Water Resources and Economics 13 (2016) 19–29

Contents lists available at ScienceDirect

Water Resources and Economics

journal homepage: www.elsevier.com/locate/wre

Theoretical implications of institutional, environmental, and technological changes for capacity choices of water projects

Yang Xie*, David Zilberman

Department of Agricultural and Resource Economics, University of California, Berkeley, CA, United States

ARTICLE INFO

Article history:
Received 8 December 2014
Received in revised form
8 June 2015
Accepted 25 August 2015

Keywords:
Dam
Water-transfer project
Rainwater harvesting
Water reform
Climate change
Irrigation-technology adoption

ABSTRACT

This paper constructs a model for determining the optimal capacities of water projects, including, but not limited to, diversion dams, flood-control dams, water-transfer projects, and rainwater-harvesting systems. The model helps us analyze the impacts of institutional, environmental, and technological changes on the capacity choices of water projects. The analysis identifies the conditions under which water reforms, flood damages, and climate change could lead to larger optimal water-project capacities. We also systematically analyze the relation between water-project capacities and water-conservation technologies (e.g., drip irrigation) and identify the conditions under which they are complements. The paper implies that the design of water projects should not be separated from the institutional, environmental, and technological conditions both upstream and downstream.

1. Introduction

Dams, reservoirs, canals, and other water projects play an important role in our life. Frequently, these projects have been motivated by political consideration and concerns have been raised about the efficiency of their design. The cost–benefit analysis method has since been introduced. However, one major critique of the method and its symbol, the *Principles and Guidelines* for assessment of water projects [94], is that they still overemphasize “hard” engineering solutions, ignoring the problem-solving capacities of “soft” management and institutional solutions in water management (e.g., [105,97]). Moreover, one of the keys to many water-policy debates, for example, the debate in response to the current lasting drought in California (e.g., [40]), is always that people predict improvements in water management to reduce the demand for water projects (e.g., [98]). In response to these considerations, this paper develops an analytical framework for the design of water projects, incorporating rising concerns about climate change and resource conservation, to investigate the implications of institutional, environmental, and technological changes on the capacity choices of water projects.

The framework is founded on a stylized model for the capacity choice of a dam with inflow uncertainty and flood damages being considered. Generally speaking, the primary purpose of real-world water projects is to divert water from the natural environment for human use. Some projects also have another purpose, which is to control water inventories over time. The dam in our model captures the first important purpose in the sense that it simply transfers water from wet seasons or water-abundant areas to dry seasons or water-scarce areas, and the dam capacity caps the amount of the water being gathered, transferred, and released. The model is then applicable to many categories of water projects, including, but not limited to, diversion dams, water-transfer projects, some flood-control dams that empty themselves in each water year, and some rainwater-harvesting systems in extremely arid areas where all gathered water in wet seasons is released in dry seasons. These projects are common and important in water-resource management for both developed and developing areas (e.g., [24,5,83,50,90,101]). For water projects that also control water inventories over time, the implications of our model will still be valid as long as the inventory-control consideration does not dominate the water-diversion consideration. For the wide applicability, we use two terms, “water project” and “dam,” interchangeably in this paper. In the most general sense, we can interpret the dam in our model as a water system and the dam capacity as the total artificial capacity of water catchment of the system.

The simplicity of our approach allows us to derive straightforward comparative-static results about the impact of water-release benefits, flood-damage estimates, and the inflow distribution on the capacity choices of water projects. We further extend the model to analyze the relation between water-project capacities and water-conservation technologies, e.g., drip irrigation and

---

* Correspondence to: 207 Giannini Hall, University of California, Berkeley, CA, United States. Fax: +1 5106438911.

E-mail addresses: phd.yang.xie@gmail.com (Y. Xie), zilber11@berkeley.edu (D. Zilberman).

http://dx.doi.org/10.1016/j.wre.2015.08.004

improved conveyance. We show that the relation is nonmonotonic and depends on the initial capacity. All of the theoretical results can provide implications for water-infrastructure policies in response to integrated water reforms, economic growth, food-security concerns, climate change, and water-conservation technologies.

The analysis in the paper is accompanied by graphical illustrations in which we specify our model to Seven Oaks Dam—one of the largest embankment dams in the United States. The consistency of the operation of the Dam with our model and the economic significance of the Dam, as shown in Appendix A, helps us to show the empirical relevance and practical significance of our theoretical results. We also provide some quantitative implications about policies in this case.

We unfold the paper as follows: the rest of this section clarifies our contribution to the literature. Section 2 builds the simple model, and Section 3 analyzes the comparative statics. Section 4 extends the model and derives the results about water-conservation technologies. Section 5 discusses the implications of all results. Section 6 concludes.

Contribution to literature: There exists a rich economic literature on the capacity choices of water projects (e.g., [73,72,33,63,86,38,77,44,47]). The tractability of our model allows us to obtain analytical results about the comparative statics on capacity choices, which are rare in the literature on water-inventory management (e.g., [11,88,49,85]). Our comparative-static analysis adds to the literature with explicit results about impacts of the water-release benefit and flood damages. About the impact of climate change, different from the focus of literature on changes in the variation of water endowment (e.g., [38]), our result emphasizes shifts between inflow shortage and abundance, which directly test the catchment or provision capacity of water projects.

The relation between water-project capacities and water-conservation technologies, to our knowledge, has not been systematically analyzed in the literature. In one respect, we add capacities of large-scale, public water projects to the list of potential factors affecting adoption of irrigation and other water-conservation technologies (e.g., surveys by [17,84,77])[1]. This result also extends Caswell and Zilberman's [19] theoretical formulation of the nonmonotonic relation between resource abundance and conservation technologies, which is well recognized in the literature (e.g., surveys by [37,59]), to water-infrastructure investment. In another respect, our result about the impact of conservation-technology adoption on the capacity choices of water projects contributes to the literature on the Jevons [54] paradox in energy economics (e.g., surveys by [43,46]) and water economics (e.g., [65,96,27,66]) about improvement in resource-use efficiency increasing resource consumption by extending the analysis to the demand for water infrastructures and highlighting the importance of the initial stage in determining the paradox. Finally, our analysis about the potential adoption of water-conservation technologies provides an alternative explanation to Schoengold and Zilberman [77] for oversized water projects.

2. The simple model

Fig. 1 illustrates our simple model for the capacity choices of water projects. In each period t, water of stochastic amount e_t flows into a dam of a capacity, $\bar{w}$. We assume that, in each period, the dam cannot hold more inflow than its capacity and that it releases all of the held water of amount w_t into a distribution and allocation system.[2] As the economics of the distribution and allocation system (e.g., [21,20]) is not our main focus, we leave the functioning of the system out of the model and only denote the agricultural, industrial, environmental, and ecological benefits from the water release as $B_t(w_t)$. The dam also prevents flood damage, $L_t(\max\{e_t, \bar{w}\} - \bar{w})$.[3] We then summarize the function of the dam by the following assumption:

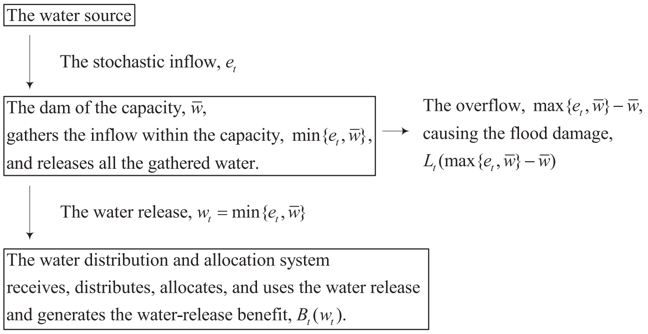

Fig. 1. A water system with a dam.

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

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

Assumption 2 (*Function properties*). The marginal water-release benefit is nonnegative and decreasing: $B_t'(\cdot) \geq 0$ and $B_t''(\cdot) < 0$. The flood damage is zero when there is no flood, it is nonnegative when there is a flood, and the marginal flood damage is nonnegative and weakly increasing: $L_t(0) = 0$, $L_t(\cdot) \geq 0$ elsewhere, $L_t'(\cdot) \geq 0$, and $L_t''(\cdot) \geq 0$. The marginal construction, maintenance, and environmental-damage costs are positive and increasing: $C'(\cdot) > 0$ and $C''(\cdot) > 0$.

The intuition behind Assumption 2 is as follows: first, the marginal benefit of water is much higher when it is scarce than when it is abundant, so the marginal water-release benefit is likely to be decreasing. Second, spillways of dams help to evacuate excessive water, so the marginal damage of spills contained within spillways is negligible. When inflows are beyond the designed capacity of spillways, floods could top dams, and the marginal flooding water would cause serious damages. Therefore, the flood damage should be generally convex and the marginal flood damage should be weakly increasing.[4] Third, resources for dam building and maintenance are always limited and larger dams make the ecological system more vulnerable to further human actions. Therefore, it is fair to assume an increasing marginal cost

---

[1] A concurrent work by Bhaduri and Manna analyzes the impact of private water storage with a proportional storing rule on the adoption of efficient irrigation technology (Bhaduri and Manna, [6]).

[2] Hydropower dams rarely release completely and a certain level of water inventories is always kept. Given this consideration, we can interpret the inflows and releases in the model as the part of inflows and releases net of this certain level of water inventories.

[3] For simplicity, we do not model each of the elements of the benefit and the damage in detail, which could be a direction for future research.

[4] Note that, in cases of flood-recession agriculture, floods can increase agricultural production (e.g., [64,39]). Our flood-damage function can be considered to be net of this kind of benefit. Also, as noted by the literature (e.g., surveys by [82,62,61]), many factors determine flood damages, including, but not limited to, duration, frequency, and intensity of floods. Consistent with the literature, however, our simple characterization of flood damages still represents one of the key factors in the determination—the total volume of flooding water—because, given the size of flooded areas, flood damages are increasing in flood depth and, given flood depth, larger flooded areas mean more economic loss.

of dam capacities.

To formalize the dam-capacity problem, we assume:

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 flood damage, net of the construction, maintenance, and environmental cost of the dam. The discount rate is $r > 0$. The discount factor is $\rho \equiv \frac{1}{1+r} \in (0, 1)$.

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

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

where an infinite planning horizon is assumed for analytical simplicity, instead of a horizon of 50–100 years, which is more realistic for dams, as recognized by Reilly [69].

For technical simplicity, we propose two more assumptions:

Assumption 4 (*Stationary water-release benefits and flood damage*). The water-release benefit is the same across time: $B_t(\cdot) = B(\cdot)$ for any t. The flood-damage 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 $F'(\cdot) = f(\cdot)$.

The two assumptions suggest that we ignore the trends in the water-release benefit, flood damage, and inflow, which are not the focus of this paper. They turn the dam-capacity problem into

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

which is equivalent to

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

The first term of the objective function is the discounted expected sum of water-release benefits, and the second term is the negative discounted expected sum of flood damage. The two terms form the benefit of the dam. The third term is 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 flood damage with respect to dam capacities are

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

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

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

The left-hand side of the condition is the marginal benefit of dam capacities, which depends on the water-release benefit, the flood-damage 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 solution of the first-order condition, $\bar{w}^*$, helps the objective function reach its maximum but not minimum.

As the cases with solutions of zero or infinite capacities add little intuition to our further analysis, we rule them out by the following assumption.[5]

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

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

All of the assumptions and the analysis suggest that the optimal dam capacity, $\bar{w}^*$, makes the marginal benefit of dam capacities equal to the marginal cost. Mathematically, $\bar{w}^*$ solves Eq (5). Graphically, $\bar{w}^*$ makes the decreasing marginal benefit, $\frac{1}{1-\rho}(1 - F(\bar{w}))B'(\bar{w}) + \frac{1}{1-\rho}\int_{\bar{w}}^{\infty} L'(e - \bar{w})f(e)\,de$, intersect with the increasing marginal cost, $C'(\bar{w})$.

3. Comparative-static analysis

Proposition 1 (*Impacts of the water-release benefit, flood damage, and inflow distribution*). *Under* Assumptions 1–6, (1) *an increase in the marginal water-release benefit*, (2) *an increase in the marginal flood damage, and* (3) *a first-order stochastically dominating shift in the inflow distribution will increase the optimal dam capacity*.

The derivation of the results is straightforward with some algebra of integration by parts. The intuition of the proposition deserves a little discussion. Recall that an additional unit of dam capacities captures one more unit of inflows when the dam reaches the initial full capacity. An increase in the marginal water-release benefit, therefore, will increase the benefit that would be generated by the additional unit of captured inflows. An increase in the marginal flood damage will increase the loss that would be avoided by the additional decrease of overflows. A first-order stochastically dominating shift in the inflow distribution will increase the probability that the dam reaches its full capacity and the loss that would be avoided by the additional decrease of overflows. All of these impacts will increase the marginal benefit of dam capacities and lead to larger optimal-capacity choices.

While one might literally expect that if the benefit from water release is improved, we would demand smaller water supply and dam capacities. This logic is found in some engineering literature, where dam designers are minimizing the cost of dams to satisfy specific engineering and policy constraints (e.g., surveys by Yeh [100], Simonovic [81]). More precisely, assume that a water system with an initial catchment capacity generates a total benefit from water release. When the marginal water-release benefit becomes higher, the initial catchment capacity will generate a larger total benefit, so the minimum capacity that is needed to generate the former total benefit will be smaller than the initial capacity. In contrast, Proposition 1 shows that, for any given capacity, the *marginal* benefit of capacities increases, so the optimal adjustment on the water system should be increasing the catchment capacity, given the marginal cost of capacities. This comparison is similar to

---

[5] The solution for the first-order condition is the solution to the dam-capacity problem if and only if the solution is nonnegative. Otherwise, the model might have a corner solution, which is a capacity of zero. 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 solution. 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.

the finding in Chakravorty et al. [21], where the optimal water use is larger under an optimal distribution system than that under a suboptimal distribution system.

4. Extension and results about water-conservation technologies

In this section, we extend the simple model by incorporating water-conservation technologies. For example, drip irrigation applies water more precisely to crops than flood irrigation does so that water is more effectively consumed by plants (e.g., [19]). Adopting better conveyance technologies and fixing leaks in channels help to reduce the rate of evaporation and leakage loss in water release (e.g., [21]). All of these technologies improve the efficiency of water releases as an input in economic production. Our characterization of these technologies is formalized by the following assumption:

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

This widely used assumption (e.g., [19,3]) means that conservation technologies increase the marginal water-release benefit when water is scarce and decrease it when water is abundant. In other words, we assume that conservation technologies rotate clockwise the marginal water-release benefit (as illustrated in the top panel of Fig. 2). Assumption 7 is straightforward if we assume that (1) the water-release benefit equals a benefit function in effective water, where conservation technologies increase water-use efficiency—the share of effective water in applied water (the water release in our model), (2) there are some biological or resource constraints on the expansion of the water-use sector, e.g., when the irrigable land is limited, and (3) the decline of the marginal benefit of effective water does not get much slower as effective water increases. Caswell and Zilberman [19] argue that the assumption is consistent with the classic three-stage model of productivity in production theory and is more plausible in irrigation water use than are some other specifications of the effective-water benefit, e.g., the Cobb and Douglas [25] specification.[6]

Under Assumption 7, we focus on the interaction of water-conservation technologies with water-project capacities. More specifically, we investigate three questions: first, under what conditions about dam capacities would water users adopt a newly available conservation technology? Second, what is the impact of the adoption on optimal dam capacities? Third, what will happen if the dam designer recognizes that the capacity decision can affect water users' adoption decisions and then affect the benefit of the dam?

4.1. Impacts of water-project capacities on conservation-technology adoption

For the first question, we consider the technology-adoption decision of a representative water user, taking the capacity of an existing dam as given, and analyze how the given capacity will affect the technology-adoption decision. We assume that the representative potential adopter is rational.

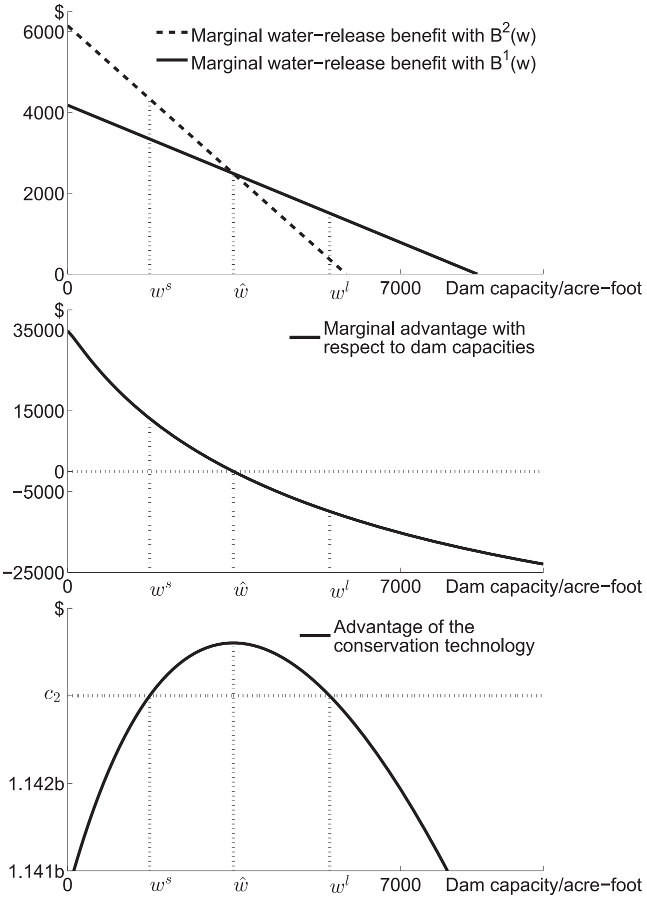

Fig. 2. The impact of dam capacities on conservation-technology adoption. Assume that a conservation technology will change the water-release benefit function from $B^1(w)$ to $B^2(w)$ with a cost of c_2. It will be adopted if and only if the dam capacity is moderate.

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

$$\max_{i\in\{1,2\}} \mathbf{E}_0\left[\sum_{s=0}^{\infty}\rho^s B_s^i(\min\{e_s,\bar{w}\})\right]-c_i, \tag{6}$$

which is equivalent to

$$\max_{i\in\{1,2\}} \frac{1}{1-\rho}\left[\int_{-\infty}^{\bar{w}} B^i(e)f(e)\,de+(1-F(\bar{w}))B^i(\bar{w})\right]-c_i, \tag{7}$$

and the water user will adopt the conservation technology ($i^* = 2$) if and only if

$$\frac{\int_{-\infty}^{\bar{w}}\Big(B^2(e)-B^1(e)\Big)f(e)\,de+(1-F(\bar{w}))\Big(B^2(\bar{w})-B^1(\bar{w})\Big)}{1-\rho} > c_2. \tag{8}$$

---

[6] Technically, the assumption is equivalent to having the elasticity of the marginal effective-water benefit with respect to effective water crossing one as effective water increases from zero. Also observe that, given any level of water use or water release, the water-conservation technology will always generate more benefit than the existing technology as long as the function of the benefit from effective water is weakly increasing. This observation explains that water users would rarely switch from efficient water-use technologies back to inefficient ones because doing so would not be beneficial.

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, we denote the left-hand side as $A(\bar{w})$, where A represents *advantage*. To investigate its shape, we calculate its derivative and have

$$A'(\bar{w}) = \frac{1}{1-\rho}(1 - F(\bar{w}))(B^{2\prime}(\bar{w}) - B^{1\prime}(\bar{w})), \tag{9}$$

which means

$$\begin{aligned} &A'(\bar{w}) > 0 \text{ and } A(\bar{w}) \quad \text{is increasing if } \bar{w} < \hat{w};\\ &A'(\bar{w}) = 0 \text{ and } A(\bar{w}) \quad \text{reaches its maximum if } \bar{w} = \hat{w};\\ &A'(\bar{w}) < 0 \text{ and } A(\bar{w}) \quad \text{is decreasing if } \bar{w} > \hat{w}. \end{aligned} \tag{10}$$

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 2 (*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 will not 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 $A(\hat{w}) \le c_2$, then, given any $\bar{w}$, the conservation technology will not be adopted.*

Fig. 2 illustrates the first statement in Proposition 2. The top panel shows that the conservation technology rotates clockwise the marginal water-release benefit 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 solutions 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 is not 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 will the conservation technology be sufficiently more beneficial than the existing technology to cover the fixed cost and it will then be adopted.

From the bottom panel of Fig. 2, it is also clear that $A(\bar{w})$ will not reach the horizontal line of height c_2 when c_2 is sufficiently large, which is about the second statement in Proposition 2.

4.2. *Impacts of conservation technologies on optimal water-project capacities*

For the second question, we consider the capacity-adjustment decision of a dam designer, taking the technology in water use as given, and analyze how conservation-technology adoption will affect the capacity-adjustment decision. Since conservation technologies change the water-release benefit, the following proposition answers the question by the similar comparative-static analysis in Proposition 1.

Proposition 3 (*Conservation technologies require smaller dams if and only if the dams are already large*). *Under* Assumptions 1–7, *if the initial optimal dam capacity is small, then adopting the conservation technology requires a larger optimal dam 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 $\hat{w} < \bar{w}^{*2} < \bar{w}^{*1}$.*

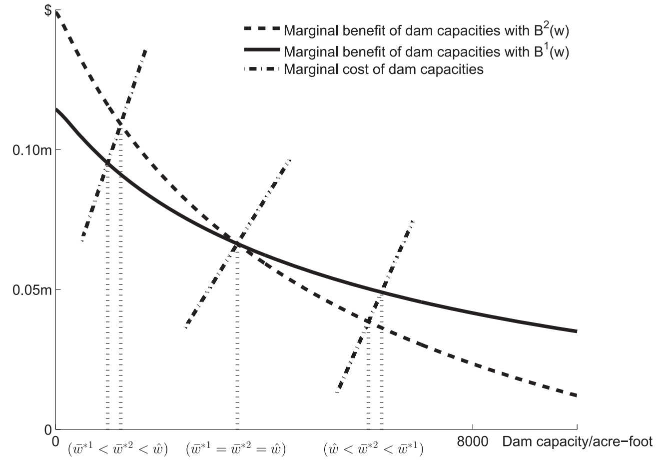

Fig. 3. The impact of conservation-technology adoption on the optimal dam capacity. Assume that a conservation technology will change the water-release benefit function from $B^1(w)$ to $B^2(w)$. Adopting the technology will rotate the marginal benefit of dam capacities clockwise, which induces a larger optimal dam capacity if and only if the optimal dam capacity given the existing technology is small.

Fig. 3 illustrates Proposition 3. Since adopting the conservation technology rotates clockwise the marginal water-release benefit, its impact on 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 1, the optimal dam capacity increases. If the initial dam capacity is large, then a similar, but opposite, logic holds.

Proposition 3 also contrasts the cost-minimization logic mentioned in Section 3. If more effective water always generates a larger benefit, it will be straightforward that, given any capacity, the dam with the conservation technology can generate more benefit than that with the existing technology. If the object is to attain the benefit of the dam with the existing technology at minimum cost, 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 water-project capacities*

For the third question about the impact of the potential adoption on the dam-capacity problem, we consider an even more interesting situation, where a social planner first decides the dam capacity. Then, the representative water user decides whether to adopt the conservation technology, so the social planner is aware of the potential adoption when the capacity decision is made.[7]

---

[7] The question can be generalized into a classic economic question about the interaction between a regulator and the regulated. For example, Amacher and Malik [1] analyze the properties of a pollution tax when the regulated firms choose

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 the adoption of the conservation technology and, second, that the dam designer is a von Stackelberg [95] leader and the representative water user is the follower. Similar problems have been seen in Zhao and Zilberman [103]—a case about resource restoration. Different from their focus on the option value and optimal timing of resource development, the von Stackelberg [95] 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

$$\frac{1}{1-\rho}(1-F(\bar{w}))B'(\bar{w})+\frac{1}{1-\rho}\int_{\bar{w}}^{\infty}L'(e-\bar{w})f(e)\,de. \tag{11}$$

Therefore, when the dam capacity does or does not lie in the range that induces the adoption, the marginal benefit of dam capacities is calculated with different marginal water-release benefits. The marginal benefit should then experience discontinuity when the dam capacity moves into or out of the range. Mathematically, under Assumptions 1–9, the marginal benefit of dam capacities becomes

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

if $\bar{w} \le w^s$ or $\bar{w} \ge w^l$;

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

if $w^s < \bar{w} < w^l$. (12)

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

Proposition 4 (*Multiple solutions with potential adoption of conservation technologies*). *Under Assumptions 1–9, it is possible to have multiple solutions to Eq. (5)—the first-order condition of the capacity-determination problem.*

Fig. 4 illustrates Proposition 4. 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. Two interesting scenarios that induce multiple intersections are with the second and the fourth marginal cost functions in the figure, respectively. We address them in the following two cases.

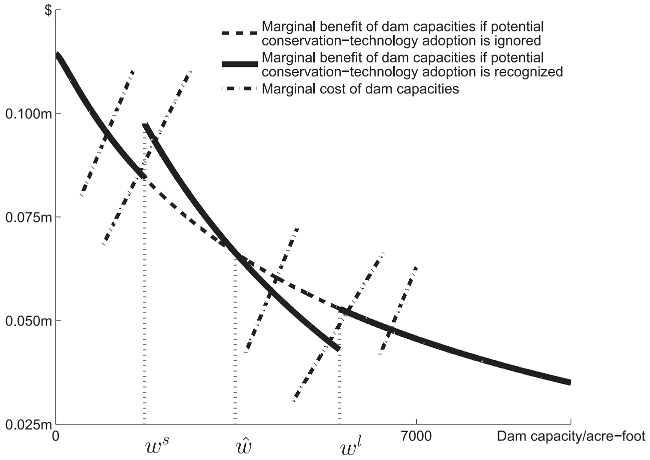

Fig. 4. The impact of potential conservation-technology adoption on the optimal dam capacity. Following Fig. 2, potential conservation-technology adoption could create multiple solutions to the first-order condition of the dam-capacity problem.

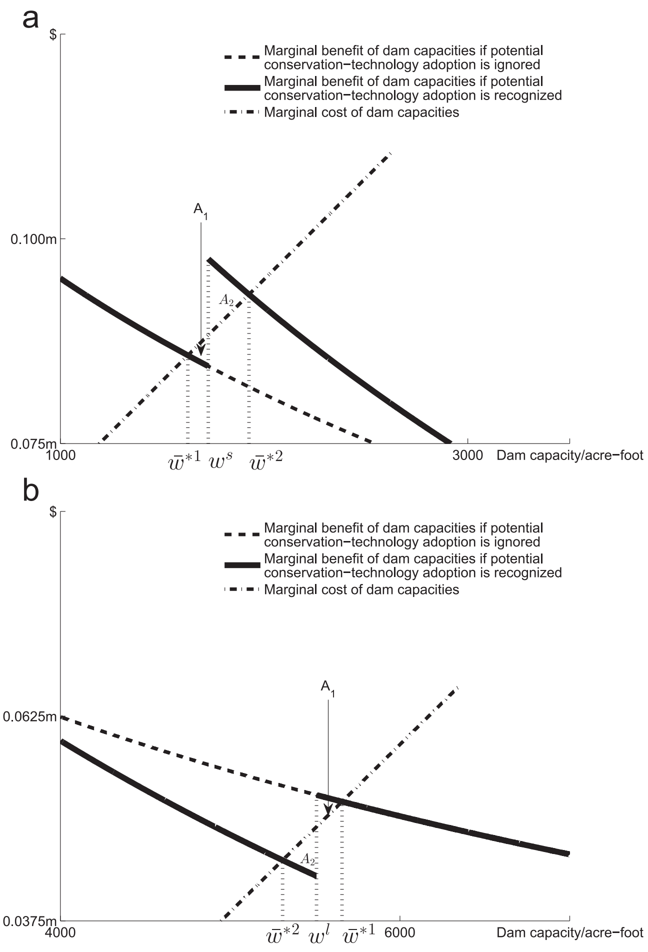

Fig. 5. Multiple intersections of the marginal benefit and the marginal cost of dam capacities. (a) Case 1: multiple intersections when dams are small. (b) Case 2: multiple intersections when dams are large. Following Fig. 4, the arbitrary marginal cost of dam capacities intersects the marginal benefit of dam capacities twice.

Case 1: Fig. 5(a) 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 moderate dam with adoption and the fixed adoption cost. In Fig. 5(a), the key to the choice is the comparison between areas A_1 and A_2. To see this point, note that (1) without adoption, the increase in social welfare when the capacity moves from $\bar{w}^s$ to $\bar{w}^{*1}$ is equal to the size of area A_1; (2) with adoption, the increase in social welfare when the capacity moves from $\bar{w}^s$ to $\bar{w}^{*2}$ is equal to the size of area A_2; and (3) when the capacity is $\bar{w}^s$, the social welfare with adoption and the social welfare without adoption are the same.[8] Therefore, if A_2

(*footnote continued*)
abatement technologies.

[8] To see the third point, note that when the capacity is $\bar{w}^s$, the water-release benefits, including fixed costs of the technologies, are the same.

is larger, then the capacity that induces adoption, $\bar{w}^{*2}$, implies higher social welfare than does $\bar{w}^{*1}$.

Case 2: Fig. 5(b) 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, $\hat{w} < \bar{w}^{*2} < w^l < \bar{w}^{*1}$. Along a similar logic to that in Case 1, if the size of A_2 is larger than that of A_1, then the capacity that induces adoption, $\bar{w}^{*2}$, should be the optimal capacity, which is smaller than the capacity without adoption, $\bar{w}^{*1}$.

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 in which adoption is given. This complication asks for serious empirical investigation about the impact of conservation technologies on the marginal water-release benefit since it would help to identify the critical capacity levels, w^s and w^l, and the relative size of A_1 and A_2.

5. Implications

All theoretical results can provide implications for capacity choices of water projects and adjustment of water systems under changes in the institutional, environmental, technological, and other conditions. We discuss the implications in this section.

5.1. Institutional changes

Many major reforms of water institutions could shift up or down the water demand and the marginal water-release benefit. Proposition 1 implies that these reforms will have a direct impact on the optimal adjustment of the total catchment capacity of a water system. One example is introducing water markets to a traditional institution of water rights (e.g., [10,41,48,21,31,8]; surveys by [34,74,106,23,87]). As argued by Zilberman and Schoengold [106], water markets incorporate the high willingness to pay for additional water by efficient individuals, who were formerly excluded because of junior or no water rights, into the marginal water-use benefit. The reform will then expand the water-release demand and, therefore, should lead to larger capacities of water projects. Particularly, in the numerical illustration of Seven Oaks Dam, calculation shows that a 5% increase in the marginal water-release benefit function will at most increase the optimal dam capacity from the existing, baseline capacity by approximately 0.6%.[9]

Another much-discussed institutional reform is about water pricing and removing subsidies from irrigation water use (e.g., surveys by [55,89,106]). Removing the subsidies could contract the irrigation demand for water and, therefore, lead to smaller optimal water-project capacities. Compared with the discussion above, interestingly, water-pricing and water-market reforms, both of which are usually considered to encourage conservation effort and conservation-technology adoption (e.g., [30]), will have different implications on the environment: Water-market reforms could cause more damages through water-project expansions while water-pricing reforms are more environment friendly in this sense.

Some other policies affecting the institution, or industrial organization, of water distribution can also alter the marginal water-release benefit and, therefore, change capacity choices of water projects. For example, Chakravorty et al. [20] show that the market power of the private Water Users Associations in the western United States could make the water conveyed into the distribution system smaller than the social optimal level. Following this idea, when the water release from a water project caps the maximum amount of water that is conveyed into the distribution system by the water-generation market, removing the market power of the Associations can weakly increase water application and then shift up the marginal water-release benefit. As another example, Chakravorty et al. [21] argue and numerically confirm that, in regions with water scarcity, centralizing conveyance investments—fixing leaks, reducing evaporation, and other maintenance operations of aqueducts—will shift up the marginal water-release benefit. The reform is important because suboptimal investment in conveyance often arises, especially when "public maintenance budgets are generally spread thinly over too many projects."[10] By Proposition 1, the two examples of institutional reforms could encourage larger water-supply projects.

5.2. Environmental changes

Since the inflow distribution is largely determined by climate, Proposition 1 implies a straightforward, but important, impact of climate change on optimal dam capacities. For many large-scale water-transfer programs, climate change could have serious impacts on the abundance of their inflows. For example, Schwabe and Connor [78] mention that global warming could reduce the natural storage capacity of the Sierra Nevada snowpacks. This impact could make precipitation increasingly fall as rain that will flow into Antelope Lake, Frenchman Lake, Lake Davis, and Lake Oroville at the foot of the Sierra Nevada and, eventually, into the California State Water Project, which transfers water from Northern to Southern California. By Proposition 1, the impact could suggest a larger optimal water-transfer capacity. Particularly for Seven Oaks Dam, the United States Bureau of Reclamation [92] predicts that in the 2020s the December–March inflow will increase by 10% but decrease in the 2050s by 3% and in 2070s by 6%. In the numerical illustration, in the 2020s scenario, a 10% rightward shift in the inflow distribution will at most increase the baseline dam capacity by 1.9% while the 2050s and the 2070s scenarios would be the opposite: a 3% leftward shift in the inflow distribution will at most decrease the baseline dam capacity by 0.6%, and a 6% leftward shift will at most cause a decrease of 1.2%.

Other environmental changes, such as climate warming, could also profoundly change the evaporation or infiltration loss when water is stored from wet seasons for dry seasons (e.g., [104]). Since a decrease in the loss rate can be considered to be an increase in the proportion of the captured (and released) water that is effectively used, its impact will be similar to that of water-conservation technologies on the marginal water-release benefit. Conversely, by Proposition 3, the evaporation increase caused by climate warming will increase the total catchment capacity of a water system if and only if the existing capacity is large.[11]

5.3. Technological changes

Adopting water-conservation technologies and improving efficiency in water use have been considered as an integrated element in water-resource management and economic development (e.g., surveys by [36,67]). Propositions 2–4 generally imply that the relation between water-conservation technologies and water-project capacities crucially depends on the initial capacity: when the initial capacity is small, expanding the capacity will encourage water users to adopt a newly available conservation technology and the

---

[9] The upper bound of the impact is calculated with a constant marginal cost of dam capacities being assumed.

[10] More examples of the problem can be found in Repetto [71].

[11] We thank one of the anonymous reviewers for suggesting the discussion.

adoption will also demand an additional dam to be built or existing capacities to be renovated. When the initial capacity is large, the opposite will hold.

More specifically, Proposition 2 suggests that governments can encourage the adoption of water-conservation technologies by building larger dams or closing some water projects in addition to other policy options or potential factors in literature (e.g., [28,19,18,29,32,79,42,57,16,58,4,76]). To find the correct policy, governments should have good knowledge about the reason why people do not 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. In the numerical illustration of Seven Oaks Dam, an increase of the dam capacity will discourage adoption of efficient irrigation technologies, because the baseline dam capacity, 7624 acre-feet, is larger than the critical level of dam capacities, 4306 acre-feet.

In the most general sense, as our model represents the total capacity of a water system to catch water from nature for human use, Proposition 3 highlights that the stage of water-resource development is important in determining the implication of water-conservation technologies on water-infrastructure investment. In places, such as sub-Saharan Africa, where initial capacities are small (e.g., [56]), adopting efficient irrigation technologies could increase the demand for water supply and, therefore, demand more investment in water infrastructure when extra inflows are available and communities have access to new projects.[12] According to Xu [99], the phenomenon has already been seen in Xinjiang—a major area of irrigated agriculture in China. In places, such as Western Europe and South Asia, where water resources have been largely exploited by water infrastructures (e.g., [80,45]), improvements in conservation efficiency could lead to smaller catchment capacities. In the case of Seven Oaks Dam, if water-input efficiency in irrigation is increased from 0.68 by 5% to 0.71, calculation shows that the baseline dam capacity will at most decrease by 3.8%. This effect will be negative because the baseline dam capacity is sufficiently large.

As water-conservation technologies have important implications on the demand for water infrastructures, ignoring technological changes in designing water systems will result in suboptimal choices of water-project capacities. In Case 2 after Proposition 4, the dam designer's ignorance of the future availability of conservation technologies will divert the capacity choice from the optimal level to a larger level. This result shows that a distortion in the marginal benefit, or demand side, of dam capacities could explain oversized water projects, which adds to Schoengold and Zilberman [77]'s explanation from the marginal cost, or supply side, of dam capacities.

5.4. *Changes in other conditions*

Some other changes in the water system also have implications on capacity choices of water projects. For example, reallocating water release among different sectors can affect the marginal water-release benefit. In the age of rising energy prices, increasing water provision for hydropower could gain extra water-release benefits. Hydropower is cleaner than fossil fuels, so the gain could also occur in the environmental sector. Having more water available for environmental services may expand variability in the use of water release to prevent saltwater from intruding, protect endangered species, and therefore improve the quality of water and the environment. Following this idea, much literature recognizes that reallocating water use from agriculture to hydropower or environmental sectors could shift up the marginal water-release benefit (e.g., [22,68,75,85]). For example, in the case of the Murray–Darling Basin, Australia's significant agricultural area, Truong [85] 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 [68].” By Proposition 1, the upward shift in the marginal water-release benefit could lead to larger dams.[13]

It is also obvious that potential flood damages are partially determined by economic activities in the areas that would be flooded. More specifically, if floods can wipe out production in flooding areas, then, the larger the economy, the larger the (marginal) economic damage caused by floods. As the economy grows, the (marginal) flood damage will increase. Proposition 1 then suggests that larger capacities of water projects will be demanded. This logic is consistent with the idea (e.g., [70,102]) that water-infrastructure investment creates not only economic prosperity but also huge potential loss from flooding. Therefore, it finally creates the demand for itself.[14] A similar logic about potential flood damages can apply to the increasing concern about food security. Floods might seriously interrupt agricultural production by flooding and waterlogging. If the loss is more of serious concern, especially in the age emphasizing food security, then larger capacities of water projects could be required. In the case of Seven Oaks Dam, a 1% increase in the function of the marginal flood damage will at most increase the optimal dam capacity from the existing capacity by approximately 1.32%.

6. Conclusion

Since the years of Jimmy Carter's Presidency (1977–1981), the attitude toward large-scale water projects in the United States has been gradually shifted in a negative direction. The lesson in Reisner's [70] *Cadillac Desert* about the overdevelopment of water resources in the American West has been well known, if not well learned. Reforming water institutions and adopting more efficient irrigation technologies are usually perceived as good substitutes for water-infrastructure investments across the globe. At the same time, the value of water projects has also been confirmed by ancient, modern, and contemporary history, especially when droughts and floods happen, and water-project expansions are considered to be an important approach to developing economy and adapting to climate change. Is the call for water-project expansions consistent with the demand for efficiency improvements in water-resource management?

This paper identifies the condition under which water reforms will optimally lead to water-project expansions. We also analyze

---

[12] We thank one of the anonymous reviewers for reminding us of these two conditions.

[13] Readers might want to focus more on the height of the dam rather than the capacity of the reservoir created by the dam. It would be helpful for our interpretation if readers note that the reservoir or dam capacity is closely correlated with the height of the dam. It is still true that reallocating water from irrigation to the environmental and energy sectors will affect the other aspects of the design of dams besides their capacities, though we focus only on capacity choices in this paper while holding other important issues in dam design constant (e.g., [53,7,52,51]).

[14] As reminded by one of the anonymous reviewers, it is also possible that richer countries can cope with floods with much better technology at a cheaper cost than less-developed countries. Therefore, less-developed countries might have a higher demand for flood control projects *given all the other conditions.*

the impact of flood-damage estimates and climate change on the optimal capacity of water projects. We then systematically analyze the nonmonotonic relation between water-project capacities and water-conservation technologies, implying that expanding water infrastructures and adopting water-conservation technologies are complements if and only if the existing artificial catchment capacities are small.

Although illustrated with the huge Seven Oaks Dam, implications of the paper are not limited to the design of large-scale, public water projects but also applicable to some small-scale, private water projects, e.g., the short-distance water-conveyance systems and the rainwater-harvesting systems in local communities, as mentioned above. These small-scale, private water projects are particularly crucial in conservation initiatives and rural development across developed and developing countries. For example, Hull [50] reports that rainwater-harvesting systems are currently emphasized in coping with the drought in the metropolitan Bay Area, California, and the United Nations Development Programme [90] has been supporting the building of microdams in the countryside of Tanzania.

All of the theoretical results in this paper assume away the impact of any institutional, environmental, or technological change on the optimal control of water inventories in water projects. This approach will not miss much as long as the change does not affect adjacent future years extremely differently and, therefore, does not radically change the optimal control. Further effort on modeling water-inventory management in capacity choices of water projects would still be helpful. Future research could also focus on the heterogeneity of water users in the relation between water-project capacities and conservation technologies. It would also be interesting to model the choice between building a large dam and constructing a dam system with several smaller dams. A more careful investigation on the role of specific reforms could help too. For example, transitions to water markets will unleash the water demand while removing subsidies from water and energy consumption could suppress the water demand. Different reforms will then provide different policy implications for water-infrastructure investments. After all, the design of water projects should not be separated from the institutional, environmental, and technological conditions both upstream and downstream.

Acknowledgments

We thank the editors, two anonymous reviewers, Kenneth Baerenklau, Bryce Contor, Ariel Dinar, John Loomis, Yacov Tsur, Nikolaos Zirogiannis, and participants in the 2014 Agricultural and Applied Economics Association Annual Meeting and the 11th Annual Meeting of the International Water Resource Economics Consortium for their valuable comments. We thank Angie Erickson for her help in editing. The expense of Yang Xie's attendance at the 2014 Agricultural and Applied Economics Association Annual Meeting was funded by the Giannini Foundation of Agricultural Economics.

Appendix A. Specification of the illustrations about Seven Oaks Dam

As reported by the United States Army Corps of Engineers [91], Seven Oaks Dam is “located 1-mile upstream of the mouth to the Upper Santa Ana Canyon” in Southern California, controlling “177 square miles of watershed.” It has been providing flood control for mainly Orange, Riverside, and San Bernardino Counties since 2000. The Corps [91] also reports that, in operation, the Dam puts the inflows during each flood season from November to February or March under control with scheduled, limited releases, benefiting the local community, and empties itself by the end of each September. According to the American Society of Civil Engineers [2], the Dam helps to avoid flood damages of more than $15 billion and “has resulted in the annual savings of millions of dollars in flood insurance premiums paid by property owners.”

The data of the inflows to the Dam for the water years (from October to September) from 1896–1897 to 2012–2013 are the daily mean discharges at the United States Geological Survey [93] Stream Site 11051500 on the Santa Ana River near Mentone, California, which have been used in the report on Seven Oaks Dam by the United States Army Corps of Engineers [91]. The logarithms of the annual November–March (flood season) inflows in acre-feet have a mean of 8.574768 and a standard deviation of 1.68557. We then specify the annual inflows as following $\ln N(8.574768, 1.68557^2)$. Fawcett [35] cites the Corps of Engineers that the Dam is to control a 100-year flood event, which corresponds to an inflow of 267,260 acre-feet.

The California Department of Water Resources [15] reports the monthly storage data of the Dam from 2005. We interpret the March storage as the amount of water that the Dam captures for human use from flood seasons. The mean of the 2005–2015 March storage is 7624 acre-feet, and we interpret it as the baseline dam capacity. Medellín-Azuara et al. [60] estimate that the agricultural water-demand elasticity is approximately 0.13 for the inland Southern California, which includes San Bernardino and Riverside Counties and other counties. According to the California Department of Water Resources [12], the 2000–2011 average equivalent unit charge for water supply for the San Bernardino Valley Municipal Water District by the California State Water Project is approximately $481 per acre-foot.

The Department [14] shows that in 2010 67.2% of the irrigated land in the Colorado River region (including San Bernardino and Riverside Counties and other counties) uses gravity irrigation, 11.2% uses sprinkler irrigation, and 20.1% uses low-volume irrigation. Brouwer et al. [9] suggest that the conservation efficiency of gravity or flood irrigation is approximately 0.6, sprinkler irrigation is approximately 0.75, and low-volume or drip irrigation is approximately 0.90. An easy, but crude, method to estimate the general conservation efficiency is to calculate the average of the conservation efficiencies among the three irrigation technologies, weighted by the acreage percentages. The calculation gives an estimate of 0.68. In figures, the water-conservation technology will increase the efficiency to 1.00.

If we assume that the water-release benefit derives a linear water-release demand that is 7624 acre-feet and has an elasticity of 0.13, given that the water price is $481 per acre-foot and that conservation efficiency is 0.68, then $B(w,\alpha) = 6149\cdot\alpha w - 0.525\cdot\alpha^2 w^2 + k_2$ and $B_1(w,\alpha) = 6149\alpha - 1.05\alpha^2 w$, where α is conservation efficiency and k_2 is an arbitrary constant.

With the baseline dam capacity, the amount of water that cannot be captured by the dam during a 100-year flood event is 267,260 −7,624=259,636 acre-feet. We assume that the flood damage starts to be positive from this point. The County of Orange Flood Division [26] estimates that “the most severe flood likely to occur” along the Santa Ana River “would cover more than 110,000 acres to a depth of three feet and would amount to more than %40 billion in economic losses.” If we assume the flood-damage function is quadratic and the loss is $40 billion when the flood is 330,000 acre-feet more than 259,636 acre-feet, then the flood-damage

Table A1
Specification of the case of Seven Oaks Dam.

Inflow in acre-feet	$e_t \sim \ln N(8.574768,\ 1.\ 68557^2),\ i.\ i.\ d.$
Discount factor	$\rho = 0.9434$
Water-release benefit in $	$B(w) = 6149 \cdot \alpha w - 0.525 \cdot \alpha^2 w^2 + k_2$
Flood damage in $	$L(x) = 0.3673 \max\{x - 259636,\ 0\}^2$
Baseline conservation efficiency	$\alpha = 0.68$
Improved conservation efficiency	$\alpha = 1.00$
Baseline dam capacity in acre-feet	$\bar{w} = 7624$

Based on the information from the California Department of Water Resources [12–15], Brouwer et al. [9], the United States Army Corps of Engineers [91], Fawcett [35], Medellín-Azuara et al. [60], the County of Orange Flood Division [26], and the United States Geological Survey [93]. Constant k_2 is arbitrary.

function is $L(x) = 0.3673 \max\{x - 259636,\ 0\}^2$, which induces $L'(x) = 0.7346 \max\{x - 259636,\ 0\}$ and $L''(x) = 0.7346 \cdot I_{x > 259636}$.

In water project evaluations, the annual discount rate recommended by the California Department of Water Resources [13] is 0.06. The corresponding discount factor is $(1 + 0.06)^{-1} = 0.9434$.

Table A1 summarizes the specification of the case of Seven Oaks Dam.

References

[1] G.S. Amacher, A.S. Malik, Pollution taxes when firms choose technologies, South. Econ. J. 68 (4) (2002) 891–906.

[2] American Society of Civil Engineers, People and Projects: Seven Oaks Dam, Accessible at ⟨http://www.asce.org/People-and-Projects/Projects/Seven-Oaks-Dam/⟩(accessed 23.10.14).

[3] N.E.Q. Ashwell, J.M. Peterson, The impact of irrigation capital subsidies on common-pool groundwater use and depletion: results for western Kansas, 11th Annual Meeting of the International Water Resource Economics Consortium, September 7–9, 2014. Washington, DC.

[4] K.A. Baerenklau, K.C. Knapp, Dynamics of agricultural technology adoption: age structure, reversibility, and uncertainty, Am. J. Agric. Econ. 89 (1) (2007) 190–201.

[5] J. Berkoff, China: The South–North Water Transfer Project—Is It Justified? Water Policy 5 (1) (2003) 1–28.

[6] A. Bhaduri, U. Manna, Impacts of water supply uncertainty and storage on efficient irrigation technology adoption, Nat. Resour. Model. 27 (1) (2014) 1–24.

[7] H.A. Bıçak, G.P. Jenkins, A. Özdemirağ, Water flow risks and stakeholder impacts on the choice of a dam site, Austral. J. Agric. Resour. Econ. 46 (2) (2002) 257–277.

[8] E. Brill, E. Hochman, D. Zilberman, Allocation and pricing at the water district level, Am. J. Agric. Econ. 79 (3) (1997) 952–963.

[9] C. Brouwer, K. Prins, M. Heibloem, Irrigation Water Management: Irrigation Scheduling: Annex I: Irrigation Efficiencies. Food and Agriculture Organization of the United Nations, Rome, 1989.

[10] H.S. Burness, J.P. Quirk, Appropriative water rights and the efficient allocation of resources, Am. Econ. Rev. 69 (1) (1979) 25–37.

[11] O.R. Burt, Optimal resource use over time with an application to ground water, Manag. Sci. 11 (1) (1964) 80–93.

[12] California Department of Water Resources, Bulletins 132-63–99 and 132-00–11: Management of the California State Water Project, Accessible at: ⟨http://www.water.ca.gov/swpao/bulletin_home.cfm⟩, 1963–2013 (accessed 21.11.14).

[13] California Department of Water Resources, California Department of Water Resources Economic Analysis Guidebook, Accessible at: ⟨http://www.water.ca.gov/economics/guidance.cfm⟩, 2008 (accessed 21.11.14).

[14] California Department of Water Resources, Irrigated Agricultural Acreage in California by Crop and by Irrigation Method in 1991, 2001, and 2010, Accessible at: ⟨http://www.water.ca.gov/landwateruse/surveys.cfm⟩, 2010 (accessed 21.11.14).

[15] California Department of Water Resources, California Data Change Center: Seven Oaks Dam (SVO), Accessible at: ⟨http://cdec.water.ca.gov/index.html⟩, 2015 (accessed 19.05.15).

[16] J.M. Carey, D. Zilberman, A model of investment under uncertainty: modern irrigation technology and emerging markets in water, Am. J. Agric. Econ. 84 (1) (2002) 171–183.

[17] M.F. Caswell, Irrigation technology adoption decisions: empirical evidence, in: A. Dinar, D. Zilberman (Eds.), The Economics and Management of Water and Drainage in Agriculture, Springer-Verlag, New York, 1991, pp. 295–312.

[18] M.F. Caswell, E. Lichtenberg, D. Zilberman, The effects of pricing policies on water conservation and drainage, Am. J. Agric. Econ. 72 (4) (1990) 883–890.

[19] M.F. Caswell, D. Zilberman, The effects of well depth and land quality on the choice of irrigation technology, Am. J. Agric. Econ. 68 (4) (1986) 798–811.

[20] U. Chakravorty, E. Hochman, C. Umetsu, D. Zilberman, Water allocation under distribution losses: comparing alternative institutions, J. Econ. Dyn. Control 33 (2) (2009) 463–476.

[21] U. Chakravorty, E. Hochman, D. Zilberman, A spatial model of optimal water conveyance, J. Environ. Econ. Manag. 29 (1) (1995) 25–41.

[22] B. Chatterjee, R.E. Howitt, R.J. Sexton, The optimal joint provision of water for irrigation and hydropower, J. Environ. Econ. Manag. 36 (3) (1998) 295–313.

[23] H. Chong, D. Sunding, Water markets and trading, Annu. Rev. Environ. Resour. 36 (2006) 239–264.

[24] I. Chung, O. Helweg, Modeling the California State Water Project, J. Water Resour. Plan. Manag. 111 (1) (1985) 82–97.

[25] C.W. Cobb, P.H. Douglas, A theory of production, Am. Econ. Rev. 18 (1928) 139–165.

[26] County of Orange Flood Division, Santa Ana River Project: Introduction, Accessible at: ⟨http://ocflood.com/sarp/⟩, 2014 (accessed 21.11.14).

[27] M. Dagnino, F.A. Ward, Economics of agricultural water conservation: empirical analysis and policy implications, Int. J. Water Resour. Dev. 28 (4) (2012) 577–600.

[28] P.A. David, Technical Choice Innovation and Economic Growth: Essays on American and British Experience in the Nineteenth Century, Cambridge University Press, London, 1975.

[29] A. Dinar, M.B. Campbell, D. Zilberman, Adoption of improved irrigation and drainage reduction technologies under limiting environmental conditions, Environ. Resour. Econ. 2 (4) (1992) 373–398.

[30] A. Dinar, J. Letey, Agricultural water marketing, allocative efficiency, and drainage reduction, J. Environ. Econ. Manag. 20 (3) (1991) 210–223.

[31] A. Dinar, Y. Tsur, Efficiency and Equity Considerations in Pricing and Allocating Irrigation Water, World Bank Policy Research Working Paper No. 1460, 1995.

[32] A. Dinar, D. Yaron, Adoption and abandonment of irrigation technologies, Agric. Econ. 6 (4) (1992) 315–332.

[33] N.J. Dudley, O.R. Burt, Stochastic reservoir management and system design for irrigation, Water Resources Research 9 (3) (1973) 507–522.

[34] K.W. Easter, M.W. Rosegrant, A. Dinar, Formal and informal markets for water: institutions, performance, and constraints, World Bank Res. Obs. 14 (1) (1999) 99–116.

[35] W.K. Fawcett, Seven Oaks Dam, Accessible at: ⟨http://www.redlandsfortnightly.org/papers/7oaksdam.htm⟩, 1999 (accessed 19.05.15).

[36] G. Feder, R.E. Just, D. Zilberman, Adoption of agricultural innovations in developing countries: a survey, Econ. Dev. Cult. Change 33 (2) (1985) 255–298.

[37] G. Feder, D.L. Umali, The adoption of agricultural innovations: a review, Technol. Forecast. Soc. Change 43 (3-4) (1993) 215–239.

[38] A.C. Fisher, S.J. Rubio, Adjusting to climate change: implications of increased variability and asymmetric adjustment costs for investment in water reserves, J. Environ. Econ. Manag. 34 (3) (1997) 207–227.

[39] J. Fox, J. Ledgerwood, Dry-season flood-recession rice in the Mekong Delta: two thousand years of sustainable agriculture?, Asian Perspect. 38 (1) (1999) 37–50.

[40] K. Freking, Congress Focuses on Dams Amid California's Drought, Associated Press, New York, March 23.

[41] M. Gisser, R.N. Johnson, Institutional restrictions on the transfer of water rights and the survival of an agency, in: T.L. Anderson (Ed.), Water Rights: Scarce Resource Allocation, Bureaucracy, and the Environment. Harper & Row Publishers, New York, 1984, pp. 137–161.

[42] G. Green, D. Sunding, D. Zilberman, D.D. Parker, Explaining irrigation technology choices: a microparameter approach, Am. J. Agric. Econ. 78 (4) (1996) 1064–1072.

[43] L.A. Greening, D.L. Greene, C. Difiglio, Energy efficiency and consumption—the rebound effect—a survey, Energy Policy 28 (6–7) (2000) 389–401.

[44] M.S. Haddad, Capacity choice and water management in hydroelectricity systems? Energy Econ. 33 (2) (2011) 168–177.

[45] A. Hasanain, S. Ahmad, M.Z. Mehmood, S. Majeed, G. Zinabou, Irrigation and Water Use Efficiency in South Asia, Global Development Network Working Paper Series No. 68, 2013.

[46] E.G. Hertwich, Consumption and the rebound effect: an industrial ecology perspective, J. Ind. Ecol. 9 (1–2) (2005) 85–98.

[47] H. Houba, K.-H. Pham-Do, X. Zhu, Capacity Choice of Dams Under Rivalry Use and Externalities, Tinbergen Institute Discussion Paper 2014-143/II, 2014.

[48] C.W. Howe, D.R. Schurmeier, W.D. Shaw Jr., Innovative approaches to water allocation: the potential for water markets, Water Resour. Res. 22 (4) (1986) 439–445.

[49] N. Hughes, T. Goesch, Management of Irrigation Water Storages: Carryover Rights and Capacity Sharing, Australian Bureau of Agricultural and Resource Economics Research Report, September 10, 2009.

[50] D. Hull, California drought: a run on rain barrels, San Jose Mercury News, February 6, 2014.

[51] Z. Hurwitz. Dam Standards: A Rights-Based Approach: A Guidebook for Civil Society, International Rivers, Berkeley, CA, 2014.

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

[53] International Union for Conservation of Nature, World Bank, Large Dams: Learning from the Past, Looking at the Future, World Bank, Washington, DC, 1997.

[54] W.S. Jevons, The Coal Question; An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal Mines, MacMillan & Co., London, 1865.

[55] R. Johansson, Pricing Irrigation Water: A Literature Survey, World Bank Policy Research Working Paper 2449, 2000.

[56] R. M. J. Kadigi, G. Tesfay, A. Bizoza, G. Zinabou, Irrigation and water use

efficiency in Sub-Saharan Africa, Global Development Network Working Paper Series No. 63. 2013.

[57] M. Khanna, D. Zilberman, Incentives, precision technology and environmental protection, Ecol. Econ. 23 (1) (1997) 25–43.

[58] P. Koundouri, C. Nauges, V. Tzouvelekas, Technology adoption under production uncertainty: theory and application to irrigation technology, Am. J. Agric. Econ. 88 (3) (2006) 657–670.

[59] E. Lichtenberg. Agriculture and the environment, in: Handbook of Agricultural Economics, vol. 2(A), 2002, pp. 1249–1313.

[60] J. Medellín-Azuara, J.A. Vergati, D.A. Sumner, R.E. Howitt, J.R. Lund, Analysis of Effects of Reduced Supply of Water on Agricultural Production and Irrigation Water Use in Southern California, University of California Agricultural Issues Center, Davis, California, 2012.

[61] B. Merz, H. Kreibich, R. Schwarze, A. Thieken, Assessment of economic flood damage, Nat. Hazards Earth Syst. Sci. 10 (8) (2010) 1697–1724.

[62] F. Messner, E. Penning-Rowsell, C. Green, V. Meyer, S. Tunstall, A. van der Veen, Evaluating flood damages: guidance and recommendations on principles and methods, in: Integrated Flood Risk Analysis and Management Methodologies Report T09-06-01, FLOODsite Project, 2007.

[63] D. Miltz, D.C. White, Sedimentation and the economics of selecting an optimum reservoir size, Water Resour. Res. 23 (8) (1987) 1443–1448.

[64] T.K. Park, Early trends toward class stratification: chaos, common property, and flood recession agriculture, Am. Anthropol. 94 (1) (1992) 90–117.

[65] J.M. Peterson, Y. Ding, Economic adjustments to groundwater depletion in the High Plains: do water-saving irrigation systems save water?, Am. J. Agric. Econ. 87 (1) (2005) 147–159.

[66] L. Pfeiffer, C.Y.C. Lin, Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence, J. Environ. Econ. Manag. 67 (2) (2014) 189–208.

[67] S. Postel, P. Polak, F. Gonzales, J. Keller, Drip irrigation for small farmers: a new initiative to alleviate hunger and poverty, Water Int. 26 (1) (2001) 3–13.

[68] J. Quiggin, Repurchase of renewal rights: a policy option for the National Water Initiative, Austral. J. Agric. Resour. Econ. 50 (3) (2006) 425–435.

[69] J. Reilly, Climate change and global agriculture: recent findings and issues, Am. J. Agric. Econ. 77 (3) (1995) 727–733.

[70] M. Reisner, Cadillac Desert: The American West and Its Disappearing Water, revised and updated Edition, Penguin Books, New York, 1993.

[71] R.C. Repetto, Skimming the Water: Rent-Seeking and the Performance of Public Irrigation Systems, World Resources Institute, Washington, D.C, 1986.

[72] C. Revelle, E. Joeres, W. Kirby, The linear decision rule in reservoir management and design: 1, Development of the stochastic model, Water Resour. Res. 5 (4) (1969) 767–777.

[73] W. Rippl, The capacity of storage-reservoirs for water-supply, Minutes Proc. Inst. Civil Eng. 71 (1883) 270–278.

[74] R.M. Saleth, A. Dinar, Institutional changes in global water sector: trends, patterns, and implications, Water Policy 2 (3) (2000) 175–199.

[75] K. Schoengold, T. Sproul, D. Zilberman, Irrigated agriculture in an era of high energy prices, in: Y. Villacampa Esteve, C.A. Brebbia, D. Prats Rico, (Eds.), Sustainable Irrigation: Management, Technologies and Policies II, WIT Transactions on Ecology and the Environment, vol. 112, WIT Press, Southampton, 2008. pp. 53–62.

[76] K. Schoengold, D.L. Sunding, The impact of water price uncertainty on the adoption of precision irrigation systems, Agric. Econ. 45 (6) (2014) 729–743.

[77] K. Schoengold, D. Zilberman, The economics of water, irrigation, and development, in: Handbook of Agricultural Economics, vol. 3(1), 2007, pp. 2933-2977.

[78] K.A. Schwabe, J.D. Connor, Drought issues in semi-arid and arid environments, Choices 27 (3) (2012).

[79] F.A. Shah, D. Zilberman, U. Chakravorty, Technology adoption in the presence of an exhaustible resource: the case of groundwater extraction, Am. J. Agric. Econ. 77 (2) (1995) 291–299.

[80] Z. Shah, M.D. Kumar, In the midst of the large dam controversy: objectives, criteria for assessing large water storages in the developing world, Water Resour. Manag. 22 (12) (2008) 1799–1824.

[81] S.P. Simonovic, Reservoir systems analysis: closing gap between theory and practice, J. Water Resour. Plan. Manag. 118 (3) (1992) 262–280.

[82] D.I. Smith, Flood damage estimation: a review of urban stage-damage curves and loss functions, Water SA 20 (3) (1994) 231–238.

[83] T. Sumi, Designing and operating of flood retention dry dams in Japan and USA, in: Proceedings of the 8th International Conference on Hydro-Science and Engineering, 2008, pp. 8–12.

[84] D. Sunding, D. Zilberman, The agricultural innovation process: research and technology adoption in a changing agricultural sector, in: Handbook of Agricultural Economics, vol. 1(A), 2001, pp. 207–261.

[85] C.H. Truong, An analysis of storage capacity reallocation impacts on the irrigation sector, Environ. Resour. Econ. 51 (1) (2012) 141–159.

[86] Y. Tsur, The stabilization role of groundwater when surface water supplies are uncertain: the implications for groundwater development, Water Resour. Res. 26 (5) (1990) 811–818.

[87] Y. Tsur, On the economics of water allocation and pricing, Annu. Rev. Resour. Econ. 1 (2009) 513–536.

[88] Y. Tsur, T. Graham-Tomasi, The buffer value of groundwater with stochastic surface water supplies, J. Environ. Econ. Manag. 21 (3) (1991) 201–224.

[89] Y. Tsur, T. Roe, R. Doukkali, A. Dinar, Pricing Irrigation Water: Principles and Cases from Developing Countries, Resources for the Future Press, Washington, DC, 2004.

[90] United Nations Development Programme, Rain Water Harvesting Improves Lives of Tanzanian Farmers, Accessible at: 〈http://www.undp.org/content/undp/en/home/ourwork/environmentandenergy/successstories/water-harvesting-improves-lives-tanzanian-farmers/〉, 2014 (accessed 22.11.14).

[91] United States Army Corps of Engineers, Seven Oaks Dam Water Conservation Feasibility Report, vol. II. United States Army Corps of Engineers, Los Angeles District, 1997.

[92] United States Bureau of Reclamation, Climate Change Analysis for the Santa Ana River Watershed, Accessible at: 〈http://www.usbr.gov/WaterSMART/bsp/docs/finalreport/SantaAnaWatershed/TechMemo1-SantaAnaWatershedBasinStudy.pdf〉, 2013 (accessed 22.11.14).

[93] United States Geological Survey, National Water Information System Stream Site 11051500 Santa Ana River near Mentone, Accessible at: 〈http://waterdata.usgs.gov/ca/nwis/inventory/?site_no=11051500〉, 2014 (accessed 22.11.14).

[94] United States Water Resources Council, Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies, United States Government Printing Office, Washington, DC, 1983.

[95] H.F. von Stackelberg, Marktform und Gleichgewicht, Julius Springer, Vienna, 1934.

[96] F.A. Ward, M. Pulido-Velazquez, Water conservation in irrigation can increase water use, Proc. Natl. Acad. Sci. 105 (47) (2008) 18215–18220.

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

[98] World Wide Fund for Nature, Dam solutions: Easing Agricultural Pressure, Available at: 〈http://wwf.panda.org/what_we_do/footprint/water/dams_initiative/dams/agriculture/〉, 2014 (accessed 22.11.14).

[99] J. Xu, Personal Conversation, National School of Development, Peking University, Beijing, May 15, 2015.

[100] W.W.-G. Yeh, Reservoir management and operations models: a state-of-the-art review, Water Resour. Res. 21 (12) (1985) 1797–1818.

[101] M. Zavalloni, M. Raggi, D. Viaggi, Water harvesting reservoirs with internal water reallocation: a case study in Emilia Romagna, Italy, J. Water Supply: Res. Technol.–Aqua 63 (6) (2014) 489–496.

[102] J. Zhai, W. Deng, Flooding, floodplain development and management in China, in: B. Stoecker, W. Grosse, W. Li (Eds.), Ecosystem Service and Sustainable Watershed Management Towards Flood Prevention, Pollution Control, and Socio-Economic Development in North China, Universität zu Köln, Cologne, 2000, pp. 183–192.

[103] J. Zhao, D. Zilberman, Fixed costs, efficient resource management, and conservation, Am. J. Agric. Econ. 83 (4) (2001) 942–957.

[104] T. Zhu, M.W. Jenkins, J.R. Lund, Estimated impacts of climate warming on California water availability under twelve future climate scenarios, J. Am. Water Resour. Assoc. 41 (5) (2005) 1027–1038.

[105] D. Zilberman, R.C. Griffin, D.D. Parker, M.J. Mazzotta, J.J. Opaluch, W.F. Hyde, D.M. Larson, A.C. Fisher, Review of Principles and Guidelines, Department of Agricultural and Resource Economics, University of California, 1994.

[106] D. Zilberman, K. Schoengold, The use of pricing and markets for water allocation, Can. Water Resour. J. 30 (1) (2005) 47–54.