Managing Water Use during Droughts of Unknown Duration

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Abstract

We propose that during a drought, the price of water should be a market-based estimate of a price determined after the drought that would have been appropriate. Our mechanism requires water users to purchase bonds for the highest reasonable estimate of the post-drought-determined price. The bond’s redemption value would be the difference between the bond’s face value and this price. To inform water users of the cost of water, and to ensure that buying bonds did not create undue burdens, these bonds would be tradable. The net revenue from the bonds would be distributed among water users.

I. Introduction

Consider a water reservoir that provides water to multiple users. The area suffers from a drought whose duration is unknown. What is the best approach to managing the reservoir during this time? We describe a regulatory system that uses a market to continuously adjust the cost of using water while implicitly revealing water users’ subjective beliefs about the duration of the drought.

It might seem optimal to divide the available water equally, permit users to trade among each other, and let each user manage his share according to his private belief regarding the duration of the drought. This solution is attractive as long as the plight of users who underestimate the length of the drought and hence run out of water prematurely does not concern the other users. But if the possibility of neighbors dying of thirst or losing their harvest motivates those who still have water to share their reserves when some users run out of water, then such implicit insurance might motivate some users to be overly optimistic about the drought’s duration. Parallel to arguments supporting mandatory purchase of health insurance, mandatory use of seat belts in cars, or mandatory depiction of
negative health effects from smoking on cigarette packages, there is an argument that water users might prefer a regulatory system that provides users with a strong incentive to not ignore shortages of water.

A simple regulatory system requires a regulator with appropriate knowledge of the area’s climatic and atmospheric conditions to estimate the length of the drought with sufficient precision. ¹ If this regulator also knows the water demand schedules of all users,² then she can set a price per gallon of water that leads to optimal water use for the duration of the drought. However, the regulator might not have better knowledge of the climatic and atmospheric conditions than the users, so it would be desirable to devise a regulatory system that provides users with incentives to (1) inform the regulator about their own beliefs regarding the length of the drought, and (2) conserve water according to their own beliefs regarding the severity of the drought even if the regulator seems to mis-estimate the drought’s severity.

The regulatory system that we propose here is an adaptation of the pricing mechanism for greenhouse gases described in Tideman and Plassmann (2010). That mechanism combines two well-established tools that facilitate decision making when costs are uncertain. The first tool is the requirement that those who might engage in potentially costly activities post some form of bail that will be refunded if the activity turns out not to impose any cost on society. Granting bail is a common approach to providing an incentive to those suspected of a crime to appear in court, where nonappearance leads to forfeiture of the bail. The environmental literature has introduced the idea of assurance bonds as bail for activities with potentially large social cost (see, for example, Constanza and Perrings, 1990, and Gerard and Wilson, 2007). Assurance bonds require that

¹ See Mishra and Singh (2011) for a review of the literature on drought modeling and on the prediction of the lengths of droughts.
polluters post bail (= purchase a bond with face value) equal to the estimate of the largest cost that today’s pollution might cause; the bail is used to cover any damages that are discovered in the future, and the bail is returned to the polluter if the polluter can prove that any possible damages will not occur. The obvious drawback of a bail system is that cash flow problems (or alternatively, the fees charged by bail bondsmen) might prevent worthwhile activities that have potentially large costs that are much greater than their expected costs.

The second tool is a prediction market that provides information about peoples’ beliefs regarding the occurrence of future events—for example, their beliefs about the result of a future effort to estimate the cost of today’s pollution. There is considerable evidence that prediction markets provide better estimates of future statistics than what might be obtained by averaging the surveyed opinions of those familiar with the events in question.3 Hence there is an interesting possibility of combining the concept of assurance bonds with a prediction market in which these bonds are traded. This will permit bond holders to avoid cash flow problems by immediately selling their bonds in this market, while allowing regulators to use the bond’s spot price—which reflect the market participants’ beliefs about the bond’s future redemption value—as guidance for estimating the expected severity of the risk that is faced.

In the present paper we offer a novel application of the concept of assurance bonds to water consumption during droughts of unknown duration. Our pricing mechanism requires users of water to purchase bonds whose face value is the regulator’s estimate of the upper bound on reasonable estimates of the cost of using water during the drought, reflecting the regulators’ belief about the longest drought that can reasonably be expected. The bond’s redemption value is set at the difference between the bond’s face value and the regulator’s post-drought

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3 See, for example, Dohlman et al. (2000), Berg et al. (2008), and Hamilton (2009).
estimate of the price of using water that would have been appropriate. The bond’s market price is determined in a secondary prediction market. The ability to trade the bonds ensures that the requirement to purchase bonds at a price that exceeds the expected cost of using water does not create cash-flow problems that would prevent users from consuming the amounts of water that are optimal for them. The bond’s price provides information about the beliefs of buyers and sellers of bonds regarding the prospective severity of the drought, and the rate at which bonds are purchased reveals the demand for water at the current net price (bond cost less market value of the bond).

The current application to droughts differs in two important aspects from the mechanism described in Tideman and Plassmann (2010). That pricing mechanism addresses the situation where emitters purchase assurance bonds for the harm caused by today’s emissions of CO₂, and it determines the bonds’ redemption value on the basis of the best estimate of this harm in 30 years. One difference between the two mechanisms stems from the source of the uncertainty that they accommodate: the mechanism in Tideman and Plassmann (2010) offers an improvement over traditional assurance bonds as well as over Pigouvian taxes that are levied on negative externalities whose harm is uncertain, while the current mechanism offers a solution to the efficient depletion of a resource when there is uncertainty about how long the resource needs to last.

The other difference stems from the resolution of the uncertainty in the two applications. In the current mechanism, the arrival of rain that ends the drought completely resolves the uncertainty regarding the drought’s duration, hence the mechanism provides users with an incentive to consume the amount of water that is objectively optimal ex post. Thus the bond’s redemption value can be defined in a way that does not require human judgment. But since the bond is redeemed only once it rains, its duration is uncertain. Unless there is a market for bonds of uncertain duration, the current mechanism requires the regulator to
estimate the appropriate interest rate, and water users bear the cost if the market discounts the bonds at a higher rate.

In contrast, the mechanism in Tideman and Plassmann (2010) makes use of the expectation that the uncertainty regarding the harm of today’s CO₂ emissions will be reduced, but not necessarily eliminated, 30 years from now. Hence the bond’s duration—30 years—is certain, and since there already is a market for 30-year zero-coupon bonds, polluters do not bear any additional cost related to an estimate of the appropriate interest rate. However, unless the cost of the emission in 2013 will be know with certainty in 2043, the bond’s redemption value still depends on an estimate in 2043 of the cost of the harm of emissions in 2013. Hence for the mechanism to work as intended, market participants must believe that in 30 years it will be possible to generate a valid estimate of this cost. Because there will be no disagreement about the appropriate redemption value of the bond that we introduce in this paper, the mechanism that we propose here is arguably less problematic.

We are not aware of any comparable pricing mechanism for the management of resource depletion under uncertainty. The literature on water management during droughts generally describes case studies of how countries, states, and municipalities have accommodated past droughts and plan to prepare for future droughts. For example, Renwick and Green (2000) report the effectiveness of different demand side management policies of eight California water agencies, indicating that price as well as non-price policies were effective in reducing demand. Olmstead and Stavins (2009) review the literature on various water conservation programs, including water-conserving technology standards, mandatory water use restrictions, combinations of conservation programs, as well as attempts to regulate water use by adjusting the price of water. They conclude that managing water demand by adjusting the price of water is more cost effective than non-price conservation programs, in addition to being easier to monitor and
to enforce. However, this literature does not address the particular difficulties that arise when a given stock of water must last for a period of unknown length.

The remainder of the paper is organized as follows. In Section 2, we establish the rules for optimal water consumption through the benchmark case of a single user who owns the reservoir. In Section 3, we describe the pricing mechanism for multiple users who have joint ownership of the reservoir. We compare the pricing mechanism with conventional regulation in Section 4, and we conclude in Section 5.

II. A single water user

Consider a water reservoir that is owned and used by just one person. The reservoir holds a certain amount of water; it empties as the owner uses water, and it is filled by rain. Once the water falls below a certain level, $\bar{S}$, the owner views the situation as a “drought” during which consumption might drain the reservoir completely in the absence of a systematic reduction in consumption.\footnote{If there is a minimum water level beyond which further drainage causes unacceptable damage to the reservoir, then “complete drainage” refers to drainage to that level.} Assume that, when rain comes, it ends the drought by filling the reservoir beyond $\bar{S}$. If time 0 marks the beginning of a drought—that is, the reservoir’s level is $\bar{S}_0 = \bar{S}$ —and no rain falls between time 0 and time $t$, then the reservoir’s water level at time, $S_t$, is

$$S_t = \bar{S}_0 - \int_0^t c_s \, ds$$

(1)

and $\dot{S}_t = -c_t$, where $c_t$ is the owner’s consumption of water at time $t$.

The owner’s utility is $\bar{V}$ when there is no drought and the water level is at least $\bar{S}$, and the owner receives utility $u(c_t)$ from water consumption at time $t$ during times of drought. Hence if the arrival of rain ends a drought at time $t$, then the present value of the owner’s utility at time 0 is
$$U_0 = \int_0^t u(c_s) e^{-s\theta} \, ds + \bar{V} e^{-t\theta},$$

where $\theta$ is the owner’s rate of time preference.

The arrival of rain follows a stochastic process, and optimal water use during times of drought depends on the memory properties of this process. A stochastic process is memoryless if the probability that it will rain within any specified number of days does not depend on how many days the drought has already lasted. A range of memory assumptions are reasonable. For example, if it is known from past experience that droughts in a specific region generally last between 75 and 125 days, then the fact that a drought has lasted 100 days might increase the probability of rain in the next 25 days. The appropriate memory assumption depends on the circumstances of the specific application. For the remainder of this paper, we assume that the arrival of rain follows a (memoryless) Poisson process. We do not want to argue that a Poisson process is necessarily most appropriate, but a Poisson process leads to a simple optimal consumption path of water that permits us to illustrate the characteristics of our regulatory mechanism with reasonable clarity.

If, at time 0, the reservoir’s level is $\bar{S}_0$ and the owner believes at time 0 that the arrival of rain follows a Poisson process with parameter $\lambda_0$ (the inverse of the expected value of the length of the drought at time 0), then the owner’s expected utility is:

$$E[U_0] = \int_0^\infty \left\{ \int_0^t u(c_s) e^{-s\theta} \, ds + \bar{V} e^{-t\theta} \right\} \lambda_0 e^{-t\lambda_0} \, dt$$

$$= \int_0^\infty (u(c_t) + \lambda_0 \bar{V}) e^{-t(\theta + \lambda_0)} \, dt.$$  

5 The second line in equation (3) follows from the first after integration by parts.
The owner determines the consumption path of water that maximizes his expected utility $E[U_0]$ subject to the state equation $S_t = c_t$, which he does by choosing the $c_t$'s that minimize the Hamiltonian
\[ H = u(c_t)e^{-t(\theta+\lambda_0)} + \mu_t(-c_t) \] (4)
with co-state variable $\mu_t$. If, for example, the owner’s utility function is
\[ u(c_t) = \frac{c_t^{1-\gamma-1}}{1-\gamma}, \] (5)
then the optimal consumption path of water is
\[ c^*_t(\lambda_0, S_0) = c^*_0(\lambda_0, S_0)e^{-\frac{(\theta+\lambda_0)t}{\gamma}} \] (6)
with $c^*_0(\lambda_0, S_0) = e^{\frac{\theta+\lambda_0}{\gamma}S_0}$. Thus optimal consumption is highest at time 0, and it decreases at a rate of $e^{-\frac{\theta+\lambda_0}{\gamma}}$ as the drought continues.

At some time $\tau$ during the drought, the owner might revise his estimate of the expected length of the drought; he incorporates this revision into his optimization process by adjusting the Poisson parameter. Hence if $\lambda_\tau$ denotes the Poisson parameter that the owner considers valid at time $\tau$ and $S_\tau$ is the reservoir level at time $\tau$, then the owner’s optimal consumption path from time $\tau$ onwards is
\[ c^*_t(\lambda_\tau, S_\tau) = c^*_t(\lambda_\tau, S_\tau)e^{-\frac{(\theta+\lambda_\tau)t}{\gamma}} \] (7)
with $c^*_0(\lambda_\tau, S_\tau) = e^{\frac{\theta+\lambda_\tau}{\gamma}S_\tau}$ and $t \geq \tau \geq 0$.

The drought ends when it rains at time $T$, resolving the uncertainty about the drought’s duration. Which consumption path can the owner reasonably wish in retrospect that he had chosen? *Ex post*, optimal consumption would have incorporated the knowledge that the drought would end at time $T$, hence avoiding uncertainty. But it seems fruitless for the owner to wish that he could have predicted the future with certainty; it seems more reasonable to acknowledge that the best he could have done prior to time $T$ would have been to assume $\lambda_t = ...
Different assumptions about what the owner could have foreseen might be reasonable in some cases; for example, depending on the memory structure of the stochastic process that governs the arrival of rain, it might be appropriate to assume that the parameters of the process would change as time progressed. Because we assume that the stochastic process is memoryless, consistency requires the assumption that $\lambda_t$ does not change over time. Thus in retrospect, the appropriate consumption path would have been

$$c_t^*(T, \bar{S}_0) = c_0^*(T, \bar{S}_0) e^{-\frac{(\theta + 1) t}{\gamma}}$$

(8)

with $c_0^*(T, \bar{S}_0) = \frac{(\theta + 1)}{\gamma} \bar{S}_0$, which differs from (7) as long as $\lambda_t \neq \frac{1}{T}$ for some $t$.

The reduction in the owner’s utility that results from determining his consumption path according to (7) rather than (8) is a measure of the cost of imperfect forecasting.

**III. Multiple water users**

Now consider a water reservoir that is owned by and that serves $n > 1$ users. If, at the beginning of the drought, the users divide the water equally among themselves so that every user receives $\bar{S}_0/n$, then user $j$ determines his optimal water usage according to

$$c_{jt}^* \left( \lambda_{0j}, \frac{\bar{S}_0}{n} \right) = c_{0j}^* \left( \lambda_{0j}, \frac{\bar{S}_0}{n} \right) e^{-\frac{(\theta_j + \lambda_{0j}) t}{\gamma_j}}$$

(9)

with $c_{0j}^* \left( \lambda_{0j}, \frac{\bar{S}_0}{n} \right) = \frac{(\theta_j + \lambda_{0j})}{\gamma_j} \bar{S}_0$, where a subscript $j$ indicates that the parameter is specific to user $j$. Users with high rates of time preference (large $\theta_j$) and low rates of decreasing marginal utility (small $\gamma_j$) who expect the drought not to last very long (large $\lambda_{0j}$) are likely to run low on water first. If such users can expect to receive support from other users who have more water left, then it might be
advantageous for any individual user to withdraw more water than would be
optimal given his endowment $S_0/n$, hence acting as if he were assuming that the
drought would not last very long. To preclude such moral hazard, the $n$ users
might want to manage water use according to an alternative regulatory
mechanism.

For regulatory effort to be successful there must be a regulator with some
knowledge of the users’ demand functions for water and an appropriate
understanding of the stochastic process that governs the arrival of rain. Hence,
for there to be any hope that regulation will improve upon the situation in which
users manage their water use individually, we must assume that there is a
regulator whom the users trust to determine a social welfare function of water
consumption, $W$, and hence the market demand function for water with sufficient
accuracy. If there is no such regulator, then water management by individual
users is likely to be best.

Part 1 of the regulatory mechanism: The mandatory purchase of a bond

Our regulatory mechanism requires that, at time $\tau$, the regulator estimate the
maximum remaining length of the drought that can reasonably be expected. One
simple way of estimating this length is to use the cumulative density function of
the stochastic process that governs the arrival of rain to determine the time span
during which it will rain with a probability of, say, 99%. Moyé and Kapadia
(1995) offer an alternative approach that relies on the non-parametric theory of
runs.

Denote by $T_\tau^{max}$ the regulator’s belief at time $\tau$ regarding the end of the
time span by which the drought will have ended with a probability of 99%. The
regulator uses the social welfare function $W$ and equation (7) to determine the
(conservative) consumption of water at time $\tau$ that would be optimal if $T^\text{max}_t - \tau$ were the expected value of the drought’s length, $^6$

$$c^*_\tau \left( \frac{1}{T^\text{max}_t - \tau}, \bar{S}_\tau \right) = \frac{\left( \theta + \frac{1}{T^\text{max}_t - \tau} \right)}{\gamma} \bar{S}_\tau,$$

(10)

where $\theta$ and $\gamma$ represent the social rate of time preference and the rate at which social marginal utility decreases with consumption, respectively. Knowledge of $W$, $c^*_\tau \left( \frac{1}{T^\text{max}_t - \tau}, \bar{S}_\tau \right)$, and the social budget constraint at time $\tau$ permits the regulator to determine the price $P \left( c^*_\tau \left( \frac{1}{T^\text{max}_t - \tau}, \bar{S}_\tau \right), W \right)$ per unit of water—say, one gallon—that provides users with the incentive to consume the amount of water that would be optimal at time $\tau$ if the drought were certain to end at $T^\text{max}_t$.

The mechanism requires that every user of water purchase, for every gallon that he wishes to consume at time $\tau$, a zero-coupon bond with face value $P \left( c^*_\tau \left( \frac{1}{T^\text{max}_t - \tau}, \bar{S}_\tau \right), W \right)$. If the drought ends at time $T < T^\text{max}_t$, the bond is redeemed for the overpayment that arose from the assumption that the drought would end at $T^\text{max}_t$ rather than $T$, plus interest for the bond’s duration of $T - \tau$. The bond pays the market daily interest rate $i_\tau$ that prevailed at time $\tau$. If the drought ends at $T > T^\text{max}_t$, then the bond’s redemption value is zero. If $T < T^\text{max}_t$, then, at time $T$, the regulator uses equation (8) to determine the consumption path of water that would have been optimal in retrospect, had the regulator assumed $\lambda_0 = \frac{1}{T}$ at every time from 0 to $T$; she also determines, for each $\tau$, the price per gallon of water $P \left( c^*_\tau \left( \frac{1}{T}, \bar{S}_0 \right), W \right)$ that would have provided users

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$^6$ At any time $\tau \geq 0$, the drought’s expected remaining length is $T^\text{max}_t - \tau$ if one believes that the arrival of rain is governed by a Poisson process with parameter $\frac{1}{T^\text{max}_t - \tau}$. Thus to determine planned consumption at any time $t \geq \tau$, the regulator assumes that $\lambda_t = \frac{1}{T^\text{max}_t - \tau}$. 
with the incentive to consume the prescribed amount of water, \( c_t^* \left( \frac{1}{T}, \bar{S}_0 \right) \), at time \( \tau \). The time \( T \) redemption value of a bond that was issued at time \( \tau \) is

\[
\rho_\tau = \max \left[ \left( P \left( c_t^* \left( \frac{1}{T_{t_{\max} - \tau}}, \bar{S}_\tau \right), W \right) - P \left( c_t^* \left( \frac{1}{T}, \bar{S}_0 \right), W \right) \right) e^{i_\tau (T - \tau)}, 0 \right].
\]

This redemption value implies that the user of a gallon of water at time \( \tau \) will be as well of as if (1) he had paid the price required for optimal consumption of water that was derived under the assumption that, at time 0, the drought had an expected duration of \( T \), and (2) he had invested the difference between the initial price and the final price in a zero-coupon bond with duration \( T - \tau \) that paid the daily interest rate \( i_\tau \). If \( T > T_{t_{\max}} \), then it seems appropriate not to charge users for having paid too little at time \( \tau \) since the price of water that the regulator determined at time \( T, P \left( c_t^* \left( \frac{1}{T}, \bar{S}_0 \right), W \right) \), was beyond what was she considered reasonably possible at time \( \tau, P \left( c_t^* \left( \frac{1}{T_{t_{\max} - \tau}}, \bar{S}_\tau \right), W \right) \). Preventing the redemption value from becoming negative accommodates this understanding.

The bond’s interest rate \( i_\tau \) should reflect the uncertainty of the bond’s maturity date. Since there is a general market for bonds with uncertain maturity dates (callable bonds), the regulator can use information from that market to determine an appropriate interest rate to pay on the bonds. She will also need to invest the revenue. Since she will need to redeem the bonds at an uncertain date, her investment choices will be either bank deposits with extremely low interest rates or government bonds that pay more but entail risk of a change in their value if they are redeemed prior to maturity. Determining an optimal investment strategy for this situation is beyond the scope of this paper. It will probably be sensible to require the bond holders to accept some risk of deficient interest payments to eliminate the possibility of default. This assignment of risk will be feasible because users who are required to purchase water bonds will have to
accept whatever terms are offered. However, we argue below that the closer $i_\tau$ is to the interest rate that would emerge from a market, the less objectionable it may be to require users to purchase water bonds.

**Part 2 of the regulatory mechanism: A spot market in which the bonds are traded**

The mechanism’s second part is a spot market in which the water bonds are traded. The bond’s price in this spot market reflects the beliefs of the market participants regarding the drought’s expected duration as well as their risk tolerance for the uncertainty regarding the bond’s maturity date and possibly its interest rate.

This bond market achieves three goals. First, it ensures that the requirement to pay a price that is derived from the maximum duration of the drought that can reasonably be expected at time $\tau$ does not prevent water use by those who would have been able to pay the price derived from the drought’s expected duration. Such users can immediately sell the bond at its current spot market price, $p_\tau$, and thus pay effectively only $P\left(c^*_\tau \left(\frac{1}{T^\max_{\tau}}, \bar{S}_\tau \right), W \right) - p_\tau$ per gallon.

As an example, consider a regulator who believes at time $\tau$ that there is a 99% probability that the drought will end within 100 days, and who estimates that a price of a gallon of water at time $\tau$ of $10 will lead to consumption $c^*_\tau \left(\frac{1}{100}, \bar{S}_\tau \right)$, which is optimal if the drought has that expected length. Market participants place the expected length of the drought at 40 days, and they estimate the appropriate price of a gallon of water at time $\tau$ to be $4 if the drought has that expected length. If the interest rate for a bond with an expected maturity date in 40 days is 0.01% per day compounded continuously, then the bond’s expected redemption value is $6.024$. If time is discounted continuously at a rate of 0.01% per day as well, then the bond’s time $\tau$ spot market price is $p_\tau = 6$. Hence a
water user could purchase the bond for $10 and sell it immediately on the spot market for $6, thereby paying the $4 per gallon of water that the spot market participants consider the efficient price.

To achieve the goal of not burdening water users by requiring them to pay too much for water, it is desirable that, if there is no general market for bonds with uncertain durations, the regulator identify, as accurately as possible, the interest rate \( i_\tau \) that reflects the uncertainty of the bond’s maturity date. The farther \( i_\tau \) falls below the effective market discount rate, the greater is the loss of a user who must sell the bond immediately. If, for example, the discount rate is 0.011% because market participants believe that the interest rate of 0.01% does not appropriately reflect the uncertainty of the bond’s duration, then the bond’s spot market price is only \( p_t = $5.998 \). Hence the water user loses about two-tenth of a cent if he sells the bond immediately.

The second goal of introducing the bond market is to provide the regulator with information about the beliefs of the market participants regarding the drought’s expected length. If the spot market price differs greatly from \( P \left( c_+^t \left( \frac{1}{T_{\tau \max} - \tau}, \bar{S}_\tau \right) , W \right) - P(c_+^t(\lambda_\tau, \bar{S}_\tau), W) \), where \( \lambda_\tau \) is the inverse of the regulator’s estimate of the expected length of the drought, then the regulator learns that the market participants’ beliefs regarding the expected length of the drought differs greatly from her own estimate; she can use this information to revise her estimate \( T_{t \max} \).

Last but not least, the bond market offers some protection to users from regulators who are incompetent or malfeasant. Because a bond issued at time \( \tau \) will have a redemption value of zero if it turns out that \( T > T_{t \max} \), the bond’s spot market price will fall to zero if the market participants believe that the regulator has greatly underestimated the expected length of the drought. The spot market price therefore signals that the regulator and the market participants have very
different beliefs regarding the expected duration of the drought. Conversely, if the regulator greatly overestimates the maximum length of the drought that can reasonably be expected relative to the market participants’ estimate, the spot market price of bonds will be high, thereby permitting water users to escape overly strict regulation.

Because the purpose of the bonds is to provide an incentive to consume the optimal amounts of water over time, rather than to generate government revenue, it is possible to redistribute the net revenue from the bonds among the water users when the drought is over (unless there is a very short drought and a severe loss in the value of the government bonds in which the revenue was invested). One possibility is to distribute the net revenue equally among all users, in the form of $n$ tradable water-revenue bonds with a redemption value equal to $1/n^{th}$ of the total net revenue after redeeming the water-usage bonds. Apart from transactions costs, the participant with average demand would get as much in water-revenue bonds as she paid in water-usage bonds. In comparison to distributing the revenue equally among the users after the drought has ended, tradable water-revenue bonds have the advantage of enabling users with cash-flow constraints to acquire water during the drought.

IV. Comparison of our regulatory mechanism with conventional regulation

Conventional regulation requires that the regulator estimate the expected length of the drought, $\frac{1}{\lambda_t}$, and then set either a price per gallon, $P(c^*(t), \tilde{S}_t, W)$, or a limit on the quantity of water that users can consume every day, $c^*(t, \lambda_t, \tilde{S}_t)$. Following the simple idea that additional observations are likely to increase the accuracy and precision of an estimator, it is desirable to base the estimate of $\lambda_t$ on as much input from informed persons as possible. There is considerable evidence that
prediction markets predict future outcomes of events with higher accuracy and precision than what non-market-based prediction methods like polls are able to deliver. Our secondary bond market is such a prediction market that provides participants with the incentive to offer their best estimates of the expected length of the drought. The regulator can therefore use the bond’s price to adjust her own estimate of $\lambda_r$, which is likely to lead to more efficient consumption of water during the drought.

Unlike conventional regulation, our pricing mechanism also provides users with an incentive to conserve water, even if the regulator grossly underestimates the length of the drought. Consider the case of an inexperienced regulator who knows much less about the area’s climatic and atmospheric conditions than the users who may have accumulated considerable experience with droughts in the area. Assume that the regulator underestimates the expected length of the drought considerably, with $\lambda_r \ll T$. Under a conventional regulatory mechanism, the regulator will either distribute too much water or set a price that is too low—hence users who expect the length of the drought to exceed the regulator’s expected length have an incentive to acquire and privately store more than the efficient amount of water, thus emptying the reservoir prematurely. In contrast, under our pricing mechanism, users know that the redemption value of their bonds will ultimately be based on the price that reflects the drought’s actual length, at least as long as $T_r^{\text{max}} > T$. Thus users have an incentive to overconsume water only if they believe that the bond’s spot market price exceeds the discounted present value of the bond’s expected redemption value. And even if the regulator’s expected upper limit $T_r^{\text{max}}$ is far too optimistic so that the bond’s spot market price falls to zero and users ultimately pay less than the efficient price for their consumption of water,
(1) the price suggested by this upper limit, \( P\left(c^*_t\left(\frac{1}{\tau_{\text{max}}},\tilde{S}_t\right),W\right) \), still exceeds the price \( P(c^*_t(\lambda_t,\tilde{S}_t),W) \) implied by the regulator’s expected length of the drought, thus leading to lower consumption than what one would observe under conventional regulation, and

(2) a bond market price of zero signals to the regulator that she may have severely underestimated the expected length of the drought, permitting her to adjust her estimate immediately.

Conventional regulatory mechanisms do not provide users with an incentive to act upon their own best estimate of the length of the drought if they believe that the regulator’s price is far too low.

Our regulatory mechanism is well suited for managing a water reservoir with instantaneous lateral flow during times of drought because the homogeneity of water implies that every user can be regarded as the marginal user. The mechanism is somewhat less well suited for applications in which users of identical amounts of water affect the water table in different ways. For example, consider the problem of managing the use of a groundwater aquifer in which the extraction of water through wells leads to cone-shaped depressions of the water table that fill slowly over time. If a well’s effect on the water table depends on the well’s location, then some water users impose a larger cost on their immediate neighbors than others do. Guilfoos et al. (2013) show that optimal groundwater management in a model that assumes instantaneous lateral flow (the so-called “bathtub model”) differs from optimal management if lateral water flow follows Darcy’s law. Because optimal water use differs across the locations of users under these circumstances, the bond’s price would differ across locations as well. Although location specific prices do not provide any conceptual difficulties for our pricing mechanism, market participants are unlikely to be able to estimate the
bonds’ redemption values if each bond applies to a specific location with a specific optimal depletion rate.

V. Conclusion

The regulatory mechanism that we describe in this paper offers a novel application of assurance bonds to the task of managing the optimal depletion of a resource when there is uncertainty about how long the resource needs to last. It is well suited for applications in which every user affects the resource in the same way and can therefore be regarded as the marginal user. Hence it is applicable to the management of water reservoirs during droughts of uncertain duration, to the management of oil reserves during times of emergency, and to the distribution of staple food during times of famine or bad harvests.

The pricing mechanism requires a regulator who can determine the optimal depletion rates of the resource for different spans of time for which the resource needs to last. The regulator must have sufficient knowledge of the nature of the emergency to estimate its duration with sufficient accuracy, and the regulator must also be able to determine the market demand schedule for the use of the resource. This is a minimum requirement for there to be any hope that any kind of regulation will improve upon the efficiency of decentralized allocation decisions. If the resource users do not trust the regulator to be able to determine acceptable depletion rates during as well as after the conclusion of the emergency, then individual resource management is their best alternative.
References


