Balancing Risk Assessment and Life Cycle Analysis of On Site Water Reuse Approaches

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Outline

- The need for adaptation in our water infrastructure

- Recent history of EPA-ORD work
  - Focus on collaboration with state/local National Blue Ribbon Commission for Onsite Non-Potable Water Systems
    - Risk assessment to inform regulatory guidance
    - Integrated assessment of alternative scenarios using system level costs and impacts

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Fourth National Climate Assessment

Vol I: The Climate Science Special Report (2017)

- Chronic, long duration hydrological drought is increasingly possible before the end of the century

- Heavy rainfall is increasing in intensity and frequency across the US and is expected to continue to increase

- Average sea levels are expected to continue to rise several inches in the next 15 years and by 1-4 feet by 2100. A rise of as much as 8 feet cannot be ruled out

Fourth National Climate Assessment

Vol II: Impacts, Risks, & Adaptation in the US (2018)

- Water
  - Persistent, significant changes in water quantity and quality are evident across the country, presenting on-going risk to coupled human and natural systems
  - Deteriorating water infrastructure compound the climate risks, current approaches to infrastructure (design, operation, financing regulation) do not account for climate change, and current risk management does not typically account for changing risks, co-occurrence of multiple events/cascading infrastructure failure
  - Water management strategies designed in view of an evolving future we can only partially anticipate will help prepare the nation. Developing new water management and planning approaches may require updating the regulatory, legal, and institutional boundaries that constrain innovation in water management, community planning, and infrastructure design

The basic paradigms of environmental and natural resources law are preservation and restoration, both of which are based n the assumption that natural systems fluctuate within an unchanging envelope of variability (“stationarity”).

Third National Climate Assessment

IPCC Sixth Climate Assessment (2022)

"Available evidence on projected climate risks indicates that opportunities for adaptation to many climate risks will likely become constrained and have reduced effectiveness should 1.5º C global warming be exceeded and that, for many locations on Earth, capacity for adaptation is already significantly limited. The maintenance and recovery of natural and human systems will require the achievement of mitigation targets"

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"General availability of water and other materials, relative to demand, and the general lack of treatment technologies and monitoring/autonomous control capabilities"

"The main factors that resulted in the development of the current urban water management system no longer exist."

G.T. Daigger, S. Sharvelle, M. Arabi, and N.G. Love. 2019. Progress and Promise Transitioning to the One Water/Resource Recover Integrated Urban Water Management Systems J. Environ. Eng. 145(10):04019061

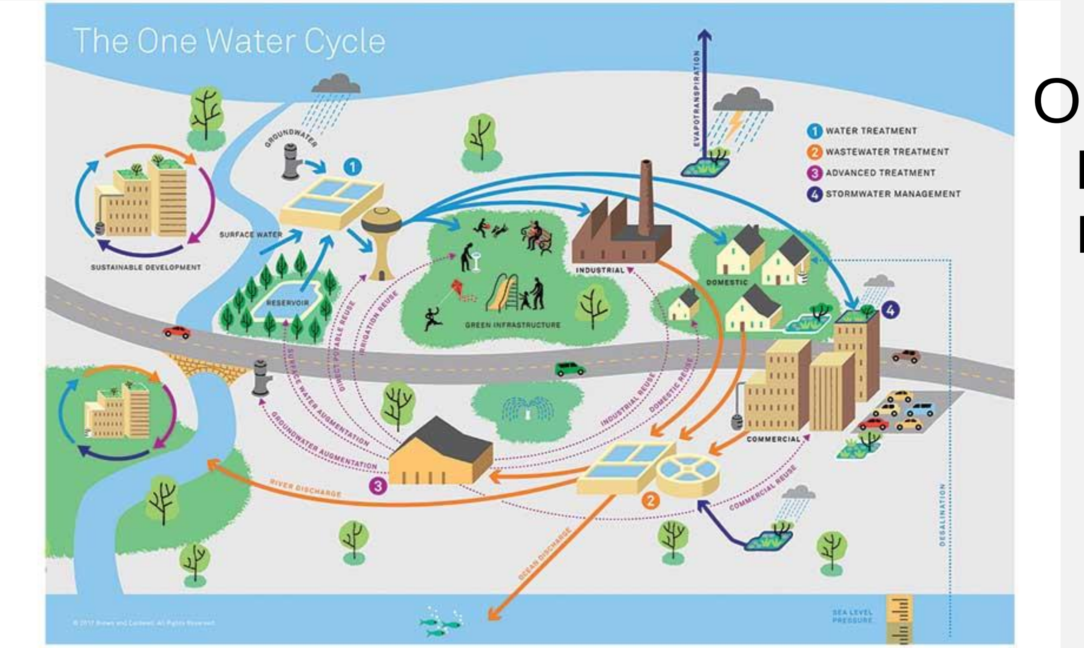
Transitions in the Water Sector

	Historic	*Future*
Relationship to Economy	Provide cost-effective water services	Part of circular economy
Functional Objective	Comply with regulations	Produce useful products
Optimization Functions	Infrastructure Cost	Water, energy, materials
Water Supply	Remote	Local
Systems Components	Separate drinking, storm, waste	Integrated, multipurpose
System Configuration	Centralized	Hybrid (C & Distributed)
Financing	Volume Based	Service Based
Institutions	Single-purpose utilities	Water cycle utilities
System Planning	“Plumb up” the planned city	Linked to city planning

G.T. Daigger, S. Sharvelle, M. Arabi, and N.G. Love. 2019. Progress and Promise Transitioning to the One Water/Resource Recovery Integrated Urban Water Management Systems J. Environ. Eng. 145(10):04019061

Thinking Broadly

in a Shrinking World



One Water

- Many, “tightening” cycles
- Planned holistically

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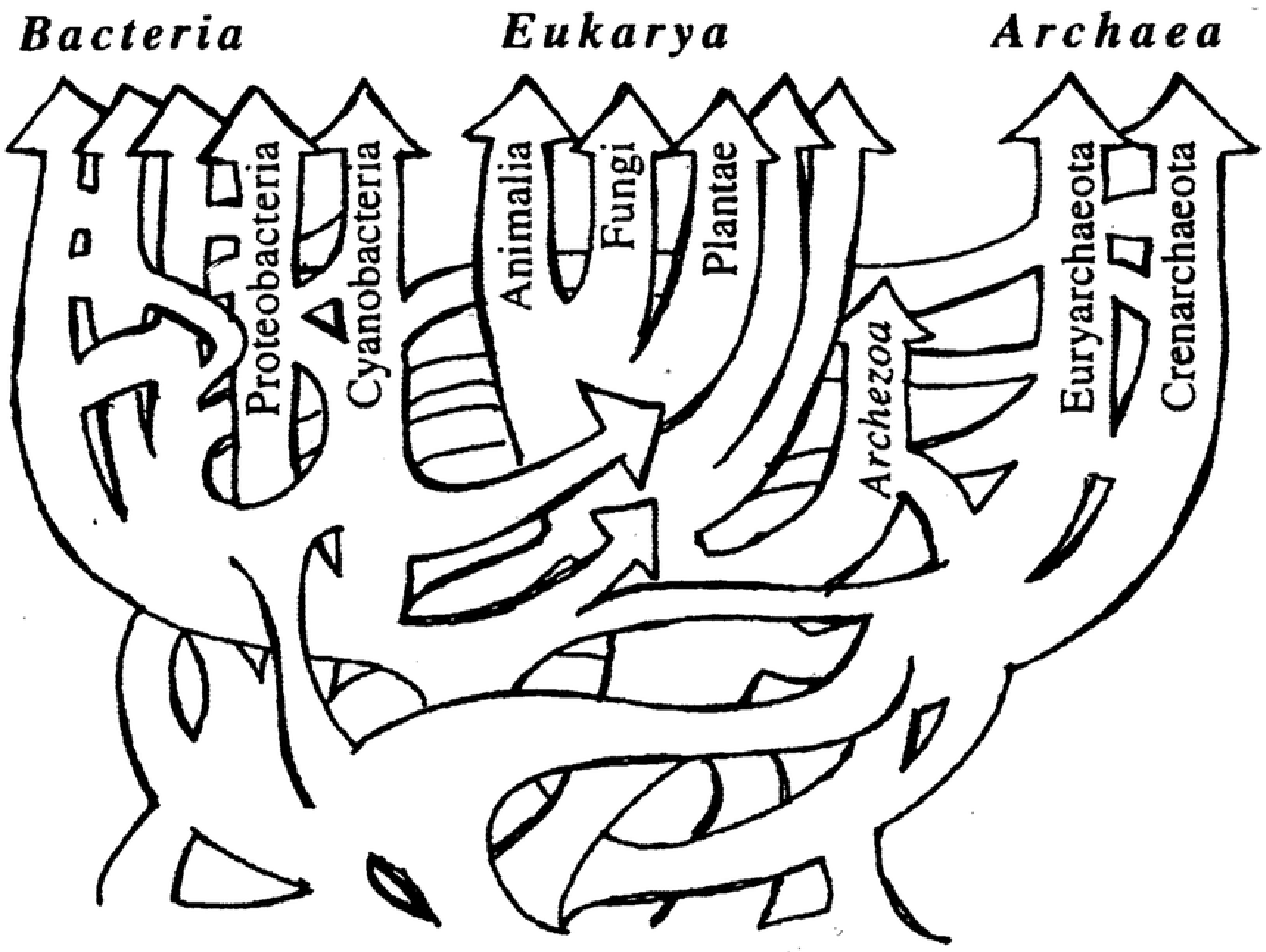


Ford Doolittle’s Reticulated Tree Of Life

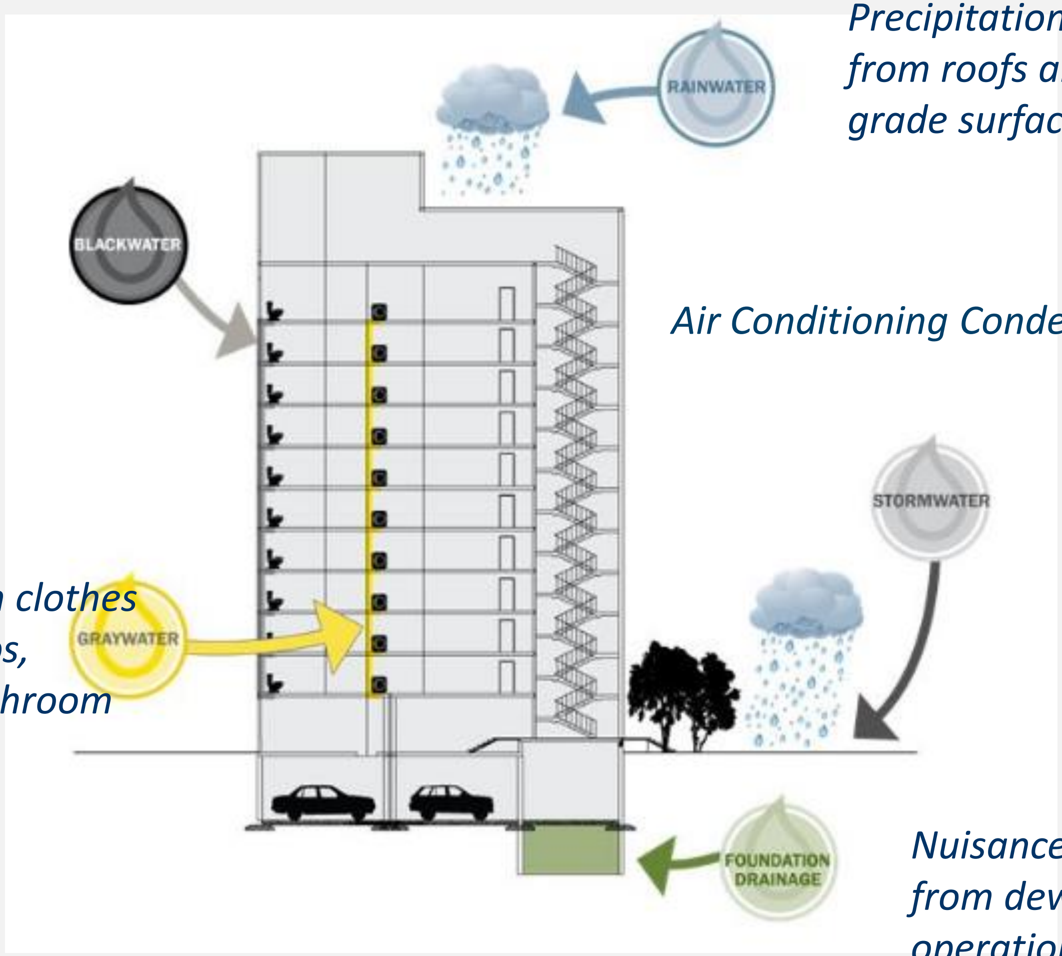
Sunk Cost Effect (Viswanathan and Linsey 2013)

"Researchers and engineers tend to generate ideas with lower novelty and variety if they have already invested significant amounts of time, money, and effort in support of an existing path"

Example used by Rabaey et al. (Water Research 105, 116276, 2020)

Improving overall efficiency of a DW system by improving centralized treatment plant efficiency rather addressing the distribution system where expenditure of energy (and manpower) is greater

Buildings Produce Water



Precipitation collected from roofs and above-grade surfaces

Wastewater from toilets, dishwashers, kitchen sinks, and utility sinks

Air Conditioning Condensate

Precipitation collected at or below grade

Wastewater from clothes washers, bathtubs, showers, and bathroom sinks

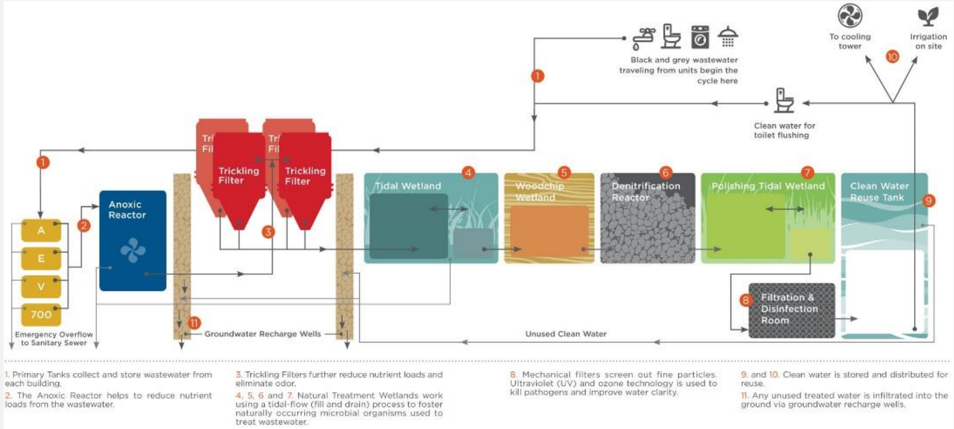
Nuisance groundwater from dewatering operations

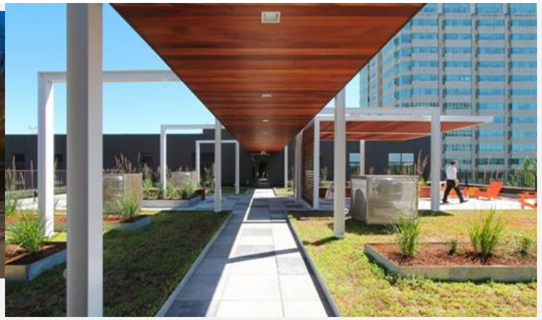
Increasing Building Scale Reuse Across US

The Solaire, Battery Park, NYC

25,000 gpd of wastewater
Membrane Bioreactor
Toilet Flushing, cooling, irrigation

Hassalow on Eighth Portland





60,000 gpd wastewater
Treatment includes landscaping
Toilet Flushing, cooling, irrigation

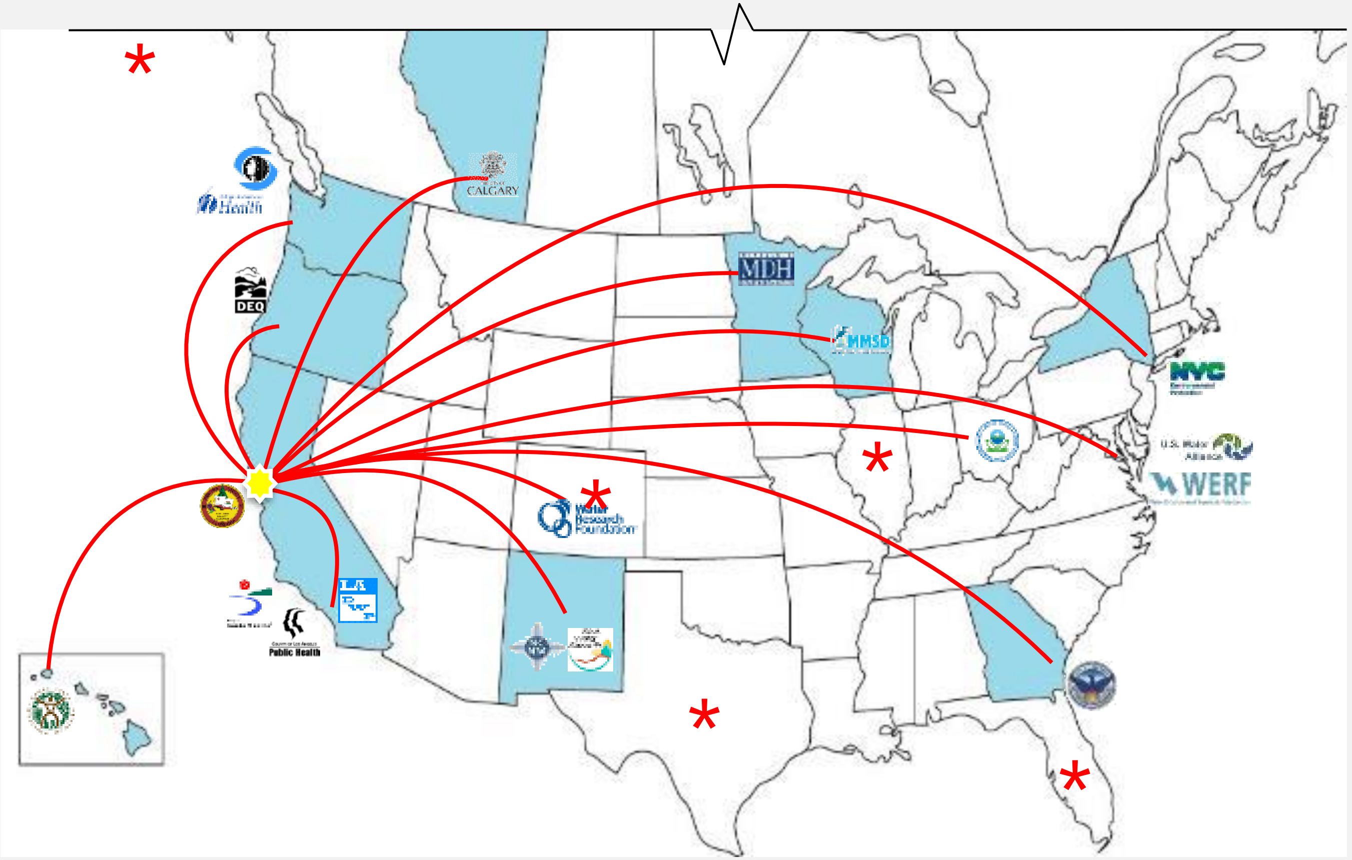
181 Fremont, San Francisco

5,000 gpd greywater
Membrane bioreactor
Toilet flushing

gpd - gallons per day

Problem Formulation

- Stakeholder (utilities & public health agencies) meeting in 2014
- Local management programs are needed
- Water quality parameters and monitoring are needed to protect public health



US Water Alliance

Water Quality:
Graywater Use to Flush Toilets

	BOD_5 (mg L^{-1})	TSS (mg L^{-1})	Turbidity (NTU)	Total Coliform (cfu/ 100ml)	*E. Coli* (cfu/ 100ml)	Disinfection
California	10	10	2	2.2	2.2	0.5 – 2.5 mg/L residual chlorine
New Mexico	30	30	-	-	200	-
Oregon	10	10	-	-	2.2	-
Georgia	-	-	10	500	100	-
Texas	-	-	-	-	20	-
Massachusetts	10	5	2	-	14	-
Wisconsin	200	5	-	-	-	0.1 – 4 mg L^{-1} residual chlorine
Colorado	10	10	2	-	2.2	0.5 – 2.5 mg/L residual chlorine
Typical Graywater	80 - 380	54 -280	28-1340	$10^{7.2}$ – $10^{8.8}$	$10^{5.4}$ – $10^{7.2}$	N/A

National Sanitation Foundation 350 Water Quality for Graywater Use for Toilet Flushing

Parameter	Class R[a]		Class C[b]	
	Test Average	Single Sample Maximum	Test Average	Single Sample Maximum
$CBOD_5$ (mg/l)	10	25	10	25
TSS (mg/l)	10	30	10	30
Turbidity (NTU)	5	10	2	5
E. coli (MPN/100 ml)	14	240	2.2	200
pH (SU)	6.0-9.0		6.0-9.0	
Storage vessel residual chlorine (mg/l)	≥ 0.5 - ≥ 2.5		≥ 0.5 - ≥ 2.5	

[a] Class R: Flows through graywater system are less than 400gpd
[b] Class C: Flows through graywater system are less than 1500gpd

Consistent standards for rigorous performance assessment ,

But, not risk based…….

Should I design my treatment system based on the observed levels of risk indicators in the effluent?

Are there good predictors of risk?

No. Unless you are directly monitoring different microbial risks or at least risks groups.

This analysis best reserved for developing and testing unit processes, not monitoring. Maybe eventual

Risk of what?

Fecal content?

Generally, yes. Indicator bacteria

Fecal source can be important

Is the removal of the risk indicator quantitatively predictive of risk reduction?

No, Bacteria are different then other pathogens of interest….viruses, parasites.

Design system based on the removal of relevant risks

log removals of major groups of microbial risks (viruses, protozoan, bacteria)

Shift to process based design.

Performance of treatment trains of different unit processes (s)

Shifts focus of monitoring from the effluent to the processes

Hazard Analysis and Critical Control Point (HACCP)

Developed by NASA (in collaboration with Pillsbury and US Army Labs) in the 1960’s

Produce safe food for astronauts

Based on an engineering approach (and munition production)

- Identify, evaluate, and control hazards

Transferred to the food industry in the 1970’s

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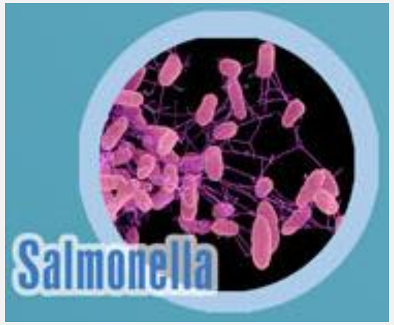
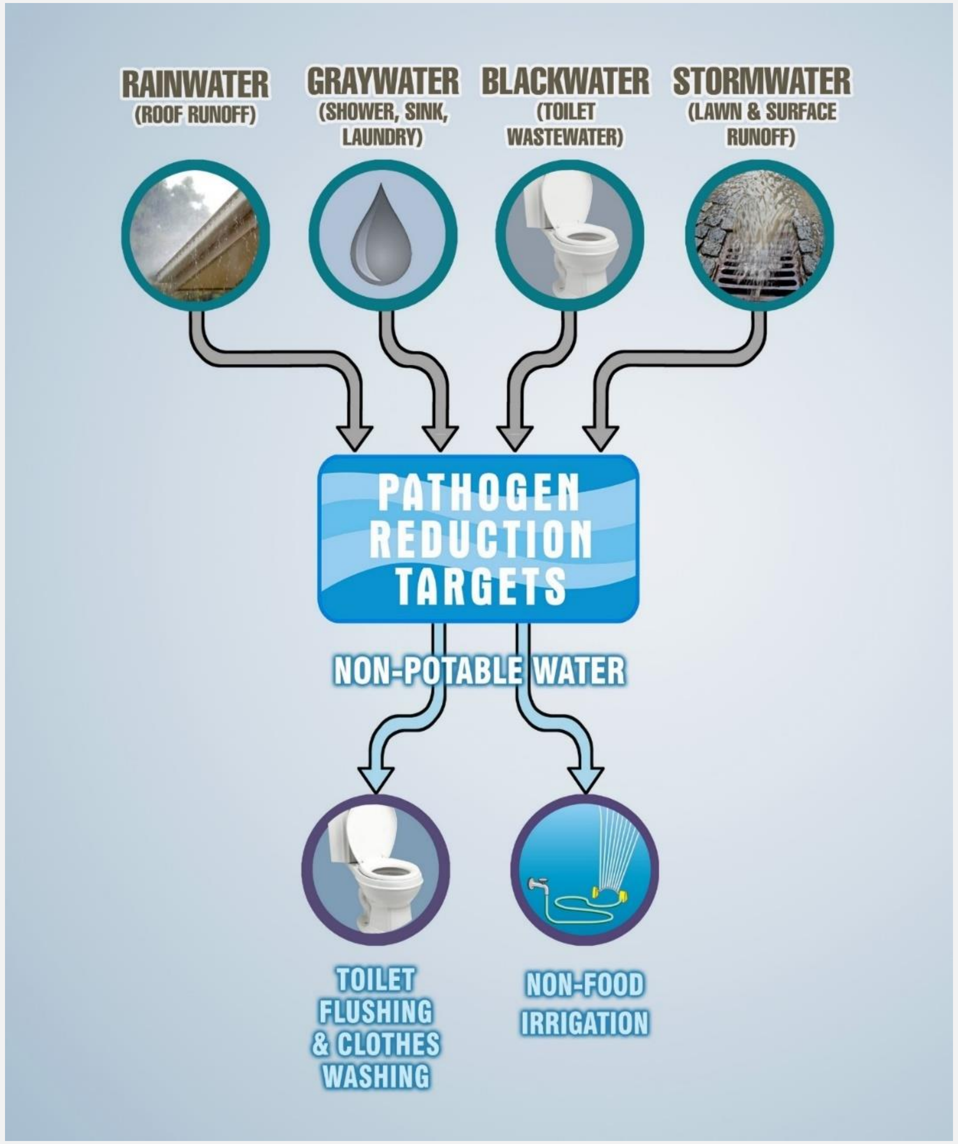
Reference Pathogens



How do you define acceptable treatment?

- Quality of alternative source waters?
- Scaling effects for decentralized systems?
- Fit-for-purpose water?



Quantitative Microbial Risk Assessment

“Source” Waters

(roof runoff, stormwater, graywater, blackwater)

End Use

Non-Potable

Potable

A Structured Framework

Transparent underlying assumptions

Flexible and Adaptable

Epidemiology-Based Approach

Fecal contamination of water

- Fecal indicator concentration in water
- Indicator content of raw feces

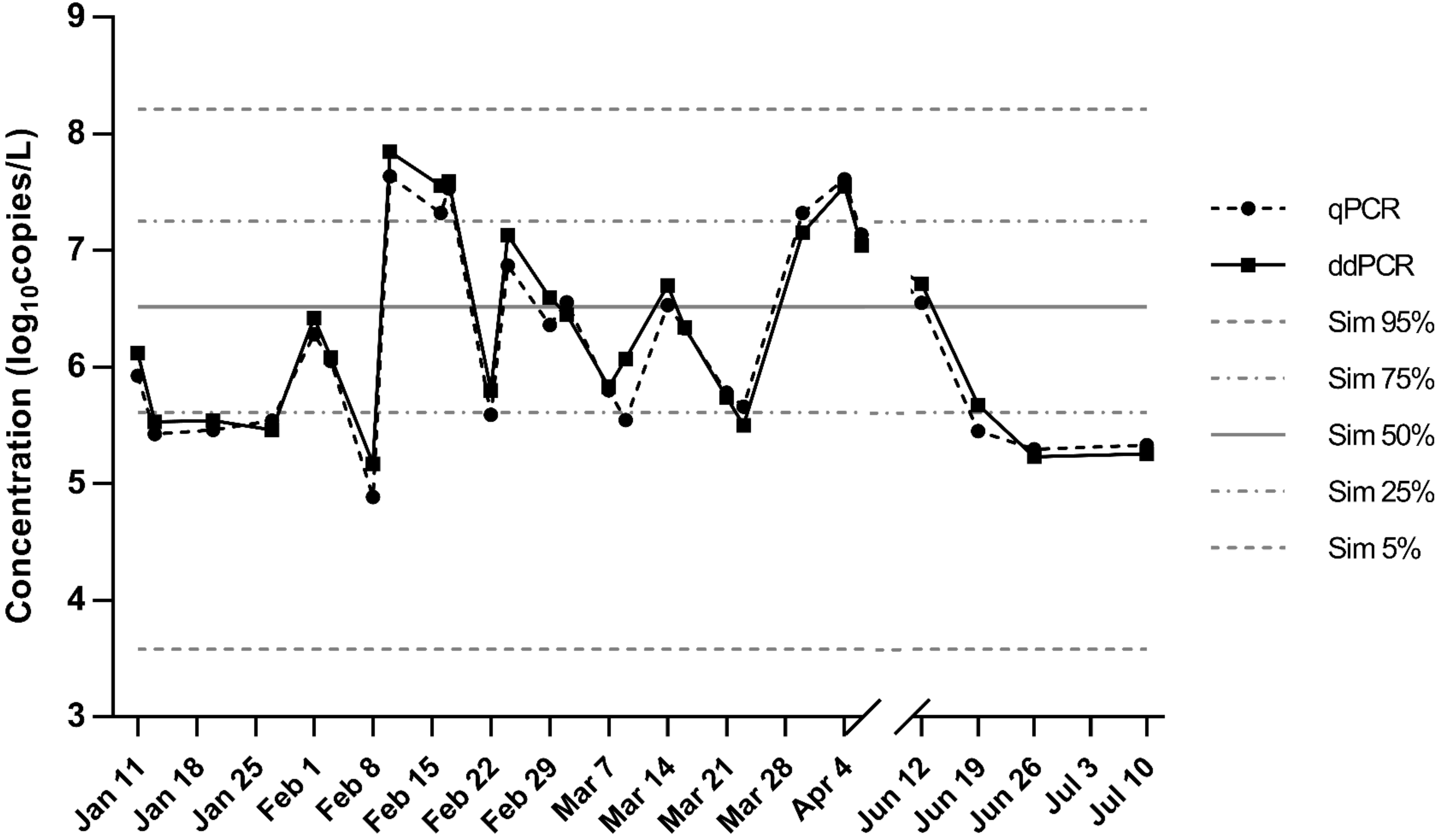
Number of users shedding pathogens

- Population size
- Infection rates
- Pathogen shedding durations

Pathogen concentrations in water

- Pathogen densities in feces during an infection
- Dilution by non-infected individuals

Onsite Wastewater from SFPUC Building Wastewater Modeled and Measured



Ingestion Exposure Volumes

Use	Volume (L)	Days/year	Fraction of pop.
Home			
Toilet flush water	0.00003	365	1
Clothes washing	0.00001	100	1
Accidental ingestion or cross-connection w/ potable	2	1	0.1
Municipal irrigation/dust suppression	0.001	50	1
Drinking	2	365	1

NRMMC, EPHC, AHMC (2006). Australian guidelines for water recycling: managing health and environmental risks (Phase 1).

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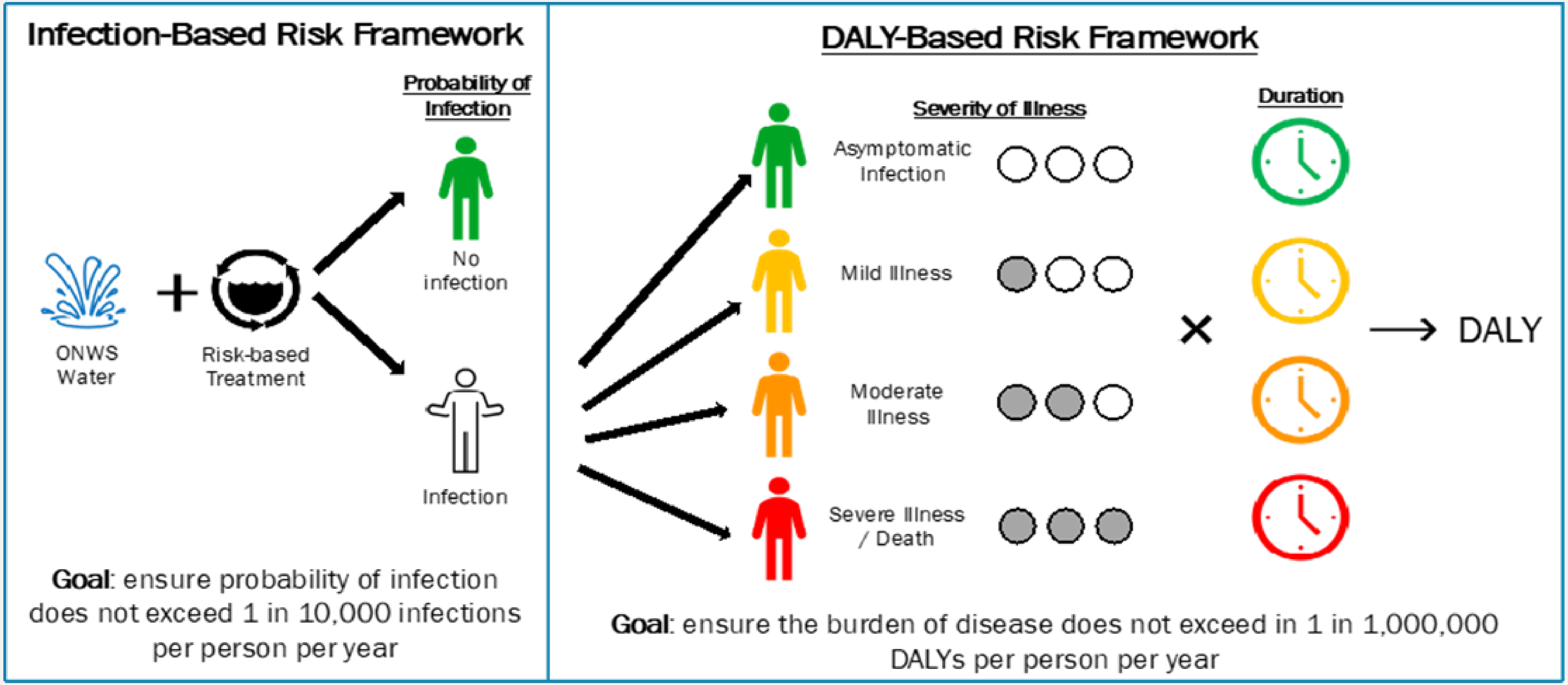
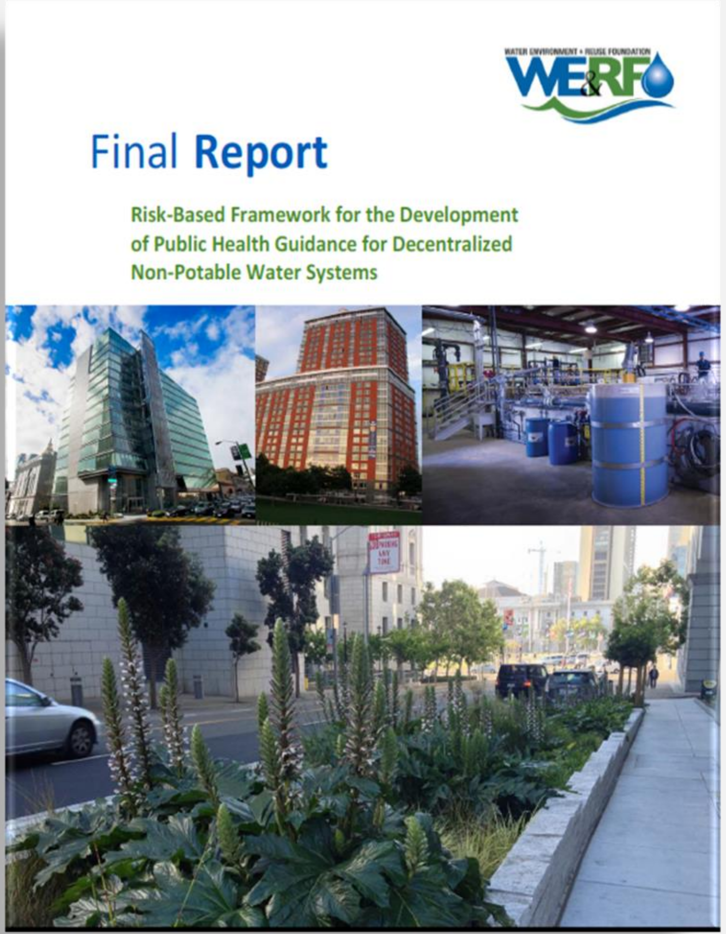
Approach: Developing Risk-based Pathogen Reduction Targets

- "Risk-based" targets attempt to achieve a specific level of protection (aka tolerable risk or level of infection)
  - 10^{-4} infections per person per year (ppy)
  - 10^{-2} infections ppy
  - 10^{-6} disability adjusted life years (DALY) ppy
- Example: World Health Organization (2006) risk-based targets for wastewater reuse for agriculture

What are DALYs?



Gao et al. Science of the Total Environment 511 (2015) 268–287



Water Use Scenario	Log10 Reduction Targets for 10^{-4} (10^{-2}) Per Person Per Year Benchmarks[b,i]		
	Enteric Viruses[c]	Parasitic Protozoa[d]	Enteric Bacteria[e]
Domestic Wastewater or			

Risk-based approach increasingly adopted

Colorado, California, Washington

Austin, San Francisco

Or actively considered

Oregon, Hawaii, Arizona

Potential integration with building codes

ICC, IAPMO, NSF

Sharvelle et al. (2017) Risk-Based Framework for the Development of Public Health Guidance for Decentralized Non-Potable Water Systems
Schoen et al. (2017) Microbial Risk Analysis 5, 32-43

Recent Efforts Resulting in Different LRTs (NBRC)

Source Water	Virus[1]				Protozoa					Bacteria			
	2017	CA	DALY	2022	2017	CA (*Giardia*)	CA (*Crypto*)	DALY	2022	2017	CA	DALY	2022
Onsite Wastewater	8.5	8.0	10.0	11.5	7.0	6.5	5.5	6.5	7.0	6.0	n/a	5.5	7.5
Graywater	6.0	6.0	7.5	9.0	4.5	4.5	3.5	4.0	4.5	3.5	n/a	3.5	5.5
Stormwater (10^{-1} dilution)	5.5	7.0	8.0	9.5	5.5	5.5	4.5	6.0	6.5	5.0	n/a	5.5	6.5
Stormwater (10^{-3} dilution)	3.5	n/a	6.0	7.5	3.5	n/a	n/a	4.0	4.5	3.0	n/a	3.5	4.5
Stormwater (10^{-4} dilution)	n/a	n/a	5.0	6.5	n/a	n/a	n/a	3.0	3.5	n/a	n/a	2.5	3.5
Roof Runoff	n/a	n/a	n/a	n/a	n/a	1.5	n/a	1.0	2.0	3.5	n/a	3.5	5.0

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Comparison of Approaches

	2017 Guidance	2021 Update*
Onsite Sewage/Blackwater	Scale-based simulation/fecal contamination model	Municipal dataset (DPR-2)
Graywater	Scale-based simulation/fecal contamination model	Dilution of municipal sewage (DPR-2)
Stormwater	Dilution of municipal sewage (literature review)	Dilution of municipal sewage (DPR-2)
Roof runoff	Animal contamination model; bacteria only	Measurement dataset (Alja'fari et al.); protozoa only
End uses	Indoor use, irrigation	Indoor use, irrigation, fire suppression, car washing
Reference pathogens	*Norovirus*, *Cryptosporidium*, *Campylobacter*	Adenoviruses, *Giardia*; no bacteria

**Recommendations to CA DDW by NWRI 2021 IAP*

LRT Calculation – What changed?

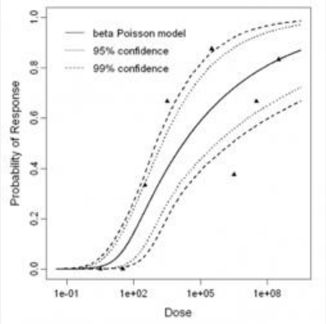
Source Water Pathogen Concentrations

Treatment

Concentration in treated water

Exposure Types & Volumes

Exposure



Dose-response

Risk

Changes

Same

Same exposure assumptions

Same dose-response assumptions

Same risk goal: 10^{-4} annual infection ris

New datasets evaluated

New LRTs developed

New end-uses evaluated

Different reference pathogens selected

LRTs for bacteria not required

Further Updates in LRTs by US EPA ORD

- Updated dose response data for *Norovirus*
  - Maintain *Norovirus* as reference viral pathogen

- Maintained modeling based estimate of pathogens in locally collected waters
  - Distinctive nature of onsite vs municipal water

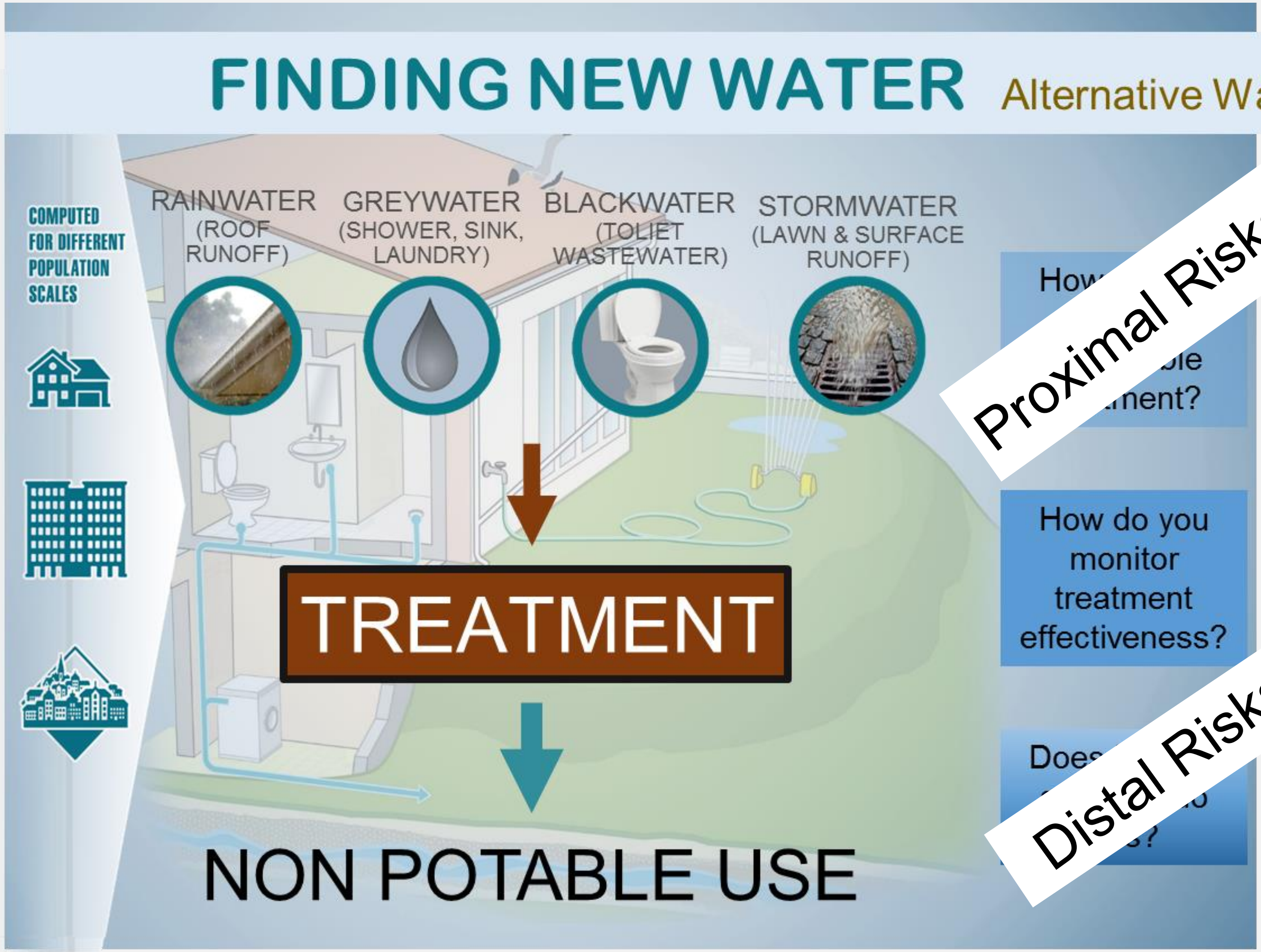
- Updated new concentration data based on new studies (as with CA approach)

- Developed LRTS for different health benchmarks
  - Infection
  - DALYS

Single Family Home Considerations (Risk)

- Fewer people, disease occurrence less frequent
- Other exposure pathways for enteric pathogens in the household much greater than current health benchmarks for reuse
- Some proposed household recycling approaches (e.g., recirculating showers) raise new considerations
  - Only exposed to your own shower water
  - But new exposure pathways (inhalation, dermal)
  - How do rapidly recirculating systems maintain water quality to minimize risks from growth of opportunistic pathogens n the plumbing?

FINDING NEW WATER Alternative Water Reuse



Proximal Risks

Distal Risks

Partners

San Francisco Water Power Sewer
Services of the San Francisco Public Utilities Commission

National Blue Ribbon Commission for Onsite Non-potable Water Systems

Water Environment & Reuse Foundation (WE&RF)

US Water Alliance

Report

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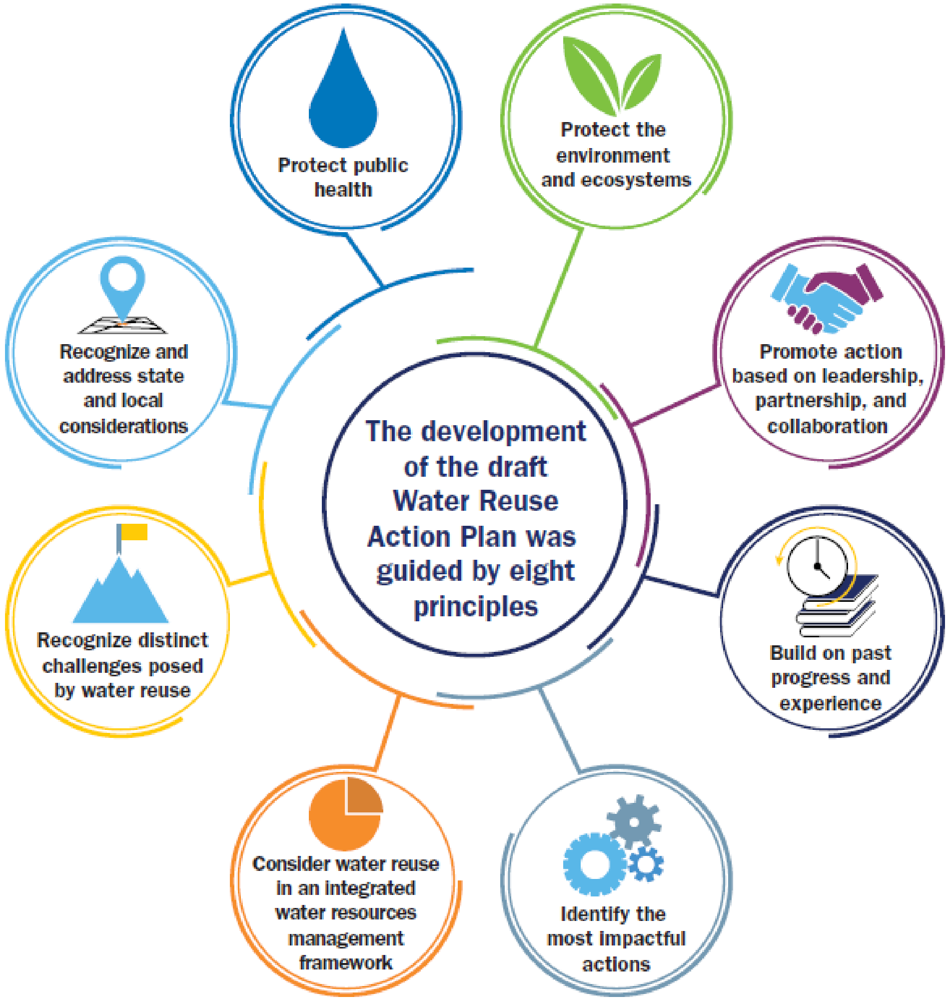
Guiding Principles of the Water Reuse Action Plan

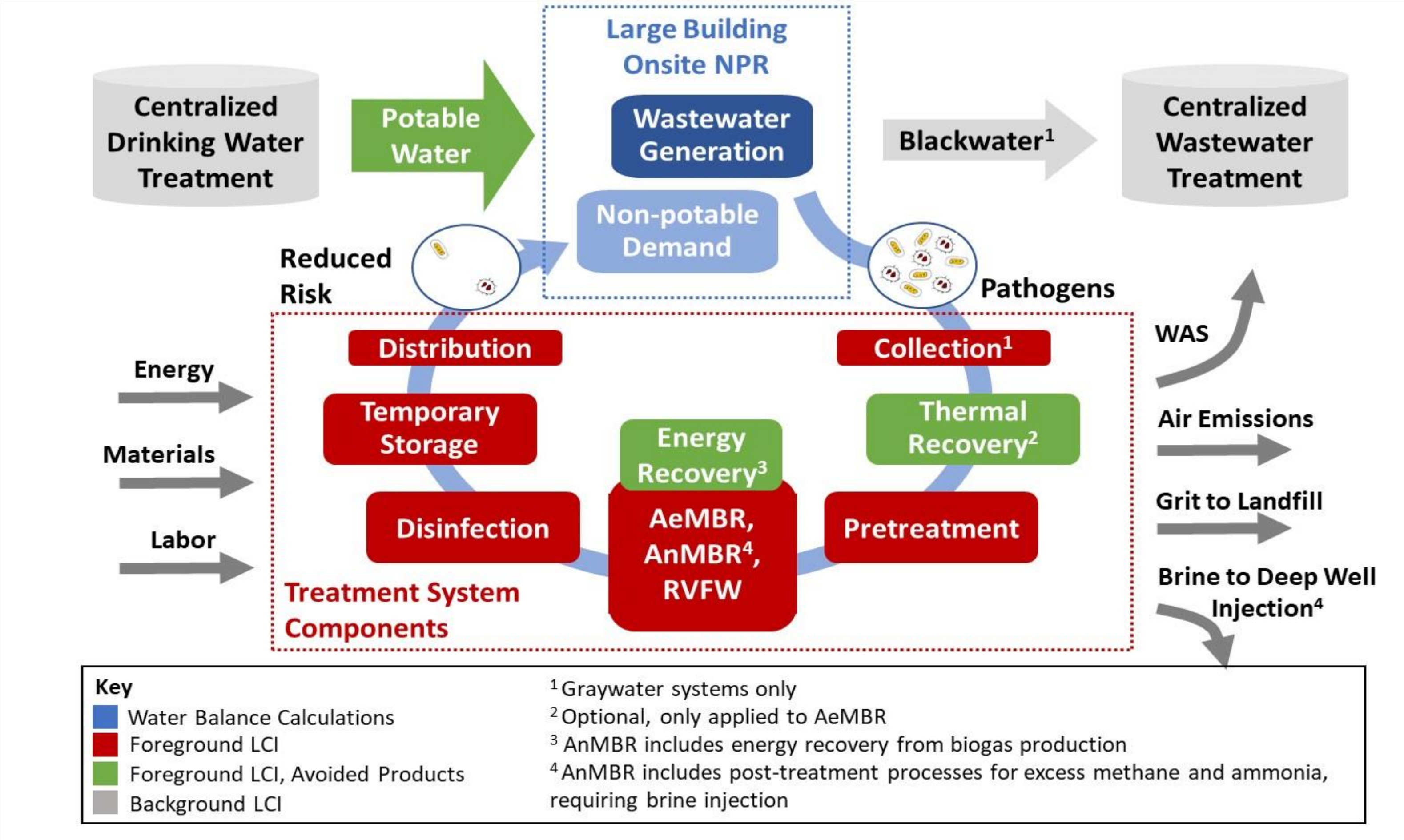


Source: www.epa.gov/sites/production/files/2019-09/documents/water-reuse-action-plan-draft-2019.pdf

Does it make sense to do this?

- Avoid burden-shifting with respect to economic and environmental impacts
- System level assessment of decentralized systems, including impacts on existing centralized infrastructure?

Life Cycle Approach



Analyze cost and environmental impact of systems treating mixed wastewater and source separated graywater for onsite NPR (0.01-0.016 MGD). Integrated results with microbial risk assessment.

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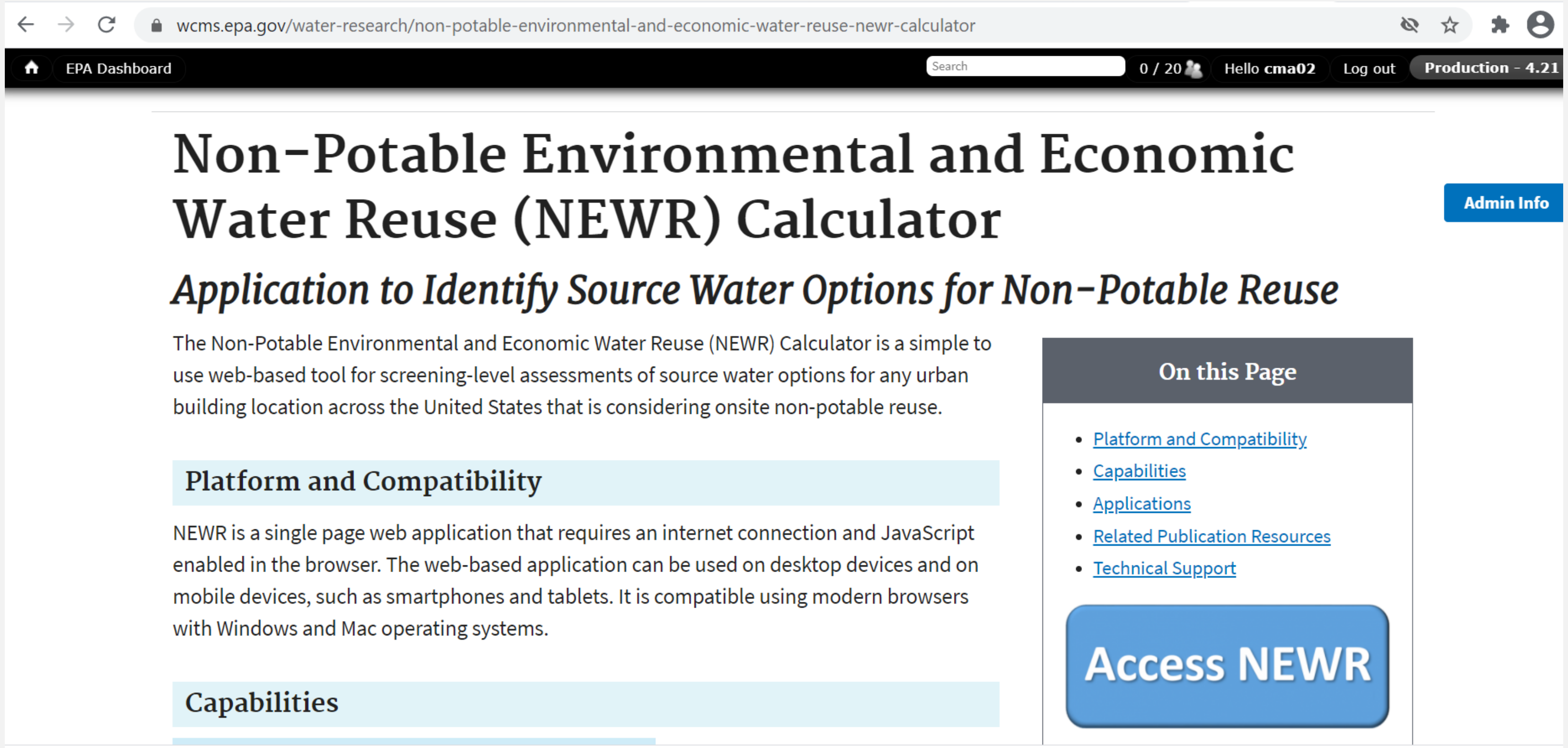
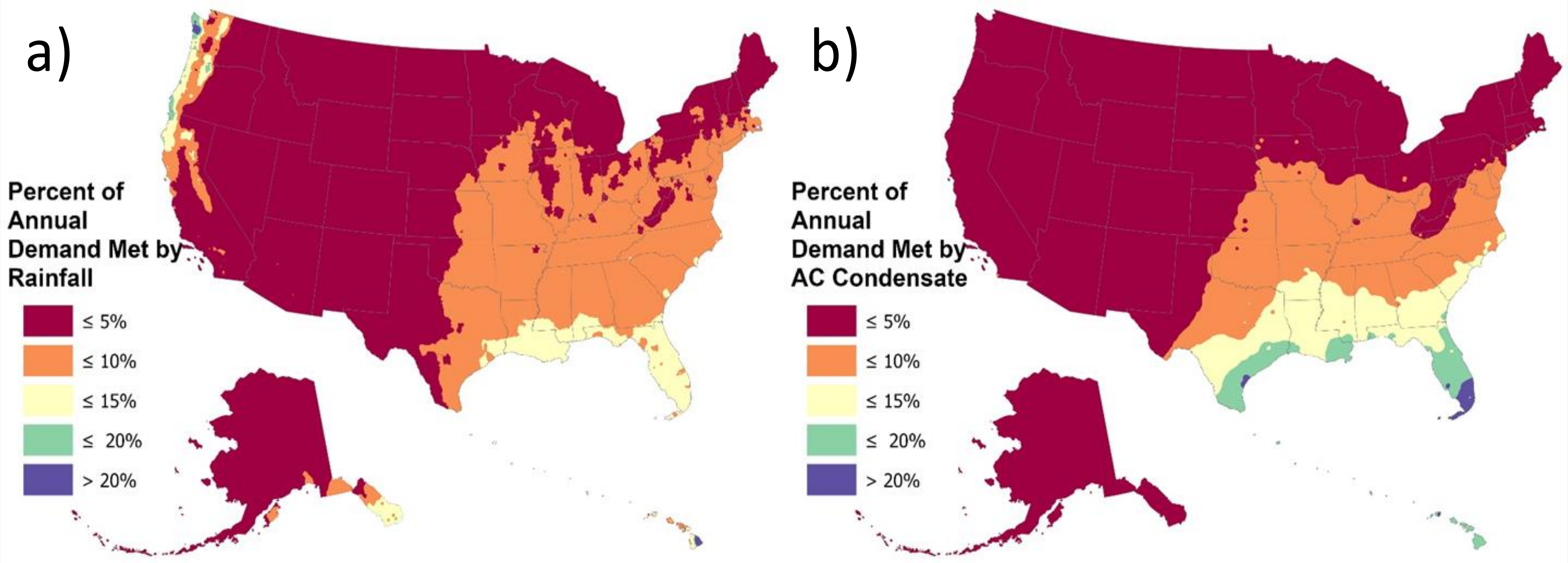
NEWR – Non-potable Environmental and Economic Water Reuse Calculator



Research Questions:

What is the most environmentally and cost-effective source water(s) to meet large building non-potable water needs?

Percent of Annual Non-Potable Demand Met



Mixed WW and GW systems always meet non-potable demand under modeled conditions.

Scenario Generation

Simulation Parameter	Simulation Set 1 – "Large Building"	Simulation Set 2 – "Large Building –AWWA"	Simulation Set 3 – "Random Generator"	Note (Units):
Geographic Coverage				
Geographic Coverage	Entire U.S.	AWWA Cities[a]	Entire U.S.	see Figure S1 for Simulation Set 1, Figure S11 for Simulation Set 3
# of ZIP Codes	40,873	3,382	1,276	
NEWR Inputs				
Building Type	Mixed Use	Mixed Use	Mixed Use	70% residential, 30% commercial
Building Occupants	1,100	1,100	min = 50 max = 1,100	count (persons)
Building Floors	19	19	min = 2 max = 20	count (floors)
Building Footprint/Occ.	18.2	18.2	min = 10 max = 20	Used to constrain area/occupant ratio (ft^2/person)
Building Footprint	20,000	20,000	min = 500 max = 22,000	Calculated as building occupants x area/occupant (ft^2)
Irrigated Area	0	0	min = 0% max = 100%	High water use area as a percentage of total building footprint (ft^2)

a – each of the 234 cities included within AWWA's 2019 rate survey (AWWA, 2019)
b – for Simulation Set 3, water balance results represent simulated ranges, not maximum ranges based on NEWR inputs
c – SWA = Source Water Availability

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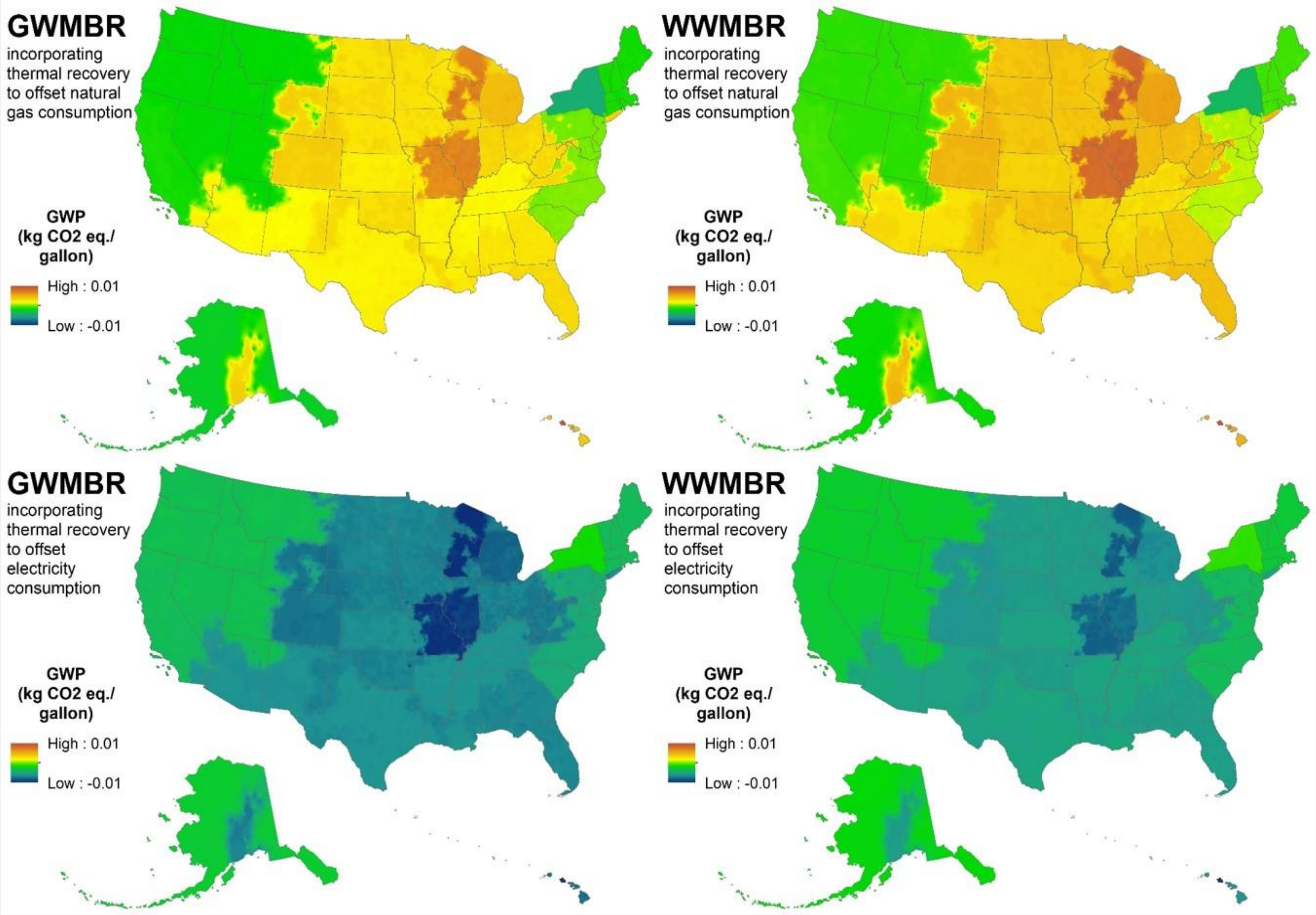
Fixed Building Global Warming Potential Across Source Waters

(With thermal recovery offsetting NG (top) and electricity (bottom))



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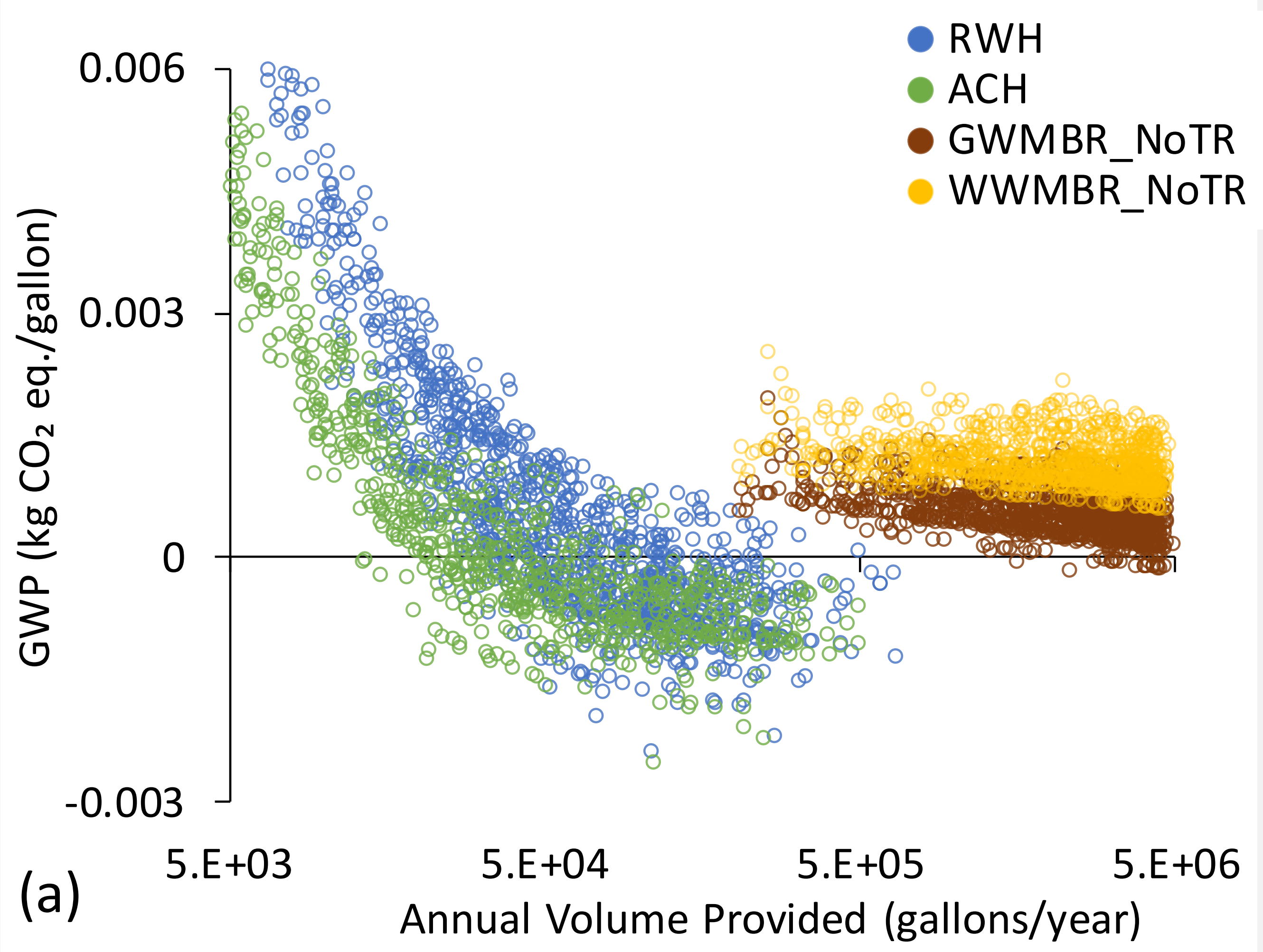
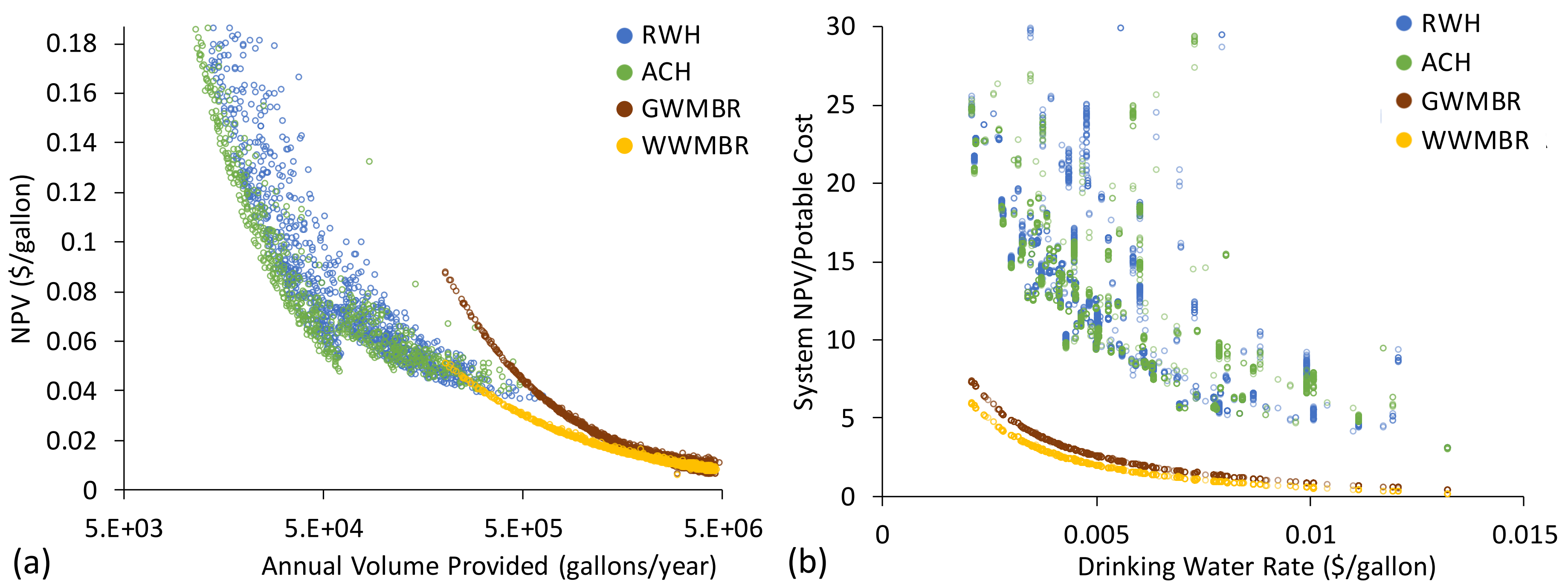
Global Warming Potential Across Source Waters, Variable Location and Building Characteristics



- 50-1,100 occupants
- 10-20 ft^2/occupant (500-22,000 ft^2)
- 2-20 floors

Net Present Value Across Source Waters, Variable Location and Building Characteristics



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Summary of Geospatial Analysis

- In most areas of the country, rainwater and AC condensate provide less than 10% of non-potable needs for large buildings
  - Where available, these water sources can provide an environmentally beneficial, but costly, option for reuse
- Wastewater and graywater provide 100% of the demand
  - Energy demands for treatment lead to environmental impacts, especially in areas with carbon intensive energy grids
  - Can be a cost effective source, especially where drinking water costs are high
- Planning and design of non-potable systems needs to be regionally specific and the NEWR tool provides local developers a quantitative, screening level assessment of the relative costs/benefits

Life Cycle Costs and Impacts of Household Systems

- Previous work on decentralized systems indicate life cycle costs and impacts are inversely dependent on building size
  - Smallest systems evaluated to date (500 people, ~100,000 gallons/year) produced water with a NPV of .08$ /gallon and net increases in GWP compared to centralized supply
  - Household system could be at least an order of magnitude greater in cost and GWP

- This analysis is for the urban environment where access to centralized water and wastewater is available.
  - Different potential solutions/calculations for rural settings

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Research Gaps

- **Risk Assessment**
  - Improve data on contaminant levels in alternative source waters to improve risk models
  - Define unit process based removal rates to optimize system design
    - Methods/surrogates to reflect infective virus removal
    - Grouping based approaches to chemicals (analogous to microorganisms)
  - Assess fit for purpose health risk benchmarks
    - E.g., household based, occupational exposures
    - Broader (and more distal) impacts of alternative water systems
- **Systems Analysis**
  - Expand screening level cost and impact assessment tools to help inform decision making
  - Leverage data from early adopters of alternative water systems to improve fidelity of life cycle models and refine system designs
  - Translate life cycle impacts to health impacts for linkage to risk assessment (e.g., DALYs, dollars)

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Final Thoughts/Future Directions

- Provide clear regulatory guidance to limit bottlenecks for implementing new approaches, using a risk framework which:
  - Can be flexibly and correctly applied to various fit for purpose options
- Develop life cycle costs and impacts of different options to inform decision making
  - Continue to evaluate new treatment options, including expansion to district scale approaches, and increased recovery options
- Safe and effective implementation of multiple solutions

ORD Bibliography on ONWS Risk

MA Jahne, ME Schoen, JL Garland, and NJ Ashbolt. 2017. Simulation of enteric pathogen concentrations in locally collected greywater and wastewater for microbial risk assessments. Microbial Risk Analysis 5, 44-52

ME Schoen and J Garland. 2017. Review of pathogen treatment reductions for onsite non-potable reuse of alternative source waters Microbial Risk Analysis 5, 25-31

ME Schoen, NJ Ashbolt, MA Jahne, and JL Garland. 2017. Risk-Based Enteric Pathogen Reduction Targets for Non-Potable and Direct Potable Use of Roof Runoff, Stormwater, and Greywater. Microbial Risk Analysis 5, 32-43 ME Schoen, MA Jahne, JL Garland. 2018. Human health impact of cross-connections in non-potable reuse systems. Water 10(10), 1352

ME Schoen, MA Jahne, and J Garland, 2018. Human health impact of non-potable reuse of distributed wastewater and greywater treated by membrane bioreactors. Microbial Risk Analysis 9, 72-8

ME Schoen, MA Jahne, and J Garland. 2020. A risk-based evaluation of onsite, non-potable reuse systems developed in compliance with conventional water quality measures. Journal of Water and Health 18 (13) 331-344

MA Jahne, NE Brinkman, SP Keely, BD Zimmerman, EA Wheaton, and JL Garland. 2020. Droplet digital PCR quantification of norovirus and adenovirus in decentralized wastewater and greywater collections: implications for water reuse. Water Research 169:113-213

ME Schoen, M A Jahne, and JL Garland. 2020. Enteric pathogen treatment requirements for non-potable water reuse when exposure data is limited. Environmental Science & Technology Letters 7(12) 943-947

ME Schoen, MA Jahne, JL Garland, L Ramirez, AJ Lopkin, and KA Hamilton. 2021. Quantitative microbial risk assessment of antimicrobial resistant and susceptible *Staphylococcus aureus* in reclaimed waters. Environmental Science & Technology 55(22) 15255

Ala'fari, S, Sharvelle, NE Brinkman, M Jahne, S Keely, EA Wheaton, J. Garland, C, Welty, MC Sokup, and T. Meixner. 2022. Characterization of roof runoff microbial quality in 4 US cities with varying climate and land use characteristics. Water Research 225:119-123

M Jahne, M, Schoen, A Kaufman, B. Pecson, A, Oliveri, S. Sharvelle, A. Anderson, N. Ashbolt, and J. Garland. 2023. Enteric pathogen reduction targets for onsite non-potable water systems: A critical evaluation. Water Research 233: 119742

ME Schoen, J Garland, JA, Soller, SX Thimons, and MA Jahne. 2023. Onsite Nonpotable Water Systems Pathogen Treatment Targets: A Comparison of Infection and Disability-Adjusted Life Years (DALYs) Risk Benchmark Approaches. Environmental Science & Technology 57(26):9559–9566

United States Environmental Protection Agency

ONWS LCA/LCC Literature

Arden, S., Morelli, B., Cashman, S., Ma, C., Jahne, M. and Garland, J. (2021) Onsite Non-potable Reuse for Large Buildings: Environmental and Economic Suitability as a Function of Building Characteristics and Location. Water Research 191 116635. doi:10.1016/j.watres.2020.116635.

Arden, S., Morelli, B., Schoen, M., Cashman, S., Jahne, M., Ma, C., Garland, J. (2020). Human health, economic and environmental assessment of onsite non-potable water reuse systems for a large, mixed-use urban building. Sustainability. 12, 5459. doi:10.3390/su12135459.

Morelli, B. and Cashman, S. (2019). Life cycle assessment and cost analysis of distributed mixed wastewater and graywater treatment for water recycling in the context of an urban case study. EPA/600/R-18/280

Ghimire, S. R., Johnston, J. M., Garland, J., Edelen, A., Ma, X. C., & Jahne, M. (2019). Life cycle assessment of a rainwater harvesting system compared with an AC condensate harvesting system. *Resources, Conservation and Recycling*, 146, 536-548.

Morelli, B., Cashman, S., Ma, X(C)., Garland, J., Bless, D., Jahne, M. September 2019. Life Cycle Assessment and Cost Analysis of Mixed Wastewater and Graywater Distributed Treatment for Non-Potable Reuse in San Francisco. WEFTEC conference proceeding paper. Chicago, IL.

Cashman, S., Ma, X(C)., Mosley, J., Garland, Crone, B., Xue, X. 2018. Energy and greenhouse gas life cycle assessment and cost analysis of aerobic and anaerobic membrane bioreactor systems: Influence of scale, population density, climate, and methane recovery. *Bioresource Technology*, 254, 56–66.

Cashman, S., Mosley, J., Ma, X(C)., Garland, J., Cashdollar, J., Bless, D. 2016. Life Cycle Assessment and Cost Analysis of Water and Wastewater Treatment Options for Sustainability: Influence of Scale on Membrane Bioreactor Systems. EPA report: EPA/600/R-16/243.