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

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Abstract: Investments in water use efficiency and water storage capacity are two common approaches to tackling water scarcity and adapting to climate change. We show that they are not always substitutes. Efficiency improvement can increase the demand for storage capacity in two scenarios: (1) if it increases water demand; (2) if, as a result of re-optimization of water inventory control, it increases the probability that the storage capacity will be exhausted. We identify properties of water demand and productivity under which the two scenarios will happen, and illustrate the potential complementarity using an empirical example of the California State Water Project. The results are also applicable to choices among infrastructure investment, improved consumption efficiency, and conservation of other storable resources, for example, energy.

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WATER SCARCITY is among the most important constraints imposed on social and economic development, and climate change is projected to make this constraint even tighter in the future (e.g., Intergovernmental Panel on Climate Change, Jiménez Cis-

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neros et al. 2014). Several water management approaches have been proposed to tackle water scarcity and adapt to climate change. These approaches include investing in water infrastructure such as dams, reservoirs, and canals (e.g., Graf 1999), adopting water conservation measures such as drip irrigation, more effective water conveyance technologies, water recycling, and improving efficiency in hydropower generation (e.g., Caswell 1991; Chakravorty et al. 1995; Sunding and Zilberman 2001; Schoengold and Zilberman 2007; Mishra et al. 2011), institutional reforms in water markets and pricing (e.g., Burness and Quirk 1979; Sampath 1992; Easter et al. 1999; Dinar 2000), and other efforts such as developing drought-tolerant varieties and biological technologies (e.g., Umezawa et al. 2006).

While individual approaches have received much attention in the literature, much less is known about the relationship between these approaches. In this paper, we investigate the following question: will water conservation measures that improve input efficiency in water use decrease or increase the demand for water storage capacity?[1] In other words, are storage capacity and efficiency substitutes or complements?[2]

The answer is important for resolving a water management and policy debate between water storage and conservation initiatives. As recognized by the World Commission on Dams (2000), dams, reservoirs, and other water storage facilities provide huge benefits in the agricultural, energy, and urban sectors and have contributed substantially to human civilizations, yet they have frequently been accompanied by huge environmental, ecological, social, and economic costs and have caused major struggles across the world.[3] Improving input efficiency in water use is therefore perceived as an important alternative (e.g., Schwabe and Connor 2012). In many water policy debates, for example, the debate in response to the devastating California drought of 2012–16, storage investment and efficiency improvement have been fiercely competing for limited resources, and some even see this "as an either-or scenario" (e.g., Tom Stokely quoted by Fimrite 2014).[4] Unsurprisingly, this competition is often caused by the intuitive assertion that efficiency and storage capacity are substitutes—higher efficiency

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[1] In the paper we use "demand" and "marginal benefit" (of storage capacity) interchangeably.

[2] In the paper we often abbreviate "input efficiency in water use" and "water use efficiency" as "efficiency."

[3] For more narratives, see Reisner (1993, originally 1986), Jackson and Sleigh (2000), McCully (2001), and Fischhendler and Zilberman (2005). For examples of econometric studies on the economic and environmental consequences of dams, see Duflo and Pande (2007), Hansen, Libecap, and Lowe (2011), and Hansen, Lowe, and Xu (2014).

[4] For more examples of the debate, see Calefati (2014), Dunning and Machtinger (2014), and Hanson (2015). For estimates of the drought impact, see Howitt, Medellín-Azuara, et al. (2014), and Howitt, MacEwan, et al. (2015).

should decrease the demand for storage capacity (e.g., Gleick et al. 2003, 1; Brink et al. 2004, 28).

Our analysis shows conceptually and numerically that the assertion of substitution is not always true; instead, efficiency improvements in water use could increase the storage capacity demand. We show this by building a stylized model for choices of dam capacity, identifying two channels through which efficiency improvement can affect the capacity demand. The first is the *marginal-water-benefit* channel: will higher efficiency increase water demand, that is, the marginal benefit of water and, thus, the capacity demand? The second is the *full-dam-probability* channel: will higher efficiency encourage the dam operator to store more water now, increasing the likelihood of running out of storage capacity in face of excessive inflow in the future, that is, the full-dam probability and, thus, the capacity demand?

As a sufficiently strong positive effect through either of these two channels can expand the storage capacity demand, here comes the main message of our paper—complementarity could hold in two scenarios:

1. When the marginal-water-benefit channel is positive, that is, when higher efficiency would increase water demand. This would happen if and only if the water demand is elastic.
2. Even if the marginal-water-benefit channel is negative, as long as the full-dam-probability channel is positive. This would happen if the water demand is inelastic while the second-order elasticity of the marginal productivity of effective water (SEMP) is smaller than two.

Policy makers should then be extremely careful in estimating water demand elasticity and SEMP, because, if conservation measures and storage expansion are complements (and if they are both cost-effective), deploying only one of them would be economically inefficient; a joint deployment of both is preferable.

If the two channels have opposite directions, for example, in the second scenario above, policy makers should rely on numerical exercise to discover which channel dominates. Accordingly, we numerically illustrate our theoretical results by simulating an extended version of our model with a specification based on the irrigation water inventory management problem of the California State Water Project, which is “the largest state-built, multipurpose, user-financed water project” in the United States, irrigating “about 750000 acres of farmland” as of 2010 (California Department of Water Resources 1963–2013). Besides confirming all theoretical predictions, this illustration suggests that, in this case, the complementarity between water storage capacity and water use efficiency is likely to hold, and it is more pronounced when considering the impact of efficiency improvement on storage expansion than vice versa. For example, under the specification of the most practical relevance, a 5% efficiency improvement could raise the optimal dam capacity by about 1%, while a 5% storage expansion can induce efficiency improvement by no more than 0.2%.

The paper is unfolded as follows. Section 1 discusses the position of our paper in literature. Section 2 builds the model, incorporating both input efficiency in water use and dynamic control of water inventories in response to stochastic inflow patterns, while holding constant site selection and other important issues in dam design (e.g., International Commission on Large Dams 2007, 24). In the model, within each period, the dam is assumed to first catch water during a wet season and hold it until a dry season, fulfilling its *water catchment* function. In the dry season, the dam may release water for productive use or store water to prepare for uncertain inflows in the future, fulfilling its *stochastic control* function. Section 3 analyzes the model, presents the two channels, which come from the two functions, respectively, and shows the main results of the paper. Section 4 discusses implications of our theory on economic development, trade policies, the relationship between conservation effort and outcomes, and a range of water policy issues. Section 5 presents the numerical illustration. We conclude in section 6 with more discussion on robustness and interpretations of our results and on potential directions of future research.

1. POSITION IN LITERATURE

To our knowledge, this paper is the first to consider the impact of water use efficiency under stochastic control of water inventories on capacity choices of water projects.[5] Applying an analytical approach to the comparative statics on the marginal benefit and optimal choices of storage capacity is also rare in the literature on optimal inventory management of water and other storable commodities.[6] Fisher and Rubio (1997) make an admirable attempt in this direction on real-time dam renovations, even though their model does not include the water catchment function of dams. Their analysis is also restricted to the mean level of the equilibrium, while our analysis is applied to the whole equilibrium.

As we will discuss in section 4, our results about the impact of efficiency improvement on the demand for water storage capacity also shed some light on the question of whether storage expansion will increase or decrease the incentive for efficiency improvement. This contribution adds to the rich literature on irrigation technology adoption,

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[5] This literature started as early as Rippl (1883). Relatively recent examples are not limited to Tsur (1990), Haddad (2011), Houba et al. (2014), and Xie and Zilberman (2016).

[6] For an early application of dynamic programming to water management, see Burt (1964). Examples of later contributions are not limited to Burness and Quirk (1980), Gisser and Sánchez (1980), Tsur and Graham-Tomasi (1991), Knapp and Olson (1995), Chatterjee et al. (1998), and Truong (2012). For pioneering works on commodity inventory management, see Working (1933) and Gustafson (1958). Later notable works are not limited to Samuelson (1971), Gardner (1979), Newbery and Stiglitz (1979), Knapp (1982), Wright and Williams (1982, 1984), Scheinkman and Schechtman (1983), Williams and Wright (1991), Deaton and Laroque (1992), Chambers and Bailey (1996), Bobenrieth H. et al. (2002), Asche et al. (2015), and Oglend and Kleppe (2017).

which considers the impacts of many factors on adoption and water conservation.[7] In particular, case studies by Amarasinghe et al. (2008) and Oberkircher and Hornidge (2011) suggest that simple farm-level water storage structures, for example, small ponds near farms, could encourage farmers to adopt more efficient irrigation technologies; Bhaduri and Manna (2014) analyze the impact of farm-level water storage given a fixed, proportional rule in controlling water inventories; Xie and Zilberman (2016) show that the impact of storage capacities with only the water catchment function can be nonmonotonic. Our analysis in this paper suggests that optimally controlled storage capacity can affect irrigation technology adoption and conservation, noting that large dams and reservoirs with more sophisticated inventory control usually affect a large number of water users.

The possible complementarity between improved input efficiency and extra storage capacity is further related to the broader literature of resource economics. The potential positive impact of efficiency on the demand of storage capacity is linked to the rebound effect, also named the Jevons (1865) paradox and the Khazzoom (1980)–Brookes (1992) postulate, namely, a rebound in the demand for energy or water use because of the decline in their prices as a result of efficiency improvement in the use of the resource, offsetting the resource-saving effect of this efficiency improvement (e.g., surveys by Greening et al. 2000; Alcott 2005; Sorrell 2009; Berbel et al. 2015).[8] 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 gross consumption of the resource. The implication about the potential positive impact of storage capacity on efficiency is also related to the literature on underinvestment in efficiency improvement in energy and other resource use (e.g., surveys by Jaffe et al. 2004; Gillingham et al. 2009; Linares and Labandeira 2010; Allcott and Greenstone 2012; Gerarden et al., forthcoming). Our analysis adds underinvestment in storage of resources to the list of potential factors inducing underinvestment in resource use efficiency.

Last, but not least, our analysis has some counterintuitive implications for the rich body of literature on the relationship between infrastructure investment and resource conservation.[9] If our counterintuitive predictions are correct, then under some circum-

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[7] For examples, see 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. (2016), and Taylor and Zilberman (2017).

[8] For examples of individual studies, see Scheierling, Young, and Cardon (2006), Ward and Pulido-Velazquez (2008), Berbel and Mateos (2014), Pfeiffer and Lin (2014), Chan and Gillingham (2015), and Cobourn (2015).

[9] Examples include Chomitz and Gray (1996), Nelson and Hellerstein (1997), Pfaff (1999), Cropper et al. (2001), Deng et al. (2011), Chakravorty et al. (2015), Kaczan (2016), and He et al. (2017).

stances construction of smaller dams in response to concerns about the environmental externalities of large dams could also reduce incentives for adoption of more efficient irrigation technologies. The huge progress and potential of this adoption across the world (e.g., Postel 2013) could also increase the demand for water storage investment and could eventually increase both consumptive use of water and environmental damage. This implication extends the emerging agreement among water economists that adoption of efficient irrigation technologies often leads to higher consumptive/effective use of water (e.g., International Water Resource Economics Consortium 2014), by introducing storage capacity to the discussion.

2. MODEL

The model entails two nested decisions. The designer of a dam is making a decision to choose the dam capacity. When making the choice, the designer takes into consideration the storage-release decision that the dam operator would make given the chosen capacity. We now introduce the two decisions backwards.

2.1. Operation of a Dam Given the Dam Capacity

The dam operator dynamically controls water inventories in the dam in response to stochastic inflow, given two key parameters—the dam capacity, $\bar{a}$, and water use efficiency, α, maximizing the expected discounted value of water releases. As illustrated by figure 1, we assume that the dam operation involves two periods, 0 and 1, and that, in each period, a wet season precedes a dry season. The amount of water availability in the wet season of period 0, $a_0 > 0$, is stochastic. Given the initial water availability, the dam captures as much water as its capacity, $\bar{a}$, allows, so the water catchment is $\min\{a_0, \bar{a}\}$. In the dry season of period 0, no water is added to the dam, and the dam operator chooses how much water to release, $w_0 \in [0, \min\{a_0, \bar{a}\}]$, and how much to store and carry to

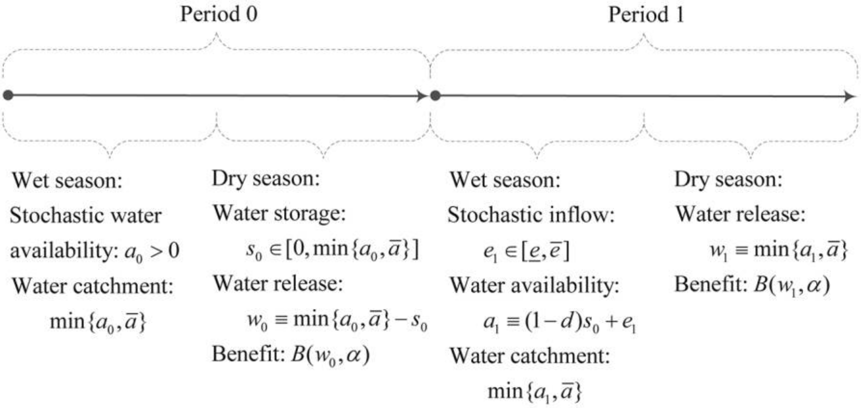

Figure 1. Operation of the dam in the two-period model

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 capacity. 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 $d \in [0, 1]$ 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 of period 1, again, no water is added to the dam, and the dam 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 $B(w_t, \alpha)$, and the dam operator's storage-release decision is to maximize the expectation of the net present value of the benefits of water release in the two dry seasons, given $\bar{a}$, α, and a_0.

In this model, the dam capacity has two functions:

1. The water catchment function: It sets the maximum amount of water that human use diverts from the natural environment and moves between seasons or areas.[10] This function entails transferring water within periods.
2. The stochastic control function: It gives room to control water inventories dynamically in response to stochastic inflow. This function involves allocating water across periods.

There are alternative ways to model functions of dam capacity. For example, Fisher and Rubio (1997) and Hughes and Goesch (2009) assume that dams have only the stochastic control function and that spills generate irrigation benefit. In our model, we recognize the water catchment function of dams and assume that spills in wet seasons are not captured and therefore cannot be utilized to generate benefit. Our approach is closer to reality because it captures both the seasonal gap between water endowment and water demand and the uncertainty in future water availability, consistent with some models in economics (e.g., Truong 2012) and most models about dams in the field of applied probability theory (e.g., Moran 1959).

Following the idea of Caswell and Zilberman (1986), we assume that the benefit of water release, $B(w_t, \alpha)$, is generated by effective water, αw_t, so that the function of water benefit can be specified as $B(w_t, \alpha) \equiv \mathcal{B}(\alpha w_t)$, where $\alpha \in [0, 1]$ measures input efficiency, defined as the proportion of applied water that is effectively used. Adopting more efficient irrigation technologies, improving conveyance, and applying water recycling and reuse would then increase α, because they increase the proportion of water input that is effectively used in production. The specification can also apply to hydropower generation, because the power output from a dam is proportional to the product

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[10] The wet and dry seasons can also be interpreted as a water-abundant area and a water-scarce area.

of the efficiency of the generator and the volume of water release flowing through the generator, that is, αw_t (Andrews and Jelley 2013, 100). We assume that regular assumptions, such as $\mathcal{B}''(\cdot) < 0$, $\mathcal{B}(\cdot)$ is continuously differentiable almost everywhere, and $0 < \mathcal{B}'(\cdot) < \infty$, also apply here. For terminology, we call $B_w(w_t, \alpha) \equiv \alpha\mathcal{B}'(\alpha w_t)$ the marginal benefit of water (release) or just water demand.

Under the stochastic control of water inventories, given the distributions of a_0 and e_1, the (gross) value that is generated by the dam is

$$W^*(\bar{a}, \alpha) \equiv \mathbf{E}[V^*(\bar{a}, a_0, \alpha)], \text{ where} \tag{2}$$

$$V^*(\bar{a}, a_0, \alpha) \equiv \max_{w_0, s_0}\{B(w_0, \alpha) + \rho\mathbf{E}_0[B(w_1, \alpha)]\} \qquad \text{subject to} \tag{3}$$

$$s_0 \geq 0, w_0 = \min\{a_0, \bar{a}\} - s_0 \geq 0, a_1 = (1 - d)s_0 + e_1, w_1 = \min\{a_1, \bar{a}\}, \tag{4}$$

where $\rho \in [0, 1)$ is the discount factor.

2.2. Choice of the Dam Capacity

Taking efficiency, α, and the distributions of a_0 and e_1 as given, the dam designer maximizes the dam-generated value, $W^*(\bar{a}, \alpha)$, net of the construction, maintenance, and environmental damage cost, $C(\bar{a})$, by choosing the dam capacity, $\bar{a}$:

$$\max_{\bar{a} \geq 0} W^*(\bar{a}, \alpha) - C(\bar{a}). \tag{5}$$

This decision can also be interpreted as how much to adjust the total storage capacity of a huge water system by introducing a new dam or removing an old dam. The dam cost should also include social cost, for example, displacement of residents and demolition 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, supporting aquatic species, in the form of overflows. We have the regular assumption that the marginal cost function is positive and increasing, that is, $C'(\cdot) > 0$ and $C''(\cdot) > 0$.

The first-order condition for the dam capacity choice is

$$W^*_{\bar{a}}(\bar{a}, \alpha) = C'(\bar{a}). \tag{6}$$

The left-hand side is the marginal benefit of dam capacity. The right-hand side is the marginal cost of dam capacity. Assuming an interior solution, the optimal dam capacity, $\bar{a} = \bar{a}^*$, should make the marginal benefit equal to the marginal cost. A change in efficiency will change the marginal benefit of dam capacity and, therefore, could change the optimal dam capacity. The impact of α on $W^*_{\bar{a}}(\bar{a}, \alpha)$, that is, $W^*_{\bar{a}\alpha}(\bar{a}, \alpha)$, will therefore play a major role in our analysis.

For simplicity, we focus on this two-period model in our following analysis. Appendix A.4 presents the straightforward extension to a horizon of $T + 1 \geq 2$ periods. Parallel results for the extended model are proven in Xie and Zilberman (2018).

3. ANALYSIS AND RESULTS

To analyze the impact of efficiency improvement on the marginal benefit of dam capacity, we first look at this marginal benefit:

> **Proposition 1:** The marginal benefit of dam capacity is
>
> $$W^*_{\bar{a}}(\bar{a}, \alpha) = B_w(\bar{a} - \bar{s}, \alpha) \cdot \mathbf{P}[a_0 > \bar{a}] + \rho B_w(\bar{a}, \alpha)\mathbf{E}[\mathbf{P}[(1 - d)s^*_0 + e_1 > \bar{a}|a_0]], \tag{7}$$
>
> where $s^*_0 \equiv s^*_0(\bar{a}, a_0, \alpha)$ denotes the optimal amount of water to be stored and $\bar{s}$ denotes $s^*_0(\bar{a}, a_0, \alpha)$ for $a_0 \geq \bar{a}$.

We prove proposition 1 in appendix A.1 by analyzing the inventory control problem. Proposition 1 carries an important intuition: if and only if the dam was full in a wet season, which corresponds to $a_0 > \bar{a}$ or $a_1 \equiv (1 - d)s^*_0 + e_1 > \bar{a}$, a marginal increase in dam capacity will capture some additional water to generate the marginal benefit of water release in the following dry season, which is $B_w(\bar{a} - \bar{s}, \alpha)$ or $B_w(\bar{a}, \alpha)$.

Proposition 1 suggests that efficiency improvement (higher α) affects the marginal benefit of dam capacity ($W^*_{\bar{a}}(\bar{a}, \alpha)$) through two channels.

3.1. The Marginal-Water-Benefit Channel

The first channel is a marginal-water-benefit channel, that is, efficiency improvement affects the marginal benefits of the dry-season water release given the dam was full in the former wet season ($B_w(\bar{a} - \bar{s}, \alpha)$ and $B_w(\bar{a}, \alpha)$).

Properties of this channel are intuitive. As we show in appendix A.2, if efficiency improvement will increase water demand, then the sub-impact through this channel will be positive. This situation will happen, if the water demand is elastic or, equivalently, if the elasticity of the marginal productivity of effective water, EMP $\equiv -\alpha w \mathcal{B}''(\alpha w)/\mathcal{B}'(\alpha w)$, is smaller than one. This result follows the established literature on the importance of the EMP in the relationship between water demand and water use efficiency (e.g., Caswell and Zilberman 1986; the survey by Lichtenberg 2002).

Estimates of industrial water demand elasticity and EMP vary extensively across sectors, and elastic water demand and EMP < 1 can appear (e.g., Schneider and Whitlatch 1991; Wang and Lall 2002; Féres and Reynaud 2005; Kumar 2006), suggesting that higher efficiency can increase water demand. For the agricultural water use, some studies also find empirically that adoption of more efficient irrigation technologies can increase water use by expanding irrigated acreage (e.g., Ward and Pulido-Velazquez 2008; Pfeiffer and Lin 2014). These estimates suggest a positive marginal-water-benefit channel, with which higher efficiency in production could increase the demand for water storage capacity.

That said, many studies for the agricultural and residential uses find that EMP > 1 and water demand is often inelastic, at least when the water price is low (e.g., surveys by Scheierling, Loomis, and Young 2006; Worthington and Hoffman 2008). In these cases, higher efficiency will decrease water demand, and this effect itself implies a decrease in the demand for dam capacity. Nevertheless, the negative sub-impact through the marginal-water-benefit channel can be reversed and efficiency and storage capacity can still be complements, because of the existence of the other channel.

3.2. The Full-Dam-Probability Channel

As proposition 1 suggests, the demand for dam capacity depends not only on water demand, but also on the likelihood that the dam will reach its full capacity in the future, that is, $\mathbf{E}[\mathbf{P}[(1-d)s_0^* + e_1 > \bar{a}|a_0]]$. The higher this likelihood, the higher the demand for dam capacity, ceteris paribus.

It is important to note that this likelihood can be affected by efficiency improvement, because the improvement can require re-optimizing the storage-release schedule of the dam, that is, $s_0^*(\bar{a}, a_0, \alpha)$. For example, if the re-optimization encourages the dam operator to store more water now, the dam will have less room to hold future inflows and, therefore, it will become more likely to reach its full capacity in the future. Therefore, efficiency improvement can affect the demand for dam capacity through this full-dam-probability channel.

As we will show, it turns out that a positive full-dam-probability channel and a negative marginal-water-benefit channel are compatible, so efficiency improvement can decrease water demand and increase the demand for dam capacity simultaneously. We now focus on providing a sufficient condition for a positive full-dam-probability channel, assuming a negative marginal-water-benefit channel, that is, assuming EMP > 1 or, equivalently, inelastic water demand such that efficiency improvement will decrease water demand.

If the full-dam probability is always zero, or if it is never optimal to store any water in the first period, then the sub-impact through the full-dam-probability channel will vanish. We now assume that neither occurs, so this sub-impact does exist. We can then present the following result, which is proven in appendix A.3.

Proposition 2 (Positive full-dam-probability channel given negative marginal-water-benefit channel): Assuming that efficiency improvement will decrease the marginal benefit of water, if the decrease will be larger at larger amounts of water use, then it will (weakly) increase the optimal amount of water to be stored and the full-dam-probability channel will be (weakly) positive. Mathematically, assuming $B_{w\alpha}(w, \alpha) \leq 0$, then

$$\frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha} \geq 0 \quad \text{and} \quad \frac{\mathrm{d}\mathbf{E}[\mathbf{P}[(1-d)s_0^* + e_1 > \bar{a}|a_0]]}{\mathrm{d}\alpha} \geq 0, \tag{8}$$

if $B_{w\alpha w}(w, \alpha) \leq 0$, $B_{www}(w, \alpha) \leq 0$, and $B_{w\alpha ww}(w, \alpha) \geq 0$ for any $w \in [\underline{e}, (1-d)\bar{s} + \bar{e}]$, where $\bar{s}$ denotes $s_0^*(\bar{a}, a_0, \alpha)$ for $a_0 \geq \bar{a}$.

3.2.1. *Intuition of Proposition 2*

As the proposition concerns how higher efficiency will change the optimal storage-release decision, we start with the Euler equation, which determines the decision. The Euler equation is

$$\underbrace{B_w(\min\{a_0, \bar{a}\} - s_0^*, \alpha)}_{\text{Current marginal benefit of water}} = \underbrace{\rho(1-d)\mathbf{E}_0\left[\overbrace{I_{(1-d)s_0^*+e_1\leq\bar{a}}}^{\substack{\text{Capacity will}\\ \text{not run out}}} \cdot \overbrace{B_w((1-d)s_0^* + e_1, \alpha)}^{\substack{\text{Marginal benefit of water}\\ \text{at future availability}}}\right]}_{\text{Discounted expected future marginal benefit of water}}. \tag{9}$$

By this equation, the optimal water storage is at the level $s_0^* > 0$ such that the current marginal benefit of water is equal to the discounted expected future marginal benefit of water. The indicator function on the right-hand side, $I_{(1-d)s_0^*+e_1\leq\bar{a}}$, reminds us that, if the dam will be full in the future, any additional water to be stored will not be able to generate any benefit.

Under the condition in proposition 2, higher efficiency will decrease water demand, so it will decrease both sides of the Euler equation. Moreover, the decrease will be greater on the left-hand side than on the right-hand side, so the left-hand side will become lower than the right-hand side (we will discuss the reason in more detail below). To keep the two sides equal, the dam operator will then store more water, raising the current marginal benefit of water and decreasing the discounted expected future marginal benefit of water. This re-optimization will then increase the probability that the dam will be full in the future, because it decreases the room in the dam to hold future inflows.

3.2.2. *Details of the Impact of Higher Efficiency on the Euler Equation*

To be more precise, why will the negative impact of higher efficiency on the left-hand side of the Euler equation dominate the impact on the right-hand side? To answer the question, it is important to observe two fundamental asymmetries between the two sides, both implied by the smaller-than-one net discount factor, that is, $\rho(1-d) \leq 1$, and the nonnegative likelihood of a full dam in the future, which is equivalent to $I_{(1-d)s_0^*+e_1\leq\bar{a}} \leq 1$:

1. If water demand changes, its impact on the right-hand side of the Euler equation will be suppressed, because $\rho(1-d) \leq 1$ and $I_{(1-d)s_0^* + e_1 \leq \bar{a}} \leq 1$.
2. The current marginal benefit of water must be lower than the expected marginal benefit of water at the future water availability, that is,

$$B_w(\min\{a_0, \bar{a}\} - s_0^*, \alpha) \leq \mathbf{E}_0[B_w((1-d)s_0^* + e_1, \alpha)], \tag{10}$$

because, otherwise, the left-hand side of the Euler equation would always be higher than its right-hand side and storing any positive amount of water would become suboptimal. Inequation (10) further suggests that the current water release, $\min\{a_0, \bar{a}\} - s_0^*$, must be relatively large when compared with the distribution of the future water availability, $(1-d)s_0^* + e_1$, because the marginal benefit of water is decreasing in the amount of water use.

Proposition 2 supposes that higher efficiency decreases the marginal benefit of water more at larger amounts of water use. Given the second asymmetry, that is, the current water release is relatively large, we can then roughly deduce that higher efficiency will decrease the current marginal benefit of water, that is, the left-hand side of the Euler equation, more than it will decrease the marginal benefit of water at the future water availability, $B_w((1-d)s_0^* + e_1, \alpha)$. By the first asymmetry, the impact of the decrease in $B_w((1-d)s_0^* + e_1, \alpha)$ on the right-hand side of the Euler equation will be further suppressed. Therefore, we can gather that higher efficiency will decrease the left-hand side of the Euler equation more than the right-hand side (see technical details in app. A.3).

3.2.3. Theoretical Remarks

It is important to clarify that, when the full-dam probability is sufficiently high, that is, when $I_{(1-d)s_0^* + e_1 \leq \bar{a}}$ is sufficiently likely to be zero, both of the asymmetries can still hold, even if the net discount factor were unrealistically greater than one, that is, even if $\rho(1-d) > 1$. Therefore, proposition 2 provides a sufficient but not necessary condition for a positive full-dam-probability channel in the presence of a negative marginal-water-benefit channel.

Under what conditions is the decrease in the marginal benefit of water caused by efficiency improvement at larger amounts of water use? Intuitively, it will happen if the decline of the marginal productivity of effective water happens steadily as effective water increases. The second-order elasticity of the marginal productivity of effective water, SEMP $\equiv -\alpha w \mathcal{B}'''(\alpha w)/\mathcal{B}''(\alpha w)$, can denote this property. As the marginal-water-benefit channel is governed by the EMP, we can state proposition 2 using the EMP and SEMP.

> **Corollary 1** (Alternative exposition of proposition 2): Assuming EMP ≥ 1, the full-dam-probability channel will be (weakly) positive, if the decline of the marginal productivity of effective water happens steadily as effective water increases, that is, if SEMP ≤ 2.

Proposition 2 and corollary 1 extend the literature's focus on the EMP to the SEMP. This extension is intuitive from the perspective of economic theory. The full-dam-probability channel corresponds to the stochastic control function of dam capacity. An increase in efficiency increases effective water given water use; the change in the control rule of water inventories is determined by the relative impacts of more effective water on the marginal productivity of effective water at the current versus the future levels of effective water, so it should be determined by the third-order property of the benefit of effective water. The SEMP is just a measure of the third-order property.

3.3. Possible Complementarity between Efficiency and Storage Capacity

By proposition 2 and our analysis on the marginal-water-benefit channel in appendix A.2, we can identify the conditions under which complementarity between efficiency and storage capacity is possible:

> **Proposition 3** (Possibility of complementarity): Water storage capacity and water use efficiency could be complements, that is, efficiency improvement could increase the marginal benefit of dam capacity.
>
> 1. If the improvement will increase water demand (in this case the marginal-water-benefit channel will be positive).
> 2. Or if both of the following are true: the improvement decreases the marginal benefit of water and this decrease is larger at larger amounts of water use (in this case the full-dam-probability channel will be positive).
>
> Mathematically, $W^*_{\bar{a}\alpha}(\bar{a}, \alpha)$ could be positive:
>
> 1. If $B_{w\alpha}(w, \alpha) \geq 0$ for any $w \in [(1-d)\bar{s} + \underline{e}, \bar{a}]$;
> 2. Or, if $B_{w\alpha}(w, \alpha) \leq 0$, $B_{w\alpha w}(w, \alpha) \leq 0$, $B_{www}(w, \alpha) \leq 0$, and $B_{w\alpha ww}(w, \alpha) \geq 0$ for any $w \in [\underline{e}, (1-d)\bar{s} + \bar{e}]$.

3.3.1. Theoretical Remarks

The second, counterintuitive case in proposition 3 relies on the probabilistic nature of whether the dam will be full in the future. Therefore, this case would not exist if the future inflow to the dam were deterministic. As we have shown in proposition 2, this case also relies on the capability of efficiency to affect the storage-release decision, which would be assumed away if the water inventories were not controlled dynamically by the dam operator. Therefore, by incorporating stochastic control of water inventories, our model is arguably the simplest model that can capture the full-dam-probability channel and, therefore, the counterintuitive possible complementarity between efficiency and storage capacity in the presence of substitution between efficiency and water demand.

We can also write proposition 3 in terms of properties of the water demand and marginal productivity of effective water as a rule of thumb for the possibility of complementarity:

Corollary 2 (Rule of thumb for the possibility of complementarity): Water storage capacity and water use efficiency could be complements, that is, efficiency improvement could increase the marginal benefit of dam capacity:

1. If water demand is elastic, that is, if EMP ≤ 1, which means the marginal productivity of effective water declines slowly.
2. Or if EMP ≥ 1 and SEMP ≤ 2, which means the marginal productivity of effective water declines quickly and the decline happens steadily as effective water increases.

3.4. Examples of Applications to Specific Water Demand

As Vaux et al. (1981) recognize, isoelastic and linear water demands are convenient in empirical studies and influential in policy making. We then apply our theory to the specifications:

Corollary 3 (Isoelastic water demand): When water demand is isoelastic, dam capacity and water use efficiency will be complements, if and only if the water demand is elastic.

The intuition of corollary 3 is as follows: for isoelastic water demand, the impact of efficiency improvement on the marginal benefit of water is always proportional, resembling a change of numeraire. Therefore, the optimal storage-release decision is not affected, so the full-dam-probability channel vanishes and only the marginal-water-benefit channel matters. Corollary 3 then follows.

Corollary 4 (Linear water demand): When water demand is linear, dam capacity and water use efficiency could be complements:

1. If the water demand is in the elastic range (EMP ≤ 1), which will be guaranteed when the initial dam capacity is sufficiently small, that is, if $\bar{a} \leq \hat{w}$, where $\hat{w}$ solves $-\alpha\hat{w}\mathcal{B}''(\alpha\hat{w})/\mathcal{B}'(\alpha\hat{w}) = 1$.

2. Or if the water demand is in the inelastic range (EMP ≥ 1), which will be guaranteed when the minimum of the inflow is sufficiently large, that is, if $\underline{e} \geq \hat{w}$.

The intuition of corollary 4 is as follows: in case 1, the marginal-water-benefit channel will be positive; in case 2, the marginal-water-benefit channel will be negative, while the full-dam-probability channel will be positive, because the SEMP for linear water demand is zero, that is, smaller than two. Because complementarity may happen as long as at least one of the two channels is positive, corollary 4 follows.

Corollaries 3 and 4 imply that the functional form of water demand is critical in determining complementarity or substitution. For example, isoelastic, inelastic water demand suggests substitution, while linear, inelastic water demand still allows the possibility of complementarity.

4. DISCUSSION

4.1. The Marginal-Water-Benefit Channel

As we show in appendix A.2, the direction of the marginal-water-benefit channel is governed by the EMP, which indicates whether the marginal productivity of effective water declines slowly or quickly. In reality, at least two factors that affect the EMP deserve special attention. The first is land constraints—it is natural to expect that the marginal productivity of effective water should decline much more slowly when irrigable land is not constrained and irrigators can expand planted areas than when irrigators have to exploit the constrained irrigable land. Water use on each field might decrease due to more efficient irrigation technologies, but the aggregate demand for gross water use can still increase through the extensive margin when significantly more land becomes irrigated (e.g., Ward and Pulido-Velazquez 2008; Pfeiffer and Lin 2014.[11]

The second factor is the stage of the development of water resources. In areas such as 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 efficiency improvement will decrease water demand. For areas such as sub-Saharan Africa, where agriculture is still mainly fed by rain (e.g., Kadigi et al. 2013), the opposite is more likely to hold. Following this logic, some scholars have already observed that, given unconstrained irrigable areas and small initial water catchment capacity, adoption of more efficient irrigation technologies positively correlates with water demand and, therefore, with the demand for water storage projects.[12]

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[11] The statement was also confirmed by personal conversation with Ariel Dinar at the World Bank, Washington, DC, on September 9, 2014.

[12] The statement was confirmed, for example, by personal conversation with Jintao Xu at Peking University, Beijing, on May 15, 2015, about Xinjiang, a major area of irrigated agriculture in China.

Since the EMP and water demand elasticity are equivalent, factors affecting the water demand elasticity are also important in identifying the direction of the marginal-water-benefit channel. For example, since Marshall (1890), economists know well that the factor demand elasticity is positively correlated with the elasticity of the demand for the commodity produced using the factor. This observation further carries 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 tends to be elastic. In this case, improvements in efficiency, which can result from international aid, could optimally lead to higher demand for irrigation dams needed for commodity production. On the other hand, in cases of dams used to produce nonexported commodities or commodities with low demand elasticities, for example, electricity and staple food for domestic consumption, water demand tends to be inelastic, so the marginal-water-benefit channel can be negative. These implications suggest that aid programs tackling water challenges in developing countries should have a joint perspective about international trade, conservation, and water infrastructure.

4.2. The Full-Dam-Probability Channel

Even though we identify the full-dam-probability channel, some questions could still emerge about its relevance. First, identifying the full-dam-probability channel will be useless if the dam is never full, but do dam capacities ever run out? The answer is yes, and the full-dam probability is often not zero. For example, the main reservoir of the California State Water Project, Lake Oroville, has seen positive overflows in 57% of the years from 1975 to 2010, when the dam was not able to capture any more water in the wet season for the following dry season.

Second, in our theory, higher efficiency will increase the full-dam probability, only if the efficiency improvement encourages the dam operator to store more water, but how likely is the condition to hold in reality? As the point we make is novel, to our knowledge, there is no empirical evidence in the literature either way. Our analysis is still useful, because we can help to explain numerical results in practice, not only for linear and isoelastic demand, but also for exponential, nonparametric, or any arbitrary specifications of the water benefit or demand.

Third, could the increase in the full-dam probability, if there is any, really dominate a negative marginal-water-benefit channel, so that the demand for water storage capacity would eventually become higher? The short answer is yes, and we will address it with numerical illustrations in section 5.

4.3. Impact of Dam Expansion on Efficiency Improvement

Our investigation of how efficiency improvement will change the demand for dam capacity can also shed some light on how dam expansion will change the incentive for efficiency improvement. To see this point, the cross partial of the dam-generated value, $W^*_{\bar{a}\alpha}(\bar{a}, \alpha)$, also shows how the capacity, $\bar{a}$, will affect the marginal contribution of efficiency, $W^*_{\alpha}(\bar{a}, \alpha)$. For a representative water user who owns the downstream of the dam, $W^*_{\alpha}(\bar{a}, \alpha)$ describes her demand for efficiency improvement. Therefore, the impact of dam expansion on the demand for efficiency improvement and the impact of higher efficiency on the demand for dam capacity always have the same sign.

We can also decompose the impact of dam expansion on the demand for higher efficiency into two channels. The first channel concerns the impact of more water provided by the dam on the marginal benefit of efficiency in each period. The second channel involves how re-optimizing the storage-release schedule in response to dam expansion will affect the marginal contribution of efficiency in the long run. The two channels correspond to the marginal-water-benefit channel and the full-dam-probability channel, respectively, which we have identified in the efficiency impact on the demand for dam capacity.

4.4. Policy Implications of Complementarity or Substitution

When water storage capacity and water use efficiency are complements, a few implications are possible. First, public storage capacity can be expanded without discouraging efficiency improvement, for example, adopting more efficient technologies in irrigation, water conveyance, water recycling, and hydropower generation. Second, policy makers might believe that subsidizing water users to improve input efficiency could make it unnecessary to expand water storage, but the subsidies could backfire by increasing the demand for investment in water storage. Third, if policy makers choose to expand water storage, this choice will be better justified if they supplement this choice by inducing water users to improve their efficiency, using policy tools such as subsidies, technological regulation, and water pricing reforms. When storage capacity and efficiency are substitutes, some opposite policy implications follow.

The case of complementarity also provides some probably counterintuitive relationships between conservation effort and conservation outcomes. For example, more effort in conservation, such as more adoption of efficient irrigation technologies, could lead to higher demand for dams and eventually more dam building. Larger dam capacities mean that more water will be captured in the long run, and higher efficiency in water use means that the water catchment will be used more effectively. Therefore, this greater conservation effort could lead to more effective use of water, which is sometimes called consumptive use of water, that is, the amount of water that is truly diverted from the natural environment for human use. More dam building also means more environmental damage. Therefore, more conservation effort could induce worse conservation outcomes.

Last but not least, in the case of complementarity, assuming that a policy maker is maximizing the social welfare that is related to water storage capacity and that both dam building and efficiency improvement are cost-effective, limited resources should be distributed in a balanced way between these two approaches, instead of being concentrated on either side with the other side being ignored. Only extreme substitution can make investing in a single approach an optimal allocation of resources.

5. AN EMPIRICAL EXAMPLE WITH NUMERICAL ILLUSTRATIONS

5.1. Specification

In this section, we present numerical illustrations of our results by simulating an extended version of this model where the water inventory management has an infinite-period horizon ($T = \infty$ in app. A.4). The simulation is based on the irrigation water inventory management problem of the California State Water Project. Table 1 summarizes the specification, which is mainly based on information from the California Department of Water Resources (1963–2013, 1976–2014, 1990–2014, 1998–2005, 2008).[13]

In particular, we use three specifications of irrigation water demand in the illustrations, which are all empirically relevant to agricultural water demand in California: (1) isoelastic, elastic, with elasticity of −1.21, which is estimated by Frank and Beattie (1979); (2) isoelastic, inelastic, with elasticity of −0.79, which is estimated by Schoengold et al. (2006); and (3) linear, with elasticity of −0.79 when the demand is equal to the 1975–2010 mean of the annual water deliveries from the Project to agricultural use—this linear water demand is equivalent to the linear water demand estimated by Schoengold et al. (2006). All the three specifications can help us confirm the validity and empirical relevance of our theoretical results. This is because the two isoelastic specifications correspond to corollary 3 and the linear specification corresponds to corollary 4.

That said, which among the three specifications would have the most practical relevance? In terms of the elasticity of irrigation water demand, the literature finds it usually smaller than one. In terms of the functional form, as Caswell and Zilberman (1986) recognize, linear water demand is more consistent than isoelastic demand with the classic three-stage model of the marginal productivity of water in irrigation, in the sense that the EMP varies from zero to infinity as water use increases; it is also empirically more flexible, because it can predict heterogeneous impact of efficiency improvement on water use with respect to different levels of water prices and different amounts of initial water use. Because the third specification has a linear functional form and is inelastic at the historical mean of agricultural water deliveries, we recognize that this specification would have the most practical relevance.

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[13] Details of the specification are given in Xie and Zilberman (2018).

Table 1. Specification of the Numerical Illustrations

Horizon	$T = \infty$
Inflow in acre-feet	$e_t \sim$ Adjusted, estimated historical inflows, i.i.d.
Evaporation loss rate	$d = .04$
Discount factor	$\rho = .9434$
Benefit of water release in $ (one in each illustration)	$B(w, \alpha) = 3.0 \times 10^7 \cdot (\alpha w)^{1-(1/1.21)}$ $B(w, \alpha) = -7.1 \times 10^9 \cdot (\alpha w)^{1-(1/.79)}$ $B(w, \alpha) = 181.0 \cdot \alpha x - \frac{1.5\times 10^{-4}}{2} \cdot (\alpha x)^2$, where $x \equiv \min\{w, \frac{181.0}{1.5\times 10^{-4}\cdot \alpha}\}$
Baseline water use efficiency	$\alpha = .7135$
Baseline dam capacity in acre-feet	$\bar{a} = 2025335$

5.2. Foci of Illustrations

For each of the three cases of water demand, we focus on four questions. The first question is whether efficiency improvement in irrigation (higher α) will increase or decrease the marginal benefit of dam capacity, $W^*_{\bar{a}}(\bar{a}, \alpha) = B_w(\bar{a} - \bar{s}, \alpha) \cdot \Sigma_{t=0}^{\infty} \rho^t \mathbf{E}[\mathbf{P}[a^*_t > \bar{a} | a_0]]$. The impact will further be decomposed into the sub-impact on $B_w(\bar{a} - \bar{s}, \alpha)$, that is, through the marginal-water-benefit channel, and the sub-impact on $\Sigma_{t=0}^{\infty} \rho^t \mathbf{E}[\mathbf{P}[a^*_t > \bar{a} | a_0]]$, that is, through the full-dam-probability channel.

The second question is how this change in the marginal benefit of dam capacity will be reflected in the optimal choice of storage capacity ($\bar{a}^*$). Without information about the marginal cost of capacity, the most we can do is to estimate the range of the impact: if the marginal cost of dam capacity is assumed to be perfectly horizontal, then we can derive the upper bound of the change in optimal capacity that would be caused by the efficiency improvement.

Similarly, the third question concerns the impact of capacity expansion (larger $\bar{a}$) on the marginal contribution of efficiency to the dam-generated value ($W^*_{\alpha}(\bar{a}, \alpha)$), while the fourth question involves its reflection on the optimal choice of efficiency (α^*).

5.3. Numerical Results

5.3.1. Isoelastic Water Demands

To answer the first question, figures 2 and 3 plot numerical results for the two isoelastic water demands, respectively. The results confirm the prediction of corollary 3 that, given isoelastic water demand, efficiency improvement will increase the demand for dam capacity if and only if the water demand is elastic. Moreover, in both figures, the sub-impact through the full-dam-probability channel is exactly zero. This observation further confirms the logic of corollary 3, that is, when water demand is isoelastic, the full-dam-probability channel vanishes.

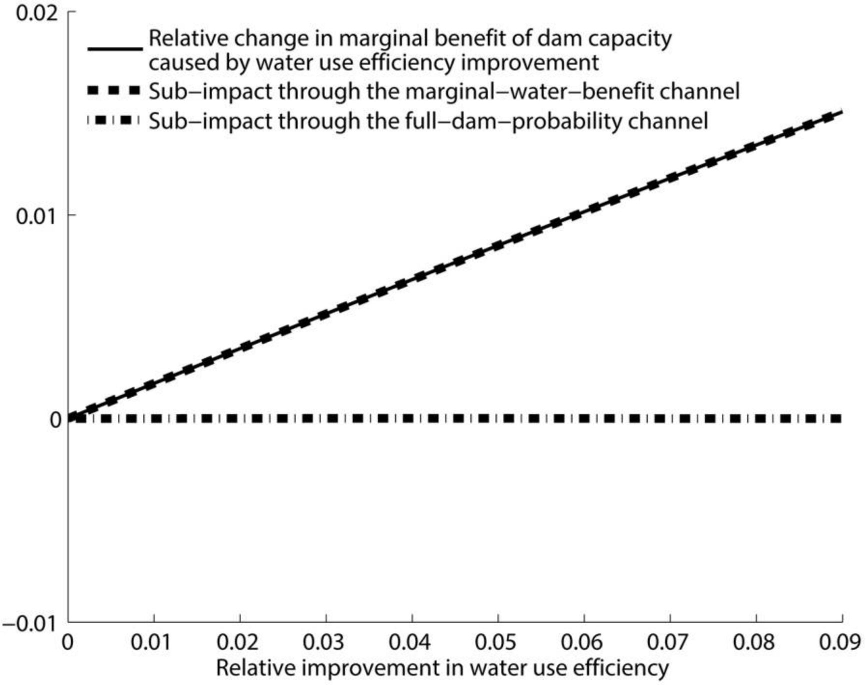

Figure 2. Two-channel decomposition for the isoelastic, elastic water demand

Tables 2 and 3 report answers to all of the four questions given a reasonable 5% improvement in efficiency or expansion of dam capacity. The tables show that the impact from efficiency to dam capacity and the impact vice versa always have the same sign, confirming our discussion in section 4.

5.3.2. *Linear Water Demand*

Figure 4 plots results of the two-channel decomposition for the linear water demand. Given this specification, since around three-quarters of the inflow distribution is higher than the critical level beyond which the water demand is inelastic, the inelastic range of the water demand is mostly relevant. Section 3 and appendix A.2 predict a negative marginal-water-benefit channel, a positive full-dam-probability channel, and the possibility of the full-dam-probability channel to dominate. Figure 4 confirms all of them.

Comparing figures 3 and 4 further confirms the importance of specifications of water demand, because in both cases the underlying water demand has a price elasticity of −0.79 at the historical mean of agricultural water deliveries. However, the demand functions differ in their functional forms. The difference in functional forms leads to different predictions about complementarity or substitution. The difference in pre-

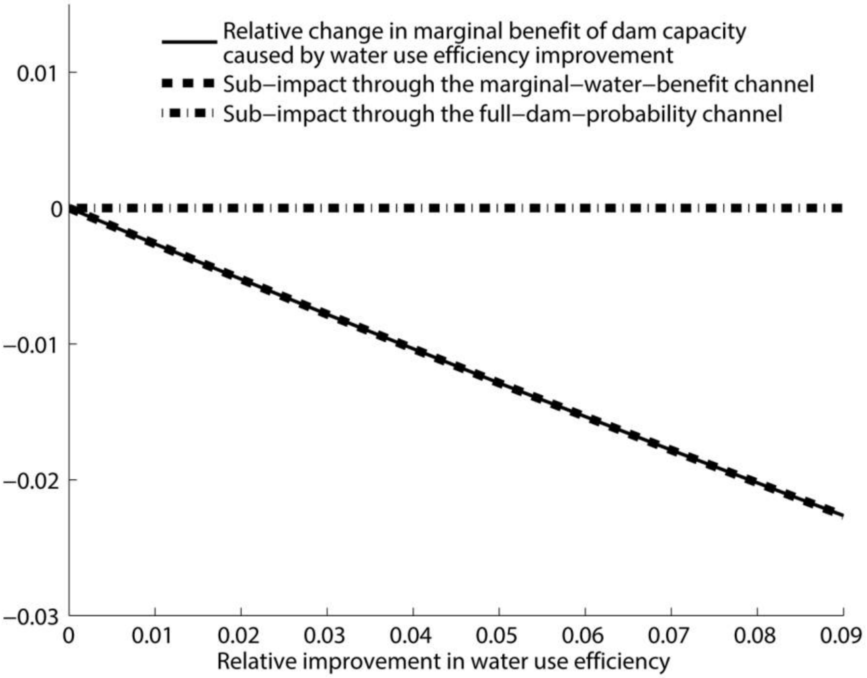

Figure 3. Two-channel decomposition for the isoelastic, inelastic water demand

dictions results from whether the effect of efficiency improvement on the storage-release decision rule is significant and, equivalently, whether the full-dam-probability channel is prominent.

As recognized earlier, among the three water demand specifications, this linear specification has the most practical value. Figure 4 does show complementarity. Therefore, for the irrigation water inventory management problem of the California State Water Project, balanced distribution of limited resources for storage expansion and efficiency improvement will be desirable, as long as the two approaches are both cost-effective.

Table 4 reports more results given a 5% increase in efficiency or in dam capacity. Two observations deserve attention. First, as in tables 2 and 3, the impact from efficiency to dam capacity and the impact vice versa always have the same sign. Second, as in tables 2 and 3, again, table 4 shows that the complementarity between dam capacity and efficiency is more pronounced on the impact of efficiency improvement on the incentive for dam expansion, but not the other way around, since 4.87 is greater than 0.31 and 0.97 is greater than 0.18.

We conclude the numerical exercise by comparing economists' value-maximization logic with the cost-minimization logic in the engineering literature (e.g., the survey by

Table 2. Numerical Results for the Isoelastic, Elastic Water Demand

Variable	
	Relative Change (%) Caused by a 5% Increase in Water Use Efficiency
Marginal benefit of dam capacity	.85
Sub-impact through the marginal-water-benefit channel	.85
Sub-impact through the full-dam-probability channel	.00
Optimal dam capacity	(0, .10]
	Relative Change (%) Caused by a 5% Increase in Dam Capacity
Marginal contribution of water use efficiency	.03
Optimal water use efficiency	(0, .04]

Note. Two-channel decomposition: $1 + 0.85\% = (1 + 0.85\%) \times (1 + 0.00\%)$.

Yeh 1985). Following the cost-minimization logic, to reach a specific target of the dam-generated value, the required dam capacity is unambiguously smaller when efficiency is higher, because higher efficiency means a higher dam-generated value at any given dam capacity. In this particular case, given a 5% improvement in efficiency, the baseline dam-generated value would still be attained even if the dam capacity were reduced by 29.6% from the baseline level. On the contrary, as shown in table 4, the value-

Table 3. Numerical Results for the Isoelastic, Inelastic Water Demand

Variable	
	Relative Change (%) Caused by a 5% Increase in Water Use Efficiency
Marginal benefit of dam capacity	−1.29
Sub-impact through the marginal-water-benefit channel	−1.29
Sub-impact through the full-dam-probability channel	.00
Optimal dam capacity	[−.14, 0)
	Relative Change (%) Caused by a 5% Increase in Dam Capacity
Marginal contribution of water use efficiency	−.06
Optimal water use efficiency	[−.05, 0)

Note. Two-channel decomposition: $1 - 1.29\% = (1 - 1.29\%) \times (1 + 0.00\%)$.

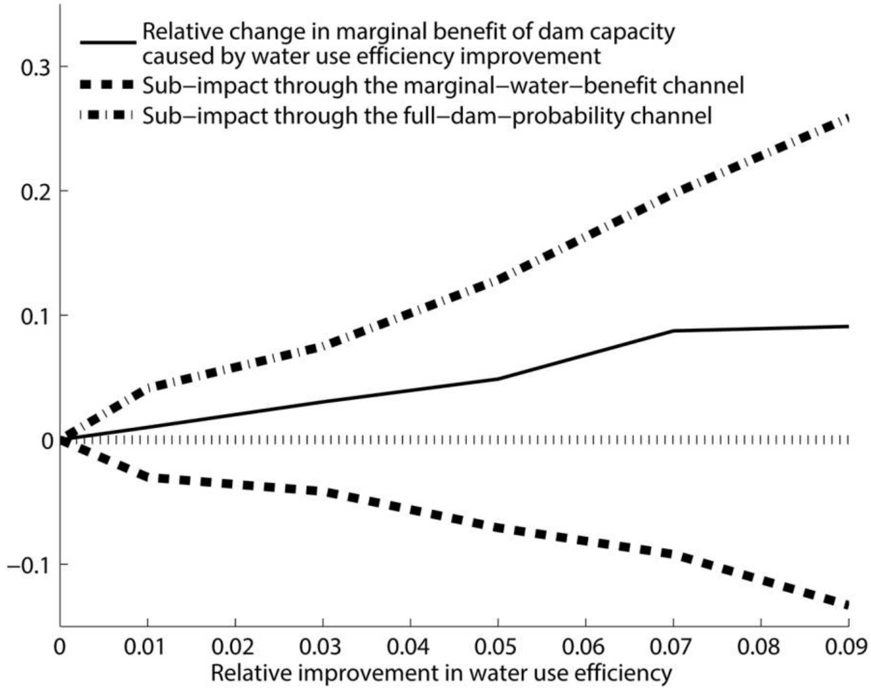

Figure 4. Two-channel decomposition for the linear water demand

maximization logic suggests that dam expansion by at most 0.97% will be demanded to take the full advantage of this efficiency improvement.

6. CONCLUSION

A prevailing perception regards water conservation and storage capacity as substitutes. We recognize in this paper, however, that whether they substitute or complement each other depends on two factors: first, whether conservation will increase or decrease water demand; second, how it will change the optimal storage-release schedule and, equivalently, whether it will increase or decrease the probability that storage capacity will run out in the future. This recognition allows us to derive conditions under which complementarity may appear. In particular, even if higher efficiency will decrease water demand (EMP > 1), when the marginal productivity of effective water is declining steadily (SEMP < 2), higher efficiency can still increase the demand for storage capacity.

For simplicity, our model assumes away many important factors in water inventory management and storage design. Our qualitative result about the impact of efficiency improvement on the storage capacity demand will still hold, as long as the missing factor is not correlated with efficiency, for example, if damages caused by floods are not

Table 4. Numerical Results for the Linear Water Demand

Variable	
	Relative Change (%) Caused by a 5% Increase in Water Use Efficiency
Marginal benefit of dam capacity	4.87
Sub-impact through the marginal-water-benefit channel	−7.07
Sub-impact through the full-dam-probability channel	12.84
Optimal dam capacity	(0, .97]
	Relative Change (%) Caused by a 5% Increase in Dam Capacity
Marginal contribution of water use efficiency	.31
Optimal water use efficiency	(0, .18]

Note. Two-channel decomposition: 1 + 4.87% = (1 − 7.07%) × (1 + 12.84%).

correlated with the efficiency. Even if the missing factor is correlated with the efficiency, for example, the return flow of irrigation to groundwater, our qualitative result will not change much, as long as this factor does not much alter the first- and second-order properties of the marginal productivity of effective water. Even if the missing factor does radically alter the properties of the marginal productivity of effective water, our recognition of the marginal-water-benefit and full-dam-probability channels will still be valid, as long as the focal storage facilities have both the water catchment and stochastic control functions. That said, there are also dams in areas where the peaks of the water endowment and the water demand generally overlap. The water catchment function of these dams is then less important. For these water storage facilities, however, our analysis of the stochastic control function and the full-dam-probability channel is still applicable.

Our results imply that policy makers should not separately design the two categories of policies—expanding storage capacities and improving water use efficiency. In particular, given that linear water demand approximates reality reasonably well (e.g., Caswell and Zilberman 1986; Schoengold et al. 2006; Hendricks and Peterson 2012), complementarity between these two approaches is especially not impossible in countries that have little water storage infrastructure and in countries that have generally abundant inflows and large initial dam capacity, because, for the former, efficiency improvement will increase the water demand, and, for the latter, efficiency improvement will increase the likelihood that dams reach their full capacities. If complementarity does appear, resources should not be concentrated only on one approach with the other being ignored, if both approaches are cost-effective.

Because the relationship between the policies is important in policy debates and could be counterintuitive, it deserves more serious theoretical modeling and empirical investigation. Further effort could be made to specify the improvement in water use efficiency, for example, modeling conservation technology adoption with heterogeneous water users and specific land constraints. The cost of dams that will be correlated with 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 relationship between water storage expansion and other approaches in water resource management, for example, introducing water markets to existing systems of water rights and adopting drought-tolerant varieties in agriculture, with the background of climate change, which changes water demand, evaporation rates, and inflow distributions. The implications could be particularly important for areas where interseasonal variation and interannual uncertainty of water endowment and demand are significant, for example, the western United States and the Himalaya–Hindu Kush region, so that the water catchment and stochastic control functions are both prominent.

In a more general perspective, our analysis of the marginal benefit of storage capacity can be applied and extended to investigate investment decisions in other contexts, such as the joint management of water, food, and energy inventories. Ultimately, introducing political economy into the discussion between water infrastructure and conservation effort will be necessary, because water storage investment and conservation measures can have different distributional implications, and efficiency improvements in general water conveyance and in specific water uses can also have different welfare impacts for the same stakeholder.

APPENDIX

A.1. Proof of Proposition 1

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

First, note that optimal management of water inventories will not allow the zero-release scenario; otherwise, the marginal benefit of water release in period 0 would be so high that releasing even a tiny bit of water would be beneficial.

Second, if the positive-storage scenario happens, the value generated by the dam will be

$$V^*(\bar{a}, a_0, \alpha) = B(\min\{a_0, \bar{a}\} - s_0^*, \alpha) + \rho \mathbf{E}_0[B(\min\{(1-d)s_0^* + e_1, \bar{a}\}, \alpha)], \quad \text{(A1)}$$

while $B_w(\min\{a_0, \bar{a}\} - s_0^*, \alpha) = \rho(1-d)\mathbf{E}_0[I_{(1-d)s_0^* + e_1 \le \bar{a}} \cdot B_w((1-d)s_0^* + e_1, \alpha)]$.

Third, if the zero-storage scenario happens, the dam-generated value will be

$$V^*(\bar{a}, a_0, \alpha) = B(\min\{a_0, \bar{a}\}, \alpha) + \rho \mathbf{E}_0[B(\min\{e_1, \bar{a}\}, \alpha)], \quad \text{(A2)}$$

while $B_w(\min\{a_0, \bar{a}\}, \alpha) \ge \rho(1-d)\mathbf{E}_0[I_{e_1 \le \bar{a}} \cdot B_w(e_1, \alpha)]$.

Collecting the positive-storage and the zero-storage scenarios, we can derive

$$\begin{aligned} W_{\bar{a}}^*(\bar{a}, \alpha) &= \mathbf{E}[V_{\bar{a}}^*(\bar{a}, a_0, \alpha)] \\ &= \mathbf{E}[I_{a_0 > \bar{a}} \cdot B_w(\bar{a} - s_0^*, \alpha) + \rho B_w(\bar{a}, \alpha)\mathbf{P}[(1-d)s_0^* + e_1 > \bar{a} | a_0]] \quad \text{(A3)} \\ &= B_w(\bar{a} - \bar{s}, \alpha) \cdot \mathbf{P}[a_0 > \bar{a}] + \rho B_w(\bar{a}, \alpha)\mathbf{E}[\mathbf{P}[(1-d)s_0^* + e_1 > \bar{a} | a_0]] . \end{aligned}$$

A.2. Details of the Marginal-Water-Benefit Channel

As shown by the expressions of $B_w(\bar{a} - \bar{s}, \alpha)$ and $B_w(\bar{a}, \alpha)$, an increase in α can change water demand, $B_w(\cdot, \alpha)$, which will exert a direct impact on $B_w(\bar{a} - \bar{s}, \alpha)$ and $B_w(\bar{a}, \alpha)$. An increase in α can also affect $B_w(\bar{a} - \bar{s}, \alpha)$ indirectly by changing the optimal amount of water to be stored in the first dry season when the dam was full in the first wet season, $\bar{s}$, and, therefore, the optimal amount of water to be released, $\bar{a} - \bar{s}$.

The aggregate direction of this marginal-water-benefit channel will be determined by the direction of the direct impact, that is, whether higher efficiency will shift up or down water demand. To see this point, consider the storage-release decision, given the dam was full in the former wet season. The dam operator is weighing the current marginal benefit of water and the discounted expected future marginal benefit of water. If efficiency improvement increases water demand, then both sides of the trade-off will increase. Therefore, regardless of whether the dam operator will store more or less water, the resulted marginal benefit of water will increase. The same logic applies to the case in which efficiency improvement decreases water demand. Therefore, we have the following proposition.

Proposition 4 (The marginal-water-benefit channel): The marginal-water-benefit channel will be (weakly) positive if and only if efficiency improvement will increase water demand. Mathematically, $\mathrm{d}B_w(\bar{a} - \bar{s}, \alpha)/\mathrm{d}\alpha$ and $\mathrm{d}B_w(\bar{a}, \alpha)/\mathrm{d}\alpha$ will be (weakly) positive/negative if $B_{w\alpha}(w, \alpha)$ 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 $a_0 \ge \bar{a}$.

Xie and Zilberman (2018) present a formal proof of proposition 4. Also note that efficiency improvement will increase water demand if and only if the water demand is elastic. This is because, given any water price, higher efficiency will decrease the price of effective water and increase the amount demanded for effective water. If and only if the water demand is elastic, demanded effective water will increase even more than the decrease in the price of effective water, which is actually the increase in efficiency. In this case, the demanded gross water use increases given any water price, that is, the water demand increases. The notion of the elasticity of the marginal productivity of effective water (EMP) is also helpful, since it is the inverse of the water demand elasticity.

> **Corollary 5** (Alternative exposition of proposition 4): The marginal-water-benefit channel will be (weakly) positive if and only if water demand is elastic, that is, if and only if EMP ≤ 1.

A.3. Proof of Proposition 2

First note that

$$\frac{\mathrm{d}\mathbf{E}[\mathbf{P}[(1-d)s_0^* + e_1 > \bar{a} | a_0]]}{\mathrm{d}\alpha}$$

and

$$\frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha}$$

have the same sign. Second, by totally differentiating the Euler equation, we know that

$$\frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha}$$

and $B_{w\alpha}(\min\{a_0, \bar{a}\} - s_0^*, \alpha) - \rho(1-d)\mathbf{E}_0[I_{(1-d)s_0^* + e_1 \leq \bar{a}} \cdot B_{w\alpha}((1-d)s_0^* + e_1, \alpha)]$ have the opposite sign. Therefore, we can focus on $B_{w\alpha}(\min\{a_0, \bar{a}\} - s_0^*, \alpha) - \rho(1-d)$ $\mathbf{E}_0[I_{(1-d)s_0 + e_1 \leq \bar{a}} \cdot B_{w\alpha}((1-d)s_0 + e_1, \alpha)]$.

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

$$\begin{aligned} & B_{w\alpha}(\min\{a_0, \bar{a}\} - s_0^*, \alpha) - \rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^* + e_1 \leq \bar{a}} \cdot B_{w\alpha}((1-d)s_0^* + e_1, \alpha)\right] \\ & \leq B_{w\alpha}(\min\{a_0, \bar{a}\} - s_0^*, \alpha) - \mathbf{E}_0[B_{w\alpha}((1-d)s_0^* + e_1, \alpha)]. \end{aligned} \tag{A4}$$

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

$$\begin{aligned}
&B_{w\alpha}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)-\rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}}\cdot B_{w\alpha}((1-d)s_0^*+e_1,\alpha)\right]\\
&\le B_{w\alpha}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)-\mathbf{E}_0[B_{w\alpha}((1-d)s_0^*+e_1,\alpha)]\\
&\le B_{w\alpha}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)-B_{w\alpha}((1-d)s_0^*+\mathbf{E}_0[e_1],\alpha).
\end{aligned}\tag{A5}$$

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

$$\begin{aligned}
B_w(\min\{a_0,\bar{a}\}-s_0^*,\alpha)&=\rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}}\cdot B_w((1-d)s_0^*+e_1,\alpha)\right]\\
&\le\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}}\cdot B_w((1-d)s_0^*+e_1,\alpha)\right]\\
&\le\mathbf{E}_0[B_w((1-d)s_0^*+e_1,\alpha)]\le B_w((1-d)s_0^*+\mathbf{E}_0[e_1],\alpha),
\end{aligned}\tag{A6}$$

so $\min\{a_0,\bar{a}\}-s_0^*\ge(1-d)s_0^*+\mathbf{E}_0[e_1]$. When $B_{w\alpha}(w,\alpha)\le 0$, $B_{w\alpha ww}(w,\alpha)\ge 0$, and $B_{www}(w,\alpha)\le 0$ for $w\in[\underline{e},(1-d)\bar{s}+\bar{e}]$ and $B_{w\alpha w}(w,\alpha)\le 0$ for any $[(1-d)s_0^*+\mathbf{E}_0[e_1],\min\{a_0,\bar{a}\}-s_0^*]$,

$$\begin{aligned}
&B_{w\alpha}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)-\rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}}\cdot B_{w\alpha}((1-d)s_0^*+e_1,\alpha)\right]\\
&\le B_{w\alpha}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)-B_{w\alpha}((1-d)s_0^*+\mathbf{E}_0[e_1],\alpha)\le 0.
\end{aligned}\tag{A7}$$

Note that $\min\{a_0,\bar{a}\}-s_0^*\le(1-d)\bar{s}+\bar{e}$ and $(1-d)s_0^*+\mathbf{E}_0[e_1]\ge\underline{e}$. We can then state that, when $B_{w\alpha}(w,\alpha)\le 0$, $B_{w\alpha w}(w,\alpha)\le 0$, $B_{w\alpha ww}(w,\alpha)\ge 0$, and $B_{www}(w,\alpha)\le 0$ for any $w\in[\underline{e},(1-d)\bar{s}+\bar{e}]$,

$$B_{w\alpha}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)-\rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}}\cdot B_{w\alpha}((1-d)s_0^*+e_1,\alpha)\right]\le 0,\tag{A8}$$

which means

$$\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha}\ge 0$$

for any a_0 in this case. The proposition then follows.

A.4. Extension with Multiple Periods

Assume there are $T+1$ periods and $T\ge 1$. The dam-generated value then becomes

$$W^{T*}(\bar{a},\alpha)\equiv\mathbf{E}\left[V^{T*}(\bar{a},a_0,\alpha)\right],\ \text{where}\tag{A9}$$

$$V^{T*}(\bar{a},a_0,\alpha)\equiv\max_{\{w_t\}_{t=0}^{T},\{s_t\}_{t=0}^{T}}\mathbf{E}_0\left[\sum_{t=0}^{T}\rho^t B(w_t,\alpha)\right]\qquad\text{subject to}\tag{A10}$$

$$\begin{aligned} &s_t \geq 0, w_t \geq 0, w_t + s_t = \min\{a_t, \bar{a}\} \text{ for any } t \geq 0; \\ &a_0 = e_0; a_t = (1-d)s_{t-1} + e_t \text{ for any } t \geq 1;\ w_T = \min\{\bar{a}, a_T\}, \end{aligned} \tag{A11}$$

where $e_t \in [\underline{e}, \bar{e}] \sim e$, independently and identically distributed. For more details about the extension, parallel results, and discussion on other potential extensions, for example, declining discount rates (e.g., Arrow et al. 2014) and recursive preferences (e.g., Howitt et al. 2005), see Xie and Zilberman (2018).

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