Water Reuse in the Republic of Singapore

Thomas J. Grizzard
Virginia Tech CEE Department
Occoquan Laboratory

Drinking Water

- Provision of safe, healthful, plentiful, and secure drinking water is one of the most basic societal needs
- In the early 21st Century, this goal is increasingly difficult:
  - Urban populations are increasing rapidly, with over half the earth's inhabitants now residing in cities (early 2007)
  - In the US, over half the population resides on 20% of the land in the coastal margin
  - Over a billion of Earth's inhabitants have no access to safe drinking water
  - Problems most obvious in undeveloped and developing countries
  - Even in the developed world, there are increasing mismatches between the locations of safe and reliable water sources and the locations of human populations

Urbanization Trends Increase the Pressure

- In 2007, for the first time, half the earth's population resided in cities (UN 2006, Wimberly et al. 2007)
- Over half the US population resides in the coastal margin, which is 20%of the continental land mass (CMOP 2008)
- There will be a 40% increase in water consumption by 2025.
- Today 1.2 billion people do not have adequate access to drinking water and 2.4 billion people not connected to waste water systems.
- By 2025, one third of the world's population will be affected by water shortages and by 2050, 60 percent.

So, where's the water today?

Source	Volume	% of Total	Renewal Time
	(1,000 km^3)		
Oceans	1,370,000	97.61	3,100 yrs
Polar Ice	29,000	2.08	16,000 yrs
Groundwater	4,067	~~0.295~~	300 yrs
Fresh Lakes	126	0.009	1 – 600 yrs
Saline Lakes	104	~~0.008~~	10 – 1,000 yrs
Soil Moisture	67	~~0.005~~	280 days
Atmosphere	14	~~0.0009~~	9 days
Rivers	1.2	0.00009	12 – 20 days

∑ = 0.00909%

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Sources: *Limnology* by Cole, Waveland Press, 1984; *Limnology* by Wetzel, Academic Press, 2001

So Where's all the Water….continued?

- Excluding groundwater, accessible fresh water accounts for only ~ 0.00909% of the total water on earth

- Of that, 60% is in three places:
  - Great Lakes in North America
  - Lake Baikal in Asia
  - Lake Tanganyika in Africa

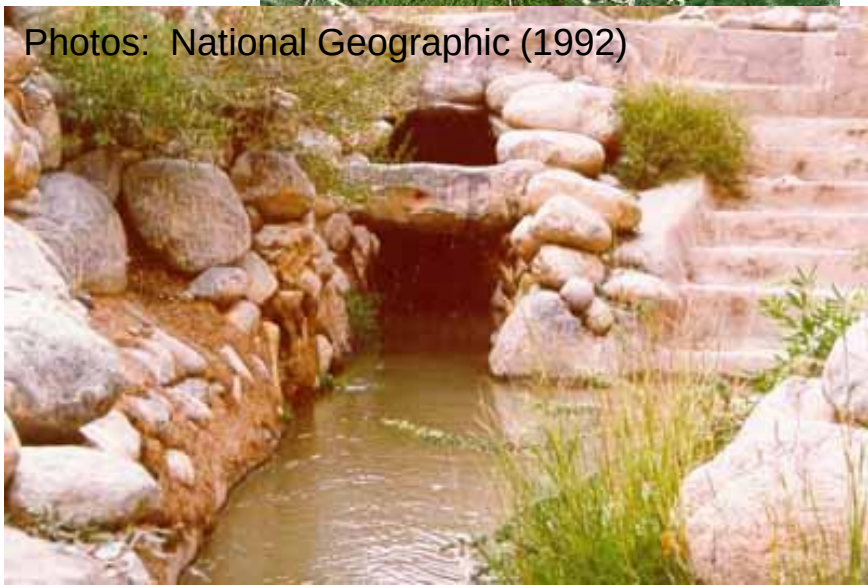
- So, of the previous 0.009%, only 40% is more globally distributed (~0.0036%)

The problem is often not the overall availability of water, but rather regional disconnects between water availability and concentrations of human populations

Not necessarily a new problem…

Early Evidence of Delivery of Public Water Supply (*c.* 6,000 B.P.)

- Archeological record shows that supply tunnels (*qanats*) were used to bring water to ancient cities in Middle East (Persia)
- Water from foothills of the northern mountains transported to the southern plains for irrigation and domestic use
- Still in use in Teheran as late as 1935.



Photos: National Geographic (1992)

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Roman Aqueduct and Copy…

Pont du Gard
(France, ~2000 BP)

19th Century copy in
Malaga, Spain

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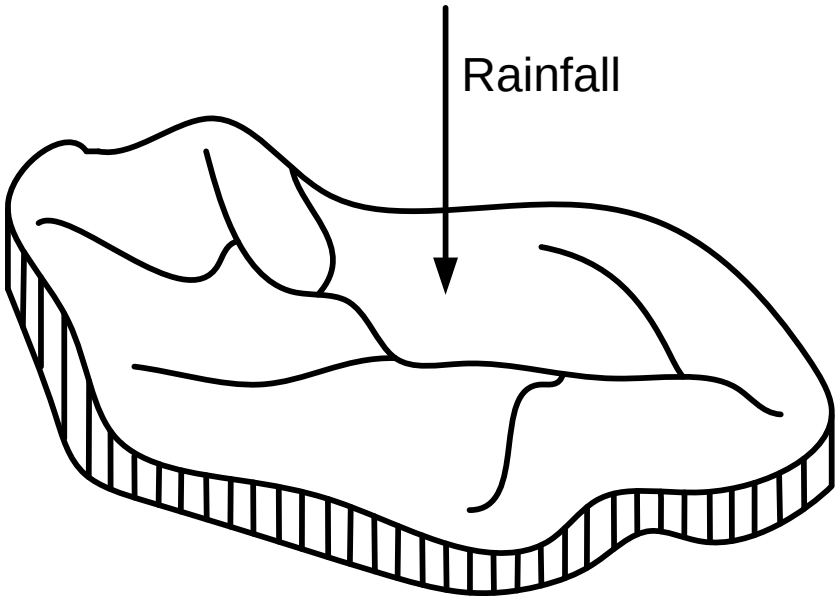
Importance of Water and Population Distribution

- Per capita rainfall statistic:
  - Annual rainfall multiplied by drainage area and divided by population
    - Per Capita Rainfall= $\frac{\text{(Annual Rainfall) x (Land Area) x CF}}{\text{Population}}$
  - m^3/capita/yr gallons/capita/yr.
  - World variability



Some Per Capita Rainfall Examples

Country or Region	Annual Rainfall (inches)	Land Area (sq. mi.)	Pop. (millions)	Per Capita Rainfall (10^3 Gal/cap/yr)	Per Capita Rainfall (10^3 m^3/cap/yr)
Saudi Arabia	4.0	900,004	21.1	2,959	11.20
Arizona	13.1	113,642	5.1	5,043	19.09
U.S. Average	-	-	-	7,789	29.48
Potomac Watershed	~ 40.0	14,670	5.0	2,039	7.72
Singapore	86.6	267	5.0	80	0.30

Note: Singapore calculation does not include imported water from Malaysian Catchments

How can we provide enough water?

- Conservation?
  - Limited success in the US
  - Usage driven by lifestyle
- Importation or transport across watershed boundaries?
  - Possible and is being done in some places
  - Usually meets with strong opposition (Great Lakes)
- Use of sea water?
  - Technology has been around for 50 years
  - Not widely used due to rising energy costs
- Reuse (or, is it safe to drink the sewage?)

A Closer Look at Reuse

- Pros:
  - Already in a pipe
  - Lower salt content than sea water
  - Reasonably consistent quality of “feedstock”
  - Technologies for reclamation already exist
  - Cost effective when compared to other raw water sources
- Cons:
  - Potential for unknown chemical contamination
  - Potential for unknown microbial contamination
  - Aesthetics (the YUCK factor)
  - Contaminants of Emerging Concern (PPCP’s)

Chemical Contaminants

- We have a good handle on conventional contaminants
- Contaminants of emerging concern
  - Personal care products (PCP's)
  - Endocrine disrupting compounds (EDC's)
    - Pharmaceuticals
    - Pesticides/herbicides
  - DBP's still an issue…..(*e.g.,* NDMA)
- Lots of work to be done in this area
  - Degradation products
  - Health Effects (ecosystem **and** human)
  - Removal technologies
    - Both water reclamation and water treatment

Microbial Contaminants: Protozoans, Bacteria, Viruses

- Generally rely on multiple barrier concept
  - Biological treatment
  - Physical/Chemical Processes
  - Disinfection
  - Residence time in the environment
  - Physical/Chemical/Biological processes in water treatment
- Each process may achieve ~2 log (100x) reduction, but there is high variability among specific microbes

So what's going on in water reuse?

- It should surprise no one that potable water reuse already occurs
- There really is no "new" water….
  - "Unplanned" reuse has always occurred
  - Usually try to manage with spatial and/or temporal separation of contamination source and water intake…..
- The surprise is that "planned" indirect potable reuse has been going on in the US for over 3 decades….
- Leadership in development of large scale IPR has been in Asia and in the US western states.

Some Potable Reuse Definitions

- **Direct Potable Reuse:** Injection of recycled water directly into the potable water supply distribution system downstream of the water treatment plant, or into the raw water supply immediately upstream of the water treatment plant
- **Indirect Potable Reuse (Planned):** Reclamation and treatment of wastewater and return to the natural water cycle upstream (time or space) of the drinking water treatment plant
- **Indirect Potable Reuse (Unplanned):** Unplanned (or Incidental) indirect potable reuse is wastewater entering the natural water system (creeks, rivers, lakes, aquifers), and eventually being extracted for drinking water

Milestone Potable Reuse Projects

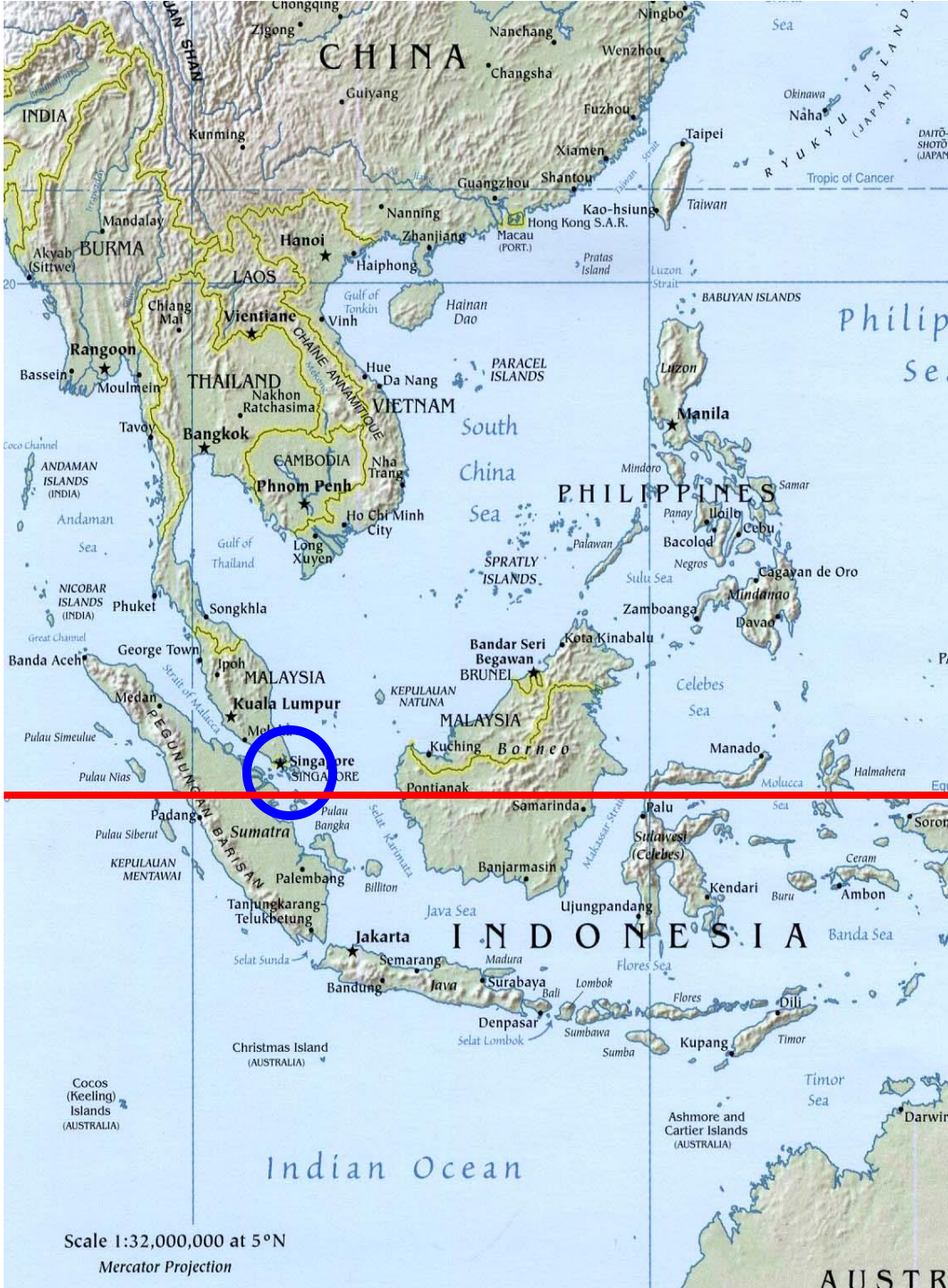
- 1977 - Water Factory 21 (Orange County CA)
- 1978 - Upper Occoquan Service Authority (Fairfax, VA)
- 2002 - NEWater (Singapore, Southeast Asia)
- 2008 - Groundwater Replenishment System (Orange County CA)
- 2009 – Broad Run Water Reclamation Facility (Loudoun Water)
- 20?? - Who's next?

Indirect Potable Reuse: The Next Generation

Republic of Singapore

Singapore Location

- Southeast Asia on Southern tip of MaIaysian Peninsula
- ~ 1^{o} north of Equator
- Population = 5 million
- Density >18,000/mi.^{2}
- NO natural resources
  - No minerals
  - No energy
  - No groundwater



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Republic of Singapore

Issues Affecting Water

- Singapore left Malaysian Federation in 1965
  - Purchased ~40% (184 mgd) of raw drinking water supply water from Malaysia in 2010

- Existing agreements on supply from Johor, Malaysia expire in **2011** and 2061
  - Must plan for reduction in availability of Johor Water

- Also facing a doubling of demand by 2061

Singapore Water Quantity Requirements

- Daily water consumption (2011): 460 mgd US
  - ~43 gpcd domestic consumption

- Consumption distribution:
  - 2011: 55% Commercial/Industrial
    45% Domestic
  - 2061: 70% Commercial/Industrial
    30% Domestic

  - Industrial Demand: Cooling, microelectronics, petrochemicals, pharmaceuticals

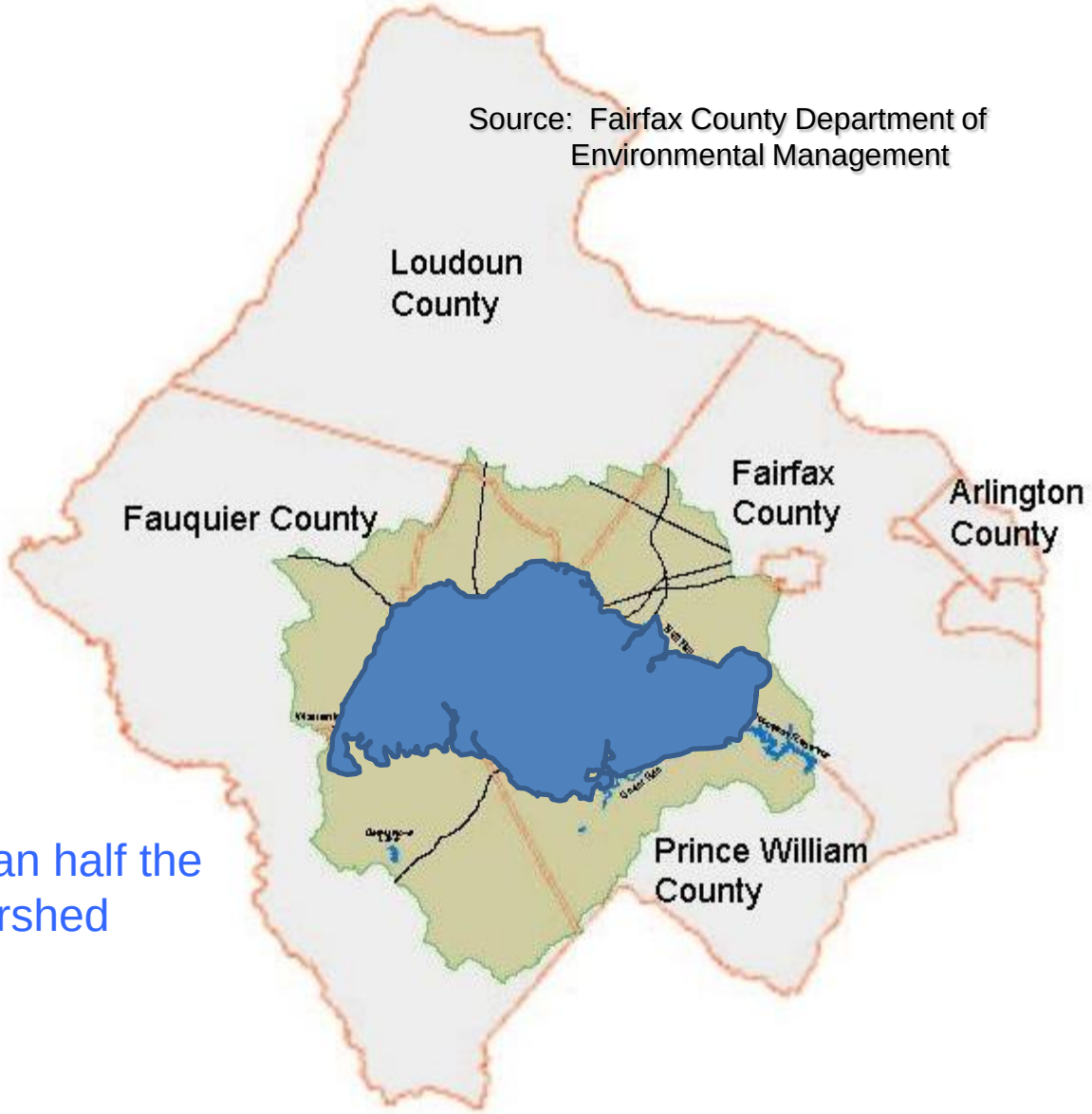
Why the worry about water supply when you get 90 inches of rain?

Summary of Singapore Water Supply Issues

- Inadequate availability of local water supply catchments
  - Much of the 267 mi.^{2} island land area is devoted housing, industry, and commerce
- Inadequate availability of land for storage reservoirs for either untreated or treated water
- Uncertainty about the availability of water from another nation (Malaysia)

Source: http://www.cia.gov

Source: Fairfax County Department of Environmental Management



Singapore is slightly less than half the area of the Occoquan Watershed

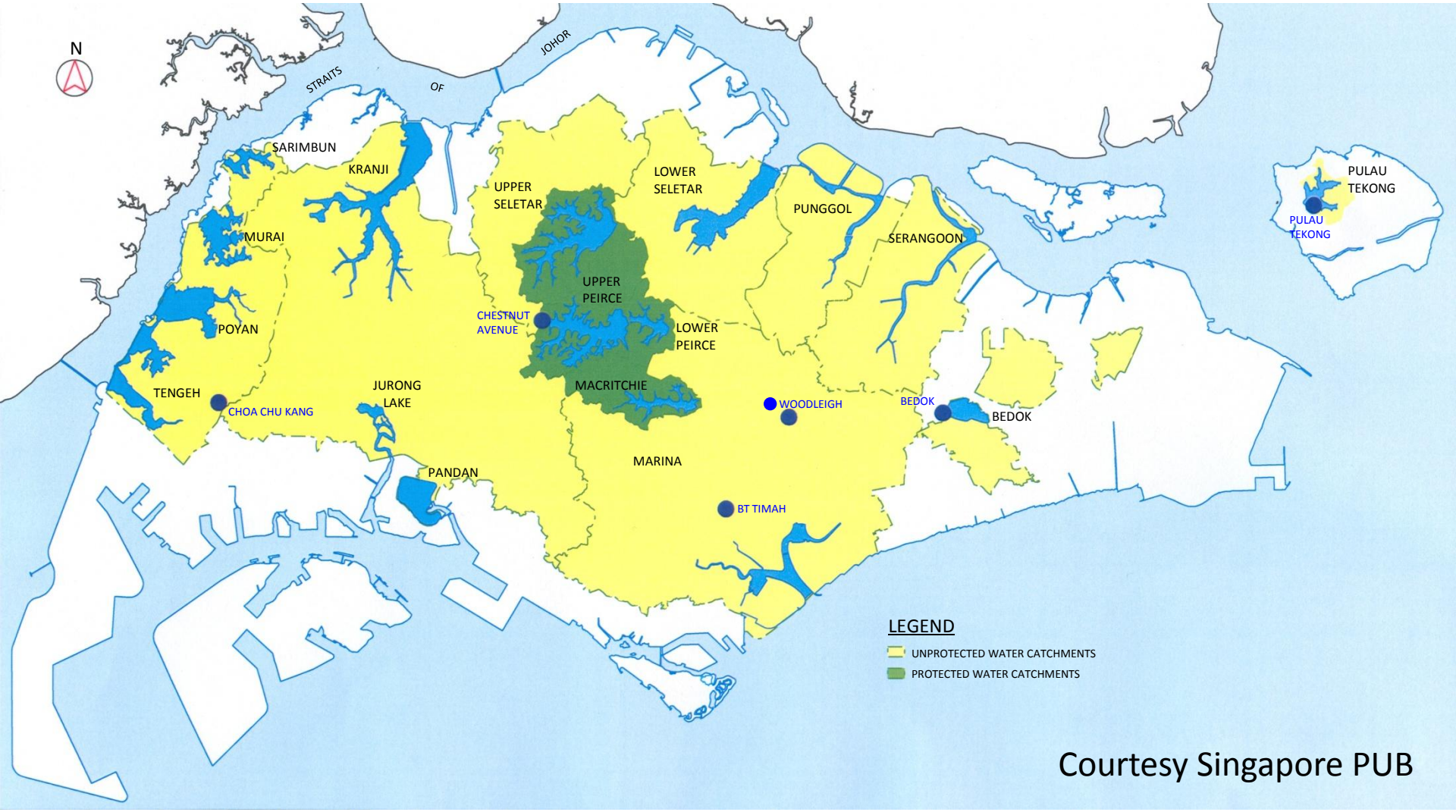
Unusual Raw Water Storage Reservoir Issues….

Solutions for Singapore: The 4 National Taps

- Continue with Malaysian sources as available
- Conservation
- Develop Singaporean surface catchments to fullest extent possible
  - Stormwater harvesting in "new town" areas
- Develop new sources:
  - Desalination
  - NEWater (新生水)

Conservation, New Storage, and New Catchments

- Per capita water consumption is 43 gal/day
  - Reduce to 39 gpcd by 2020
- Reduced unaccounted for water to <5%
- Develop new storage reservoirs at estuarine embayments
  - Nine projects completed
  - Marina Bay is most visible
- Increase stormwater harvesting in urban catchments
  - Can now capture drainage from 65% of the island



Courtesy Singapore PUB

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Local Catchments

- Can currently capture ~210 mgd
- Stormwater harvesting in “New Town” areas
- New surface storage
  - Creating seawater barrier to convert Singapore River estuary into freshwater storage reservoir
  - Drainage is some of the most urbanize parts of the island
  - Goal is using 65% of island as water supply catchment

New Sources

- Desalination
  - Private sector initiative (“SingSpring”)
    - Design, Build, Own, OperateBeginning in 2005, providing ~ 40 mgd
    - Long term prospects affected by rising energy costs

- Indirect Potable Reuse (NEWater)
  - Direct to Industrial Users
    - *De* facto increase in potable supply
  - Replenishment of surface water reservoirs
  - Piloting use of MBR effluent as NEWater feed source

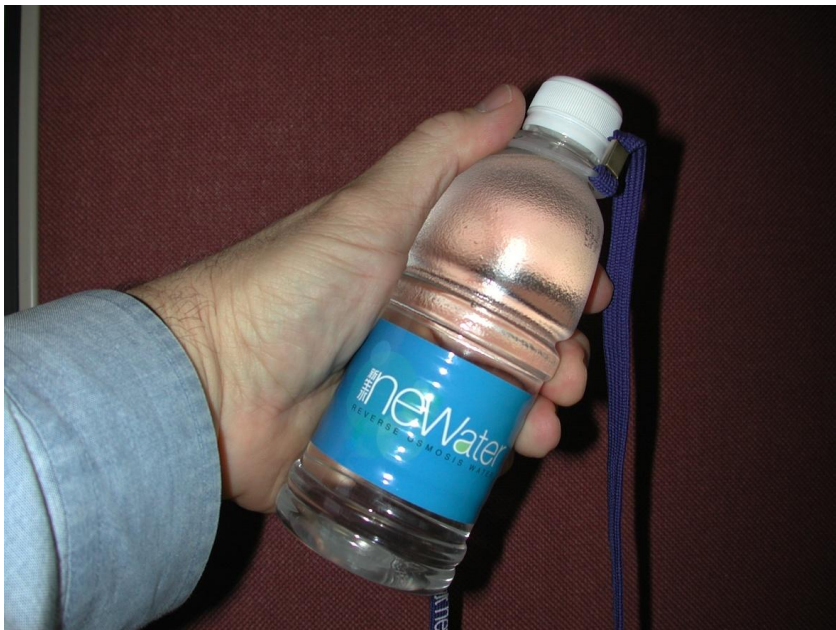
Completed Marina Barrage Views, 2008

Looking North from Marina Bay


RIVER TAXI
TEL: 33 66 111
FAX: 33 66 112
SP 1214Z
TOWN
Located in The Fullerton Singapore • Call 6877 8128
SC1243F

NEWater Plan

- Public acceptance of **direct** reuse is at 82%
- Current plan is to remain an indirect reuse system
- Water is of such high quality that it is best not used for the “lower” quality demands of drinking water
  - Most is delivered to industrial facilities for cooling and process water
    - Semiconductor manufacturing, petrochemicals, etc.
- Water not sold to industry is returned to drinking water reservoirs
  - Currently 6-7%



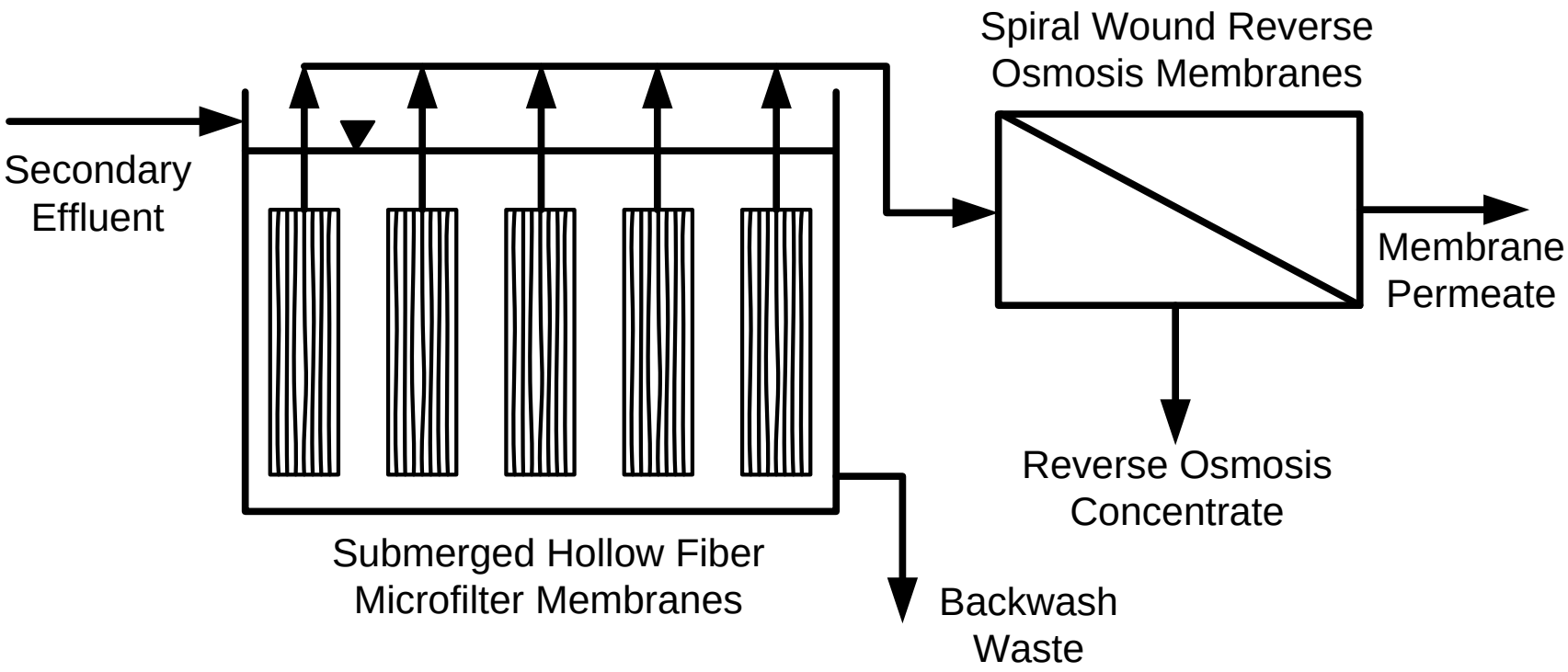
Bedok NEWater Factory Visitor Center

Satellite View of Changi WRP (2007)

NEWater Process

- Secondary effluent feedwater
  - 95% domestic at plants chosen
- Microscreening (0.3 mm)
- Microfiltration (0.2 um)
- Reverse Osmosis (< 0.0005 um)
- UV Disinfection
- pH Adjustment with caustic (NaOH)

Abbreviated NEWater Process Schematic



Membrane

- If one square meter of membrane were expanded to the area of the Pacific Ocean (165 x 10^6 km^2):
  - Reverse Osmosis (RO) pores would be the size of a dime
  - Nanofiltration (NF) pores would be the size of a half dollar
  - Ultrafiltration (UF) pores would be the size of a silver dollar
  - Microfiltration (MF) pores would range from a foot to nearly 20 feet across

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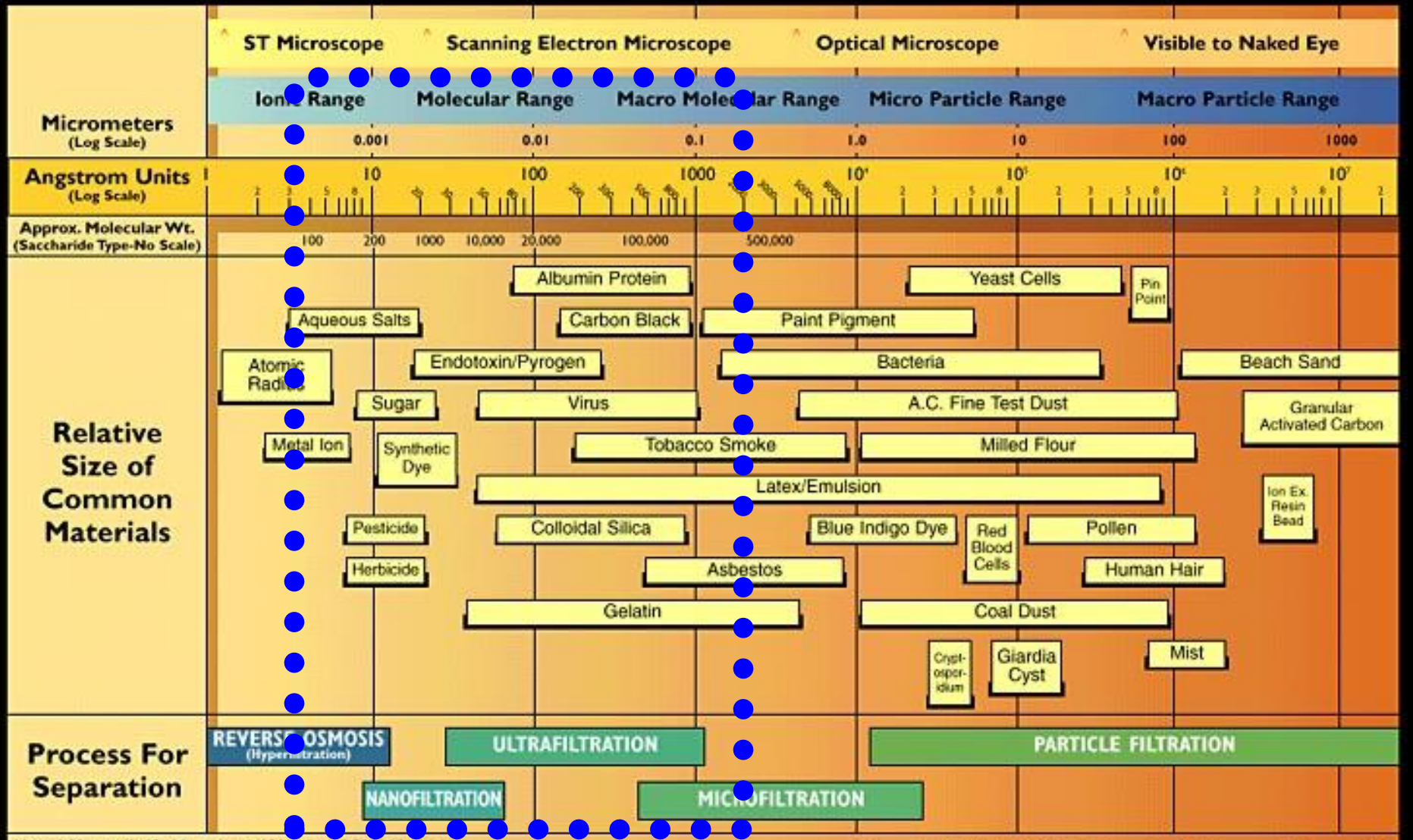
The Filtration Spectrum



Note: 1 Micron (1x10⁻⁶ Meters) = 4x10⁻⁵ Inches (0.00004 Inches)
1 Angstrom Unit = 10⁻¹⁰ Meters = 10⁻⁴ Micrometers (Microns)

Osmonics, Inc.
Corporate Headquarters
5951 Clearwater Drive • Minnetonka, Minnesota 55343-8990 USA
Toll Free: 800/848-1750 Fax: 612/933-0141

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NEWater Quality

- TOC: < 70 ppb
- TDS: ≤ 50 mg/L
- Cond: < 70 uS/cm
- pH: 7.0 – 8.0
- TTHM: ND

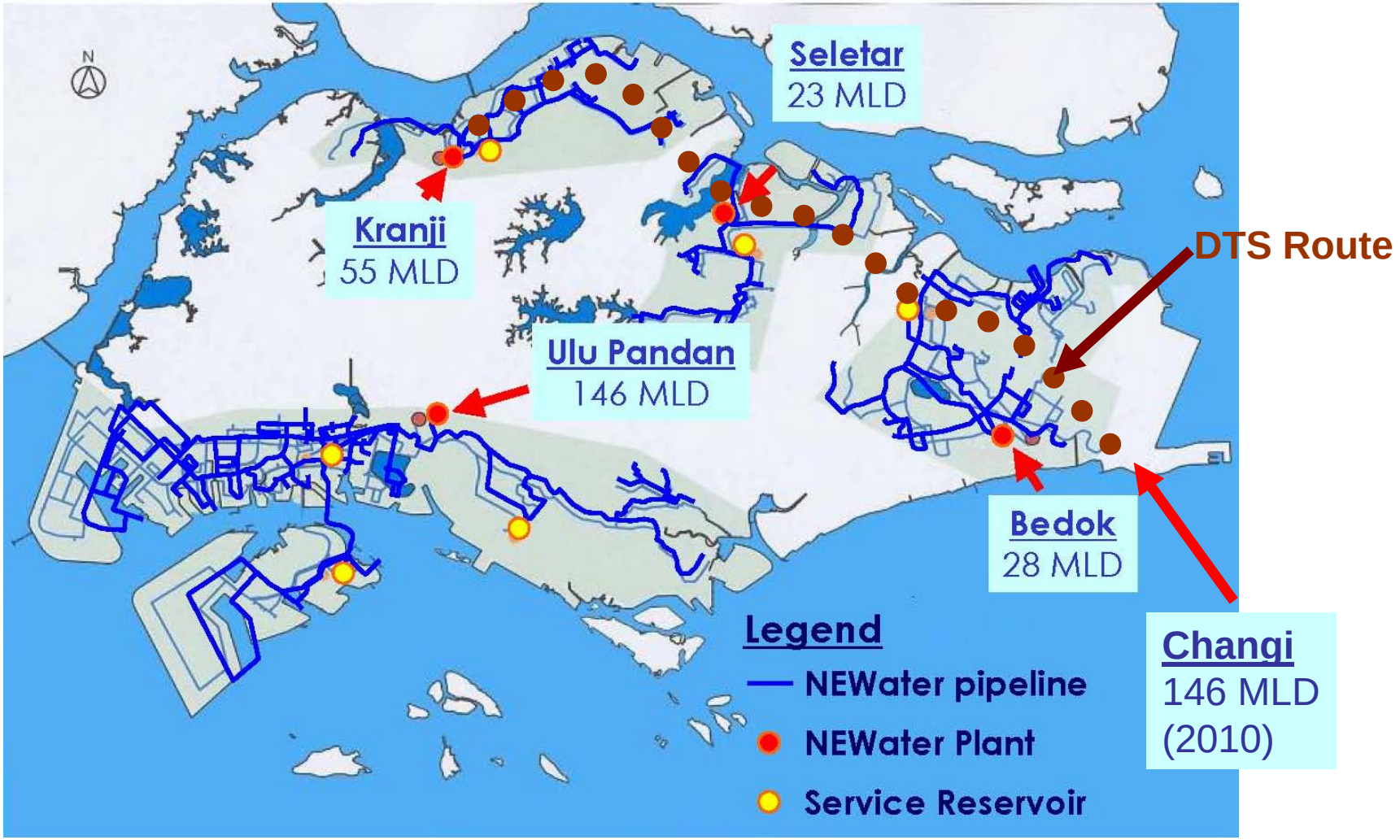
- Fecal Coliform: ND
- *Cryptosporidium*: ND
- Enterovirus: ND
- HPC: ~ 5 cfu/mL

- Very high water quality creates industrial use demand

NEWater in 2011

- Existing Plants
  - Bedok (22 mgd US)
  - Kranji (20 mgd US)
  - Seletar (6 mgd US)
  - Ulu Pandan (38 mgd US)
  - Changi (60 mgd US)
- 2011 production capacity is ~146 mgd
  - Triple by 2060
  - Industrial users are biggest customers
    - Process water
    - Cooling water
  - ~7% goes to replenish storage reservoirs

NEWater Production and Distribution

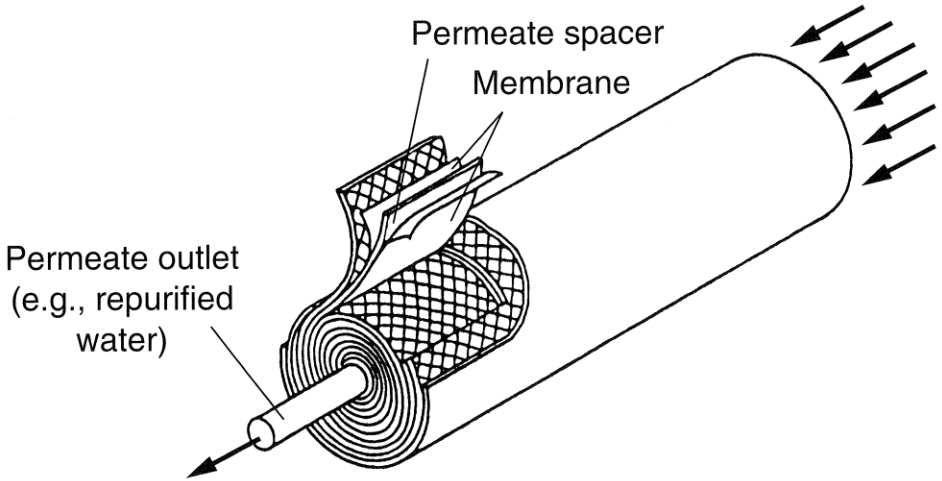


Zenon Microfilter “Zeeweed” Cassette being removed for maintenance

Close-up view of Zenon Microfilter Hollow Fibers in “Zeeweed” Cassette

Bedok NEWater Plant
(RO Membrane Gallery)

Spiral-Wound Reverse Osmosis Membrane Cartridge



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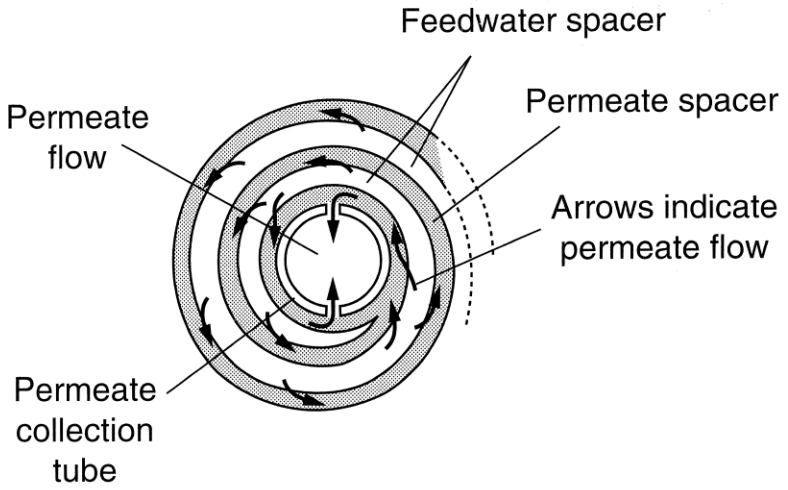

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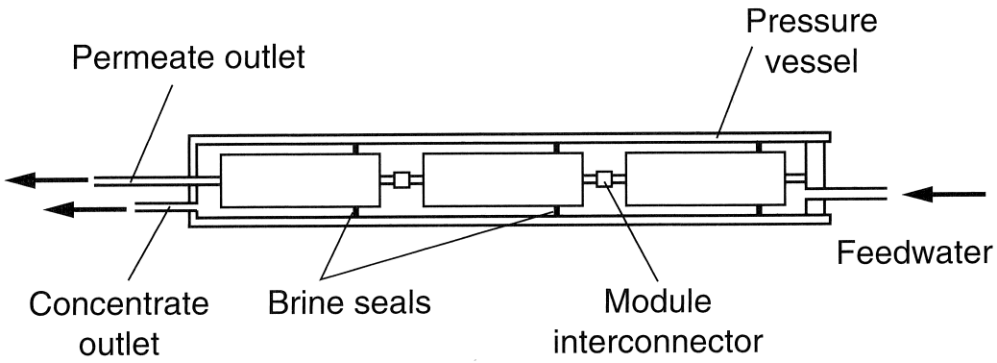


Bedok newater Plant
(UV Disinfection)

Groundwater Replenishment System

Orange County Water District
Costa Mesa, California

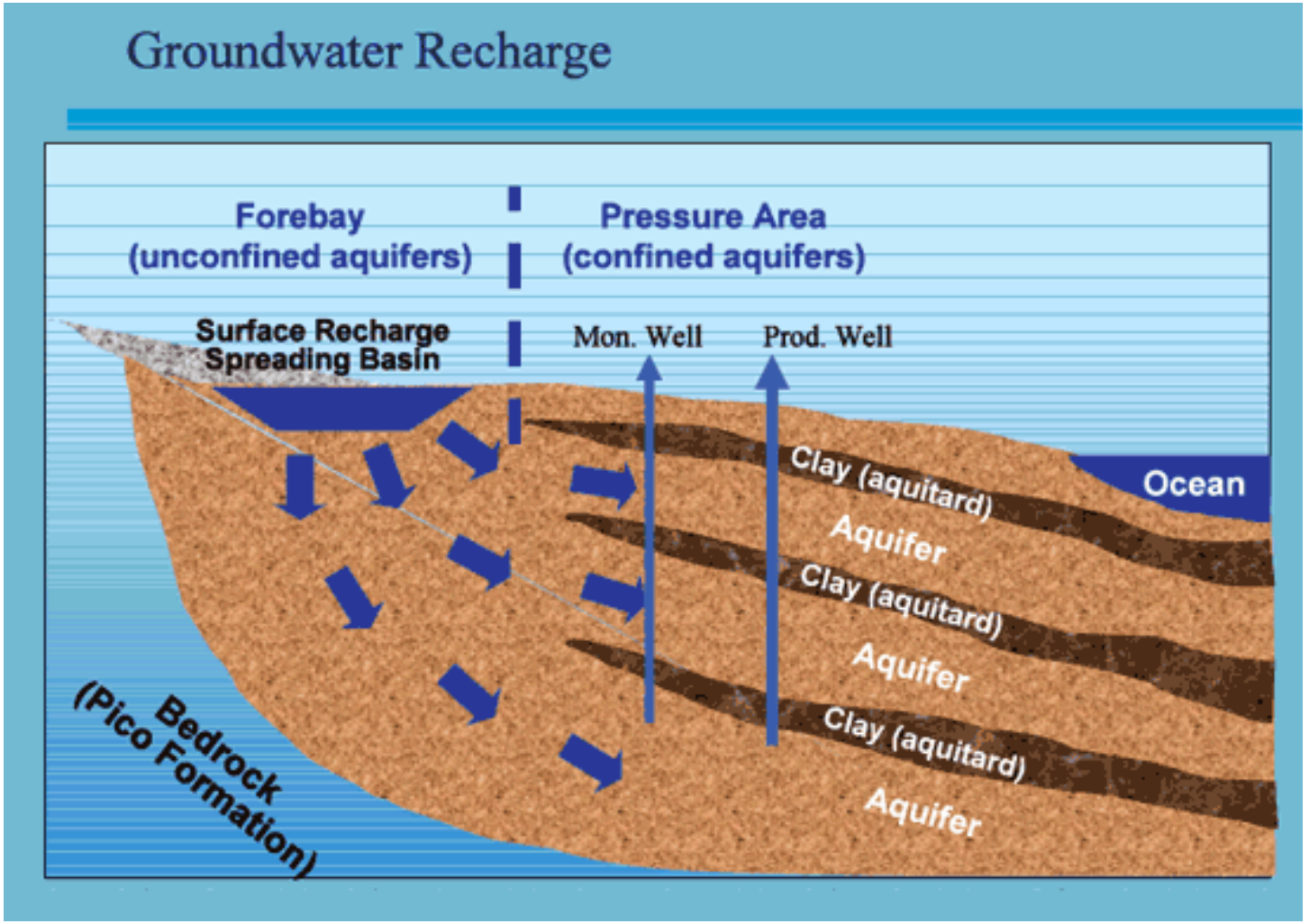
Groundwater Replenishment System Orange County, CA

- Built on research base from Water Factory 21
- Arid landscape
- Very little “local” water available (Santa Anna River)
  - Agricultural irrigation withdrawals
- Imported water from upstate and Colorado River not enough to meet requirements
- Planned potable reuse…..through groundwater recycle
  - Seawater intrusion barrier and groundwater replenishment

GWRS

- Similar to NEWater except that it includes advanced oxidation process
- Feedstock is conventional secondary discharges
- Process is: MF → RO → [UV+H_2O_2]
- Strip CO_2 and adjust pH before injection
- Operational in late 2007 at 70 mgd
- 1st Expansion under design….
- Major problem to date: Can't run at full capacity because of sewage shortage

Seawater Barrier Maintenance with Groundwater Replenishment System



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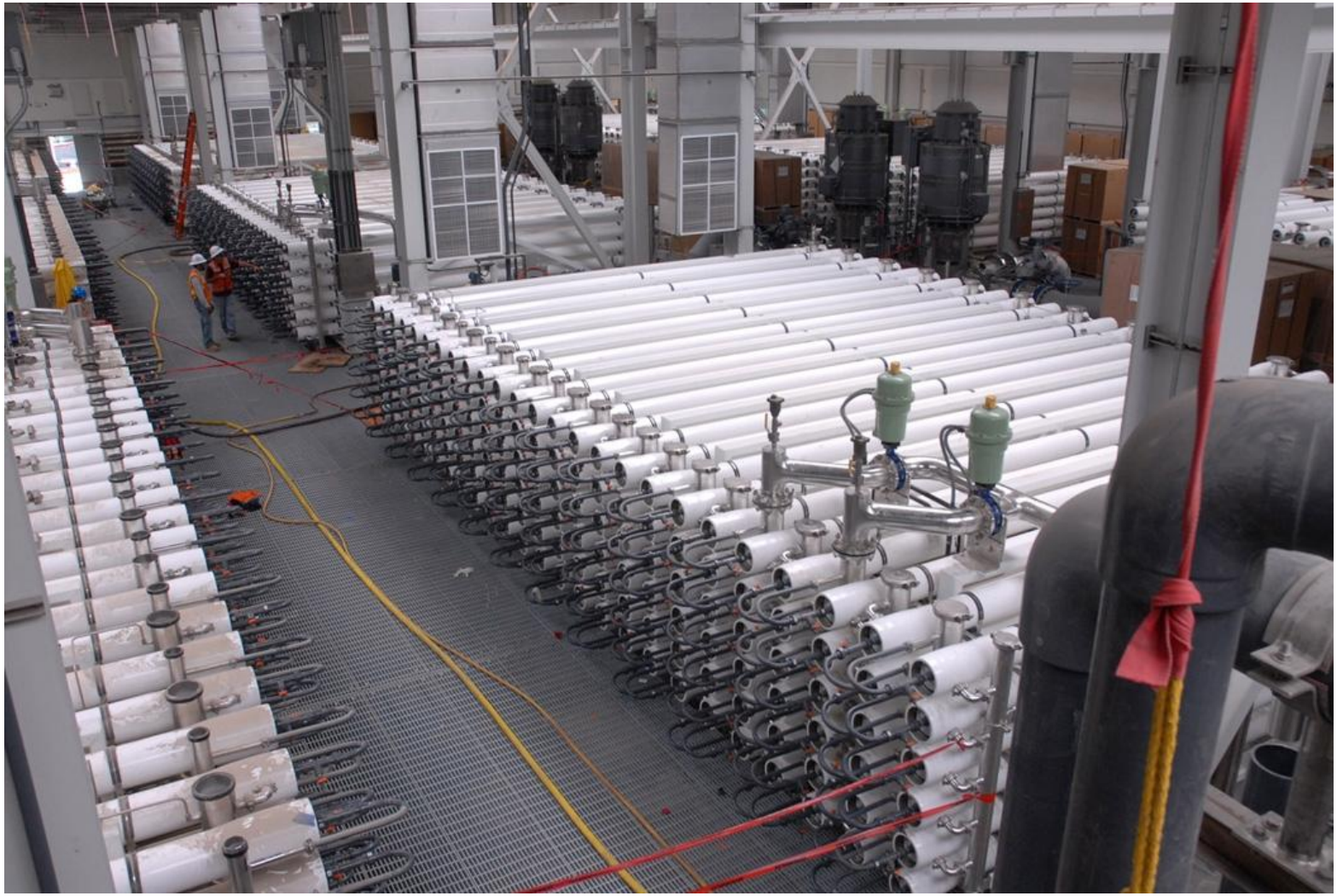
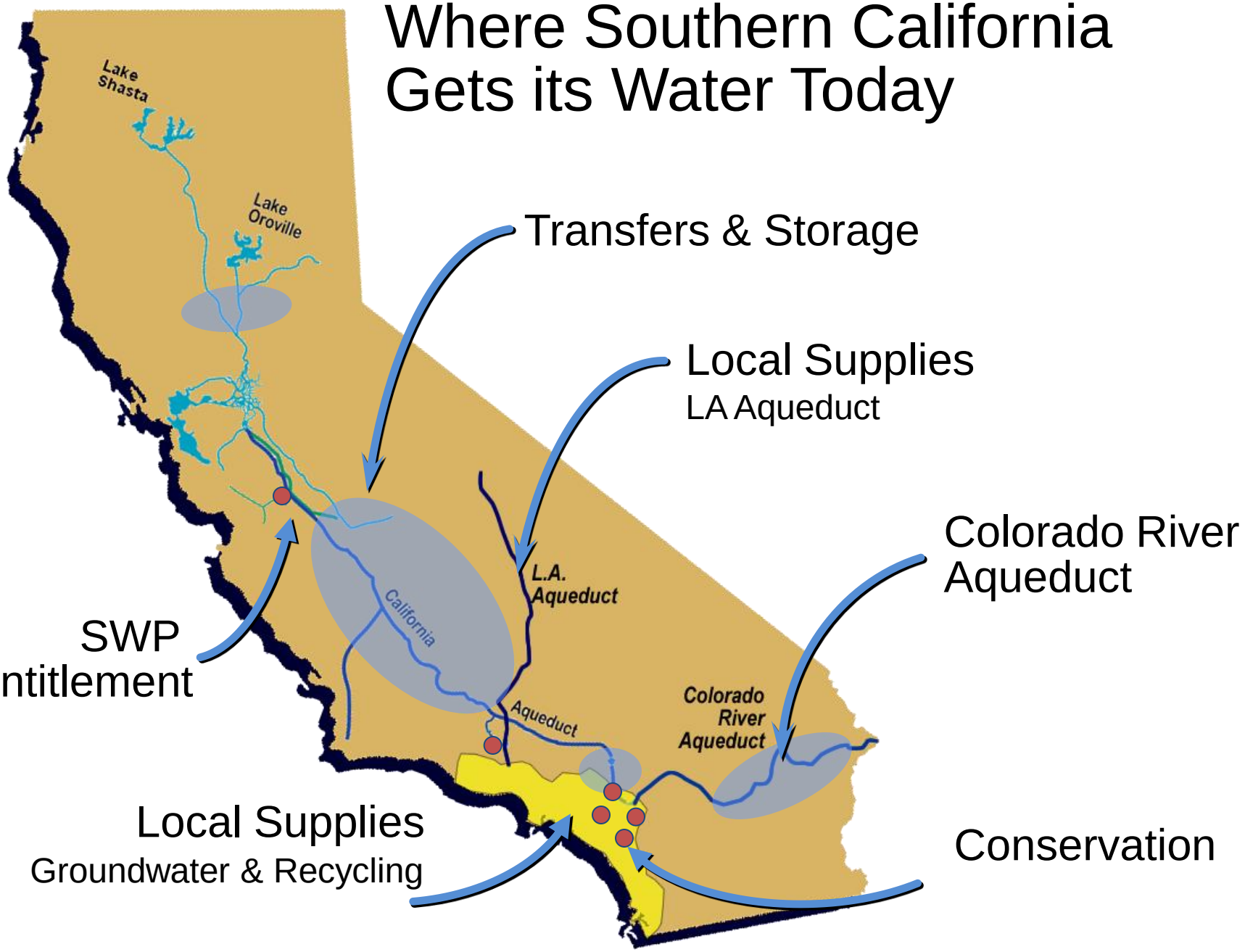
RO Gallery at GWRS



The Curious Case of San Diego

- If ever there was a candidate for IPR……
- San Diego gets:
  - 10-20% of its water from local catchments
  - 80-90% from:
    - State Water Project: Diverted from Northern California
    - Colorado River Project: Lake Havasu pipeline (242 mi.)
  - Future regulation will limit or reduce imported water
- Opposition to IPR……yuck?
- So what do you do in an urban area of 3,000,000 people at the end of a river with a 440 sq. mi. watershed?

Where Southern California Gets its Water Today



San Diego River

- 440 sq. mi. drainage
- Urban areas: Part of San Diego, El Cajon, La Mesa, Poway, Santee
- 475,000 population
- Five (5) reservoirs
- Water supply to 760,000
- Rainfall
  - 11- 26 inches (Coast – Headwaters)
  - Average flow at San Diego (after diversions):
  - 38 cfs (1983 – 2010) reaches the Pacific Ocean
    - Diversions for water supply and irrigation
    - El Capitan Lake & San Vicente Reservoir

Questions?