Avoiding Water Shortages: Dynamic Ramsey Pricing Rule and Its Welfare Implications

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Motivation

- With high population growth and industrialization leading to higher levels of demand, renewable resources are more prone to shortages as the supply cannot meet the aggregate demand in a given period.
  1. Shift in the composition of the aggregate water demand,
  2. Six-fold rise in the aggregate water demand between 1900 and 1995 compared to three-fold increase in population.
- Meanwhile, environmental uncertainty (e.g. climate change) results in high volatility in stochastic recharge rates, which affects the resource management decisions and the performance of an economy.
- In addition to the increase in demand and the more volatile supply, cross-subsidization in resource pricing not only has efficiency implications for the resource allocation across user groups, but also adds to the frequency of shortages.

Research Questions

In this paper, we aim to answer the following questions:

- To avoid shortages, how does a benevolent water supplier choose between controlling demand (via increasing prices) and increasing supply (via desalination, networking)?
- To what extent does cross-subsidization distort the optimal flow and stock of water? What is the overall effect and is it significant?
- How does the balanced budget rule distort, if at all, the optimal sectoral consumption and water savings? What would happen if the supplier is allowed to save for the future?

Literature

- **Water Shortages:** In the world ... Canada (He and Horbulyk, 2010), Iran (Montazar et al., 2010), Spain (Roib'as et al., 2007), Middle East (Allan, 1997), Italy (Rossi and Somma, 1995), Denmark (Thomsen, 1993).

  In the United States ... Virginia in 2002 (Halich and Stephenson, 2009), California during 1970s and early 1990s (Hall, 2009), Texas High Plains (Seo et al., 2008), Tampa Bay (Yuhas and Daniels, 2006).
- **Welfare Effects of Shortages:** Elnaboulsi (2009), Roib'as et al. (2007), Woo (1994).
- **Ramsey Pricing:** Diakité et al. (2009), Garcia and Reynaud (2004), Schuck and Green (2002), Griffin (2001).
- **Crop Composition/Irr Technologies:** He and Horbulyk (2010), Montazar et al. (2010), Seo et al. (2008), de Fraiture and Perry (2002).
- **Dynamic Models:** Castelletti et al. (2008), Howitt et al. (2002), Schuck and Green (2002).

Key Features

1. We set up a dynamic model for optimal water flows and stock, while introducing two constraints:
   * Dynamic revenue constraint forces the supplier to *at least* break even.
   * Dynamic resource constraint is to account for aggregate demand and supply.
2. Any net revenue (after costs) can be saved to finance future costs.
3. The supplier has access to an external water resource (desalination technology, networking, spot markets), which can be used along with/instead of price increases.
4. We perform comparative dynamics to evaluate the effects of cross-subsidization on prices.

Main Findings

1. It is optimal for the planner to save some of its net revenues for the future.
2. Cross-subsidization distorts the optimal sectoral prices in favor of the preferred group. Without it, the central planner may find it optimal to make a loss from one user-group, and offsets it by charging a higher price to the other group.
3. Using water data from Turkey, we conclude that cross-subsidization does not significantly lead to shortages. The average stock without cross-subsidization equals $296.8\mathrm{hm}^3$ with a standard deviation of $3\mathrm{hm}^3$. When the central planner cross-subsidizes agriculture, the average stock drops only by about $4\mathrm{hm}^3$, which corresponds to 1.35 percent and is an insignificant decrease.

Agents

- Government (Water Utility): Manages water supply and sets the water prices.
- Consumers: Households demand for tap water.
- Producers: Agriculture demand for irrigation water.

Details

Timeline of the Problem

1. The supplier observes how much water and bonds are saved from last period.
2. The supplier chooses water prices before observing the shocks in the current period.
3. During the period,
   * the current shocks are observed,
   * the supplier releases water given tap and irrigation water demands.
   * the supplier *may bring* more water from the external source.
4. The supplier saves the rest of water and net revenue (bonds) for next period.

Benevolent Supplier

The supplier aims

- to maximize discounted expected lifetime utility of agents:
- subject to two constraints:
  1. dynamic resource constraint
  2. dynamic revenue constraint.

A water shortage occurs in any period, when the actual supply is less than the sum of aggregate demand for water and water savings.

$$\underbrace{w'(\boldsymbol{\theta})}_{\text{Savings}} + \underbrace{q_1(p_1;\boldsymbol{\theta}^o)}_{\text{Tap Water}} + \underbrace{q_2(p_2;\boldsymbol{\theta}^o)}_{\text{Irr Water}} > \underbrace{S(w,\boldsymbol{\theta}^o)}_{\text{Stock}};\ \exists\ \boldsymbol{\theta}^o$$

.

Recursive Formulation of the SDP Problem

$$V\left(w, b, \boldsymbol{\theta}_{-1}\right) = \max\ \mathcal{E}_{\boldsymbol{\theta}|\boldsymbol{\theta}_{-1}} \left\{ (\text{CS } + \delta \text{ Agr. Profits }) \frac{1}{1+\delta} + \beta\, V\left(w', b', \boldsymbol{\theta}\right) \right\}$$

$\ni$ Dynamic Resource Constraint,

Dynamic Revenue Constraint

Notation:

- $\boldsymbol{\theta}$: a vector of exogenous stochastic shocks that may affect the environment
- $\mathcal{E}_{\boldsymbol{\theta}|\boldsymbol{\theta}_{-1}}$: expectation operator over the current shock vector, given last period's shock vector
- δ: degree of cross-subsidization

Details

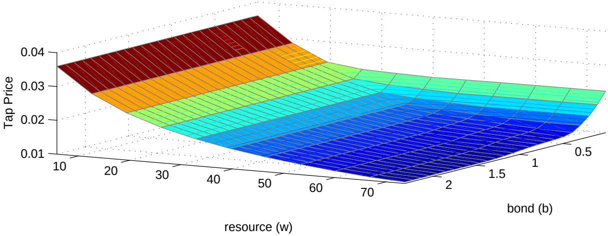
Sectoral Water Prices

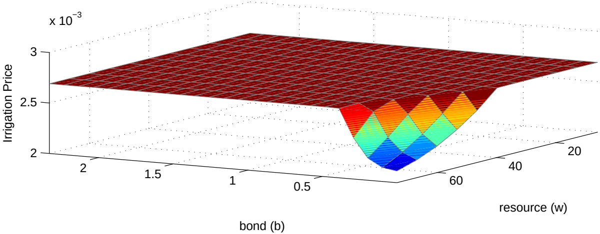
$$p_1 = \text{Inverse-Elasticity Rule} + \text{Marginal Value of Water} + \text{Marginal Cost}$$

- Inverse-Elasticity Rule is the effect of the revenue constraint
- Marginal Value of Water is the shadow price due to scarcity
- Marginal Cost is the marginal production and transfer cost.

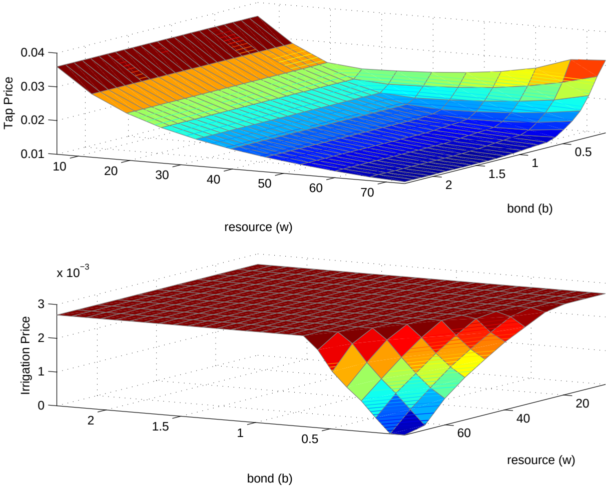
Details

Optimal prices with no cross-subsidization ($\delta = 1$)





Optimal prices with cross-subsidization ($\delta = 1.5$)



Comparative Dynamics

δ controls the degree of cross-subsidization

- If δ equals one, then the marginal rate of transformation between agricultural and households sectors equals one.
- If δ exceeds one, then the government values the agriculture's profits more, so the agricultural sector will be cross-subsidized.

Question: How does cross-subsidization affect water prices?

- The irrigation price declines as the degree of cross-subsidization increases
- The tap water price increases as δ increases because of the revenue constraint

External Water Demand

Suppose that marginal benefit of savings bonds is more than that of water, then two important results follow:

1. The demand for external water equals zero for at least one state of the shock vector.
2. The government's demand for external water is positive only during a water shortage.

External Water Use

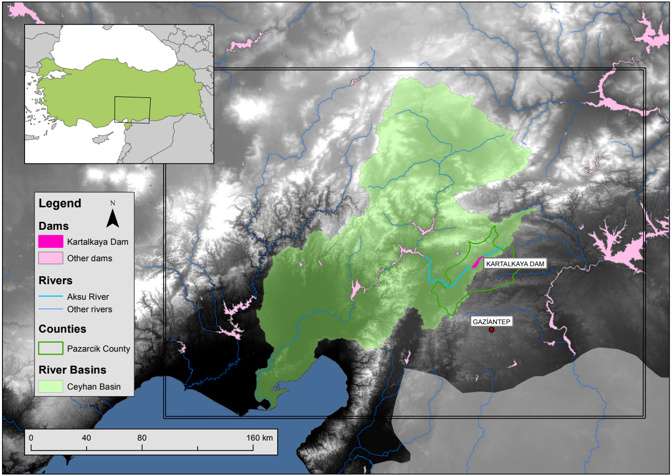
- If the price of the external supply is very high, then the government is not allowed to bring water from the external course.
- If the price of the external supply is very low, then water is essentially abundant: the government can use as much as it needs.

Question: How does the price of external water affect sectoral prices?

- Higher the price of the external supply makes it harder for the government to support the current stock with external water.
- The water prices increase to avoid shortages.

Figure: Geographical (GIS) Map of Cukurova

Details



Estimation Procedure

Data:

- Prices depends on the revenue constraint, but not on water scarcity.
- The ACP rule implies that price equals average cost.
- No bonds savings or no external water source.

Therefore, one can separate the two user groups to estimate the demand:

- Estimate the demand for tap and irrigation water
- Solve the SDP problem

Details

Simulation Results: Dynamic Ramsey Pricing (DRP) Rule

DRP Rule	p_x	δ	S	x	w'	q_1	q_2
mean	0.01	1	296.8146	1.3402	70.0863	110.7038	108.3712
std			2.9686	0.1064	0.7395	0.4284	1.7752
mean	0.01	1.1	294.5687	1.5726	67.8197	109.1651	112.6096
std			2.7043	0.1089	0.5452	0.587	2.1988
mean	0.01	1.25	293.5167	1.6739	66.7692	108.166	114.904
std			2.5794	0.1114	0.4354	0.6956	2.4544
mean	0.01	1.5	293.3023	1.708	66.5499	107.1563	116.2808
std			2.5546	0.1161	0.425	0.8317	2.6764
mean	0.01	2	292.2104	8.3477	65.428	93.8057	136.0284
std			2.447	0.5365	0.4273	1.9047	4.6355
mean	1	1	298.5194	0.017	71.8014	113.073	97.1029
std			3.1518	0.003	0.8154	0.1536	0.7774
mean	1	1.1	298.2909	0.0197	71.5911	111.6333	102.6497
std			3.1249	0.0028	0.799	0.225	1.3643
mean	1	1.25	297.8554	0.0237	71.0925	109.0693	110.5947
std			3.0744	0.0024	0.761	0.4932	2.2266
mean	1	1.5	296.5529	0.0288	69.7882	106.4173	116.2488
std			2.9186	0.0026	0.6445	0.8057	2.8683
mean	1	2	295.2347	0.0335	68.4743	104.8961	117.2604
std			2.7852	0.003	0.6313	1.0798	3.305
mean	5	1	298.5987	0.0031	71.8398	113.0921	97.0232
std			3.1614	0.0006	0.8186	0.1553	0.7732
mean	5	1.1	298.4652	0.003	71.7248	111.9931	101.407
std			3.1461	0.0006	0.8112	0.1942	1.2469
mean	5	1.25	298.1776	0.0044	71.3962	109.1672	110.4158
std			3.1125	0.0005	0.7854	0.4859	2.2665
mean	5	1.5	297.0587	0.0055	70.2928	106.5898	116.1413
std			2.9781	0.0005	0.6869	0.7869	2.8952
mean	5	2	295.2122	0.0066	68.4507	104.8416	117.235
std			2.7847	0.0006	0.6356	1.089	3.3289

Simulation Results: Dynamic Ramsey Pricing (DRP) Rule (cont.d)

DRP Rule	p_x	δ	Welfare	Cons. Surplus	Agr. Profits	Gov't Revenue	External Water Cost
mean	0.01	1	0.3914	0.3445	0.4382	0.1216	0
std			0.0518	0.0725	0.0694	0.0786	0
mean	0.01	1.1	0.3945	0.2002	0.5711	0.137	0
std			0.0565	0.0684	0.0652	0.086	0
mean	0.01	1.25	0.4098	0.1012	0.6566	0.1426	0
std			0.0579	0.0955	0.0935	0.0844	0
mean	0.01	1.5	0.441	-0.0259	0.7523	0.1437	0
std			0.0606	0.1264	0.1223	0.0851	0
mean	0.01	2	0.5449	-2.0081	1.8215	0.6836	0
std			0.0715	0.3474	0.2206	0.0997	0
mean	1	1	0.3139	0.4983	0.1296	0.1876	0
std			0.1128	0.2151	0.028	0.1721	0
mean	1	1.1	0.318	0.3731	0.268	0.2054	0
std			0.1133	0.2145	0.054	0.1771	0
mean	1	1.25	0.3364	0.1401	0.4935	0.2327	0
std			0.1166	0.2048	0.0674	0.1846	0
mean	1	1.5	0.375	-0.1415	0.7194	0.2593	0
std			0.1193	0.2192	0.1214	0.1931	0
mean	1	2	0.4457	-0.3755	0.8563	0.2893	0
std			0.1238	0.2424	0.1324	0.2155	0
mean	5	1	0.3128	0.498	0.1276	0.1888	0
std			0.1151	0.2199	0.0285	0.1754	0
mean	5	1.1	0.3154	0.4034	0.2355	0.2014	0
std			0.1141	0.2191	0.0509	0.1788	0
mean	5	1.25	0.3392	0.15	0.4906	0.2261	0
std			0.1177	0.2106	0.0853	0.1857	0
mean	5	1.5	0.376	-0.1173	0.7048	0.2552	0
std			0.1199	0.2192	0.1182	0.1936	0
mean	5	2	0.4433	-0.386	0.858	0.2948	0
std			0.1261	0.2454	0.1295	0.2213	0

Where To Now?

1. *Application:* This model can easily be applied to different datasets/regions.

2. *Policy Evaluation:* Using the Euler equation for optimal prices, we can indeed reverse engineer how much weight suppliers put on resource and revenue constraints? This could be done using Non-LS or GMM techniques.

3. *Water Markets:* We could endogenize the marginal cost of the external water and hypothesize to what extent a market for water could help avoid shortages in this setup.

4. *LPMs in Resource Management:* We could focus on the effect of shortages on agriculture using Lower-Partial Moments: Roseta-Palma and Saglam (2014) currently under progress.

Consumers: Households

- Consumers spend their fixed income on tap water and a composite good.
- Quasi-linear preferences for the utility function:
- Tap water may have different uses, such as drinking (price-non-responsive) and non-drinking (price-responsive) components.

$$\mathcal{U}(q_1, y; \boldsymbol{\theta}) = U(q_1 - \underline{q}_1; \boldsymbol{\theta}) + y$$

- Utility maximization problem leads to the total demand for tap water.

$$\max_{<q_1>} U(q_1 - \underline{q}_1; \boldsymbol{\theta}) - p_1 \; q_1$$
$$\Rightarrow U'(q_1 - \underline{q}_1; \boldsymbol{\theta}) = p_1$$

Producers: Agriculture

- Producers are identical farmers in a perfectly competitive output market.
- Mixed-Choice Problem:
  * Farmers choose which crop to produce.
  * Having chosen the crop, the farmers then decide how much land to allocate.

$$\begin{aligned} \Pi =& \max\left(\Pi_1, \Pi_2, \ldots, \Pi_N, \Pi_{N+1}\right), \text{ where} \\ \Pi_c =& \max_{<\ell_c, q_{2,c}>} p_c^F \; F_c(\ell_c, q_{2,c}) - p_2 \; q_{2,c} + \mu_c \; \ell_c; \; \forall c = 1, \ldots, N \\ \Pi_{N+1} =& \mu_{N+1} \ell_c \\ & \ni \ell_c \leq \bar{\ell} = 1 \end{aligned}$$

- Partial Equilibrium with iid shocks across farmers and time

Producers: Agriculture

Back

Given a distribution of the shocks, one can calculate

- Probability of choosing crop c: $\mathrm{Pr}(\mathrm{a_c} = 1 \mid \mathrm{p_2}, \boldsymbol{\theta})$
- Expected total profit by agriculture: $\mathcal{E}_{\boldsymbol{\theta}}\Pi(p_2; \boldsymbol{\theta})$
- Expected demand for irrigation water: $\mathcal{E}_{\boldsymbol{\theta}}q_2(p_2; \boldsymbol{\theta})$

Government Constraints

1. Dynamic Resource Constraint: Intertemporal resource allocation of water

$$w'(\boldsymbol{\theta}) + q_1(p_1;\boldsymbol{\theta}) + q_2(p_2;\boldsymbol{\theta}) \leq S(w,\boldsymbol{\theta}) + x(\boldsymbol{\theta});\ \forall\ \boldsymbol{\theta}, \tag{1}$$

Notation:

- $w'(\boldsymbol{\theta})$: water savings for next period
- $q_1(p_1;\boldsymbol{\theta}), q_2(p_2;\boldsymbol{\theta})$: demand for tap and irrigation water
- $S(w,\boldsymbol{\theta})$: stock of water in the reservoir
- $x(\boldsymbol{\theta})$: external water demand through desalination technology or networking.

Government Constraints

2. Dynamic Revenue Constraint:

$$b'(\boldsymbol{\theta}) + p_x\ x(\boldsymbol{\theta}) \leq (p_1 - c_1)\ q_1(p_1; \boldsymbol{\theta}) + (p_2 - c_2)\ q_2(p_2; \boldsymbol{\theta}) + \\ R\ b - \tau;\ \forall\ \boldsymbol{\theta}, \tag{2}$$

Notation:

- $b'(\boldsymbol{\theta})$: bond savings for next period
- $p_x\ x(\boldsymbol{\theta})$: cost of external water purchase
- $R\ b$: return on bond from last period
- c_1, c_2: marginal cost of production for tap and irrigation water
- τ: fixed cost of water production

Dynamic Ramsey Pricing

Back

$$V\left(w, b, \boldsymbol{\theta}_{-1}\right)=\max_{<\mathbf{p}, w'(\boldsymbol{\theta}), b'(\boldsymbol{\theta}), x(\boldsymbol{\theta})>} \mathcal{E}_{\boldsymbol{\theta}|\boldsymbol{\theta}_{-1}}\left\{\frac{U\left[q_1(p_1;\boldsymbol{\theta})\right]-p_1\ q_1(p_1;\boldsymbol{\theta})+\delta\ \Pi(p_2;\boldsymbol{\theta})}{1+\delta}\right\}+$$

$$\beta\ \mathcal{E}_{\boldsymbol{\theta}|\boldsymbol{\theta}_{-1}}\left[V\left(w'(\boldsymbol{\theta}), b'(\boldsymbol{\theta}), \boldsymbol{\theta}\right)\right]$$

$$\ni w'(\boldsymbol{\theta})+q_1(p_1;\boldsymbol{\theta})+q_2(p_2;\boldsymbol{\theta}) \leq S(w,\boldsymbol{\theta})+x(\boldsymbol{\theta});\ \forall\ \boldsymbol{\theta},$$

$$b'(\boldsymbol{\theta})+p_x\ x(\boldsymbol{\theta}) \leq (p_1-c_1)\ q_1(p_1;\boldsymbol{\theta})+(p_2-c_2)\ q_2(p_2;\boldsymbol{\theta})+R\ b-\tau;\ \forall\ \boldsymbol{\theta},$$

$$q_1(p_1;\boldsymbol{\theta}), q_2(p_2;\boldsymbol{\theta}), w'(\boldsymbol{\theta}), x(\boldsymbol{\theta}) \geq 0$$

Estimation: Irrigation Water Back

- Tap water price:

$$p_1 = \left[\frac{\mathcal{E}_{\boldsymbol{\theta}}(\mu(\boldsymbol{\theta}) - 1/(1+\delta)) \ (-q_1(p_1;\boldsymbol{\theta}))}{\mathcal{E}_{\boldsymbol{\theta}}\mu(\boldsymbol{\theta}) \ \partial q_1(p_1;\boldsymbol{\theta})/\partial p_1} \right] + \frac{\mathcal{E}_{\boldsymbol{\theta}}(\lambda(\boldsymbol{\theta}) \ \partial q_1(p_1;\boldsymbol{\theta})/\partial p_1)}{\mathcal{E}_{\boldsymbol{\theta}}(\mu(\boldsymbol{\theta}) \ \partial q_1(p_1;\boldsymbol{\theta})/\partial p_1)} + c_1.$$

- Irrigation water price:

$$p_2 = \left[\frac{(\delta/(1+\delta)) \ \partial \mathcal{E}_{\boldsymbol{\theta}}\Pi(p_2;\boldsymbol{\theta})/\partial p_2 - \mathcal{E}_{\boldsymbol{\theta}}\mu(\boldsymbol{\theta}) \ q_2(p_2;\boldsymbol{\theta})}{\mathcal{E}_{\boldsymbol{\theta}}\mu(\boldsymbol{\theta}) \ \partial q_2(p_2;\boldsymbol{\theta})/\partial p_2} \right] + \frac{\mathcal{E}_{\boldsymbol{\theta}}\lambda(\boldsymbol{\theta}) \ \partial q_2(p_2;\boldsymbol{\theta})/\partial p_2}{\mathcal{E}_{\boldsymbol{\theta}}\mu(\boldsymbol{\theta}) \ \partial q_2(p_2;\boldsymbol{\theta})/\partial p_2} + c_2.$$

Data

- Data collection:
  - Water flows data from the State Water Works
  - Irrigation price and land allocation data from the local water user associations
  - Tap price, quantity, and water sanitation data from the municipality
  - Climatic variables from Turkish Meteorological Institute
- Monthly time-series data from 01/1984 to 08/2007
- Irrigation prices and land allocation are yearly data from 1984 to 2007.

Figure: Reservoir Flows

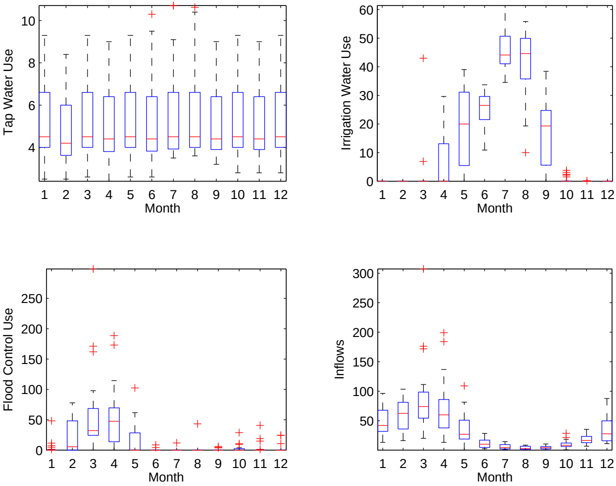


Figure: Crop Composition

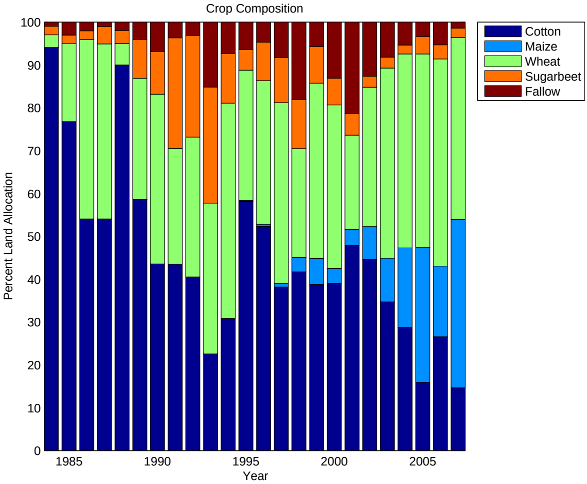


Figure: Tap Price vs Revenue: Inelastic demand for tap water.

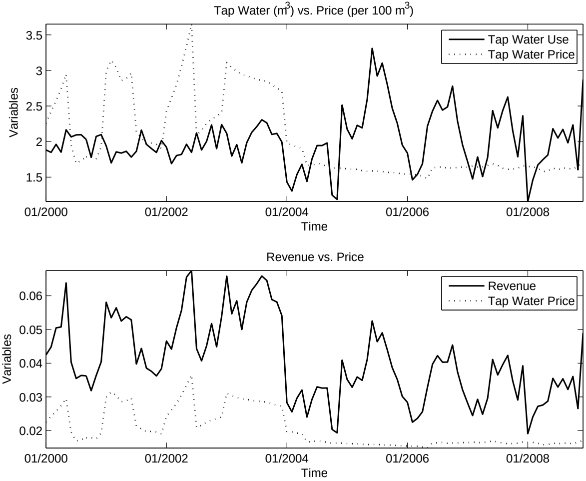


Figure: Irrigation Prices

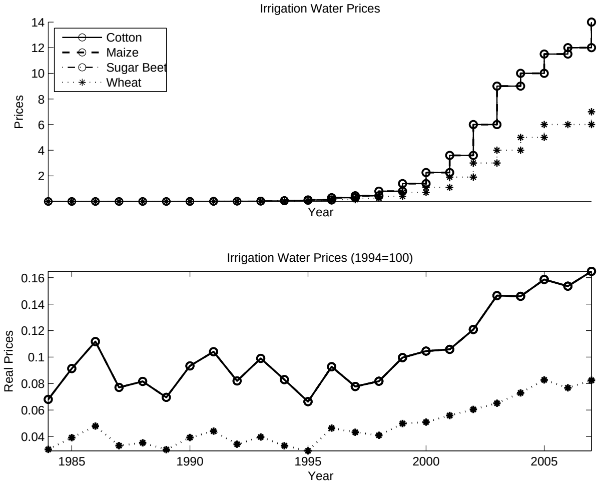


Figure: Irrigation Water Demand

Back

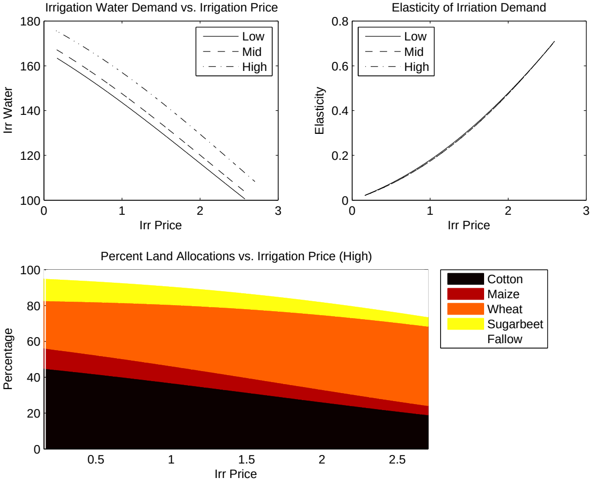


Figure: Irrigation Water Demand

Solving the SDP Problem

- I aggregated the flows data to annual frequency to have a single value function:
  - Estimate the Tobit model for the water release for flood control,
  - Estimate AR(1) process for the crop prices,
  - Fit the gamma distribution for the annual inflows,
  - Use Chebychev Polynomials to approximate the value function.
- Solve the SDP problem for different values of δ and p_x.
- Simulate the economy for 100 years for $5,000$ times across δ and p_x under the ACP and DRP rules.
- Compute the summary statistics for key variables in each case.

Simulation Results: Average-Cost Pricing (ACP) Rule

ACP Rule	p_x	δ	S	x	w'	q_1	q_2
mean	0.01	1	233.6464	15.2873	6.1326	95.3225	147.4785
std			4.555	1.7694	2.84	0	0.0305
mean	0.01	1.1	233.6464	15.2873	6.1326	95.3225	147.4785
std			4.555	1.7694	2.84	0	0.0305
mean	0.01	1.25	233.6464	15.2873	6.1326	95.3225	147.4785
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mean	0.01	1.5	233.6464	15.2873	6.1326	95.3225	147.4785
std			4.555	1.7694	2.84	0	0.0305
mean	0.01	2	233.6464	15.2873	6.1326	95.3225	147.4785
std			4.555	1.7694	2.84	0	0.0305
mean	1	1	233.6464	15.2873	6.1326	95.3225	147.4785
std			4.555	1.7694	2.84	0	0.0305
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std			4.555	1.7694	2.84	0	0.0305
mean	5	1	233.6464	15.2873	6.1326	95.3225	147.4785
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std			4.555	1.7694	2.84	0	0.0305

Simulation Results: Average-Cost Pricing (ACP) Rule (cont.d) Back

ACP Rule	p_x	δ	Welfare	Cons. Surplus	Agr. Profits	Gov't Revenue	External Water Cost
mean	0.01	1	-0.7006	-1.7449	2.476	0.0001	1.0662
std			0.4061	0	0.083	0.0004	0.4159
mean	0.01	1.1	-0.6001	-1.7449	2.476	0.0001	1.0662
std			0.4057	0	0.083	0.0004	0.4159
mean	0.01	1.25	-0.4661	-1.7449	2.476	0.0001	1.0662
std			0.4052	0	0.083	0.0004	0.4159
mean	0.01	1.5	-0.2785	-1.7449	2.476	0.0001	1.0662
std			0.4046	0	0.083	0.0004	0.4159
mean	0.01	2	0.0028	-1.7449	2.476	0.0001	1.0662
std			0.4037	0	0.083	0.0004	0.4159
mean	1	1	-106.2611	-1.7449	2.476	0.0001	106.6266
std			41.5815	0	0.083	0.0004	41.5933
mean	1	1.1	-106.1606	-1.7449	2.476	0.0001	106.6266
std			41.5809	0	0.083	0.0004	41.5933
mean	1	1.25	-106.0266	-1.7449	2.476	0.0001	106.6266
std			41.5802	0	0.083	0.0004	41.5933
mean	1	1.5	-105.839	-1.7449	2.476	0.0001	106.6266
std			41.5792	0	0.083	0.0004	41.5933
mean	1	2	-105.5576	-1.7449	2.476	0.0001	106.6266
std			41.5776	0	0.083	0.0004	41.5933
mean	5	1	-532.7678	-1.7449	2.476	0.0001	533.1334
std			207.9546	0	0.083	0.0004	207.9664
mean	5	1.1	-532.6673	-1.7449	2.476	0.0001	533.1334
std			207.9541	0	0.083	0.0004	207.9664
mean	5	1.25	-532.5333	-1.7449	2.476	0.0001	533.1334
std			207.9533	0	0.083	0.0004	207.9664
mean	5	1.5	-532.3457	-1.7449	2.476	0.0001	533.1334
std			207.9523	0	0.083	0.0004	207.9664
mean	5	2	-532.0644	-1.7449	2.476	0.0001	533.1334
std			207.9507	0	0.083	0.0004	207.9664