Integrating the Value of Reservoir Storage into Water Tariff Design: Application to Multipurpose Hydropower Regulation
Outline

• Context

• Model & research question/objectives

• Results

• Discussion
Multipurpose Hydropower Reservoir Regulation Under Variable Rainfall & Electricity Prices

Trade-offs
Foregone hydro profits
Dynamic value of water & energy services
Irrigation water pricing?

Hydropower boom
Efficiency of water allocation?
Conventional regulation not flexible
Tariff design?

Conventional hydropower regulation

But efficient water reallocation requires dynamic regulation not just operating boundaries & information
Theoretical approach & contribution

• Opportunity costs are fundamental to water resources governance

• Marginal User Cost (MUC):
  • ‘foregone benefit from not having an additional unit of water storage available in the future’

• MUC can be estimated (e.g. Moncur & Pollack 1988)
Theoretical approach & contribution

- Water tariffs and (volumetric) water prices
- Opportunity costs rarely incorporated into water tariffs:
  - Calculation not straightforward, not transparent for water consumers
  - Price spikes with expected water scarcity
    & ↑ cost of inputs
- Other regulatory objectives generally prioritised over efficiency in tariff design
Theoretical approach & contribution

• Many studies on water tariff design
  • e.g. Turvey (1976); Feldman (1972); Renzetti (1992); Olmstead & Stavins (2009)

• Pulido-Velazquez et al. (2013) use hydro-economic simulations to calculate user cost for multi-reservoir system
  • Raw values processed into storage-dependent step function
  • Followed by Macian-Sorribes et al. (2015) and Lopez-Nicolás (2018)
Khadem et al. (2018) estimate economic value of interannual storage

Chu and Grafton (2018) derive ‘risk-adjusted user cost’ for water pricing in the ACT
  • Optimal timing of supply-side investment
  • Avoidance of welfare-reducing water restrictions

All previous studies use some form of mathematical programming to calculate MUC

None consider pricing water services provision from a hydropower reservoir
Contributions & Research Question

• Contributions:
  1. First paper on water tariff design for regulating multipurpose hydropower reservoirs
  2. ‘Rule of thumb’ (heuristic) to estimate marginal user cost without mathematical programming

• Research question:
  • What is the optimal design of irrigation water tariffs for hydropower governance in the presence of electricity price spikes and electricity supply obligations?
Price stability (PS) tariff vs marginal user cost (MUC) tariff?

- PS is retrospective average
- MUC is estimated value of future benefits foregone by current extractions

What are costs of price stability controls?

- Foregone hydro profits
- Foregone electricity
- Electricity purchases
- Water allocation efficiency

Objective function:

- Hydropower profit maximization
- Control is hydro extractions
- Stochastic dynamic programming
- Aggregate results 1000 simulations (basic model + sensitivity analysis)
Hydropower generation scheduling

Hydropower operator knows available reservoir storage ($S_t$), the season ($\phi_t$), marginal electricity revenue ($r_t$) & the environmental flows ($v_t$) & evaporation ($\xi_t S_t$) during period $t$.

Hydropower operator calculates water price ($p_t$) according to expectations of electricity prices ($L_{t+1}$) or current and previous prices ($L_t, L_{t-1}, L_{t-2}$).

Operator schedules period $t$ water allocation to hydropower generation ($x_t$).

Environment flows ($v_t$) are released and evaporation ($\xi_t S_t$) occurs.

The current period weather state ($B_{t+1}$) is known and inflows ($f_t$) occur.

Farmers’ water demand function shifts according to weather/season state ($\gamma_t(B_t)$) & water price ($p_t$). Irrigation extractions ($\bar{y}_t$) occur.

Operator estimates period $t$ irrigation water demand ($\bar{y}_t$). [MUC tariff is updated with scarcity premium if electricity imports expected in period $t+1$]

Operator estimates value of different storage levels for beginning of the next period ($S_{t+1}$) given the transition of weather ($B_{t+1}$) and electricity prices ($L_{t+1}$).

The period $t+1$ starting storage level is known ($S_{t+1}$).

The new electricity price level ($r_{t+1}$) becomes known and expectations are formed of the value of different levels of storage in $t+2$.
Stochastic variables

Markov processes for stochastic weather \((B_t)\) and stochastic electricity prices \((L_t)\)

| Probability of Dry, Normal, and Wet Weather in the forthcoming Winter Season \((\phi_t = 2)\) | Probability of Dry, Normal, and Wet Weather in the forthcoming Summer Season \((\phi_t = 1)\) |
|---|---|---|---|---|---|
| \(\tilde{C}_t\) | \(B_t = d\) | \(B_t = n\) | \(B_t = d\) | \(\tilde{C}_t\) | \(B_t = d\) | \(B_t = n\) | \(B_t = w\) |
| \(d\) | 0.6 | 0.3 | 0.6 | \(d\) | 0.5 | 0.2 | 0.3 |
| \(n\) | 0.3 | 0.4 | 0.3 | \(n\) | 0.4 | 0.6 | 0.4 |
| \(w\) | 0.1 | 0.3 | 0.1 | \(w\) | 0.1 | 0.2 | 0.3 |
Irrigation water demand, price & weather

\[ i_t = \begin{cases} \gamma_t(p_t)^\alpha & \text{if } \gamma_t(p_t)^\alpha \leq S_t + \tilde{f}_t - x_t - \xi_tS_t - v_t - S_{RISK} \\ \max(0, S_t + \tilde{f}_t - x_t - \xi_tS_t - v_t - S_{RISK}) & \text{otherwise} \end{cases} \]

Excess irrigation demand can occur
Water tariffs

Standard Volumetric (SV) Tariff

Marginal revenue from hydropower generation in period $t = r_t$

$$p_t = \frac{1}{a} \times (g_t(L_t) + \theta c \bar{c})$$

Production parameter of water

Renewable energy certificate revenue

Price Stability (PS) Tariff (3-period average)

Fixed probability water scarcity premium

$$p_t = \frac{1}{a} \times \left( \frac{(1 + \omega(\psi - 1))(g_t(L_t) + g_t(K_t) + g_t(J_t))}{3} + \theta c \bar{c} \right)$$

Electricity price 2 periods ago
Marginal User Cost (MUC) Tariff

1. Assume an additional unit of water storage generates hydropower in \( t+1 \)

2. Estimate expected marginal hydropower revenue in \( t+1 \) and calculate expected volumetric water price

3. Calculate expected storage at beginning of \( t+1 \)
   - Assume period \( t \) hydropower generation meets electricity supply obligation
   - Estimate period \( t \) expected inflows from \( t-1 \) weather
   - Estimate expected irrigation extractions from Step (2) price
Marginal User Cost (MUC) Tariff

4. If expected storage at beginning of period $t+1$ is less than water volume equating to minimum electricity supply obligation:
   
   - Augment volumetric price in Step (2) with premium reflecting higher cost of purchasing electricity

\[
p_t = \begin{cases} 
\frac{1}{a} \times (E(g_{t+1}(L_t)) + \theta^c \bar{c}) & \text{if } \frac{1}{a} \times (E(S_{t+1}|x_t = x(e_{MIN})) - S_{IRR}) \geq e_{MIN} \\
\frac{1}{a} \times ((\psi - 1) \times E(g_{t+1}(L_t)) + \theta^c \bar{c}) & \text{if } \frac{1}{a} \times (E(S_{t+1}|x_t = x(e_{MIN})) - S_{IRR}) < e_{MIN}
\end{cases}
\]

Water scarcity premium
\[
E(S_{t+1}|x_t = x(e_{MIN})) = S_t + E(\tilde{f}_t(B_t, \phi_t)) - E(\tilde{i}_t(B_t, L_t)) - \xi_t S_t - v_t
\]
Profit functions (SV Tariff)

Hydropower

\[
\pi^H_t(B_t, K_t, L_t, x_t) = \frac{1}{a} \times x_t \times r_t(L_t) - \psi g_t(L_t) \times \max(0, e_{MIN} - e_t(x_t)) + i_{t-1}(B_t, K_t) \times p_{t-1}(K_t)
\]

Irrigation

\[
\pi^I_t(B_t, L_t, x_t) = \frac{\alpha}{\gamma_t(B_t)\bar{\alpha}(\alpha + 1)} \left( \frac{\alpha+1}{\alpha+1} i_t^{\alpha}(B_t, L_t, x_t) - i_{CHOKE_t} \frac{\alpha+1}{\alpha}(B_t) \right)
\]

\[
+ p_{CHOKE} \times i_{CHOKE_t}(B_t) + p_t(L_t) \times \hat{r}_t(B_t, L_t, x_t)
\]
Solving the model for optimal hydropower extractions

Bellman equation (SV Tariff)

\[
V(S_t, \phi_t, B_t, K_t, L_t) = \max_{x_t} \left[ \pi_t^H(S_t, \phi_t, B_t, K_t, L_t) + \frac{1}{1 + \rho} EV(S_{t+1}, \phi_{t+1}, B_{t+1}, K_{t+1}, L_{t+1}) \right]
\]

Stochastic Dynamic Programming

- Backward induction to calculate value of all coordinates in the state space
- Forward simulation with randomised timepath for stochastic weather and electricity prices
## Aggregate results

1000 simulations; 10 years (20 seasons)

**Costs:** ↓ hydro profits ↓ electricity generation  
↑ electricity purchases ↓ efficiency water allocation

**Subsidy:** ↑ irrigation profits & extractions (PS Tariff)

<table>
<thead>
<tr>
<th>Tariff</th>
<th>Average water extractions (St. dev.)</th>
<th>Average NPV benefits (St. dev.) $ millions</th>
<th>Electricity generation GWh</th>
<th>Electricity purchases GWh</th>
<th>Average NPV of cost of electricity purchases $ millions</th>
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<tbody>
<tr>
<td>Standard Volumetric</td>
<td>474.7 GL (72.4 GL)</td>
<td>$83.3 ($14.6)</td>
<td>900.4 (137.3)</td>
<td>215.5 (51.3)</td>
<td>$12.9 ($4.0)</td>
<td>266.8 GL (23.0 GL)</td>
<td>$52.8 ($4.0)</td>
<td>$136.1 ($11.6)</td>
</tr>
<tr>
<td>Price Stability</td>
<td>481.0 GL (72.0 GL)</td>
<td>$84.8 ($14.9)</td>
<td>912.4 (136.6)</td>
<td>204.8 (51.6)</td>
<td>$12.3 ($4.0)</td>
<td>257.7 GL (23.7 GL)</td>
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<td>Marginal User Cost</td>
<td>492.2 GL (67.4 GL)</td>
<td>$91.5 ($13.5)</td>
<td>933.6 (127.9)</td>
<td>172.9 (54.9)</td>
<td>$10.5 ($4.3)</td>
<td>236.4 GL (14.6 GL)</td>
<td>$49.1 ($2.7)</td>
<td>$140.6 ($11.5)</td>
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</table>
Histogram of foregone hydropower profits
Water prices for an example simulation
Time path of cumulative hydropower profits for example simulation

Total MUC profits – Total PS profits = $8.9 mill (~8% fall under PS Tariff)
<table>
<thead>
<tr>
<th>Scenario</th>
<th>Costs of price stability controls</th>
<th>Indirect irrigation subsidy</th>
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<tbody>
<tr>
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<td>Foregone hydropower benefits $ millions</td>
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<tr>
<td>Primary model</td>
<td>$6.6 (7.3%)</td>
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<td>Minimum electricity supply obligation</td>
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<tr>
<td>$e_{MIN} = 0$</td>
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Summary of key results:

• Price controls reduce hydro profits (7% to 14%) relative to marginal user cost tariff

• Price controls indirectly (& inefficiently) subsidise irrigation water provision

• Heuristic for estimating marginal user cost for extractions from multipurpose water storage

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NPV Hydropower Benefits MUIC Tariff - NPV Hydropower Benefits PS Tariff for each simulation ($ millions)
Discussion

1. **Price stability controls generate private/social costs**
   - Subsidies do not come for free
   - Tariffs need to provide incentives for multipurpose operations

2. **Incorporating MUC in water tariffs is practically achievable**
   - But harder for more water uses and non-market values
Discussion

3. Price stability controls can prevent efficient water reallocation to irrigation
   • Dynamic inefficiency
   • Locking in high prices (e.g. RET)

4. “One policy instrument, one objective”
   • Tinbergen principle applies to water pricing (but some exceptions)
   • Alternative irrigation support measures:
     • Cash transfers & rebates
     • Extension & supply-chain support
Thank you

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References


Additional slides
Calculating irrigation profits

Irrigation profits \((A+B) = \) Total benefits of water extraction \((A+B+C+D)\) – Total costs of water extraction \((C+D)\)

Define inverse demand function and choke price to find profit function
<table>
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<th>Variable</th>
<th>Mathematical Notation</th>
<th>Value</th>
</tr>
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<tr>
<td>Minimum and maximum storage volume</td>
<td>$S_{MIN}, S_{MAX}$</td>
<td>150000 ML, 449000 ML</td>
</tr>
<tr>
<td>Risk storage level volume</td>
<td>$S_{RISK}$</td>
<td>164000 ML</td>
</tr>
<tr>
<td>Irrigation buffer storage volume</td>
<td>$S_{IRR}$</td>
<td>217000 ML</td>
</tr>
<tr>
<td>Inflows, by season and weather type</td>
<td>$F = {f_{\phi=1,d}, f_{\phi=1,n}, f_{\phi=1,w}}$</td>
<td>${18227 ML, 22679 ML, 39375 ML}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>${59850 ML, 88207 ML, 122905 ML}$</td>
</tr>
<tr>
<td>Random inflow shock</td>
<td>$\varepsilon_t$</td>
<td>$0.87 w.p. 0.2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.97 w.p. 0.2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1 w.p. 0.2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.03 w.p. 0.2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.13 w.p. 0.2$</td>
</tr>
<tr>
<td>Evaporation rate of storage</td>
<td>$\xi_t = {\xi_{t=1}, \xi_{t=2}}$</td>
<td>0.138</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.049</td>
</tr>
<tr>
<td>Seasonal environmental flows</td>
<td>$v_t = {v_{\phi=1} \text{ if } \phi = 1, v_{\phi=2} \text{ if } \phi = 2}$</td>
<td>${4000 ML}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>${1000 ML}$</td>
</tr>
<tr>
<td>Electricity price levels ($/MWh$)</td>
<td>$L = {L_1, L_2, L_3}$</td>
<td>${31.96$, $44.40$, $102.31}$</td>
</tr>
<tr>
<td>Conversion factor for water releases into energy (MWh/ML)</td>
<td>$\alpha$</td>
<td>0.5272</td>
</tr>
<tr>
<td>Maximum extractions for hydropower</td>
<td>$X_{MAX,\phi_t} = {X_{MAX,\phi_t=1}, X_{MAX,\phi_t=2}}$</td>
<td>${65681 ML}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>${66044 ML}$</td>
</tr>
<tr>
<td>Price elasticity of water demand</td>
<td>$\alpha$</td>
<td>-0.81</td>
</tr>
<tr>
<td>Fixed seasonal irrigation extractions (ML)</td>
<td>$\bar{\phi}<em>t = {\bar{\phi}</em>{t=1}, \bar{\phi}_{t=2}}$</td>
<td>${15114 ML}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>${14895 ML}$</td>
</tr>
<tr>
<td>Weather and electricity price transition matrices</td>
<td>See Appendix A3 in Chapter 3</td>
<td></td>
</tr>
<tr>
<td>Carbon market starting price ($/MWh$)</td>
<td>$c_0$</td>
<td>$41.11$</td>
</tr>
<tr>
<td>Accreditation per unit of hydropower generated</td>
<td>$\theta_c$</td>
<td></td>
</tr>
<tr>
<td>Scaling parameter for the water demand/marginal benefit function</td>
<td>$\gamma = {\gamma_{\phi=1, d}, \gamma_{\phi=1, n}, \gamma_{\phi=1, w}}$</td>
<td>${952477$, $746125$, $503291}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>${960030$, $735314$, $500033}$</td>
</tr>
<tr>
<td>Choke price for irrigation water ($/ML$)</td>
<td>$p_{CHOOSE}$</td>
<td>$611$</td>
</tr>
<tr>
<td>Choke volume for irrigation extraction (ML by weather/season)</td>
<td>$t_{CHOOSE} = {t_{CHOOSE_{\phi=1,d}}, t_{CHOOSE_{\phi=1,n}}, t_{CHOOSE_{\phi=1,w}}}$</td>
<td>${5274 ML$, $4131 ML$, $2787 ML}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>${5316 ML$, $4072 ML$, $2769 ML}$</td>
</tr>
<tr>
<td>Number of time periods</td>
<td>$t$</td>
<td>20 seasons (10 years)</td>
</tr>
<tr>
<td>Initial reservoir volume</td>
<td>$S_0$</td>
<td>310000 ML</td>
</tr>
<tr>
<td>Discount factor (per seasonal time-step)</td>
<td>$\rho$</td>
<td>0.015</td>
</tr>
<tr>
<td>Ratio of electricity purchase cost to the electricity price level</td>
<td>$\psi$</td>
<td>1.27</td>
</tr>
<tr>
<td>Maximum/Minimum volume of electricity supply per season</td>
<td>$e_{MAX,MIN}$</td>
<td>124585 MWh, 37375 MWh</td>
</tr>
<tr>
<td>Probability of electricity purchases</td>
<td>$\omega$</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Histogram of inefficient water allocation