Implications of Climate Change for Adaptations through Water Infrastructure and Conservation

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Abstract

We analyze the adaptation of water systems to climate change through infrastructure and conservation. We build a simple model in which the primary purpose of water-storage capacities is to manage inter-seasonal variation in water endowment and demand, and climate change is assumed to change total precipitation, its rain/snow distribution, evaporation of water stored in reservoirs, and the water demand. We show that the impact of climate change on the marginal benefit of water-storage capacities and input-efficiency in water use depends on the intensity of climate change and initial conditions about the climate and water demand, and climate change does not necessarily lead to increases or decreases in either conservation or storage. Some of our results are apparently counterintuitive and can generate policy and more general implications for adaptations to climate change in the water sector.

Keywords: Water storage, water-use efficiency, dam, reservoir, drip irrigation, flood control, snowpack

JEL Codes: Q25, Q54, Q28, Q15

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Abstract

We analyze the adaptation of water systems to climate change through infrastructure and conservation. We build a simple model in which the primary purpose of water-storage capacities is to manage inter-seasonal variation in water endowment and demand, and climate change is assumed to change total precipitation, its rain/snow distribution, evaporation of water stored in reservoirs, and the water demand. We show that the impact of climate change on the marginal benefit of water-storage capacities and input-efficiency in water use depends on the intensity of climate change and initial conditions about the climate and water demand, and climate change does not necessarily lead to increases or decreases in either conservation or storage. Some of our results are apparently counterintuitive and can generate policy and more general implications for adaptations to climate change in the water sector.

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1   Introduction

Climate change is among the most important challenges we face today, as it has been changing profoundly the interaction between humans and the source of their life – water, by changing the water demand, water supply, and our ability to meet the gap between them. Based on extensive assessment on these changes, the Intergovernmental Panel on Climate Change (IPCC, 2014) and many other surveys have advocated water conservation and water infrastructure among the most important strategies to adapt to the challenge of climate change (e.g., Smit and Skinner, 2002; Keller

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et al., 2000; McCartney and Smakhtin, 2010; Grafton et al., 2013; Kurukulasuriya and Rosenthal, 2013; the United Nations World Water Assessment Programme, 2014; Zilberman, 2015).

In this paper we present a theoretical analysis on the optimal adaptation to climate change through water conservation, e.g., input-efficiency improvement in water use – like adopting more-efficient irrigation systems, investing in better conveyance technologies, and increasing water recycling and reuse – and through water infrastructure, e.g., water-storage capacities like dams and reservoirs. We focus on three important, well-established dimensions of climate-caused changes in the water sector:

1. The first dimension is the change in the level, uncertainty, and seasonal distribution of water supply. As the IPCC (2014, p. 251) reports, "water resources are projected to decrease in many mid-latitude and dry subtropical regions, and …even where increases are projected, there can be short-term shortages due to more variable streamflow (because of greater variability of precipitation) and seasonal reductions of water supply due to reduced snow and ice storage." As an important example, Schwabe and Connor (2012) state: "[The Sierra Nevada] snowpack, which currently provides storage equal to approximately 50% of all major man-made storage in California, is predicted to decline as climate warms. Precipitation will increasingly fall as rain rather than snow resulting in earlier springtime runoff in volumes greater than current storage capacity can handle." Similar changes in snow-dominated areas across the world (Barnett et al., 2005, p. 303) could affect "more than one-sixth of the Earth's population."

2. The second dimension is the decrease in the efficiency of artificial water-storage capacities, e.g., the warming-caused increase in evaporation loss, since the IPCC (2014, p. 240) projects that evaporation will increase "almost everywhere, especially at higher northern latitudes."

3. The third dimension is the change in the water demand, as many researches have projected that global warming could change the water demand in different directions across sectors and areas (e.g., survey by the IPCC, 2014).

Our analysis is first based on a single-year, two-season, deterministic model of water systems, in which a dam captures water and prevents flood damages in the wet season, holds the captured water till the dry season, and then releases it for human use. A social planner is assumed to maximize the benefit of the dry-season water release net of the wet-season flood damage, by choosing the optimal water-storage capacity and water-use efficiency, in response to changes in the demand for water, seasonal distribution of water endowment, and the evaporation rate of water stored in the dam from the wet to the dry season. To consider the impact of climate change on the seasonal distribution of the water supply, we incorporate the role of snowpacks as a natural water-storage capacity that stores some of the wet-season precipitation as snow and moves it to the dry season as snowmelt, suffering much less evaporation loss than water stored in artificial water-storage capacities – the dam. We also extend this model later with uncertainty in total precipitation.

The simplicity of our model allows us to conduct comparative-static analysis on the marginal benefits of water-storage capacities and water-use efficiency. We identify the role of water-demand parameters in determining the optimal adaptations to climate change through water infrastructure and conservation and complementarity/substitution between these adaptations. Results imply that significant climate change could induce less investment in water infrastructure, while modest climate change could do the opposite. We also discuss implications of our results throughout our analysis.

As our model does capture the primary water-catchment purpose of water-storage capacities to manage inter-seasonal variation of water endowment and demand, our result will be especially applicable to water systems where water endowment and demand generally do not overlap with each other. In the most general sense, we can interpret the dam capacity in our model as the total artificial capacity of water catchment of a water system. In the conclusion of this paper, we will also discuss potential extensions of our model and directions of future research.

Related literature. In general, our paper contributes to the literature on the adaptation to climate change (e.g., historical perspective of Olmstead and Rhode, 2014; extensive assessment and policy

implications by the IPCC, 2014), particular in the water sector with numerical analysis (e.g., Tanaka et al., 2006; Medellín-Azuara et al., 2008; Rosenberg et al., 2008; Connell-Buck et al., 2011; Lloret and Costello, 2011; Howitt, 2014; Mall et al., 2006; Mukherjee and Schwabe, Forthcoming; Rehana and Mujumdar, 2014). Besides concentrations on land use and water policies in response to climate change (e.g., summaries by Ringler and Ebrahim, 2015; Zilberman, 2015), few examples of relatively recent theoretical analysis on infrastructure and conservation include Fisher and Rubio (1997), Bhaduri and Manna (2014), and Xie and Zilberman (Forthcoming): Fisher and Rubio (1997) focus on the impact of uncertainty in annual water endowment on water-storage capacities, considering only their stochastic-control purpose but not the water-catchment purpose. Bhaduri and Manna (2014) investigate the impact of this uncertainty on stochastic control of water-use efficiency. Xie and Zilberman (Forthcoming) analyze the impact of a first-order stochastically dominating shift in annual water endowment on water-catchment capacities. We will cover not only the level and uncertainty of annual water endowment but also its seasonal distribution, which directly tests the water-catchment capacity of water systems. Besides these elements we will also analyze the evaporation and demand impacts.

There are extensive threads of literature on capacity choices of water projects (e.g., Rippl, 1883; Revelle et al., 1969; Nayak and Arora, 1971; Dudley and Burt, 1973; Houck, 1979; Manning and Gallagher, 1982; Miltz and White, 1987; Tsur, 1990; Afshar et al., 1991; Fisher and Rubio, 1997; Edirisinghe et al., 2000; Mousavi and Ramamurthy, 2000; Schoengold and Zilberman, 2007; Haddad, 2011; Houba et al., 2014; Xie and Zilberman, Forthcoming; surveys by Yeh, 1985; Simonovic, 1992) and water-use efficiency improvement, especially in agriculture (e.g., surveys by Caswell, 1991; Sunding and Zilberman, 2001; Schoengold and Zilberman, 2007). This paper, together with Bhaduri and Manna (2014) and Xie and Zilberman (Forthcoming), is among the early effort that discusses the relation between water storage and conservation under climate change in theory, and we contributes by incorporating both the natural water storage (snowpacks) and man-made reservoirs and analyzing their implications. Our analysis shows that these implications are especially important in the context of climate change, and are affected by the specification of the water pro-

ductivity and demand. We also extend the literature on the importance of the properties of the marginal productivity of effective water in conservation and water availability (e.g., Caswell and Zilberman, 1986) to their importance in the context of climate change.

2 The Single-Year, Two-Season, Deterministic Model

2.1 Assumptions

Assume that there is only one period or water year, in which there are two seasons. Figure 1 illustrates the functioning of the water system in our model. In the first, wet season, precipitation is e_0, γ of which is in the form of rain and $1 - \gamma$ of which is in the form of snow. A dam with a capacity of $\bar{a}$ captures the rain and gets water of $\min\{\gamma e_0, \bar{a}\}$. The overflow, $\max\{\gamma e_0 - \bar{a}, 0\}$, generates flood damage, $D(\max\{\gamma e_0 - \bar{a}, 0\})$, with $D(\max\{\gamma e_0 - \bar{a}, 0\}) = 0$ for any $\gamma e_0 \leq \bar{a} + \hat{a}$, $D'(\cdot) \geq 0$, and $D''(\cdot) \geq 0$.

In the second, dry season, the dam releases all of what it has net of evaporation within the water year, $(1 - \delta)\min\{\gamma e_0, \bar{a}\}$, to water users. The snow melting, $(1 - \gamma)e_0$, also goes with water flow and is used. The total water use is then $w_0 \equiv (1 - \delta)\min\{\gamma e_0, \bar{a}\} + (1 - \gamma)e_0$. The water use generates benefit of $B(w_0, \alpha, c)$, where $\alpha \in [0, 1]$ is water-use efficiency and c is a parameter capturing the impact of climate change on water benefit. We further assume that the benefit is generated by effective water, $\mathcal{B}(\alpha w_0, c)$. We could interpret adopting more-efficient irrigation technologies instead of flood irrigation, investment in water-conveyance technologies to reduce leaking and evaporation loss during water transfer, development in water recycling and reuse, and other input-efficiency improvement in water use as an increase in α. The function of the benefit of effective water, $\mathcal{B}(\cdot, \cdot)$, is assumed to satisfy $0 < \mathcal{B}_1(\cdot) < \infty$ and $\mathcal{B}_{11}(\cdot) \leq 0$. Equivalently, $0 < B_1(w, \alpha, c) < \infty$ and $B_{11}(w, \alpha, c) \leq 0$.

[Figure 1 about here.]

We would like to make two remarks here. First, snowpacks store water more efficiently than

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reservoirs do since water stored in reservoirs experiences more intensive evaporation. We model this feature by assuming positive evaporation in reservoirs, δ, and zero evaporation in snowpacks. One can also interpret the dam in this model as less-efficient artificial water-storage systems and the snowpacks as more-efficient natural water-storage capacities including groundwater. For simplicity, in this model, we assume away the optimal control of these natural water-storage capacities – all the precipitation that fell as snow in the wet season will melt and be used in the dry season.

Second, climate change will change several parameters in this model:

1. Water demand: It will change c and, therefore, the water benefit and water demand, given water-use efficiency, α.

2. Water endowment: It will change the total amount of precipitation, e_0, and its rain/snow distribution, γ.

3. Water-storage efficiency: It will change the rate of evaporation loss in the dam within the water year, δ, and more intensive evaporation means lower storage efficiency.

These changes are especially relevant to California, where the Sierra Nevada snowpacks store precipitation in the winter and provide water flow with snowmelt for irrigation and other uses during the summer, but total wet-season precipitation could decrease, while the proportion of rain will increase and evaporation will become more intensive due to warming and snowpack reduction (e.g., Schwabe and Connor, 2012). This pattern, especially the change in the snow/rain distribution of precipitation and inter-seasonal distribution of water supply, is even more general and important beyond California and the Sierra Nevada: As projected by Barnett et al. (2005, p. 303), many snow-dominated areas will experience "a shift in peak river runoff to winter and early spring, away from summer and autumn when demand is highest," and, "[w]ith more than one-sixth of the Earth's population relying on glaciers and seasonal snow packs for their water supply, the consequences of these hydrological changes for future water availability – predicted with high confidence and already diagnosed in some regions – are likely to be severe." Examples in Barnett et al. (2005)

include the western United States, the Himalaya–Hindu Kush area, the Rhine River, the Canadian prairies, and the Andes region.

We assume the problem of the designer of the water system as

$$\max_{\bar{a}\geq 0,\alpha\in[0,1]} \quad V^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) - C(\bar{a}, \alpha), \tag{1}$$

where the (gross) value that is generated by the dam capacity is

$$V^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) \equiv B((1-\delta)\min\{\gamma e_0, \bar{a}\} + (1-\gamma)e_0, \alpha, c) - D(\max\{\gamma e_0 - \bar{a}, 0\}), \tag{2}$$

and $C(\bar{a}, \alpha)$ is the total cost of the water-storage capacity and water-use efficiency.

2.2 Analysis and Results

The first-order conditions are

$$V_1^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) = C_1(\bar{a}, \alpha); \tag{3}$$

$$V_5^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) = C_2(\bar{a}, \alpha). \tag{4}$$

We will focus on the impact of climate change on the left-hand sides of these two first-order conditions, which are the marginal benefits of water-storage capacities and water-use efficiency – the incentives of water-storage investment and water-use efficiency improvement.

2.2.1 Implications for Adaptations through Water Infrastructure

The marginal benefit of dam capacities is

$$V_1^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) = I_{\gamma e_0 > \bar{a}} \cdot \left[(1-\delta)B_1\left((1-\delta)\bar{a} + (1-\gamma)e_0, \alpha, c\right) + D'(\gamma e_0 - \bar{a})\right]. \tag{5}$$

This expression carries an important intuition: If the dam were not full in the wet season, then any additional dam capacity would be useless. If the dam is full in the wet season, then the additional dam capacity will avoid the marginal flood damage in the wet season and bring the marginal benefit of water in the dry season.

Comparative statics in Appendix A.1 derives the following proposition and table:

Proposition 1. *The impacts of climate change on the marginal benefit of water-storage capacities are as follows:*

- *If climate change significantly decreases total precipitation or if a significantly more proportion of wet-season precipitation falls as snow, then any additional water-storage capacity will be useless.*

- *If climate change modestly decreases total precipitation and if the relative consideration of dry-season water use dominates/is dominated by wet-season flood control, the marginal benefit of water-storage capacities will increase/decrease.*

- *If climate change increases/decreases the proportion of wet-season precipitation that falls as rain, then the marginal benefit of water-storage capacities will increase/decrease.*

- *If climate change makes evaporation more intensive and if the water demand is sufficiently inelastic/not extremely inelastic, then the marginal benefit of water-storage capacities will increase/decrease.*

- *If climate change increases/decreases the water demand, then the marginal benefit of water-storage capacities will increase/decrease.*

More precisely, $V_1^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) = 0$ if $\gamma e_0 < \bar{a}$; $V_{16}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) \geq 0$ if and only if $B_{13}\left((1-\delta)\bar{a} + (1-\gamma)e_0, \alpha, c\right) \geq 0$; $V_{12}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) \leq 0$ if and only if $-\frac{B_{11}((1-\delta)\bar{a}+(1-\gamma)e_0,\alpha,c)}{D''(\gamma e_0 - \bar{a})} \geq \frac{\gamma}{(1-\delta)(1-\gamma)}$; $V_{13}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) \geq 0$; $V_{14}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) \geq 0$ if and only if $-\frac{B_1(w_0,\alpha,c)}{w_0 B_{11}(w_0,\alpha,c)} \leq \frac{(1-\delta)\bar{a}}{(1-\delta)\bar{a}+(1-\gamma)e_0}$ at $w_0 = (1-\delta)\bar{a} + (1-\gamma)e_0$.

Proposition 1 has many interesting implications and we discuss some examples here. This proposition first implies that large and small extents of climate change could lead to opposite adaptations through water infrastructure: A sizable decrease in total precipitation could significantly decrease the probability that additional water-storage capacities would be useful – in this model the probability is either one or zero – so it could make water-infrastructure investment less beneficial. A small decrease in total precipitation, however, will decrease water available for human use and, therefore, increase the marginal benefit of water-storage capacities by increasing the marginal benefit of water use, given the flood control consideration is minor. This comparison further suggests that, if the intensities of climate change accumulates in the long run, then the optimal adaptations in the short run should consider the cost of reversing, since it could become optimal in the future that these short-run adaptations need to be abandoned or reversed.

Proposition 1 also suggests that, under the background of climate change, competing water uses, e.g., the urban, industrial, and residential sectors and rural, agricultural sector, might not be as competitive with each other as often observed in water policy debates (e.g., Hanemann and Dyckman, 2009; Madani and Lund, 2011). For example, in highly industrially or residentially developed areas, the flood control consideration is major, and an increase in the proportion of wet-season precipitation that falls as rain – as in California about the Sierra Nevada snowpack (e.g., Schwabe and Connor, 2012) – could make larger water-storage capacities desirable. This water-storage expansion could in turn help to sustain agricultural production, even if the agricultural water demand is dampened by warming that makes the areas less viable for agricultural production. Similarly, some warming driven increase in the agricultural water demand could led to water-infrastructure investments. These investments could then strengthen the ability to control floods and, therefore, boost the industrial and residential development.

Third, one might have expected that more intensive evaporation will definitely make artificial water-storage capacities less desirable, since it weakens the ability of reservoirs to transfer water intertemporally. Proposition 1 shows, however, that it will lead to higher demand for water-storage

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capacities if the water demand is sufficiently inelastic. The intuition is still simple: More intensive evaporation means that the additional water catchment in wet seasons will give less additional water to be used in dry seasons, which means a lower value of the additional water catchment; it also means less water will be available in dry seasons in total, which means a higher value with of the additional water catchment. Therefore, if the water-demand is sufficiently inelastic, then more intensive evaporation could even increase the marginal value of water catchment and the marginal benefit of dam capacities. This case is not impossible in the agricultural sector, as the irrigation demand is usually inelastic (e.g., Moore et al., 1994; Schoengold et al., 2006; Hendricks and Peterson, 2012; survey by Scheierling et al., 2006), so more intensive evaporation could actually increase the demand for irrigation dams.

Finally, Proposition 1 suggests that it could be more likely to be beneficial to expand water-storage capacities if climate change increases the water demand. This could be the case for agricultural water demand in India, China, and other countries in south and east Asia, as projected by Chaturvedi et al. (2013) and for the residential water demand for some developing countries under climate warming (e.g., Zapata, 2015). Migration in response to climate change could also has heterogenous impacts on the water demand across the globe (e.g., McLeman and Smit, 2006; Reuveny, 2007; Black et al., 2011), and changes in crop patterns and other human adaptations (e.g., the IPCC, 2014) should also have different implications on the water demand and corresponding adjustment in water infrastructure.

2.2.2 Implications for Adaptations through Water Conservation

The marginal benefit of water-use efficiency is

$$V_5^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) = B_2((1 - \delta) \min\{\gamma e_0, \bar{a}\} + (1 - \gamma)e_0, \alpha, c). \tag{6}$$

Another proposition and another table follow the analysis in Appendix A.2:

Proposition 2. *The impacts of climate change on the marginal benefit of water-use efficiency are*

as follows:

- *If climate change decreases total precipitation and if water-use efficiency improvement decreases/increases the water demand, then the marginal benefit of water-use efficiency will increase/decrease.*

- *If climate change increases the proportion of total precipitation that falls as rain and if water-use efficiency improvement decreases/increases the water demand, then the marginal benefit of water-use efficiency will increase/decrease.*

- *If climate change makes evaporation more intensive and if water-use efficiency improvement decreases/increases the water demand, then the marginal benefit of water-use efficiency will increase/decrease.*

- *If climate change increases/decreases the marginal contribution of input efficiency in water use, then the marginal benefit of water-use efficiency will increase/decrease.*

More precisely, $V_{25}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) \leq 0$, $V_{35}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) \geq 0$, and $V_{25}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) \geq 0$ if and only if $B_{12}((1-\delta)\min\{\gamma e_0, \bar{a}\} + (1-\gamma)e_0, \alpha, c) \leq 0$; $V_{56}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) \geq 0$ if and only if $B_{23}((1-\delta)\min\{\gamma e_0, \bar{a}\} + (1-\gamma)e_0, \alpha, c) \geq 0$.

[Table 2 about here.]

Intuitively, lower total precipitation and more intensive evaporation suggest less water available for human use in dry seasons. Relatively less snow than rain in wet seasons also worsen dry-season water scarcity, since less precipitation will be stored in natural water-storage capacities – snowpacks, which suffers less evaporation or overflow loss than stored in artificial water-storage capacities – dams and reservoirs. Proposition 2 suggests, however, that lower water availability does not definitely lead to improvement in water-use efficiency, and it will lead to conservation if and only if higher input-efficiency in water use would decrease the water demand. In this case, the demand for water should be inelastic and the marginal productivity of effective water (EMP) should be high (EMP > 1).

Climate change can also change the marginal contribution of water-use efficiency or more-efficient technologies in water use. As discussed above, climate change can change the water demand, which will affect the usefulness of water-use efficiency improvement. For example, climate change could improve or deteriorate land quality. As more-efficient irrigation technologies are augmenting the land quality (e.g., Caswell and Zilberman, 1986), the change in land quality will directly change the usefulness of drip and sprinkle irrigations. Proposition 2 suggests that if climate change slightly deteriorates land quality then more adoption of these irrigation technologies could be more likely to be beneficial, while a significant deterioration of land quality could drive farmers to migrate and leave conservation investment meaningless in the original places.

2.2.3 Relation between Water-Storage Capacities and Water-Use Efficiency

It is obvious that if investment in any one between water-storage capacities or water-use efficiency is not economical, the optimal policy will not be to invest in it. If both approaches are economical, then whether a balanced distribution is optimal will depend on the relation between water infrastructure and conservation: Are they substitutes or complements? In our model, the answer forms the following proposition with the proof in Appendix A.3:

Proposition 3. *Water-storage capacities and water-use efficiency will be complements if and only if water-use efficiency improvement will increase the inverse demand for water.*

Since the dam in our model has only the water-catchment purpose, Proposition 3 follows the same spirit of Xie and Zilberman (Forthcoming). Proposition 3 could help to see whether expanding water storage and improving water-use efficiency together would be optimal in enhancing social welfare – it would be optimal if both approaches are economical and if they are not extremely substitutive. Proposition 3 also implies that, in the real world where policymakers or people could use both approaches to adapt to climate change, the complementarity/substitution between these adaptations might magnify or offset the direct policy implications of climate change.

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3 Extension with Uncertainty in Total Precipitation

We now extend the model by assuming that total precipitation in the wet season will be $e_0 \pm \sigma$ with the same probability. The dam-generated value then becomes

$$
\begin{aligned}
&V^*(\bar{a}, e_0, \gamma, \delta, \alpha, c, \sigma) \\
&= \frac{1}{2} \cdot [B((1-\delta)\min\{\gamma(e_0 - \sigma), \bar{a}\} + (1-\gamma)(e_0 - \sigma), \alpha, c) - D(\max\{\gamma(e_0 - \sigma) - \bar{a}, 0\})] \\
&+ \frac{1}{2} \cdot [B((1-\delta)\min\{\gamma(e_0 + \sigma), \bar{a}\} + (1-\gamma)(e_0 + \sigma), \alpha, c) - D(\max\{\gamma(e_0 + \sigma) - \bar{a}, 0\})].
\end{aligned}
$$

(7)

A third proposition and another table summarizes the impacts of more uncertain precipitation on water storage and conservation:

Proposition 4. *The impact of an increase in uncertainty of total precipitation is as follows:*

- *If climate change significantly increases the uncertainty, then the marginal benefit of water-use efficiency could decrease.*

- *If climate change modestly increase the uncertainty and if the marginal benefit of water use and the marginal damage of floods are convex, then the marginal benefit of water-storage capacities will increase.*

- *If climate change increase the uncertainty and if the marginal productivity of effective water is not extremely convex, then the marginal benefit of water-use efficiency will decrease.*

More precisely, a sizable increase in σ could decrease $I_{\gamma(e_0 - \sigma) > \bar{a}}$ to zero and increase $I_{\gamma(e_0 + \sigma) > \bar{a}}$ to one; $V_{17}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c, \sigma) \geq 0$ if $B_{111} \geq 0$ and $D''' \geq 0$; $V_{57}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c, \sigma) \leq 0$ if $B_{121} \leq 0$.

[Table 3 about here.]

The proof is in Appendix 4. On the one hand, Proposition 4 replicates the qualitative result in Fisher and Rubio (1997) that slightly more uncertain water endowment will suggest more valuable marginal water-storage capacities if the marginal value of water is convex, though without

incorporating optimal control of water inventories as in Fisher and Rubio (1997). Proposition 4 is different from the result in Bhaduri and Manna (2014) that more uncertain water endowment will decrease the incentive to improve water-use efficiency if the marginal productivity of effective water is convex.

Adding to the implication of Proposition 1, Proposition 4 implies another possibility that the implication of climate change for adaptation through water infrastructure depends on the intensity of climate change, since slightly more volatile total precipitation will lead to higher demand for water-storage capacities with convex marginal benefit of water use and marginal damage of floods, while a larger increase in the uncertainty could decrease the the demand. This point reemphasizes that adaptations in water infrastructure could differ in the short and the long runs when climate change evolves dynamically.

Considering Propositions 1, 2, and 4 together, we also see that the two climate-change scenarios – "wet seasons wetter, dry seasons drier" and "wet years wetter, dry years drier" – have quite different implications on adaptations, in spite of similar perceptions that extreme climate conditions are more often and severe. The former is about changes in seasonal distribution of water endowment, and Propositions 1 and 2 suggest that the optimal adaptation to these changes should depend on the elasticity of the water demand (or the EMP), while the latter scenario is about changes in uncertainty in water endowment, and Proposition 4 suggests that the optimal adaptations to these changes should depend on the curvature of the water demand. Moreover, when the water demand is inelastic, water-storage expansions and water-use efficiency improvement could be both adopted to adapt to the former scenario, but might not be optimal in the latter scenario.

4   Concluding Remark

This paper analyzes the implications of climate change for water-infrastructure investment and water-use efficiency improvement through the water supply, demand, and efficiency in artificial water storage. Using a simple model, we identify the conditions that determine the direction of

these implications.

Our theoretical results highlight the point that there is substantial heterogeneity in the implications of climate change for water infrastructure and conservation across different channels – through the water demand, water endowment, or water-storage efficiency; different purposes of water storage – to supply water or control floods; different properties of the water demand – its elasticity and curvature; and the intensity of climate change – significant or modest. To answer whether water-storage expansion and water-use efficiency improvement are optimal adaptations to climate change, it would then be necessary to compare these different implications through at least these three channels and to consider the complementarity or substitution between water storage and conservation.

This paper is open to several extensions and we conclude by discussing some of them. First, besides managing the inter-seasonal variation of water endowment, the purpose of water-storage capacities to manage the inter-annual variation of water endowment can also be incorporated. Another potential extension is to incorporate the dynamics of the stock of snowpacks, which could be treated exogenous if we ignore mitigation effort on climate warming, or endogenous if we assume this effort can make a difference. Management of the stock of groundwater could also be considered. In this case, a dynamic control problem with multiple state variables would be necessary. Climate change itself is also an uncertain and evolving process, so option value will occur when learning through time before investing in irreversible adaptation strategies. Since the design of water system is a long and elaborate project, following our and other scholars' theoretical efforts, more empirical and simulation analysis will be useful in considering water adaptation strategies. That said, this paper does illustrate the importance of recognizing natural water-storage capacities to obtaining more consistent control of water infrastructure and conservation to adapt to climate change, especially for areas where inter-seasonal variation of water endowment and demand is significant, e.g., the western United States and the Himalaya–Hindu Kush region.

A Appendices

A.1 Proof of Proposition 1

A large decrease in e_0 or γ will decrease the marginal benefit of dam capacities to zero.

More results are straightforward with a little bit algebra as follows: First, the water-demand impact of climate change on the marginal benefit of dam capacities is

$$V_{16}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) = I_{\gamma e_0 > \bar{a}} \cdot (1 - \delta) B_{13} \left((1 - \delta)\bar{a} + (1 - \gamma)e_0, \alpha, c \right), \tag{8}$$

which depends on whether climate change will increase or decrease the water demand.

Second, the impact of a small change in the total amount of precipitation is

$$V_{12}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) = I_{\gamma e_0 > \bar{a}} \cdot (1 - \delta)(1 - \gamma) \underbrace{B_{11} \left((1 - \delta)\bar{a} + (1 - \gamma)e_0, \alpha, c \right)}_{(-)}$$

$$+ I_{\gamma e_0 > \bar{a}} \cdot \underbrace{\gamma D''(\gamma e_0 - \bar{a})}_{(+)}. \tag{9}$$

Therefore, a small decrease in the total amount of precipitation will increase the marginal benefit of water use in the dry season but will decrease the marginal flood damage in the wet season. If the (marginal) flood damage is minor, for example, if $\gamma e_0 - \bar{a} \le \hat{a}$, then the positive impact of the marginal benefit of water use in the dry season will dominate.

Third, the impact of a shift in the snow/rain distribution of the precipitation will be

$$V_{13}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) = -I_{\gamma e_0 > \bar{a}} \cdot e_0 (1 - \delta) B_{11} \left((1 - \delta)\bar{a} + (1 - \gamma)e_0, \alpha, c \right)$$

$$+ I_{\gamma e_0 > \bar{a}} \cdot e_0 D''(\gamma e_0 - \bar{a}) \ge 0. \tag{10}$$

This impact is straightforward: More rains in wet seasons directly test the water-catchment capacity of the water storage and makes the marginal dam capacity more valuable.

Finally, the impact of the rate of evaporation within the water year is

$$V_{14}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) = -I_{\gamma e_0 > \bar{a}} \cdot \underbrace{B_1\left((1-\delta)\bar{a} + (1-\gamma)e_0, \alpha, c\right)}_{(+)}$$

$$- I_{\gamma e_0 > \bar{a}} \cdot \underbrace{(1-\delta)\bar{a}B_{11}\left((1-\delta)\bar{a} + (1-\gamma)e_0, \alpha, c\right)}_{(-)}, \qquad (11)$$

which is positive if and only if

$$-\frac{B_1\left((1-\delta)\bar{a} + (1-\gamma)e_0, \alpha, c\right)}{[(1-\delta)\bar{a} + (1-\gamma)e_0]\,B_{11}\left((1-\delta)\bar{a} + (1-\gamma)e_0, \alpha, c\right)} \le \frac{(1-\delta)\bar{a}}{(1-\delta)\bar{a} + (1-\gamma)e_0}, \qquad (12)$$

which means the water-demand elasticity is smaller (more inelastic) than $\frac{(1-\delta)\bar{a}}{(1-\delta)\bar{a}+(1-\gamma)e_0} < 1$.

A.2   Proof of Proposition 2

First, the impact of climate change on water conservation through water demand is

$$V_{56}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) = B_{23}((1-\delta)\min\{\gamma e_0, \bar{a}\} + (1-\gamma)e_0, \alpha, c), \qquad (13)$$

which is positive if climate change and water-use efficiency are complements in water use.

Second, the impact of total precipitation is

$$V_{25}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) = [I_{\gamma e_0 \le \bar{a}} \cdot (1-\delta)\gamma + 1 - \gamma]\,B_{12}((1-\delta)\min\{\gamma e_0, \bar{a}\} + (1-\gamma)e_0, \alpha, c), \quad (14)$$

which is positive if and only if $B_{12}((1-\delta)\min\{\gamma e_0, \bar{a}\} + (1-\gamma)e_0, \alpha, c) \ge 0$. In this case, the elasticity of the marginal productivity (EMP) of effective water is low (EMP $<$ 1) and the water demand is elastic.

The impact of the distribution between rain and snow is

$$V_{35}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) = [I_{\gamma e_0 \le \bar{a}} \cdot (1-\delta)e_0 - e_0]\,B_{12}((1-\delta)\min\{\gamma e_0, \bar{a}\} + (1-\gamma)e_0, \alpha, c), \quad (15)$$

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which is negative if and only if $B_{12}((1-\delta)\min\{\gamma e_0, \bar{a}\} + (1-\gamma)e_0, \alpha, c) \geq 0$. In this case, again, EMP < 1 and the water demand is elastic.

The impact of the rate of evaporation within the water year is

$$V_{45}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) = -\min\{\gamma e_0, \bar{a}\}B_{12}((1-\delta)\min\{\gamma e_0, \bar{a}\} + (1-\gamma)e_0, \alpha, c), \quad (16)$$

which is negative if and only if $B_{12}((1-\delta)\min\{\gamma e_0, \bar{a}\} + (1-\gamma)e_0, \alpha, c) \geq 0$. Similarly, this result is straightforward since more intensive evaporation suggests smaller dry-season water availability.

A.3   Proof of Proposition 3

To see the relation between these two approaches, we calculate the cross-partial derivative,

$$V_{15}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c) = I_{\gamma e_0 > \bar{a}} \cdot (1-\delta)B_{12}\left((1-\delta)\bar{a} + (1-\gamma)e_0, \alpha\right), \quad (17)$$

which will be zero if γe_0 is small, while positive if $B_{12}\left((1-\delta)\bar{a} + (1-\gamma)e_0, \alpha\right) \geq 0$.

A.4   Proof of Proposition 4

The marginal benefit of dam capacities is then

$$
\begin{aligned}
&V_1^*(\bar{a}, e_0, \gamma, \delta, \alpha, c, \sigma) \\
&= \frac{1}{2} \cdot I_{\gamma(e_0-\sigma)>\bar{a}} \cdot \left[(1-\delta)B_1\left((1-\delta)\bar{a} + (1-\gamma)(e_0-\sigma), \alpha, c\right) + D'(\gamma(e_0-\sigma) - \bar{a})\right] \\
&+ \frac{1}{2} \cdot I_{\gamma(e_0+\sigma)>\bar{a}} \cdot \left[(1-\delta)B_1\left((1-\delta)\bar{a} + (1-\gamma)(e_0+\sigma), \alpha, c\right) + D'(\gamma(e_0+\sigma) - \bar{a})\right]. \quad (18)
\end{aligned}
$$

First, the impact of a small increase in uncertainty is then

$$V_{17}^*(\bar{a}, e_0, \gamma, \delta, \alpha, c, \sigma)$$

$$= \frac{1}{2} \cdot I_{\gamma(e_0+\sigma)>\bar{a}} \cdot (1-\delta)(1-\gamma)B_{11}\left((1-\delta)\bar{a} + (1-\gamma)(e_0+\sigma), \alpha, c\right)$$

$$+ \frac{1}{2} \cdot I_{\gamma(e_0+\sigma)>\bar{a}} \cdot \gamma D''(\gamma(e_0+\sigma) - \bar{a})$$

$$- \frac{1}{2} \cdot I_{\gamma(e_0-\sigma)>\bar{a}} \cdot (1-\delta)(1-\gamma)B_{11}\left((1-\delta)\bar{a} + (1-\gamma)(e_0-\sigma), \alpha, c\right)$$

$$- \frac{1}{2} \cdot I_{\gamma(e_0-\sigma)>\bar{a}} \cdot \gamma D''(\gamma(e_0-\sigma) - \bar{a})$$

$$= \frac{1}{2}(1-\delta)(1-\gamma) \cdot \left[I_{\gamma(e_0+\sigma)>\bar{a}} \cdot B_{11}\left((1-\delta)\bar{a} + (1-\gamma)(e_0+\sigma), \alpha, c\right) \right.$$

$$\left. - I_{\gamma(e_0-\sigma)>\bar{a}} \cdot B_{11}\left((1-\delta)\bar{a} + (1-\gamma)(e_0-\sigma), \alpha, c\right) \right]$$

$$+ \frac{1}{2} \cdot \left[I_{\gamma(e_0+\sigma)>\bar{a}} \cdot \gamma D''(\gamma(e_0+\sigma) - \bar{a}) - I_{\gamma(e_0-\sigma)>\bar{a}} \cdot \gamma D''(\gamma(e_0-\sigma) - \bar{a}) \right], \quad (19)$$

which will be positive if the marginal benefit of water use and the marginal damage of floods are convex.

Second, consider a significant increase in the uncertainty. If this increase makes a dam that is formerly never full become full at half probability, then the marginal benefit of dam capacities increases from zero. If the dam that is full at half probability, then the full-dam probability will not change after the increase in the uncertainty. In this case, the marginal benefit of dam capacities will increase/decrease if the marginal benefit of water use and the marginal damage of floods are convex/concave. If the increase in the uncertainty makes a dam that is formerly always full become full at half probability, then the marginal benefit of dam capacities will decrease if the consideration of water use dominates flood control.

The marginal benefit of water-use efficiency is

$$V_5^*(\bar{a}, e_0, \gamma, \delta, \alpha, c, \sigma)$$

$$= \frac{1}{2} \cdot B_2((1-\delta)\min\{\gamma(e_0+\sigma), \bar{a}\} + (1-\gamma)(e_0+\sigma), \alpha, c)$$

$$+ \frac{1}{2} \cdot B_2((1-\delta)\min\{\gamma(e_0-\sigma), \bar{a}\} + (1-\gamma)(e_0-\sigma), \alpha, c). \quad (20)$$

The impact of an increase in uncertainty is then

$$
\begin{aligned}
V_{57}^*&(\bar{a}, e_0, \gamma, \delta, \alpha, c, \sigma) \\
&= \frac{1}{2} \cdot \left[I_{\gamma(e_0+\sigma) \leq \bar{a}} \cdot (1-\delta)\gamma + 1 - \gamma \right] B_{12}((1-\delta)\min\{\gamma(e_0+\sigma), \bar{a}\} + (1-\gamma)(e_0+\sigma), \alpha, c) \\
&\quad - \frac{1}{2} \cdot \left[I_{\gamma(e_0-\sigma) \leq \bar{a}} \cdot (1-\delta)\gamma + 1 - \gamma \right] B_{12}((1-\delta)\min\{\gamma(e_0-\sigma), \bar{a}\} + (1-\gamma)(e_0-\sigma), \alpha, c),
\end{aligned}
$$

$$(21)$$

which will be negative if $B_{121} \leq 0$. In this case, the marginal productivity of effective water is not very convex.

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Table 1: Implications of climate change on water-storage investment

Channel	Potential change	Impact
Water demand	Increase	$+$
	Decrease	$-$
Water endowment	Small decrease in total	$+$, iff water use dominates flood control
	Huge decrease in total	$-$
	More as rain, less as snow	$+$
Storage efficiency	Decrease	$+$, iff water demand is sufficiently inelastic

Table 2: Implications of climate change on water-use efficiency improvement

Channel	Potential change	Impact
Water demand	Increase	$+$, iff climate change complements efficiency in water use
	Decrease	$-$, iff climate change complements efficiency in water use
Water endowment	Decrease in total	$+$, iff efficiency decreases water demand
	More as rain, less as snow	$+$, iff efficiency decreases water demand
Storage efficiency	Decrease	$+$, iff efficiency decreases water demand

Table 3: Implications of uncertainty change in water endowment

Impact on MB of …	Potential uncertainty change	Impact
Water-storage capacities	Large increase	$-$, if dams are always full and if water use dominates flood control
	Large increase	$+$, if dams are never full
	Large increase	$+$, if dams are half full and if the marginal water utility is convex
	Small increase	$+$, if the MB of water and MD of floods are convex
Water-use efficiency	Increase	$-$, if the MP of effective water is not extremely convex

Overflows, $\max\{\gamma e_0 - \bar{a}, 0\}$ → Flood damage, $D(\max\{\gamma e_0 - \bar{a}, 0\})$

Rain, γe_0 → Water catchment, $\min\{\gamma e_0, \bar{a}\}$ — Evaporation rate, δ → Water release, $(1-\delta)\min\{\gamma e_0, \bar{a}\}$

Total precipitation, e_0

Total water use, $w_0 \equiv (1-\delta)\min\{\gamma e_0, \bar{a}\} + (1-\gamma)e_0$ → Water benefit, $B(w_0, \alpha, c)$

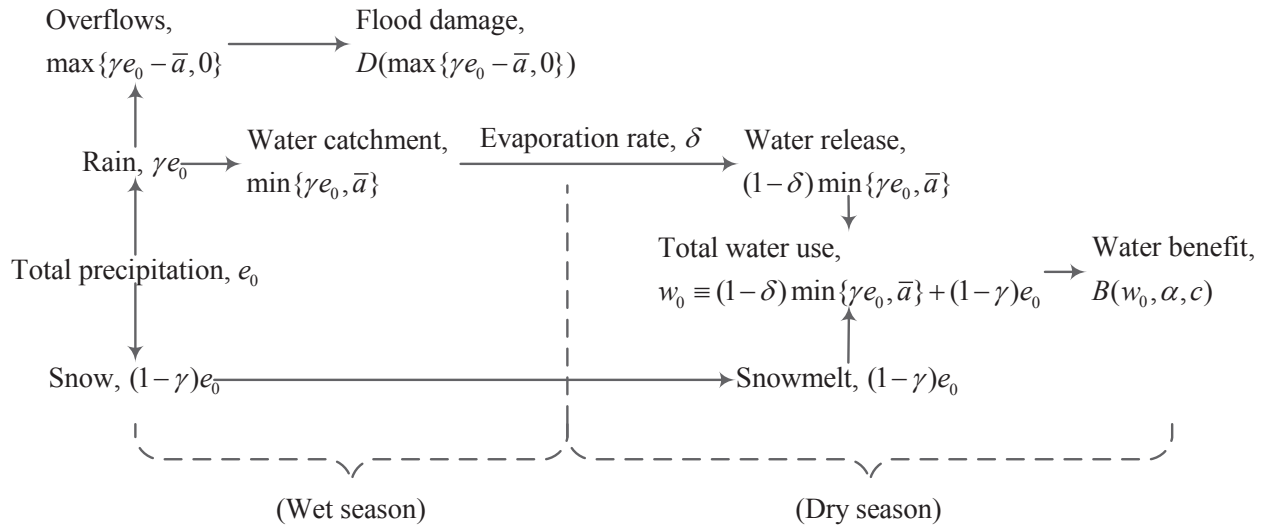Snow, $(1-\gamma)e_0$ → Snowmelt, $(1-\gamma)e_0$

(Wet season)   (Dry season)

Figure 1: Functioning of the water system