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

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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

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http://dx.doi.org/10.1016/j.wre.2015.08.004
2212-4284/

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

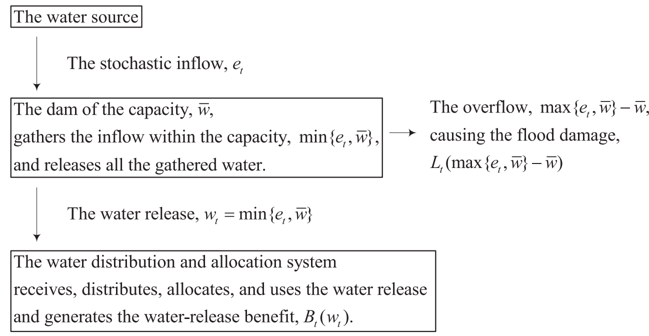

Fig. 1. A water system with a dam.

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:

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.