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CENTER FOR WATERSHED SCIENCES

Household Water and Energy Use - the Nexus that Connects Us

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Outline

- Perspectives on Water/Energy Analysis
- Purposes of Analysis
- Approaches to Analysis
- Alvar Escriva-Bou’s modeling results
- Hard parts/Opportunities/Conclusions

Water/Energy Analysis Perspectives

Water connects us all with each other and the world

- Household Perspective
- Water and Energy Utility perspectives
- Society perspective – local, regional, national
- Global perspective

Each perspective has different purposes

Purposes of Analysis - Households

- Happiness
- Minimize cost
- Reduce energy and water use
- Drought management

Households don’t pay for analysis.

Purposes of Analysis – Water & Energy Utilities

- Minimize cost
- Demand management – peak energy/water use
- Reduce energy and water use
- Drought management
- Other extreme events – outages, etc.
- Use data from smart meters, network sensors
- Utilities pay for analysis (but not enough).

Purposes of Analysis - Society

- Minimize cost
- Reduce energy and water use
- GHG emission reduction
- Drought management
- Utility and environmental regulation
- Societies pay little for analysis rarely.

Approaches to Analysis – Empirical

- Big and medium data – Econometrics, regression, machine learning – “top down”
- Advantages – Real data & experiences, immediate applicability, common methods
- Disadvantages – Conditions of calibration data, future changes, causality unclear
- Examples – Price elasticity of demand studies since Gottlieb 1963; gobs of local & meta-studies

Approaches to Analysis – Mechanistic

- Build demands from end-uses with behavioral assumptions, often optimization – “bottom up”
- Advantages – Mechanistic, detailed causal understanding of causes of demand and changes
- Disadvantages – Some end uses lack data; household motivations not completely clear; never completely mechanistic
- Examples – Rosenberg and Abdallah (2014); Escriva-Bou (2015); Lund (1995)

Alvar Escriva-Bou's results +

Escriva-Bou, A., J. R. Lund, and M. Pulido-Velazquez (2015), Modeling residential water and related energy, carbon footprint and costs in California, *Environ Sci Policy*, *50*(0), 270-281.

Escriva-Bou, A., J.R. Lund, M. Pulido-Velazquez, “Optimal residential water conservation strategies considering embedded energy in California,” *Water Resources Research*, Volume 51, Issue 6, pages 4482–4498, June 2015.

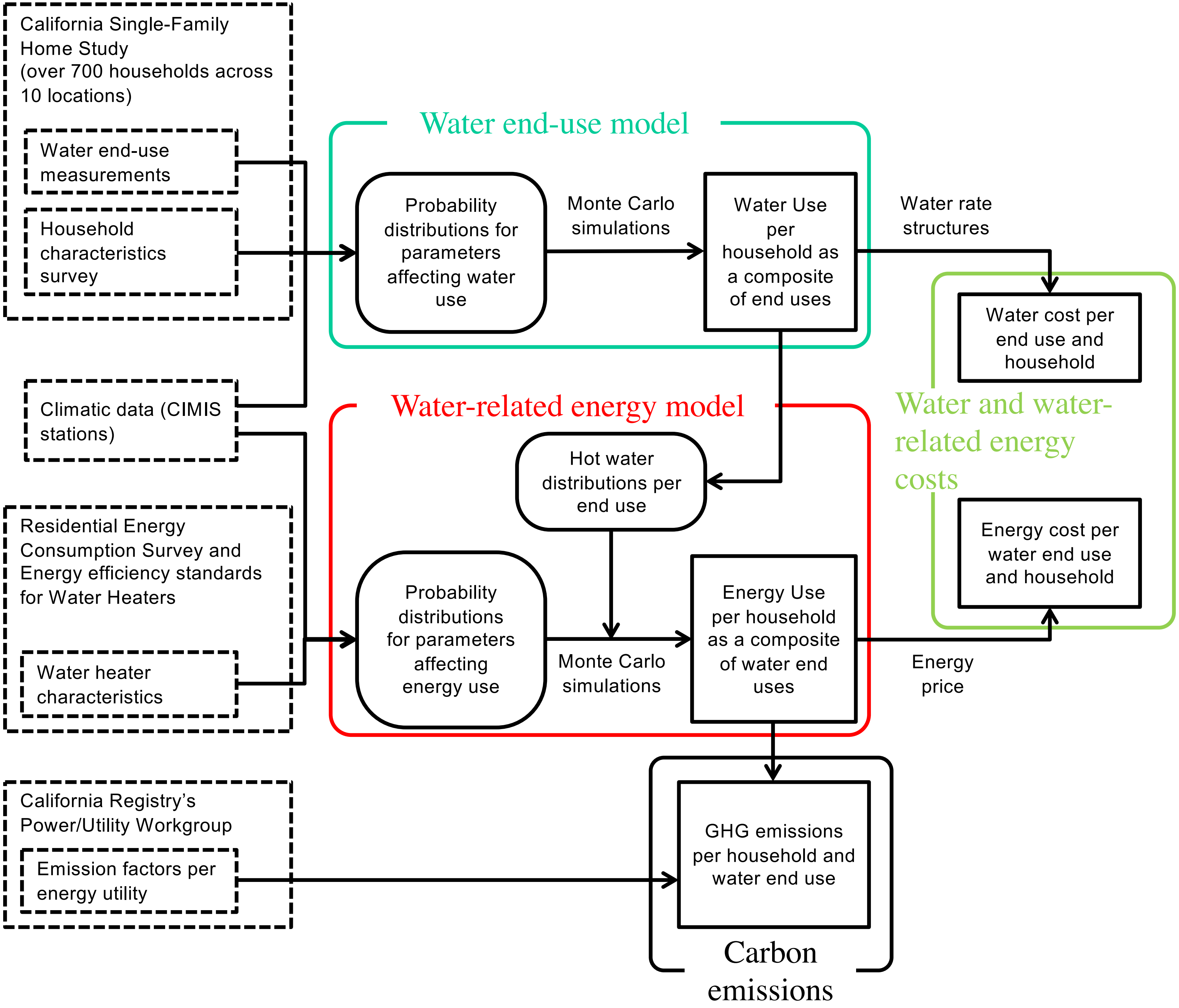
Following...

Rosenberg, D.E., T. Tarawneh, R. Abdel-Khaleq, and J.R. Lund, “Modeling Integrated Water-User Decisions in Intermittent Supply Systems,” *Water Resources Research*, Vol. 43, No. 7, July 2007.

1) Residential water and related energy, carbon footprint and costs in California*

- What energy and GHG emissions come from residential water end-uses?
- Does spatial variability and heterogeneity affect water and energy use?
- How do water and energy rate structures affect costs to households?

*Escriva-Bou, A., J. R. Lund, and M. Pulido-Velazquez (2015), Modeling residential water and related energy, carbon footprint and costs in California, *Environ Sci Policy*, *50*(0), 270-281.



California Single-Family Home Study (over 700 households across 10 locations)

Water end-use measurements

Household characteristics survey

Climatic data (CIMIS stations)

Residential Energy Consumption Survey and Energy efficiency standards for Water Heaters

Water heater characteristics

California Registry's Power/Utility Workgroup

Emission factors per energy utility

Water end-use model

Probability distributions for parameters affecting water use

Monte Carlo simulations

Water Use per household as a composite of end uses

Water rate structures

Water-related energy model

Hot water distributions per end use

Probability distributions for parameters affecting energy use

Monte Carlo simulations

Energy Use per household as a composite of water end uses

Energy price

Water and water-related energy costs

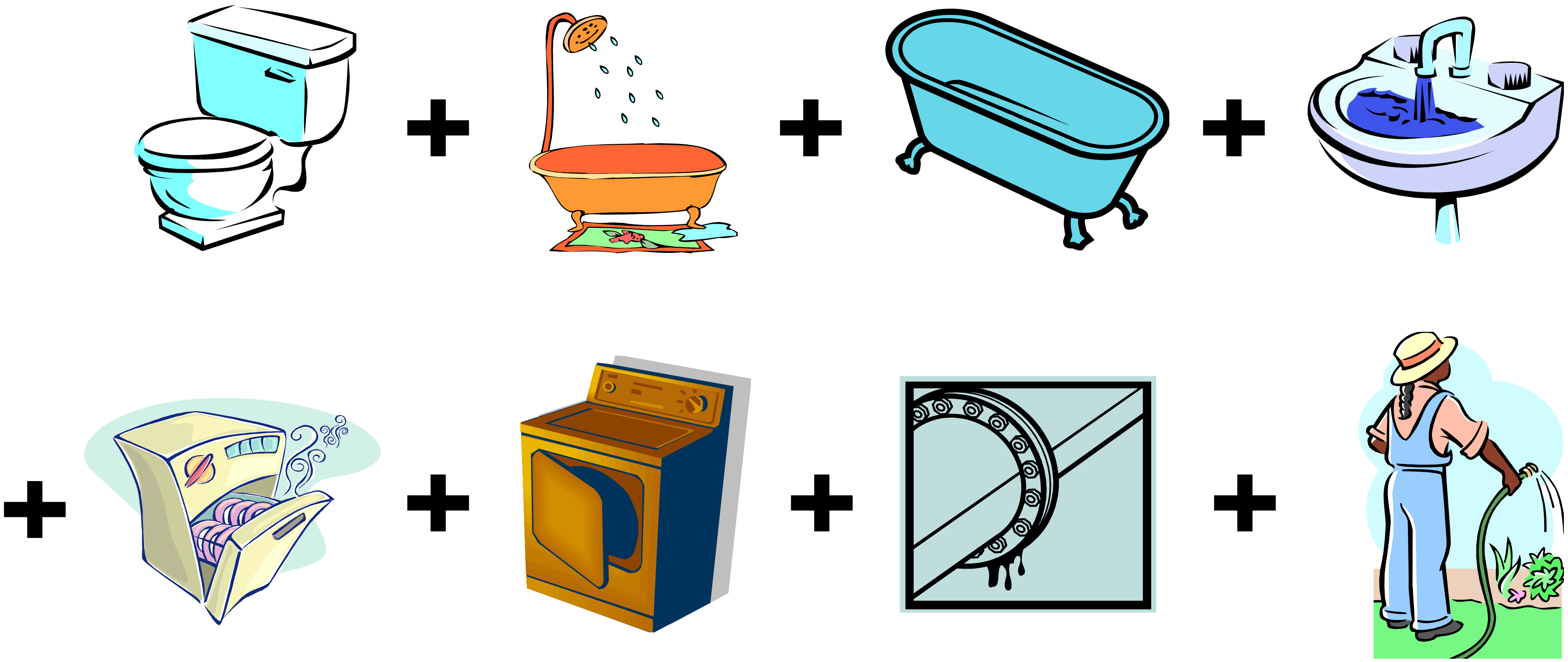
Water cost per end use and household

Energy cost per water end use and household

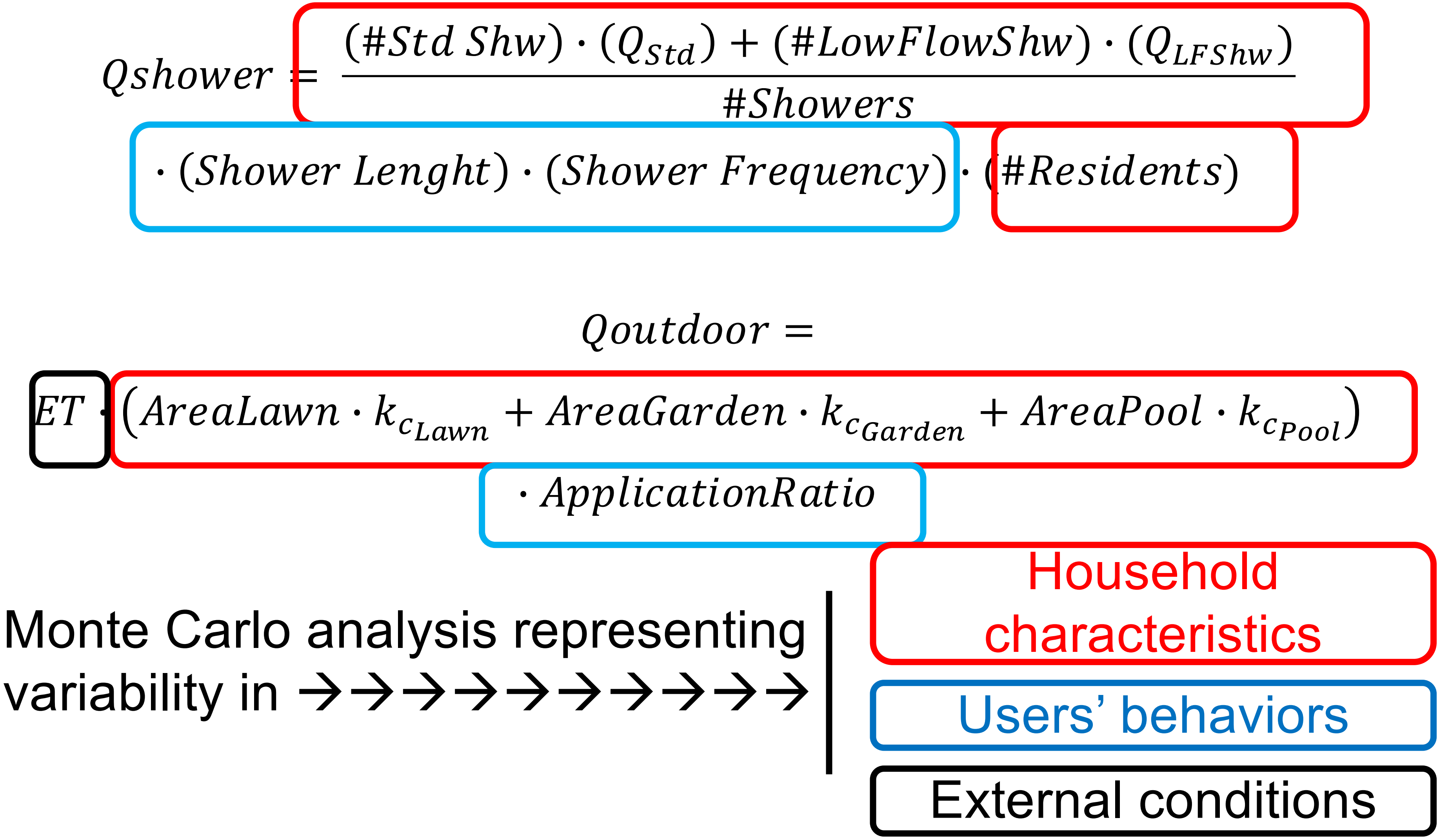
Carbon emissions

GHG emissions per household and water end use

Water End-Use Model



Water End-Use Models



$$Qshower = \frac{(\#Std\ Shw)\cdot(Q_{Std}) + (\#LowFlowShw)\cdot(Q_{LFShw})}{\#Showers}$$

$$\cdot\,(Shower\ Lenght)\cdot(Shower\ Frequency)\cdot(\#Residents)$$

$$Qoutdoor =$$

$$ET\cdot\left(AreaLawn\cdot k_{c_{Lawn}} + AreaGarden\cdot k_{c_{Garden}} + AreaPool\cdot k_{c_{Pool}}\right)$$

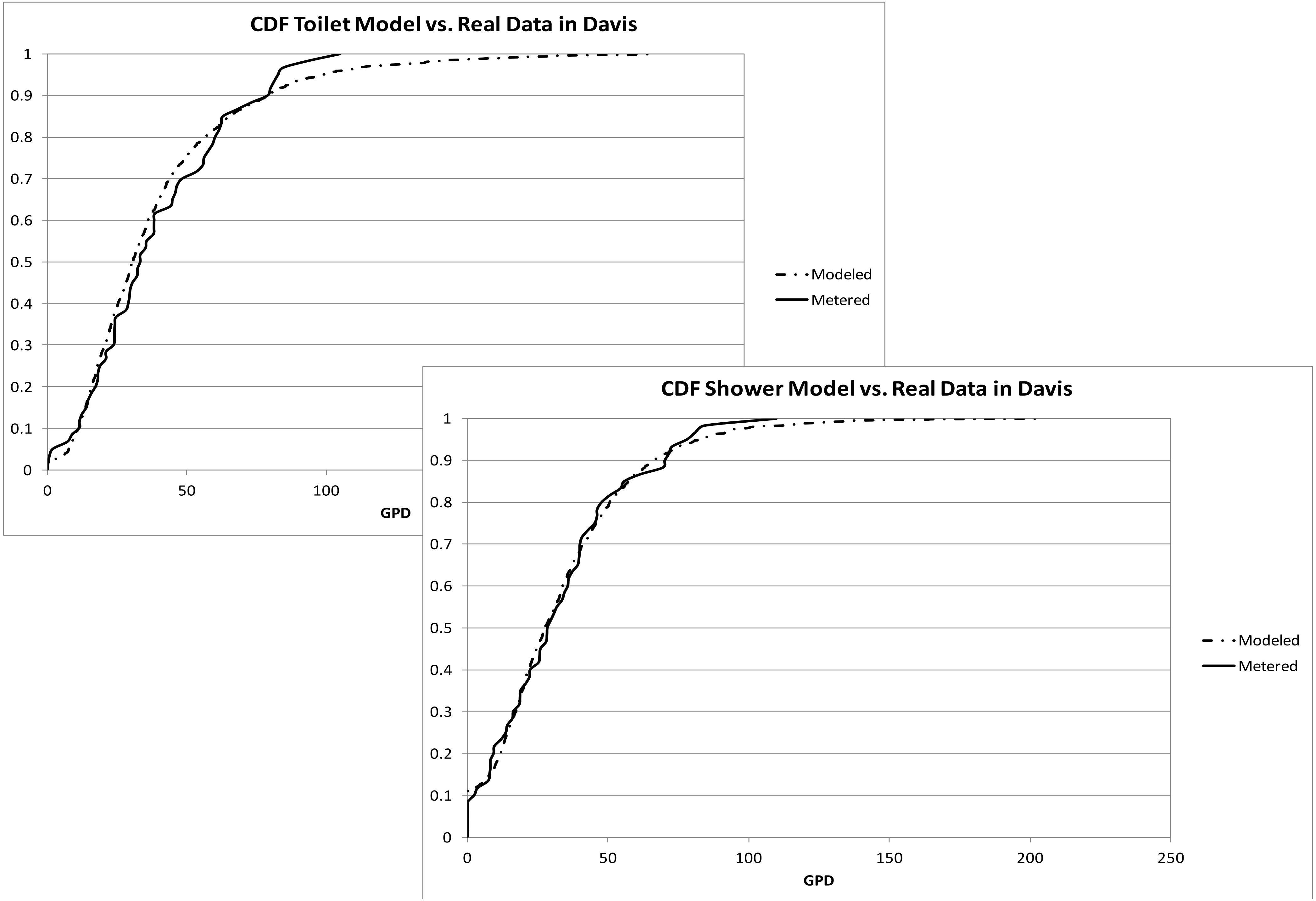
$$\cdot\,ApplicationRatio$$

Monte Carlo analysis representing variability in →→→→→→→→→→

Household characteristics

Users' behaviors

External conditions


CDF Toilet Model vs. Real Data in Davis

CDF Shower Model vs. Real Data in Davis

Water-Related Energy End-Use Model

- From End-Water Uses → Hot water, using hot water prob. distributions per end-use (EBMUD, 2002).

- Energy Calculation – WHAM (Lutz et al., 1999):

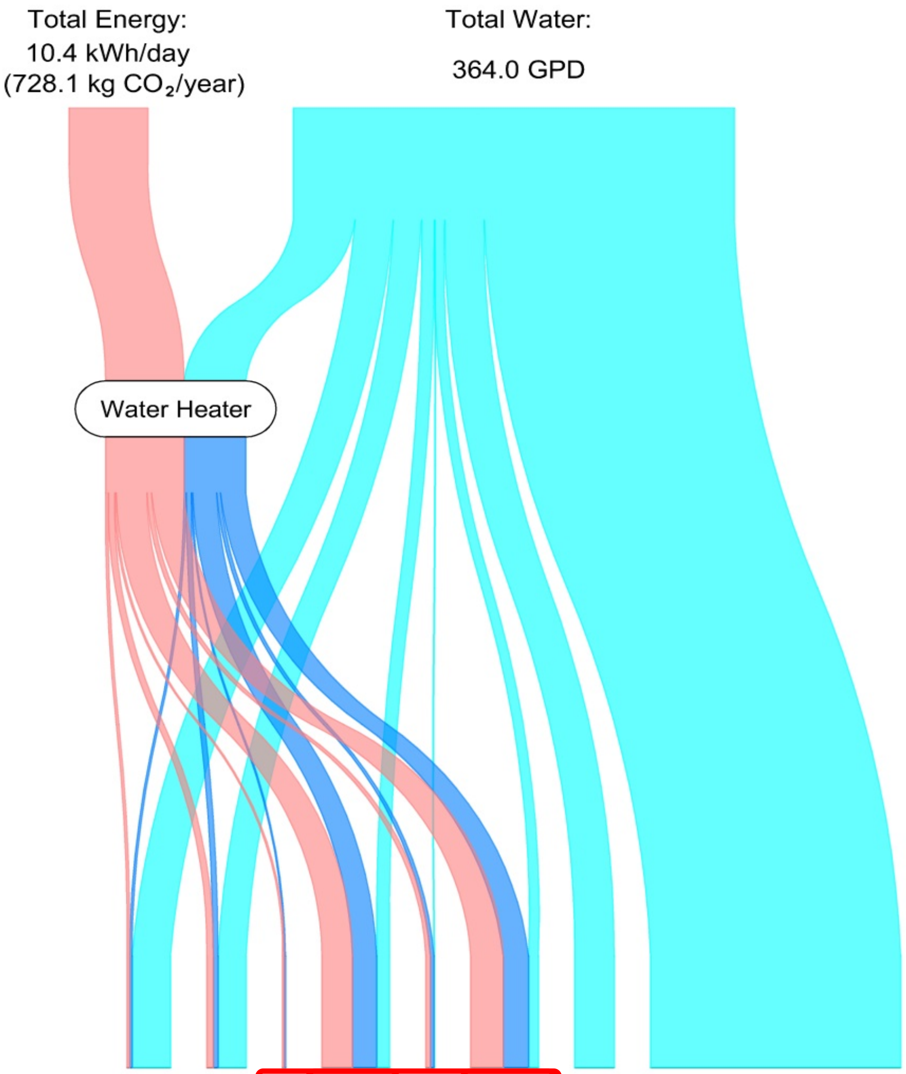
$$Q_{in} = \frac{vol \cdot den \cdot Cp \cdot \boxed{(T_{tank}} - \boxed{T_{in})}}{\boxed{\eta_{re}}} \cdot \left(1 - \frac{\boxed{UA} \cdot \boxed{(T_{tank}} - \boxed{T_{amb})}}{\boxed{P_{on}}}\right) + 24 \cdot \boxed{UA} \cdot \boxed{(T_{tank}} - \boxed{T_{amb})}$$

Household characteristics

Users' behaviors

External conditions

California overall results per household

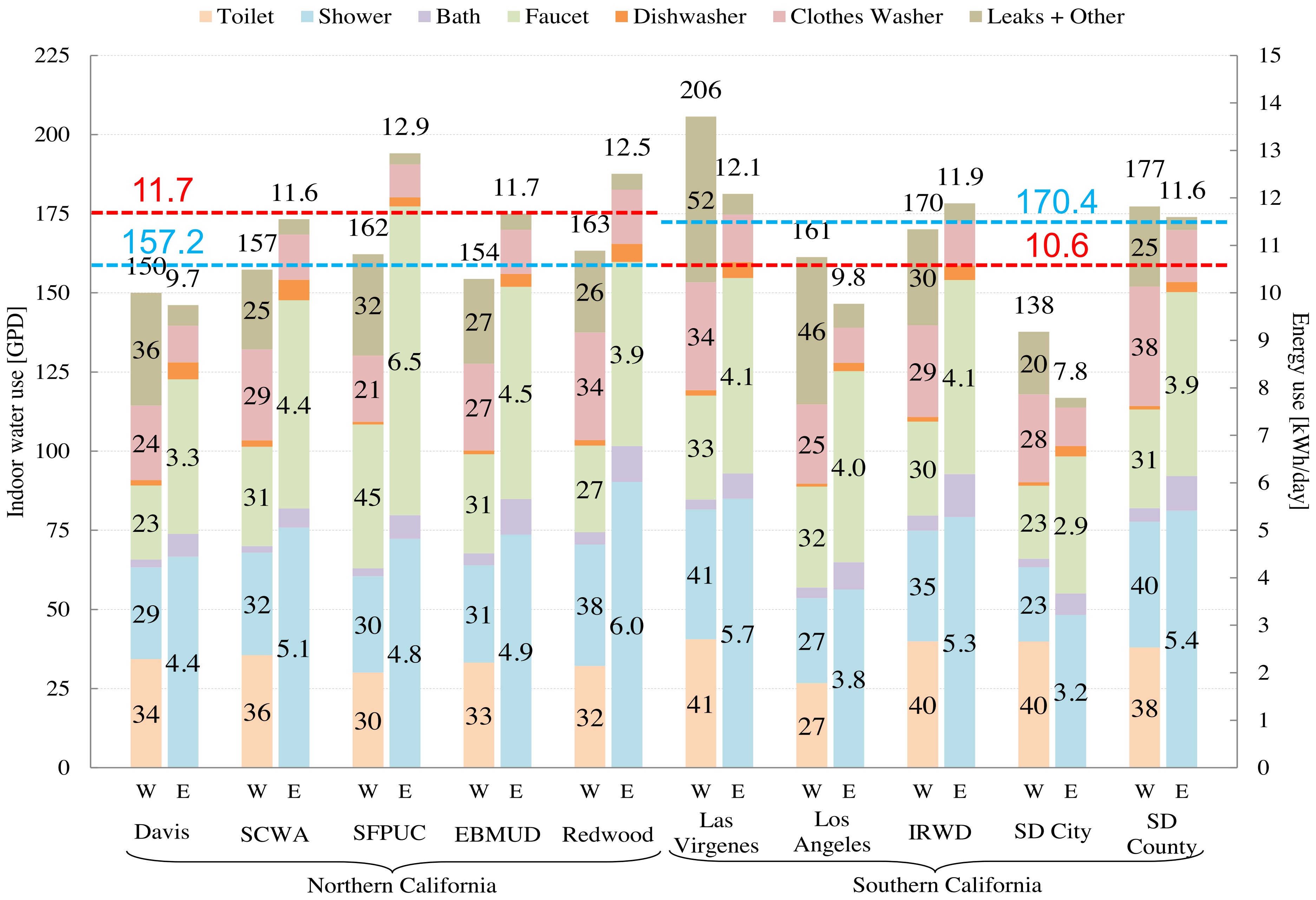


	L/O	CW	DW	Faucet	Bath	Shower	Toilet	Outdoor	Total
Cold Water (GPD)	31.7	23.1	0.0	10.6	0.4	8.1	32.5	206.6	313.0
Hot Water (GPD)	1.8	4.2	1.1	19.9	3.0	20.9	0.0	0.0	51.0
Energy (kWh/day)	0.4	0.8	0.2	4.0	0.6	4.3	0.0	0.0	10.4
CO_2 (kg/year)	26.2	58.8	16.2	283.4	42.6	300.8	0.0	0.0	728.1
Water cost ($/month)	7.3	6.2	0.3	6.8	0.7	6.5	7.5	44.3	79.8
Energy cost ($/month)	0.5	1.1	0.3	5.4	0.8	5.8	0.0	0.0	13.9
Total cost ($/month)	7.8	7.3	0.6	12.2	1.6	12.6	7.5	44.3	93.7

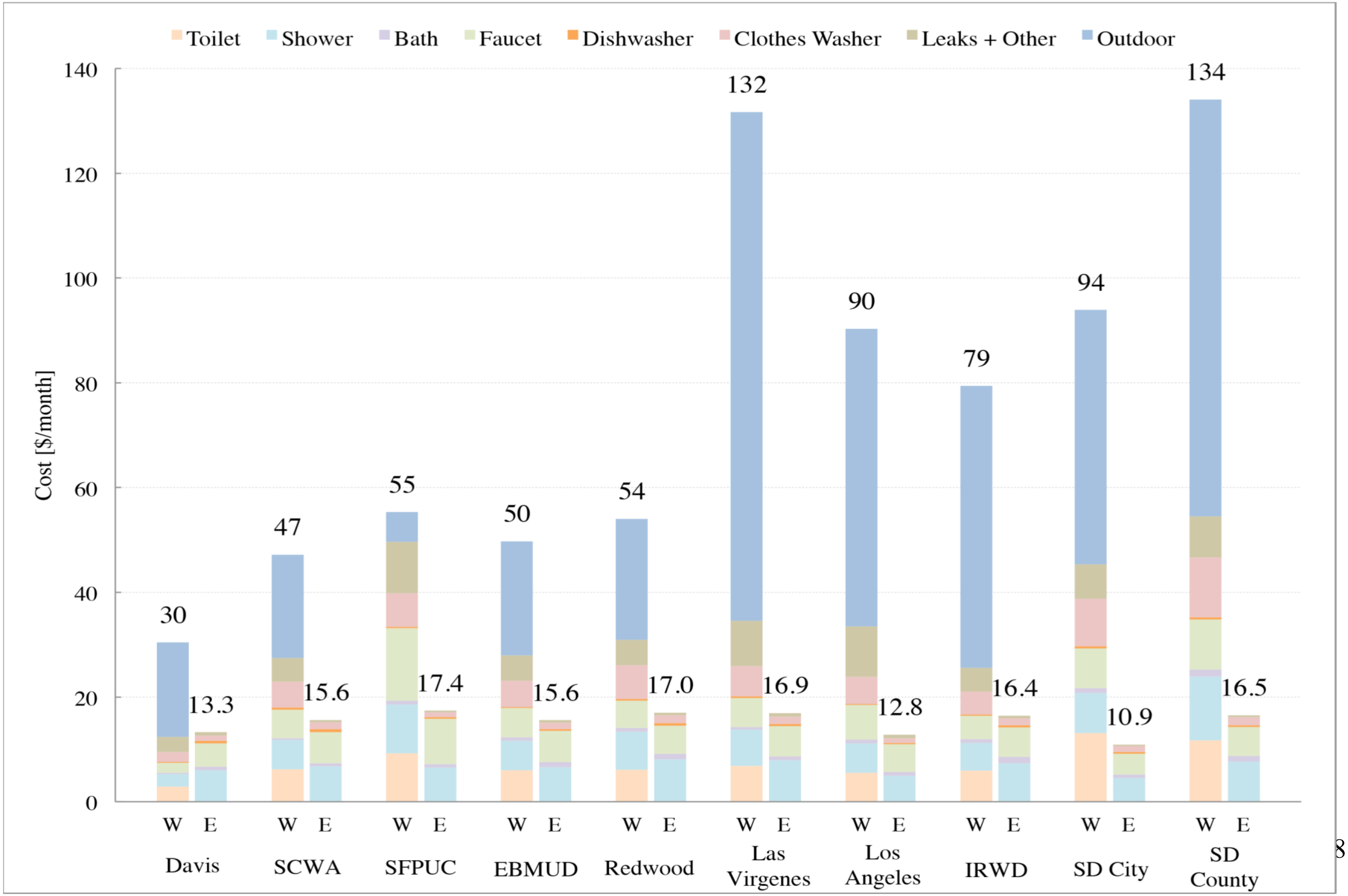
80% of total water-related energy

2% total per capita GHG emissions

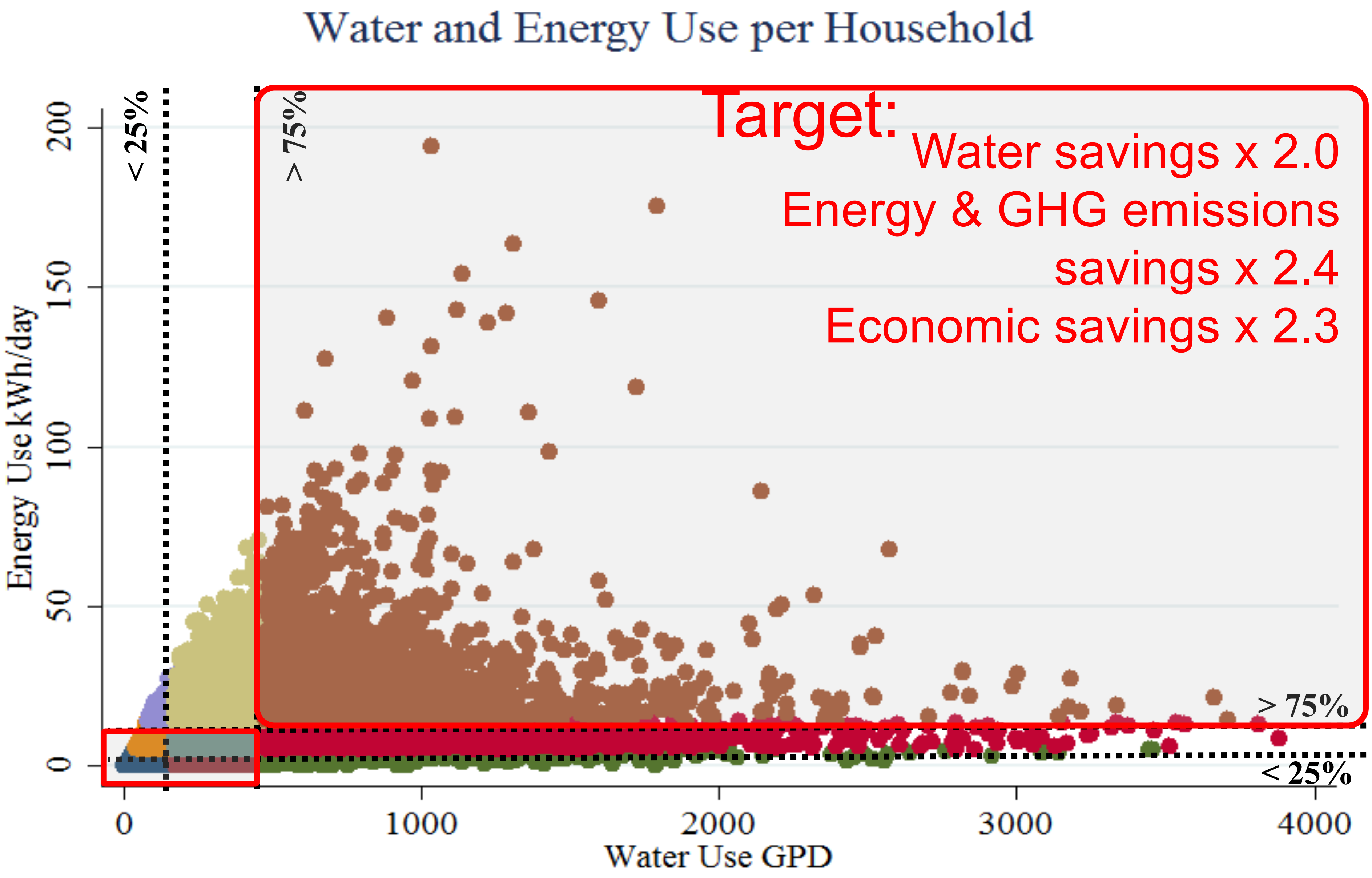
Household water and energy per city



Household water and energy costs per city



Heterogeneity in consumption



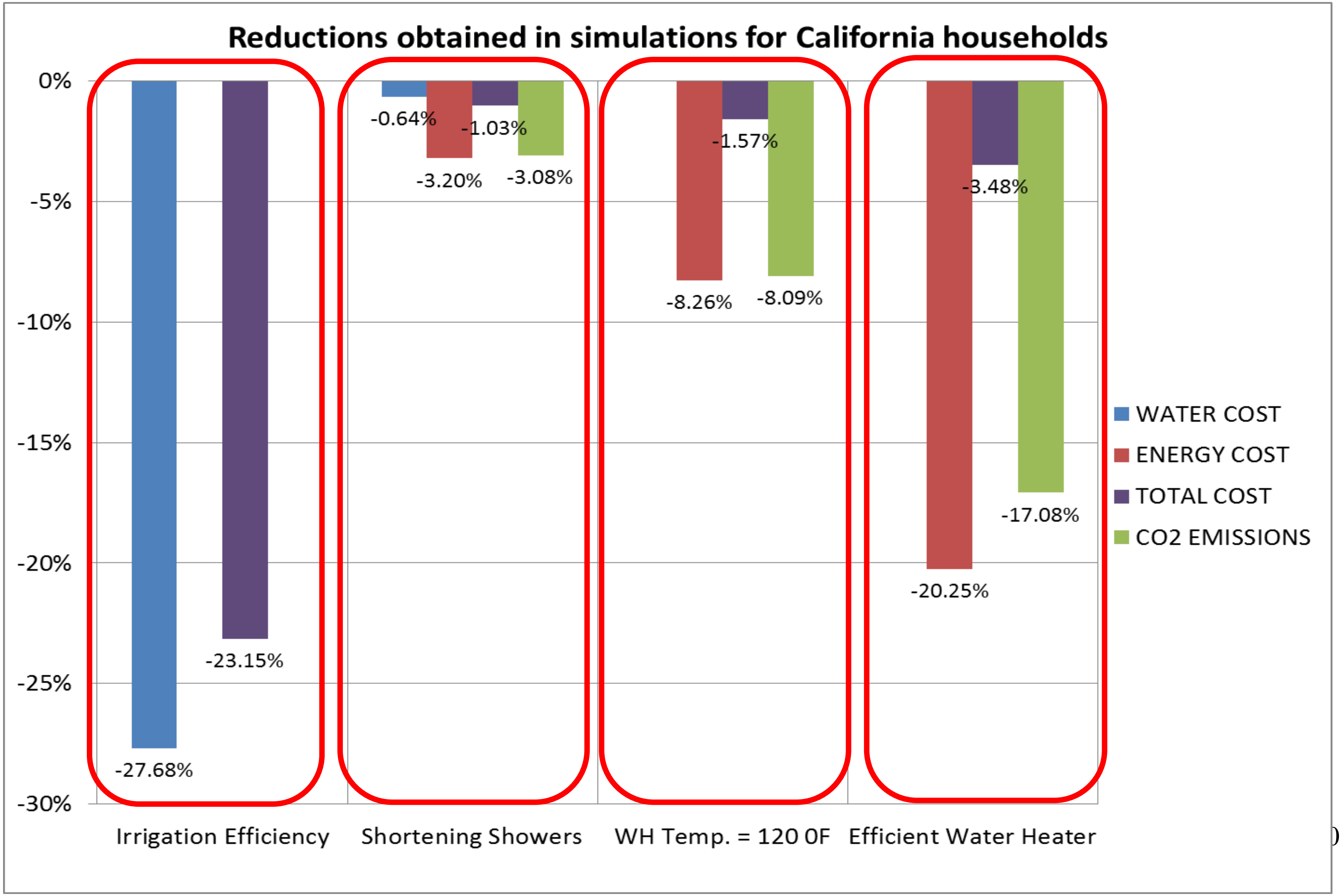
Target:

Water savings x 2.0

Energy & GHG emissions savings x 2.4

Economic savings x 2.3

Results show potential for joint management



Policy implications from mechanistic modeling

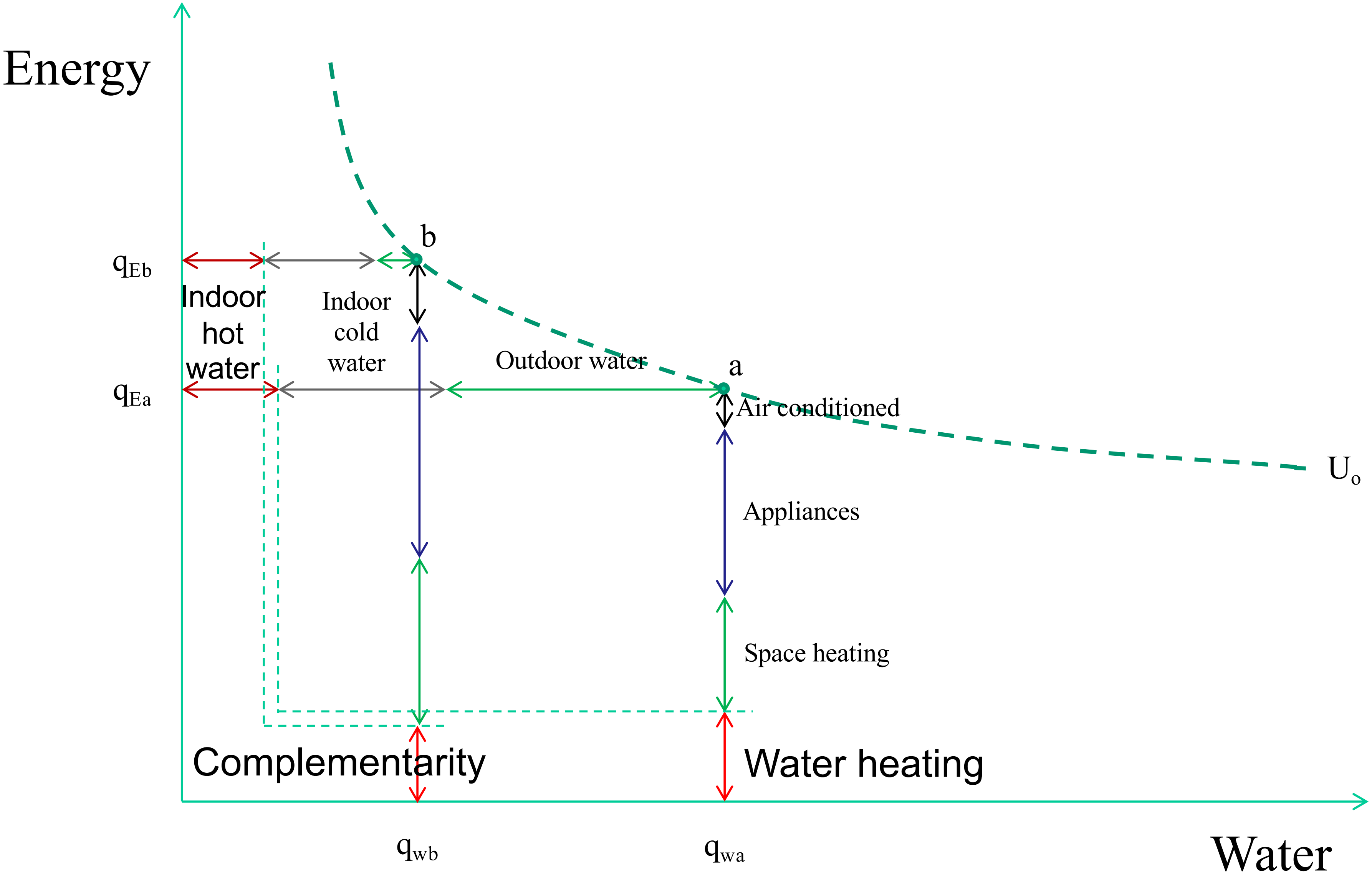
- Faucet + shower ≈ 80% water-related energy
- Air and inlet temperatures affect energy use
- “Willingness to adopt” conservation depends on:
  - Current consumption
  - Household stock
  - Water and energy prices
- Targeting
  - More than doubles cost-effectiveness of rebates

2) Least-cost water conservation mix for California households considering energy

- What is the least-cost water conservation mix for households, given water and energy prices?
- Does including energy affect willingness to adopt conservation actions?
- How significant are own- and cross-price elasticities?

*Escriva-Bou, A., J. R. Lund, and M. Pulido-Velazquez (2015), Optimal residential water conservation strategies considering related energy in California, *Water Resources Research*.

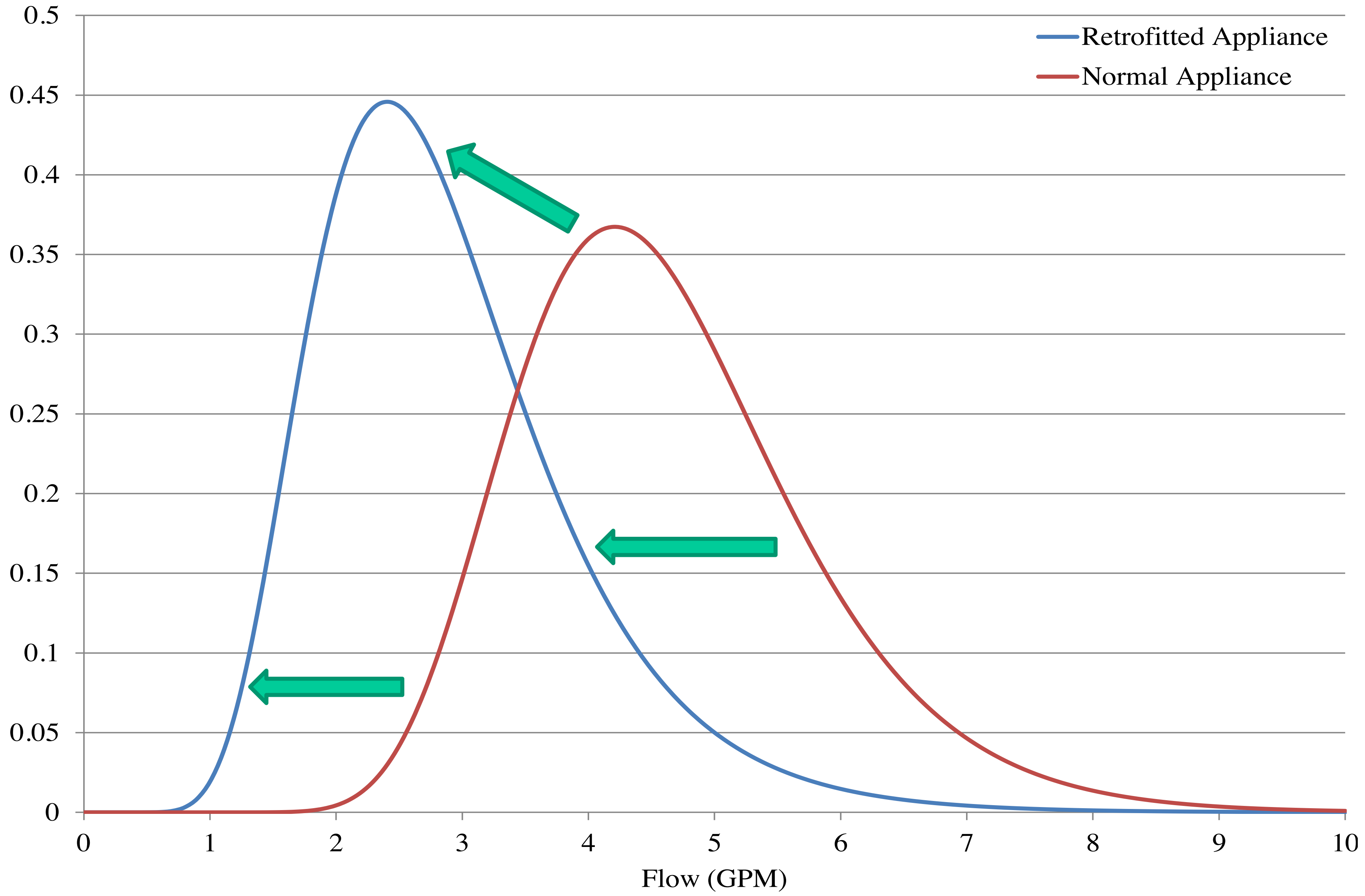
The economics behind the model: Complementarity of demand



Household optimization process

- Each household has conservation options
  - Long-term: Retrofits
  - Short-term: Behavioral
- Each action has
  - Cost
    - » Annualized costs for retrofits
    - » “Hassle costs” for behavioral changes
  - Effectiveness
    - » Water
    - » Energy
    - » Greenhouse gas emissions

Conservation Actions: Savings and Technological Shifts



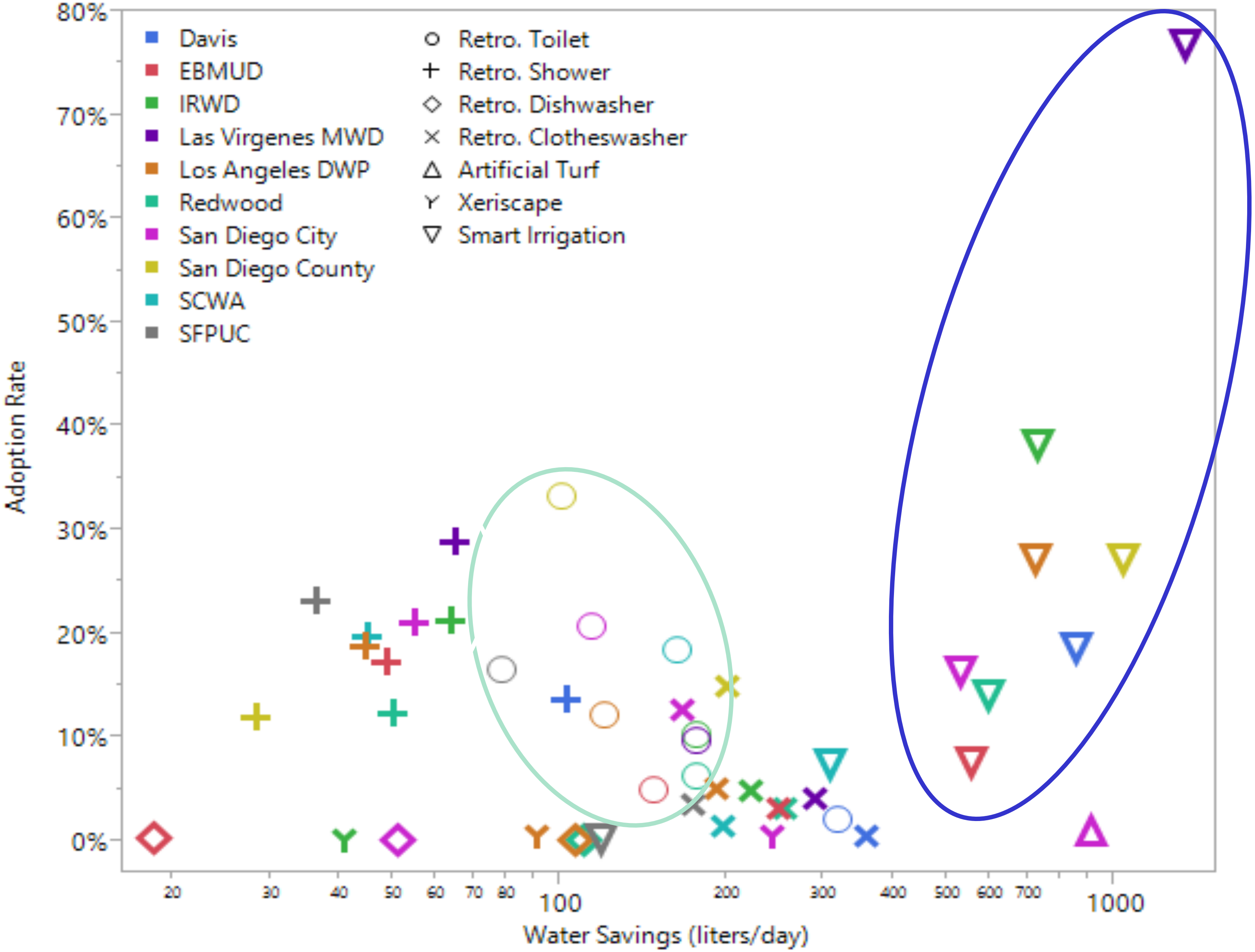
Optimization Model

$$Minimize\ TOTAL\ COST = \sum_{wlt} C_{wlt} \cdot X_{wlt} + \sum_{elt} C_{elt} \cdot X_{elt} + B \cdot \left[\sum_{we} p_{we} \cdot \left(\sum_{ee} p_{ee} \cdot \left\{ D \cdot \left(\sum_{wst} C_{wst} \cdot X_{wst_{we,ee}} + \sum_{est} C_{est} \cdot X_{est_{we,ee}} \right) + B_{W_{we}} + B_{E_{ee}} \right\} \right) \right]$$

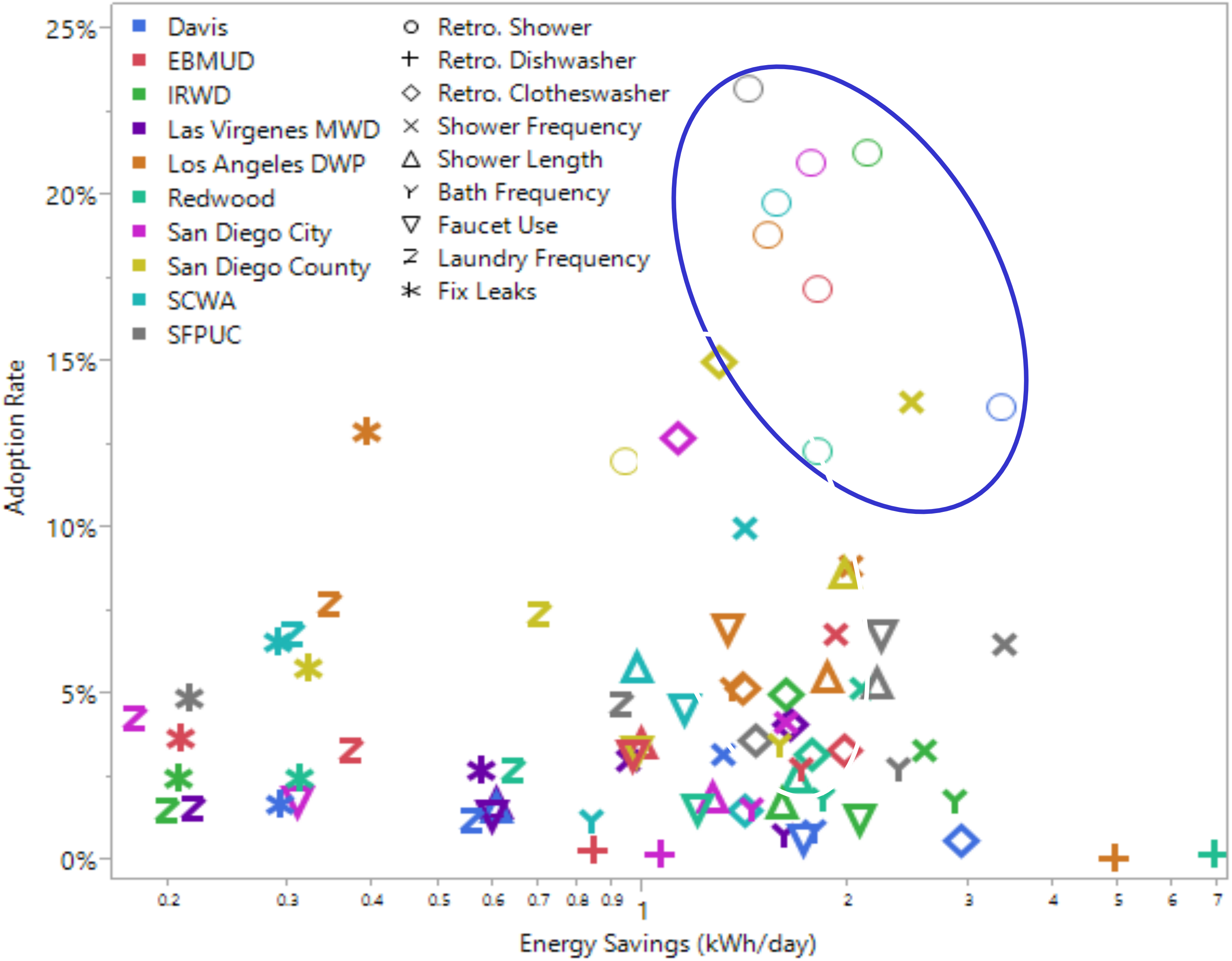
Subject to:

- Decision variables are binary
- Savings are less than initial use (upper bound) and resource availability
- Mutually exclusive actions
- Interdependence among actions

Water savings for long-term actions



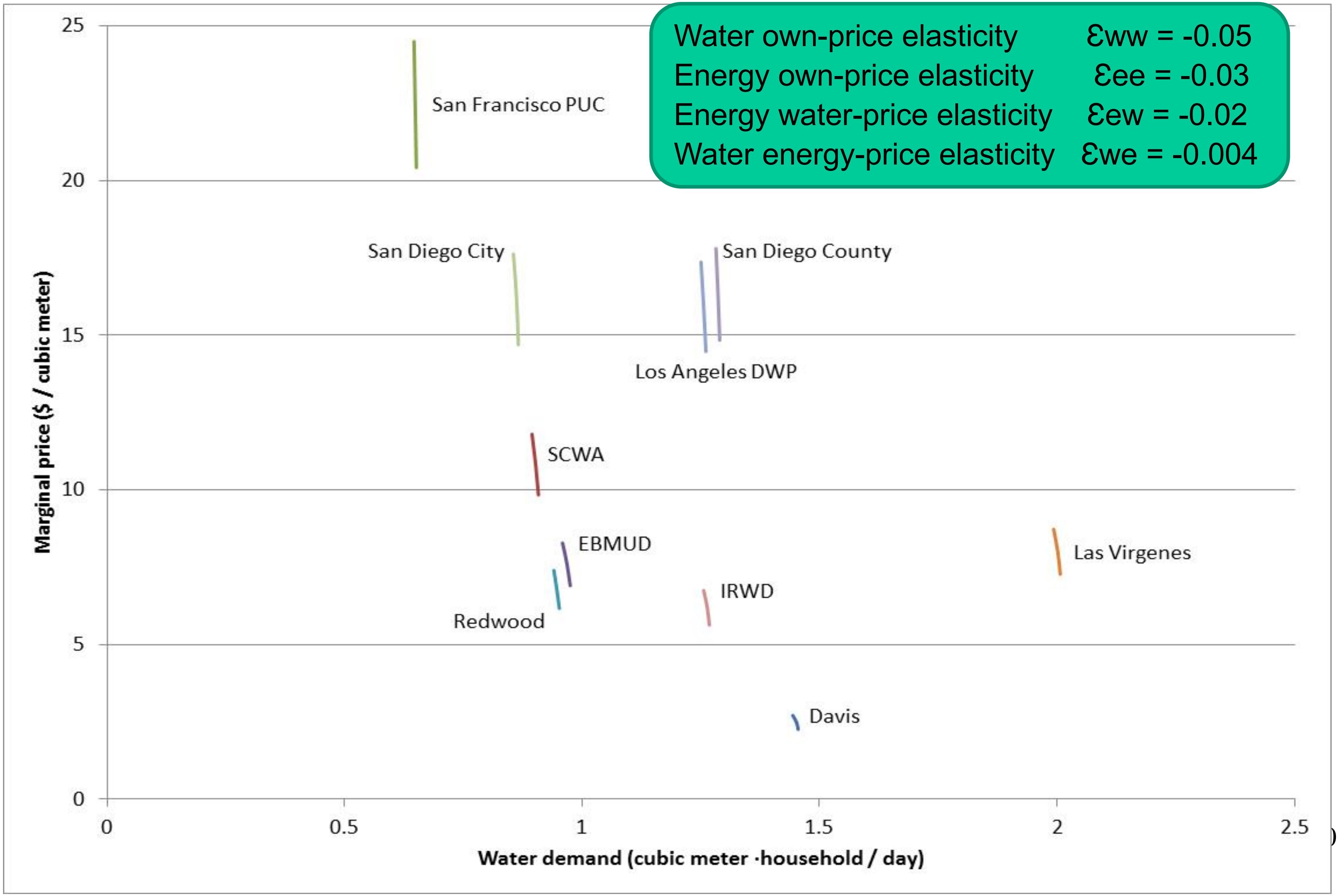
Energy savings for water-related actions



Increased conservation when energy is included

- Adoption rate:
  - Retrofit shower: +7.9%
  - Retrofit clothes washer: +1.7%
  - Reduce shower length: +3.2%
  - …
- Increased savings:
  - Indoor water savings: +24%
  - Energy savings: +30%
  - GHG savings: +53%

Demand functions and elasticities



Water own-price elasticity	Ɛww = -0.05
Energy own-price elasticity	Ɛee = -0.03
Energy water-price elasticity	Ɛew = -0.02
Water energy-price elasticity	Ɛwe = -0.004

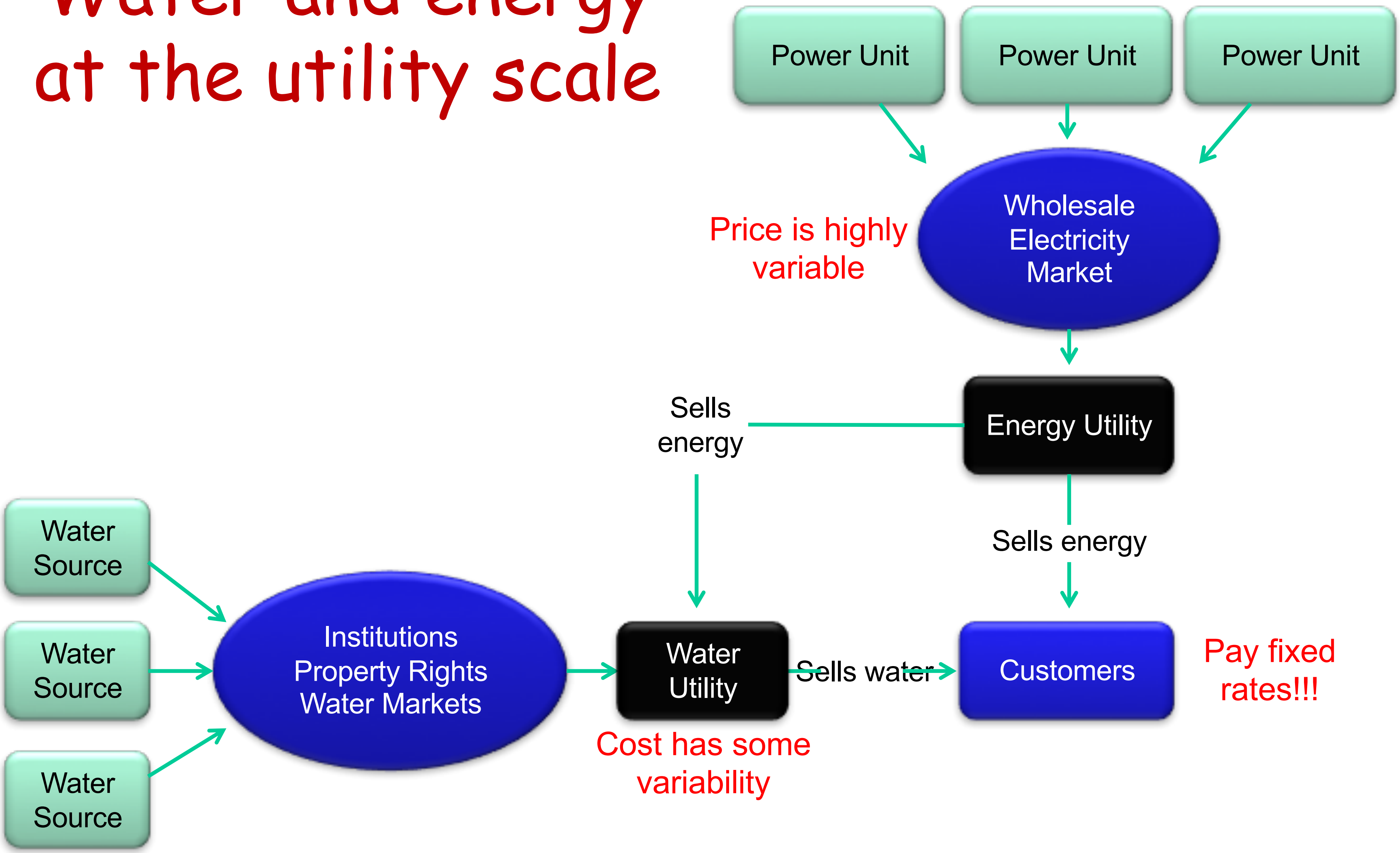
Policy implications from Mechanistic Modeling

- Including water-related energy should increase water conservation (and energy and GHG savings).
- Outdoor and toilet save most water; shower, faucet and clothes washer better save energy.
- Behavioral actions: Much to do!

3) Coupling hourly end-use and utility-scale water-energy models

- How much energy and GHG emissions are embedded in urban water cycle?
- What are effects of water conservation on water and energy utilities?
- Are there synergies for water and energy utilities working together?

Water and energy at the utility scale



Power Unit

Power Unit

Power Unit

Wholesale Electricity Market

Price is highly variable

Energy Utility

Sells energy

Sells energy

Water Source

Water Source

Water Source

Institutions
Property Rights
Water Markets

Water Utility

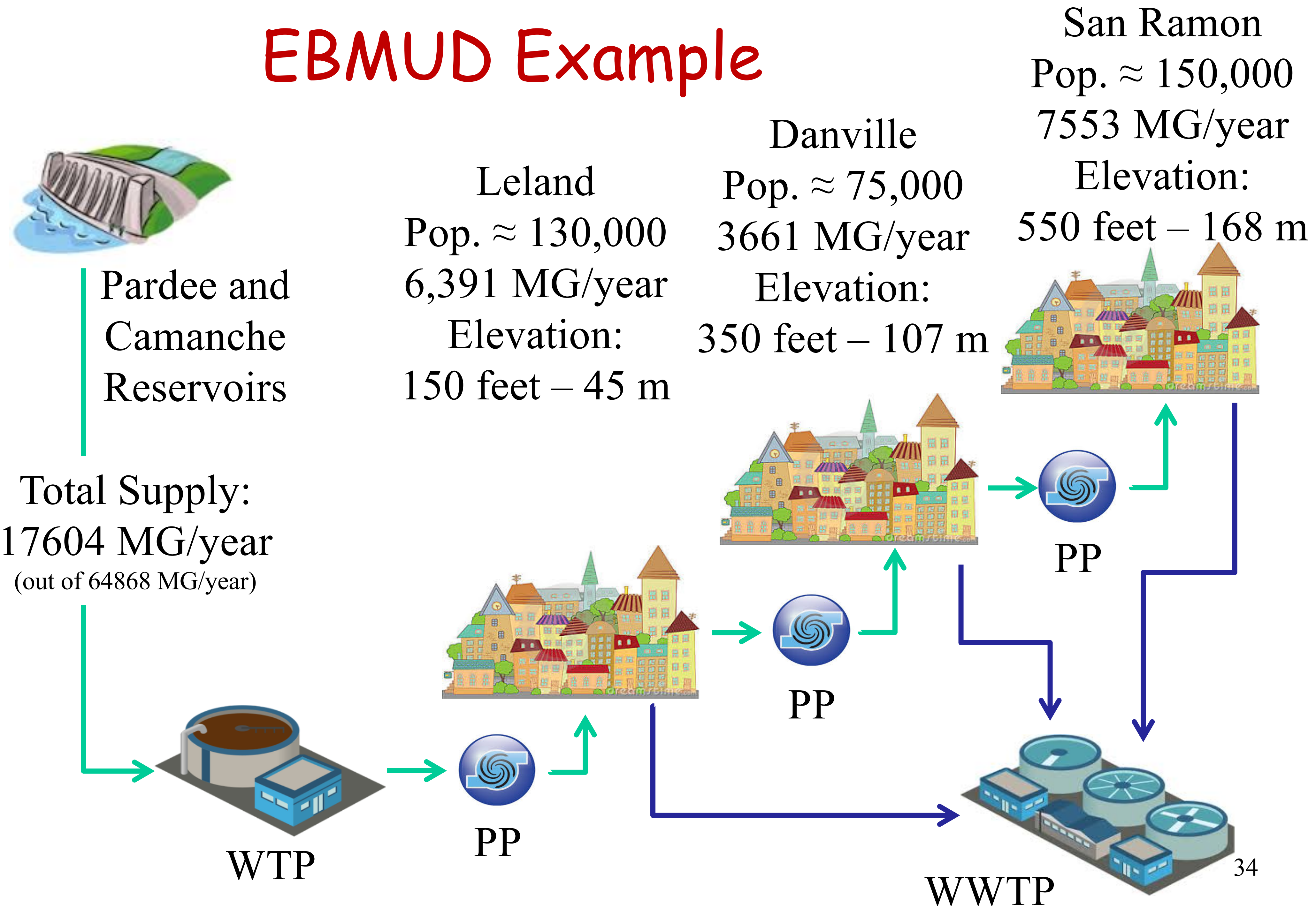
Sells water

Customers

Pay fixed rates!!!

Cost has some variability

EBMUD Example



Pardee and
Camanche
Reservoirs

Total Supply:
17604 MG/year
(out of 64868 MG/year)

WTP

PP

Leland
Pop. ≈ 130,000
6,391 MG/year
Elevation:
150 feet – 45 m

PP

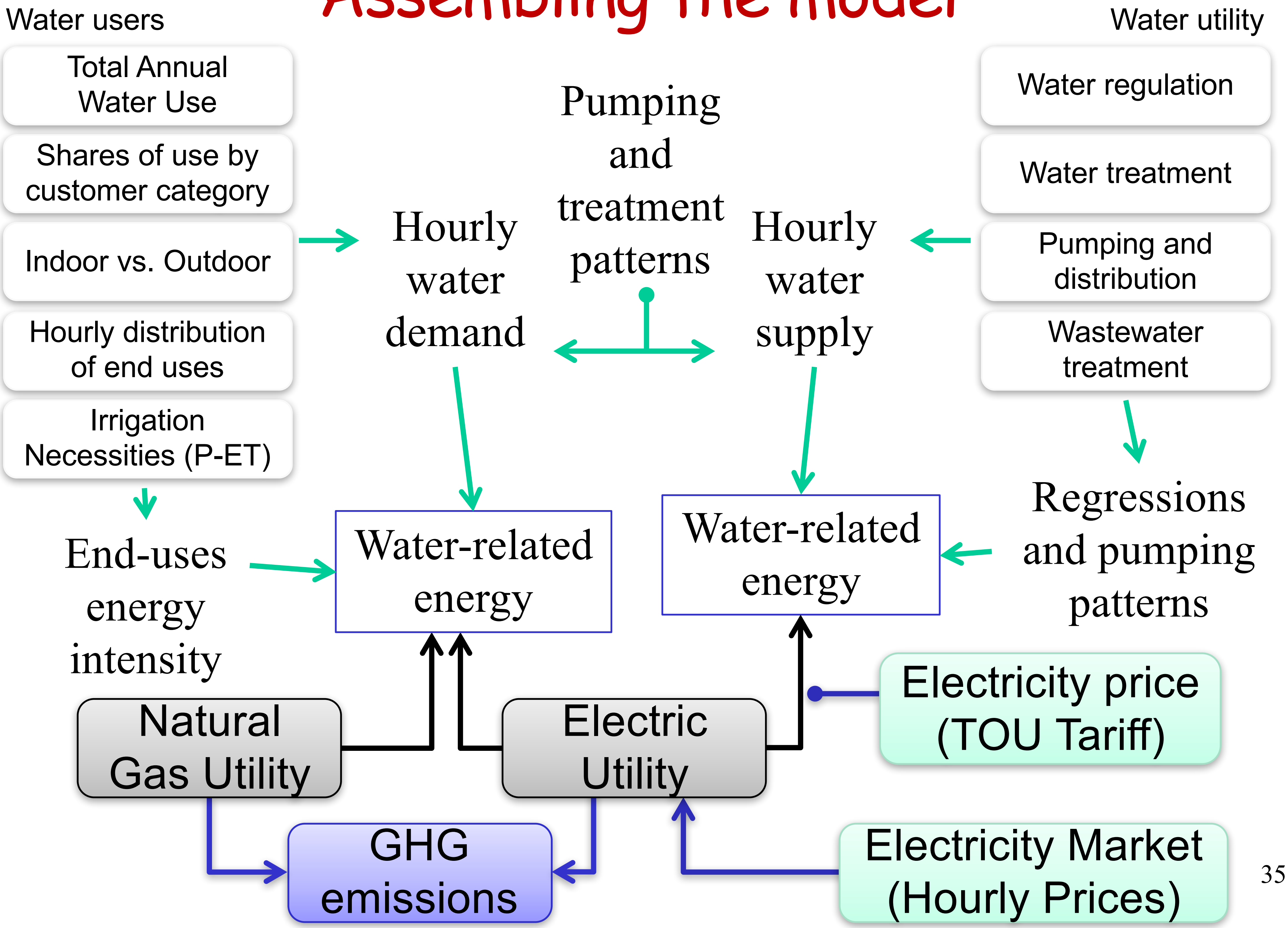
Danville
Pop. ≈ 75,000
3661 MG/year
Elevation:
350 feet – 107 m

PP

San Ramon
Pop. ≈ 150,000
7553 MG/year
Elevation:
550 feet – 168 m

WWTP

Assembling the model



Water users

Total Annual Water Use

Shares of use by customer category

Indoor vs. Outdoor

Hourly distribution of end uses

Irrigation Necessities (P-ET)

End-uses energy intensity

Hourly water demand

Pumping and treatment patterns

Hourly water supply

Water utility

Water regulation

Water treatment

Pumping and distribution

Wastewater treatment

Regressions and pumping patterns

Water-related energy

Water-related energy

Natural Gas Utility

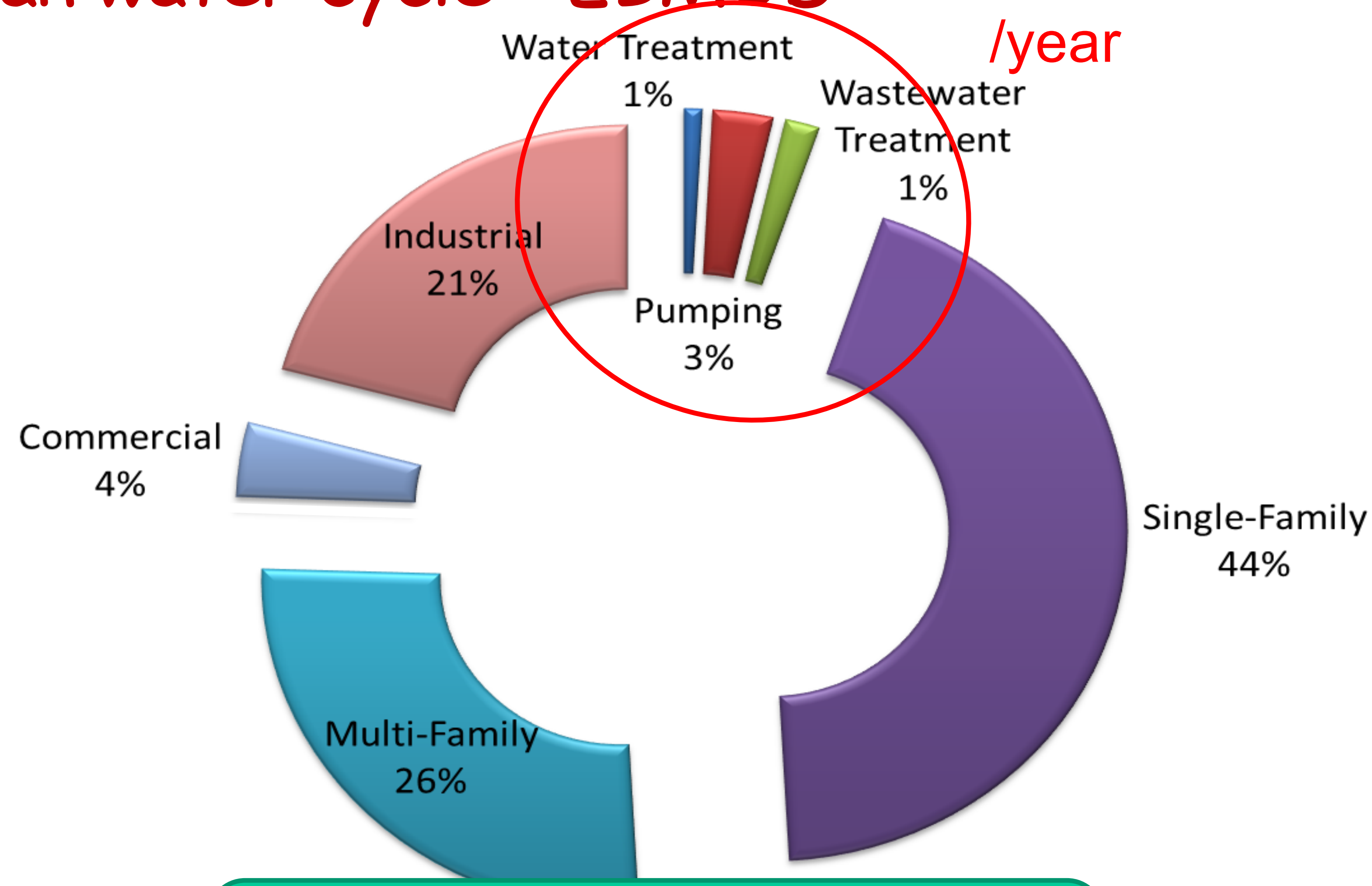
Electric Utility

Electricity price (TOU Tariff)

GHG emissions

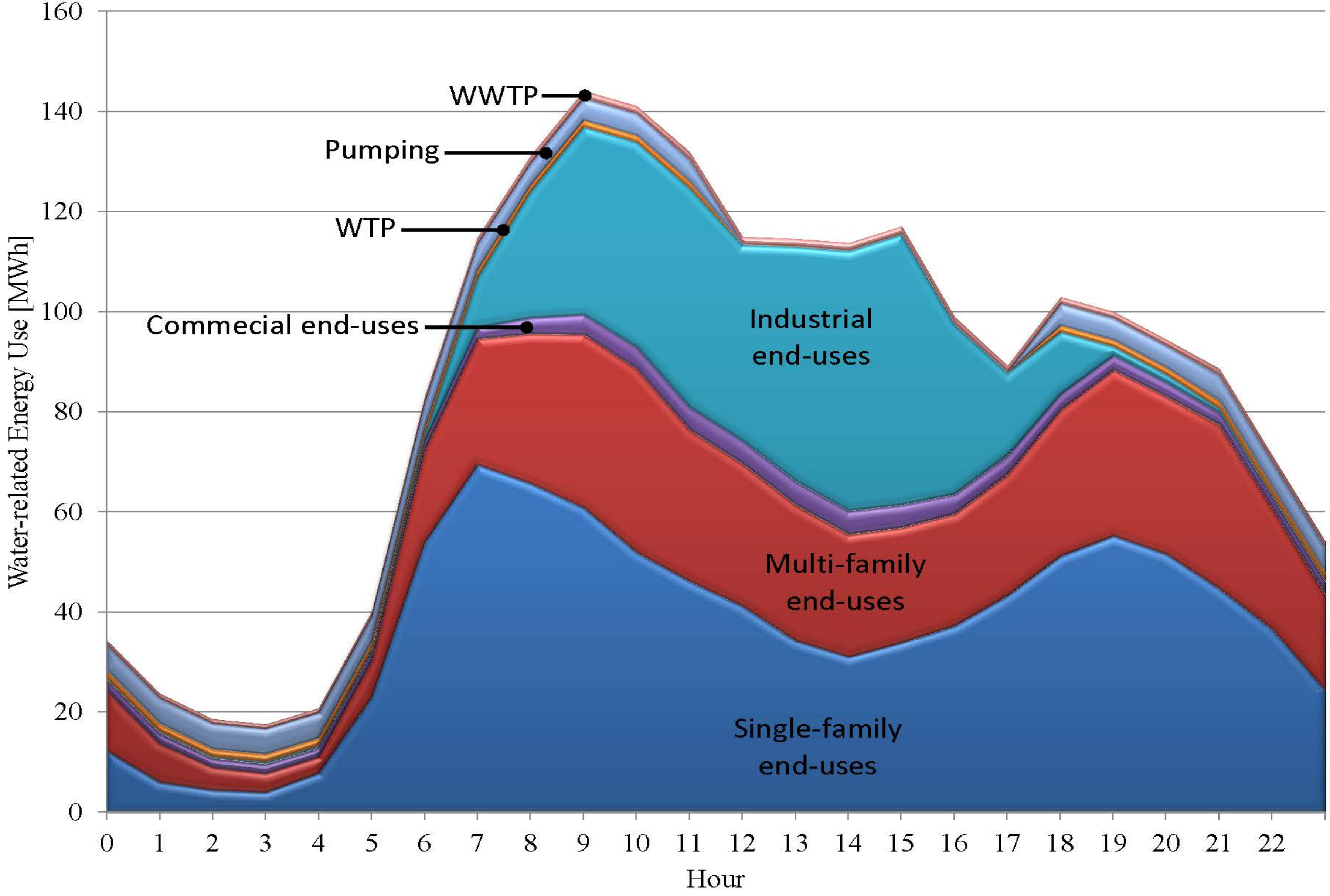
Electricity Market (Hourly Prices)

Water-related energy consumption in the urban water cycle - EBMUD



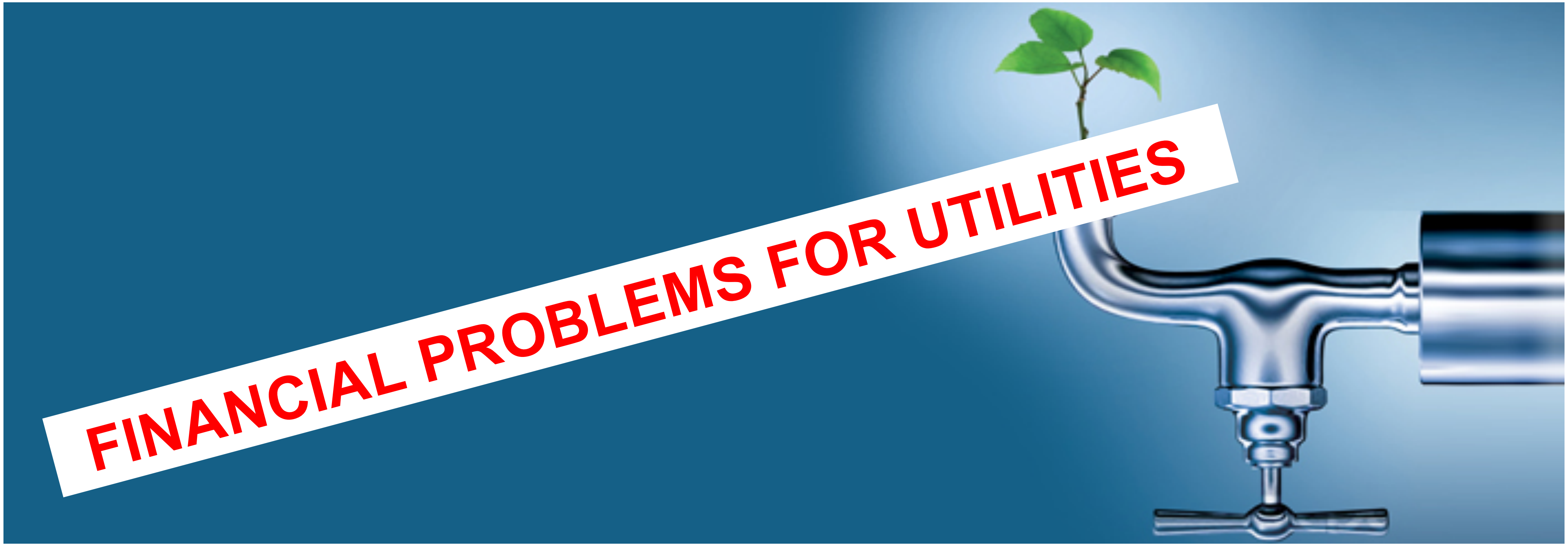
Urban water cycle
Total emissions per capita: 406 kg CO_2/year
4.5% total emissions per capita in CA

Shifting Water Use Peaks to Off-Peak Energy Hours Has Economic Benefits



Results

- Optimal water conservation
  - – Water use: 6% reduction
  - – Energy use: 5% reduction
  - – GHG emissions: 5% reduction
  - – Energy cost for water utility: 4.5% reduction



Results

- Demand-response (peak shaving): Outdoor, clothes washer and dishwasher use are moved to off-peak hours.
  - Water use: Equal
  - Energy use: Equal
  - GHG emissions: Needs more discussion
  - Energy cost for water utility: 3% reduction
  - Energy cost for energy utility: 4% reduction

Policy implications

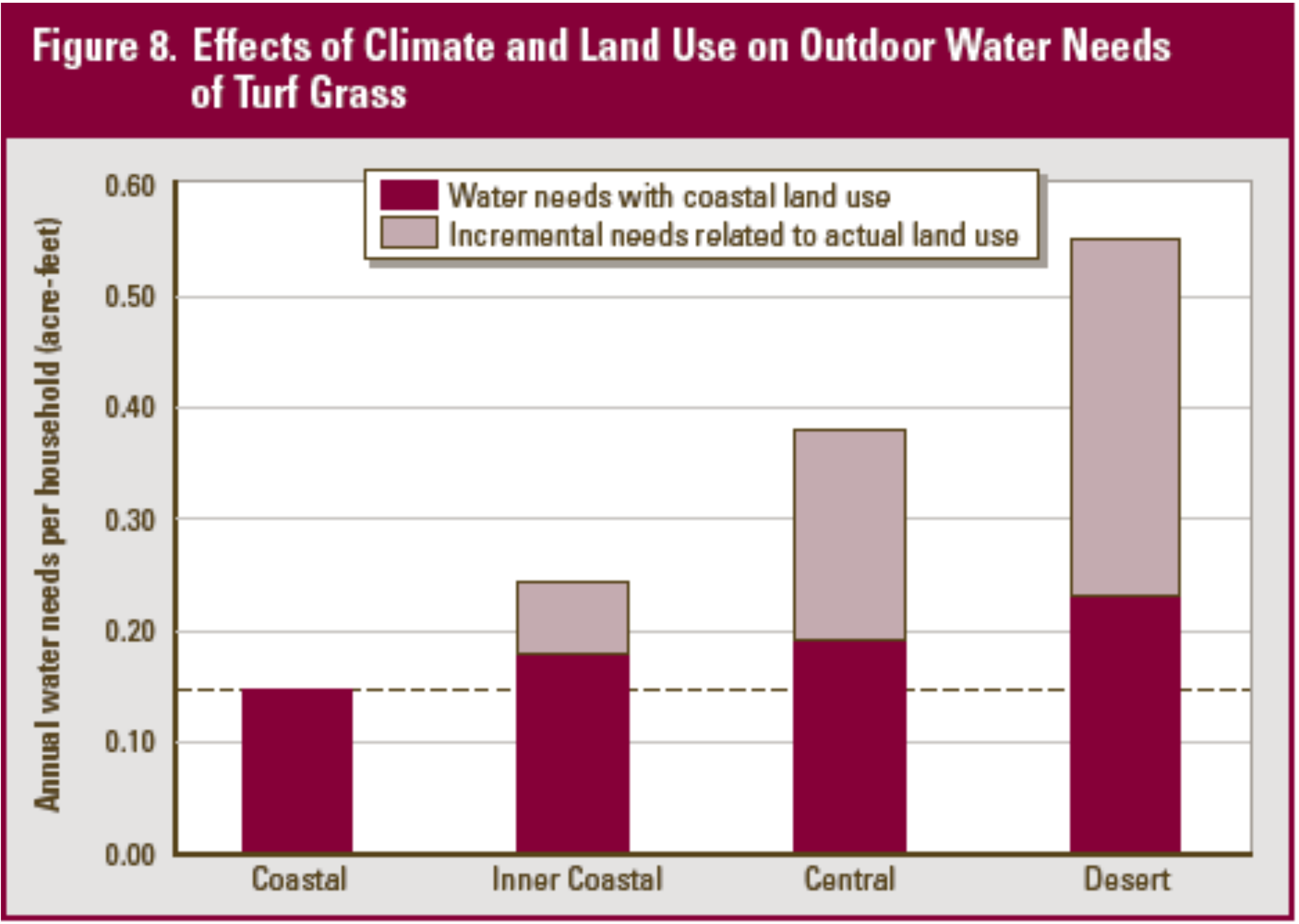
- Saving water reduces some GHG emissions.
- Synergies exist for water and energy utilities working together.
- Temporal water demand management can be very effective to reduce energy peaks.

Hard Parts Left to Do

- Outdoor water use and WTP estimation
- Monte Carlo modeling for outdoor use
- Energy - Hot water heater efficiency
- Getting data organized – starting to happen
- Testing models systematically and reconciling with empirical modeling

Effects of Climate and Land Use

- Larger lawns & warmer, drier climate increase landscape water use
- Landscape type will also affect!



Hanak and Davis, 2009

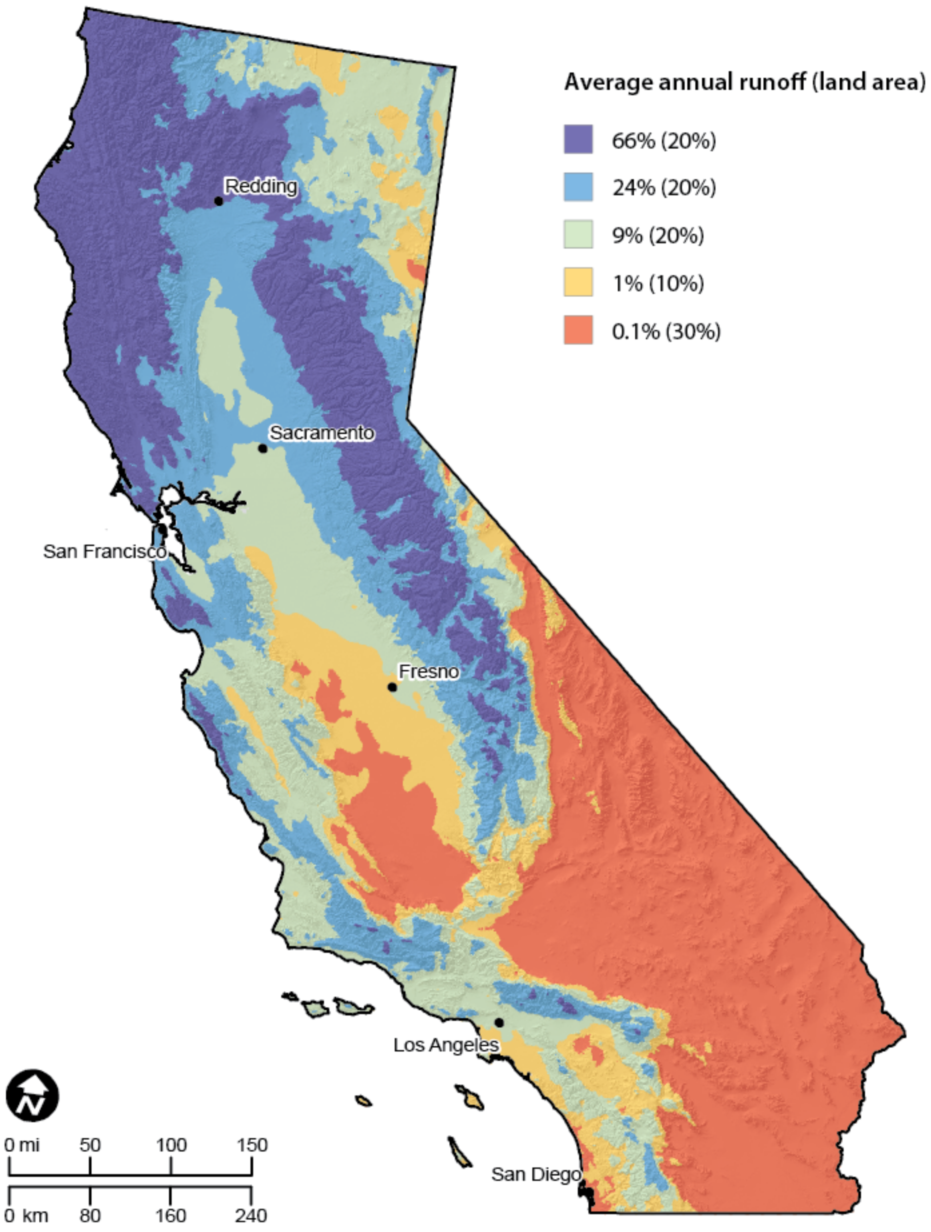
Opportunities

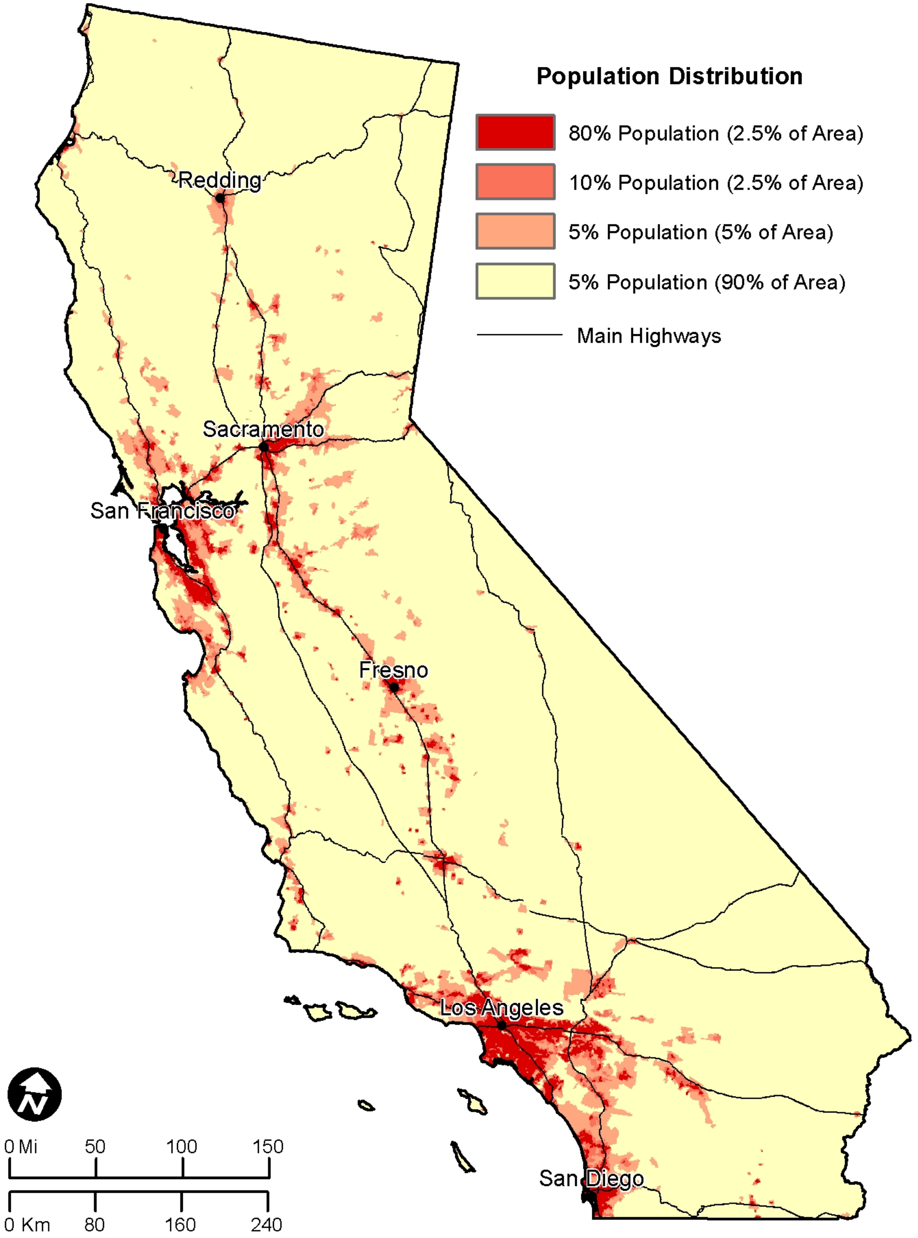
- Smart meter data will drown us in data
- Commercialize mechanistic modeling
- Integrate with other supply and demand management activities at social, utility, and household scales
- Include more risk and financial analysis

Conclusions

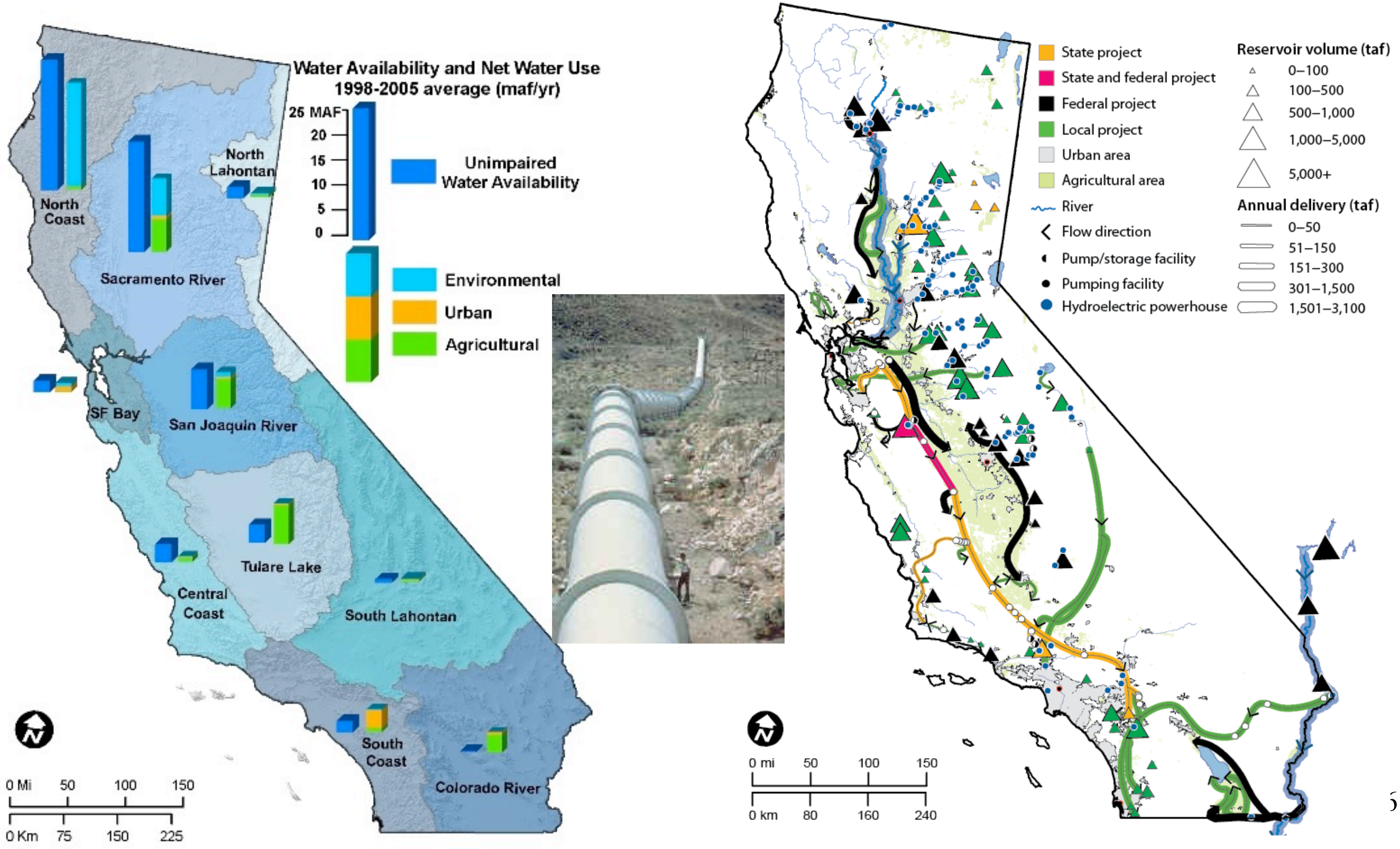
- Nexus modeling is harder, but more interesting and useful than just yacking about X-Y-Z nexus
- Mechanistic modeling, better organizes problem with more flexibility and insights than empirical modeling alone
- Empirical and Mechanistic modeling should work better together
- Future looks bright for research and applications

Water and People in California





California depends on an engineered statewide network



Effects of Climate and Land Use

- Average Water Requirements of Turf Grass for Small Single-Family Lots

Region	Yard Size (sf)	Weighted Average ET0 (inches/year)	Annual Water Requirements (af)	Increase over Region with Lowest Need
San Francisco Bay Area	6,308	45.9	0.19	—
South Coast	7,623	49.8	0.25	31%
San Joaquin Basin	7,060	54.4	0.26	33%
Tulare Basin	7,711	56.2	0.29	50%
Sac. Metro region	8,129	56.8	0.31	59%
Inland Empire	8,858	56.2	0.33	72%

Hanak and Davis, 2006

AU and CA urban water use

- Urban CA could reduce use by 30-50+% with AU use rates.

Location		**Residential Use, gpcd**
Portland, OR		58
Albuquerque, NM		74
Tucson, AZ		97
Denver, CO		104
California		**104**
	San Francisco	46
	Oakland/East Bay	73-83
	San Diego	73-92
	San Jose	81-85
	Los Angeles	91-99
	Sacramento	**113-120**
Australia		**54**
	Melbourne	40
	Brisbane	45
	Canberra	50
	Sydney	55
	Perth	75

Cahill and Lund, 2009

Biggest difference in AU and CA use is usually outdoors

	California				Australia					
	East Bay Area		California		Perth		Melbourne		Gold Coast	
End Use	Use, gpcd	% of total	Use, gpcd	% of total	Use, gpcd	% of total	Use, gpcd	% of total	Use, gpcd	% of total
Toilet	20	21%	13	10%	9	9%	8	13%	5	13%
Shower/Bath	15	16%	13	10%	14	14%	14	24%	15	37%
Washing Machine	14	15%	10	8%	11	11%	11	19%	8	19%
Faucets	10	11%	11	9%	7	7%	7	12%	7	17%
Leaks	5	5%	10	8%	2	2%	4	6%	1/2	1%
Other	1	1%	2	1%	1	1%	1	1%	1/2	1%
Outdoor	30	32%	67	53%	55	56%	15	25%	5	12%
Total	95	100%	126	100%	99	100%	60	100%	42	100%

Cahill and Lund, 2006

Melbourne 25”
Queensland 48”
Perth 29”