cdot B_{11}(w^*(\bar{a},(1-d)s_0^*+e_1,\alpha),\alpha)\right]\\ \le&\, 0.\end{aligned} \tag{66}$$

With the similar analysis as in the two-period stochastic model, we know that, when $B_{12}(w,\alpha)\le 0$, $B_{121}(w,\alpha)\le 0$, $B_{111}(w,\alpha)\le 0$, and $B_{1211}(w,\alpha)\ge 0$ for any $w\in[\underline{e},(1-d)\bar{s}+\bar{e}]$,

$$B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)-\rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}}\cdot V_{23}^*(\bar{a},(1-d)s_0^*+e_1,\alpha)\right]\le 0. \tag{67}$$

Therefore, $\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha}\ge 0$. Note that the similar discussion about weaker conditions also applies.

Collecting the two cases of $s_0^*(\bar{a},a_0,\alpha)\in[0,\min\{\bar{a},a_0\})$, we see $\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha}\ge 0$ and $\frac{\partial F_{a_1^*|\bar{a},a_0,\alpha}(\bar{a};\bar{a},a_0,\alpha)}{\partial\alpha}=-(1-d)f_{e_1}(\bar{a}-(1-d)s_0^*)\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha}\le 0$.

Now consider $\frac{\partial F_{a_2^*|\bar{a},a_0,\alpha}(\bar{a};\bar{a},a_0,\alpha)}{\partial\alpha}$. For any realization of (e_1,e_2), see

$$a_2^*=(1-d)s_1^*(\bar{a},a_1^*,\alpha)+e_2=(1-d)s_1^*(\bar{a},(1-d)s_0^*(\bar{a},a_0,\alpha)+e_1,\alpha)+e_2. \tag{68}$$

Therefore,

$$\frac{da_2^*}{d\alpha}=(1-d)\left[\frac{\partial s_1^*(\bar{a},a_1^*,\alpha)}{\partial\alpha}+(1-d)\frac{\partial s_1^*(\bar{a},a_1^*,\alpha)}{\partial a_1^*}\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha}\right] \tag{69}$$

With the similar analysis as for $\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha}$, we know that $\frac{\partial s_1^*(\bar{a},a_1,\alpha)}{\partial\alpha}\ge 0$. We also know that in equilibrium $\frac{\partial s_1^*(\bar{a}, a_1^*, \alpha)}{\partial a_1^*} \geq 0$. Therefore, $\frac{da_2^*}{d\alpha} \geq 0$. Therefore, there is a first-order stochastic shift in the distribution of a_2^* conditional on a_0, so $\frac{\partial F_{a_2^*|\bar{a}, a_0, \alpha}(\bar{a}; \bar{a}, a_0, \alpha)}{\partial \alpha} \leq 0$.

Similarly, we know $\frac{\partial F_{a_t^*|\bar{a}, a_0, \alpha}(\bar{a}; \bar{a}, a_0, \alpha)}{\partial \alpha} \leq 0$ for any $t \geq 1$. Therefore, the second term of the CPD is positive. □

A.6 Specification of the Numerical Illustrations

The California State Water Projects captures water from the Sierra Nevada through the Feather River into Lake Oroville, the main storage facility of the Project.[15] In each year, inflows and spills are predominately during winter and spring (January–May). Water stored in Lake Oroville is released into the Oroville-Thermalito Complex (Thermalito Forebay), then transported from the Complex southward through the Feather River, the Sacramento River, and the California Aqueduct, and stored in reservoirs locating along the Project from the north to the south. Around May–June, the Project decides water allocation for contractors in the current year, which generates irrigation benefit in the second half of the year. Around November–December, observing storage in principal reservoirs, the Project announces a preliminary plan for water allocation in the next year. This operation pattern fits our model and we can use the calendar year as the time unit in the specification of the model.

The 1974–2010 data of the end-of-calendar-year storage in principal reservoirs of the California State Water Project are available from the California Department of Water Resources (1963–2013, 1976–2014). The Department (1963–2013) reports the 1975–2010 data of the project wide deliveries. According to the Department (1976–2014), the average annual evaporation-loss rate of the water storage in the five primary storage facilities—Antelope Lake, Frenchman Lake, Lake Davis, Lake Oroville, and the San Luis Reservoir—in 1976, 1981, 1986, 1991, 1996, and 2001 is 0.038, which is approximately 0.04. The Department (1976–2014; 1990–2014) also reports the 1975–2010 data of the amount of spills from Lake Oroville. Given the evaporation-loss rate, the 1974–2010 end-of-calendar-year storage data, the 1975–2010 delivery data, and the 1975–2010 spill data, we can find the corresponding 1975–2010 inflows by calculation, which have a mean of 3891587 acre-feet and a corrected sample standard deviation of 1444480 acre-feet. The total amount of water that is captured by the Project, which is the end-of-calendar-year storage plus the project wide deliveries, has a mean of 7285378 acre-feet for the 20 years that saw positive spills among the 36 years. We set the storage capacity that is equivalent to our model as 7285378 acre-feet.[16]

[15]The Project starts from three reservoirs in the Upper Feather area—Antelope Lake, Frenchman Lake, and Lake Davis. Spills and releases from the three reservoirs flow into the Feather River.

[16]The Department (1963–2013) reports that the project wide storage capacity is 5.4038 million acre-feet

The Department (1963–2013) records the 1975–2010 data of the annual deliveries to agricultural use, which have a mean of 936098 acre-feet or, equivalently, 27.80% of the total delivery. We use this percentage to adjust the inflow distribution and the storage capacity, which means that, for agricultural use, the baseline storage capacity is $0.2780 \times 7285378 = 2025335$ acre-feet and the inflow distribution has a mean of $0.2780 \times 3891587 = 1081861$ acre-feet and a corrected sample standard deviation of $0.2780 \times 1444480 = 401565$ acre-feet. The distribution of the adjusted, estimated historical inflows, which we use in the illustrations, is uniform with 36 possible values.[17]

The Department (1998–2005) publishes its annual estimates of irrigated crop areas, consumed fractions, and applied water per unit of area. The latest data available online are for 2005. We calculate the benchmark water-use efficiency in the following procedure: First, we focus on the county-level data for the 18 counties that were served by the 29 long-term contracting agencies of the California State Water Project at the end of 2010.[18] Second, for each county and each crop among the 20 categories of crops, we calculate the total amount of applied water in 2005 by multiplying the irrigated crop area with the applied water per unit area.[19] Third, for each county and each crop, we calculate the total amount of effective water by multiplying the total amount of applied water with the consumed fraction. Finally, we aggregate the total amounts of applied and effective water by counties and crops, and calculate the overall water-use efficiency by dividing the total amount of effective water over the total amount of applied water, which is 0.7135.

A recent estimate of the price elasticity of the water demand for irrigation in California by Schoengold et al. (2006) is -0.79 with panel data in which the mean price is \$46.49 per thousand cubic meters, which is approximately \$57 per acre-foot.[20] We then assume that, in our specification, the water demand should be 936098 acre-feet if the water price is \$57 per acre-foot and the water-use efficiency is 0.7135.[21] Given this assumption, we specify three

at the end of 2010. This is not the capacity equivalent to our model.

[17]The 36 values are 239001, 345959, 538214, 584182, 611960, 632764, 683223, 794128, 824611, 824867, 846706, 888651, 894498, 928424, 968210, 999585, 1052469, 1059629, 1106896, 1108130, 1111920, 1151602, 1186559, 1210988, 1309659, 1336180, 1398546, 1403399, 1409113, 1432491, 1473347, 1486822, 1609242, 1761617, 1813942, and 1919462.

[18]The 18 counties include Alameda, Butte, Kern, Kings, Los Angeles, Napa, Orange, Plumas, Riverside, San Bernardino, San Diego, San Luis Obispo, Santa Barbara, Santa Clara, Solano, Stanislaus, Ventura, and Yuba Counties. The 29 agencies are listed in the California Department of Water Resources (1963–2013, Bulletin 132-11, p. 11).

[19]The 20 categories include grain, rice, cotton, sugar beets, corn, beans, safflower, other field crops, alfalfa, pasture, tomatoes for processing, tomatoes for market, cucurbits, onions and garlics, potatoes, other truck crops, almonds and pistachios, other deciduous fruit crops, subtropical fruits, and vines.

[20]We read the variable cost of water in Schoengold et al. (2006)'s Table 2 as the price.

[21]Note that only the relative price but not the absolute price matters, so the number of the price does not matter for the results that we illustrate.

functions of the benefit of water release satisfying, respectively, that 1) the derived water demand (or marginal benefit of water release) is isoelastic and has an elasticity of -1.21, 2) the derived water demand is isoelastic and has an elasticity of -0.79, and 3) the derived water demand is linear and has an elasticity of -0.79 when the demand is 936098 acre-feet. We also assume free disposal of water so that the marginal benefit of water will never be negative. The three functions of the benefit of water release are then shown as in Table 1.

In water project evaluations, the annual discount rate recommended by the California Department of Water Resources (2008) is 0.06. The discount factor is then $(1 + 0.06)^{-1} = 0.9434$. We then finish specifying the empirical example, as shown in Table 2.