The Economics of Water Project Capacities and Conservation Technologies

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Abstract

This paper builds a model determining optimal capacities of diversion dams or water transfer projects. The model incorporates stochastic inflows to the dams and the role of the dam capacity in reducing overflows, and gives a closed-form expression of the marginal benefit of capacities. Comparative static analysis suggests that larger water projects could be required by 1) improvements in water management efficiency, 2) upward shifts in the marginal overflow-caused loss, or 3) more abundant inflows. The result provides important policy implications about the impact of integrated water reforms, rising concern about food security, and climate change on optimal water project capacities. The model is also applied to analyze the relation between water project capacities and conservation technologies, showing 1) that too large or too small water projects could discourage adopting conservation technologies, 2) that the impact of conservation technologies on optimal capacities is ambiguous, and 3) that if designers of water projects take water users' potential adoption of conservation technologies into account, the first-order condition of the capacity determination model could have multiple solutions.

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1   Introduction

Water is arguably the most important natural resource in social, economic, and political development, and eventually, the source of life and death. Water is subjected to large variability and special inequality, however, both across time and between regions. The variability and the inequality make water the focal issue in world and local cooperation and conflicts, and to overcome the variability and the inequality, people build dams, reservoirs, canals, and other water projects to store, release, and transfer water intertemporally and interregionally.

Stabilization and improved allocation of water justify investments in water projects, since they provide agricultural, industrial, environmental, and other social-economic benefits to society. Yet, building large water projects also incurs enormous cost in construction, maintenance, and environmental externality. Moreover, the benefit and the cost are not distributed equally among regions and people, so in both developed and developing countries, large water projects are always not only economically significant, but also politically sensitive.[1]

Motivated by political considerations, water projects have been major public work, but not always justified on the ground of economic efficiency. Realizing it, international organizations recommend to establish cost-benefit criteria to evaluate water projects and determine their optimal capacities. This area has therefore seen the flourish of the cost-benefit analysis method. The success of the method has been symbolized by the *Principles and Guidelines* (1983) of the United States. As recognized in Zilberman et al. (1994), however, one major critique of the method and the *Principles and Guidelines* is that they lead to the design of water projects that overemphasizes "hard" engineering solutions, ignoring the problem-solving capacities of "soft" management and institutional solutions. The critique has also been highlighted in the recent California drought and the related policy discussions, as the expansion of water project capacities and the policies encouraging conservation and recycling are competing bitterly for limited policy resources.[2] In this paper, we develop a new

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[1]A controversial term *hydraulic civilizations* is coined by historian Wittfogel (1957), associating the authoritarian regime in East Asia with the large-scale public water projects in the area. Fischhendler and Zilberman (2005) discuss the political implications of the United States Central Valley Project Improvement Act of 1992. Duflo and Pande (2007) examine the productivity and distributional effects of large irrigation dams in India. For other examples, see McCully (2001) and Singh (2002). Among others, recent and ongoing examples are about the series of dams in the Amazon Basin in South America and along the Yangtze River in China, with the Belo Monte Dam in Brazil and the Three Gorges Dam in China topping the lists, respectively. Examples of the media coverage include Kennedy (2001), Lyons (2012), *The Economist* (2013a, 2013b), and Cheng (2014), among others. Jackson and Sleigh (2000) detail the social-economic impacts of resettlement for the Three Gorges Dam in China. Another ongoing example specifically about water scarcity and water projects is about the proposed canal from the Paraíba do Sul to the Cantareira Water System, initiated by the Governor of São Paulo, Brazil. For media coverage, see Carvalho (2014) and de Araúo (2014a,b).

[2]On the one hand, several bills have been introduced to the Congress to authorize and fund expansion of

analytical framework for the design of water projects, incorporating rising concerns about climate change, resource conservation, and water-provided food, energy, and environmental amenities. The framework provides insights about the implications of the changes in the institutional, environmental, and technological conditions on optimal water project capacities.

The framework is founded on a stylized model for the optimal capacity determination of a dam. The dam sits upstream, gathers inflows in wet seasons, and releases all the gathered water downstream in dry seasons, generating agricultural, industrial, and environmental benefits. The model incorporates stochastic inflows to the dam and the role of the dam capacity in reducing overflows, and the incorporation is done in such a simple way that we can find a closed-form expression of the marginal benefit of dam capacities. The comprehensiveness and the simplicity establish the novelty of our model with respect to literature (e.g. Tsur (1990), Fisher and Rubio (1997), and Schoengold and Zilberman (2007, p.2943,2955)).

Our model links the marginal benefit of dam capacities to the benefit of water releases, and takes into account the inflow distribution and the losses caused by overflows. This feature allows our framework to obtain major conceptual results with implications to major policy problems, about water project capacities, water allocation institutions, tradeoffs among alternative water-dependent services, water distribution systems, climate change, resource conservation, and the relation among them. We believe that the importance and variety of the results, implications, and insights will allow rich discussions and investigations.

The first category of the insights comes from the comparative static analysis around the water release benefit, which suggests that many improvements in water management efficiency could lead to larger optimal capacities of water projects. We find conditions under which institutional reforms, technological reforms, and reduced concentration of water allocation will affect optimal dam capacities. We discuss four improvements as examples of the implications, which are 1) reforming water rights to water markets, which, for example, has been encouraged in the western United States by the Central Valley Project Improvement Act of 1992, 2) reallocating water from irrigation to hydropower or environmental sectors in the age of rising energy prices, which has been discussed in literature, for example, about Australia's Murray–Darling Basin, 3) optimally centralizing conveyance investments,

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water storage and conveyance capacities, including at least the California Emergency Drought Relief Act of 2014, the Upper San Joaquin River Storage Act of 2014, the Shasta Dam Expansion Act of 2014, the San Luis Reservoir Expansion Act of 2014, the Sacramento Valley Water Storage and Restoration Act of 2014, and the Sacramento–San Joaquin Valley Emergency Water Delivery Act of 2014. Californian lawmakers have also been discussing issuing water bonds to finance more water projects. On the other hand, there are also voices suspecting the usefulness of increasing capacities and requiring more funding for recycling projects and conservation technology adoption. Examples of discussions on the recent Californian water policy issues include Calefati (2014), Feinstein (2014b,a), Freking (2014), Garamendi (2014a,b), and Nirappil (2014), among others.

which has been analyzed in Chakravorty et al. (1995), and 4) weakening the market power of monopsony, like the Water Users Associations in the United States, in water generation markets, which has been discussed in Chakravorty et al. (2009). The discussion can be generalized to a framework suggesting that integrated improvements in water management efficiency, for example the Central Valley Project Improvement Act, could optimally require more or larger water projects. The implication contrasts the cost-minimization logic which predicts smaller water projects under higher efficiency of water distribution, allocation, use, and management.

The second category of the insights emerges with the comparative static analysis around the loss caused by overflows. We show that larger dams are needed if the marginal overflow loss increases. The analysis contributes to literature, since economic models about dam capacity determination rarely present explicit impacts of the overflow loss on optimal capacities. The analysis also suggests that if the marginal overflow loss is positively correlated with economic growth, then economic growth could require larger capacities of water projects, and that if the economic loss caused by overflow-interrupted food supply is more seriously concerned, especially in the age emphasizing food security, then larger capacities of water projects could be needed.

The comparative static analysis around the inflow distribution provides the third category of the insights. We show that if the inflow to the dam is more abundant in both dry and wet years, or more precisely, has its distribution shifted to the right in a first-order dominating way, then the dam could be optimally larger. This result contributes to the literature about the impact of climate change on optimal capacities of water projects, examples of which include Fisher and Rubio (1997), among others. Different to Fisher and Rubio (1997), who focus on the impact of variability of inflows, we focus on the impact of the general abundance of the inflows. This result implies that if warming makes water more abundant in the source area of water transfer programs, the programs might optimally need to prepare larger transfer capacities. The implication is practically important, since the scenario of warming-caused inflow change might not be too wild for some large, important water transfer programs, for example the California State Water Project and China's South–North Water Transfer Project.

Last but not least, our model insights about the relation between dam capacities and conservation technologies, which, to our knowledge, hasn't been systematically analyzed in literature. In this paper, we analyze the relation in a framework where a dam capacity decision and a technology adoption decision are to be made respectively by a dam designer and a representative water user.[3] We characterize conservation technologies as rotating

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[3]Readers can regard the approach as a simplified integrated watershed management, which incorporates

clockwise the marginal water release benefit function. This characterization is consistent with that in Caswell and Zilberman (1986) and some other literature. With the characterization, we analyze the relation from the following three perspectives:

Impacts of dam capacities on conservation technology adoption Though public water projects usually affect a large number of water users and potential adopters, they are almost ignored in the literature that studies factors affecting conservation technology adoption.[4] We fill the gap by showing a non-monotonic impact of dam capacities on the incentive of adopting conservation technologies. This impact suggests that too large or too small dams could discourage adopting conservation technologies. This result is also consistent with the studies that finding a non-monotonic relation between resource abundance and conservation technology adoption: on the one hand, more abundant water or resource availability substitutes the need of conservation; on the other hand, having too little water or resource leaves too little room for conservation technologies to aggregate their marginal-benefit advantage over existing technologies to cover the fixed adoption cost.

Impacts of conservation technologies on optimal dam capacities The comparative static analysis of our capacity determination model shows that the impact of conservation technology adoption on optimal dam capacities is ambiguous, and depends on the dam capacity with existing technologies. Compared with the literature on capacity determination, which includes Tsur (1990), Fisher and Rubio (1997), Schoengold and Zilberman (2007, p.2943,2955), and others, it is novel that we identify conservation technology adoption as a potential factor affecting the dam capacity decision. The result also contrasts the cost-minimization logic in capacity determination, which would unambiguously predict a smaller dam with conservation technologies.

Impacts of potential adoption of conservation technologies on optimal dam capacities We consider another setting in which the dam designer recognizes that her dam capacity decision would affect water users' technology adoption decision, and would then affect the benefit of the dam. Different to the literature like Zhao and Zilberman (2001) that focuses on the option value and optimal timing of resource development, our setting makes the potential adoption create a discontinuous marginal benefit of dam capacities. The discontinuity potentiates multiple solutions to the first-order condition of the capacity determination model, making the dam capacity problem not only more complicated, but also more

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decision-making at different levels of water systems.

[4]We shall discuss the literature in more detail in Section 4.

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interesting. The analysis also suggests that one reason for oversized water projects could be the designer's overlooking of the future potential adoption of conservation technologies.

The paper is unfolded as follows. Section 2 builds and solves the model for optimal dam capacity determination. Section 3 analyzes the comparative statics of the model, and presents theoretical and practical implications of the analysis. Section 4 analyzes the relation between dam capacities and conservation technologies. Section 5 concludes the paper with summary and directions for extensions and further research.

2   An optimal dam capacity problem and its solution

In this Section we build a model for the determination of optimal dam capacities. In each period t, water of stochastic amount e_t flows into the dam of a capacity $\bar{w}$, and then the dam releases water of amount w_t into a distribution and allocation system. As the economics of the distribution and allocation system has been discussed in detail in Chakravorty et al. (1995) and Chakravorty et al. (2009) and isn't our paper's main focus, we leave the functioning of the system out of the model.

In our model, the water release is determined by the following Assumption.

Assumption 1 (Water release determination). *The dam capacity caps the maximum amount of the release:* $w_t = \min\{e_t, \bar{w}\}$.

Assumption 1 means that in each period, the dam cannot hold more inflow than how much its capacity allows, and the dam releases all of the held. Readers can regard the dam as a diversion dam or water transfer project which sits upstream, gathers inflows in wet seasons, and releases all the gathered water downstream in dry seasons, generating agricultural, industrial, environmental, and ecological benefits. For simplicity, we don't consider the intertemporal water inventories in the dam. In a concurrent paper, Xie and Zilberman (2014) build and analyze a parallel model which incorporates the optimal management of water inventories.

In each period, the benefit of the dam includes the benefit generated by the water release, $B_t(w_t)$, net of the loss caused by overflows from the dam, $L_t(\max\{e_t, \bar{w}\} - \bar{w})$.[5] This setting completes the water system with the dam, as illustrated in Figure 1.

Before the dam is built, its designer recognizes the construction and maintenance cost, $C(\bar{w})$, and the environmental damage cost, $D(\bar{w})$. The properties of the benefit, the loss, and the cost functions are formalized by the following Assumption.

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[5]For simplicity we don't model each of the elements of the benefit and the loss in detail, which could be a direction for future research.

The water source

The stochastic inflow, e_t

The dam of the capacity, $\overline{w}$, gathers the inflow within the capacity, $\min\{e_t, \overline{w}\}$, and releases all the gathered water.

The water release, $w_t = \min\{e_t, \overline{w}\}$

The water distribution and allocation system receives, distributes, allocates, and uses the water release, and generates the water-release benefit, $B_t(w_t)$.

The overflow, $\max\{e_t, \overline{w}\} - \overline{w}$, causing the overflow loss, $L_t(\max\{e_t, \overline{w}\} - \overline{w})$
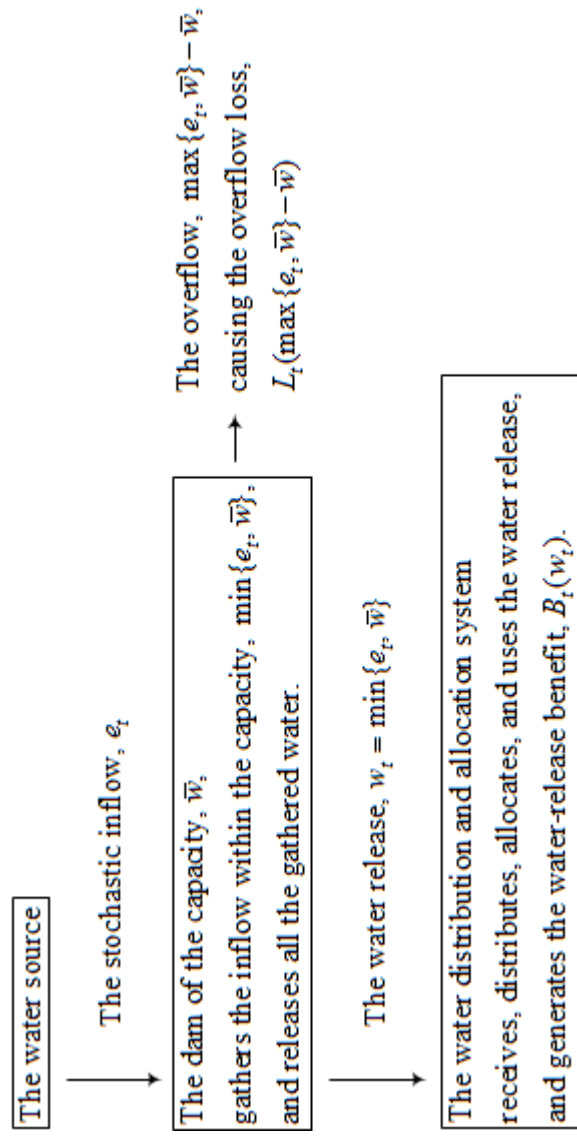
Figure 1: A water system with a dam

Assumption 2 (Function properties). *The marginal water release benefit is non-negative and decreasing: $B'_t(\cdot) \geq 0$ and $B''_t(\cdot) < 0$. The overflow loss is zero when there is no overflow, it is positive when there is an overflow, and the marginal overflow loss is positive and weakly increasing: $L_t(0) = 0$, $L_t(\cdot) > 0$ elsewhere, $L_t'(\cdot) > 0$, and $L_t''(\cdot) \geq 0$. The marginal construction and maintenance cost is positive and increasing: $C'(\cdot) > 0$ and $C''(\cdot) > 0$. The marginal environmental damage cost is positive and increasing: $D'(\cdot) > 0$ and $D''(\cdot) > 0$.*

Assumption 2 isn't very unrealistic. For example, the water release benefit depends on the design of the distribution system, the pricing scheme of water, the institution of water allocation, the efficiency of water application, and many other things, but most importantly, the marginal benefit of water should be much higher when it is scarce than when it is abundant, so a decreasing marginal water release benefit is reasonable; huge overflows weaken the economy's ability to react to additional overflows, so the marginal overflow loss should be weakly increasing; resource of dam building and maintenance is always limited, so assuming increasing marginal construction and maintenance cost isn't too wild; larger dams make the ecological system more vulnerable to further human actions, so it is fair to assume an increasing marginal environmental damage cost.[6] Furthermore, as we shall see later, Assumption 2 makes our optimal dam capacity problem, which is formalized by the following Assumption, have solutions.

Assumption 3 (The social planner's problem with a discount factor). *A social planner chooses the dam capacity to maximize the discounted expected sum of water release benefits minus overflow losses, net of the construction, maintenance, and environmental cost of the dam. The discount factor $\rho \in (0, 1)$.*

With Assumptions 1 and 2, Assumption 3 presents the optimal dam capacity problem:

$$\max_{\bar{w} \geq 0} \quad \mathbf{E}_0 \left[\sum_{s=0}^{\infty} \rho^s \left(B_s(\min\{e_s, \bar{w}\}) - L_s(\max\{e_s, \bar{w}\} - \bar{w}) \right) \right] - C(\bar{w}) - D(\bar{w}). \quad (1)$$

For technical simplicity, we propose another two Assumptions.

Assumption 4 (Stationary water release benefits and overflow losses). *The water release benefit function is the same across time: $B_t(\cdot) = B(\cdot)$ for any t. The overflow loss function is the same across time: $L_t(\cdot) = L(\cdot)$ for any t.*

Assumption 5 (Inflows i.i.d.). *The stochastic inflow is identically and independently distributed as e, with the cumulative distribution function $F(\cdot)$ and the probability density function $f(\cdot)$, where $F'(\cdot) = f(\cdot)$.*

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[6]The environmental damage of dams could be correlated with how water releases are used. In this model we model the environmental damage that is related to water releases into the water release benefit function.

The two Assumptions suggest that we ignore trends in the water release benefit, the overflow loss, and the inflow. They turn the optimal dam capacity problem into

$$\max_{\bar{w} \geq 0} \quad \frac{1}{1 - \rho} \mathbf{E}\left[B(\min\{e, \bar{w}\}) - L(\max\{e, \bar{w}\} - \bar{w}) \right] - C(\bar{w}) - D(\bar{w}), \qquad (2)$$

which is equivalent to

$$\max_{\bar{w} \geq 0} \quad \frac{1}{1 - \rho}\left[\int_{-\infty}^{\bar{w}} B(e)f(e)de + (1 - F(\bar{w}))B(\bar{w}) \right] + \left(-\frac{1}{1 - \rho} \int_{\bar{w}}^{\infty} L(e - \bar{w})f(e)de \right)$$
$$- C(\bar{w}) - D(\bar{w}). \qquad (3)$$

In the objective function, the first term is the discounted expected sum of water release benefits, and the second term is the negative discounted expected sum of overflow losses. The two terms form the benefit of the dam. The third and the fourth terms form the cost of the dam. By Leibniz's integral rule, the marginal values of the discounted expected sum of water release benefits and the negative discounted expected sum of overflow losses with respect to dam capacities are

$$\frac{1}{1 - \rho}(1 - F(\bar{w}))B'(\bar{w}) > 0 \text{ and } \frac{1}{1 - \rho} \int_{\bar{w}}^{\infty} L'(e - \bar{w})f(e)de > 0, \qquad (4)$$

respectively. The first-order condition of the problem is then

$$\frac{1}{1 - \rho}(1 - F(\bar{w}))B'(\bar{w}) + \frac{1}{1 - \rho} \int_{\bar{w}}^{\infty} L'(e - \bar{w})f(e)de = C'(\bar{w}) + D'(\bar{w}). \qquad (5)$$

The left-hand side of the condition is the marginal benefit of dam capacities, which depends on the water release benefit function, the overflow loss function, and the inflow distribution. The right-hand side is the marginal cost of dam capacities. Assumptions 2, 4, and 5 guarantee that the marginal benefit is decreasing and the marginal cost is increasing, so the root of the first-order condition, $\bar{w}^*$, helps the objective function to reach its maximum but not minimum.[7]

The root is the solution to the optimal dam capacity problem if and only if the root is nonnegative. Otherwise, the model might have a corner solution, which is a capacity of zero.

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[7]The first term in the marginal benefit is the product of a positive constant and two positive, decreasing functions, so it is decreasing in $\bar{w}$. The second term is the product of a positive constant and an positive integral. The integral is decreasing in $\bar{w}$, since its derivative with respect to $\bar{w}$ is $-\frac{1}{1-\rho}\left[L'(0)f(\bar{w}) + \int_{\bar{w}}^{\infty} L''(e - \bar{w})f(e)de \right]$, which is negative. The second term is then also decreasing in $\bar{w}$. The marginal benefit is then increasing in $\bar{w}$. The marginal cost is the sum of two positive, increasing functions, so it is decreasing in $\bar{w}$.

Zero capacities could happen when the marginal cost of dam capacities is already larger than the marginal benefit when the capacity is zero. It is also possible that the first-order condition has no root. In this case, the marginal cost of dam capacities is always smaller than the marginal benefit, and the solution to the problem is an infinite capacity. As the zero-capacity and the infinite-capacity cases add little intuition to our further analysis, we rule them out by the following Assumption.

Assumption 6 (Finite, interior solutions). *The marginal benefit of dam capacities is larger than the marginal cost when the capacity is zero, while smaller when the capacity is large enough.*

Since Assumption 2 provides monotonicity and continuity for all the functions, Assumption 6 means there is always a unique, finite, and positive root of the first-order condition, which solves the optimal dam capacity problem.[8]

All the Assumptions and the analysis proves the following Proposition, the main result of this Section.

Proposition 1 (The model's solution). *Under Assumptions 1, 2, 3, 4, 5, and 6, the optimal dam capacity $\bar{w}^*$ makes the marginal benefit dam capacities equal to the marginal cost. Mathematically, $\bar{w}^*$ solves Equation (5). Graphically, $\bar{w}^*$ makes the decreasing marginal benefit $\frac{1}{1-\rho}\left(1 - F(\bar{w})\right)B'(\bar{w}) + \frac{1}{1-\rho}\int_{\bar{w}}^{\infty} L'(e - \bar{w})f(e)de$ intersect with the increasing marginal cost $C'(\bar{w}) + D'(\bar{w})$.*

Proposition 1 characterizes the solution to our model, a model with minimal but still necessary complication. Literature has proposed several models about optimal determination of water project capacities. Almost all of the models carry minimal and necessary complication for their own purposes, but are generally either too simplified, unnecessarily complicated, or too general for our purpose. For example, Schoengold and Zilberman (2007, p.2943) model the marginal benefit of dam capacities in a static, black-box style, which is sufficient for their focus on the logic of oversized water projects, but might be difficult to proceed with further serious analysis and implications. In the same Chapter, Schoengold and Zilberman (2007, p.2955) also try to improve the model by incorporating water demand uncertainty and simplifying water release as the dam capacity. They stop their analysis after deriving the first-order condition, based on the intensive simplification. They also ignore the stochastic inflows and the role of the dam capacity in reducing overflows, so the improved model does extend their story to the case with water demand uncertainty, but might help

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[8]For the readers who might think corner solution should be emphasized in the optimal dam capacity problem, it could be helpful if we regard the dam capacity in our model as the storage capacity of a huge water system, in which a new dam only means a small increase in the storage capacity.

little to analyze the impact of the inflow distribution and the overflow loss on optimal dam capacities. Tsur (1990) discusses the optimal capacity of a groundwater project as a buffer of uncertain supply of surface water, but the inflow to the groundwater project is still assumed deterministic, so the model serves well as a contribution to the idea of conjunctive use of groundwater and surface water, but might help little to examine the impact of the inflow distribution.[9] As in Burt (1964, 1966, 1967, 1970), Tsur and Graham-Tomasi (1991), Truong (2012), and many other papers, the literature that incorporates stochastic inflows or dynamic control focuses on the optimal control rule of water releases or inventories, but at the same time, largely increases the difficulty in finding closed-form expressions of the marginal benefit of dam capacities. It is then difficult to analyze comparative static effects on dam capacities in the models. An admirable attempt by Fisher and Rubio (1997) finds a closed-form expression, but their continuous-time dynamic control of both the water inventory and the storing capacity, at the other extreme, is more than what we need in this paper. Moreover, their model focuses on the impact of the variability of the stochastic inflows instead of that of the whole distribution, and doesn't explicitly characterize the dam's function in controlling the overflow loss. In more general settings, Arrow and Fisher (1974) and Zhao and Zilberman (1999, 2001), among others, focus on the general option value and optimal timing of environmental restoration investment. Their treatment is out of the scope of this paper.

Contributing to the literature, our model incorporates stochastic inflows and overflow losses simultaneously, and is still so simplified that we can find the closed-form expression of the marginal benefit of dam capacities, without much loss in intuition. The closed-form expression clearly shows the dependency of the marginal benefit on the inflow distribution, the water release benefit function, and the overflow loss function. This feature allows us to minimize the complication in comparative statics, and provide implications to answer many important, theory- and policy-relevant questions about water project capacities, water allocation institutions, tradeoffs among alternative water-dependent services, water distribution systems, climate change, resource conservation, and the relation among them. We shall show the comparative statics and the implications in following Sections.

3 Comparative static analysis

In this Section we analyze the comparative statics of the capacity determination model around the water release benefit function $B(\cdot)$, the overflow loss function $L(\cdot)$, and the distribution of the stochastic inflow, which is represented by $F(\cdot)$. The analysis provides

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[9]Reducing overflows isn't applicable to groundwater projects.

important policy implications about the impact of water management efficiency and climate change on optimal capacities of water projects. Appendix A presents the comparative statics around the construction, maintenance, and environmental damage cost functions, which is more straightforward and less interesting.

3.1 The impact of the water release benefit

We exhibit the impact of the water release benefit function on optimal dam capacities by the following Proposition.

Proposition 2 (The impact of the water release benefit). *Under Assumptions 1, 2, 3, 4, 5, and 6, if the marginal water release benefit function shifts up, then the optimal dam capacity becomes larger. Mathematically and more precisely, consider two functions of the water release benefit, $B^1(\cdot)$ and $B^2(\cdot)$, and the corresponding optimal dam capacities, $\bar{w}^{*1}$ and $\bar{w}^{*2}$. If $B^{2'}(\cdot) \geq B^{1'}(\cdot)$, then $\bar{w}^{*2} \geq \bar{w}^{*1}$.*

As mentioned in Section 2, Xie and Zilberman (2014) extend Proposition 2 to the case with optimal water-inventory control. Figure 2 graphically illustrates the intuition of Proposition 2. In the Figure, upward shifting $B'(\cdot)$ shifts up the marginal benefit of dam capacities. Since the marginal benefit of dam capacities intersects with the marginal cost from above, their intersection moves to the right. By Proposition 1, the optimal dam capacity increases.

Though apparently straightforward, Proposition 2 contributes to literature, since to our knowledge, not much literature emphasizes the comparative analysis about capacity determination around the water release benefit function. For example, among papers that are specifically about capacity determination, Schoengold and Zilberman (2007, p.2943,2955) don't analyze comparative statics. Tsur (1990) mentions that larger uncertainty in surface water supply suggests a higher value of groundwater projects, but the paper doesn't emphasize whether the groundwater project capacity should be larger. Tsur (1990) does discuss the comparative statics of capacities around cost functions, but not around benefit functions.

Proposition 2 can provide important policy implications, since many improvements in water management efficiency could shift up the marginal water release benefit function. For example, we analyze four improvements, which are reforming water rights to water markets, reallocating water from irrigation to hydropower or environmental sectors in the age of rising energy prices, optimally centralizing conveyance investments, and weakening the market power of monopsony in water generation markets. By Proposition 2, all the four improvements could encourage larger dams.

$$B^{2'}(\cdot) \geq B^{1'}(\cdot) \Rightarrow \bar{w}^{*2} \geq \bar{w}^{*1}$$
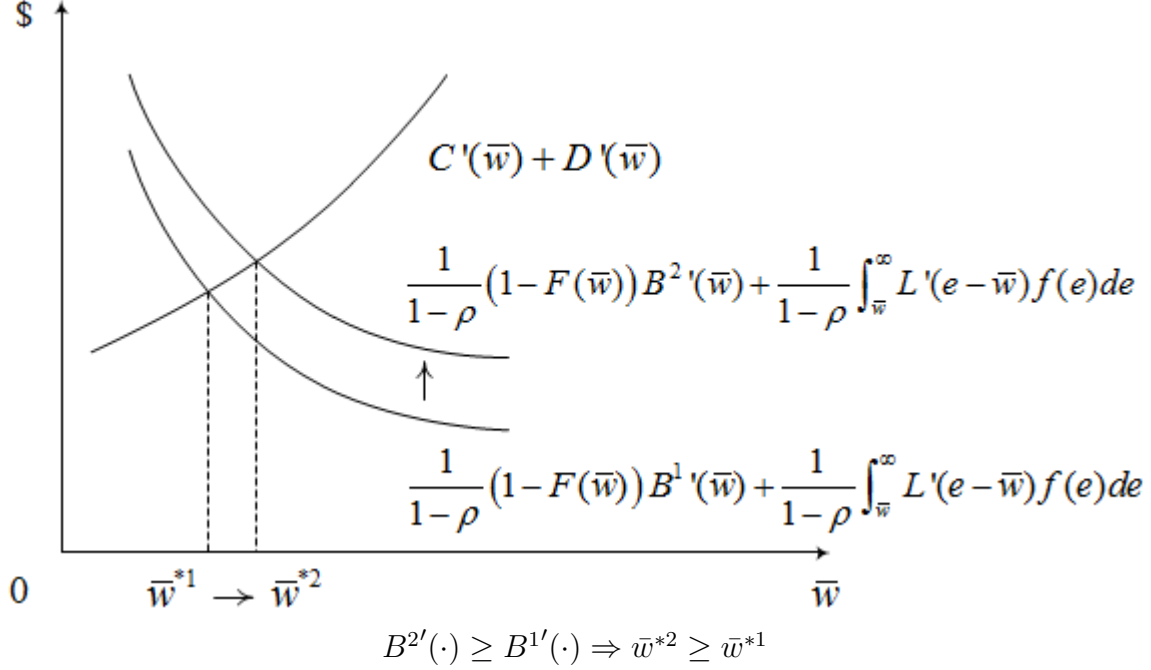
Figure 2: The impact of the water release benefit on the optimal dam capacity

Transitions from water rights to water markets Much literature recognizes that reforming a traditional water right system to market-like water allocation can improve water use efficiency, including Burness and Quirk (1979), Gisser and Sánchez (1980), Gisser and Johnson (1984), Howe et al. (1986), Chakravorty et al. (1995), Dinar and Tsur (1995), and Brill et al. (1997), among others. Good surveys about the topic include Saleth and Dinar (2000), Zilberman and Schoengold (2005), Chong and Sunding (2006), and Tsur (2009). As one example of the traditional systems, in the queuing system used in the western United States before the Central Valley Project Improvement Act of 1992, the seniority of water rights is determined by historical water use in irrigation, and water is priced by the average cost. As argued in Zilberman and Schoengold (2005), in this system, "trading bans and low water prices do not provide the owners of senior rights with the incentive to adopt water conserving technologies to reduce their water use and sell the extra water to highly efficient individuals with junior or no water rights." The Central Valley Project Improvement Act, however, allows water users to sell some of their water rights in a water market. The transition from water rights to water markets includes the high willingness-to-pay of the highly efficient individuals for additional water into the marginal water-use benefit, and has water priced by the marginal cost instead of the average cost. The two improvements expand the marginal water-use benefit, and then shift up the marginal water release benefit.[10] By

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[10]This argument is formalized in Appendix D.

Proposition 2, we have the following Implication about the impact of the transition on optimal dam capacities.

Implication 1. *Transitions from water rights to water markets could require larger capacities of water projects.*

Rising energy prices and reallocation of water from irrigation to hydropower or environmental sectors In the age of rising energy prices, increasing water provision for hydropower could gain extra water release benefit. Hydropower is cleaner than fossil fuels, so the gain could also occur in the environmental sector. Released water could also help downstream areas to resist saltwater from intruding, protect endangered species, and therefore improve the quality of water and environment. Following this idea, much literature recognizes that reallocating water use from agricultural sector to hydropower or environmental sectors could improve water management efficiency and shift up the marginal water release benefit, including Chatterjee et al. (1998), Quiggin (2006), Schoengold et al. (2008), and Truong (2012), among many others. For example, about the case of the Murray–Darling Basin, Australia's significant agricultural area, Truong (2012) reads, "it is now widely acknowledged that the (marginal) value of water use for environmental purposes is much higher than the (marginal) value of water use in irrigation and reallocation of water resources from the irrigation sector to the environmental sector will significantly enhance the efficiency in water usage (Quiggin 2006)." By Proposition 2, the upward shift in the marginal water release benefit could lead to larger dams. The following Implication documents the impact.

Implication 2. *Rising energy prices and reallocation of water from irrigation to hydropower or environmental sectors could require larger capacities of water projects.*

Optimal centralization of conveyance investments Chakravorty et al. (1995) compare "a utility that supplies water to firms but fails to invest optimally in the distribution canals" with a utility that centralizes and optimizes the investments. They discuss two pricing schemes for the suboptimal utility, which are a spatially uniform pricing solution and a water market solution, respectively. They argue that there exists a range of the level of water release in which the marginal water release benefit with optimal conveyance investments is always higher than that with suboptimal conveyance investments. The argument is confirmed by their simulation of water use for cotton irrigation in the western United States. This result implies that if the water release from our dam is always within the range, then centralizing conveyance investments will shift up the marginal water-benefit function. By Proposition 2, the shift could encourage larger dams, as documented by the following Implication.

Implication 3. *Optimal centralization of conveyance investments could require larger capacities of water projects.*

Weakening of the market power of monopsony in water generation markets
Chakravorty et al. (2009) compare the private Water Users Associations in the western U.S. with the social optimal water distribution system. The Water Users Associations are monopsonies in the water generation market, examples of which include California's water districts. As described in Congressional Budget Office of the United States (1997), the districts "appropriate water, construct reservoirs and distribution systems" and buy surface water supplies from the State or the Bureau of Reclamation. Chakravorty et al. (2009) show that the market power of the monopsony could make the water conveyed into the distribution system smaller than the social optimal level. Following this idea, when the water release from our dam caps the maximum amount of water that is conveyed into the distribution system by the water generation market (and actually applied in economy), removing the market power of the private Water Users Associations can weakly increase water application, and then shift up the marginal water release benefit.[11] Proposition 2 implies the following Implication, which documents the positive impact of the shift on dam capacities.

Implication 4. *Weakening of the market power of monopsony in water generation markets could require larger capacities of water projects.*

The four examples suggest a framework which analyzes the impact of improvements in water management efficiency on optimal capacities of water projects, and gives some empirical implications. With progresses in environmental, resource, and water economics, major water reforms have been and will be implemented, and they could help to gain extra water release benefit. For example, the purposes of the Central Valley Project Improvement Act include to increase economic and environmental benefit from the Central Valley Project through reforms in water transfers, water pricing, conservation, and wildlife restoration.[12] By Proposition 2, whether and how much the reforms would lead to larger water projects depends on whether and how much the efficiency improvements would shift up the marginal water release benefit. The dependency asks for serious empirical analysis on the impact of the reforms on the marginal water release benefit.

To conclude this Subsection, we discuss a little bit more about the intellectual interestingness of the implications of Proposition 2. One might literally expect that improvements in water management efficiency should mean more efficient water use, so it would require

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[11]This argument is formalized in Appendix E.

[12]For details about environmental impacts of the Central Valley Project Improvement Act, see United States Department of Interior et al. (1999).

smaller water supply and dam capacities. This logic is found in some engineering literature, where dam designers are minimizing cost of dams to satisfy specific engineering and policy constraints.[13] In contrast, Proposition 2 shows that weighing the *marginal* benefit and cost of dam capacities, larger dams would be required. This contrast is similar to the surprise in Chakravorty et al. (1995), where the optimal water use is larger under optimal distribution system than that under non-optimal distribution system.

A simple analysis can exploit this contrast. Along the cost-minimization logic, assume the cost minimizer's problem under the improved water benefit function $B^2(\cdot)$ as

$$
\min_{\bar{w}^2 \geq 0} \quad C(\bar{w}^2) + D(\bar{w}^2)
$$

$$
\text{s.t.} \quad \int_0^{\bar{w}^2} \left[\frac{1}{1-\rho} \left(1 - F(\bar{w})\right) B^{2'}(\bar{w}) + \frac{1}{1-\rho} \int_{\bar{w}}^{\infty} L'(e - \bar{w}) f(e) de \right] d\bar{w}
$$

$$
\geq \int_0^{\bar{w}^{*1}} \left[\frac{1}{1-\rho} \left(1 - F(\bar{w})\right) B^{1'}(\bar{w}) + \frac{1}{1-\rho} \int_{\bar{w}}^{\infty} L'(e - \bar{w}) f(e) de \right] d\bar{w}. \tag{6}
$$

The constraint means any decision $\bar{w}^2$ should make the dam with $B^2(\cdot)$ provide the same or larger benefit as the dam of the optimal capacity with $B^1(\cdot)$ does. Since $B^{2'}(\cdot) \geq B^{1'}(\cdot)$, $B^2(\cdot)$ requires smaller dams to reach the original level of the benefit of the dam of $\bar{w}^{*1}$. The cost-minimizing decision, $\hat{\bar{w}}^2$, should make the extra benefit from higher $B^{2'}(\cdot)$ equal to the loss due to a smaller dam. As shown in Figure 3, $\hat{\bar{w}}^2$ should make the size of Area A_1 exactly cover the size of of Areas A_2 and A_3. It is then clear that $\hat{\bar{w}}^2$ must be smaller than $\bar{w}^{*1}$. This decision, however, isn't economically optimal, since the marginal benefit of dam capacities is still larger than the marginal cost. The social planner's optimal decision, $\bar{w}^{*2}$, should be larger than $\hat{\bar{w}}^2$, and eventually also larger than $\bar{w}^{*1}$, making the marginal benefit equal to the marginal cost.

3.2 The impact of the overflow loss

We exhibit the impact of the overflow loss function on optimal dam capacities by the following Proposition.

Proposition 3 (The impact of the overflow loss). *Under Assumptions 1, 2, 3, 4, 5, and 6, if the marginal overflow loss function shifts up, then the optimal dam capacity becomes larger. Mathematically and more precisely, consider two functions of the overflow loss, $L^1(\cdot)$ and $L^2(\cdot)$, and the corresponding optimal dam capacities, $\bar{w}^{*1}$ and $\bar{w}^{*2}$. If $L^{2'}(\cdot) \geq L^{1'}(\cdot)$, then $\bar{w}^{*2} \geq \bar{w}^{*1}$.*

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[13]For example, see the surveys by Yeh (1985) and Simonovic (1992) about engineering literature on design and management of reservoirs.
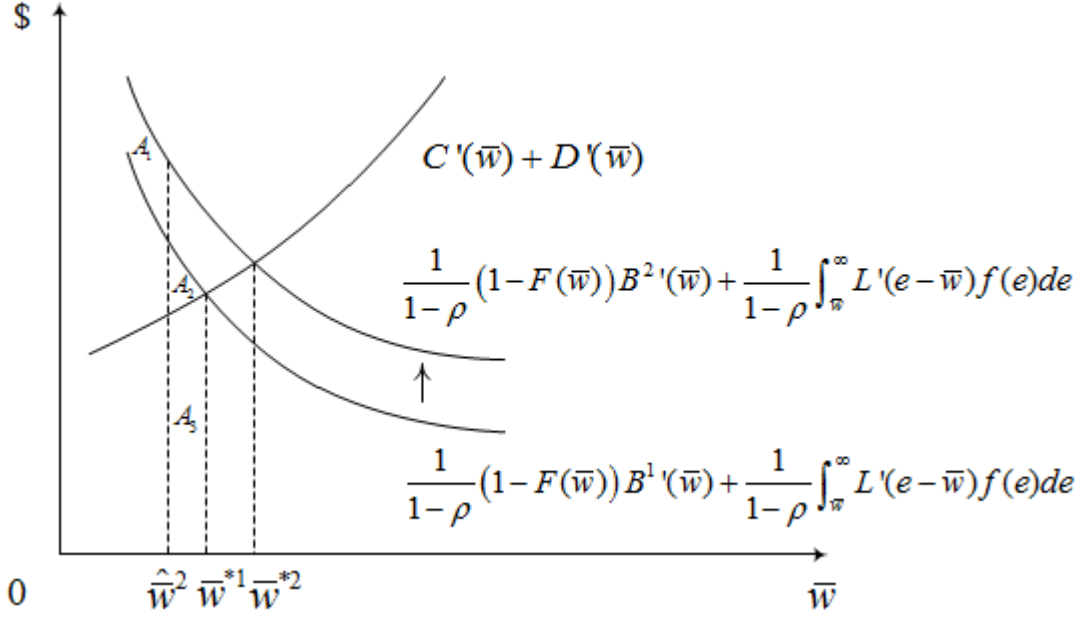
Capacity $\bar{w}^{*1}$ is optimal when the water release benefit function is $B^1(\cdot)$. Capacity $\bar{w}^{*2}$ is optimal when the water release benefit function is $B^2(\cdot)$. Capacity $\hat{\bar{w}}^2$ is the minimal capacity to provide the same or larger benefit with $B^2(\cdot)$ as the dam of $\bar{w}^{*1}$ with $B^1(\cdot)$ does. The water release benefit functions satisfy that $B^{2\prime}(\cdot) \geq B^{1\prime}(\cdot)$, so $\hat{\bar{w}}^2 \leq \bar{w}^{*1} \leq \bar{w}^{*2}$, and the size of the Areas satisfies that $A_1 = A_2 + A_3$.

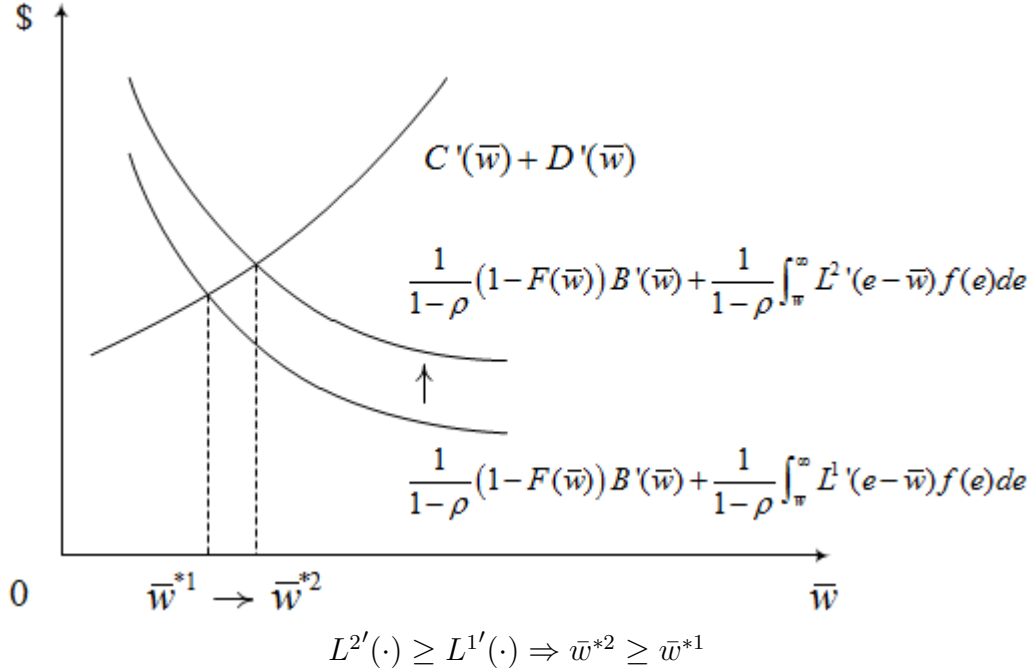Figure 3: Comparison between cost minimization and economic-profit maximization

$$L^{2\prime}(\cdot) \geq L^{1\prime}(\cdot) \Rightarrow \bar{w}^{*2} \geq \bar{w}^{*1}$$

Figure 4: The impact of the overflow loss on the optimal dam capacity

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Proposition 3 is illustrated in Figure 4. Since the marginal value of the negative discounted expected sum of overflow losses with respect to dam capacities is $\frac{1}{1-\rho} \int_{\bar{w}}^{\infty} L'(e - \bar{w})f(e)de$, an upward shift in $L'(\cdot)$ shifts up the marginal value and therefore the marginal benefit of dam capacities. Since the marginal benefit intersects with the marginal cost from above, the intersection then moves to the right. By Proposition 1, the optimal dam capacity then increases.

Though the role of dam capacities in reducing overflows is well recognized, as for example in Green et al. (2000), economic models about dam capacity determination rarely present explicit impacts of the overflow loss on optimal capacities. As mentioned in Section 2, the examples include Tsur (1990), Fisher and Rubio (1997), and Schoengold and Zilberman (2007, p.2943, 2955), among others. Proposition 3 contributes to the literature, by modeling the role of dam capacities in reducing overflows, and showing the relation among the overflow loss, the marginal benefit of dam capacities, and the optimal dam capacity.

Proposition 3 also gives policy implications. For example, if floods caused by overflows can wipe out production in flooding areas, the (marginal) economic damage caused by overflows then becomes larger as economy grows. Proposition 3 implies that larger dams are required as economy grows. The implication is documented by the following Implication.

Implication 5. *If the marginal overflow loss is positively correlated with economic growth, then economic growth could require larger capacities of water projects.*

Another example of the implications of Proposition 3 is related to the increasing concern about food security. Overflows might seriously interrupt agricultural production by flooding and waterlogging, and if the loss is more seriously concerned, especially in the age emphasizing food security, then larger capacities of water projects could be required. We conclude this Subsection by documenting this implication by the following Implication.

Implication 6. *If the marginal overflow loss is more seriously concerned in the age emphasizing food security, then the emphasis could require larger capacities of water projects.*

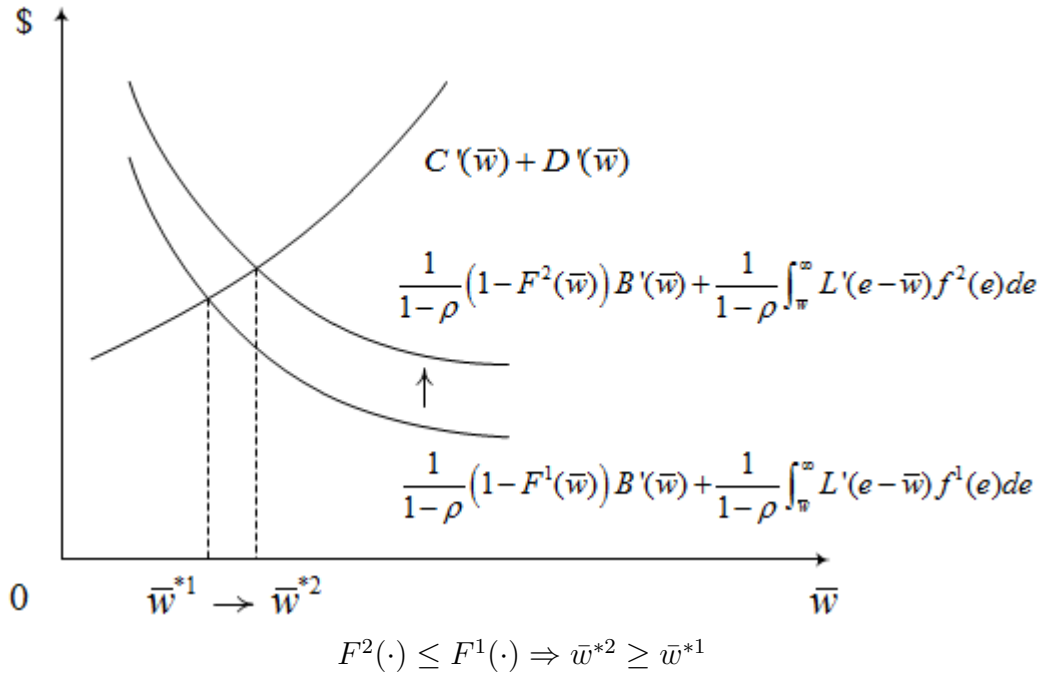## 3.3 The impact of the inflow distribution

By integration by parts, the marginal benefit of dam capacities

$$\frac{1}{1-\rho}\left(1 - F(\bar{w})\right)B'(\bar{w}) + \frac{1}{1-\rho}\int_{\bar{w}}^{\infty} L'(e - \bar{w})f(e)de$$
$$= \frac{1}{1-\rho}\left(1 - F(\bar{w})\right)B'(\bar{w}) + \frac{1}{1-\rho}\left(L'(\infty) - L'(0)F(\bar{w}) - \int_{\bar{w}}^{\infty} F(e)L''(e - \bar{w})de\right). \quad (7)$$

Since Assumption 2 requires positive $B'(\cdot)$ and $L'(\cdot)$ and nonnegative $L''(\cdot)$, a downward shift in $F(\cdot)$ shifts up the marginal benefit of dam capacities. This analysis proves the following Proposition on the impact of the inflow distribution on optimal dam capacities.

Proposition 4 (The impact of the inflow distribution). *Under Assumptions 1, 2, 3, 4, 5, and 6, if the inflow distribution is shifted in a first-order stochastically dominating way, then the optimal dam capacity becomes larger. Mathematically and more precisely, consider two cumulative distribution functions of the inflow, $F^1(\cdot)$ and $F^2(\cdot)$, and the corresponding optimal dam capacities, $\bar{w}^{*1}$ and $\bar{w}^{*2}$. If $F^2(\cdot) \leq F^1(\cdot)$, then $\bar{w}^{*2} \geq \bar{w}^{*1}$.*

$$F^2(\cdot) \leq F^1(\cdot) \Rightarrow \bar{w}^{*2} \geq \bar{w}^{*1}$$

The probability density function $f^i(\cdot)$ corresponds to the cumulative distribution function $F^i(\cdot)$, where $i = 1, 2$.

Figure 5: The impact of the inflow distribution on the optimal dam capacity

Proposition 4 is illustrated in Figure 5. In the Figure, a downward shift in $F(\cdot)$ shifts up both the marginal values of the discounted expected sum of water release benefits and the negative discounted expected sum of overflow losses, and then the marginal benefit of dam capacities. Since the marginal benefit intersects with the marginal cost from above, the intersection moves to the right. By Proposition 1, the optimal dam capacity then increases.

Since the inflow distribution is largely determined by climate, Proposition 4 implies a straightforward but important impact of climate change on optimal dam capacities, which is documented by the following Implication.

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Implication 7. *Climate change that makes the inflows more abundant could require larger capacities of water projects.*

The Corollary is important since it contributes to the literature about the impact of climate change, especially on optimal capacities of water projects. For example, Fisher and Rubio (1997) study the impact of the variability of water resource, which could be induced by climate change, on optimal water storage capacities. For many large-scale water transfer programs, however, climate change could also have serious impacts on the abundance of their inflows. For example, Schwabe and Connor (2012) mention that warming could reduce the natural storage capacity of the Sierra Nevada snowpacks. This impact could make precipitation increasingly fall as rain which will eventually flow into the California State Water Project, which transfers water from Northern to Southern California. By Proposition 4, the impact could suggest a larger optimal water transfer capacity. A similar impact could also happen to China's South–North Water Transfer Project, which transfers water from Southern to Northern China, as Piao et al. (2010) project a potential increasing trend of the runoff of the Yangtze River, the main water source of Southern China.

4 The relation between dam capacities and conservation technologies

This section analyzes the relation between dam capacities and conservation technologies. More specifically, we ask three questions: First, under what conditions about dam capacities would water users adopt a newly-available conservation technology? Second, what is the impact of adopting the technology on optimal dam capacities? Third, what will happen if the dam designer recognizes that her capacity decision can affect water users' adoption decision and then affect the benefit of the dam?

The key to these questions is how to characterize conservation technologies. Our characterization is formalized by the following assumption.

Assumption 7 (A costly conservation technology)**.** *A conservation technology would change the water release benefit function from $B^1(w)$, which is associated with the existing technology, to $B^2(w)$. There exists $\hat{w}$ so that $B^{2'}(w) > B^{1'}(w)$ when $w < \hat{w}$, $B^{2'}(w) = B^{1'}(w)$ when $w = \hat{w}$, and $B^{2'}(w) < B^{1'}(w)$ when $w > \hat{w}$. The corresponding fixed costs of the two technologies are $c_2 > 0$ and $c_1 = 0$.*

Assumption 7 means that conservation technologies increase the marginal water release benefit when water is scarce, while decreases it when water is abundant. In other words, we

assume that conservation technologies rotate clockwise the marginal water release benefit function. Notably, this characterization is different to that in Zhao and Zilberman (2001) for example, in which the conservation technology shifts down the marginal benefit of resource, but consistent with that in Caswell and Zilberman (1986) and some other literature.

Assumption 7 is straightforward, if we assume 1) that the water release benefit equals to a benefit function in effective water, whose share in the released water is increased by conservation technologies, 2) that there is a finite upper bound of the water release benefit, which could result from some constraints on the expansion of the water using sector, and 3) that the curvature of the marginal effective water benefit isn't too positive. As argued in Caswell and Zilberman (1986), the Assumption means that the elasticity of the marginal effective water benefit with respect to effective water crosses one, which is more plausible in irrigation water use, than some other specifications of the effective water benefit function, for example the Cobb and Douglas (1928) specification, are. We show the following example to illustrate the Assumption. A more formal justification can be found in Appendix B.

Example 1 Consider an effective water benefit function $\mathcal{B}(\mathcal{W}) = \mathcal{W}(2a - \mathcal{W})$, where $\mathcal{W} \in [0, a]$ is the effective water, and $a > 0$ is a parameter. Note that the effective water benefit function is weakly increasing, and that its marginal value is weakly decreasing. Assume a technology is assumed to effectively use α of the water release, w, so $\mathcal{W} = \alpha w$. Therefore we can write the water release benefit function as $B(w) = \alpha w(2a - \alpha w)$. The marginal water release benefit is then $B'(w) = 2a\alpha - 2\alpha^2 w$. Now consider the existing technology that gives $\alpha = \alpha_1$ and the conservation technology that gives $\alpha = \alpha_2$, where $\alpha_2 > \alpha_1$. The two corresponding marginal water release benefit functions are then respectively $B^{1'}(w) = 2a\alpha_1 - 2\alpha_1^2 w$ and $B^{2'}(w) = 2a\alpha_2 - 2\alpha_2^2 w$. Since $\alpha_2 > \alpha_1$, the intercept on the vertical axis of $B^{2'}(w)$ is then higher than $B^{1'}(w)$'s, the intercept on the horizontal axis of $B^{2'}(w)$ is then lower than $B^{1'}(w)$'s, and $B^{2'}(w)$ is steeper than $B^{1'}(w)$. Simple algebra also gives $\hat{w} = \frac{a}{\alpha_2 + \alpha_1}$. We can conclude that the conservation technology rotates clockwise the marginal water release benefit function around $w = \hat{w}$.

Under Assumption 7, we answer the three important questions in the following Subsections, respectively.

4.1 Impacts of dam capacities on conservation technology adoption

Under what conditions about dam capacities would water users adopt a newly-available conservation technology? To answer this question, first assume the representative potential

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adopter is rational.

Assumption 8 (Rational adoption of the representative water user). *The representative water user chooses whether to switch from the existing technology to the conservation technology by comparing the respective discounted expected sums of water release benefits net of the fixed costs.*

Assumption 8 implies that the conservation technology will be adopted if and only if the representative water user could gain from the adoption. Mathematically, under Assumptions 1, 2, 4, 5, 7, and 8, the representative water user's technology adoption problem is

$$\max_{i\in\{1,2\}} \quad \mathbf{E}_0\left[\sum_{s=0}^{\infty} \rho^s B_s^i(\min\{e_s, \bar{w}\})\right] - c_i, \tag{8}$$

which is equivalent to

$$\max_{i\in\{1,2\}} \quad \frac{1}{1-\rho}\left[\int_{-\infty}^{\bar{w}} B^i(e)f(e)de + (1 - F(\bar{w}))B^i(\bar{w})\right] - c_i, \tag{9}$$

and the water user will adopt the conservation technology, which means $i^* = 2$, if and only if

$$\frac{\int_{-\infty}^{\bar{w}}\left(B^2(e) - B^1(e)\right)f(e)de + (1 - F(\bar{w}))\left(B^2(\bar{w}) - B^1(\bar{w})\right)}{1-\rho} > c_2. \tag{10}$$

The left-hand side of the condition is the discounted comparative benefit of adopting the conservation technology over not adopting, or the conservation technology's *advantage*, and the right-hand side is the fixed cost of the adoption. For notational simplicity, denote the left-hand side as $A(\bar{w})$, where A represents *advantage*. To investigate its shape, we calculate its derivative and have

$$A'(\bar{w}) = \frac{1}{1-\rho}(1 - F(\bar{w}))\left(B^{2'}(\bar{w}) - B^{1'}(\bar{w})\right), \tag{11}$$

which means

$$A'(\bar{w}) > 0 \text{ and } A(\bar{w}) \text{ is increasing, if } \bar{w} < \hat{w};$$
$$A'(\bar{w}) = 0 \text{ and } A(\bar{w}) \text{ reaches its maximum, if } \bar{w} = \hat{w};$$
$$A'(\bar{w}) < 0 \text{ and } A(\bar{w}) \text{ is decreasing, if } \bar{w} > \hat{w}. \tag{12}$$

This analysis implies that the conservation technology's advantage is smaller with large or small dams than with dams of moderate capacities. This implication proves the following Proposition, which documents the impact of dam capacities on conservation technology

adoption.

Proposition 5 (Too small or too large dams discourage adopting conservation technologies)**.**
*Under Assumptions 1, 2, 4, 5, 7, and 8, if the dam is too large or too small, then the
conservation technology won't be adopted. Mathematically and more precisely, the following
two statements are true:*

1) If $A(\hat{w}) > c_2$, then the conservation technology will be adopted if and only if $w^s < \bar{w} < w^l$, where w^s and w^l solve $A(\bar{w}) = c_2$.

2) If $A(\hat{w}) \leq c_2$, then given any $\bar{w}$, the conservation technology won't be adopted.

Figure 6 illustrates the first statement in Proposition 5. The top panel exhibits that the
conservation technology rotates clockwise the marginal water release benefit function around
$\bar{w} = \hat{w}$. The mid panel presents the marginal advantage of the conservation technology, which
intersects the horizontal axis from above at $\bar{w} = \hat{w}$. The bottom panel shows the advantage,
which flips its monotonicity in $\bar{w}$ at $\bar{w} = \hat{w}$. In the panel, a horizontal line of height c_2
intersects $A(\bar{w})$, and identifies the two roots to $A(\bar{w}) = c_2$, w^s and w^l. The three panels give
the following observations: when the dam is small, the conservation technology is marginally
more beneficial than the existing technology, but the cumulative benefit isn't large enough to
cover the fixed cost of adoption; when the dam is large, then the conservation technology is
marginally less beneficial than the existing technology, so the cumulative benefit is decreasing
and the fixed cost becomes even more difficult to be covered; only when the dam is neither
too small nor too large, the conservation technology will be sufficiently more beneficial than
the existing technology to cover the fixed cost, and it will then be adopted.

From the bottom panel of Figure 6, it is also clear that $A(\bar{w})$ won't reach the horizon-
tal line of height c_2 when c_2 is sufficiently large, which is about the second statement in
Proposition 5.

To my knowledge, Proposition 5 is the first result about impacts of public water projects
on conservation technology adoption, though public water projects usually affect a large
number of water users and potential adopters. Following the threshold model of technol-
ogy adoption in David (1975), numerous theoretical and empirical studies about irrigation
and conservation technology adoption have emerged. Caswell (1991) surveys the literature
about factors affecting adoption choices. Notable examples include Feinerman (1983), Fein-
erman and Vaux (1984), Caswell and Zilberman (1986), Dinar and Knapp (1986), Caswell
et al. (1990), Dinar and Yaron (1990, 1992), Dinar and Letey (1991), Dinar and Zilberman
(1991a,b), Dinar et al. (1992), Lynne et al. (1995), Shah et al. (1995), Green et al. (1996),
Khanna and Zilberman (1997), Carey and Zilberman (2002), Foltz (2003), and Koundouri
et al. (2006), among others. The factors in focus include farm size, labor availability, tenure
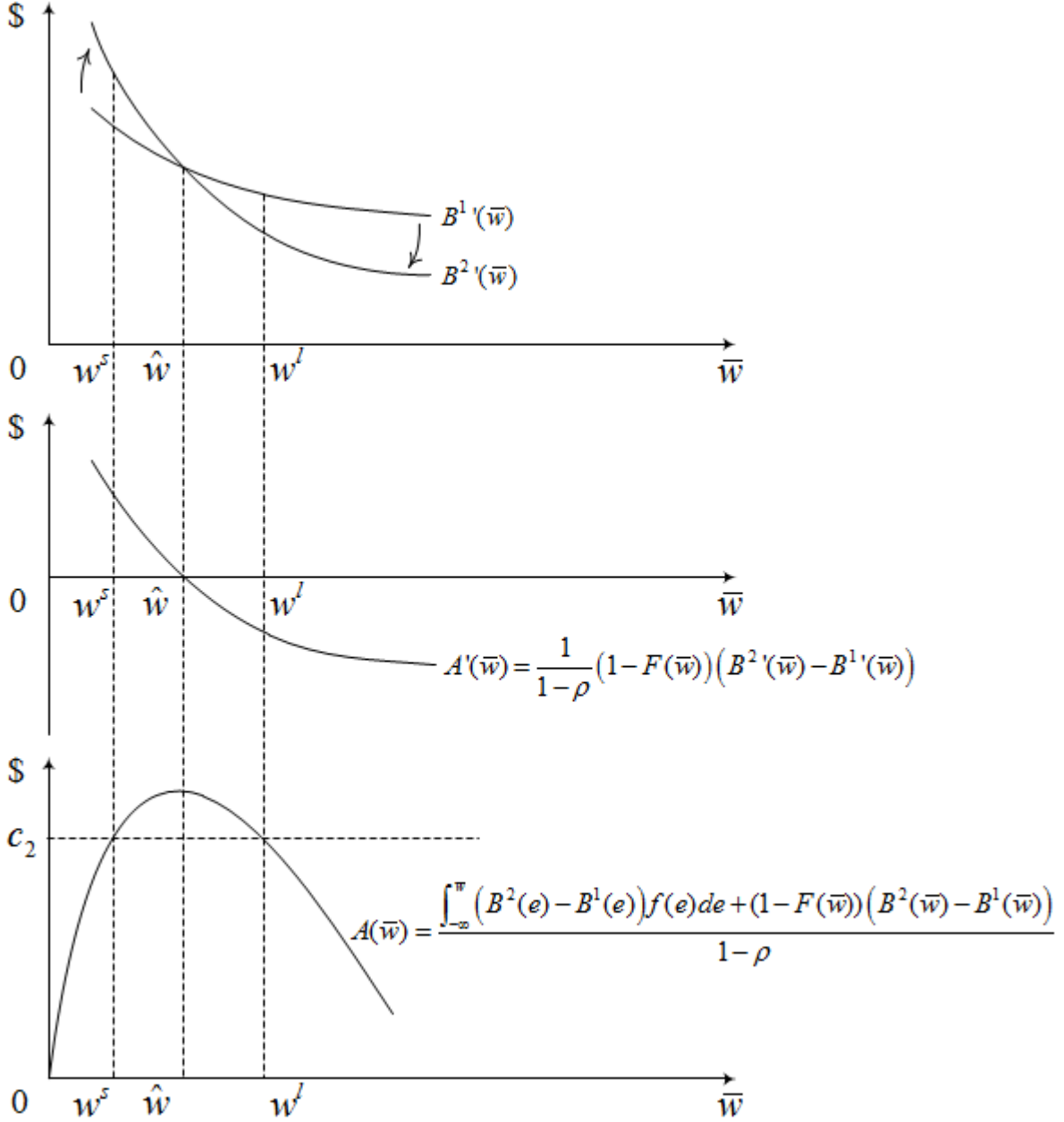
Figure 6: Impacts of dam capacities on conservation technology adoption

systems, market imperfection and learning cost, economic variables (water price and others), capital constraints, water-related endowments (land quality, well depth, climate, and others), production risk, human capital, resource exhaustibility, water markets, agricultural characteristics, policies, and psychology, among others, and good surveys are also written by Feder et al. (1985), Sunding and Zilberman (2001), and Schoengold and Zilberman (2007). Apparently no studies, however, have ever discussed the impact of dam capacities.[14] Propo-

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[14]One reason for the lack of attention of the impact of water projects on conservation technology adoption

sition 5 fills the gap by showing a non-monotonic impact of dam capacities on the incentive of adopting conservation technologies.

Proposition 5 is also consistent with the studies on the potential non-monotonic relation between resource abundance and conservation technology adoption. Caswell and Zilberman (1986) shows that when applied water is little, adopting conservation technologies could induce more water usage, while the opposite could happen when applied water is already a lot, since the elasticity of the marginal product with respect to the effectively applied water could cross unity when the applied water increases. This theoretical result is well recognized in many papers (e.g. Caswell et al. (1990), Dinar et al. (1992), Dinar and Zilberman (1991a), Shah et al. (1995), Dridi and Khanna (2005), Lichtenberg (2013), and Lin (2014)) and surveys (e.g. Feder and Umali (1993) and Lichtenberg (2002)). The non-monotonicity, especially the increasing part, has also been shown empirically relevant by studies like Peterson and Ding (2005), Frisvold and Emerick (2008), and Lin (2014), among others.[15] Proposition 5 shows that this potential non-monotonic relation could be applicable to water project capacities.

Proposition 5 suggests that governments can encourage conservation technology adoption by building larger dams or closing some water projects. To find the correct policy, the governments should have good knowledge about the reason why people don't adopt the technology: Is water so abundant that there is no need to conserve, or so scarce that there is little aggregate gain from conservation? This is an empirical question that should be answered seriously.

4.2 Impacts of conservation technologies on optimal dam capacities

Will water users' adoption of conservation technologies require larger or smaller dams? Since conservation technologies change the water release benefit function, the following Proposition answers the question by comparative static analysis of our capacity determination model around the water release benefit.

Proposition 6 (Conservation technologies require smaller dams if and only if the dams are already large). *Under Assumptions 1, 2, 3, 4, 5, and 6, and 7, if the initial optimal dam capacity is small, then adopting the conservation technology requires a larger optimal dam*

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could be the difficulty in empirically identifying the impact: on the one hand, as public water projects affect a large number of water users, there is little variation in the water project capacity across these water users; on the other hand, across the water users with different water projects, it is also difficult to argue that there are few confounding factors when we attempt to estimate the impact of water project capacity.

[15]Another non-monotonic relation is presented by Carey and Zilberman (2002), in which the impact of water markets on adoption has an opposite interactions with water endowment in the case of water abundance to the case of water scarcity.

capacity; if the initial optimal dam capacity is large, then adopting the conservation technology requires a smaller optimal dam capacity. Mathematically and more precisely, consider the optimal dam capacities with the existing technology and the conservation technology, $\bar{w}^{*1}$ and $\bar{w}^{*2}$. If $\bar{w}^{*1} < \hat{w}$, then $\bar{w}^{*1} < \bar{w}^{*2} < \hat{w}$; if $\bar{w}^{*1} = \hat{w}$, then $\bar{w}^{*1} = \bar{w}^{*2} = \hat{w}$; if $\bar{w}^{*1} > \hat{w}$, then $\hat{w} < \bar{w}^{*2} < \bar{w}^{*1}$.

Figure 7 illustrates Proposition 6. Since adopting the conservation technology rotates clockwise the marginal water release benefit function, whether it rotates up or down the marginal benefit of dam capacities depends on whether the marginal benefit intersects the marginal cost on the left or on the right of $\hat{w}$: if the initial dam capacity is small, then adopting the conservation technology rotates up the marginal benefit of dam capacities. Following the logic in Proposition 2, the optimal dam capacity increases. If the initial dam capacity is large, then a similar but opposite logic holds.
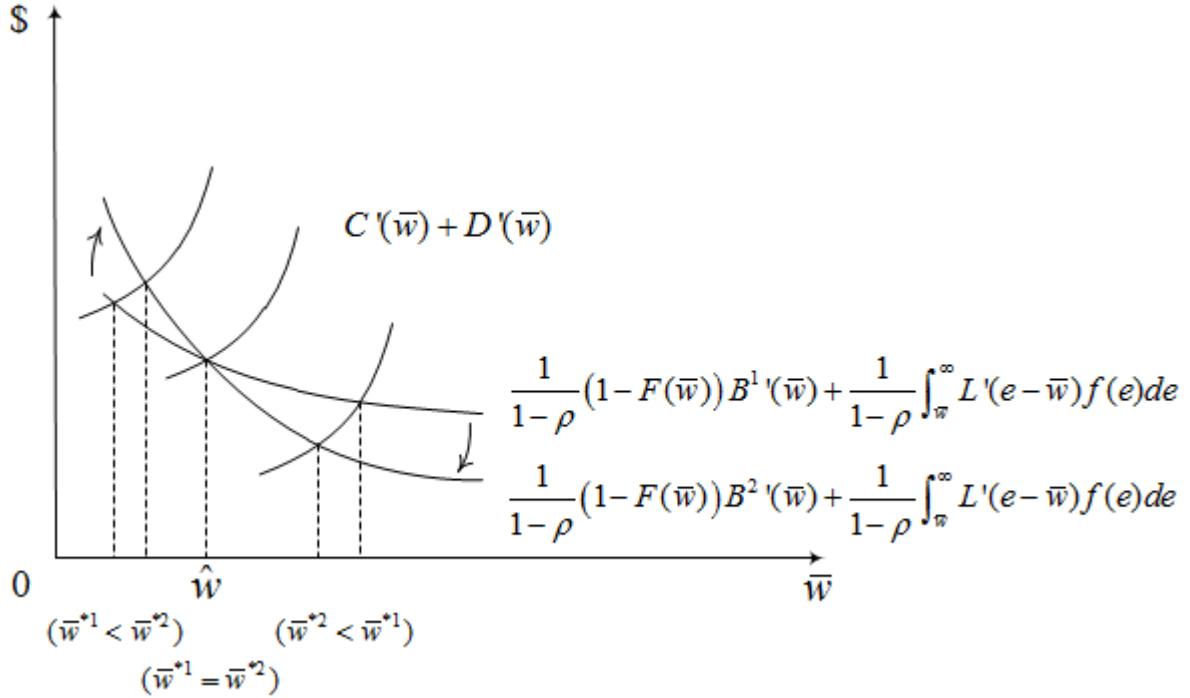

Figure 7: Impacts of conservation technologies on optimal dam capacities

Compared with literature about capacity determination, including Tsur (1990), Fisher and Rubio (1997), Schoengold and Zilberman (2007, p.2943,2955), and others, it is a novel contribution that Proposition 6 identifies conservation technology adoption as a potential factor affecting the dam capacity decision. Proposition 6 also contrasts the cost-minimization logic mentioned in Section 3. We prove in Appendix C that given any capacity, the dam with the conservation technology can generate more benefit than that with the existing

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technology does. Along the cost-minimization logic and with the target benefit level being the benefit of the dam with the existing technology, the best decision of dam capacity would then be unambiguously smaller than the initial dam capacity with the existing technology. The social optimal dam capacity with the conservation technology, however, would depend on the critical capacity level $\hat{w}$, and is larger than the initial dam capacity when the initial optimal dam capacity is small.

4.3 Impacts of potential adoption of conservation technologies on optimal dam capacities

Proposition 6 assumes that adopting conservation technologies is given. An even more interesting situation is where the water users can choose whether to adopt the conservation technology at the fixed cost after the social planner has decided the dam capacity. In other words, the dam designer should recognize that her capacity decision will affect water users' adoption decision, and then affect the benefit of the dam. What is the impact of the potential adoption on the dam capacity problem?[16]

First we formalize the situation by the following Assumption.

Assumption 9 (Potential adoption of conservation technologies). *$A(\hat{w}) > c_2$, and the social planner acknowledges the potential costly adoption of the conservation technology.*

Assumption 9 means first, that there exists a range of capacities that can induce adoption of the conservation technology, and second, that the dam designer is a von Stackelberg leader and the representative water user is the follower. Similar problems have been seen in Zhao and Zilberman (2001), for example, in a case about resource restoration. Different to their focus on the option value and optimal timing of resource development, the von Stackelberg setting of our analysis, as we shall show now, makes the potential adoption create a discontinuous marginal benefit of dam capacities.

Recall that the marginal benefit of dam capacities is

$$\frac{1}{1-\rho}\left(1 - F(\bar{w})\right) B'(\bar{w}) + \frac{1}{1-\rho} \int_{\bar{w}}^{\infty} L'(e - \bar{w}) f(e) de. \tag{13}$$

Therefore, when the dam capacity does or doesn't lie in the range that induces the adoption, the marginal benefit of dam capacities is calculated with different marginal water release

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[16]The question can be generalized into a classic economic question about the interaction between a regulator and the regulated. For example, Amacher and Malik (2002) analyze the properties of a pollution tax when the regulated firms chooses abatement technologies. For more detail about the literature, see Amacher and Malik (2002)'s references.

benefit functions. The marginal benefit should then experience discontinuity when the dam capacity moves into or out of the range. Mathematically, under Assumptions 1, 2, 3, 4, 5, 6, 7, 8, and 9, the marginal benefit of dam capacities turns out to be

$$\frac{1}{1-\rho}\left(1-F(\bar{w})\right)B^{1\prime}(\bar{w}) + \frac{1}{1-\rho}\int_{\bar{w}}^{\infty}L'(e-\bar{w})f(e)de, \text{ if } \bar{w} \leq w^s \text{ or } \bar{w} \geq w^l;$$

$$\frac{1}{1-\rho}\left(1-F(\bar{w})\right)B^{2\prime}(\bar{w}) + \frac{1}{1-\rho}\int_{\bar{w}}^{\infty}L'(e-\bar{w})f(e)de, \text{ if } w^s < \bar{w} < w^l. \quad (14)$$

The discontinuity suggests multiple intersections between the marginal benefit of dam capacities and the marginal cost, and therefore multiple solutions to Equation (5), the first-order condition. This observation is documented by the following Proposition.

Proposition 7 (Multiple solutions with potential adoption of conservation technologies).
Under Assumptions 1, 2, 3, 4, 5, 6, 7, 8, and 9, it is possible to have multiple solutions to Equation 5, the first-order condition of the capacity determination problem.

Figure 8 illustrates Proposition 7. In the Figure, the marginal benefit of dam capacities is shown by the solid lines, and it is clear that the marginal benefit experiences discontinuity at the boundaries of the range that induces adoption, w^s and w^l. We circled all intersections in all possible cases of the marginal cost function. The two interesting cases that induces multiple intersections are also circled by dotted lines. We address them in the following two Cases, respectively.

Case 1 Figure 9 illustrates this case. In this case, there are two intersections, $\bar{w}^{*2}$ and $\bar{w}^{*1}$, corresponding to adopting the conservation technology and not adopting it. Moreover, $\bar{w}^{*1} < w^s < \bar{w}^{*2} < \hat{w}$.

The social planner then faces the ultimate choice: a small dam with neither adoption nor the fixed cost, versus a not large dam with adoption and the fixed adoption cost. In Figure 9, the key to the choice is the comparison between the shadowed areas. To see this point, note 1) that without adoption, the increase in social welfare when the capacity moves from $\bar{w}^s$ to $\bar{w}^{*1}$ equals to the size of the lower shadowed area, 2) that with adoption, the increase in social welfare when the capacity moves from $\bar{w}^s$ to $\bar{w}^{*2}$ equals to the size of the higher shadowed area, and 3) that when the capacity is $\bar{w}^s$, the social welfare with adoption and that without adoption are the same.[17] Therefore, if the higher shadowed area is larger, then the capacity that induces adoption, $\bar{w}^{*2}$, implies higher social welfare than $\bar{w}^{*1}$ does. As the

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[17]To see the third point, note when the capacity is $\bar{w}^s$, the water release benefits including fixed costs of the technologies are the same.
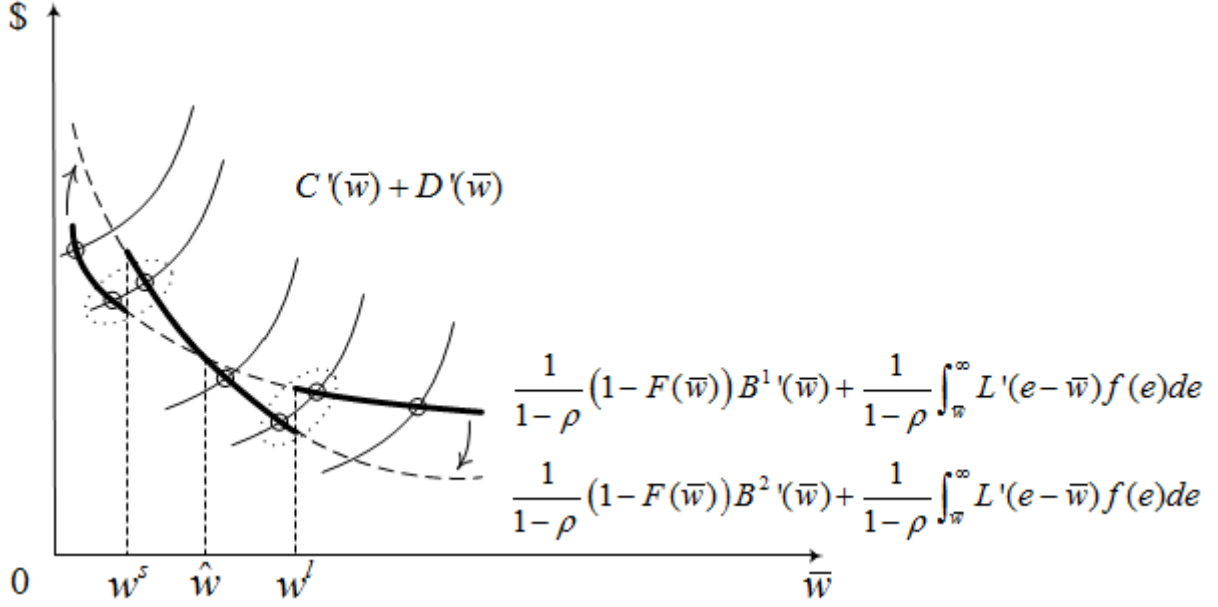
$$\frac{1}{1-\rho}\left(1-F(\overline{w})\right)B^{1\,\prime}(\overline{w})+\frac{1}{1-\rho}\int_{\overline{w}}^{\infty}L\,'(e-\overline{w})f(e)de$$

$$\frac{1}{1-\rho}\left(1-F(\overline{w})\right)B^{2\,\prime}(\overline{w})+\frac{1}{1-\rho}\int_{\overline{w}}^{\infty}L\,'(e-\overline{w})f(e)de$$

Figure 8: Impacts of potential adoption of conservation technologies on optimal dam capacities

$$\frac{1}{1-\rho}\left(1-F(\overline{w})\right)B^{1\,\prime}(\overline{w})+\frac{1}{1-\rho}\int_{\overline{w}}^{\infty}L\,'(e-\overline{w})f(e)de$$

$$\frac{1}{1-\rho}\left(1-F(\overline{w})\right)B^{2\,\prime}(\overline{w})+\frac{1}{1-\rho}\int_{\overline{w}}^{\infty}L\,'(e-\overline{w})f(e)de$$
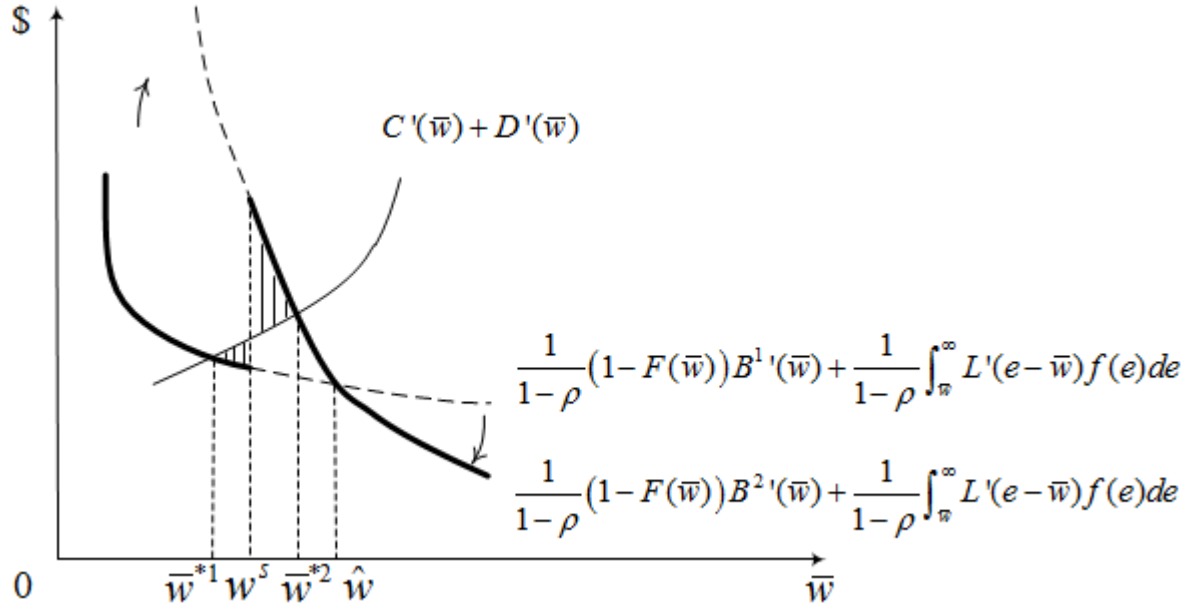
Figure 9: Impacts of potential adoption of conservation technologies on optimal dam capacities: Multiple intersections when dams are small

comparison depends on the steepness of the marginal cost of dam capacities, we have the following Corollary.

Corollary 1. *In Case 1, under Assumptions 1, 2, 3, 4, 5, 6, 7, 8, and 9, if the marginal cost of dam capacities is increasing slowly, then the optimal dam capacity induces adoption.*

Mathematically and more precisely, if $C''(\cdot) + D''(\cdot)$ is small, then $\bar{w}^* = \bar{w}^{*2}$.

Case 2   Figure 10 illustrates this case. In this case, there are two intersections, $\bar{w}^{*2}$ and $\bar{w}^{*1}$, corresponding to adopting the conservation technology and not adopting it. Moreover, $\hat{w} < \bar{w}^{*2} < w^l < \bar{w}^{*1}$.
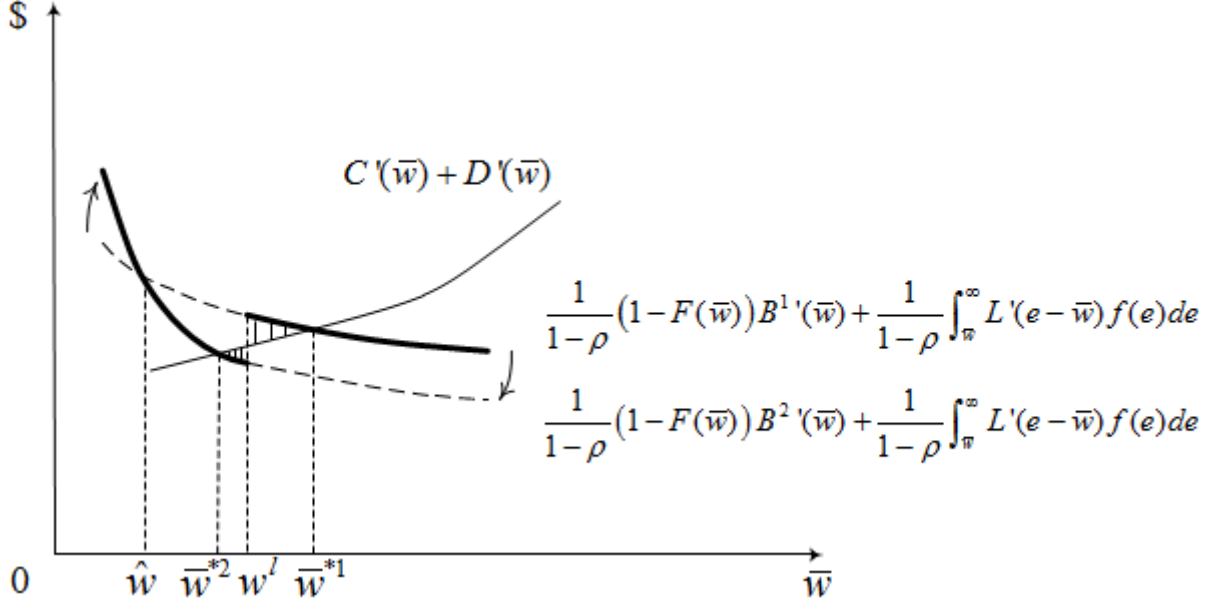

Figure 10:   Impacts of potential adoption of conservation technologies on optimal dam capacities: Multiple intersections when dams are large

The social planner then face the ultimate choice: a large dam with adoption and the fixed cost, versus a not small dam with neither adoption nor the fixed cost. Along a similar logic to that in Case 1, we have the following Corollary.

Corollary 2. *In Case 2, under Assumptions 1, 2, 3, 4, 5, 6, 7, 8, and 9, if the marginal cost of the dam capacity is increasing fast and the existing technology is very weak with abundant water, then the optimal dam capacity induces adoption. Mathematically and more precisely, if $C''(\cdot) + D''(\cdot)$ is large, then $\bar{w}^* = \bar{w}^{*2}$.*

Case 2 also sheds some new light on the logic of oversized water projects. Schoengold and Zilberman (2007) show that oversized water projects could be resulted from the distortion in the marginal dam cost. Our analysis suggests that they could also be induced by the dam designer's overlooking of the potential future adoption of conservation technologies.

Compared with our analysis in the former Subsection, the two Cases imply that the impacts of potential adoption on optimal dam capacities are more complicated than the case

with given adoption. This complication asks for serious empirical analysis about the impact of conservation technologies on the marginal water release benefit, since the analysis would help to identify the critical capacity levels, w^s and w^l, and whether the marginal cost of dam capacities is steep enough.

5   Conclusion

This paper develops a stylized model for the determination of optimal dam capacities, and analyzes how it varies under plausible scenarios. Comparative static analysis of the models shows the impact of water management efficiency, overflow losses, and climate change on optimal water project capacities: integrated water reforms, emphasis on food security, and warming-caused inflow abundance could make larger water projects desirable. This paper also systematically analyzes the non-monotonic relation between dam capacities and conservation technologies, probably as the first attempt in literature: too small or too large water projects could discourage conservation technology adoption, adoption suggests smaller projects if and only if the projects are already large, and one reason for oversized water projects could be the designer's overlooking of the future potential adoption of conservation technologies.

The model and analysis in this paper can be extended to several nontrivial directions. For example, further effort can assume water users heterogenous, and model a non-monotonic impact of dam capacities on the percentage of adoption in a population of water users. A water distribution system can be added, and it is natural to expect that only the water users neither too close to nor too far away from the water source would adopt conservation technologies. Results that are parallel to the Propositions can be derived if we incorporate optimal water-inventory control, as we are doing in Xie and Zilberman (2014). Moreover, this paper asks for more serious empirical tests on the derived analytical results.

To conclude, our paper provides a new analytical framework, suggesting that the design of water projects is not divorced from the efficiency of water use downstream, and that the changes in the institutional, environmental, and technological conditions could significantly modify the optimal scale of water projects. The issue is not how large is a water project but how valuable are the water economic and environmental services that the project provides. The framework can serve as a starting point for investigation in future research, on the economics and policy implications about the design and improvements of water systems.

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A   Appendix: Cheaper cost, larger dams

Innovation in construction and maintenance cost efficiency or decrease in the marginal environmental damage can also affect optimal dam capacities.

Proposition 8 (Cheaper or more environmentally-friendly dam-building technologies encourages larger dams). *Under Assumptions 1, 2, 3, 4, 5, and 6, if improvement in dam construction and maintenance cost efficiency shifts down the marginal construction and maintenance cost of dam capacities, or more environmentally-friendly dam building technologies shifts down the marginal environmental damage cost of dam capacities, then the optimal dam capacity becomes larger. Mathematically, consider two functions of the construction and maintenance cost of dam capacities, $C^1(\cdot)$ and $C^2(\cdot)$, two functions of the environmental damage cost of dam capacities, $D^1(\cdot)$ and $D^2(\cdot)$, and the two corresponding optimal dam capacities, $\bar{w}^{*1}$ and $\bar{w}^{*2}$. If $C^{2'}(\cdot) \leq C^{1'}(\cdot)$ or $D^{2'}(\cdot) \leq D^{1'}(\cdot)$, then $\bar{w}^{*2} \geq \bar{w}^{*1}$.*

B   Appendix: Justification of Assumption 7

Assumption 7 reads:

> There exists $\hat{w}$ so that $B^{2'}(w) > B^{1'}(w)$ when $w < \hat{w}$, $B^{2'}(w) = B^{1'}(w)$ when $w = \hat{w}$, and $B^{2'}(w) < B^{1'}(w)$ when $w > \hat{w}$.

To justify this Assumption, consider an effective water benefit function $\mathcal{B}(\mathcal{W})$, where $\mathcal{W}$ is the effective water. Assume $\mathcal{B}(\cdot)$ is smooth, $-\infty < \mathcal{B}(\infty) < \infty$, $0 < \mathcal{B}'(0) < \infty$, $\mathcal{B}''(\cdot) < 0$, and $\mathcal{B}'''(\cdot)$

is not large so that $\mathcal{B}'''(x) < -2\mathcal{B}''(x)/x$ for $x \in (0, \infty)$. A technology is assumed to use α of water release w effectively.

The water release benefit function is then $B(w, \alpha) \equiv \mathcal{B}(\alpha w)$. The marginal benefit of water release is then $\frac{\partial B(w,\alpha)}{\partial w} \equiv \alpha \mathcal{B}'(\alpha w)$. Now consider the impact of α on $\frac{\partial B(w,\alpha)}{\partial w}$. The partial derivative of $\frac{\partial B(w,\alpha)}{\partial w}$ with respect to α is

$$\frac{\partial^2 B(w,\alpha)}{\partial \alpha \partial w} = \mathcal{B}'(\alpha w) + \alpha w \mathcal{B}''(\alpha w). \tag{15}$$

On the one hand, since $0 < \mathcal{B}'(0) < \infty$, $\frac{\partial^2 B(w,\alpha)}{\partial \alpha \partial w}|_{w=0} = \mathcal{B}'(0) \in (0, \infty)$. Since $\mathcal{B}(\cdot)$ is smooth, there must exist $\underline{w} > 0$ such that $\int_0^{\underline{w}} \frac{\partial^2 B(w,\alpha)}{\partial w \partial \alpha} dw > 0$.

On the other hand, since $B(\infty, \alpha) = \mathcal{B}(\infty) \in (-\infty, \infty)$,

$$\frac{\partial B(w, \alpha)}{\partial \alpha}\bigg|_{w=\infty} = 0,$$
$$\int_0^\infty \frac{\partial^2 B(w, \alpha)}{\partial w \partial \alpha} dw = 0, \tag{16}$$

Therefore, $\int_{\underline{w}}^\infty \frac{\partial^2 B(w,\alpha)}{\partial w \partial \alpha} dw < 0$, which means there must exist $\bar{w} > 0$ such that $\frac{\partial^2 B(w,\alpha)}{\partial w \partial \alpha}|_{w=\bar{w}} < 0$.

As $\frac{\partial^2 B(w,\alpha)}{\partial \alpha \partial w}|_{w=0} = \mathcal{B}'(0) > 0$, $\frac{\partial^2 B(w,\alpha)}{\partial w \partial \alpha}|_{w=\bar{w}} < 0$, and $\frac{\partial^2 B(w,\alpha)}{\partial w \partial \alpha}$ is continuous, there must exist $\hat{w}$ such that $\frac{\partial^2 B(w,\alpha)}{\partial w \partial \alpha}|_{w=\hat{w}} = 0$.

The partial derivative of $\frac{\partial^2 B(w,\alpha)}{\partial w \partial \alpha}$ with respect to w is

$$\frac{\partial^3 B(w,\alpha)}{\partial w^2 \partial \alpha} = 2\alpha \mathcal{B}''(\alpha w) + \alpha^2 w \mathcal{B}'''(\alpha w). \tag{17}$$

Since $\mathcal{B}'''(x) < -2\mathcal{B}''(x)/x$, $\frac{\partial^3 B(w,\alpha)}{\partial w^2 \partial \alpha} < 0$, which means $\frac{\partial^2 B(w,\alpha)}{\partial w \partial \alpha}$ is decreasing in w. Therefore, the impact of α on $\frac{\partial B(w,\alpha)}{\partial w}$ is

$$\frac{\partial^2 B(w, \alpha)}{\partial \alpha \partial w} > 0, \text{ if } 0 < w < \hat{w};$$
$$\frac{\partial^2 B(w, \alpha)}{\partial \alpha \partial w} = 0, \text{ if } w = \hat{w};$$
$$\frac{\partial^2 B(w, \alpha)}{\partial \alpha \partial w} < 0, \text{ if } w > \hat{w}. \tag{18}$$

There are two technologies: the existing one can use α_1 of water release w effectively, and the newly available conservation technology can use α_2 of water release w effectively, where $\alpha_2 > \alpha_1$. The corresponding water release benefit functions are respectively $B^1(w) \equiv \mathcal{B}(\alpha_1 w)$ and $B^2(w) \equiv \mathcal{B}(\alpha_2 w)$. Assumption 7 then follows the impact of α on $\frac{\partial B(w,\alpha)}{\partial w}$.

C   Appendix: Dams are more valuable with the conservation technology than those with the existing technology

Following the analysis in Appendix B, the dam with the conservation technology always generates more benefit than the dam of the same capacity but with the existing technology. To see this point, note the dam of capacity $\bar{w}$ can generate the benefit of

$$
\int_0^{\bar{w}} \frac{1}{1-\rho}(1 - F(x))\alpha\mathcal{B}'(\alpha x)dx
$$
$$
= \int_0^{\bar{w}} \frac{1}{1-\rho}(1 - F(x))\mathcal{B}'(\alpha x)d(\alpha x)
$$
$$
= \int_0^{\bar{w}} \frac{1}{1-\rho}(1 - F(x))d\mathcal{B}(\alpha x)
$$
$$
= \frac{1}{1-\rho}\left[(1 - F(\bar{w}))\mathcal{B}(\alpha\bar{w}) - \int_0^{\bar{w}} \mathcal{B}(\alpha x)d(1 - F(x))\right]
$$
$$
= \frac{1}{1-\rho}\left[(1 - F(\bar{w}))\mathcal{B}(\alpha\bar{w}) + \int_0^{\bar{w}} \mathcal{B}(\alpha x)dF(x)\right]. \tag{19}
$$

Assume $\mathcal{B}'(\cdot) \geq 0$ for all $x \geq 0$. The benefit is then increasing in α, which means given any capacity, dams are more valuable with the conservation technology than those with the existing technology.

D   Appendix: The marginal water release benefit is shifted up by the transition from water rights to water markets

Assume the water release w is supplied to an agricultural area by an utility with a supply cost function $SC(w)$, which satisfies $SC(0) > 0$, $SC'(\cdot) > 0$, and $SC''(\cdot) > 0$. Assume that before the transition from water rights to water markets, the irrigation demand or marginal benefit of water use in agriculture is $AB_1'(w)$, and the water is priced as the average supply cost, $\frac{SC(w)}{w}$. Assume that after the transition, the irrigation demand is $AB_2'(w)$, and the water is priced as the marginal supply cost, $SC'(w)$. Assume $AB_i'(\cdot) > 0$ and $AB_i''(\cdot) < 0$, where $i = 1, 2$.

It is easy to calculate the marginal water release benefit $B^{i'}(w)$ as $AB_i'(w) - SC'(w) + NAB'(w)$, where $i = 1, 2$, and $NAB'(w)$ is the marginal water release benefit not from irrigation, guaranteeing nonnegative $B^{i'}(\cdot)$, which is required by Assumption 2.

The transition includes the high willingness-to-pay of the highly efficient individuals for additional water into the marginal water-use benefit, so $AB_2'(\cdot) > AB_1'(\cdot)$.

The transition also has water priced by the marginal cost instead of the average cost. For example, we assume that the water release w will be supplied if and only if it isn't larger than the equilibrium quantity, which is determined by the irrigation demand and the pricing scheme. We

have then

$$B^{1'}(w) = \left(AB_1{}'(\min\{w, w_1^*\}) - SC'(\min\{w, w_1^*\})\right) I_{w \leq w_1^*}(w) + NAB'(w),$$
$$\text{where } w_1^* \text{ solves } AB_1{}'(w) - \frac{SC(w)}{w} = 0;$$
$$B^{2'}(w) = \left(AB_2{}'(\min\{w, w_2^*\}) - SC'(\min\{w, w_2^*\})\right) I_{w \leq w_2^*}(w) + NAB'(w),$$
$$\text{where } w_2^* \text{ solves } AB_2{}'(w) - SC'(w) = 0. \tag{20}$$

Now assume $w_1^* > \hat{w}_1$, where $\hat{w}_1$ solves $SC'(w) - \frac{SC(w)}{w} = 0$. Since $AB_2{}'(\cdot) > AB_1{}'(\cdot)$, $w_2^* > \hat{w}_1$. We can then discuss two cases. First, when $w \leq \hat{w}_1 < w_2^*$, $B^{2'}(w) = AB_2{}'(\min\{w, w_2^*\}) - SC'(\min\{w, w_2^*\}) + NAB'(w) > AB_1{}'(\min\{w, w_1^*\}) - SC'(\min\{w, w_1^*\}) + NAB'(w) = B^{1'}(w)$. Second, when $w > \hat{w}_1$, $B^{2'}(w) \geq NAB'(w) \geq B^{1'}(w)$.

To conclude, $B^{2'}(\cdot) \geq B^{1'}(\cdot)$, which means the marginal water release benefit is shifted up by the transition from water rights to water markets.

E Appendix: The marginal water release benefit is shifted up by weakening the market power of monopsonies in water generation markets

Consider the case in which all of the water release from our dam is conveyed into the distribution system if and only if it isn't lager than the equilibrium quantity in the water generation market. Denote the derived demand of marginal benefit of conveyed water as $DD(w)$, the marginal cost associated with transfer the water from the dam to the Association as $MC(w)$. The respective marginal water release benefits with the Association and within the social optimal, centralized distribution system are then

$$B^{1'}(w) = \left(DD\left(\min\{w, w_1^*\}\right) - MC\left(\min\{w, w_1^*\}\right)\right) I_{w \leq w_1^*}(w),$$
$$\text{where } w_1^* \text{ solves } DD(w) = MC'(w)w + MC(w);$$
$$B^{2'}(w) = \left(DD\left(\min\{w, w_1^*\}\right) - MC\left(\min\{w, w_1^*\}\right)\right) I_{w \leq w_2^*}(w),$$
$$\text{where } w_2^* \text{ solves } DD(w) = MC(w). \tag{21}$$

Assuming $MC'(\cdot) > 0$, $w_1^* < w_2^*$. Therefore, $B^{1'}(w) \leq B^{2'}(w)$, which means removing the market power of the private Water Users Association can shift the marginal water release benefit up.