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

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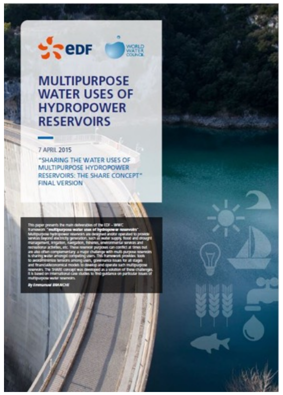
Outline

- Context
- Model & research question/objectives
- Results
- Discussion

Multipurpose Hydropower Reservoir Regulation Under Variable Rainfall & Electricity Prices

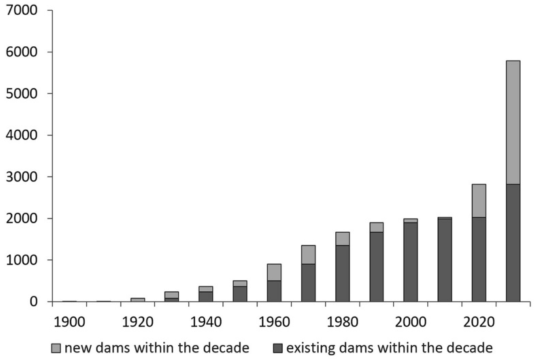


MULTIPURPOSE WATER USES OF HYDROPOWER RESERVOIRS

7 APRIL 2015

"SHARING THE WATER USES OF MULTIPURPOSE HYDROPOWER RESERVOIRS: THE SHARE CONCEPT" FINAL VERSION

Hydropower boom



Source: Zarfl et al. (2014), 'A global boom in hydropower construction', *Aquatic Sciences,* 77(1): 161-170

Trade-offs

Foregone hydro profits

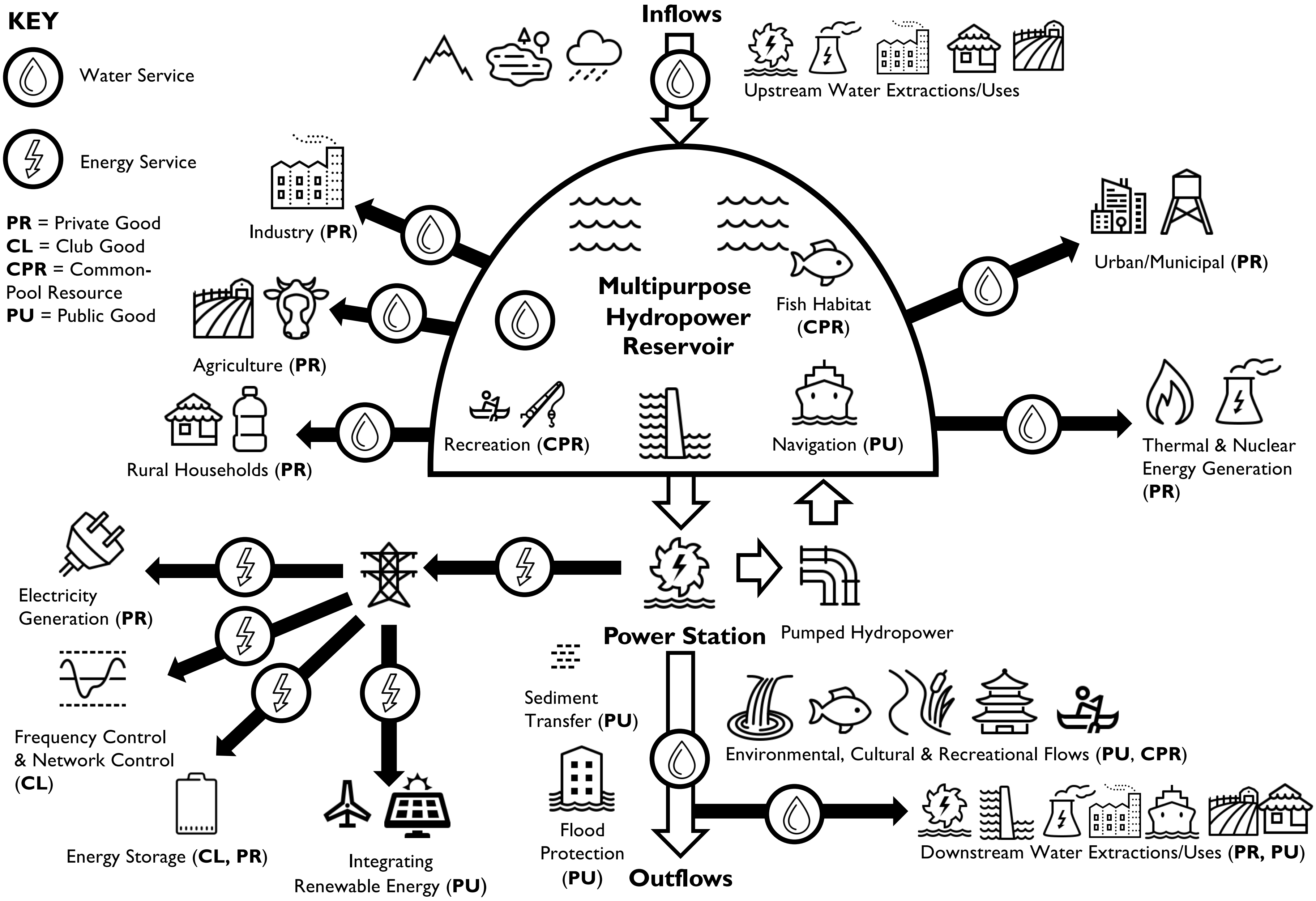
Dynamic value of water & energy services

Efficiency of water allocation?

Conventional regulation not flexible

Irrigation water pricing?

Tariff design?



KEY

Water Service

Energy Service

PR = Private Good
CL = Club Good
CPR = Common-Pool Resource
PU = Public Good

Inflows

Upstream Water Extractions/Uses

Multipurpose Hydropower Reservoir

Industry (**PR**)

Agriculture (**PR**)

Rural Households (**PR**)

Fish Habitat (**CPR**)

Recreation (**CPR**)

Navigation (**PU**)

Urban/Municipal (**PR**)

Thermal & Nuclear Energy Generation (**PR**)

Power Station

Pumped Hydropower

Electricity Generation (**PR**)

Frequency Control & Network Control (**CL**)

Energy Storage (**CL, PR**)

Integrating Renewable Energy (**PU**)

Sediment Transfer (**PU**)

Flood Protection (**PU**)

Environmental, Cultural & Recreational Flows (**PU**, **CPR**)

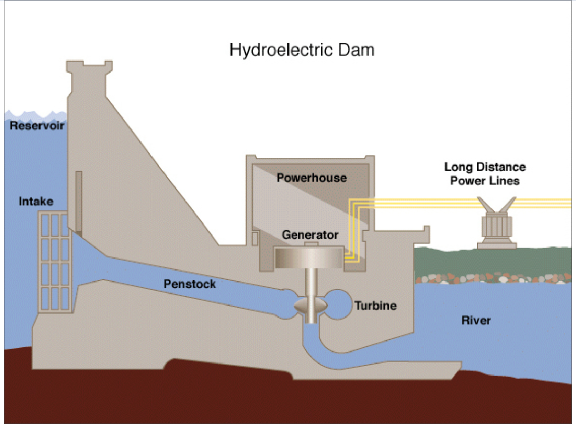
Downstream Water Extractions/Uses (**PR, PU**)

Outflows

Conventional hydropower regulation

Multi-decade licenses (30+ years)

Ex ante financial safeguards



Minimum/ maximum levels & flows

Corporate social responsibility tools

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-Nicolas (2018)

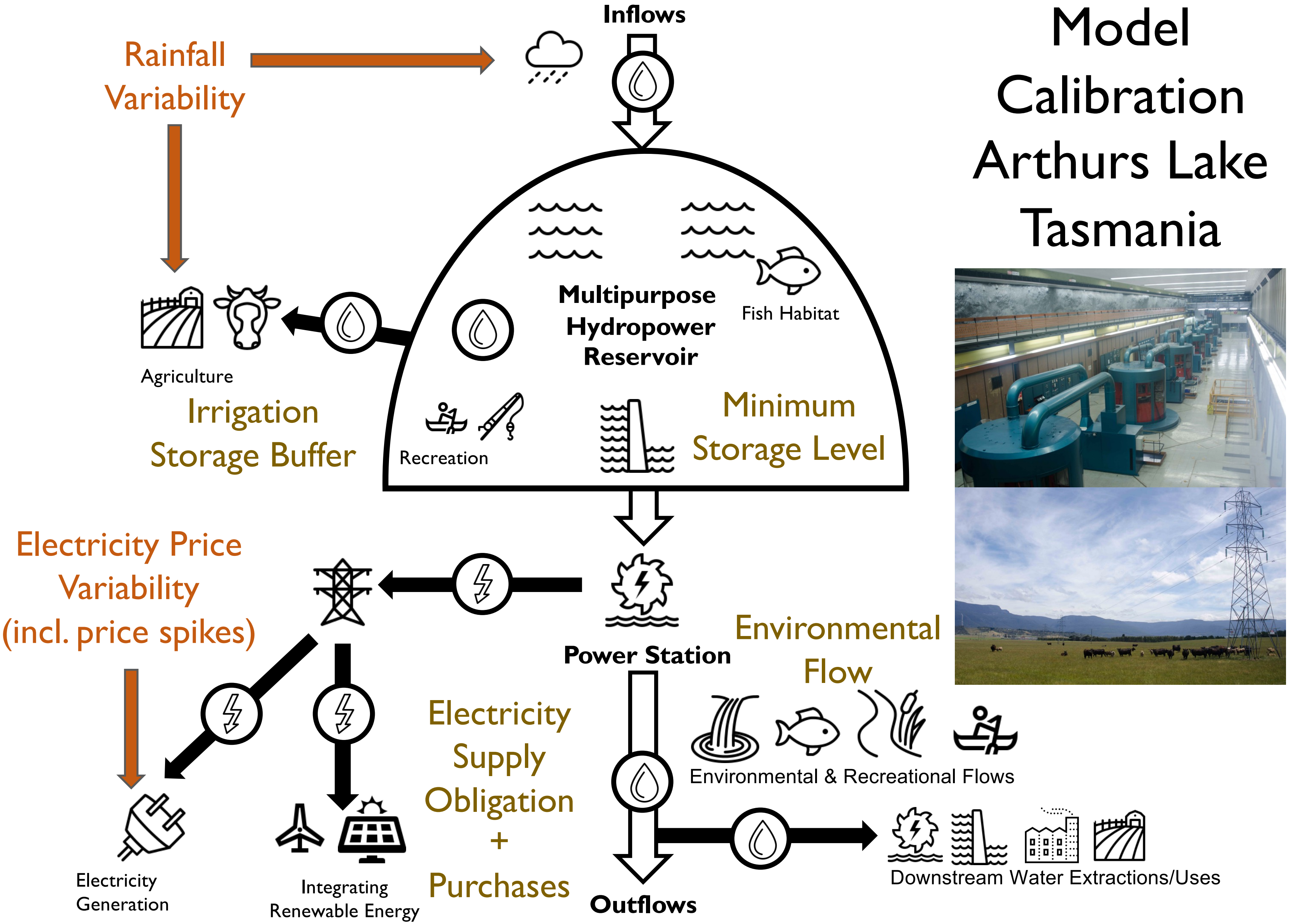
Theory & Literature

- 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?

Model Calibration Arthurs Lake Tasmania



Rainfall Variability

Inflows

Multipurpose Hydropower Reservoir

Fish Habitat

Agriculture

Irrigation Storage Buffer

Recreation

Minimum Storage Level

Electricity Price Variability (incl. price spikes)

Power Station

Environmental Flow

Environmental & Recreational Flows

Electricity Supply Obligation + Purchases

Electricity Generation

Integrating Renewable Energy

Outflows

Downstream Water Extractions/Uses

Price stability (PS) tariff vs marginal user cost (MUC) tariff?

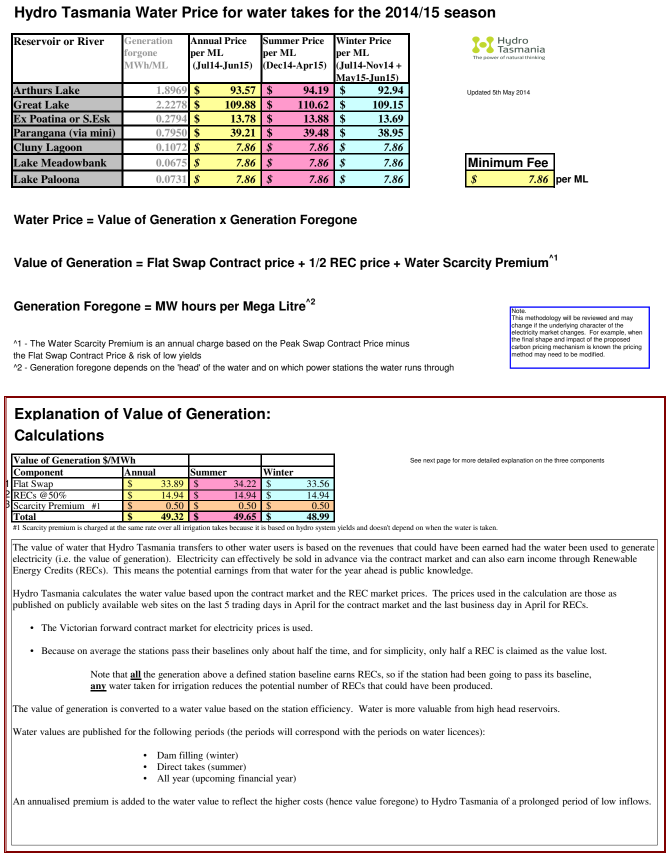
- PS is retrospective average
- MUC is estimated value of future benefits foregone by current extractions

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)



Hydro Tasmania Water Price for water takes for the 2014/15 season

Reservoir or River	Generation forgone MWh/ML	Annual Price per ML (Jul14-Jun15)	Summer Price per ML (Dec14-Apr15)	Winter Price per ML (Jul14-Nov14 + May15-Jun15)
Arthurs Lake	1.8969	**$ 93.57**	**$ 94.19**	**$ 92.94**
Great Lake	2.2278	**$ 109.88**	**$ 110.62**	**$ 109.15**
Ex Poatina or S.Esk	0.2794	**$ 13.78**	**$ 13.88**	**$ 13.69**
Parangana (via mini)	0.7950	**$ 39.21**	**$ 39.48**	**$ 38.95**
Cluny Lagoon	0.1072	***$ 7.86***	***$ 7.86***	***$ 7.86***
Lake Meadowbank	0.0675	***$ 7.86***	***$ 7.86***	***$ 7.86***
Lake Paloona	0.0731	***$ 7.86***	***$ 7.86***	***$ 7.86***

Hydro Tasmania
The power of natural thinking

Updated 5th May 2014

Minimum Fee	
$ 7.86	**per ML**

Water Price = Value of Generation x Generation Foregone

Value of Generation = Flat Swap Contract price + 1/2 REC price + Water Scarcity Premium^1

Generation Foregone = MW hours per Mega Litre^2

^1 - The Water Scarcity Premium is an annual charge based on the Peak Swap Contract Price minus the Flat Swap Contract Price & risk of low yields
^2 - Generation foregone depends on the 'head' of the water and on which power stations the water runs through

Note.
This methodology will be reviewed and may change if the underlying character of the electricity market changes. For example, when the final shape and impact of the proposed carbon pricing mechanism is known the pricing method may need to be modified.

Explanation of Value of Generation:
Calculations

Value of Generation $/MWh			
Component	**Annual**	**Summer**	**Winter**
1 Flat Swap	$ 33.89	$ 34.22	$ 33.56
2 RECs @50%	$ 14.94	$ 14.94	$ 14.94
3 Scarcity Premium #1	$ 0.50	$ 0.50	$ 0.50
Total	**$ 49.32**	**$ 49.65**	**$ 48.99**

See next page for more detailed explanation on the three components

#1 Scarcity premium is charged at the same rate over all irrigation takes because it is based on hydro system yields and doesn't depend on when the water is taken.

The value of water that Hydro Tasmania transfers to other water users is based on the revenues that could have been earned had the water been used to generate electricity (i.e. the value of generation). Electricity can effectively be sold in advance via the contract market and can also earn income through Renewable Energy Credits (RECs). This means the potential earnings from that water for the year ahead is public knowledge.

Hydro Tasmania calculates the water value based upon the contract market and the REC market prices. The prices used in the calculation are those as published on publicly available web sites on the last 5 trading days in April for the contract market and the last business day in April for RECs.

- The Victorian forward contract market for electricity prices is used.
- Because on average the stations pass their baselines only about half the time, and for simplicity, only half a REC is claimed as the value lost.

Note that **all** the generation above a defined station baseline earns RECs, so if the station had been going to pass its baseline, **any** water taken for irrigation reduces the potential number of RECs that could have been produced.

The value of generation is converted to a water value based on the station efficiency. Water is more valuable from high head reservoirs.

Water values are published for the following periods (the periods will correspond with the periods on water licences):

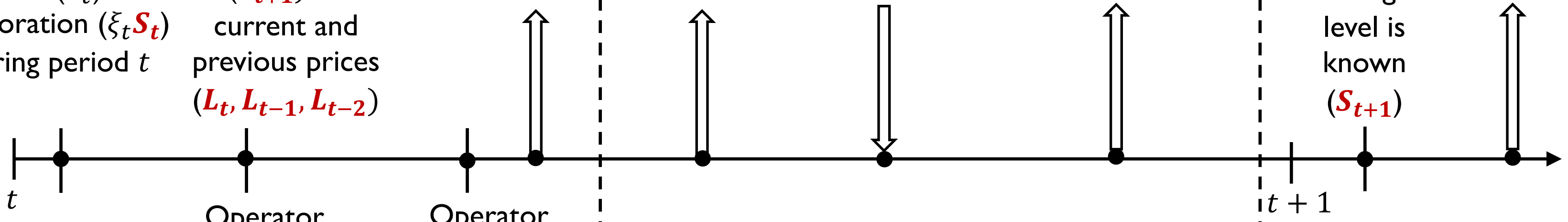
- Dam filling (winter)
- Direct takes (summer)
- All year (upcoming financial year)

An annualised premium is added to the water value to reflect the higher costs (hence value foregone) to Hydro Tasmania of a prolonged period of low inflows.

Hydropower generation scheduling

Irrigation extractions and random inflows

Hydropower generation scheduling



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

Operator calculates the expected inflows for the period t given weather in the previous period ($\boldsymbol{B_t}$)

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

Operator estimates period t irrigation water demand ($\tilde{\imath}_t$) [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 ($\boldsymbol{S_{t+1}}$) given the transition of weather ($\boldsymbol{B_{t+1}}$) and electricity prices ($\boldsymbol{L_{t+1}}$)

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

Environmental flows (v_t) are released and evaporation ($\xi_t \boldsymbol{S_t}$) occurs

The current period weather state ($\boldsymbol{B_{t+1}}$) is known and inflows ($\tilde{f}_t$) occur

Farmers' water demand function shifts according to weather/season state ($\gamma_t(\boldsymbol{B_t})$) & water price ($p_t$). Irrigation extractions ($\tilde{\imath}_t$) occur

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

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

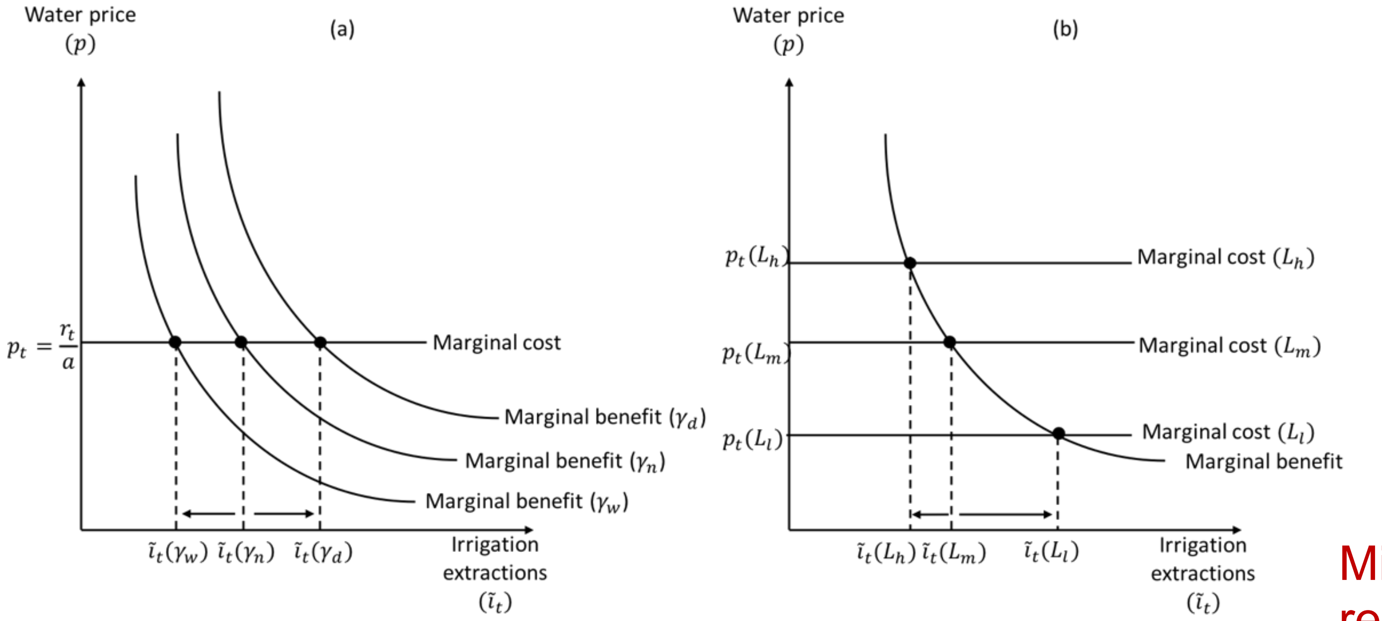
Operator schedules period t+1 water allocation to hydropower generation (x_{t+1})

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



Start of period storage level

Net inflows

Minimum reservoir level for fish habitat

$$\tilde{\imath}_t = \begin{cases} \gamma_t(p_t)^\alpha \; if \;\; \gamma_t(p_t)^\alpha \le S_t + \underbrace{\tilde{f}_t - x_t - \xi_t S_t - v_t} - S_{RISK} \\ \max\left(0, S_t + \tilde{f}_t - x_t - \xi_t S_t - v_t - S_{RISK}\right) \; otherwise \end{cases}$$

Excess irrigation demand can occur

Water tariffs

Standard Volumetric (SV) Tariff

$$p_t = \overbrace{\frac{1}{a} \times \left(g_t(L_t) + \theta^c \bar{c}\right)}^{\text{Marginal revenue from hydropower generation in period t} = r_t}$$

Production parameter of water

Renewable energy certificate revenue

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

Electricity price 2 periods ago

$$p_t = \frac{1}{a} \times \left(\frac{\left(1 + \overbrace{\omega(\psi - 1)}^{\text{Fixed probability water scarcity premium}}\right)\left(g_t(L_t) + g_t(K_t) + g_t(J_t)\right)}{3} + \theta^c \bar{c} \right)$$

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

$$p_t = \begin{cases} \frac{1}{a} \times \left(E\left(g_{t+1}(L_t)\right) + \theta^c \bar{c}\right) \; if \; \frac{1}{a} \times \left(E\left(S_{t+1} | x_t = x(e_{MIN})\right) - S_{IRR}\right) \geq e_{MIN} \\ \frac{1}{a} \times \underbrace{((\psi - 1)}_{\text{Water scarcity premium}} \times E\left(g_{t+1}(L_t)\right) + \theta^c \bar{c}) \; if \; \frac{1}{a} \times \left(E\left(S_{t+1} | x_t = x(e_{MIN})\right) - S_{IRR}\right) < e_{MIN} \end{cases}$$

$$E\left(S_{t+1} | x_t = x(e_{MIN})\right) = S_t + E\left(\tilde{f}_t(B_t, \phi_t)\right) - E\left(\tilde{\iota}_t(B_t, L_t)\right) - \xi_t S_t - v_t$$

Profit functions (SV Tariff)

Hydropower

$$\pi_t^H(B_t, K_t, L_t, x_t) = \overbrace{\frac{1}{a} \times x_t \times r_t(L_t)}^{\text{Hydropower revenues}} - \overbrace{\psi g_t(L_t) \times \max\left(0, e_{MIN} - e_t(x_t)\right)}^{\text{Cost of electricity purchases (if any)}}$$
$$+ \underbrace{i_{t-1}(B_t, K_t) \times p_{t-1}(K_t)}_{\text{Previous period's irrigation revenues}}$$

Irrigation

$$\pi_t^I(B_t, L_t, x_t) = \frac{\alpha}{\gamma_t(B_t)^{\frac{1}{\alpha}}(\alpha + 1)} \left(\tilde{i}_t^{\frac{\alpha+1}{\alpha}}(B_t, L_t, x_t) - i_{CHOKE_t}^{\frac{\alpha+1}{\alpha}}(B_t) \right)$$
$$+ p_{CHOKE} \times i_{CHOKE_t}(B_t) + \underbrace{p_t(L_t) \times \tilde{i}_t(B_t, L_t, x_t)}_{\text{Current period's irrigation charges}}$$

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

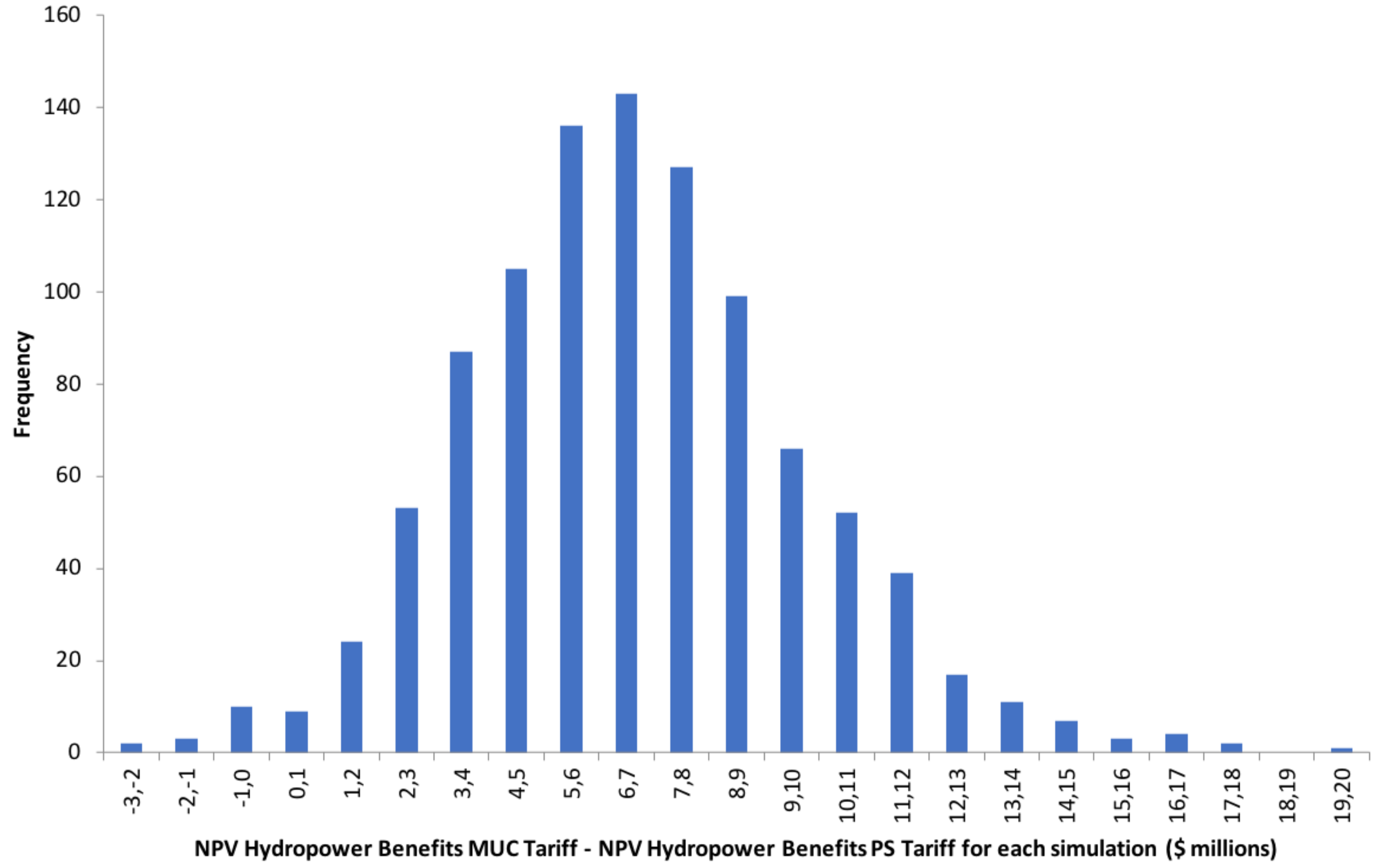
1000 simulations; 10 years (20 seasons)

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

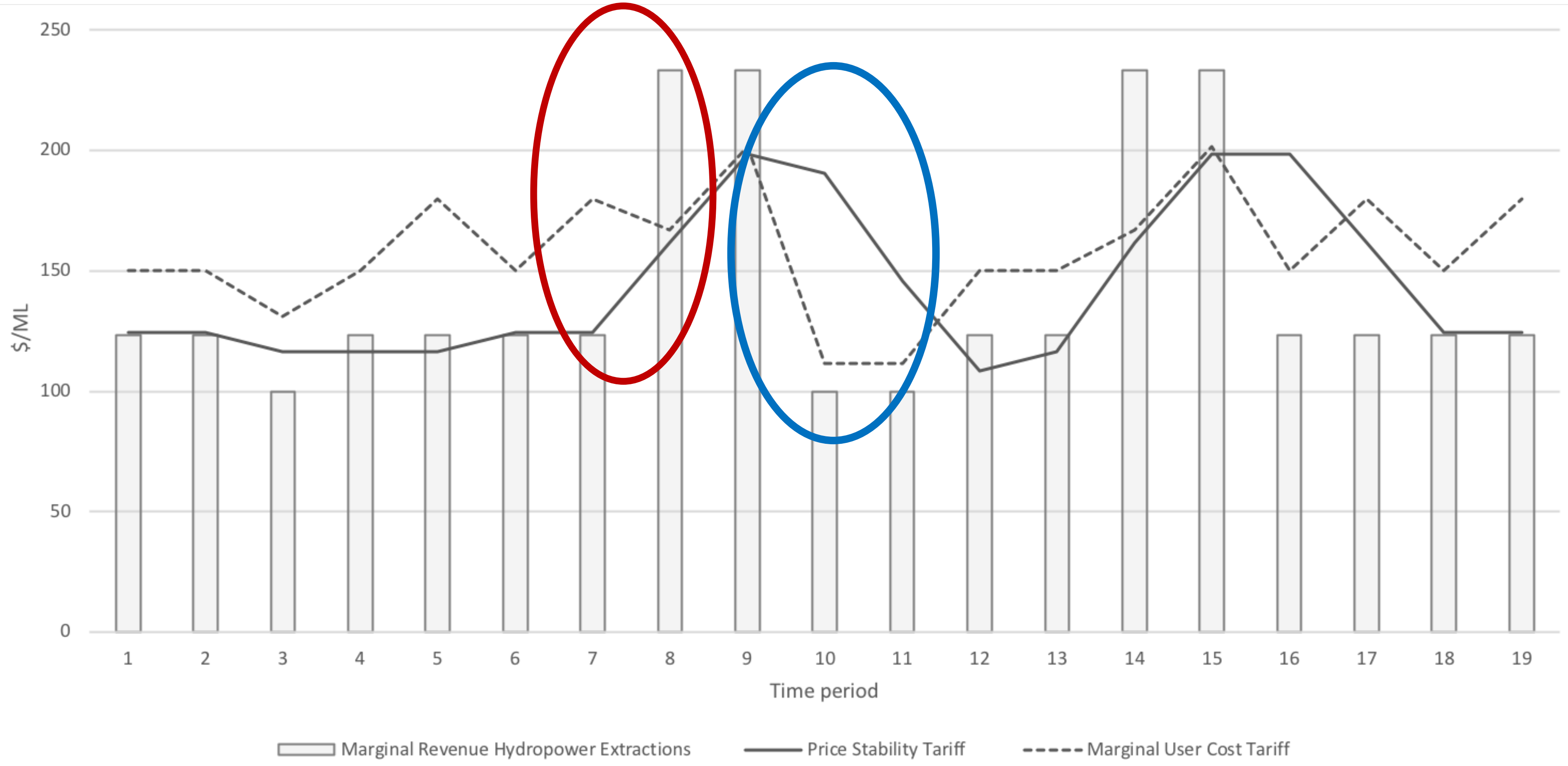
Subsidy: ↑ irrigation profits & extractions (PS Tariff)

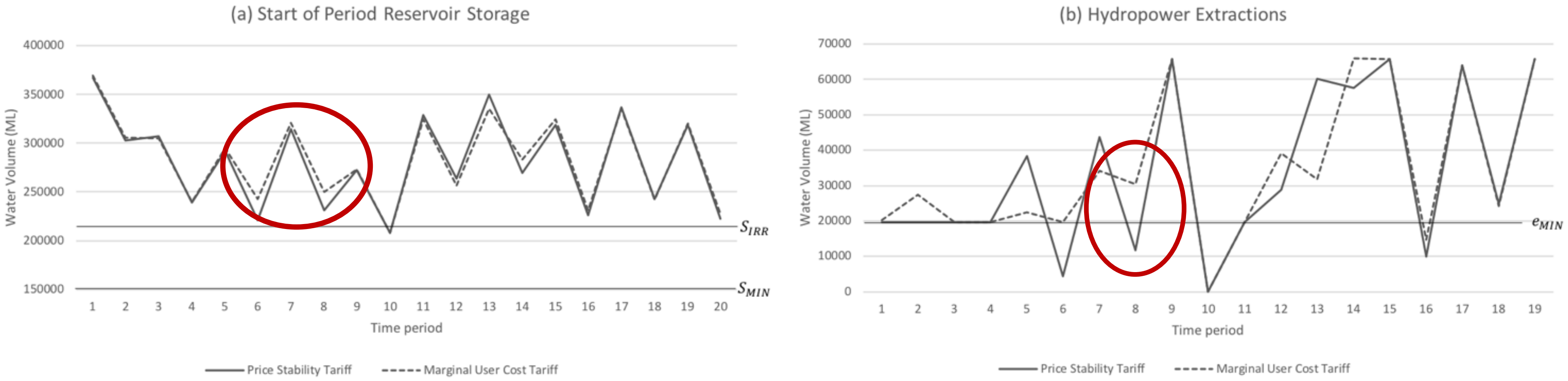
Tariff	**Hydropower**					**Irrigation**		**Total**
	Average water extractions (St. dev.)	Average NPV benefits (St. dev.) $ millions	Electricity generation GWh	Electricity purchases GWh	Average NPV of cost of electricity purchases $ millions	Average water extractions (St. dev.)	Average NPV benefits (St. dev.) $ millions	Average NPV benefits (St. dev.) $ millions
Standard Volumetric	474.7 GL (72.4 GL)	$83.3 ($14.6)	900.4 (137.3)	215.5 (51.3)	$12.9 ($4.0)	266.8 GL (23.0 GL)	$52.8 ($4.0)	$136.1 ($11.6)
Price Stability	481.0 GL (72.0 GL)	$84.8 ($14.9)	912.4 (136.6)	204.8 (51.6)	$12.3 ($4.0)	257.7 GL (23.7 GL)	$52.1 ($4.0)	$136.9 ($11.8)
Marginal User Cost	492.2 GL (67.4 GL)	$91.5 ($13.5)	933.6 (127.9)	172.9 (54.9)	$10.5 ($4.3)	236.4 GL (14.6 GL)	$49.1 ($2.7)	$140.6 ($11.5)

Histogram of foregone hydropower profits

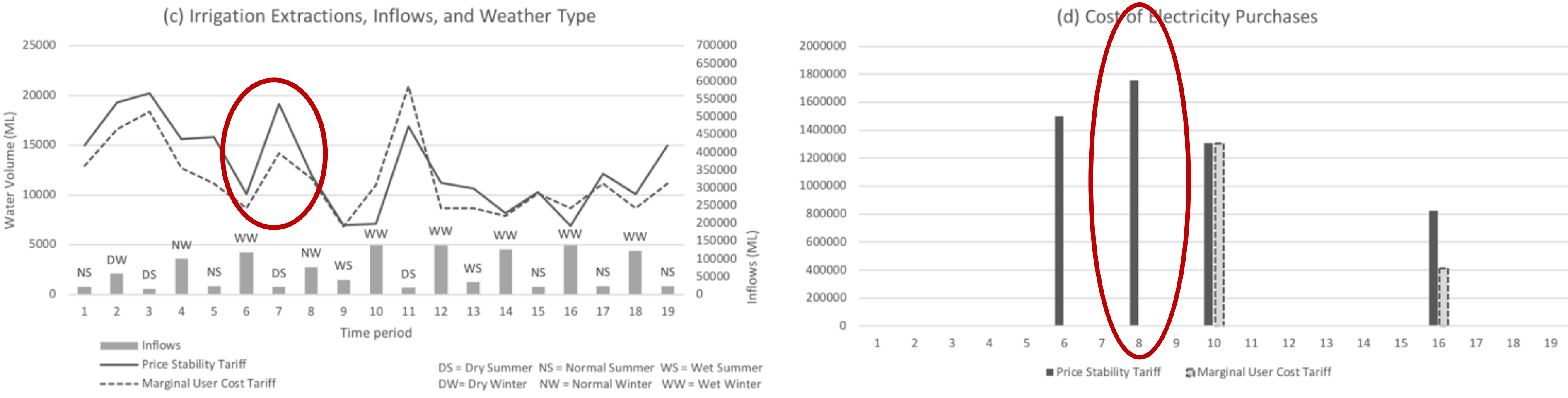


Water prices for an example simulation



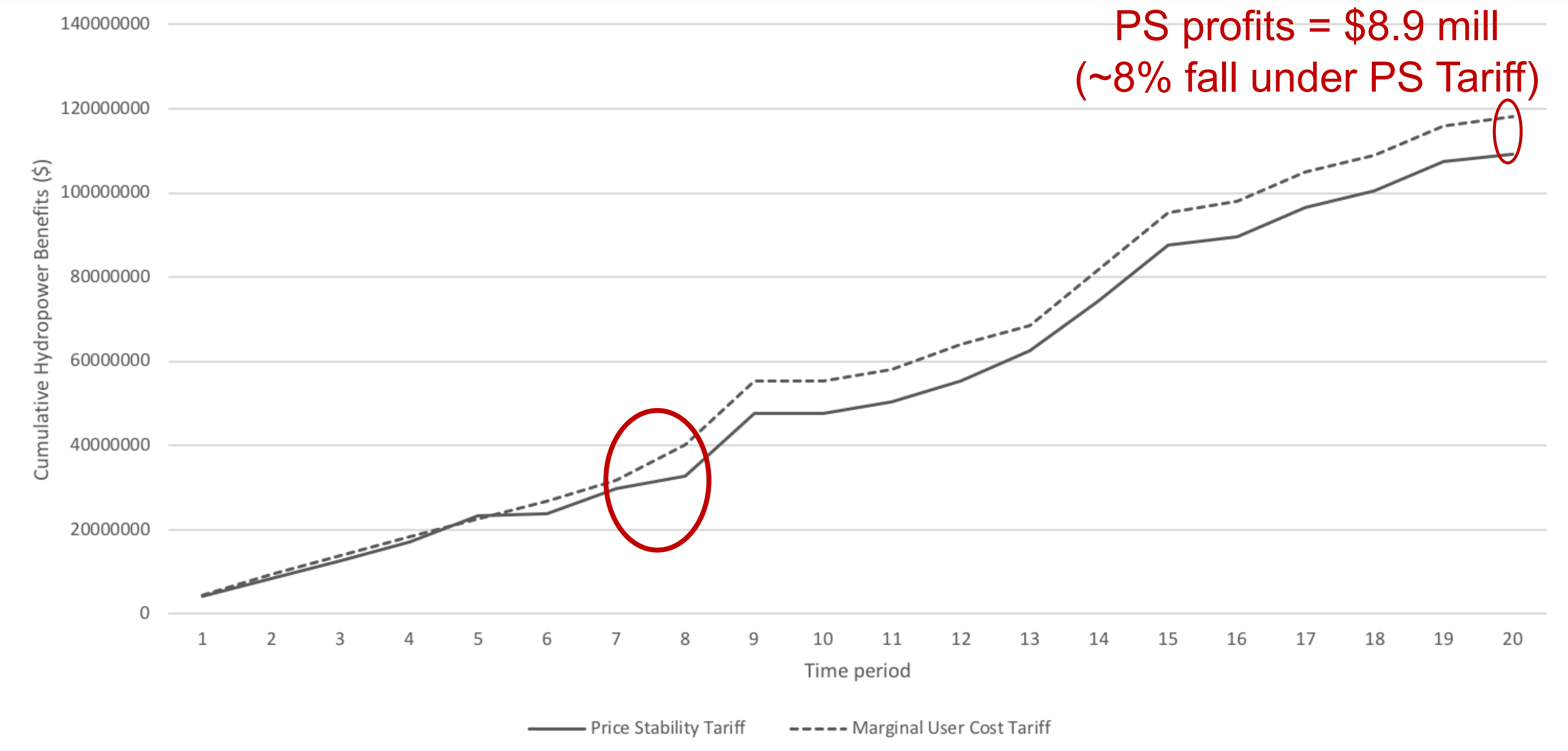

(a) Start of Period Reservoir Storage

(b) Hydropower Extractions


(c) Irrigation Extractions, Inflows, and Weather Type

(d) Cost of Electricity Purchases

Time path of cumulative hydropower profits for example simulation



Total MUC profits – Total PS profits = $8.9 mill (~8% fall under PS Tariff)

Scenario	Costs of price stability controls				Indirect irrigation subsidy
	Foregone hydropower benefits $ millions	Foregone hydroelectricity generation GWh	Cost of additional electricity purchases $ millions	Reduced efficiency of water allocation $ millions	Additional irrigation profits under PS Tariff $ millions
Primary model	$6.6 (7.3%)	21.2 (2.3%)	$1.8 (17.3%)	$3.6 (2.6%)	$3.0 (6.1%)
Minimum electricity supply obligation					
$e_{MIN} = 0$	$0.50 (0.5%)	5.6 (0.6%)	Not Applicable	$0.8 (0.1%)	$0.6 (1.2%)
$e_{MIN} = 10\%$ of e_{MAX}	$4.1 (4.2%)	20.9 (2.1%)	$0.7 (17.6%)	$1.4 (1.0%)	$2.7 (5.4%)
$e_{MIN} = 50\%$ of e_{MAX}	$11.6 (14.1%)	47.1 (13.6%)	$3.2 (13.6%)	$6.7 (5.2%)	$4.9 (10.4%)
$e_{MIN} = 70\%$ of e_{MAX}	$9.3 (13.8%)	64.3 (6.2%)	$4.0 (9.3%)	$3.0 (2.7%)	$6.2 (13.6%)
Electricity purchase premium					
$\psi = 1.16$	$3.7 (4.1%)	1.0 (0.1%)	$1.7 (15.2%)	$1.3 (1.0%)	$2.3 (4.7%)
$\psi = 1.31$	$4.8 (5.3%)	26.7 (2.9%)	$1.8 (16.5%)	$1.6 (1.1%)	$3.3 (6.7%)
High and medium electricity price level					
$L_h = \$67.71$	$2.50 (3.1%)	9.3 (1.0%)	$1.5 (12.7%)	$0.2 (0.2%)	$2.7 (5.1%)
$L_h = \$133.48$	$6.0 (5.8%)	31.0 (3.3%)	$2.0 (19.6%)	$2.5 (1.7%)	$3.5 (7.5%)
$L_m = \$67.71$	$3.4 (3.2%)	24.8 (2.4%)	$1.0 (6.0%)	$0.5 (0.4%)	$2.9 (6.5%)
Water demand and irrigation storage buffer					
Doubled water demand	$11.3 (12.3%)	77.0 (12.7%)	$3.4 (16.8%)	$2.8 (1.5%)	$8.5 (9.0%)
$S_{IRR} = S_{RISK}$	$2.6 (2.5%)	28.6 (2.66%)	$0.3 (5.3%)	$1.2 (0.8%)	$1.4 (2.9%)
Doubled water demand & $S_{IRR} = S_{RISK}$	$3.1 (3.0%)	-7.7 (0.8%)	$1.4 (9.4%)	$2.3 (1.3%)	$0.8 (1.0%)
Price elasticity of water demand					
$\alpha = -0.5$	$4.0 (4.4%)	24.7 (2.7%)	$0.7 (5.5%)	$0.7 (0.5%)	$3.3 (4.9%)
$\alpha = -0.7$	$5.4 (5.9%)	-16.1 (1.7%)	$3.1 (29.4%)	$2.2 (1.5%)	$3.0 (5.5%)
$\alpha = -0.9$	$4.8 (5.3%)	24.6 (2.6%)	$2.0 (18.8%)	$1.9 (1.4%)	$2.9 (6.5%)

Scenario	**Costs of price stability controls**				**Indirect irrigation subsidy**
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$e_{MIN} = 70\%$ of e_{MAX}	$9.3 (13.8%)	64.3 (6.2%)	$4.0 (9.3%)	$3.0 (2.7%)	$6.2 (13.6%)
Electricity purchase premium					
$\psi = 1.16$	$3.7 (4.1%)	1.0 (0.1%)	$1.7 (15.2%)	$1.3 (1.0%)	$2.3 (4.7%)
$\psi = 1.31$	$4.8 (5.3%)	26.7 (2.9%)	$1.8 (16.5%)	$1.6 (1.1%)	$3.3 (6.7%)
High and medium electricity price level					
$L_h = \$67.71$	$2.50 (3.1%)	9.3 (1.0%)	$1.5 (12.7%)	$0.2 (0.2%)	$2.7 (5.1%)
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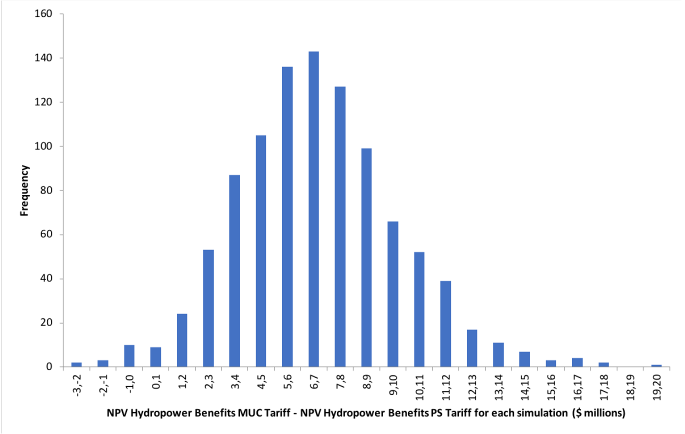
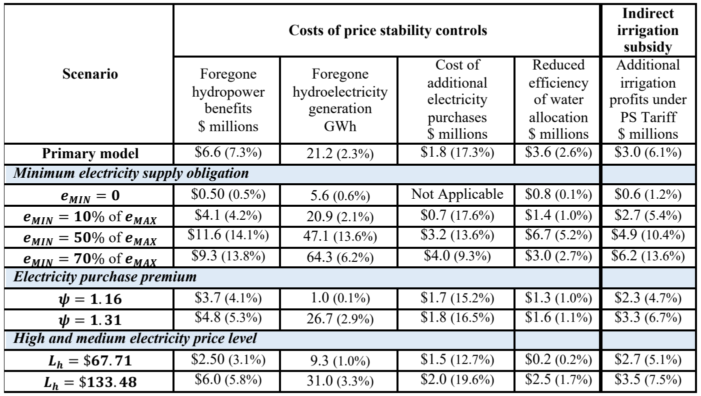
Water demand and irrigation storage buffer					
Doubled water demand	$11.3 (12.3%)	77.0 (12.7%)	$3.4 (16.8%)	$2.8 (1.5%)	$8.5 (9.0%)
$S_{IRR} = S_{RISK}$	$2.6 (2.5%)	28.6 (2.66%)	$0.3 (5.3%)	$1.2 (0.8%)	$1.4 (2.9%)
Doubled water demand & $S_{IRR} = S_{RISK}$	$3.1 (3.0%)	-7.7 (0.8%)	$1.4 (9.4%)	$2.3 (1.3%)	$0.8 (1.0%)
Price elasticity of water demand					
$\alpha = -0.5$	$4.0 (4.4%)	24.7 (2.7%)	$0.7 (5.5%)	$0.7 (0.5%)	$3.3 (4.9%)
$\alpha = -0.7$	$5.4 (5.9%)	-16.1 (1.7%)	$3.1 (29.4%)	$2.2 (1.5%)	$3.0 (5.5%)
$\alpha = -0.9$	$4.8 (5.3%)	24.6 (2.6%)	$2.0 (18.8%)	$1.9 (1.4%)	$2.9 (6.5%)

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



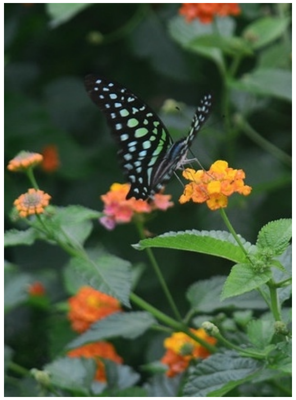


Scenario	Costs of price stability controls				Indirect irrigation subsidy
	Foregone hydropower benefits $ millions	Foregone hydroelectricity generation GWh	Cost of additional electricity purchases $ millions	Reduced efficiency of water allocation $ millions	Additional irrigation profits under PS Tariff $ millions
Primary model	$6.6 (7.3%)	21.2 (2.3%)	$1.8 (17.3%)	$3.6 (2.6%)	$3.0 (6.1%)
Minimum electricity supply obligation					
$\boldsymbol{e_{MIN} = 0}$	$0.50 (0.5%)	5.6 (0.6%)	Not Applicable	$0.8 (0.1%)	$0.6 (1.2%)
$\boldsymbol{e_{MIN}}$ = **10%** of $\boldsymbol{e_{MAX}}$	$4.1 (4.2%)	20.9 (2.1%)	$0.7 (17.6%)	$1.4 (1.0%)	$2.7 (5.4%)
$\boldsymbol{e_{MIN}}$ = **50%** of $\boldsymbol{e_{MAX}}$	$11.6 (14.1%)	47.1 (13.6%)	$3.2 (13.6%)	$6.7 (5.2%)	$4.9 (10.4%)
$\boldsymbol{e_{MIN}}$ = **70%** of $\boldsymbol{e_{MAX}}$	$9.3 (13.8%)	64.3 (6.2%)	$4.0 (9.3%)	$3.0 (2.7%)	$6.2 (13.6%)
Electricity purchase premium					
$\boldsymbol{\psi = 1.16}$	$3.7 (4.1%)	1.0 (0.1%)	$1.7 (15.2%)	$1.3 (1.0%)	$2.3 (4.7%)
$\boldsymbol{\psi = 1.31}$	$4.8 (5.3%)	26.7 (2.9%)	$1.8 (16.5%)	$1.6 (1.1%)	$3.3 (6.7%)
High and medium electricity price level					
$\boldsymbol{L_h = \$67.71}$	$2.50 (3.1%)	9.3 (1.0%)	$1.5 (12.7%)	$0.2 (0.2%)	$2.7 (5.1%)
$\boldsymbol{L_h = \$133.48}$	$6.0 (5.8%)	31.0 (3.3%)	$2.0 (19.6%)	$2.5 (1.7%)	$3.5 (7.5%)

Discussion

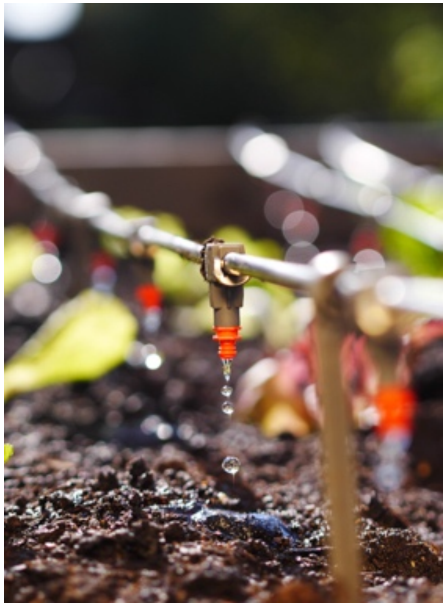
1. Price stability controls generate private/social costs
    - Subsidies do not come for free
    - Tariffs need to provide incentives for multipurpose operations

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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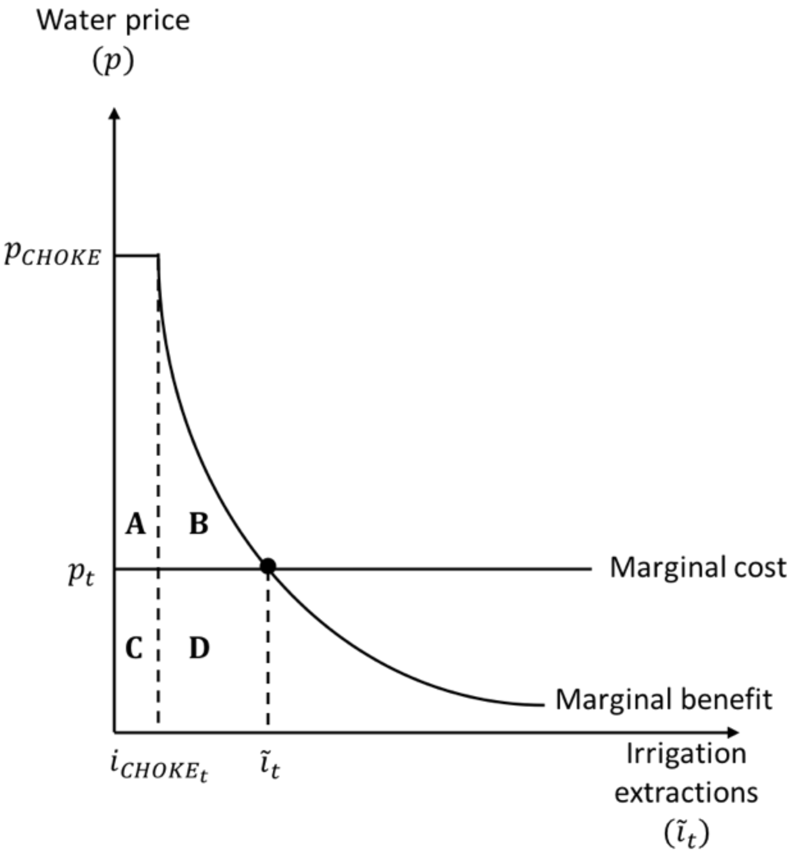
Additional slides

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

Variable	Mathematical Notation	Value
Minimum and maximum storage volume	S_{MIN}, S_{MAX}	150000 ML, 449000 ML
Risk storage level volume	S_{RISK}	164000 ML
Irrigation buffer storage volume	S_{IRR}	217000 ML
Inflows, by season and weather type	$F = \begin{Bmatrix} f_{\phi=1,d} & f_{\phi=1,n} & f_{\phi=1,w} \\ f_{\phi=2,d} & f_{\phi=2,n} & f_{\phi=2,w} \end{Bmatrix}$	$\begin{Bmatrix} 18227 \text{ ML} & 22679 \text{ ML} & 39375 \text{ ML} \\ 59850 \text{ ML} & 88207 \text{ ML} & 122905 \text{ ML} \end{Bmatrix}$
Random inflow shock	ε_t	$\varepsilon_t = \begin{cases} 0.87 \text{ w.p } 0.2 \\ 0.97 \text{ w.p } 0.2 \\ 1 \text{ w.p } 0.2 \\ 1.03 \text{ w.p } 0.2 \\ 1.13 \text{ w.p } 0.2 \end{cases}$
Evaporation rate of storage	$\xi_t = \begin{Bmatrix} \xi_{\phi_t=1} \\ \xi_{\phi_t=2} \end{Bmatrix}$	$\begin{Bmatrix} 0.138 \\ 0.049 \end{Bmatrix}$
Seasonal environmental flows	$v_t = \begin{Bmatrix} v_{\phi_t=1} \text{ if } \phi = 1 \\ v_{\phi_t=2} \text{ if } \phi = 2 \end{Bmatrix}$	$\begin{Bmatrix} 4000 \text{ ML} \\ 1000 \text{ ML} \end{Bmatrix}$
Electricity price levels ($/MWh)	$L = \{L_l \quad L_m \quad L_h\}$	$\{\$31.96 \quad \$44.40 \quad \$102.31\}$
Conversion factor for water releases into energy (MWh/ML)	a	0.5272
Maximum extractions for hydropower	$x_{MAX,\phi_t} = \begin{Bmatrix} x_{MAX,\phi_t=1} \\ x_{MAX,\phi_t=2} \end{Bmatrix}$	$\begin{Bmatrix} 65681 \text{ ML} \\ 66044 \text{ ML} \end{Bmatrix}$
Price elasticity of water demand	α	-0.81
Fixed seasonal irrigation extractions (ML)	$\bar{\imath}_{\phi_t} = \begin{Bmatrix} \bar{\imath}_{\phi_t=1} \\ \bar{\imath}_{\phi_t=2} \end{Bmatrix}$	$\begin{Bmatrix} 15114 \text{ ML} \\ 14895 \text{ ML} \end{Bmatrix}$
Weather and electricity price transition matrices	*See Appendix A3 in Chapter 3*	
Carbon market starting price ($/MWh)	c_0	$41.11
Accreditation per unit of hydroelectricity generated	θ^c	0.5
Scaling parameter for the water demand/marginal benefit function	$\gamma = \begin{Bmatrix} \gamma_{\phi=1,\ d} & \gamma_{\phi=1,\ n} & \gamma_{\phi=1,\ w} \\ \gamma_{\phi=2,\ d} & \gamma_{\phi=2,\ n} & \gamma_{\phi=2,\ w} \end{Bmatrix}$	$\begin{Bmatrix} 952477 & 746125 & 503291 \\ 960030 & 735314 & 500033 \end{Bmatrix}$
Choke price for irrigation water ($/ML)	p_{CHOKE}	$611
Choke volume for irrigation extraction (ML by weather/season)	$\tilde{\imath}_{CHOKE} = \begin{Bmatrix} \tilde{\imath}_{CHOKE_{\phi=1,d}} & \tilde{\imath}_{CHOKE_{\phi=1,n}} & \tilde{\imath}_{CHOKE_{\phi=1,w}} \\ \tilde{\imath}_{CHOKE_{\phi=2,d}} & \tilde{\imath}_{CHOKE_{\phi=2,n}} & \tilde{\imath}_{CHOKE_{\phi=2,w}} \end{Bmatrix}$	$\begin{Bmatrix} 5274 \text{ ML} & 4131 \text{ ML} & 2787 \text{ ML} \\ 5316 \text{ ML} & 4072 \text{ ML} & 2769 \text{ ML} \end{Bmatrix}$
Number of time periods	t	20 seasons (10 years)
Initial reservoir volume	S_0	310000 ML
Discount factor (per seasonal time-step)	ρ	0.015
Ratio of electricity purchase cost to the electricity price level	ψ	1.27
Maximum/Minimum volume of electricity supply per season	e_{MAX}, e_{MIN}	124585 MWh, 37375 MWh
Probability of electricity purchases (Price Stability Tariff)	ω	0.05

Histogram of inefficient water allocation