Finding New Water: Development of On-Site Non-Potable Water Reuse Systems

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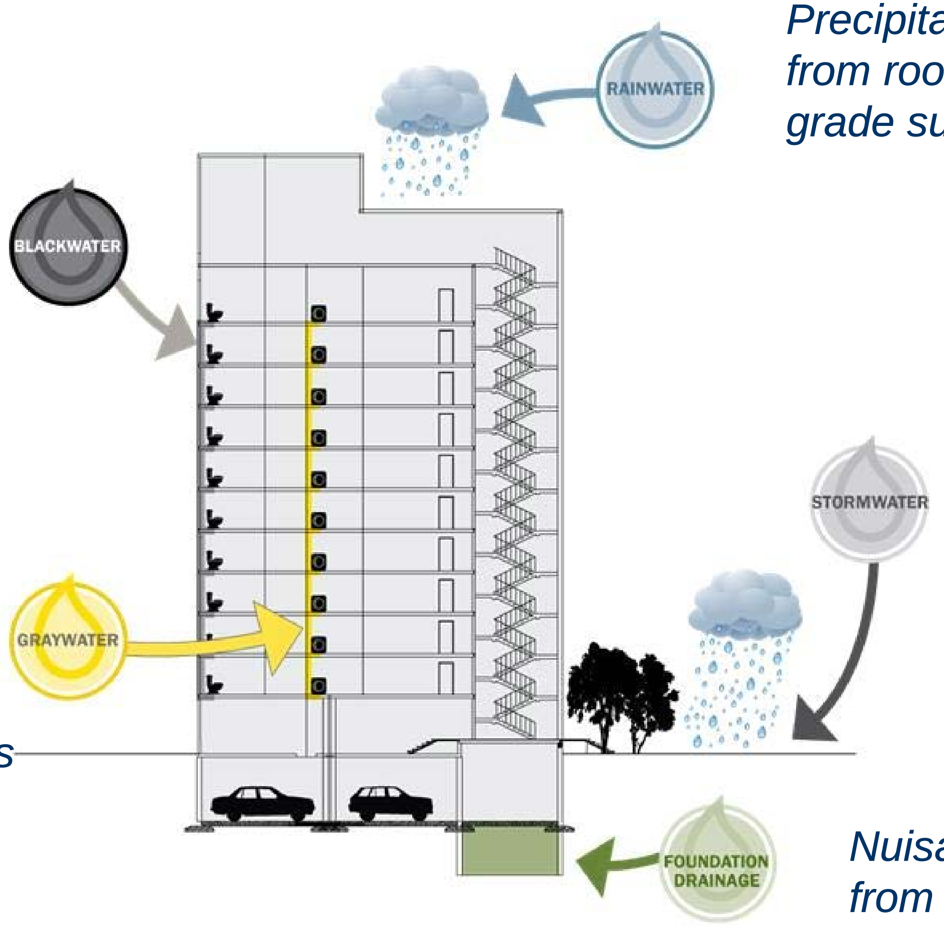
Buildings Produce Water

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

Precipitation collected from roofs and above-grade surfaces



Precipitation collected at or below grade

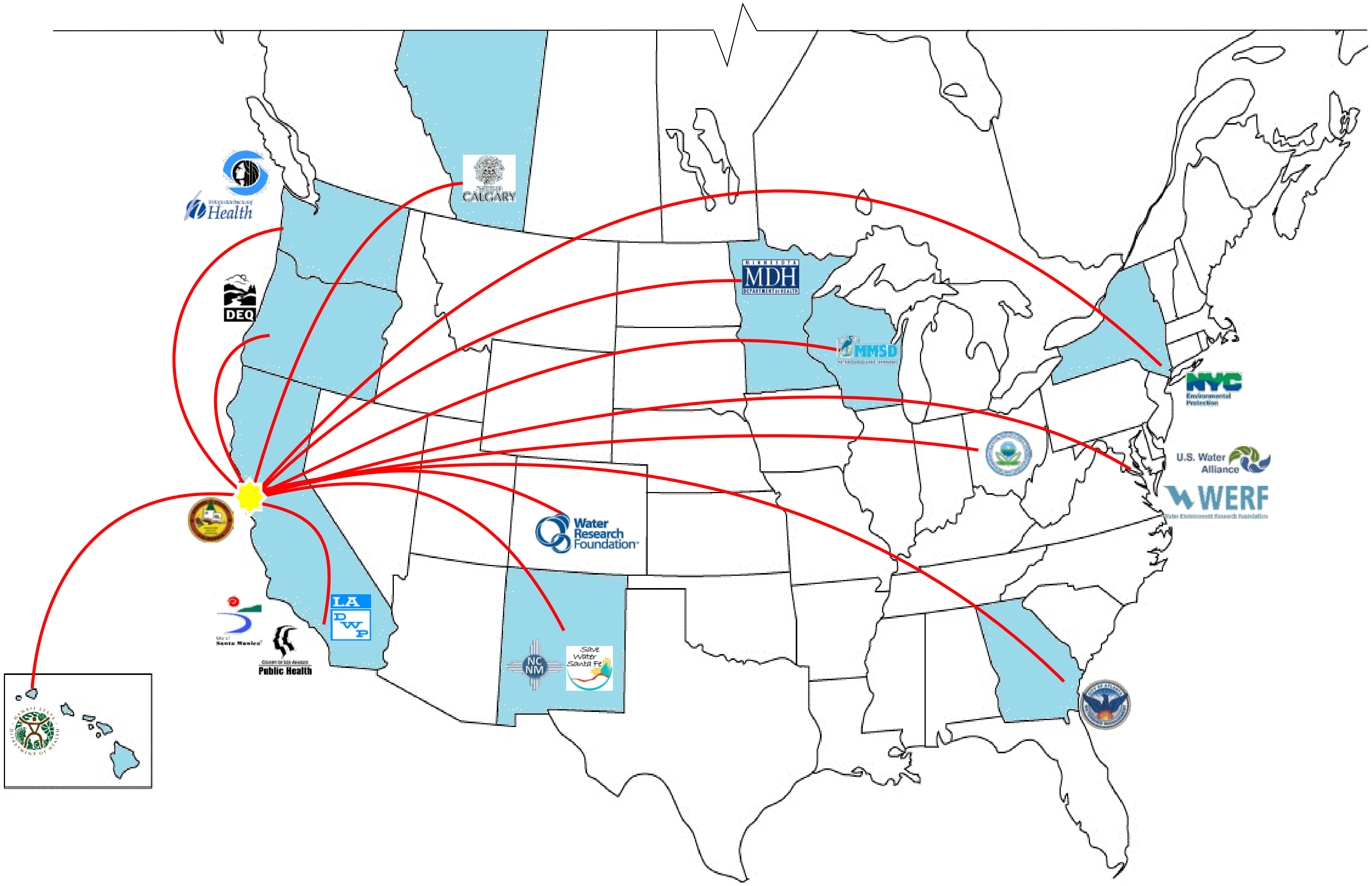
Wastewater from clothes washers, bathtubs, showers, and bathroom sinks

Nuisance groundwater from dewatering operations

Innovation in Urban Water Systems

San Francisco • May 2014

Nationwide Representation



Why are Cities Interested?

- Augmenting existing water supply portfolios and increasing capacity in small increments to meet system demands;
- Reducing potable water consumption for non-potable uses;
- Treating water only as needed for its end use application (fit-for purpose);
- Reusing water close to the source, avoiding construction of recycled water pipelines;
- Minimizing stormwater flows and maintaining capacity in our sewer systems;
- Reducing pollution and loading to sewers and water bodies;
- Increasing resiliency and adaptability of our water and wastewater infrastructure;
- Addressing flooding caused by stormwater flows;
- Deferring capital costs of large-scale infrastructure, including treatment plant expansions;
- Generating environmental amenities in urban corridors; and
- Meeting and exceeding green building and net-zero development goals.

Key Outcomes from Meeting

- Local management programs are needed

- Water quality parameters and monitoring are needed to protect public health

Innovation in Urban
Water Systems
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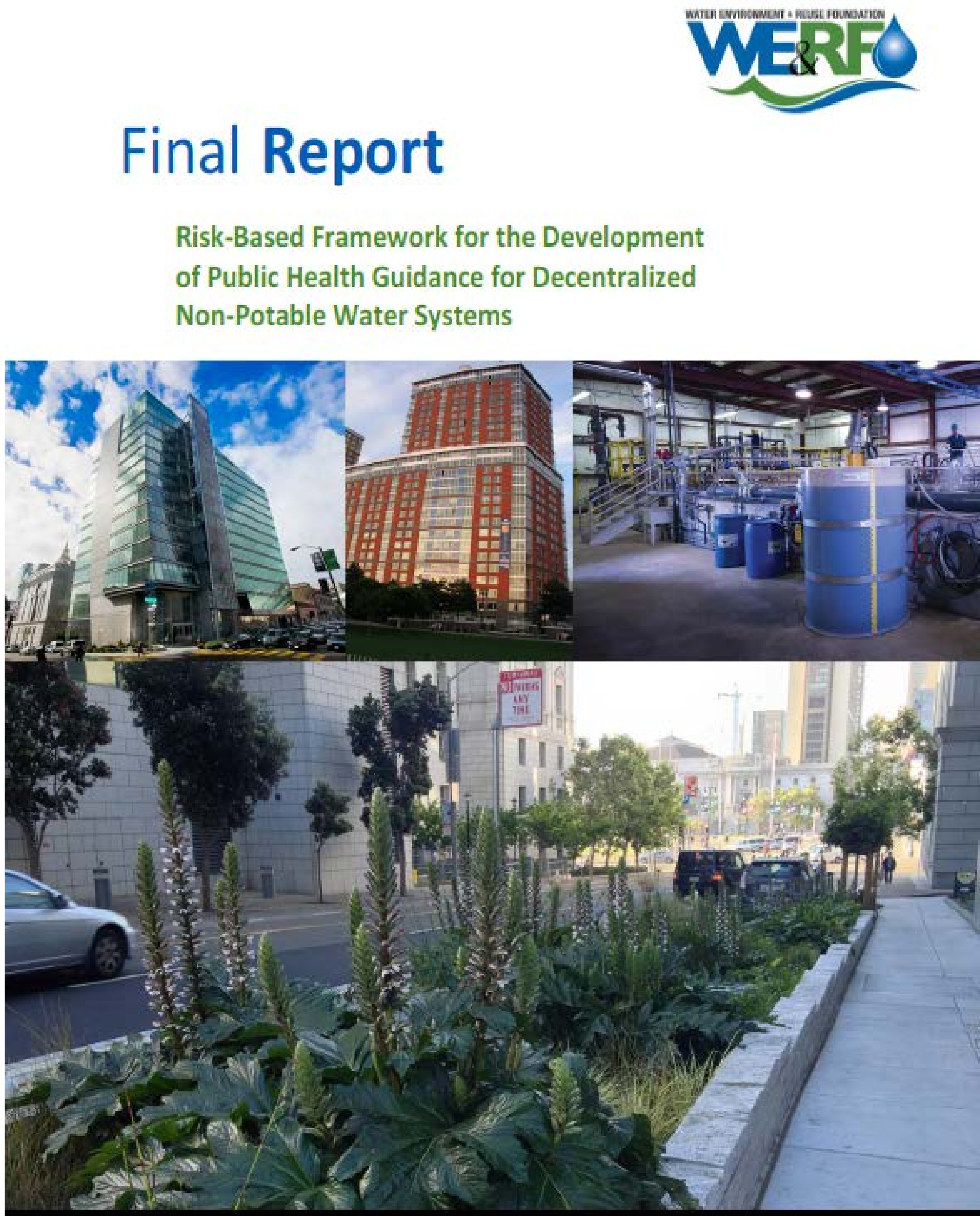
Subsequent Expert Panel
(w/ Stakeholder Advisory Committee)

Nationwide Utilities and Public Health Agencies

San Francisco, LA County, Miami-Dade, Minnesota, DC, California, Washington, Oregon, Denver, Arizona, Colorado, Seattle, New York City, Chicago, Hawaii, Los Angeles, Santa Monica, Austin, Honolulu, Portland,



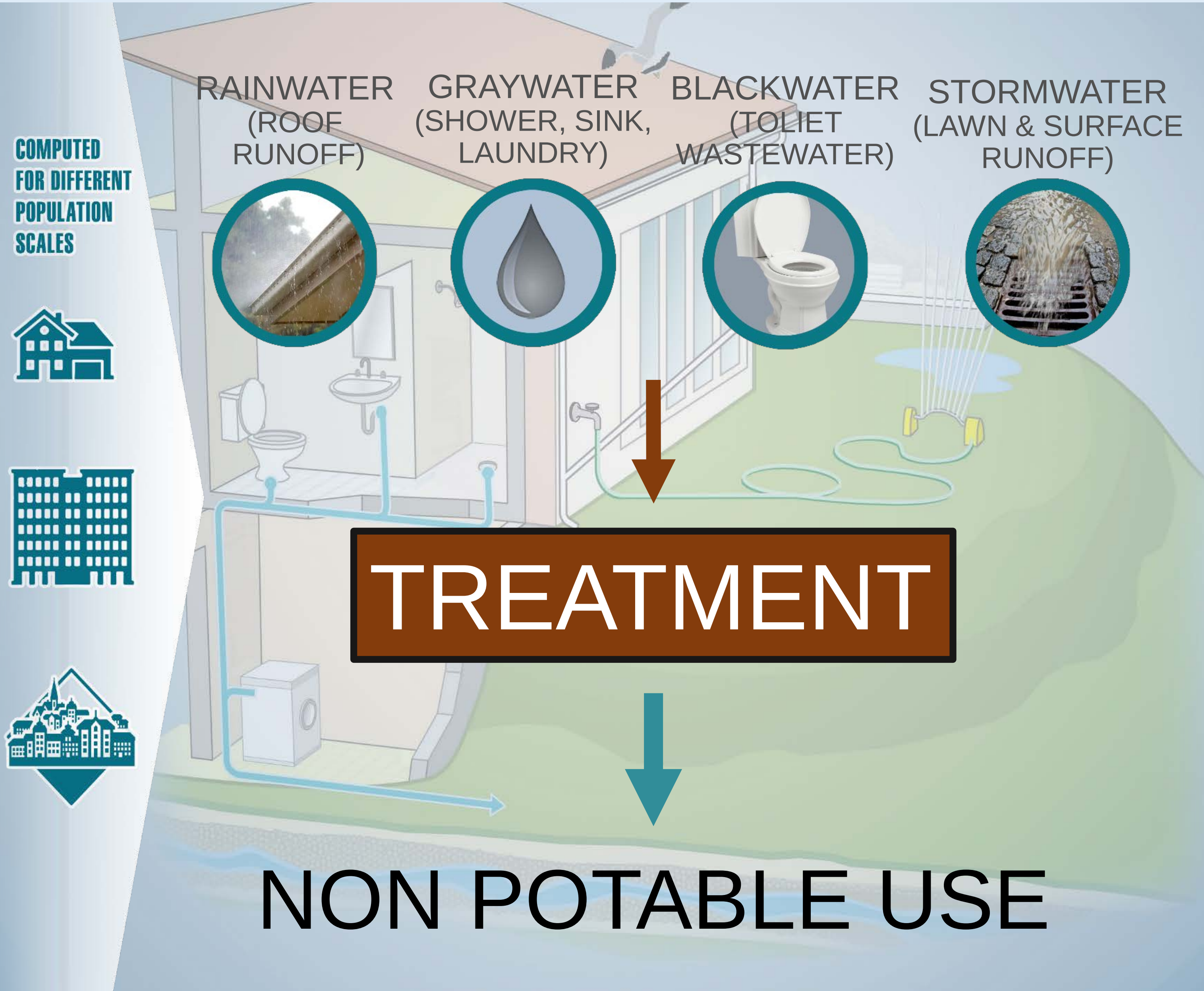
National Blue Ribbon Commission
for Onsite Non-potable Water Systems

- Goals:
  - Serve as a forum for collaboration/knowledge exchange
  - Identify new business models for water utilities
  - Craft model state guidance and policy frameworks
  - Identify additional research needs

A Guidebook for Developing and Implementing Regulations for Onsite Non-Potable Water Systems

Anticipated Released December 2018

FINDING NEW WATER Alternative Water Reuse



Does it make sense to do this?

How do you define acceptable treatment?

How do you monitor treatment effectiveness?

Partners

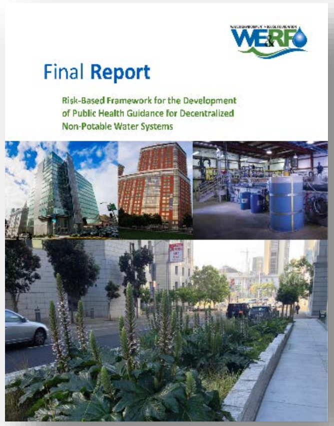
San Francisco Water Power Sewer
Services of the San Francisco Public Utilities Commission

National Blue Ribbon Commission for Onsite Non-potable Water Systems

WATER ENVIRONMENT & REUSE FOUNDATION WE&RF

US Water Alliance

Report



How do you define acceptable treatment?

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

NSF 350

- Beneficial
  - Rigorous performance standards for systems to meet for certification
  - Courageous effort to set a standards has enabled projects to move forward
- But not risk based
  - How do you directly translate those water quality parameters to your risk of being infected by the specific use of the treated waters?

My Extraterrestrial Background

Hazard Analysis and Critical Control Point (HACCP)

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

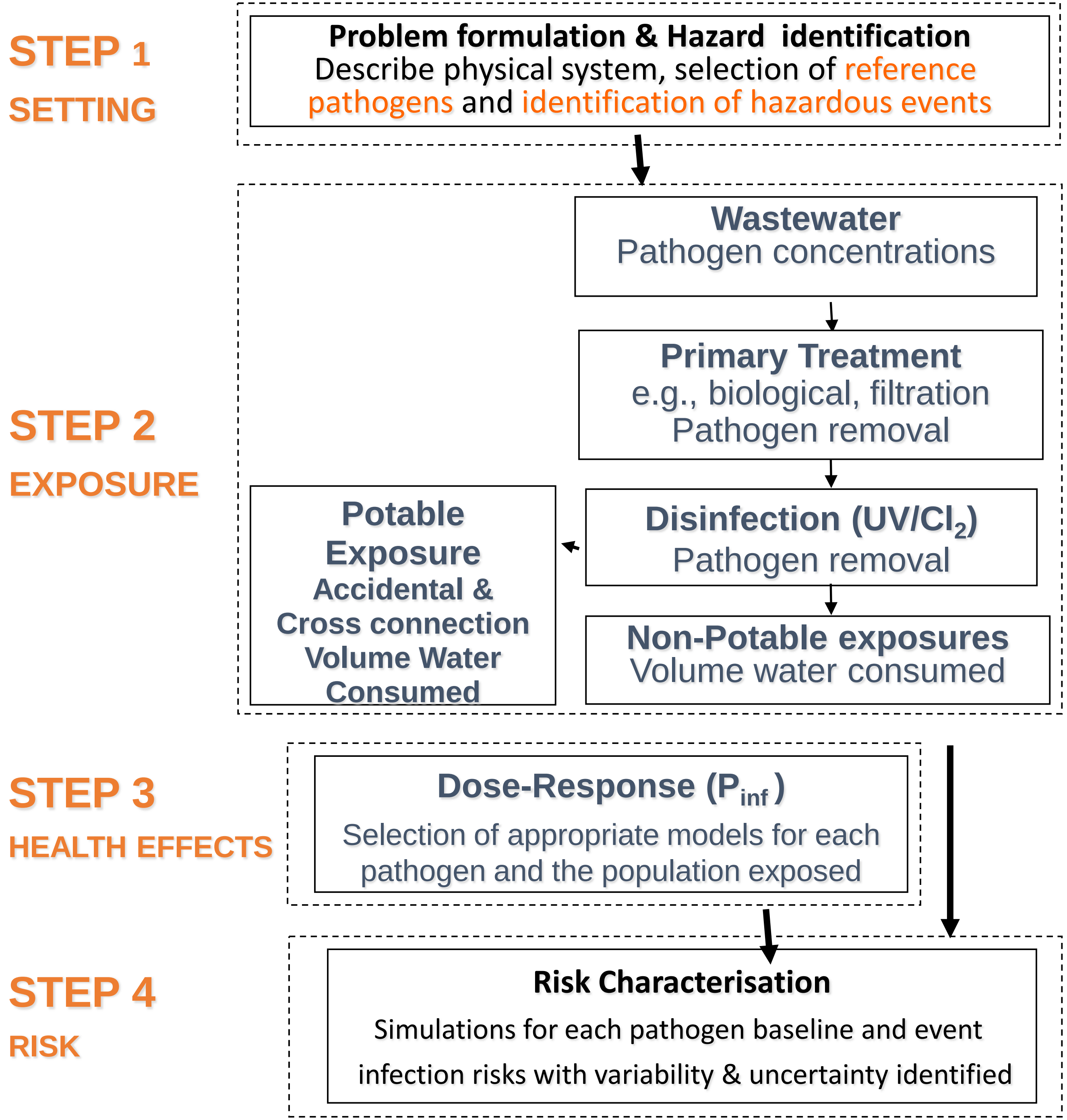
Produce safe food for astronauts

Based on an engineering approach (and munition production)

Identify, evaluate, and control hazards

Transferred to the food industry in the 1970's

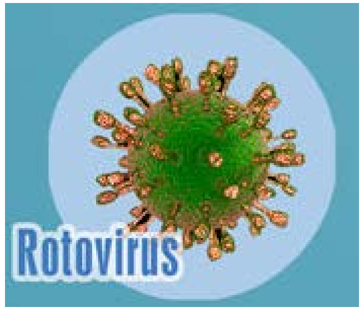
Quantitative microbial risk assessment (QMRA)

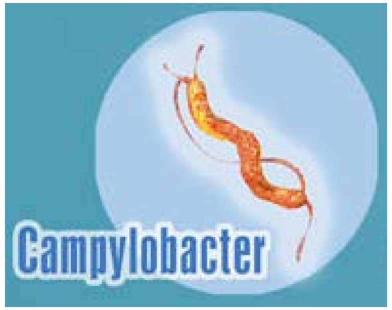


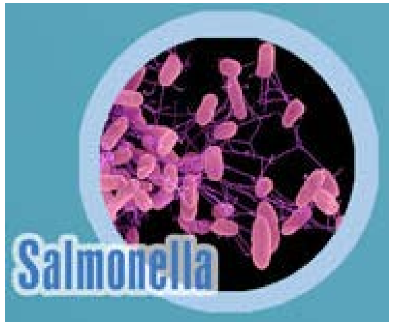
Risk-based Pathogen Reduction Targets

- "risk-based" targets attempt to achieve a specific level of protection (a.k.a. tolerable risk or level of infection)
    - 10^{-4} infections per person per year (ppy)
    - 10^{-2} infections ppy
- Example: WHO (2006) risk-based targets for wastewater reuse for agriculture

Reference Pathogens







Characterize Pathogen Density

Pathogen Observations?

Criteria:

1. N = 15
2. Conventional methods
3. Limit of detection

Yes → Characterize Density

No → Model Density

Estimation of Pathogen Density in Greywater, Blackwater

- **Epidemiology**: Indicators used to model fecal contamination of the water; pathogens in feces simulated using population infection rates and shedding characteristics

  (Barker et al. 2013a, Barker et al. 2013b, Ottoson and Stenstrom 2003, Schoen et al. 2014)

- Scalable by population size
  - Accounts for occurrence of infections and level of dilution effects

Epidemiology-Based Approach

Fecal contamination of water

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

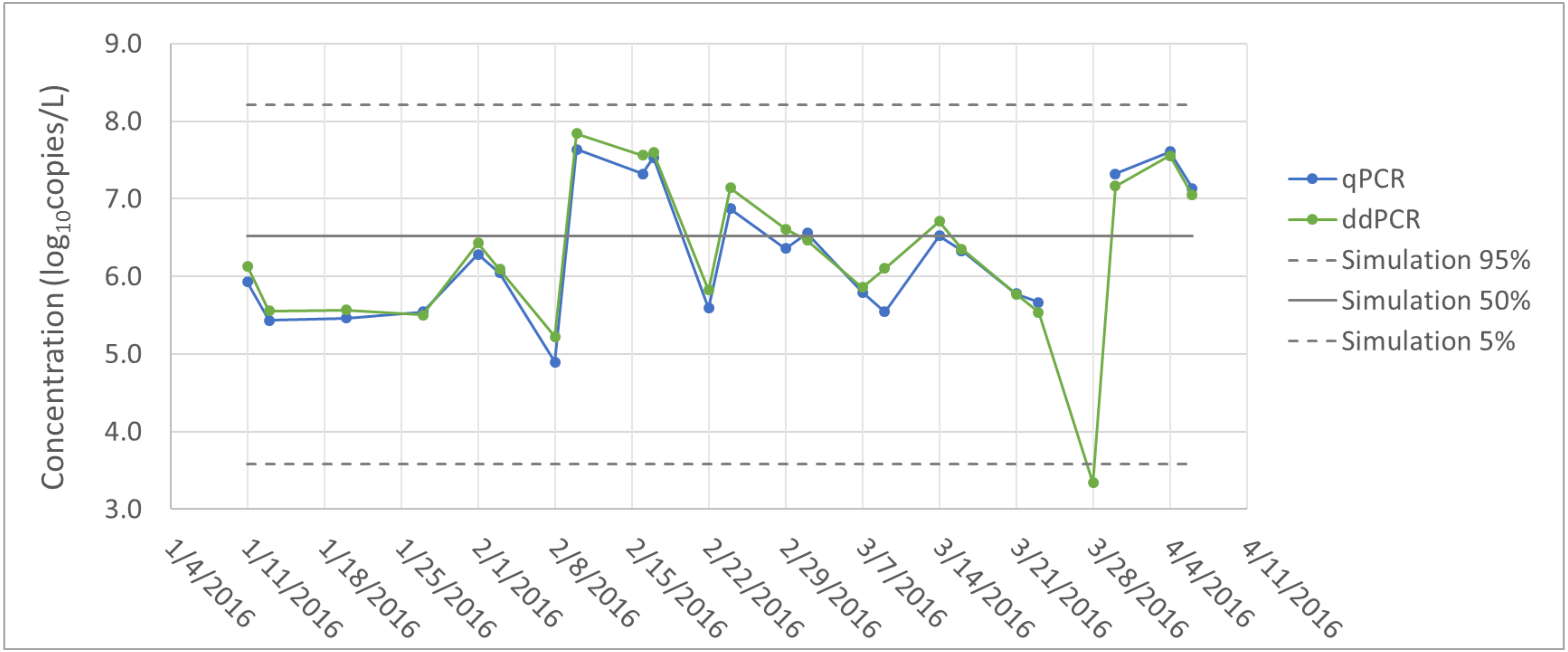
Number of users shedding pathogens

- 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

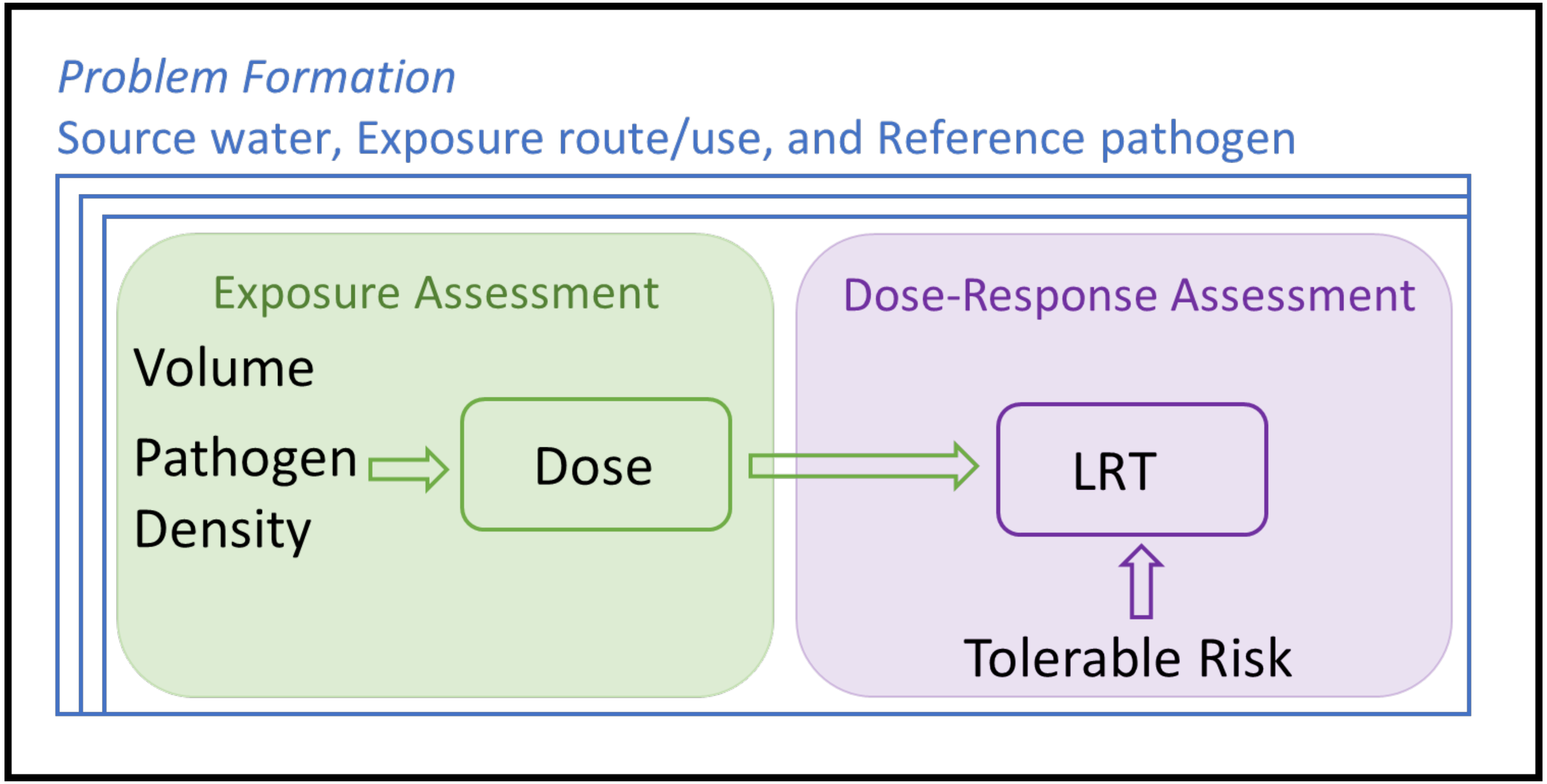


Ingestion Exposure Volumes

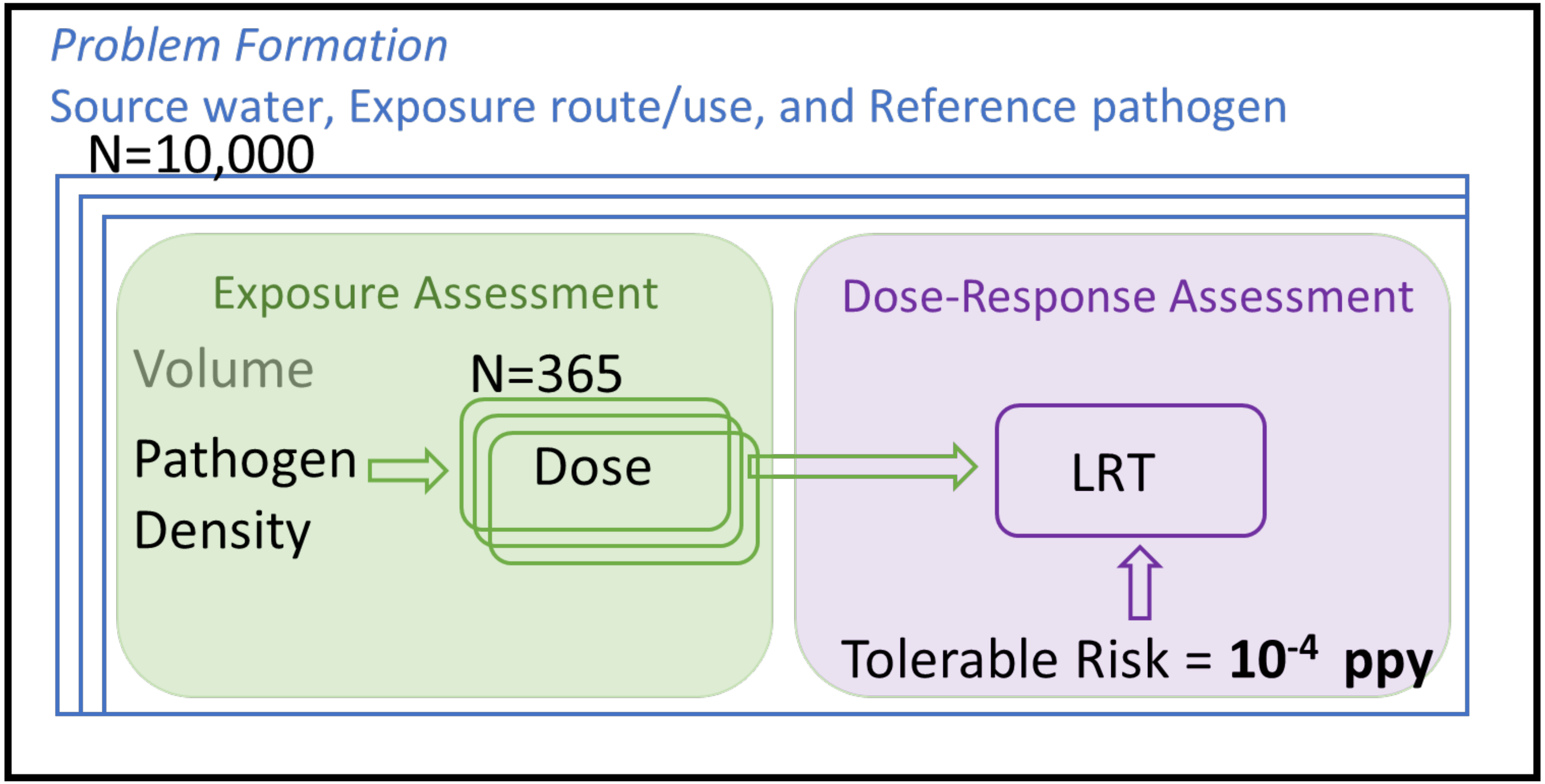
Use	Volume (L)	Days/year	Fraction of pop.
Home			
Toilet flush water	0.00003	365	1
Clothes washing	0.00001	100	1
Accidental ingestion or cross-connection w/ potable	2	1	0.1
Municipal irrigation/dust suppression	0.001	50	1
Drinking	2	365	1

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

QMRA Implementation



QMRA Implementation



Water Use Scenario	$\log_{10}$ 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 Blackwater			
Unrestricted irrigation	8.0 (6.0)	7.0 (5.0)	6.0 (4.0)
Indoor use[f]	8.5 (6.5)	7.0 (5.0)	6.0 (4.0)
Graywater			
Unrestricted irrigation	5.5 (3.5)	4.5 (2.5)	3.5 (1.5)
Indoor use[g]	6.0 (4.0)	4.5 (2.5)	3.5 (1.5)
Stormwater (10^{-1} Dilution)			
Unrestricted irrigation	5.0 (3.0)	4.5 (2.5)	4.0 (2.0)
Indoor use	5.5 (3.5)	5.5 (3.5)	5.0 (3.0)
Stormwater (10^{-3} Dilution)			
Unrestricted irrigation	3.0 (1.0)	2.5 (0.5)	2.0 (0.0)
Indoor use	3.5 (1.5)	3.5 (1.5)	3.0 (1.0)
Roof Runoff Water[h]			
Unrestricted irrigation	Not applicable	No data	3.5 (1.5)
Indoor use	Not applicable	No data	3.5 (1.5)

Sharvelle et al. (2017). Risk-Based Framework for the Development of Public Health Guidance for Decentralized Non-Potable Water Systems.

How do I ensure effective treatment?

Achieving Pathogen LRTs

Barrier	Example log removal credit			
	Virus	Bacteria	Protozoa	Factors
Depth filtration		0.25 – 1	0.5	
Cartridge filtration				
Diatomaceous earth	0.4 – 3[a]	0.1 – 3[a]	3.5 – 7[a]	DE grade
Microfiltration	1 (0 – 3.2)[b]	6 – 7[a]	4 – 7[a]	Membrane age
Ultrafiltration	6.2 (5.4 – 7.9)[b]	7.1 – 8.3[a]	6 – 7[a]	Membrane age
Reverse osmosis	2.7 - 7	4 - 6	5 - 6	Membrane seals
Advanced oxidation	6	6	6	

[a] AWWARF (2001) Removal of Emerging Waterborne Pathogens, AWWA Research Foundation.

[b] U.S. EPA (2005) Membrane Filtration Guidance Manual, EPA 815-R-06-009, Office of Water, Cincinnati, OH.

Monitoring

- Routine monitoring of indicator organisms does not provide real time information required for operation of DNWS
  - Cost prohibitive
- A new monitoring approach:
  - Start-up and Commissioning
    - Validation monitoring
      - Performance target confirmation via challenge testing (or endogenous organisms?)
  - Operational Monitoring
    - Ongoing verification of system performance
    - Continuous observations
    - Surrogate parameters correlated with LRTs
  - Controls for out of specification

Biological Organisms to Confirm Log Reduction Targets

- Measure pathogens
  - Hundreds of potential pathogens
  - Sporadic occurrence
  - Can be expensive
  - Negative results
- Measure biological surrogates that represent pathogens
  - Typical surrogates (fecal indicator organisms) too dilute
  - Spike with surrogate, calculate reduction
    - Challenge to spike large systems
  - Endogenous microbes as alternative biological surrogates

Alternative Biological Surrogate Criteria

- Endogenous to the system
- Relate to pathogen removal
- Consistently present in influent
- Present in high concentrations to allow a dynamic range of log removal
    - Target log reductions
        - Bacteria: 3 – 6 $\log_{10}$
        - Virus: 6 - 8 $\log_{10}$

Microbiome (NPR Stories)

Do We Really Need Probiotics in Our Coffee, Granola, and Nut Butter. Apr. 19, 2016

Your Invisible Neighbors: Each City has Unique Microbes. April 19, 2016

The Human Body's Complicated Relationship with Fungi. April 16, 2016

Researchers Test Microbe Wipe to Promote Babies' Health After C-Sections Feb. 1, 2016

Stomach of Ancient Iceman Held Microbes Like Ours. Jan. 7, 2016

Is This A Snowy Wonderland or the World Inside a Petri Plate Dec. 25, 2015

Tiny Witnesses: Microbes Can Tell When a Murder Victim Died. Dec. 10, 2015

Missing Microbes Provide Clues About Asthma Risk. Sept. 30, 2015

Wherever You Go, Your Personal Cloud of Microbes Follow. Sept. 22, 2015

Does This Phylum Make Me Look Fat? Aug. 20, 2015

Microbe Mix May Play Role in Preterm Birth Risk. Aug. 17, 2015

Spore Microbe Helps Fend Off Life-Threatening Bacterial Infections. May 5, 2015

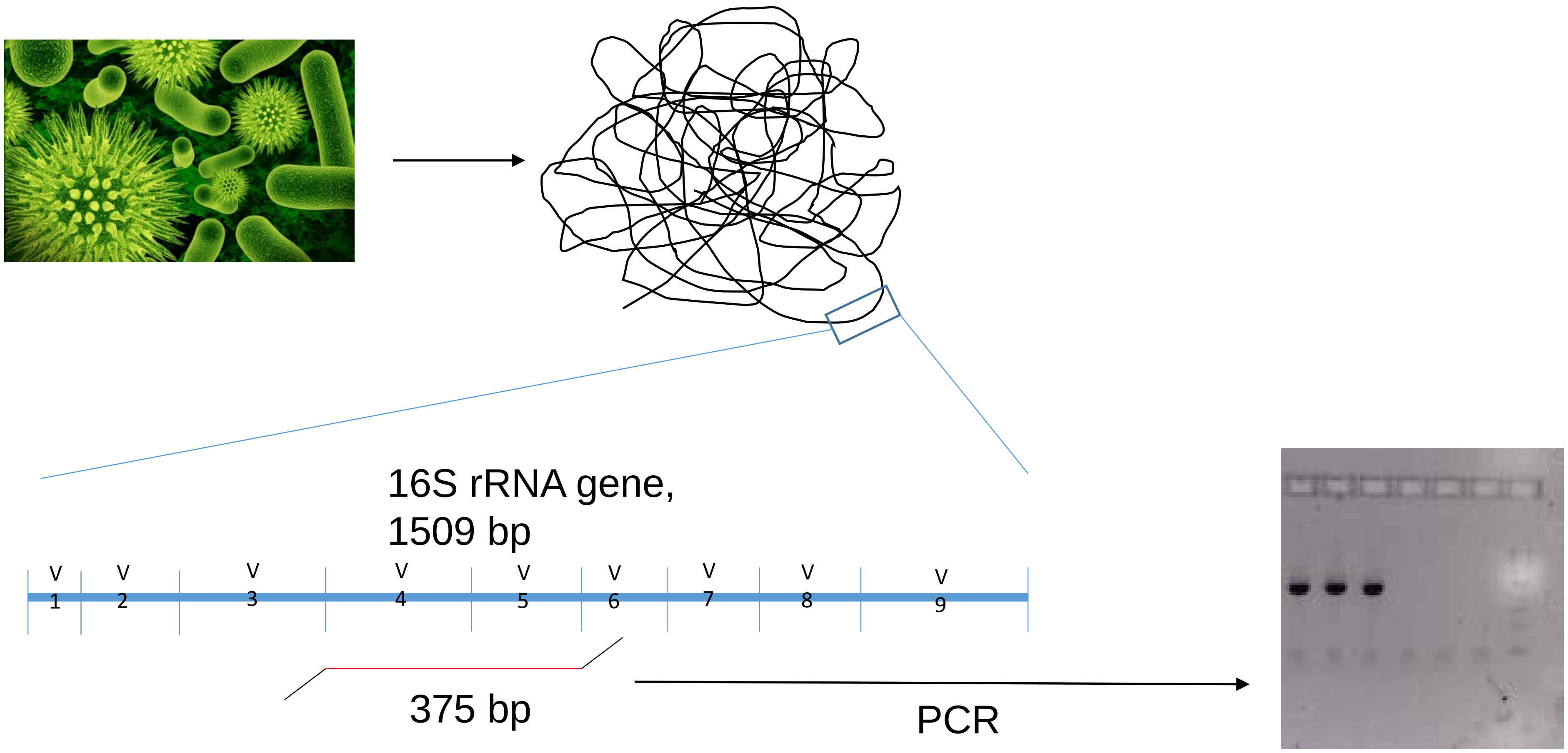
How Modern Life Depletes our Gut Microbes Apr. 21, 2015

What's Happened in the Past Decade?

- The cost of sequencing dramatically decreased
  - Human Genome Project (2003) cost about $54 million to sequence and analyze one human genome
  - Now $4,000 for a eukaryotic genome, and about one tenth of that for a bacterial genome
  - Metagenomics is the simultaneous sequencing and analysis of multiple genomes, such as those found in a microbiome, can now cost less than $1,000 for a high level analysis of a metagenome
- The Microbiome as a meme
  - An idea, belief or belief system, or pattern of behavior that spreads throughout a culture

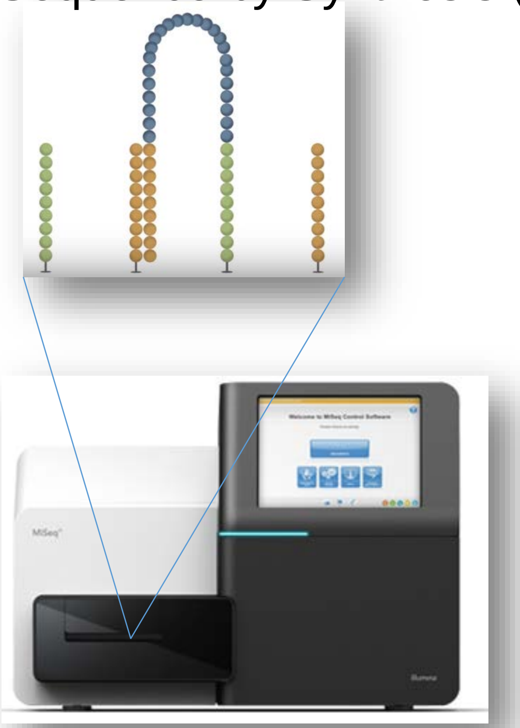
  - Microorganisms are everywhere, and Microbes are good

Microbiome Approach



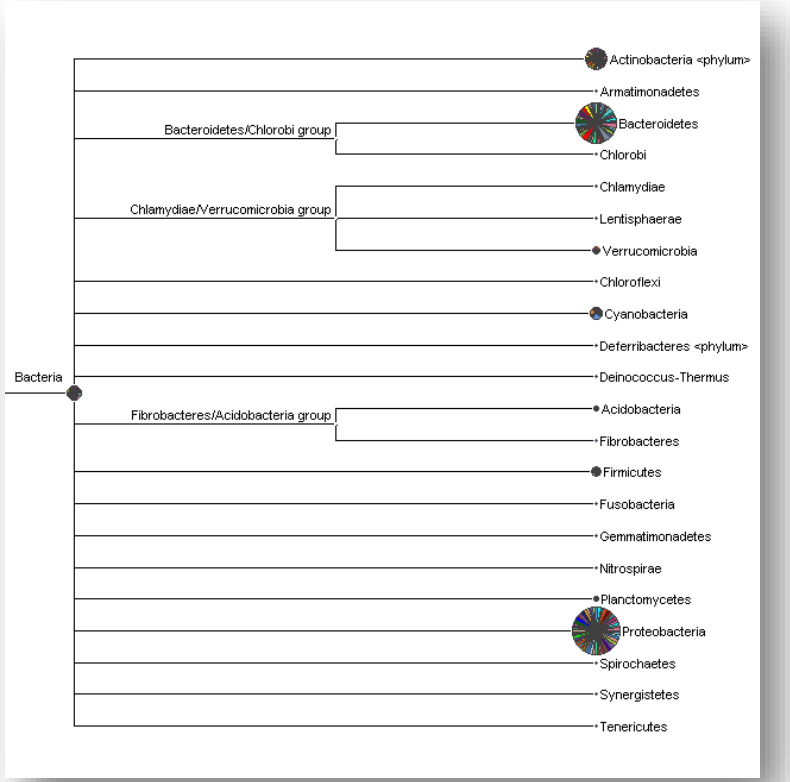
16S Sequencing and Analysis

Sequence by Synthesis (SBS)



MiSeq

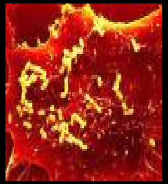
Classification



The 3-Domain System Of Biological Classification (Based on 16s rRNA gene)

100-150 MYA

Salmonella

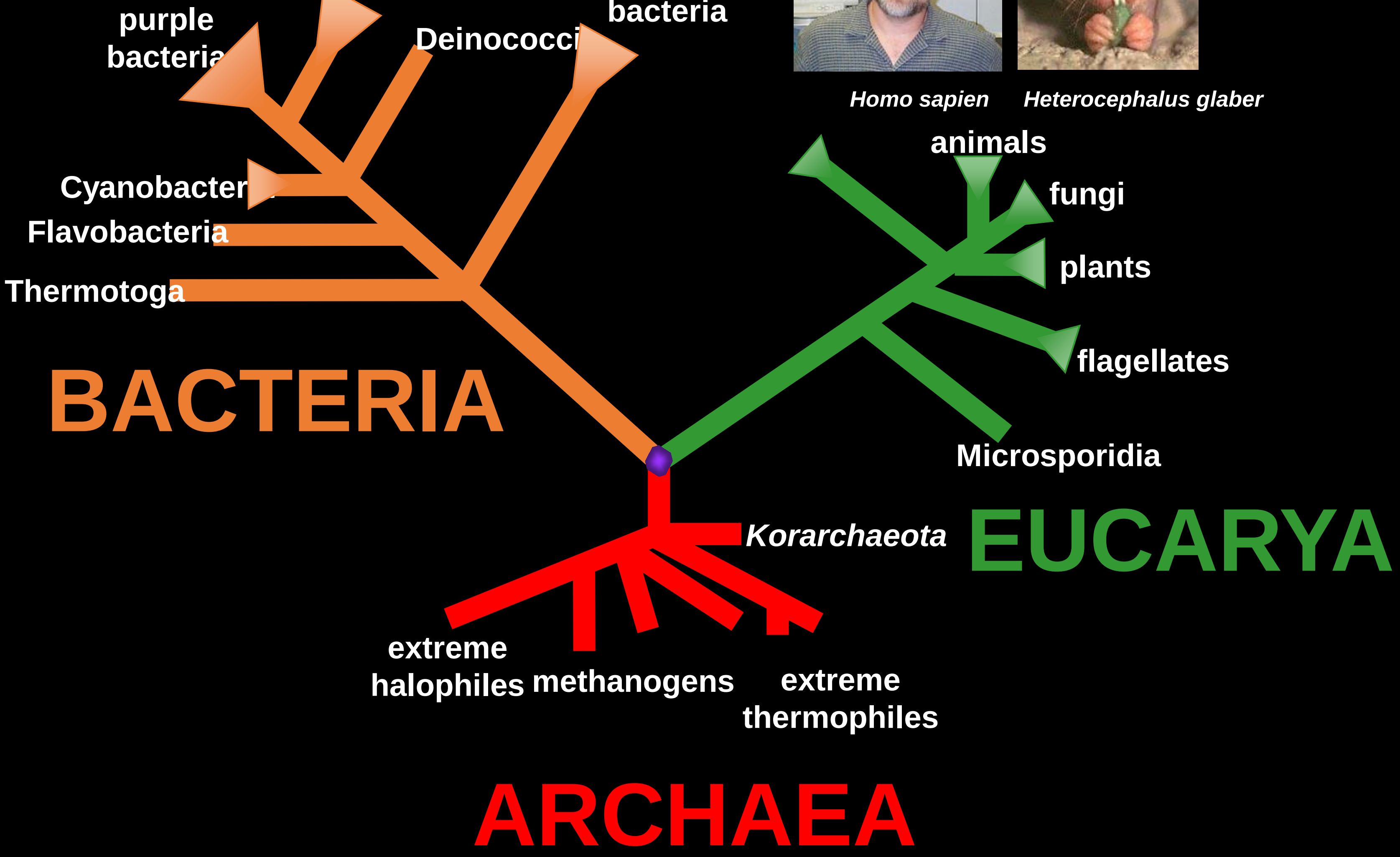


Escherichia

100 MYA

Homo sapien

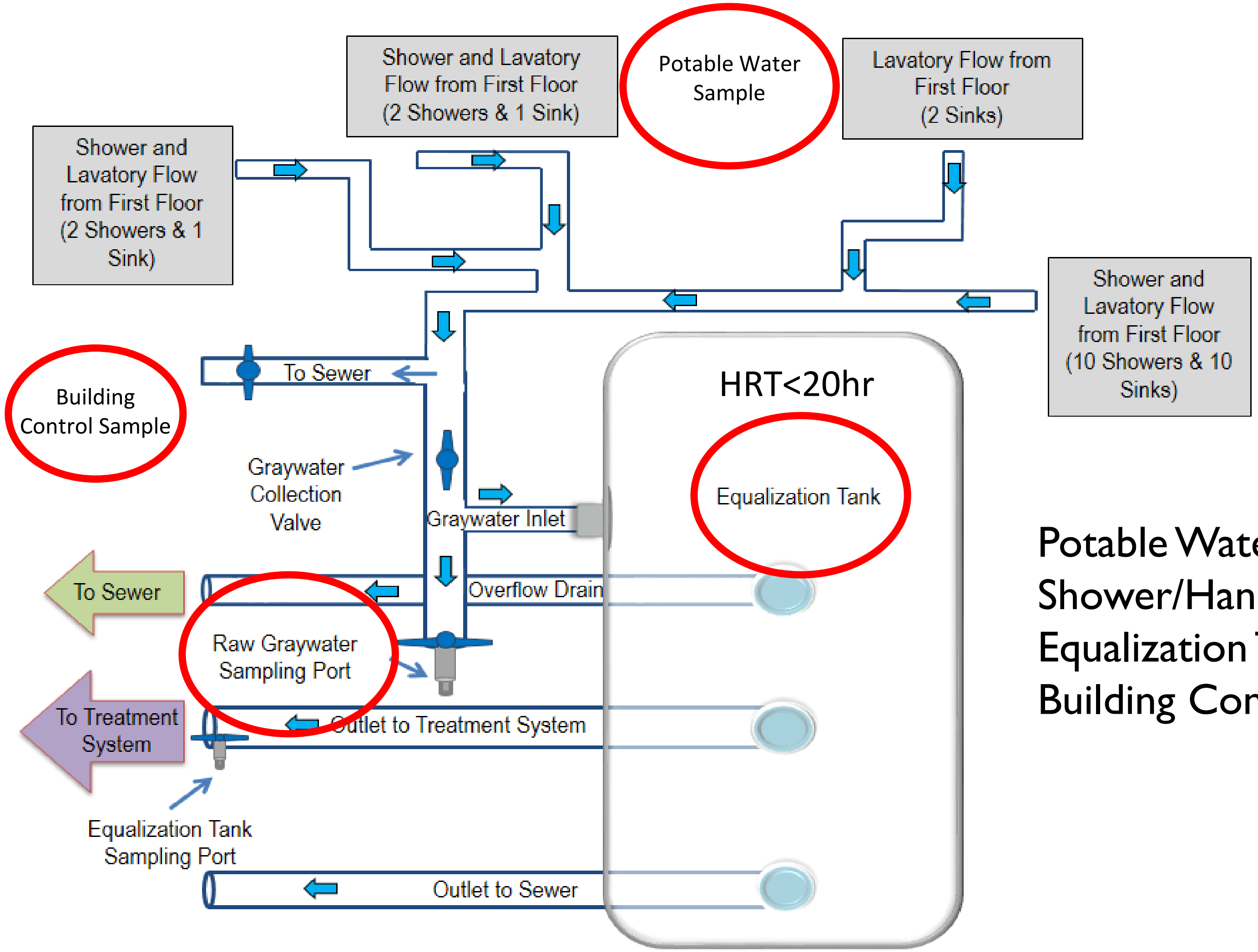
Heterocephalus glaber



Bacterial Community in Graywater

- Graywater sources
  - Dormitory at Colorado State University (CSU, Ft. Collins, CO)
    - 14 residence halls = 14 showers, 14 sinks
    - 28 person capacity
    - Composited in 946 L equalization tank
  - Athletic laundry facility at the University of Cincinnati (UC, Cincinnati, OH)
    - Launder ~10-30 garments per wash
    - Collected water directly from washing machines
- Bacterial communities analyzed by pyrosequencing 16S rRNA gene
  - Classification to genus level

CSU Graywater System



Potable Water (PW): n=1
Shower/Handwash (SH): n=18
Equalization Tank (ET): n=6
Building Control (BC): n=3

UC Commercial Washer

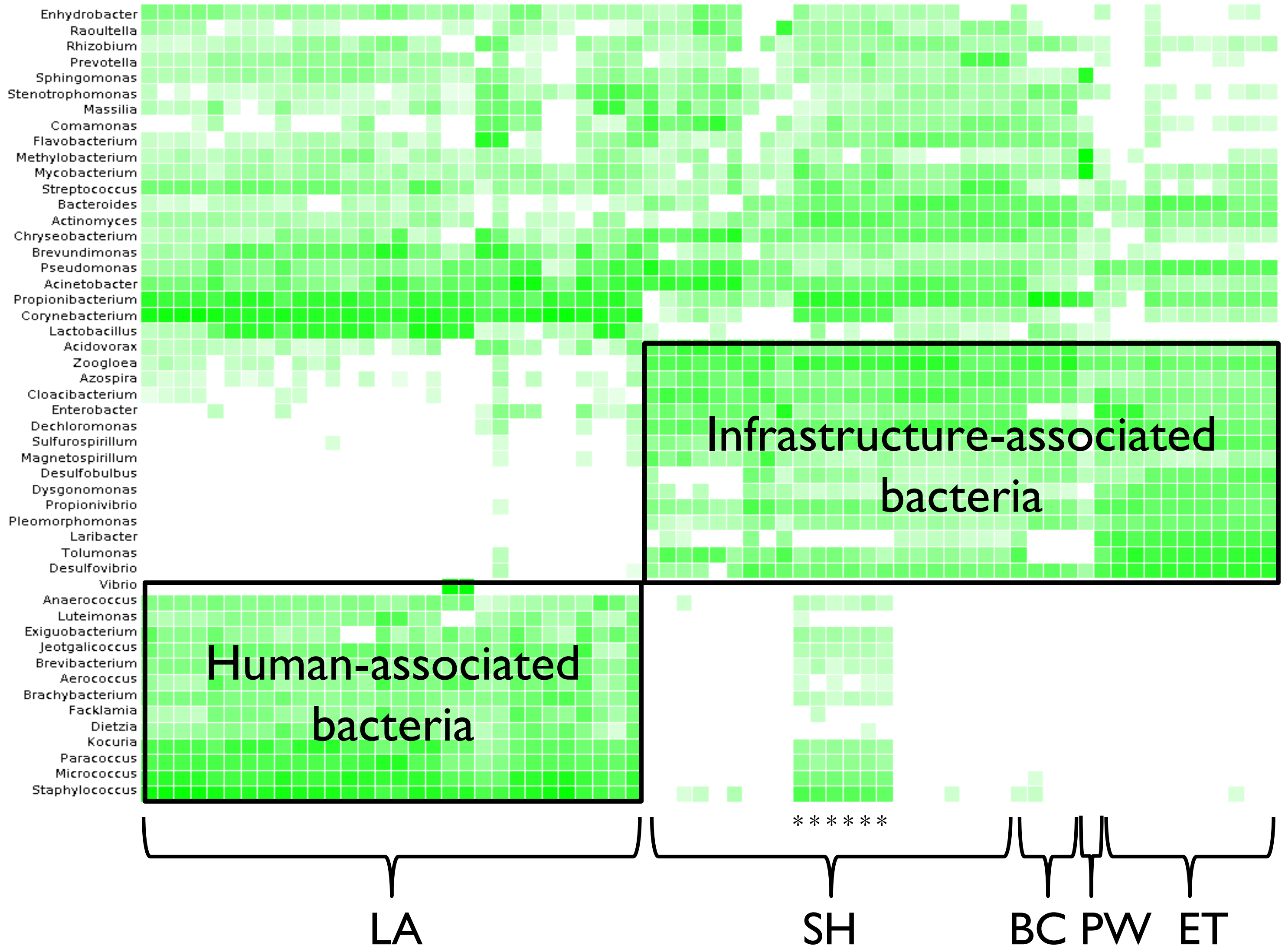
Laundry (LA): n=24

An Example of the Big Data Nature of High Throughput Sequencing

- From a collection of ~50 water samples
- Over 1.8 million raw reads generated
  - Average over 35,000 raw reads per sample

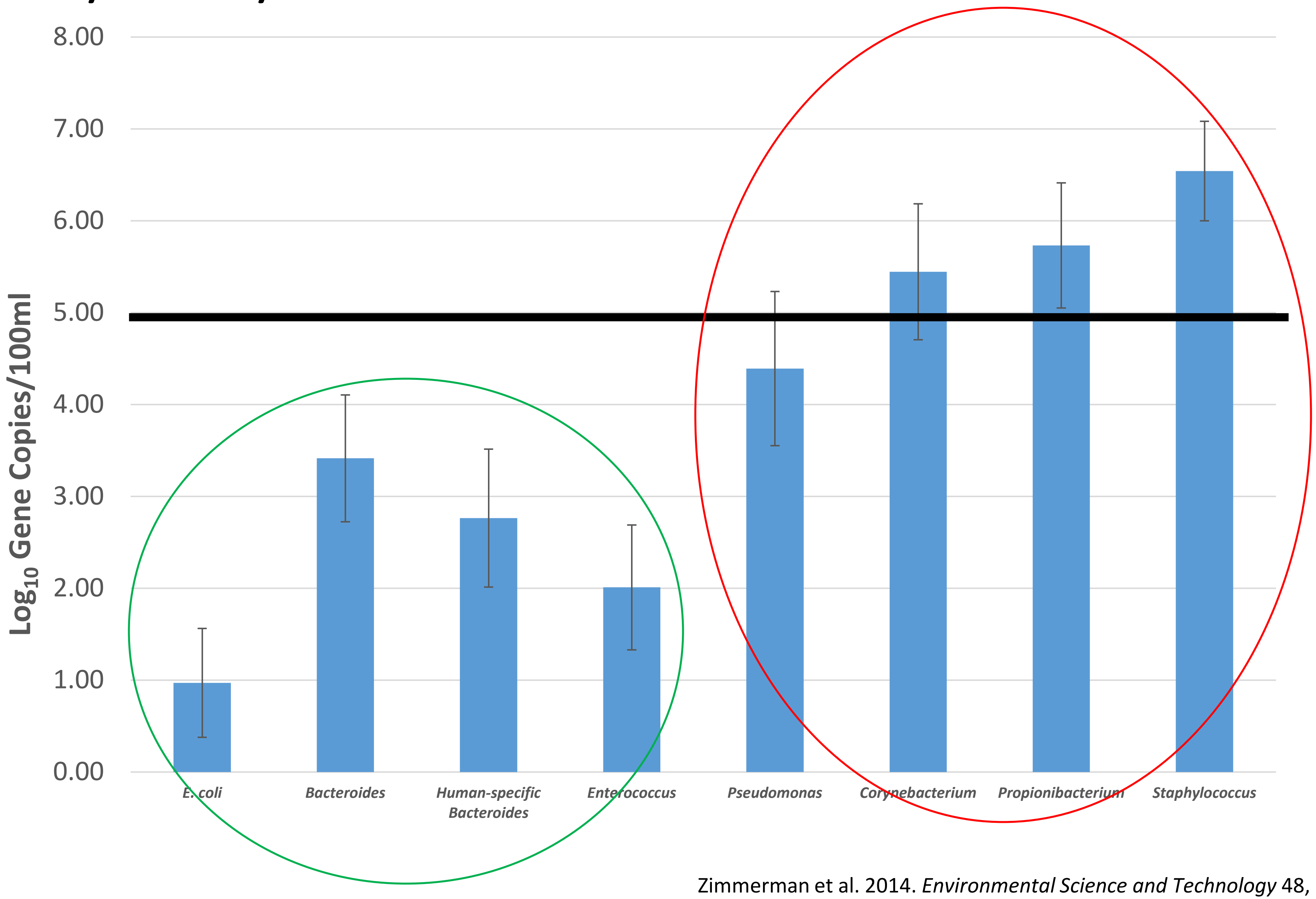
Sample Type	Number of Samples	Average Number of Genera Detected	Total Number of Genera Detected
SH	18	86	191
ET	6	53	90
BC	3	82	107
PW	1	37	37
LA	24	105	295

Log$_{10}$-scale Heat Map of Top 50 Genera Detected in Graywater



Keely et al. 2015. *Journal of Applied Microbiology* 119: 289

Quantification of Candidate Bacterial Surrogates in Laundry Graywater



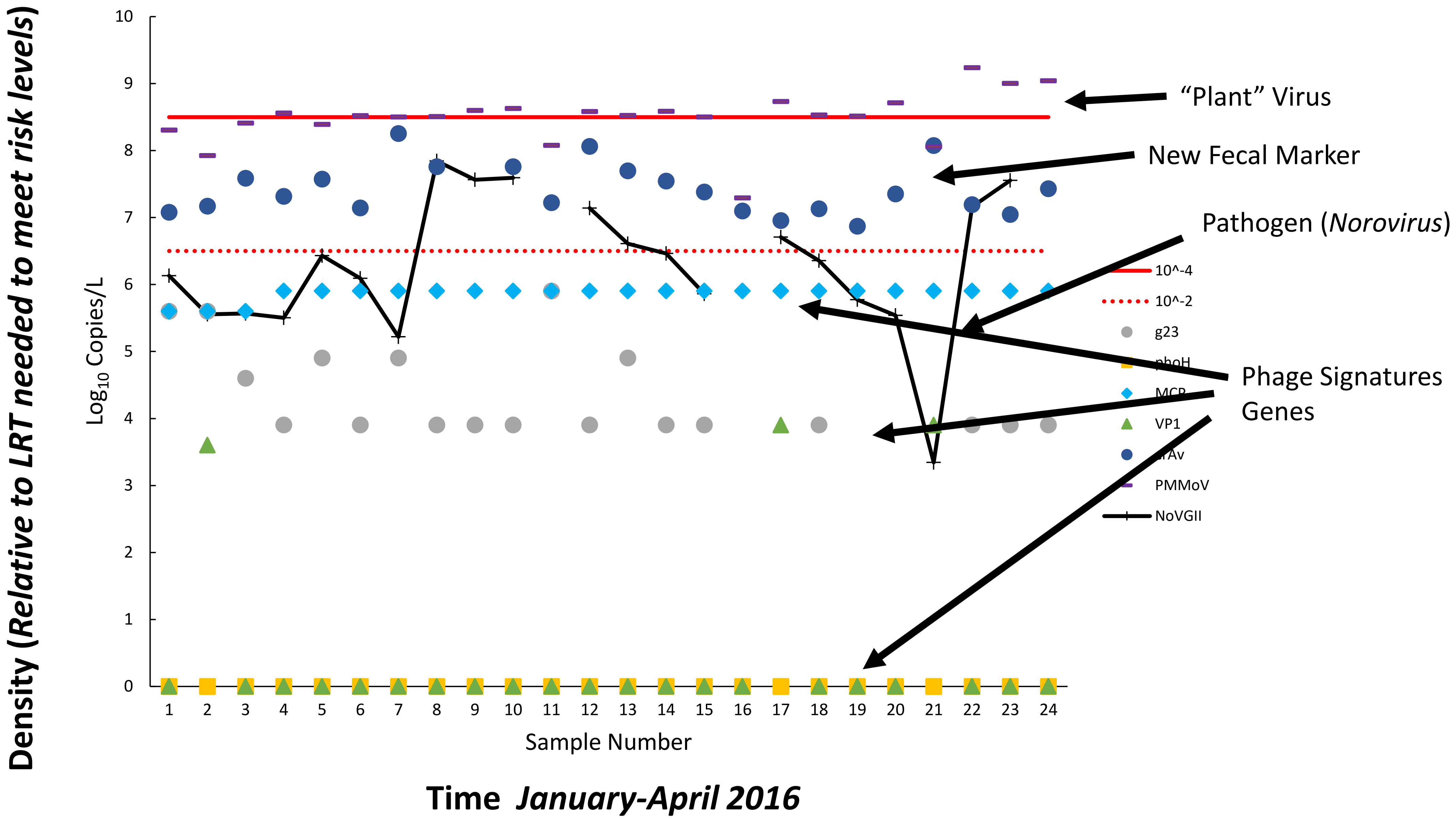
Zimmerman et al. 2014. *Environmental Science and Technology* 48, 7993

What About the Search for Viral Surrogates?

- Human associated virus
  - crAssphage[1] – phage that likely infects *Bacteriodetes,* a common human gut bacterial; in half the populations?
  - A plant virus newly reportedly to be common in human feces (pepper mottle virus; *Polyviridae,* RNA virus)
- Or, abundant phage associated with the collected wastewater prior to treatment (including those generated during biological treatment?)
  - Bacteriophage signature genes – homologous conserved genes of closely-related phage (i.e., structural proteins, auxiliary metabolism, polymerase genes)[2]
  - structural protein genes - MCP[3], VP1

[1]Dutilh et al. 2014 Nature Communications 5:4498; [2]Adriaenssens et al. 2014. AEM 80: 4470; [3]Hopkins et al. 2014. ISME 8: 2093

Virus Levels in Blackwater From SFPUC Building



So What Did I Just Say?

- Risk-Based Approach
  - Undoubtedly filled with uncertainties
  - But the key attribute is a quantifiable description (model) of the system which can be meaningfully assessed and improved

- Important to base risk analysis on pathogens, even if you are not directly measuring them
  - Traditional fecal indicators have to be applied cautiously
  - The microbiome may provide effective surrogates of treatment performance

- Providing scientific input to a motivated group of stakeholders trying to catalyze solutions
  - Stakeholder engagement in defining (and filling) the key research gaps
  - Evaluating real world systems through partnerships