Optimal reservoir capacity for climate change

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Abstract

We aim to understand the tension between how much water to store given that water flow is subject to variation and that the current distribution of flow into reservoirs is uncertain and variable a consequence of climate change conditions. Economic theory on water reserves calls for increase investment as the variance of the water flow increases, as expected by climate change; but it is not clear how much investment and for what rate of changes in mean and variance of water flow. We develop an analytical method to analyze the effects in optimal reservoir capacity for various climatic change conditions that alter the current mean and variance of water flow. We estimate an optimal reservoir capacity by stochastic dynamic programming and parameterize the model with real time data from five major reservoirs in Northern California. We illustrate that for a decrease in annual mean inflow with no corresponding change in standard deviation our results suggests a need to increase reservoir capacity; however we show that if the decrease in the mean is met with a corresponding decrease in the standard deviation no change in reservoir size is required.

Key Words: Optimal reservoir capacity, California reservoirs, water flow variability, isoclines, climate change, water resources.

Introduction

The dynamic nature of the problem of water storage posts relevant questions that present challenges and are not simple to answer; for example how much water to store given conditions of climate change; conditions that may impact water resources and create extreme events such as floods or droughts. Or yet another question how much water to release in the short term if chances are that in the near future the demand of water will out weight the supply of water. The underlying question is the uncertain nature of water flow and the best possible appropriation of the resource in order to fulfill multiple uses.

In order to answer some of the questions just addressed, we take a narrower view of the problem to address the question of water storage under uncertainty. Specifically the paper departs from the previous institutional and economic analysis and focuses on an initial economic analysis that aims to understand the problem of reservoirs and storage under climate change conditions.

The paper aims to understand the tension between how much water to store given that water flow is subject to variation and that with climate change conditions, general circulation models project that both the mean and variance of the current distribution of runoff may change as a consequence of changes in temperature, precipitation, and snow pack, making it relevant to understand how uncertainty has an impact in water reservoirs capacity.

Economic theory on water reserves calls for increase investment as the variance of the water flow increases, as expected by climate change and the question is then how much investment and for what changes in mean and variance of water flow. We develop an analytical method to analyze the effects of various climatic change conditions. We estimate an optimal reservoir capacity by stochastic dynamic programming and parameterize the model with real data from five major reservoirs in Northern California.

We run an empirical example to show the impacts on the optimal reservoir capacity for percentage changes in the current mean and in the current variance. The model developed can be parameterized to other regions to estimate the impact of climatic change conditions on reservoir capacity.

This paper fits in the debate about enlarging reservoirs or adding new infrastructure to existent ones, such as the case of Shasta Dam, the largest water reservoir in Northern California and, in the recent projections on climate change effects on water resources in California as reported by the California Climate Change Center and the California Department of Water Resources.

The empirical analysis uses time series from five major reservoirs in Northern California and aims to find the optimal size of the reservoirs given yearly inflow and outflow, the demand function and the marginal cost of building additional units of reservoirs. The question we want to address is that of the optimal reservoir capacity given climate change conditions.

We proceed as follows: section one discusses the latest research on the topic of reservoirs capacity from both the economics and the hydrology literature as well as a discussion of climate change impacts on water resources, in particular for the case of California. Section two is a discussion of the model and numerical analysis. In section three we present the results of the model and a discussion of results, and finally in section four we conclude and comment on further research.

Literature Review

Water reservoirs are extremely relevant in water resources management since they store, use and divert water for consumption, irrigation, cooling, transportation, construction, mills, power and recreation [1]. Just in the continental US there are 75,000 dams and/or reservoirs capable of storing a volume of water almost equal to one year's mean runoff, although there is considerable geographic variation; in the Northeast reservoirs store about 25% of a year's mean runoff whereas in the Southwest, reservoirs have the capacity to store up to three years mean runoff [2].

Reservoirs smooth out consumption across years and across seasons, they help to deal with extreme events such as floods and drought and allow for a more proactive water management. Nonetheless, reservoirs come with an important cost, from building infrastructure to impairing river flow that has environmental consequences and ecological impacts given the irreversibility of infrastructure projects. It is clear then that there is a tension worth analyzing. And, in view of climate change conditions, where uncertainty of runoff is expected, this tension becomes even more relevant.

Climate change has significant impact on water resources. It is expected that climate change will impact temperature, precipitation patterns, snowmelt and large area runoff as well as regional runoff. In addition, climate change may induce variability in the hydrological cycle with mean precipitation increased possibly accompanied by more extreme events or changes in runoff patterns as well as increase in drought as a result of increased temperature and evaporation with less precipitation.

The size of a reservoir is therefore relevant under climate change conditions, but the problem is to know how much reservoir capacity is necessary and for how much variation. In the simplest form, if there was no variability in water flow and demand was known then optimal reservoir capacity will tend to decrease as there is really not uncertainty and the benefits for storing water other knowing how much water is expected to flow will likely drive the decision of the reservoir.

However, once there is variability in water flow, i.e. from wet years to dry years, or from seasonal flow or seasonal demand, the question of how much water to store given that there is uncertainty about the future flows to meet the demand becomes relevant. The decision to release water today will have an impact on the decision to store water in the future making the problem of a dynamic nature. Therefore variability in flow and uncertainty drives reservoir capacity.

Much of the economics literature on water reservoirs deals with optimization strategies about how much to release and or store but few deal with specific issues of storage capacity under uncertainty conditions. In a theoretical model Fisher & Rubio (1997) study the determination of the optimal water storage capacity in a region by taking water flow into a reserve as uncertain as measured by the variance which is likely to increase with climate change. They consider that building capacity is costly and that development of water resources has environmental costs.

Fisher and Rubio (1997) found that with symmetric linear adjustment costs an increase in uncertainty implies an increase in the long-run capital stock if the marginal benefit of water withdrawals is convex and that the net marginal value of the capital stock is positively related to the instantaneous variance rate which characterizes water flow as a stochastic process.

They conclude that an increase in variance shifts upward the net marginal value function and leads to an increase in the optimal capital stock and that the existence of asymmetric linear adjustment costs reduces the variability of optimal investment in water infrastructure. The asymmetry defines a range of inaction and increases the stability of the long-run capital stock with respect to changes in variance. Finally they argue that If there is no market for water resource infrastructure and if in addition environmental restoration is costly, changes in variance do not affect the optimal level of reserves.

Burness and Quirk (1980) find a steady state probability distribution over storage of water on the Colorado River using stochastic water flows by trying to replicate the Bureau of Reclamation strategies [3]. Whereas Chaterjee and colegues (1998) find an optimal intertemporal allocation between releases of water for irrigation and reservoir head for hydropower generation but does not address storage capacity [4] and O'Hara (2006)[1] in a urban setting determines the effectiveness of precautionary investments in reservoir storage under complete and incomplete information and find preliminary results that additional reservoir storage can mitigate, but not eliminate, water shortages attributable to climate change.

Reservoir optimization is usually analyzed with stochastic dynamic programming methods. Simulation studies has shown that standardized reservoir capacity has a unique distribution that makes possible to estimate the reservoir capacity required to provide certain benefits in terms of particular risk [5, 6]. From the engineering

[1] O'Hara conclusions were presented in the Ocassional Workshop of Environmental Economics at UCSB, 2006. Document available at http://weber.ucsd.edu/~jkohara/.

perspective the link with climate change variability is approached by risk assessment (i.e. floods) and the mean and standard deviation of reservoir capacity are functions of non-dimensional net mean inflow and length of simulation period [6].

Climate change and water resources in California

California's climate is expected to become considerably warmer during this century; the increase in the temperature depends on the rate at which human activities continue to emit burning of fossil fuels. High emissions scenarios for California suggest that by the end of the century, temperatures could rise between 8 to 10.4^{o}F [7].

Global warming poses the risk of altering precipitation patterns and decreasing snow pack in the high sierras that will challenge adequate water supplies in the region. The ability of California's water supply system to adapt to significant changes in climate and population is feasible but at a significant cost that may require a change in how water is currently managed [8]. Water demand in California is also likely to change with a threefold increase in population by the end of 2100 under a high forecast scenario as well as the rise in mean temperature.

Due to water supply and water demand variability, a high impact in water infrastructure is expected and the need for anticipatory public policy and adaptive strategies necessary [7-10].

Estimates from general circulation models downscaled to California[2] suggest that the change in annual reservoir inflow in Northern California could be as low as -30% under a HadCM3 model and that the change in water year flow centroid may shift down 32 days [11]. In certain reservoirs, the change may be even more extreme. Figure 1 below shows estimates of rim inflow in four major rivers in Northern California that feed large reservoirs.

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[2] Models used are: Low-sensitivity National Center for Atmospheric Reseach/Department of Energy Parallel Climate Model (PCM) and the medium-sensitivity U.K. Met Office Hadley Centre Climate Model, version3 (HadCM3)

Northern California

Shasta

Sacramento River (Rim Inflow in TAF)			
	Annual	Oct-Mar	Apr-Sept
Wet (HCM2050)	**39.20%**	69.70%	-8.80%
Dry (PCM2050)	**-15.30%**	-9.40%	-24.60%
Historical	**5,525**	3379	2147

Trinity

Trinity River (Rim Inflow in TAF)			
	Annual	Oct-Mar	Apr-Sept
Wet (HCM2050)	**27.80%**	71.60%	-14.50%
Dry (PCM2050)	**-17.80%**	-8.10%	-27.20%
Historical	**1,217**	598	619

Oroville

Feather River (Rim Inflow in TAF)			
	Annual	Oct-Mar	Apr-Sept
Wet (HCM2050)	**51.50%**	104.20%	-12.30%
Dry (PCM2050)	**-10.20%**	1.90%	-24.70%
Historical	**3900**	2137	1763

New Melones

Stanislaus River (Rim Inflow in TAF)			
	Annual	Oct-Mar	Apr-Sept
Wet (HCM2050)	**74.00%**	98.60%	58.60%
Dry (PCM2050)	**-5.20%**	1.60%	-9.40%
Historical	**1,057**	408	649

Figure 1. Estimates of rim inflow into major reservoirs in Northern California. Source: [10]

Water resources the climate models forecast changes in mean [8, 10, 11], but estimates of the change in variance depends on the magnitude and frequency of extreme events altering the probability distribution function of the hydrological cycle resource [12]. Some modeling studies forecast that the variability of the hydrologic cycle increases as the mean precipitation increases with possible intense local storms or changes in runoff patterns. Studies are still underway to understand how natural patterns of variability such as hurricanes, rainstorms and El Niño/la Niña events affect water resources in California [13]. Impact of climate change on California water resources require that management practices be revised [14]. Van Rheenen et.al. (2004) have suggested mitigation strategies such as flood control rule curves of reservoir releases to reduce the risk associated with climate change [15]. Yao and Georgakakos (2001) assess the sensitivity of reservoir performance to various inflow forecasting models and conclude that reliable forecasts and adaptive decision systems benefit reservoir performance and dynamic operational procedures help cope with climatic change scenarios [16]. Vicuna et.al. (2007) used simulation models with a number of general circulation model scenarios to assess the sensitivity of California hydrology to climate change conditions and found greater negative impacts than previous assessments shown which translate into smaller stream flows, lower reservoir storage and decreased water supply deliveries and reliability [17]. Still, the impact of climate change in water resources systems in California is undergoing much research. Vicuna and Dracup (2007) believe that climate change impacts in reliability of water sources and water rights, reservoir objectives tradeoffs and, impact on hydropower production are in need of analysis [14].

The previous related to optimal reservoir capacity under climatic change. We believe that our analysis and in particular our analytical model adds very useful results in the discussion of the impacts of global warming in water resources systems. In what follows we develop the model and derive results that illustrate the impact of water flow variability in reservoir capacity.

Model

Consider a social planner who seeks to optimize his reservoir capacity, R. If $V(R)$ is the discounted expected present value of reservoir capacity R, and $C(R)$ is the present value cost of building that size reservoir, then the risk neutral planner seeks to solve:

$$\max_R V(R) - C(R) \qquad (1)$$

The discounted expected present value of a reservoir, $V(R)$, depends on how that reservoir is managed. We will assume that the reservoir is managed to maximize the expected discounted social welfare from extraction, over an infinite time horizon. Solving for the optimal policy function (how much water to consume in a given year, conditional upon the existing volume of water in the reservoir and the reservoir capacity), and resulting value function, is non-trivial because it involves solving an infinite-time stochastic dynamic optimization problem.

Let Y_t be the amount of water in the reservoir at the beginning of period t, so .- $0 \le Y_t \le R$. Inflow that period is F_t, which is an *i.i.d.* random variable whose density is known. Water consumption (i.e. release from the reservoir) is H_t, so $Y_t + F_t - R \le H_t \le Y_t + F_t$. The per-period benefit of water consumption is the integral under the demand curve from 0 to H_t. If $P(h)$ is the demand curve, the period-t benefit of consuming H_t is:

$$p(H_t) = \int_0^{H_t} P(h)dh \qquad (2)$$

It is convenient to define $X_t \equiv Y_t + F_t$ as the post-inflow amount of water available for extraction. For any reservoir capacity, R, the stochastic dynamic optimization problem is:

$$\max_{\{H_t\}} \sum_{t=1}^{\infty} d^t p(H_t) \qquad (3)$$

$$s.t. \quad X_{t+1} \equiv X_t - H_t + F_{t+1} \qquad (4)$$

$$and \quad X_t - R \leq H_t \leq X_t \qquad (5)$$

where d is the discount factor. The state variable of the stochastic dynamic optimization problem is X_t and the control variable is H_t. The SDPE is:

$$J(X_t) = \max_{H_t} p(H_t) + d\,EJ(X_{t+1}) \qquad (6)$$

Since the probability density function over F_t is both stationary and known, we can use *Policy Function Iteration [18]* to solve the SDPE for both the optimal policy function $(H^*(X))$ and the corresponding value function $(J(X))$. The policy function tells us exactly how much water to extract in any period given that X is available. The corresponding value function tells us the expected net present value of available water X, provided that it is optimally utilized over the infinite planning horizon. This procedure produces $J(X)$ for any reservoir capacity, R, which we can make explicit by writing $J(X;R)$.

To value a reservoir of size R, we evaluate this expression at $X = 0$ (i.e. we evaluate $J(0;R)$. This is interpreted as the expected discounted present value of reservoir capacity *R*, conditional upon optimal future use, provided that we start with no water available.[3]

To determine the optimal size reservoir requires $V(R)$ (see above), which is simply defined as: $V(R) \equiv J(0;R)$. Thus, we use *Policy Function Iteration* to solve for $V(R)$ and then find the optimal reservoir size by maximizing $V(R)-C(R)$. This yields an optimal reservoir size, R^* conditional upon parameters of the system. The parameters of particular interest are the mean and standard deviation of the *p.d.f.* over flow, *Ft*, which we denote by m and s, respectively. We express this dependence explicitly by writing $R^*(m,s)$ as the optimal reservoir size as a function of the mean and standard deviation of flow.

Parameterization

We require parameterizing the cost function, the benefits function, the *p.d.f.* over flow, and the discount factor. We adopt the following parameters, which are loosely based on evidence from Northern California's reservoirs.

<u>Cost Function</u>

The costs or building a reservoir vary largely and it depends on a number of factors such as geography and runoff as well as the type of services provided by the stored water like hydropower generation, flood protection, seasonal irrigation or recreation, to name a few. These cost estimates contemplate neither environmental costs nor ecological impacts that may increase the marginal cost of providing additional supply of water. Costs estimates across the US to store additional water vary widely from as little as $1 per acre feet in wet regions up to $191 per acre feet in dry areas [2].

[3] We could have picked some other value of X at which to evaluate $J(X)$, but this seemed fair given that we were evaluating reservoirs of any size (including 0).

We assume a constant marginal cost (per unit volume) of producing a reservoir of size R, so $C(R) = cR$. Reservoir capacity is measured in million acre feet, and we use $c = \$2,000,000$.

Benefit Function

We assume an iso-elastic demand curve of the following form:

$$P(h) = ah^{-1/b} \tag{7}$$

where a is a scaling coefficient and $-1/b$ is the elasticity of demand. Several studies estimate the elasticity of demand of approximately -0.25 [9], so we adopt a value of $b = 4$. To determine a we solved $P(h)$ for a, yielding $ph^{1/b}$ Using $b = 4$ and typical values of price ($p = \$50M / MAF$) and quantity ($h = 24\,MAF$) yields $a = 1.107E8$ [19]. Per period benefit is the integral under this function up to consumption H_t, as follows:

$$p(H_t) = \int_0^{H_t} ah^{-1/b}\,dh = \frac{abH_t^{1-1/b}}{b-1} \tag{8}$$

We adopt a discount rate of 5% (and thus a discount factor of $d = 1/1.05 = .9524$.

Density of Flow

Using annual flow data into Northern California's five largest reservoirs[4], we estimated the parameters of a normal distribution governing F_t [20]. We arrived at the following parameters: $m = 25.09$ and $s = 7.88$.[5]

Results

Under the base case of mean and standard deviation of flow, we obtain $R^*(25.09, 7.88) = 7$ suggesting that the optimal reservoir capacity is around 7 million

[4] Real-time data publicly available at the California Department of Water Resources (CDWR). Department of Flood Management at http://cdec.water.ca.gov/cgi-progs/queryCSV . The five reservoirs are: Powell, Shasta, Oriville, Trinity and New Melones.
[5] All values are in Million Acre Feet ("MAF").

acre feet. Our principal question is how this number would change under various climate change scenarios for California. Holding m constant, an increase in s is expected to increase R^*. Holding s constant, and increase in m is expected to decrease R^*. The magnitude of increase or decrease is an empirical question, so we run the following experiment.

Let Δ_m and Δ_s be the percentage deviation (from the base case) of the mean and standard deviation, respectively. E.g. $\Delta_m = 0$ represents the base case mean of 25.09, and $\Delta_s = -20$ represents a 20% decrease in the base case standard deviation (from 7.88 to 6.3). Finally, let $\tilde{R}(\Delta_m, \Delta_s)$ be the percentage change in the optimal reservoir size as a function of the percentage change in m and s. Naturally, $\tilde{R}(0,0) = 0$.

The Figure 1 below illustrates the isoclines of $\tilde{R}(\Delta_m, \Delta_s)$. The scenario under which reservoir size would need to be expanded significantly is when the standard deviation significantly increases and the mean decreases. For example, one climate change forecast for the Shasta Lake drainage (PCM2050)[6] is to decrease annual mean inflow by about 15%, that is $\Delta_m = 15$ [10]. With no corresponding change in standard deviation, this forecast suggests a need to increase reservoir capacity by about 40%. If this decrease in the mean is met with a corresponding decrease in the standard deviation of about $\Delta_s = -12$, no change in reservoir size is required. On the other hand, several other climate change forecasts suggest an increase in mean flows, which suggest that we need smaller, not larger reservoirs (see Figure 1 below).

[6] PCM2050 stands for Parallel Climate model. A general circulation model with warm temperature dry precipitation by the year 2050. For details on this scenario, see 10. T. Zhu, M. W. Jenkins and J. R. Lund, Estimated Impacts of Climate Warming on California Water Availability Under Twelve Future Climate Scenarios, California Energy Comission. Public Interest Energy research (PIER) Program (2006).

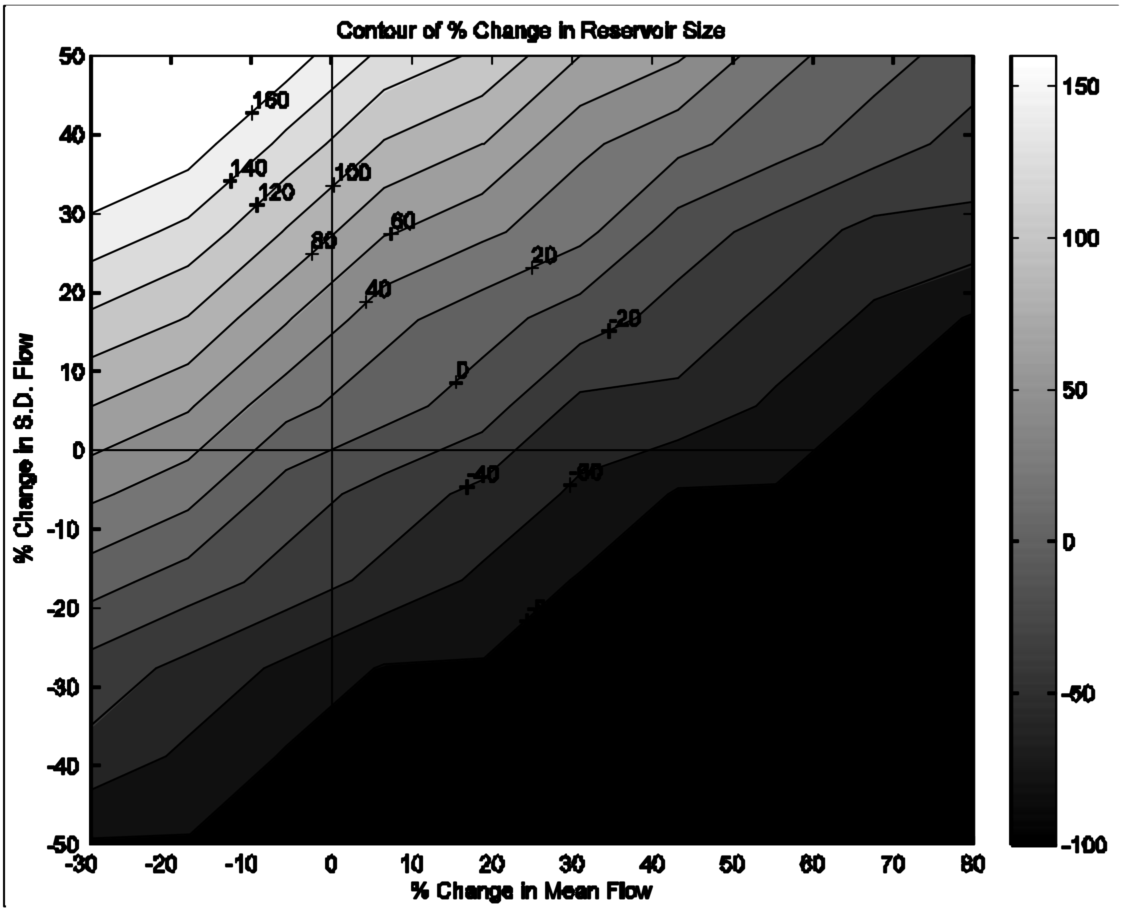

Figure 2. Isoclines for a change in reservoir size the horizontal axis represents percentage change in current mean. The vertical axis represents percentage change in current standard deviation. A movement towards the northwest of the origin represents an increase in reservoir capacity whereas a movement in the direction of the southwest represents a decrease in reservoir capacity.

Conclusions and further research

In this paper we analyze the dynamic nature of management of reservoirs and show that variability in flow and uncertainty drives reservoir capacity. In the paper we developed an analytical method to analyze optimal reservoir capacity for various climatic change conditions. We estimate the model by stochastic dynamic programming and parameterize the model with real data from five major reservoirs in Northern California. The empirical application shows the impacts on the optimal reservoir capacity for percentage changes in the current mean and in the current variance and sketched isoclines that represent optimal reservoir capacity for several combinations of change in mean and change in standard deviation. Our results are consistent with theoretical models in the economics literature. We illustrate that for a decrease in annual mean inflow with no corresponding change in standard deviation our results suggests a need to increase reservoir capacity. We show that if the decrease in the mean is met with a corresponding decrease in the standard deviation no change in reservoir size is required. The next step in our research is to extend the model to account for seasonal variations in flow and in demand and account for autocorrelated distributions of water flow.

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