Water and Energy: The Case for Distributed Water Treatment and Desalination Systems"

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Outline

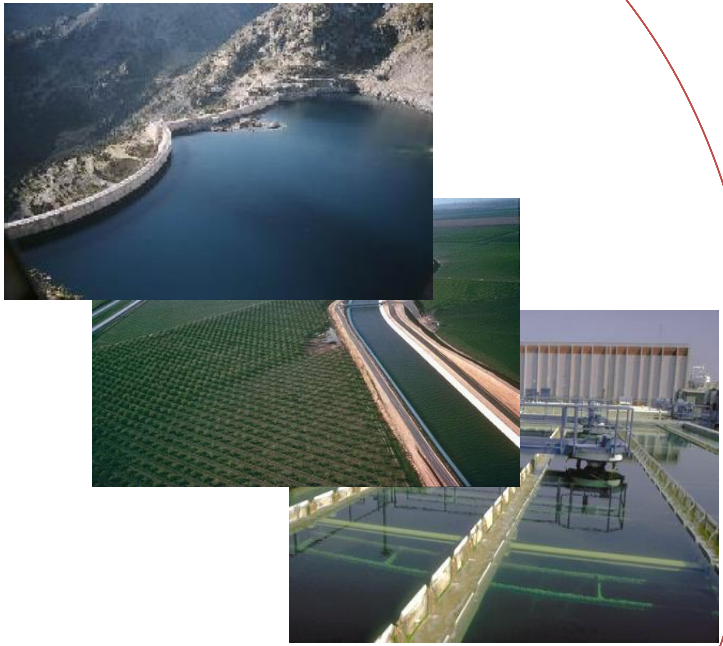
- Water and energy are inextricably linked
- The cost of water and water energy needs – The California Example
- Energy use in RO desalination & opportunities for improving process efficiency
- Centralized versus distributed water systems
- The benefits of distributed water systems and Research Needs
- Examples of small distributed water treatment systems (cooling tower blow down water, seawater, brackish water, graywater)
- Modern centralized water treatment plants – R&D Needs

Water and Energy Are Inextricably Linked

Water is used in the generation of 33% of CA electricity

Reduced water conveyance and increased water recycling

Decreased energy consumption and smaller carbon footprint



Water-related energy use: 19% of CA electrical energy and 30% (non-power plant) natural gas

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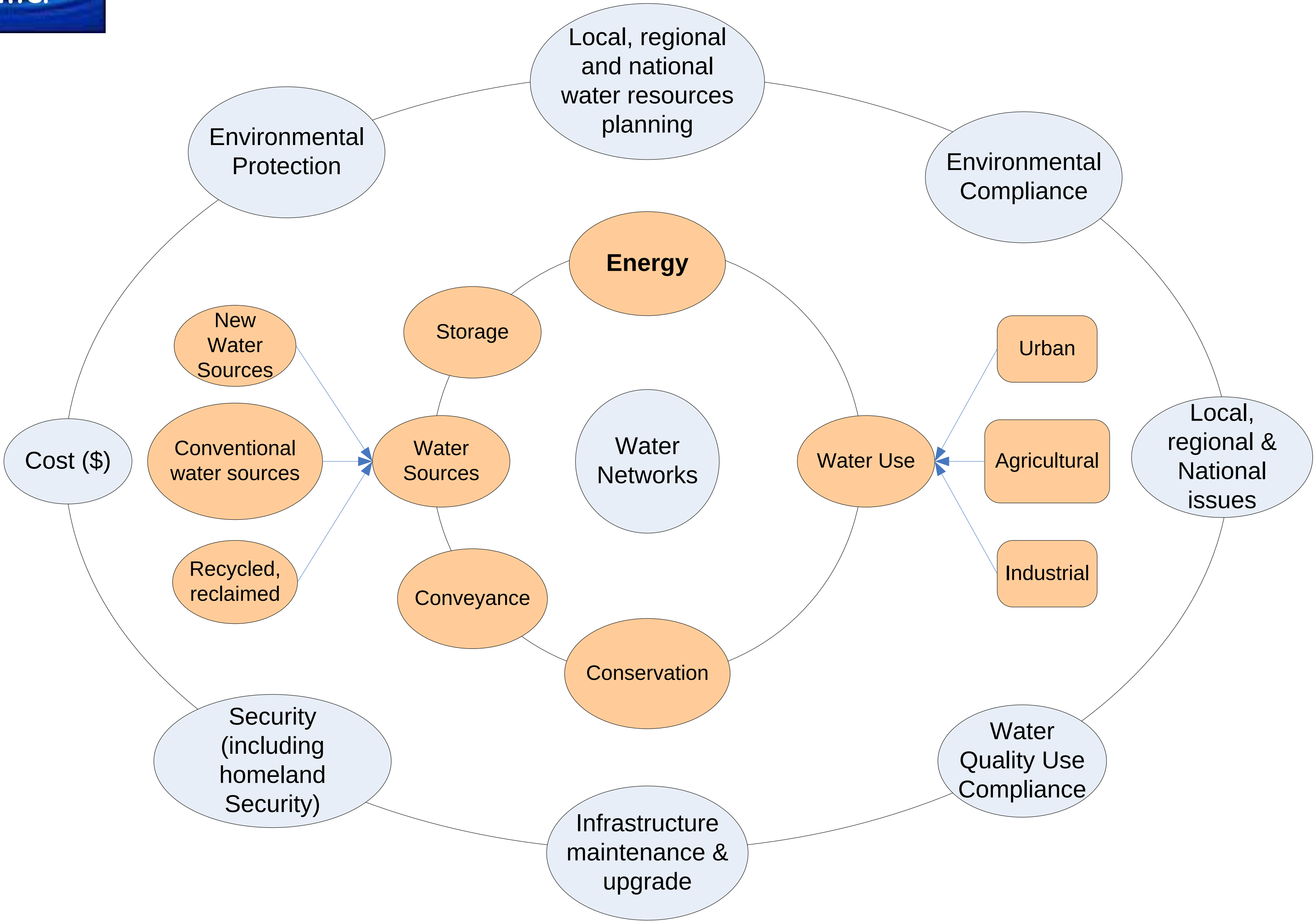
Water Networks & Energy



California Water Supply

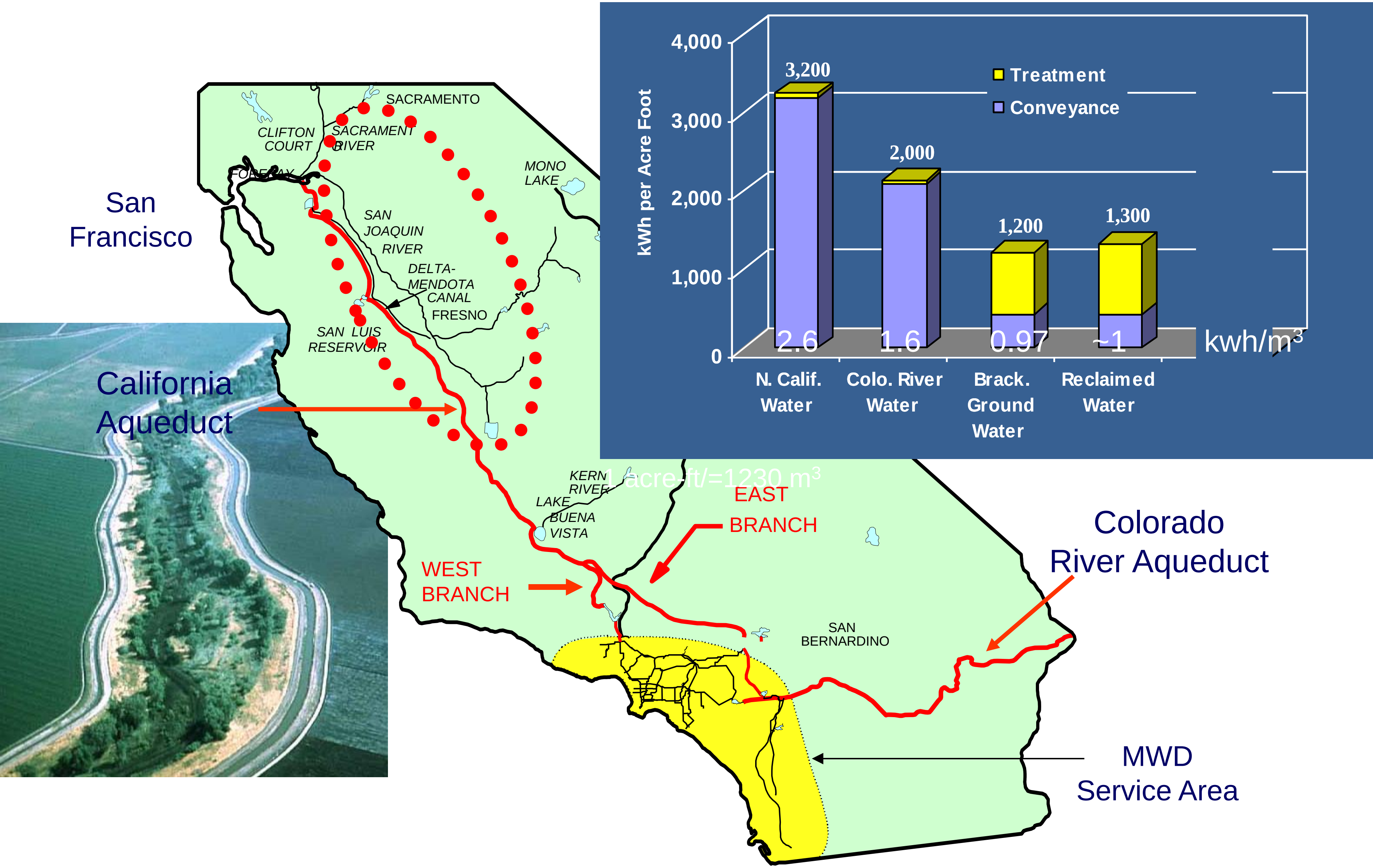
San Francisco

California Aqueduct

Colorado River Aqueduct

MWD Service Area

California Water Supply



San Francisco

California Aqueduct

1 acre-ft/=1230 m^3

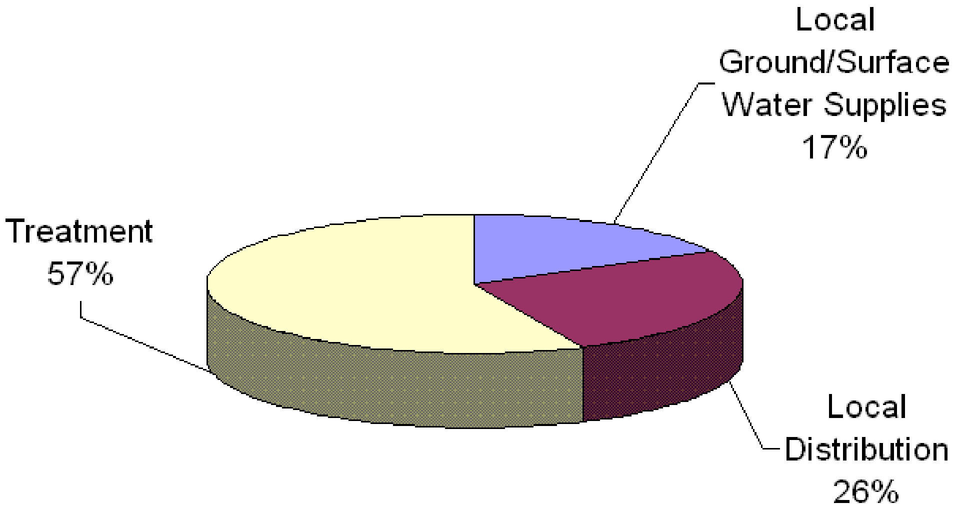
EAST BRANCH

WEST BRANCH

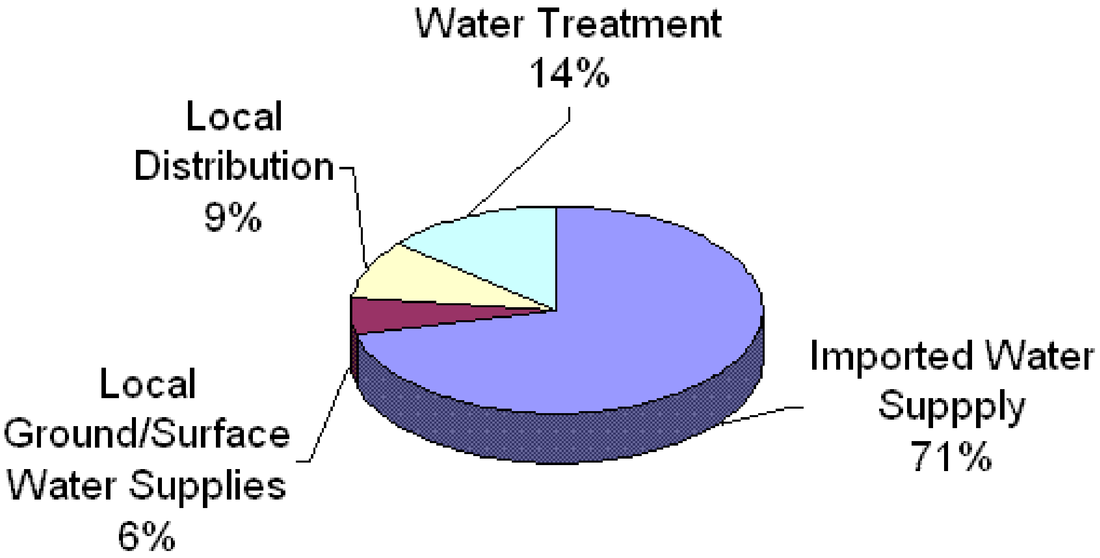
Colorado River Aqueduct

MWD Service Area

Water Energy Use for Water Production, Treatment & Distribution

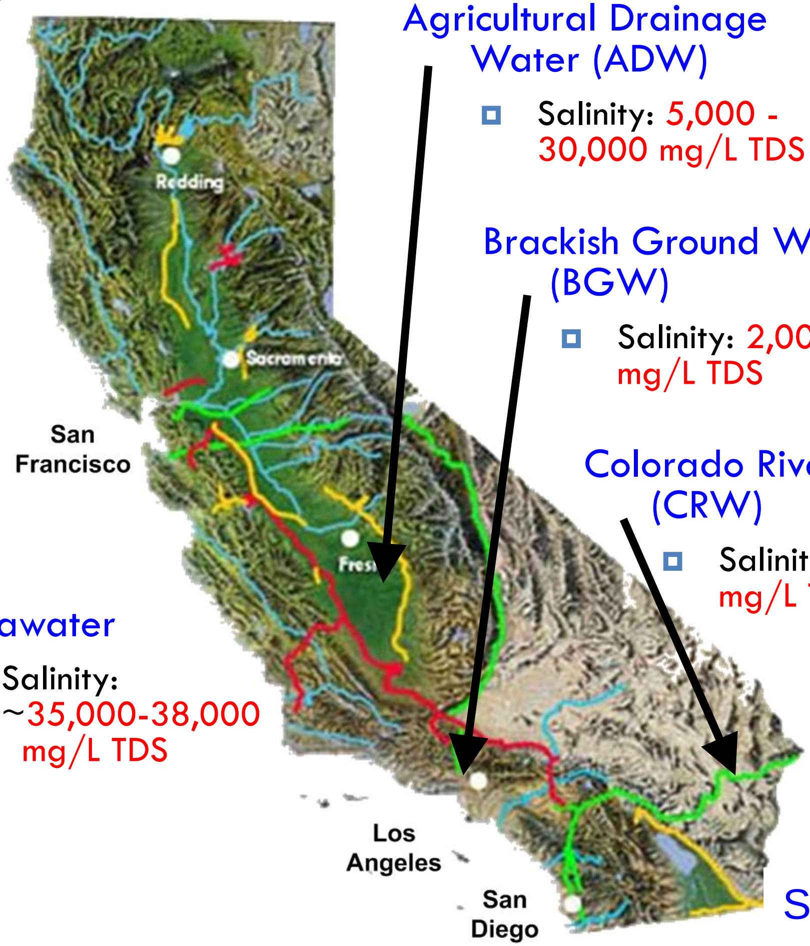


Northern California



Southern California

Saline Water Resources in California



Agricultural Drainage Water (ADW)

- Salinity: 5,000 - 30,000 mg/L TDS

Brackish Ground Water (BGW)

- Salinity: 2,000 - 15,000 mg/L TDS

Colorado River Water (CRW)

- Salinity: 700-1000 mg/L TDS

Seawater

- Salinity: ~35,000-38,000 mg/L TDS

Secondary and Tertiary treated municipal wastewater effluent: 500-1500 mg/L TDS

- Drought conditions and increasing population necessitate smarter water production and reclamation
- Opportunity to reclaim/produce water from several sources
  - Agricultural drainage water
  - Brackish groundwater
  - Seawater
  - Wastewater

McCool et al., Desalination, 261, 240-250 (2010)

Establishing Water Policy and Technical Strategies is a Challenge due to Complex Water Pricing

Water Source/Customer	**~$/AF**
Residential	400-900
MWD Water	366 – 811#
CA Water Project(c)	20-300
SJV Agricultural Water	10 - 600
Desalted Seawater(b) Desalted Brackish Water(b)	620 -1,200 200 – 600
MBR Treated Wastewater(b)	300 – 600
Bottled Water	~1x10^6

(a) low-high estimate ; (b) – excludes conveyance; (c) – farming and urban

- Average price of consumer delivered water ~$489/AF (AWWA)

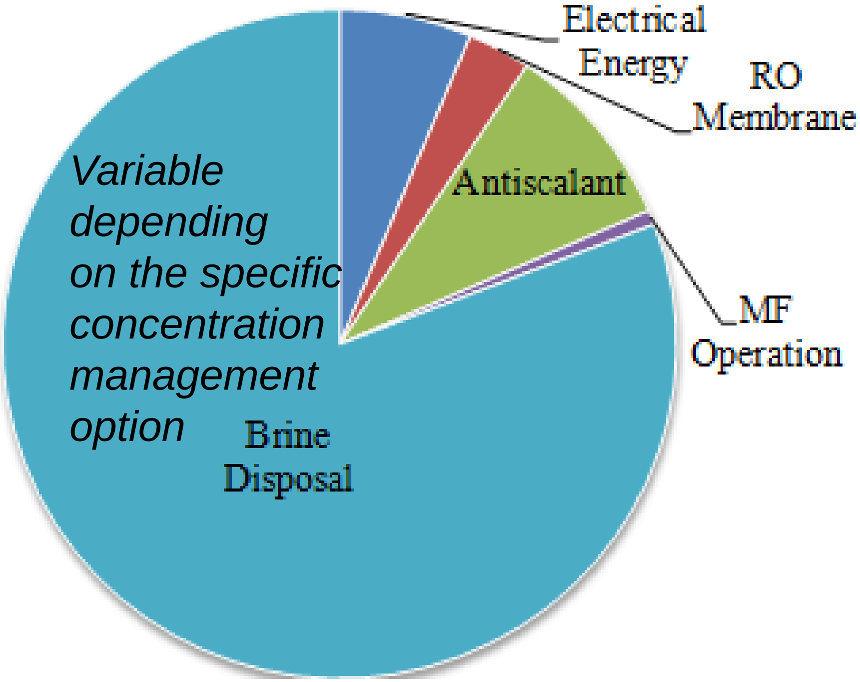
-The price of water in various CA locations can exceed the above estimates

- replenishment untreated – full Service Treated

- *1 AF = 325,851.4gallons, 1 U.S. Gallon=3.78 L*

Inland versus Seawater RO Desalination

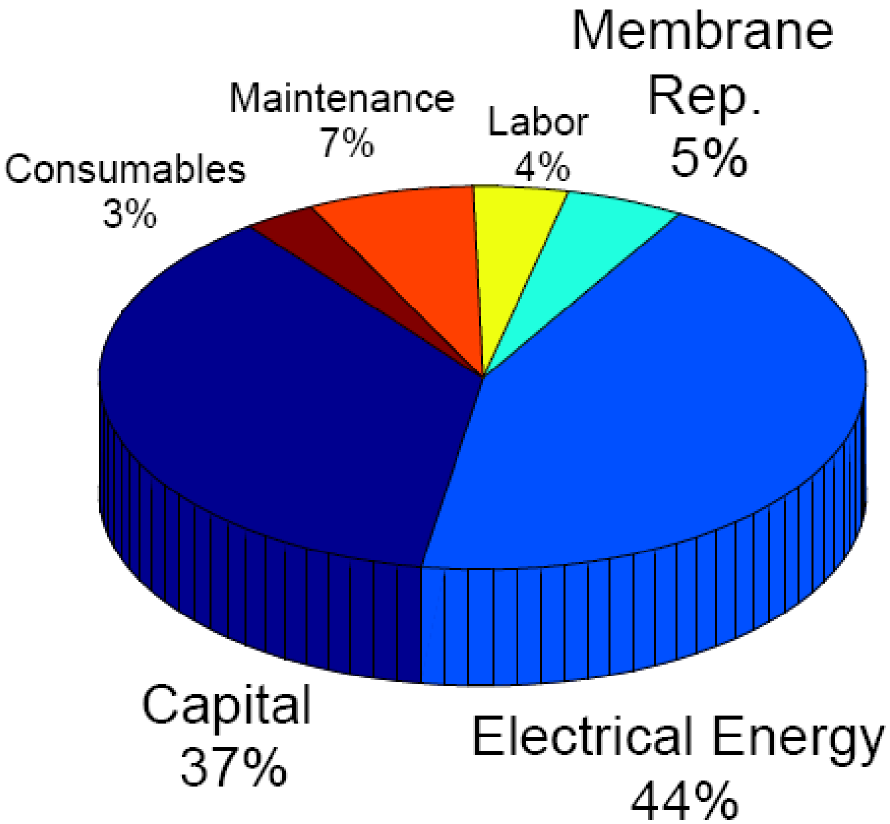
Brackish Water Desalination



Cost reduction potential:

- Increase recovery to minimize brine disposal/management costs
- Lower cost mitigation of mineral scaling/fouling

Seawater Desalination

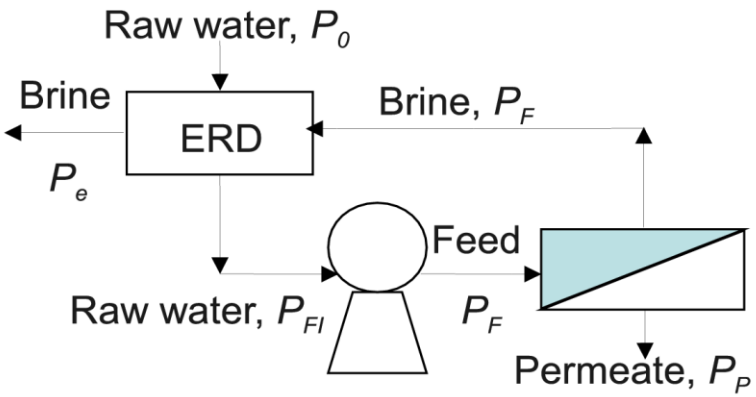


Cost reduction potential:

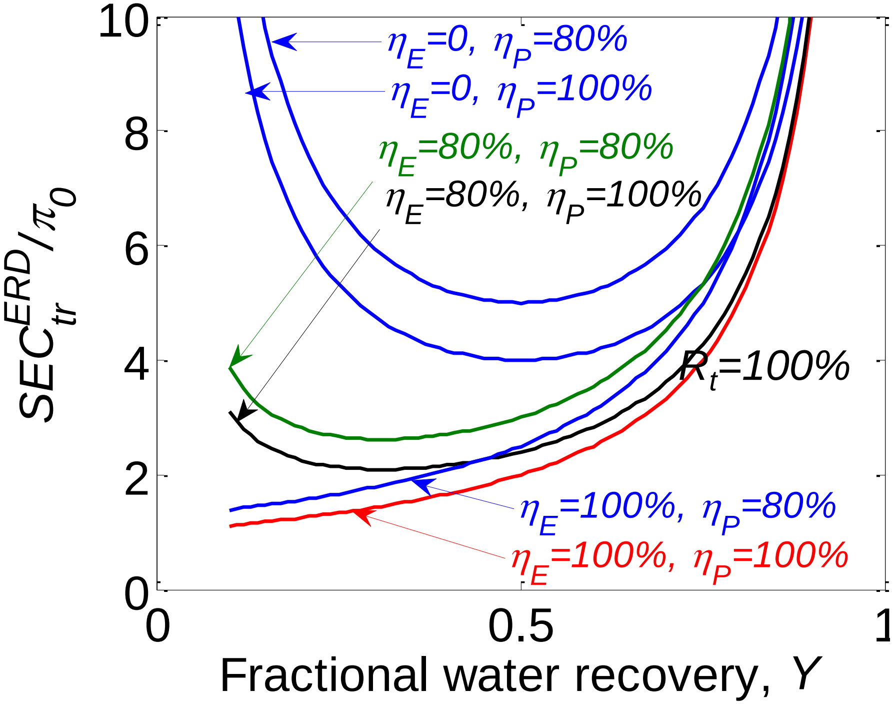
- Energy
- Capital cost
- Maintenance/labor
- Membrane & consumables

The Energy Cost of RO Desalination

Rate of pump work: $\dot{W}_{pump} = \Delta P \times \left(Q_f - \eta_E Q_b\right) / \eta_p$



Ideal Normalized SEC Curves for Different Scenarios



$$Q_p = A_m L_p (\overline{\Delta P_m} - \sigma \overline{\Delta \pi})$$
$$= A_m L_p (\overline{NDP})$$

TDS=35,000 mg/L

Global optimum: Y_{opt}=0.5:
(w/o ERD)

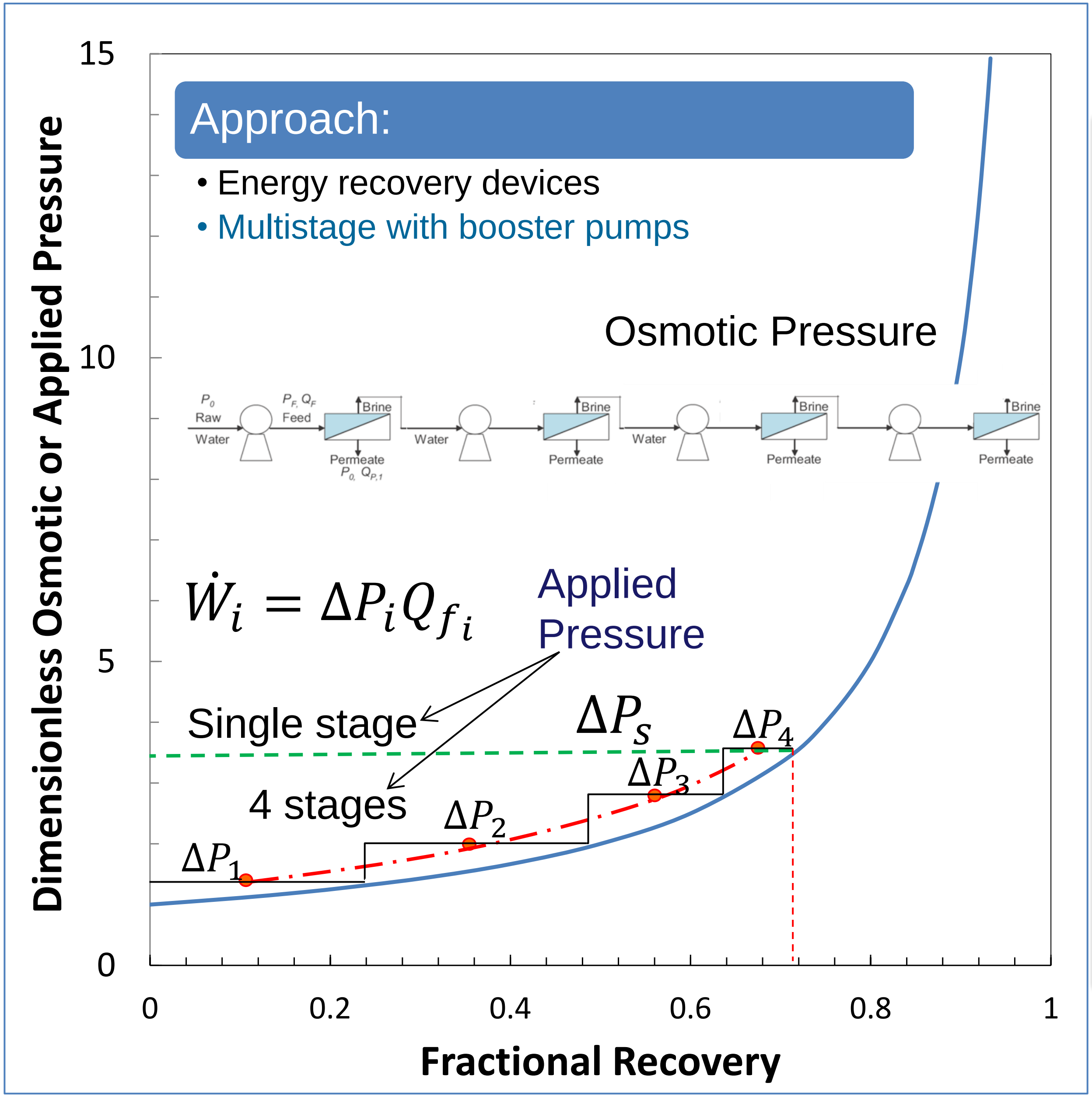
$SEC_{wo/ERD}$ = 3.2 kWh/m^3

$SEC_{w/ERD}$ = 1.6 kWh/m^3

Actual optimal recovery must consider O&M and capital costs

- At the thermodynamic restriction limit, the minimum applied pressure is a function of recovery and rejection (Y_t, R_t)
- When Y_t is small, more energy is wasted in the brine steam
- When Y_t is large, the required applied pressure increases rapidly

Process Configuration for Reduced RO Energy Consumption



Approach:

- Energy recovery devices
- Multistage with booster pumps

$$\dot{W}_i = \Delta P_i Q_{f_i}$$

Reduce energy consumption via optimized RO process configuration to enable operation close to the osmotic pressure curve, e.g.,

- multi-stage RO

System Design will depend on the balance between reduction in energy consumption relative to increased capital cost

Is Seawater Desalination Expensive?

Example: Assume water use of 150 gallons per household per day

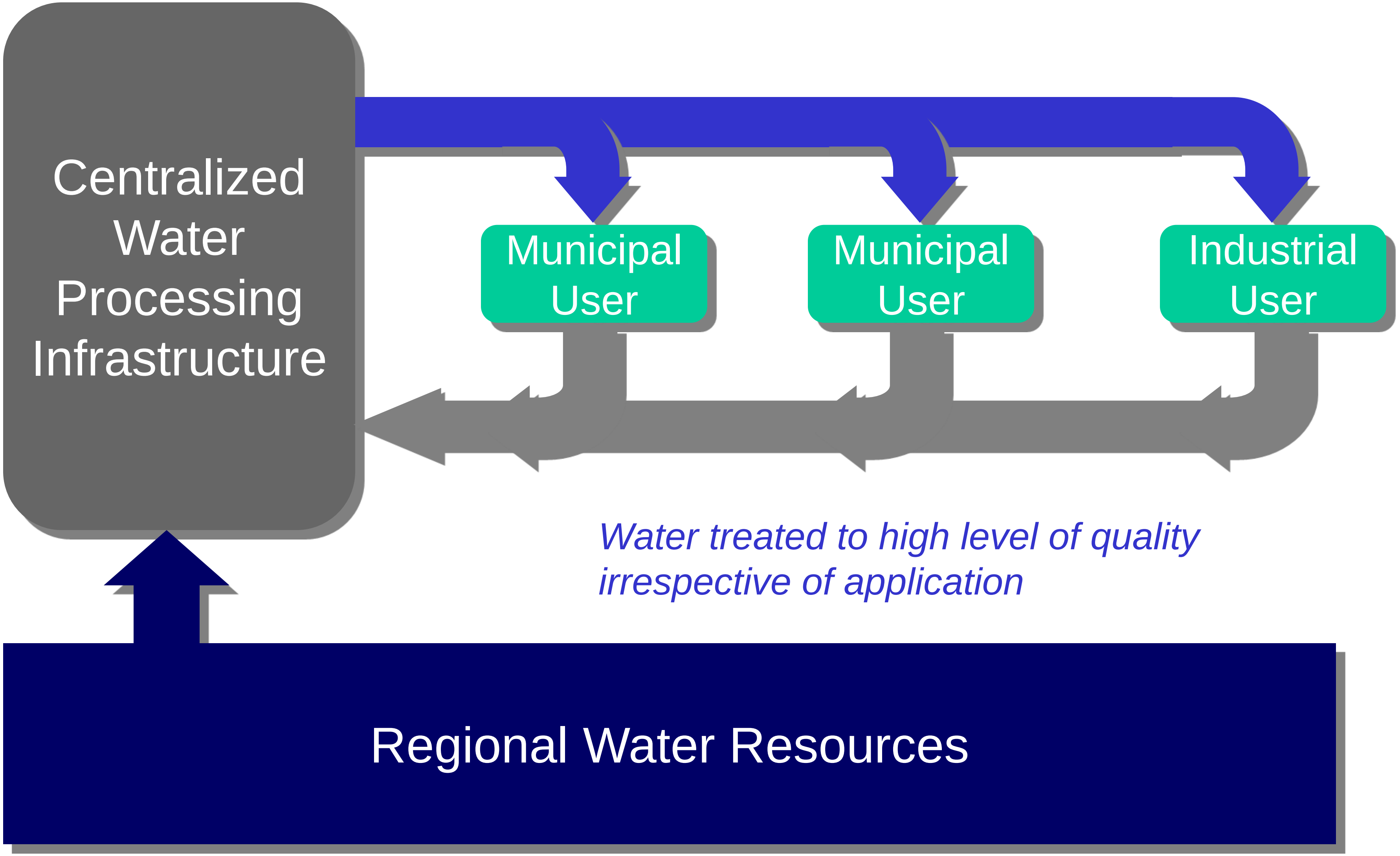
Seawater desalination cost (high-end): ~12 kWh/1000 gallons →1.8 **kWh per day or ~657 kWh annually**

Refrigerator energy use: 511 – 693 kWh annually

A/C Central daily average (based on 3 months use): 3 kWh per day
42” Plasma TV: 219 kWh annually

1 Gallon of Gasoline: ~36 kWh
2013 Chevrolet Volt requires 8.8 kWh/25 miles

Centralized Water Systems



Centralized Water Processing Infrastructure

Municipal User

Municipal User

Industrial User

Water treated to high level of quality irrespective of application

Regional Water Resources

Hyperion Treatment Plant

Los Angeles, CA

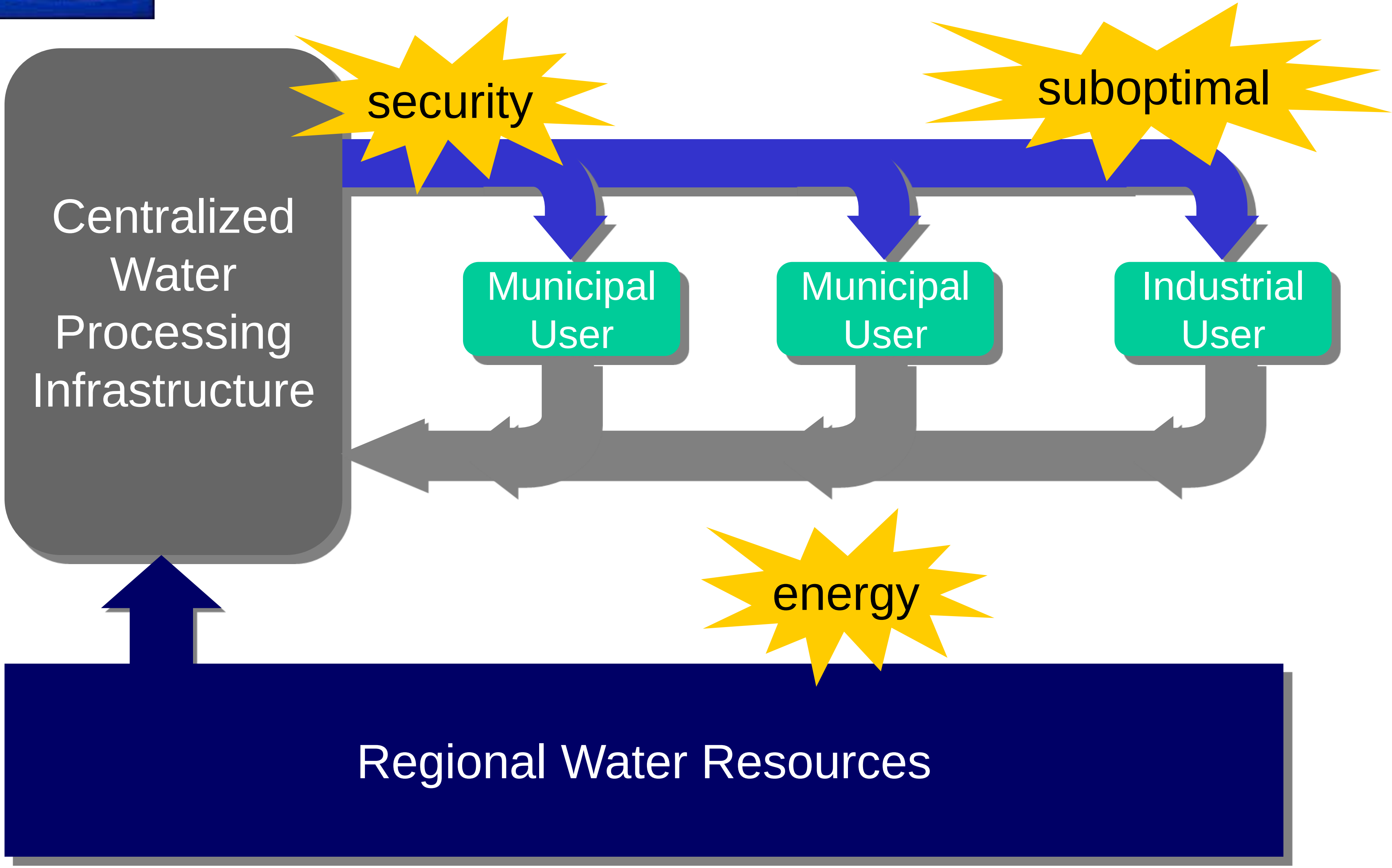
Estimated upgrade costs :$1.6B

Hyperion Treatment Plant

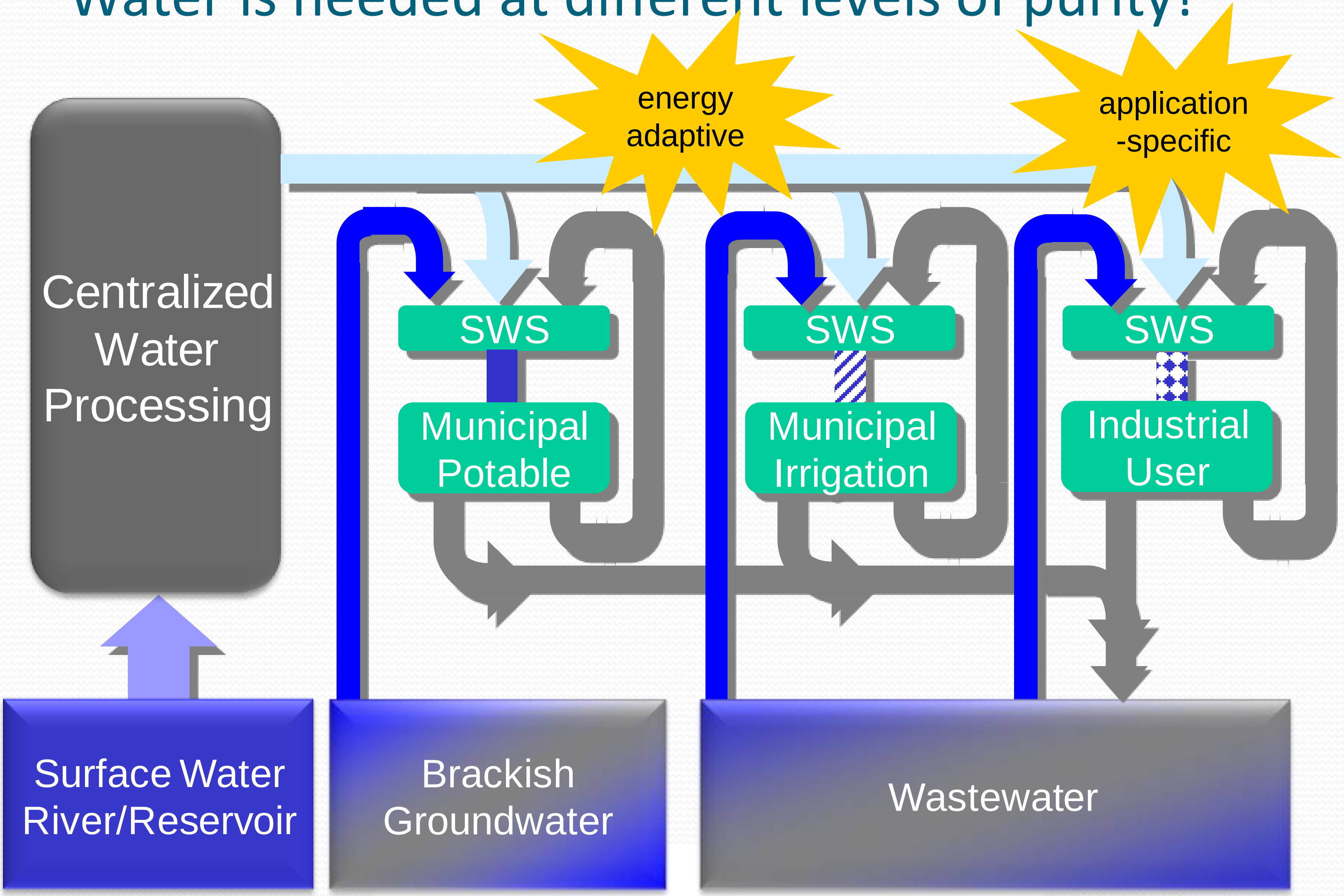
Water Technology Research Center

Centralized Water Systems

UCLA

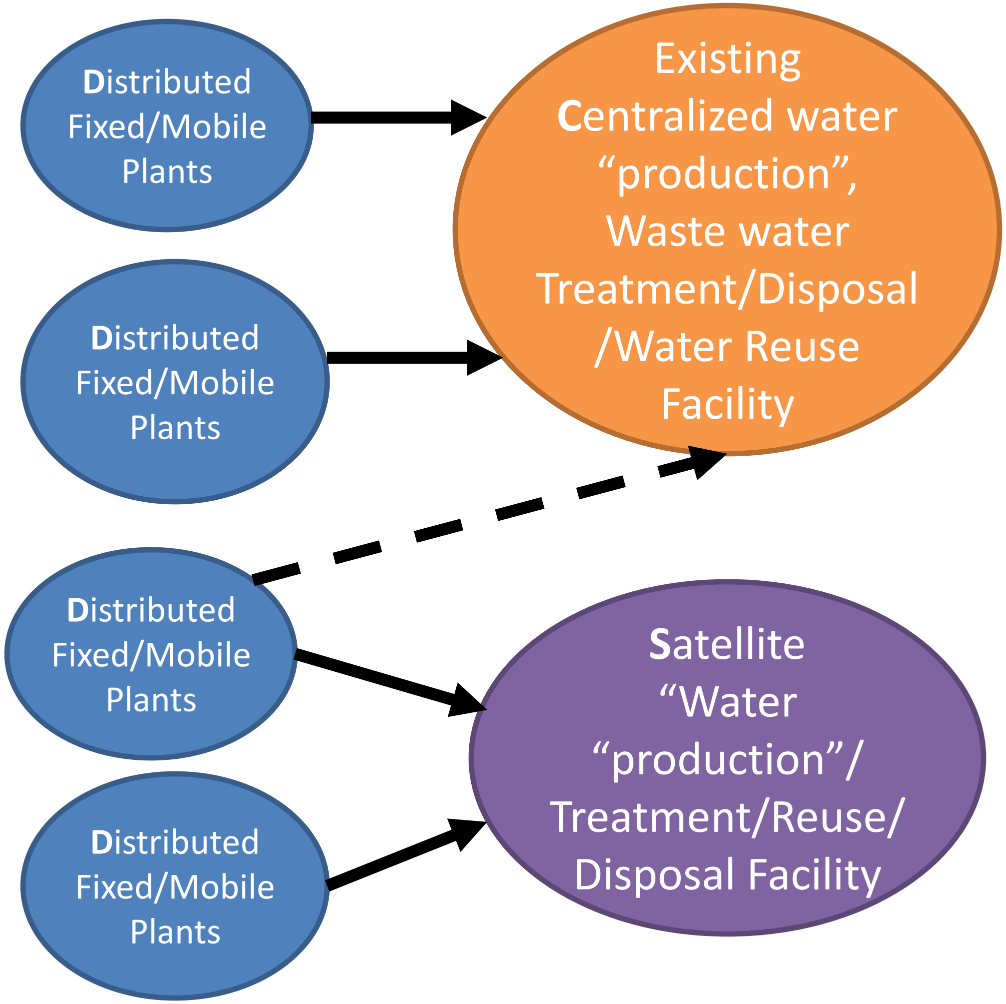


Distributed Water Processing:
Water is needed at different levels of purity!



Water Production, Conveyance and Wastewater Treatment : Distributed and Centralized Management

Near Urban Areas



Distributed Fixed/Mobile Plants

Distributed Fixed/Mobile Plants

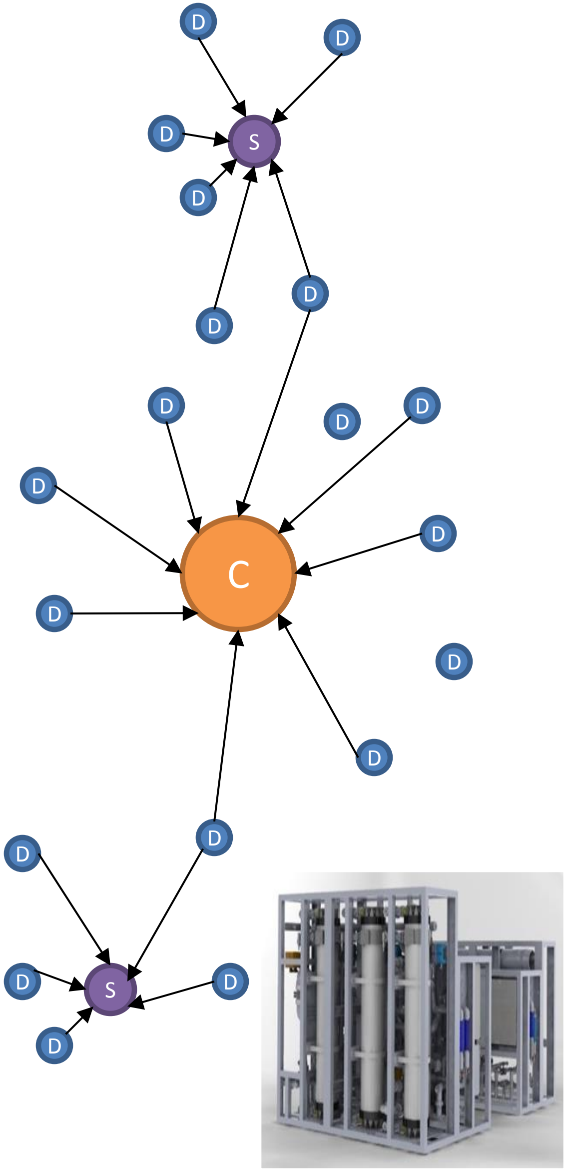
Existing **C**entralized water “production”, Waste water Treatment/Disposal /Water Reuse Facility

Remote Areas

Distributed Fixed/Mobile Plants

Distributed Fixed/Mobile Plants

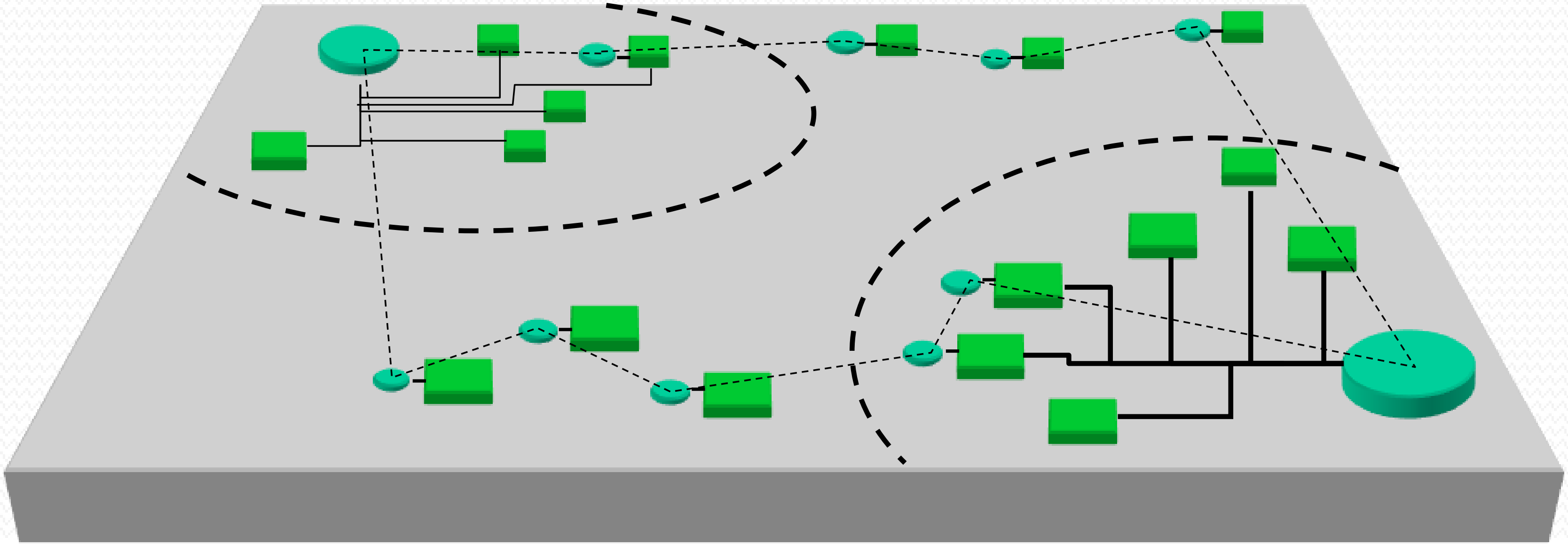
Satellite “Water “production”/ Treatment/Reuse/ Disposal Facility



Augment with existing centralized or with satellite water infrastructure for distributed drinking water treatment/ wastewater management

Distributed Water Network

- Water treatment near the “point-of-use “ and/or at the source
- Autonomous self-adaptive operation, advanced sensors, fault-detection
- Standardized modular systems
- Central supervisory system /cyberinfrastructure → “smart water systems”



Benefits:

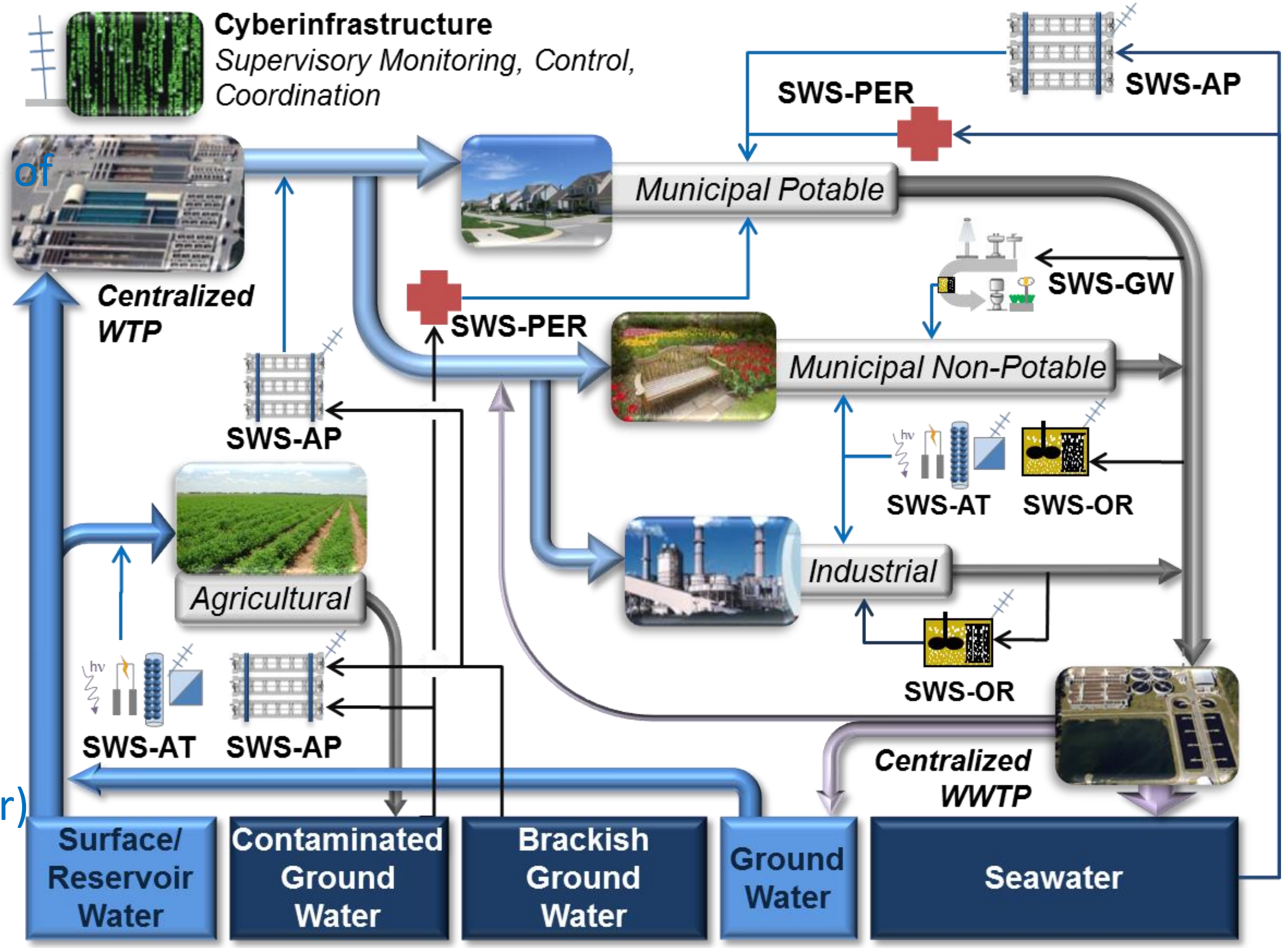
- Reduce water consumption and increased use of underutilized water sources & reuse
- Lower capital investment relative to centralized infrastructure
- Treat water to the required purity level
- Serve remote communities and treat distributed impaired water sources
- Reduce energy cost associated with water conveyance & lower carbon foot print
- Enable integration of local renewable energy resources with water systems

Augmenting Centralized Water Infrastructure with Distributed Water Systems

Technical Challenges

- ☐ Self-adaptive operation
- ☐ Flexible system architecture of modular design & Standardization
- ☐ Advanced on-board control/monitoring systems
- ☐ Remote monitoring/control
- ☐ Energy optimal operation
- ☐ Fault-detection
- ☐ Real-time optimization w.r.t utilization of alt. energy sources (e.g., wind and solar)
- ☐ Cyberinfrastructure for remote centralized supervision

A Shift in Water Resources & Management Paradigm



Technology Transfer: Fundamentals → Laboratory → Field

UCLA SIMS Treatment and Recycling of Cooling Tower Blow Down Water at the UCLA Co-Gen Plant

- Process models
- Control and optimization
- Soft sensors
- Membrane characterization
- Software design
- Advanced system design concepts

- Disposal of up to ~66,000-152,000 gallons/day
- Water unit price= $7.6/1000 Gallons
- 1,000-2,000 mg/L TDS
- Turbidity= 1.4-14 NTU
- Annual savings to UCLA ~$90K

UCLA COM2RO Smart Water System: Self-Adaptive MF/UF/O Operation and Compact system Design

US Navy base Port Hueneme, CA

Permeate production capacity:
Seawater: Up to~18,000 GPD (69 m³/day)
Brackish water: up to ~46,000 GPD (176 m³/day)

Water cost: ~ 0.55-1 /1000 m³)

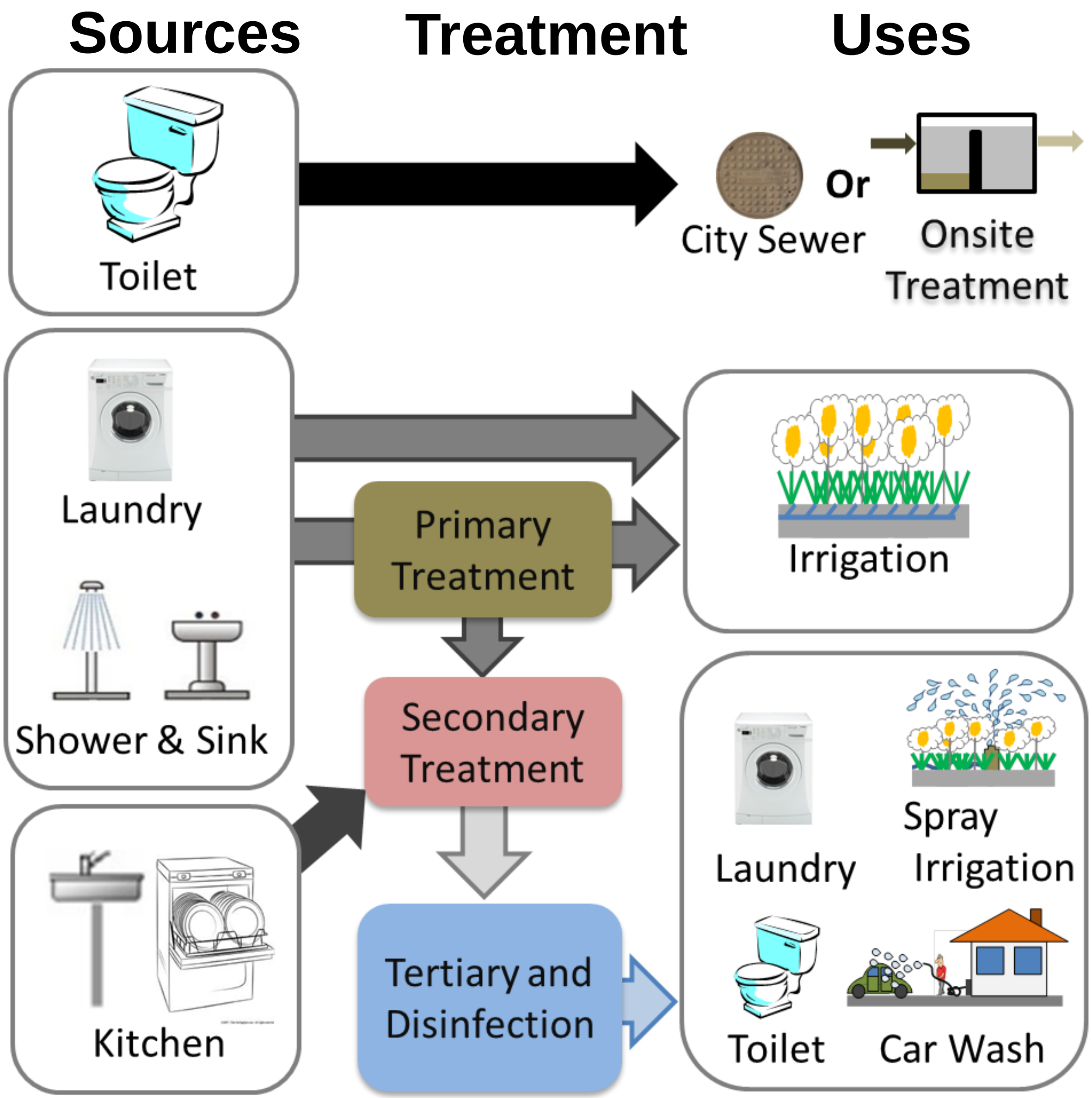
Seawater Desalting: Onshore & shipboard

COM2RO

- UCLA designed and built system operating (Since September 2010) at US Navy seawater desalination test facility at Port Hueneme
- Integrated self-adaptive operation of compact & modular UF-RO technology
- Operation without intermediate tanks (for RO feed or UF backwash)

Cohen et al, Patent Pending

Wastewater Treatment and Reuse Applications



Sources **Treatment** **Uses**

Black Water

Toilet

City Sewer **Or** Onsite Treatment

Light Graywater

Laundry

Shower & Sink

Primary Treatment

Irrigation

Dark Graywater

Kitchen

Secondary Treatment

Tertiary and Disinfection

Laundry

Spray Irrigation

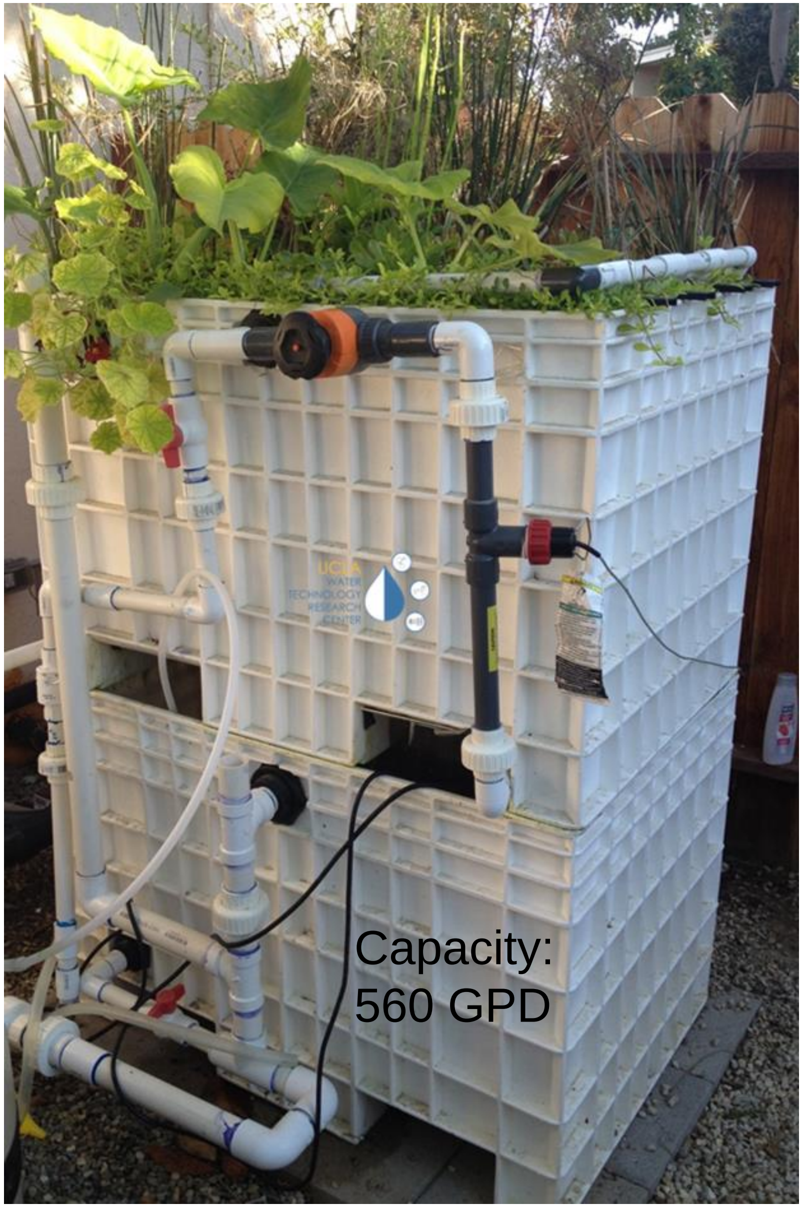
Toilet

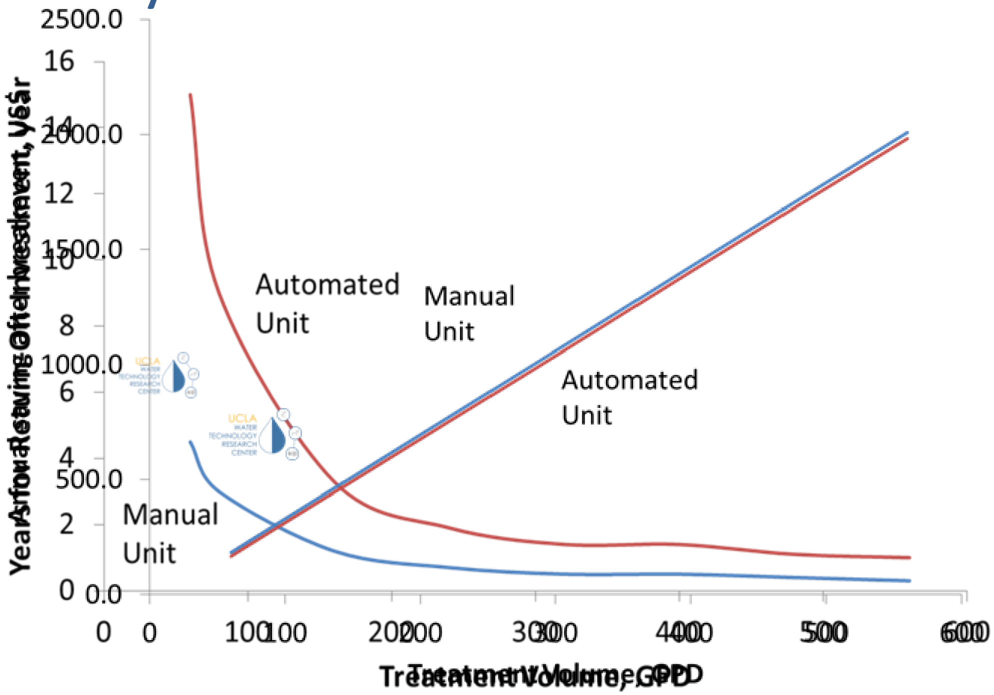
Car Wash

~40-70% of generated household wastewater

Yu, Rahardianto, Desahzo, Stenstrom & Cohen, Water Environment Research, 85, 1-13 (2013)

UCLA Gray2Blue Vertical Wetland for Residential Graywater Treatment


Capacity:
560 GPD



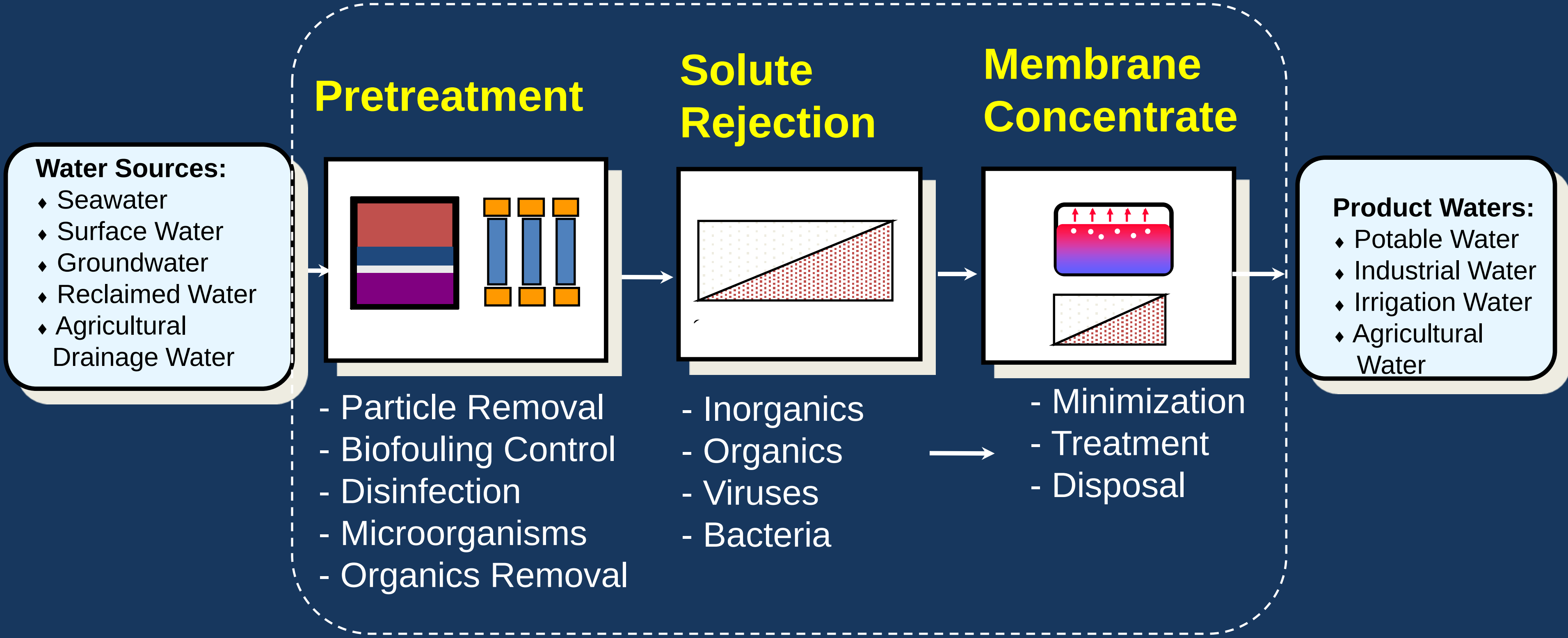
Serve a single residential or multiple neighboring homes

Low cost and low maintenance

Treat Graywater water to Title 22 for indoor use

Challenge: restrictive and conflicting regulations in the 50 States

Modern Water Treatment Facilities make use of a Sophisticated Process Train



Water Sources:
- Seawater
- Surface Water
- Groundwater
- Reclaimed Water
- Agricultural Drainage Water

Pretreatment

- Particle Removal
- Biofouling Control
- Disinfection
- Microorganisms
- Organics Removal

Solute Rejection

- Inorganics
- Organics
- Viruses
- Bacteria

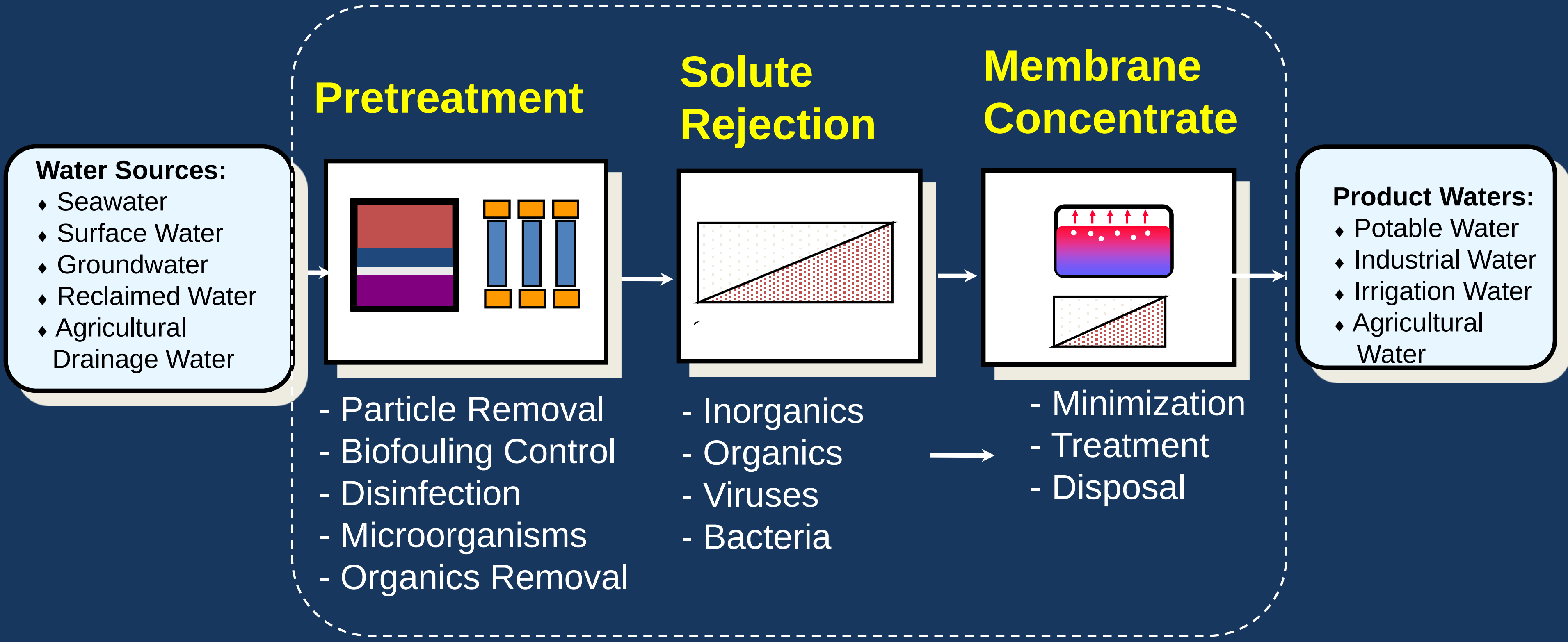
Membrane Concentrate

- Minimization
- Treatment
- Disposal

Product Waters:
- Potable Water
- Industrial Water
- Irrigation Water
- Agricultural Water

- *Modern MWT plants require significant energy (e.g., conveyance, mixing and aeration)*
- *Opportunities exist for increased level of energy/resource recovery*

Modern Water Treatment Facilities make use of a Sophisticated Process Train



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Membrane Concentrate

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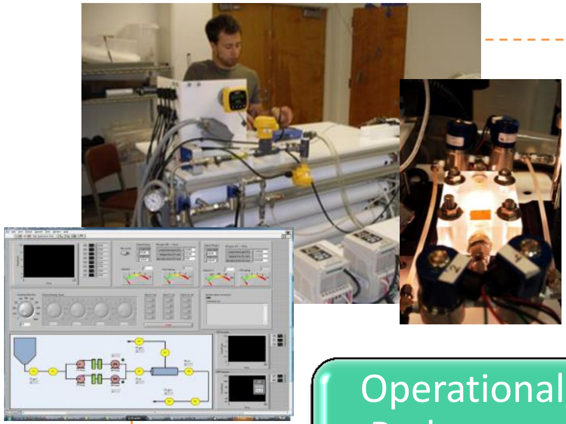
- Treatment
- Disposal

Product Waters:
- Potable Water
- Industrial Water
- Irrigation Water
- Agricultural Water

- *Current membrane-based water treatment processes lack robust control, automation and advanced process monitoring to deal with the variability of feed water quality, fouling and scaling, real-time optimization for energy minimization & reasonable cost ZLD for inland water*

Distributed Water Treatment/Desalination Technologies: R&D Needs



Control:

- Soft sensors & physical monitoring

- Optimal System & Process Design
- Reduced Plant Footprint

Membranes:

- Improve fouling resistance
- Increase water permeability

Operational: Reduce use of feed pretreatment additives

Operational:

- Reduce energy consumption

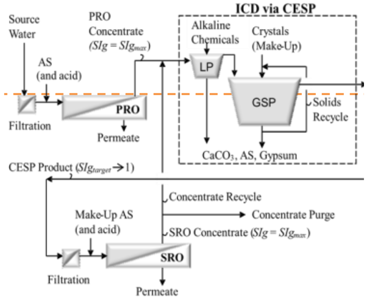
Distributed Water Systems

Inland water: - Concentrate disposal

- Target high recovery

Theory & Lab Studies

Field Studies/ Demos



$$[CO_3^{2-}]_e = [TC]_e \cdot K_{a1} \cdot K_{a2}/([H^+]_e^2 + K_{a1} \cdot [H^+]_e + K_{a1} \cdot K_{a2})$$

$$\phi(t) = \frac{\sum_{i=1}^{m\times n} 1 - \exp\left(-J_{N,i}\frac{\pi}{3}k_{g,i}t^3\right)}{m \cdot n}$$

$$\bar{N}(t) = \hat{J}_N \int_0^t \left(1 - \phi(t')\right) dt'$$

$$P(k, J_N) = \frac{\left(J_N \Delta t\right)^k e^{-J_N \Delta t}}{k!}$$

$$\bar{U} \cdot \nabla C = \nabla \cdot D \nabla C$$

$$FD = 1 - \frac{Q}{Q_o} = 1 - \frac{\left(\iint_f J_f dA + \iint_S J_S dA\right)}{\iint_o J_o dA}$$

QUESTIONS?

$$\bar{U} \cdot \nabla\left(\rho \bar{U}\right) = -\nabla p + \nabla \cdot \eta \nabla \bar{U}$$

$$J_N = A_N \exp\left(-\frac{F V_m^2 \sigma^3 f(\theta) N_a}{(RT)^3 \left(\ln(\mathrm{SI})\right)^2}\right) = A_N \exp\left(-\frac{a_N}{\left(\ln(\mathrm{SI})\right)^2}\right)$$

$$\frac{dr}{dt} = k_r' \frac{K_{sp}}{\gamma_{Ca^{2+}}\left(SO_4^{\ 2-}\right)}\left(SI_g - 1\right)$$

$$X_{Ca} = \frac{1}{2}\left((\Gamma_i + 1) - \sqrt{(\Gamma_i + 1)^2 - 4 \cdot \left(\Gamma_i - \left(\frac{K'_{CaCO_3}}{K_{a2}} \cdot \left(\frac{[H^+]_e^2}{K_{a1}} + [H^+]_e\right) + K'_{CaCO_3}\right) / [Ca^{2+}]_i^2\right)}\right)$$

Energy Production from Salinity Gradients: Pressure Retarded Osmosis

Energy Production:

$$E_{PRO} = \overline{J_{\mathrm{v}} A \Delta P_m} = AL_p \overline{(\sigma\Delta\pi - \Delta P_m)\Delta P_m}$$

Maximum energy production →

$$\frac{\partial E}{\partial \Delta P_m} = 0$$

Approximate analysis based on average flux and osmotic pressure

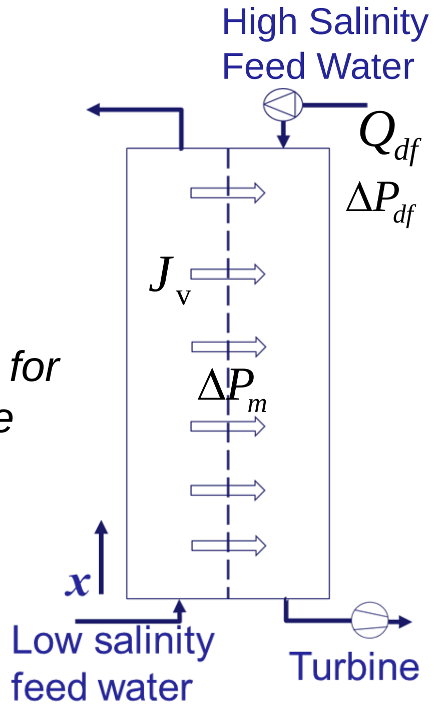
$$(\Delta P_m)_{\max} = \frac{1}{2}\Delta\pi$$

E_p - Additional pumping energy for feed water and for conc draw from the source to the plant.

$$(E_{\max})_{net} = \frac{AL_p}{2}(\Delta\pi)^2\left(\sigma - \frac{1}{2}\right) - Q_{df}\Delta P_{df} - E_p$$

Osmotic energy production (ideal when σ=1)

Pumping energy of draw solution



Reported E_{max}: ~ 1.3-10 w/m^2

Opportunities for PRO?

- Locations where the draw sol’n salinity is >> seawater salinity
- Co-location of RO/FO/PRO plants & wastewater plants

Water Source-Supply Management

- The water balance:

α =Rate of change of water storage=
Water input/capture (natural + reclaimed water recharge) –
water loss (natural + usage)

Water sustainability requires that $\alpha \geq 0$

Water-side solution to the Water-Energy Nexus:

- Reduce water use
  - Water use efficiency, water conservation
- Develop new water sources for potable and non-potable use
  - Reclaimed municipal, industrial, agricultural water sources
  - Upgrade unused/impaired water sources
  - Decrease both the energy and capital cost of water desalination
- Utilize renewable energy sources
- Environmental stewardship

Oil & Gas: Produced Water

- > 15 billion barrels of water produced with oil and gas each year, (~9.5 barrels of water per barrel of oil)
- Produced water quality can may varies withy respect to “water quality” (e.g., salinity and composition of inorganic ions, hydrocarbons, temperature and pH)
- Treatment and disposal costs
- Potential impact of surface discharge on vegetation, soil and streams
- Can treated produced water become a valuable resource?
- Constraints on Coal Bed Natural Gas Production due to environmental concerns w.r.t produced water

Reducing Water Related Energy Use

- Distributed smart (self-adaptive) water systems for water treatment and production

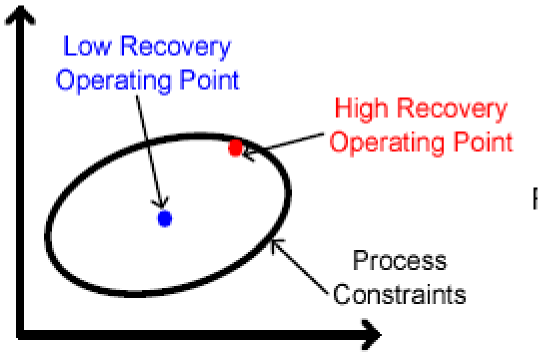
Renewable Energy for water treatment/production:

- Solar powered desalination
- Water disinfection using solar radiation
- Mechanical wind pumps (windmills)
- Energy from biomass (e.g., Biodiesel)
- Coupling of geothermal energy with water production
- Wave energy for water production (desalination)

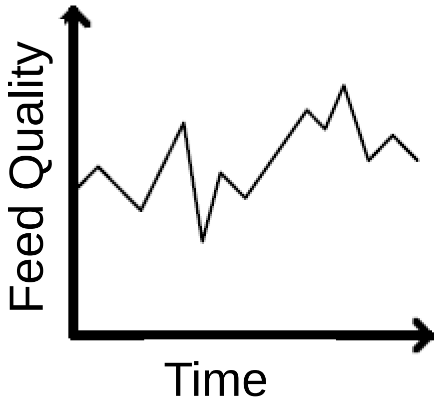
Use of Waste heat:

- Desalination, disinfection, organic destruction

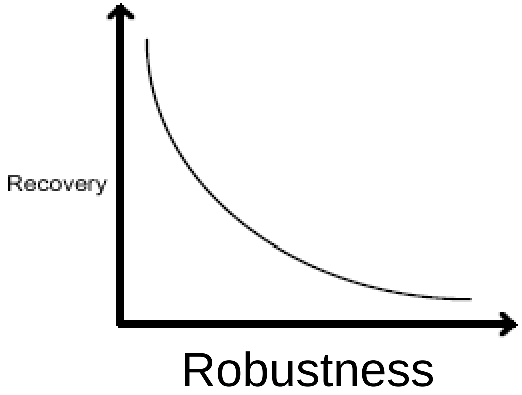
Process Control for Self-Adaptive Operation



Operation close to process constraints

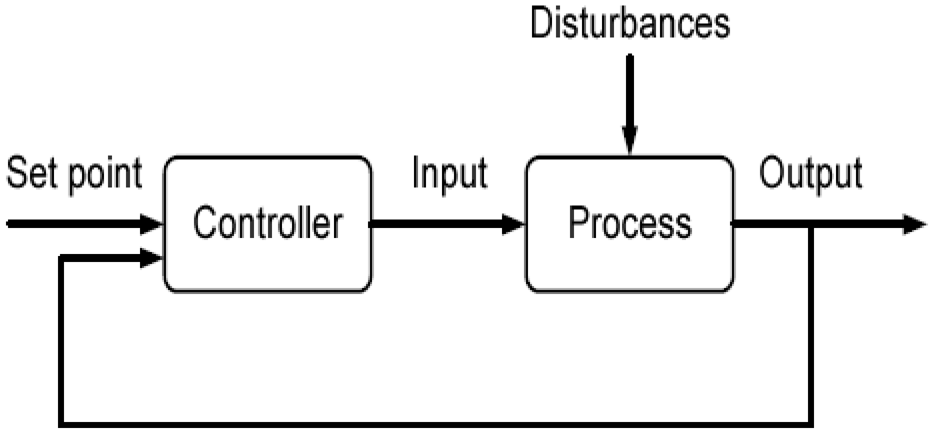


Feed water variability with time



Robustness margin significantly reduced

- Model based approach to controller design



Disturbances

Set point

Controller

Input

Process

Output