A Market for Water that Prices Hydrological, Environment, and Political Constraints

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Outline of Talk

- Growing scarcity of water resources in western US
  - Water markets seen as part of solution
- The major challenge of running a water market is very similar to major challenge of running a wholesale electricity market
  - Value of product differs over time, location and individuals
- How to capture these realities in water pricing
  - Locational marginal pricing of water
- Can account for all relevant physical, environmental, and political and other operating constraints over time and space
  - Significantly improve efficiency of water allocation process
  - Avoids costly litigation among parties over transactions
- Real-world examples of benefits of locational marginal pricing
  - Locational marginal pricing of electricity in California
- Simplified examples of locational pricing in electricity and water
  - 3-node and 4-node examples
- Next steps in implementing locational marginal pricing of water

Growing Water Scarcity

- Increasing stresses on water supply in western US (particularly in California) from
  - Agricultural use
  - Urban use (population growth)
  - Use in energy production and consumption
  - Recreational use
  - Environmental use
- Water is typically not where consumers are
  - Transportation to consumers is costly
- Water may not be available when consumer wants it
  - Storage facilities for future use

Water in California Policy Agenda

Jerry Brown's water plan is more than policy

In unveiling the latest version of the Peripheral Canal, the California governor is trying to finish what his father, Gov. Pat Brown, had started.

George Skelton

Capitol Journal

10:18 PM PDT, July 29, 2012

Gov. Jerry Brown II last week unveiled the latest version of the peripheral canal: tandem peripheral pipes. Or tunnels, as many call them.

There would be three giant intakes with fish screens punched through a levee just downriver from Sacramento carrying water into a large pool. From there, the water would flow by gravity through the two 33-foot-wide pipes beneath the delta to the southbound aqueduct.

There'd still be some pumping at the fish-killing plant, but about 80% less than currently.

The pipes' capacity would be 9,000 cubic feet of water per second. (Think one cubic foot as a basketball.) The current capacity at the pumps is 15,000 CFS. The previously proposed peripheral canal would have carried 25,000 CFS.

Challenge of Water Markets

- Water trading over space and time
- Underlying physics of water re-charge and water flow implies that injecting an acre-ft now may not be equivalent to withdrawing an acre-ft later
  - Same statement applies to an injection at one location and withdrawal at another location at the same time
- Injections and withdrawals at different points in time and/or different locations can also have adverse environmental impacts
  - Harm to fish and wildlife
- Many of the disputes surrounding water trading arises from these complications

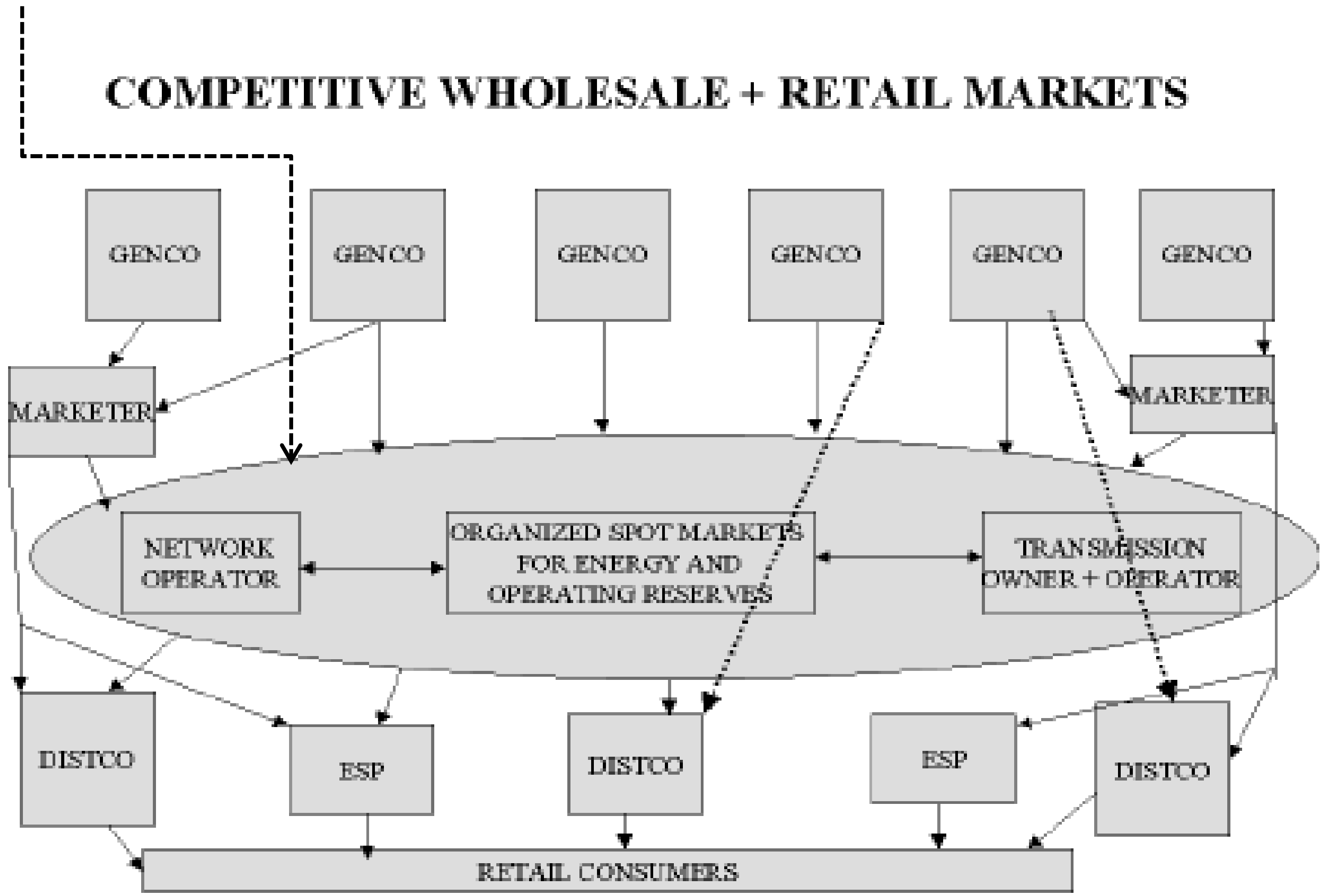
Challenge of Electricity Markets

- Underlying physics of current flow implies that injecting a MWh at one location may not be equivalent to MWh at another location
  - Transmission congestion
  - Transmission losses
  - Inertia of generation units
- Failure to account for all physical operating constraints in pricing mechanism led to many market efficiencies
  - Particularly in the US, which has significantly less transmission capacity than other industrialized countries
  - Market efficiencies are likely to be even greater as share of intermittent renewable resources increases

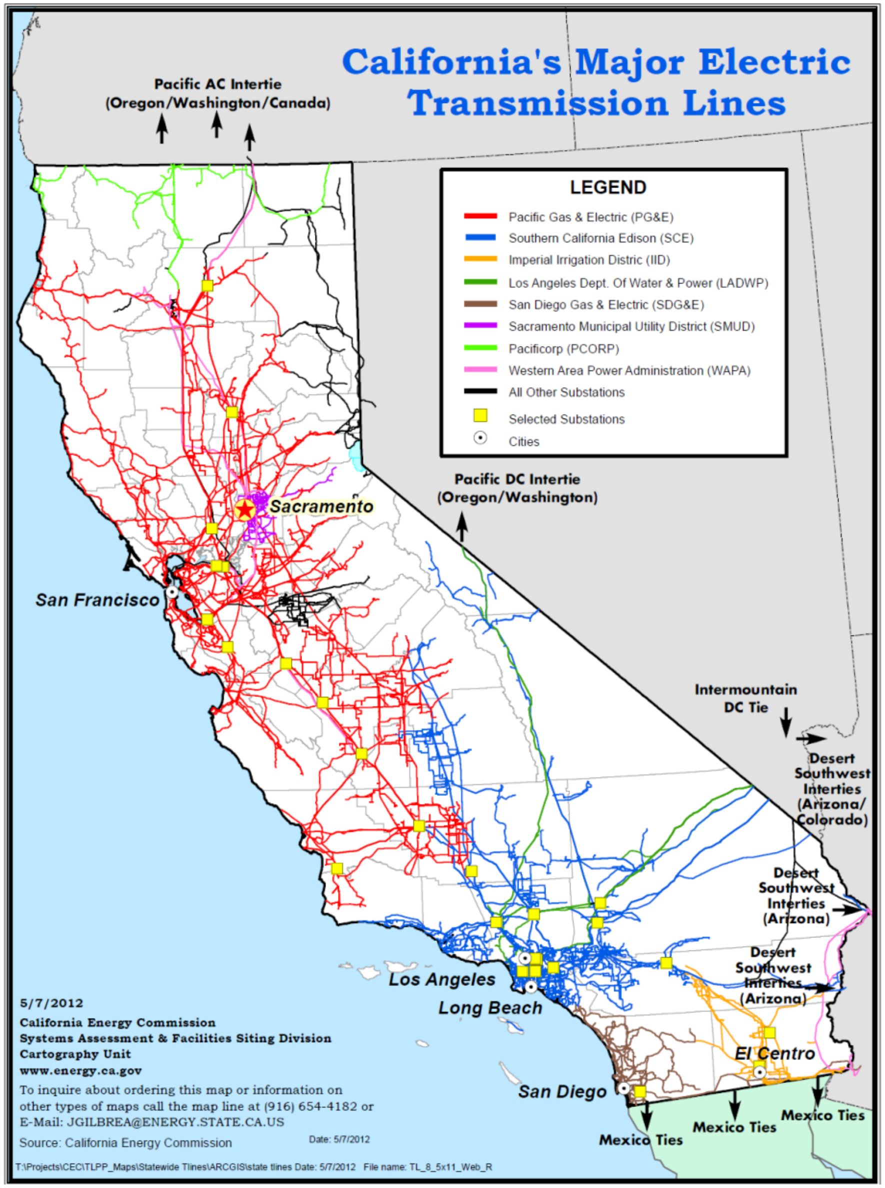
Market Operator for Electricity

- Electricity supply industry handles operation of transmission network with many suppliers and demanders using an independent system operator (ISO)
  - Operates transmission network to maintain real-time supply and demand balance and adequate operating reserves
  - Electricity sales and purchases managed through locational offers and bids
  - ISO is accepts bids and offers to maintain supply and demand balance at all locations in the transmission network
    - Subject to all relevant operating constraints on network and generation units
  - Multiple forward markets operate before actual production and consumption occurs

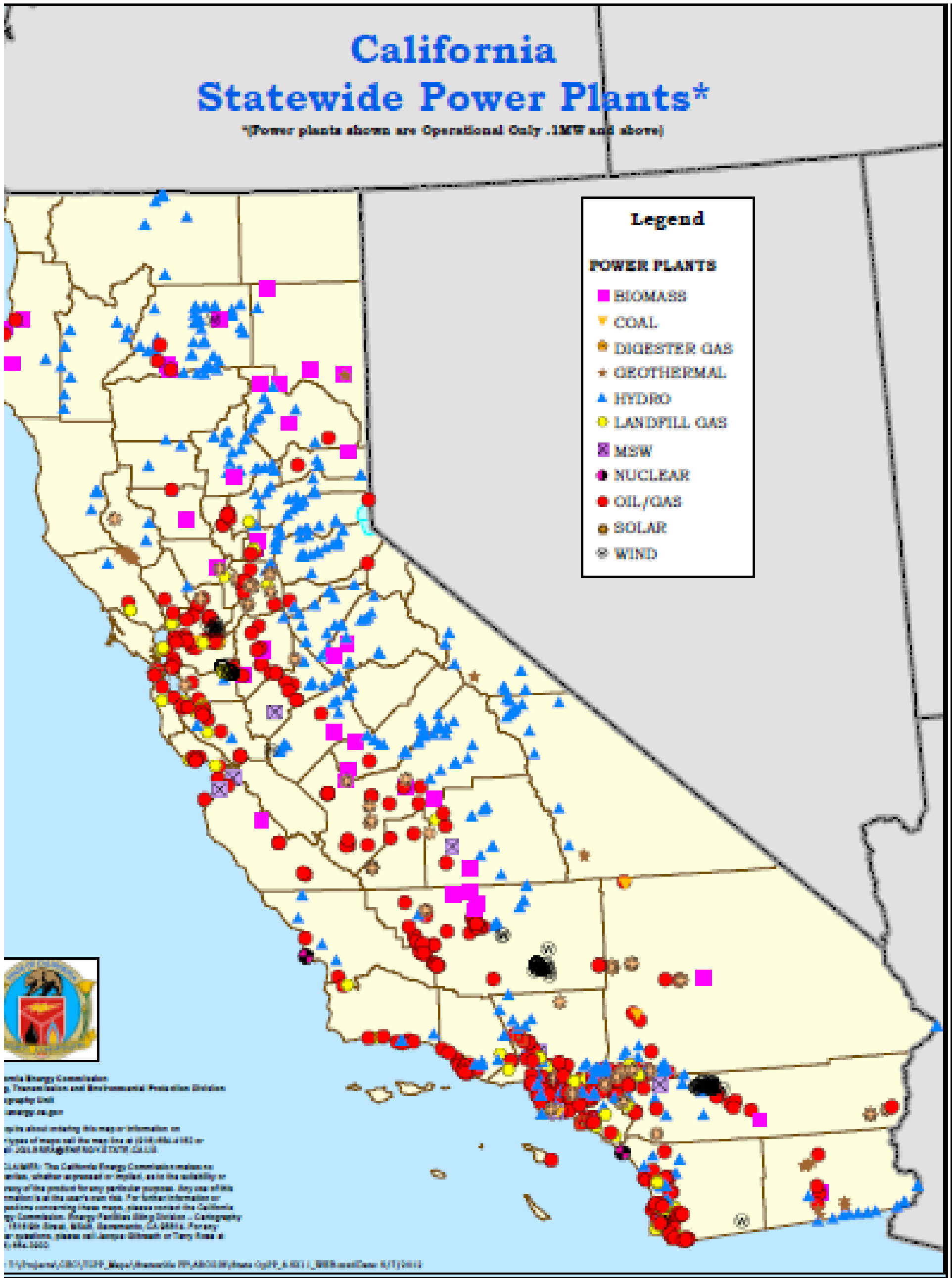
Role of ISO in Electricity Industry



Parallel Networks



Parallel Resources



Locational and Temporal Pricing of Water

- Set prices for water at each injection and withdrawal location and pre-specified times in future that accounts for all relevant operating constraints
  - Physical water flows under and above ground
  - Environmental constraints on injections or withdrawals
  - Technological constraints on pumps\
  - Political constraints on water movements
- Any constraint that can be represented mathematically can be explicitly priced

Locational and Temporal Pricing by ISO

- Participants submit willingness to inject and withdraw water at each location for pre-specified times in the future
  - Locational marginal prices (LMPs) set that incorporate physical constraints on aquifer, environmental, and other operating constraints
  - Forward market can be run many times in advance of real-time delivery date
- LMPs price willingness to inject and withdraw of all market participants **and** all relevant operating constraints on water system

Locational and Temporal Water Pricing

- Benefits of water trading likely to be larger
  - If market operates over larger geographic area
  - If market operates over longer time intervals to delivery
- Significantly reduce transactions costs associated with water trading
  - Rather than incur significant legal and administrative cost for each water trade, pay single up-front cost to establish general set of rules for trading
    - Model for natural and man-made network
    - Environmental constraints
    - Political and other institutional constraints
  - Allow all feasible trades subject to these rules

Locational Marginal Pricing of Electricity

- Locational marginal pricing is used in all US wholesale electricity markets
  - LMPs reflect transmission constraints, operating constraints on generation units, local environmental constraints, line losses, etc.
    - All constraints that prevent a megawatt-hour (MWh) at one location to equal a MWh at another location
  - All US wholesale electricity markets set LMPs at thousands of locations each hour of the day
    - California ISO, PJM Interconnection, New England ISO, New York ISO, Midwest ISO, and ERCOT

Theory of LMP Pricing

- Generalizes well-known result that economic equilibrium can be computed by finding price that maximizes sum of consumer and producer surplus
- Suppose producers submit offer (willingness to supply) curves that are step functions (p_{ij},q_{ij}) i=1,2,..K (number increments and j=1,2,…,J (number market participants)
  - p_{ij} = offer price for increment i of supplier j
  - q_{ij} = offer quantity for increment i of supplier j
- Suppose consumers submit bid (willingness to purchase) curves that are step functions Q_j – $SN_j(p)$
  - Q_j = Demand at price of zero for consumer j
  - $SN_j(p)$ = “nega-watt:” supply curve for consumer j
- Market-clearing price computed from solution to

$$\min_{\{0 \le x_{ij} \le q_{ij}\}} \sum_{j=1}^{J} \sum_{i=1}^{K} p_{ij} x_{ij} \quad s.t. \sum_{j=1}^{J} Q_j = \sum_{j=1}^{J} \sum_{i=1}^{K} x_{ij}$$

- Lagrange multiplier associated with constraint

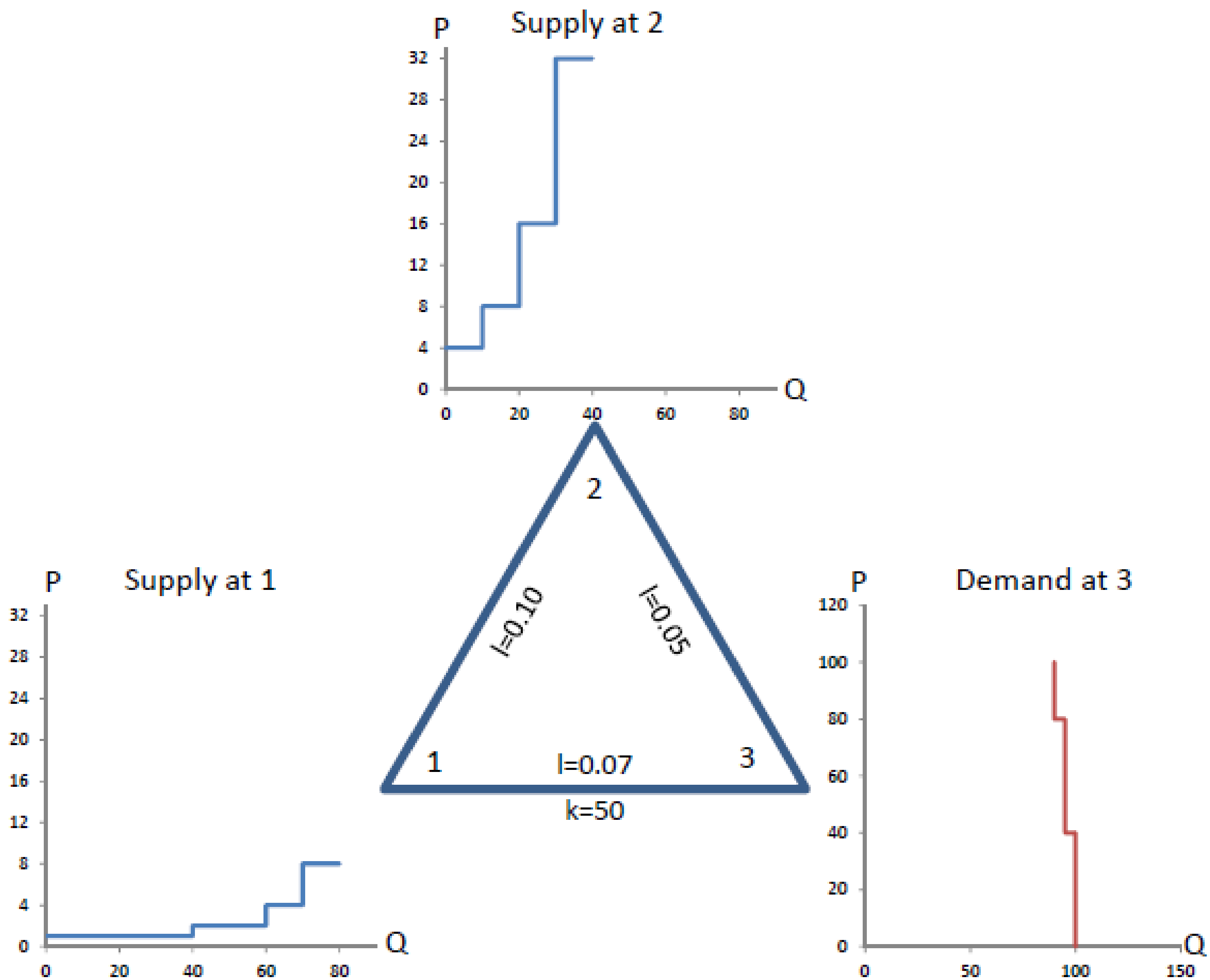
LMP Pricing Algorithm

- Minimize as-bid costs subject to network constraints
  - LMP is shadow price (change in optimized objective function value) from withdrawing an additional MWh at node in network
- 3-node example with losses and single transmission constraint
  - Lose fraction. ($0 < L_{jk} < 1$) of energy injected at node j and withdrawn at node k
  - Transmission constraint limits amount that can be injected at one end of transmission line
  - Equal resistance on all transmission links
- Kirchhoff's Law
  - Electricity follows path of least resistance in network
  - Cannot direct flow of electrons
- Same objective function as above but different constraints
  - Supply – Losses = Demand
  - Transmission constraints

Properties of LMPs

- Properties of LMP
  - LMPs reflect scarcity conditions at a location
    - Supplier can be paid more than their willingness to sell because they own a scarce resource
  - Can have locational prices above highest offer price in market
    - LMP is increase in minimized as-bid cost to due an increase in demand at a location
- LMPs can be used to value benefits of transport infrastructure expansions
  - Value of transport infrastructure is ability to substitute low-priced distant supply for high-priced local supply
  - Increase amount of $10/acre-ft water surface water than can replace $200/acre-ft groundwater local to demand center

3-Node Electrical Network



Loop Flow Constraint: $0.67q(1) + 0.33q(2) \leq 50$

3-Node Electrical Network

No Transmission Losses

Baseline			
Constraints			
2/3Q1 + 1/3Q2 ≤ 50			
Qd = 100			
l12 = 0, l31 = 0, l23 = 0		Summary: Baseline	
	Node 1	Node 2	Node 3
Quantity	60	30	10
Price	$2.00	$32.00	$62.00

Transmission Losses Priced

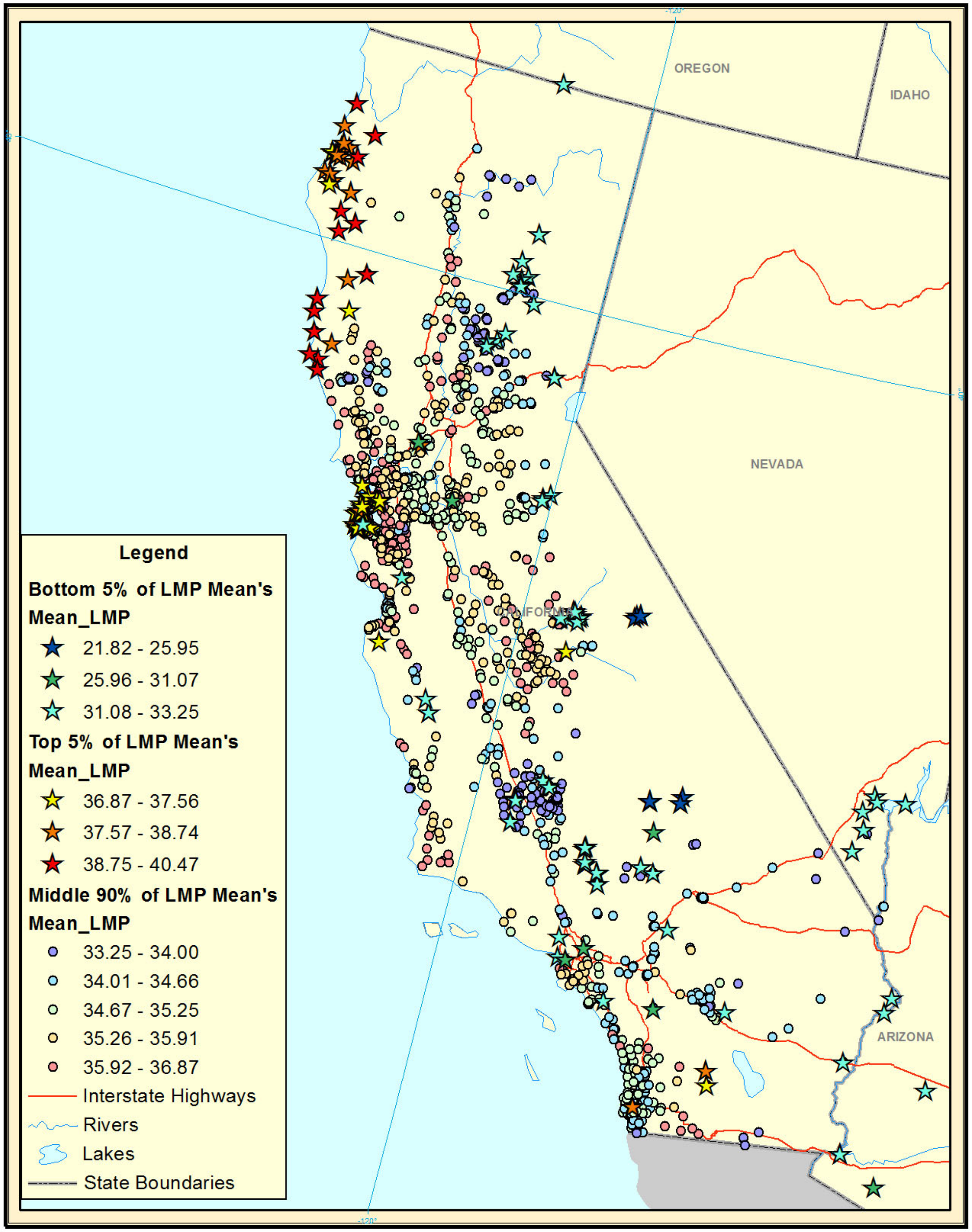
Baseline			
Constraints			
2/3Q1 + 1/3Q2 ≤ 50			
Qd = 100			
l12 = 0.10, l31 = 0.07, l23 = 0.05		Summary: Baseline	
	Node 1	Node 2	Node 3
Quantity	56.2731	37.4538	12.0849
Price	$2.00	$32.00	$80.00

Loop Flow Constraint: $0.67\,q(1) + 0.33q(2) \leq 50$ is Binding

Benefits of LMP Pricing of Electricity

- On April 1, 2009 California ISO introduced LMP (or nodal) pricing, where potentially different prices are set at over 3,000 locations in California
- Market participants are paid or pay the LMP at their node for all of the energy they buy or sell
  - California runs a multi-settlement market with a day-ahead forward market and real-time imbalance market
- Day-ahead market minimizes as-bid costs of meeting demand for energy and ancillary services at all locations in California ISO control area subject to transmission network and all relevant operating constraints for all 24 hours of following day
- Real-time market minimizes as-bid cost of meeting real-time deviations between day-ahead and real-time demands at all locations in network subject to all relevant operating constraints

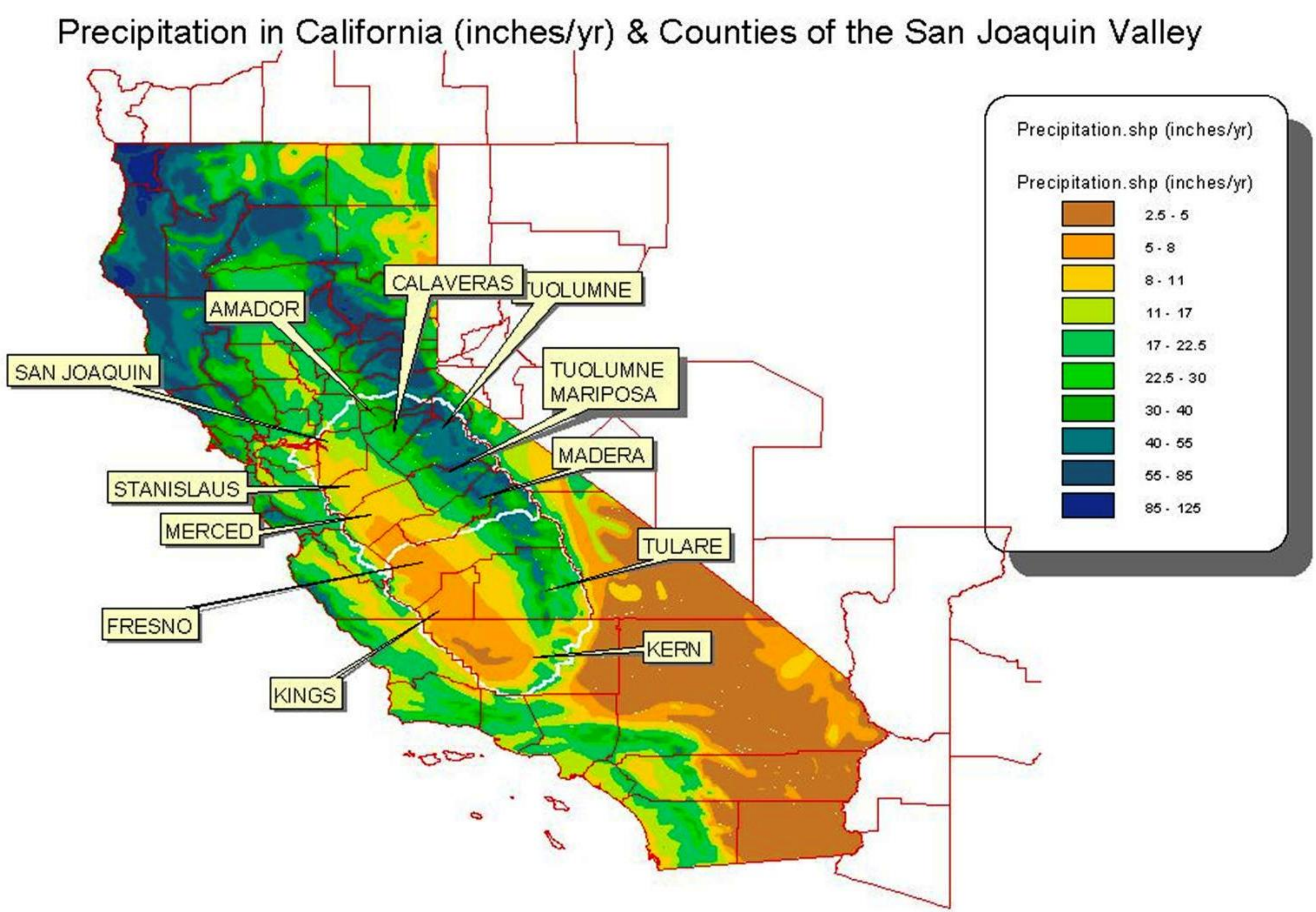
Spatial Distribution of Mean Hourly Prices for Day-Ahead Wholesale Electricity Market in California During 2009



Locational Marginal Pricing of Electricity

- Significant benefits to California from introduction of LMP market in April 2009
  - Wolak, F.A. (2011) "Measuring the Benefits of Greater Spatial Granularity in Short-Term Pricing in Wholesale Electricity Markets, *American Economic Review*, May, 247-252.
  - Average cost of dispatching thermal generation units in California fell by 2% after implementation of LMP in California
    - Annual cost savings of approximately $100 million
- Potential benefits from locational marginal pricing of water are likely to be much larger percentage of costs

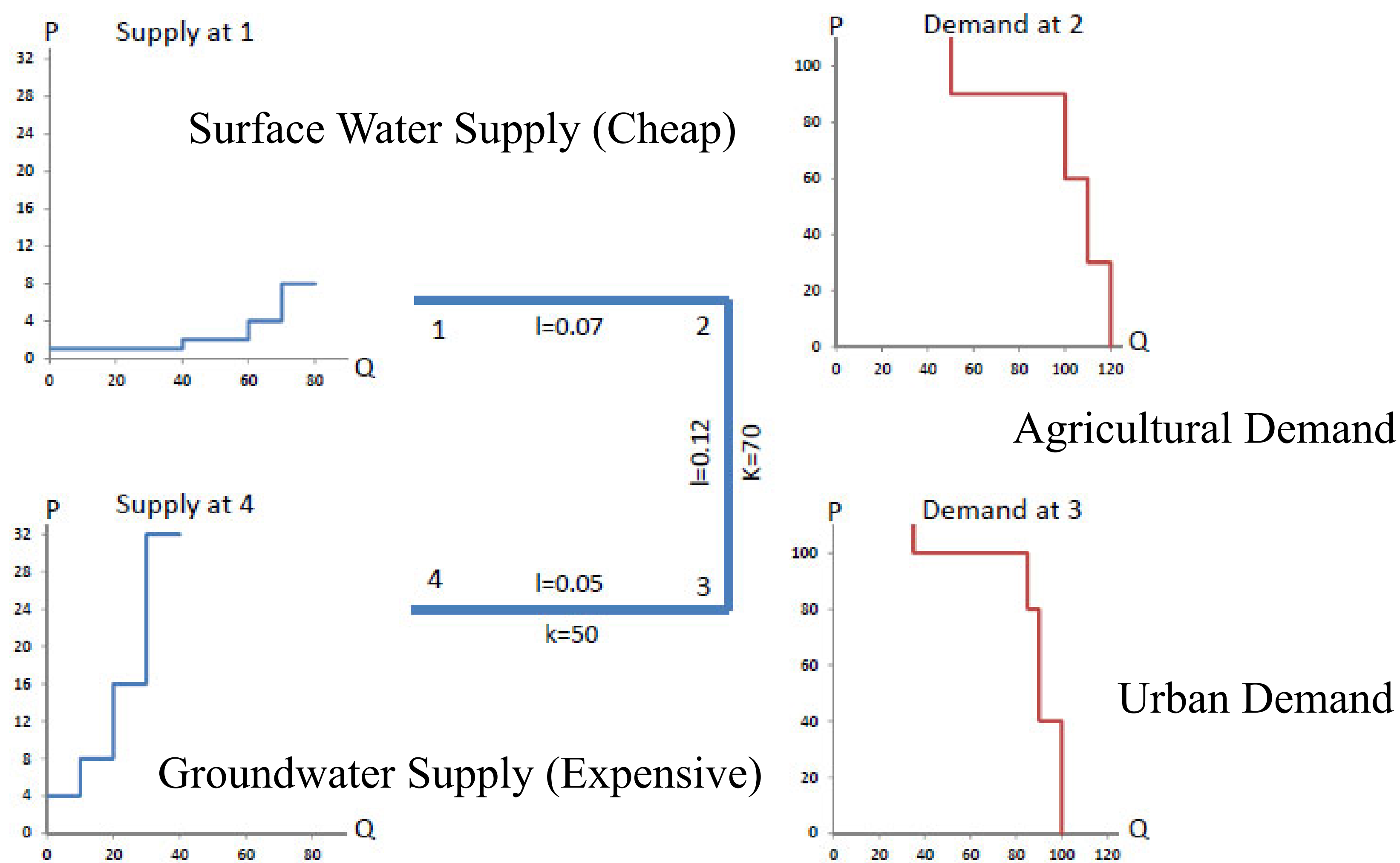
Driver of Benefits Locational Pricing



Locational Pricing of Water

- Mathematical representation of natural and man-made water delivery and storage infrastructure and environmental and political constraints on its operation
  - These are key inputs to pricing mechanism
  - Based on science and stakeholder process
- Simple 4-node example
  - Surface water node
  - Groundwater node
  - Agricultural demand node
  - Urban demand node

4-Node Locational Pricing of Water



Locational Marginal Pricing of Water

Baseline				
Constraints q23 ≤ 70, q43 ≤ 50 Qd2 = 120, Qd3 = 100 l12 = 0.07, l23 = 0.12, l43 = 0.05		Summary: This represents the initial presented conditions		
	Node 1	Node 2	Node 3	Node 4
Quantity	80	45.6	62	40
Price	$83.70	$90.00	$100.00	$95.00

Constraints q23 ≤ 70, q43 ≤ 50 Qd2 = 90, Qd3 = 100 l12 = 0.07, l23 = 0.12, l43 = 0.05		Summary: Decrease demand at Node 2		
	Node 1	Node 2	Node 3	Node 4
Quantity	80	20	58.128	40
Price	$81.84	$88.00	$100.00	$95.00

Locational Marginal Pricing of Water

Constraints				
q23 ≤ 70, q43 ≤ 25				
Qd2 = 120, Qd3 = 100				
l12 = 0.07, l23 = 0.12, l43 = 0.05		Summary: Tighten q43		
	Node 1	Node 2	Node 3	Node 4
Quantity	80	58.3841	65	25
Price	$83.70	$90.00	$102.30	$16.00

Constraints				
q23 ≤ 90, q43 ≤ 50				
Qd2 = 120, Qd3 = 120				
l12 = 0.07, l23 = 0.12, l43 = 0.05		Summary: Loosen q23 while increasing demand at Node 3		
	Node 1	Node 2	Node 3	Node 4
Quantity	80	64.9182	65	40
Price	$83.70	$90.00	$102.30	$97.16

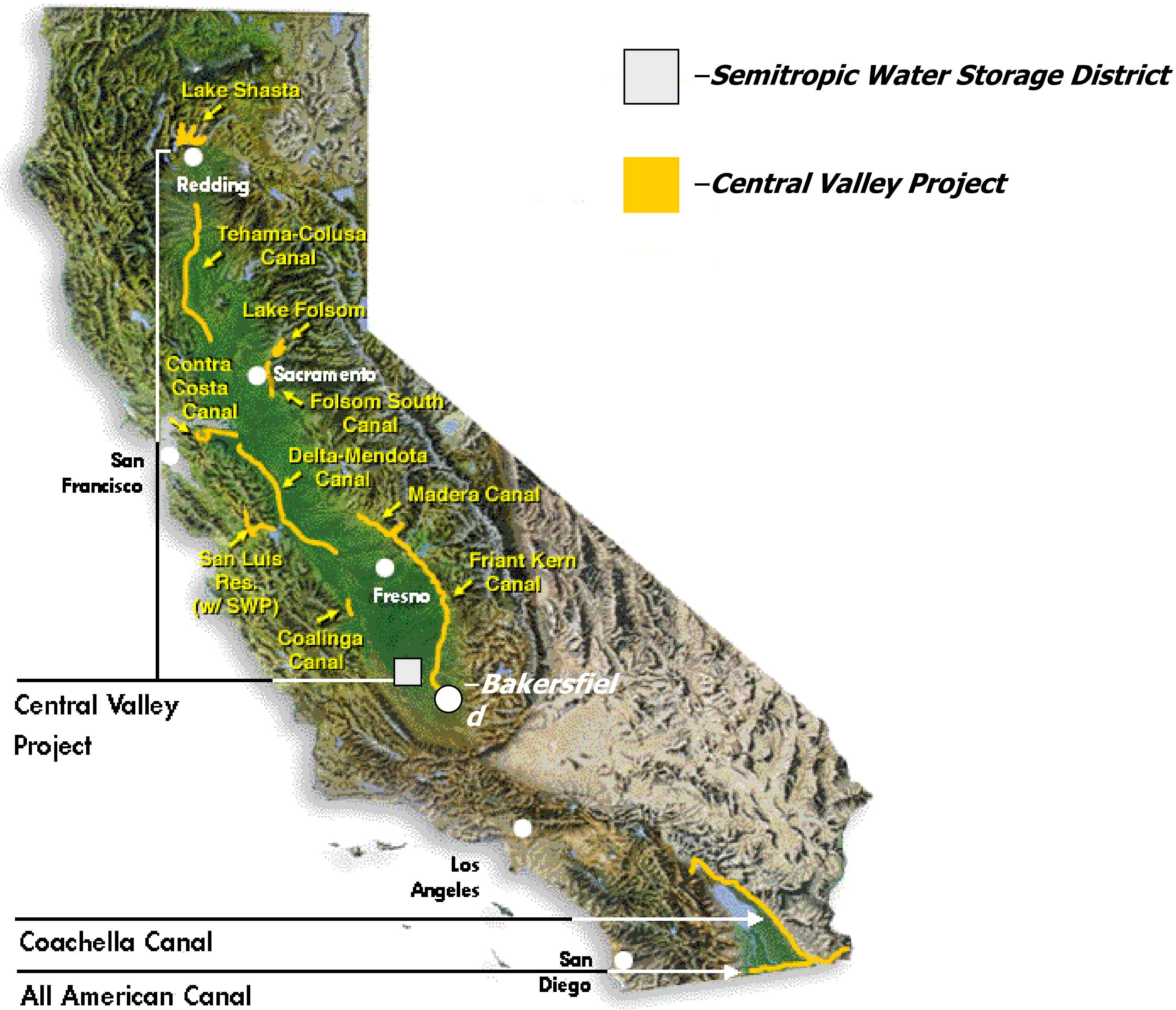
Locational Pricing of Water

- LMP has potential to set efficient prices that reflect all physical, environmental and political constraints of water system
  - If you can express constraint, it can be priced
- By definition LMPs are prices that maximizes economic benefits subject to constraints imposed
- Can run any number of forward markets in advance of actual delivery
  - Settle relative to previous forward market sales and purchases

Implementing LMP Pricing

- Mathematical model of sample small water system
  - California has a number of water banks, which are essentially very small water markets
  - Use one water bank to illustrate potential increase in feasible trades and economic benefits of implementing LMP pricing relative to current pricing mechanism
    - Model hydrology of water system
    - Environmental constraints
    - Political constraints

–Location of Semitropic Water Storage District



Conclusions

- Market mechanisms are viable approach to managing increasing water scarcity at least cost
  - Must incorporate physical, environmental, political and other operating constraints in pricing mechanism
- Locational marginal pricing does this
  - Can allow market mechanisms to be run over large geographic areas and long time intervals
- LMP is being successfully used to deliver benefits in other markets
- Has potential to deliver even proportionally greater benefits in water sector

Questions/Comments

For more information

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