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Exploring relationships between water quality and opportunistic pathogen concentrations in a full-scale green home

Ryan Julien, PE
julienry@msu.edu
PhD Student – Biosystems Engineering
Michigan State University
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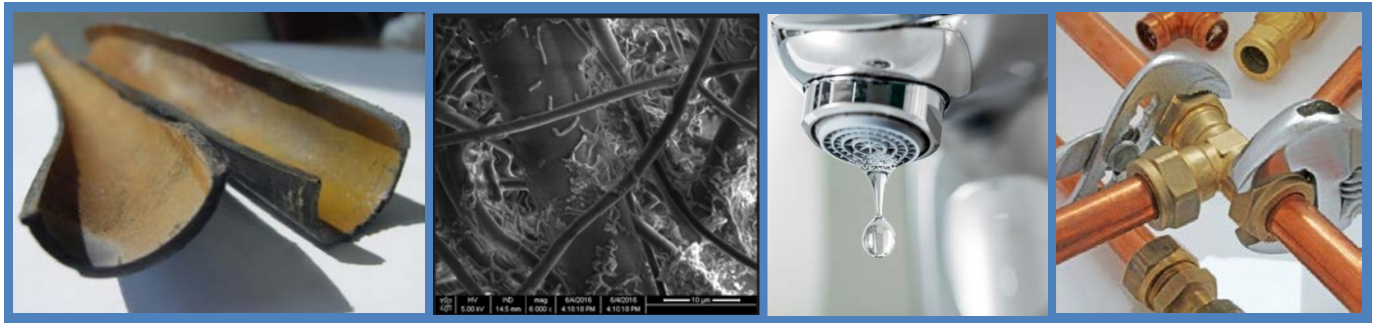
Right Sizing Tomorrow's Water Systems for Efficiency, Sustainability, & Public Health



Andrew Whelton (Lead PI at Purdue), Jade Mitchell (MSU PI), Janice Beecher (MSU co-PI), Joan Rose (MSU co-PI), Juneseok Lee (SJSU PI), Pouyan Nejadhashemi (MSU co-PI), Erin Dreelin (MSU co-PI), Tiong Gim Aw (Tulane PI), Amisha Shah (Purdue co-PI), Matt Syal (MSU co-PI), Maryam Salehi, Ryan Julien, Kara Dean, Ian Kropp

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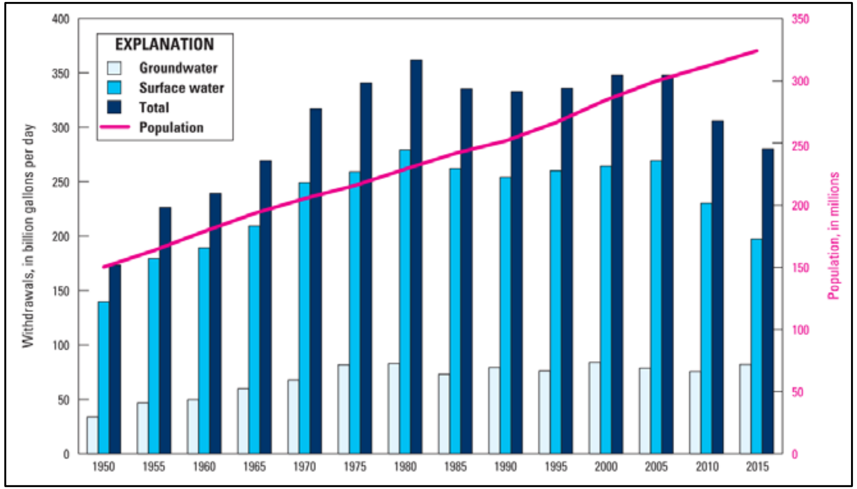
Outline

- Introduction
- Data collection
    - ReNEWW house description
    - Analytical sampling
    - Electronic logging
- Spearman’s Rank Correlation Coefficients
- Principal Component Analysis
- Conclusions

Introduction – Declining Water Demand

- Water consumption rates declining
  - US water withdrawals lowest since 1970
- Drivers of conservation
  - Mandatory: Energy Policy Act of 1992
  - Voluntary: USGBC's LEED, WaterSense
- Residential water demand declined 22% from 1999-2016 (WRF, 2016)
  - 73% of this change attributable to toilet and clothes washer efficiency alone



(Dieter et al., 2018)

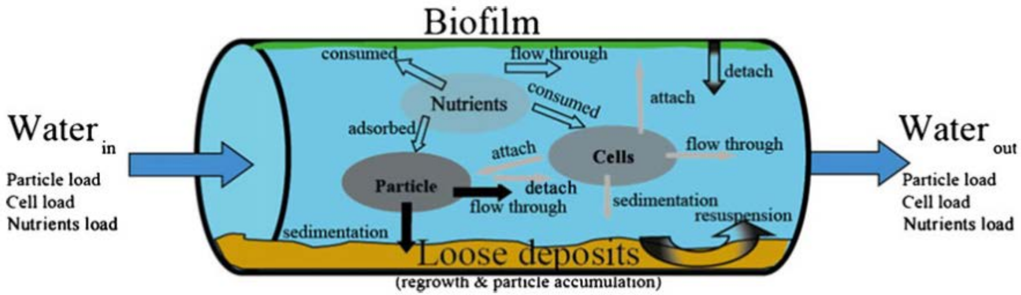
Introduction – Water Distribution Systems (WDSs)

- Plumbing often oversized
  - Design based on conservative demand estimates – e.g. Hunter's Curve (1940)
  - Contemporary water demand not considered in design guidance
- Hydraulic retention time or "water age"
  - The duration of time water spends in plumbing
  - Increased pipe diameter ➔ increased water age
- Water treatment focused on eliminating enteric pathogens
  - Unable to reproduce in WDS

Introduction – Effects of Water Age

- Decay of residual disinfectant
  - Less effective to inhibit microbial growth
  - Formation of disinfectant by-products
- Pipe material leaching
  - Material toxicity (e.g. lead, vinyl chloride)
  - Support pathogen growth (e.g. carbon from PEX)

- Premise plumbing exacerbates these issues
- Opportunistic Premise Plumbing Pathogens (OPPPs)
  - “Natural” inhabitants of pipes
    - Not realistic to eliminate
    - Generally infect only immunocompromised
  - Proliferate with elevated water age
  - Infection incidence climbing



(Liu et al., 2013)

ReNEWW House Description

- **<u>Re</u>**trofitted **<u>N</u>**et-Zero **<u>E</u>**nergy **<u>W</u>**ater, and **<u>W</u>**aste
- Constructed in 1928
- Retrofit in 2016
  - "High-efficiency" fixtures and appliances
  - PEX-A piping
  - Equipped with flowmeters at each fixture

Photo: Whirlpool Corporation

Data Collection – Analytical Sampling

- Seven sample locations at different fixtures through the home

Fixture Name	Abbreviation	Design Flowrate (LPM)	Total Volume Consumed (m^3)	Percent of Cumulative Total
Service Line	SL	NA	130.7	100%
Kitchen Sink - Cold	CKS	6.8	5.9	4%
Bathroom Sink - Cold	CBS	4.5	2.0	2%
Water Heater	WH	NA	40.6	31%
Kitchen Sink - Hot	HKS	6.8	5.2	4%
Bathroom Sink - Hot	HBS	4.5	16.2	12%
Bathroom Shower - Mixed	BSM	7.6	36.6	28%

- Several common water quality variables analyzed

Variable Name	Variable Description	Units	Percentile		
			2.5%	50.0%	97.5%
pH	pH	NA	7.36	8.00	9.04
Temp	Temperature	C	15.63	22.90	26.30
DO	Dissolved oxygen	mg/L	4.30	8.40	10.56
Total.Cl	Total Chlorine	mg/L	BDL	0.10	1.00
Free.Cl	Free Chlorine	mg/L	BDL	0.01	0.75
TOC	Total Organic Carbon	mg/L	0.42	0.81	15.36
DOC	Dissolved Organic Carbon	mg/L	0.42	0.73	18.97
Alka	Alkalinity	mg/L as $CaCO_3$	264.15	287.25	332.65
TTHM	Total Trihalomethanes	mg/L	0.05	15.57	31.55
TCC	Total Cell Count	#cells/mL	1.54E+03	3.77E+04	1.56E+06
HPC	Heterotrophic Plate Count (by culture)	CFU/100mL	4.03E+00	1.01E+04	3.60E+07
Leg.sp	Legionella spp. (by qPCR)	gene copies/100mL	2.29E+01	4.02E+03	1.78E+05

Data Collection – Electronic Logging

- Each sample fixture equipped with a flowmeter
- Continuous monitoring data decomposed into discrete events
  - Any events with less than five seconds between them were combined
- Summary metrics
  - Event volume (vol.events) – cumulative volume of water used over time period
  - Number of Events (num.events) –cumulative number of events over time period
  - Mean time since last event (MTSL) – the mean time between events over the time period
- Summary metrics were calculated over a 14-day period prior to each sample collection

Spearman's Rank Correlation Coefficients

	pH	Temp	DO	Total.Cl	Free.Cl	TCC	HPC	Leg.sp	TOC	DOC	Alka	TTHM	num.events	vol.events	mtsl
pH	1.00	0.09	-0.30	-0.20	-0.19	-0.06	0.19	0.02	0.19	0.17	0.07	0.24	-0.19	-0.11	0.18
Temp	0.09	1.00	-0.40	-0.51	-0.41	0.48	0.46	0.26	0.49	0.53	0.31	0.20	-0.29	-0.27	0.34
DO	-0.30	-0.40	1.00	0.27	0.22	-0.23	-0.35	0.13	-0.42	-0.45	-0.14	-0.34	0.38	0.34	-0.39
Total.Cl	-0.20	-0.51	0.27	1.00	0.79	-0.28	-0.30	-0.23	-0.35	-0.42	-0.21	-0.29	0.16	0.19	-0.21
Free.Cl	-0.19	-0.41	0.22	0.79	1.00	-0.14	-0.16	-0.05	-0.25	-0.27	-0.12	-0.33	0.04	0.15	-0.07
TCC	-0.06	0.48	-0.23	-0.28	-0.14	1.00	0.70	0.56	0.53	0.56	0.56	0.26	-0.19	-0.16	0.23
HPC	0.19	0.46	-0.35	-0.30	-0.16	0.70	1.00	0.57	0.61	0.60	0.50	0.37	-0.40	-0.24	0.42
Leg.sp	0.02	0.26	0.13	-0.23	-0.05	0.56	0.57	1.00	0.46	0.42	0.53	0.16	-0.29	-0.08	0.32
TOC	0.19	0.49	-0.42	-0.35	-0.25	0.53	0.61	0.46	1.00	0.97	0.36	0.65	-0.53	-0.57	0.53
DOC	0.17	0.53	-0.45	-0.42	-0.27	0.56	0.60	0.42	0.97	1.00	0.36	0.62	-0.53	-0.57	0.54
Alka	0.07	0.31	-0.14	-0.21	-0.12	0.56	0.50	0.53	0.36	0.36	1.00	0.32	-0.12	-0.17	0.14
TTHM	0.24	0.20	-0.34	-0.29	-0.33	0.26	0.37	0.16	0.65	0.62	0.32	1.00	-0.31	-0.47	0.30
num.events	-0.19	-0.29	0.38	0.16	0.04	-0.19	-0.40	-0.29	-0.53	-0.53	-0.12	-0.31	1.00	0.75	-0.99
vol.events	-0.11	-0.27	0.34	0.19	0.15	-0.16	-0.24	-0.08	-0.57	-0.57	-0.17	-0.47	0.75	1.00	-0.74
mtsl	0.18	0.34	-0.39	-0.21	-0.07	0.23	0.42	0.32	0.53	0.54	0.14	0.30	-0.99	-0.74	1.00

Spearman's Rank – Fate of Disinfectant

- Chlorine
  - Breaks down faster at higher temperature
  - Forms Total Trihalomethanes (TTHMs) in reactions with organics
  - Preserves DO in bulk water by inhibiting microbial growth
- Total Trihalomethanes (TTHM) formation
  - Requires and consumes chlorine
    - Chlorine from service line
  - Requires and consumes carbon
    - PEX as potential carbon source

	Temp	DOC	TOC	TTHM	DO
Total.Cl	-0.506	-0.421	-0.349	-0.288	0.267
Free.Cl	-0.408	-0.269	-0.253	-0.334	0.218
TTHM	0.196	0.618	0.652	1.000	-0.336

Spearman’s Rank – Effects of Water Use

- Refreshed from service line
  - Dissolved oxygen
    - Consumed by aerobic microorganisms
  - Total chlorine
    - Consumed in reactions with organic matter (forms TTHMs, disinfection by-products)

- Flushed from pipes:
  - Carbon (total and dissolved)
    - Leached from PEX piping
  - Total Trihalomethanes (TTHMs)
    - Formed when chlorine reacts with organic matter
  - Microorganisms
    - Total Cell Count (TCC)
    - Heterotrophic Plate Count (HPC) bacteria
    - Legionella spp. (Leg.sp)
      - Less impacted by vol.events than other microbes

	DO	Total.Cl	DOC	TOC	TTHM	Temp	TCC	HPC	Leg.sp
num.events	0.375	0.157	-0.529	-0.529	-0.305	-0.294	-0.192	-0.396	-0.291
vol.events	0.343	0.185	-0.573	-0.571	-0.470	-0.267	-0.157	-0.243	-0.083
mtsl	-0.386	-0.208	0.538	0.532	0.296	0.343	0.227	0.416	0.318

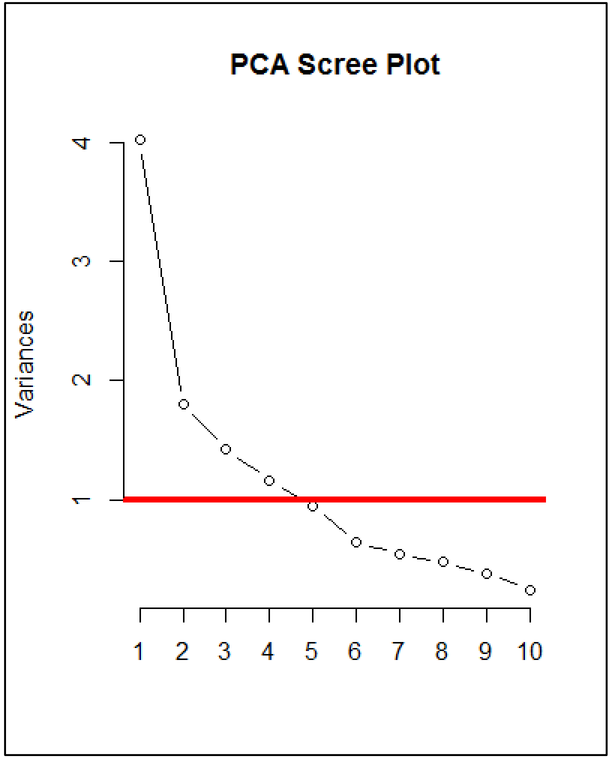
Spearman's Rank – Microbial Growth

- Microbes related to one another's success
- Conditions favoring microbial growth
  - Elevated carbon
  - Elevated temperature
- Dissolved oxygen is consumed in aerobic respiration
- Legionella specifically adapted to plumbing environment (Falkingham et al. 2015)
  - Less strongly correlated to carbon, temperature, and DO than TCC or HPC
- Alkalinity
  - All positively related

	TCC	HPC	Leg.sp	DOC	TOC	Temp	DO	Alka
TCC	1	0.701	0.563	0.564	0.531	0.477	-0.233	0.563
HPC	0.701	1	0.569	0.604	0.612	0.460	-0.351	0.503
Leg.sp	0.563	0.569	1	0.421	0.456	0.256	0.130	0.531

Principal Component Analysis

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12
pH	0.12	0.27	0.42	-0.39	0.46	0.00	0.43	-0.29	0.27	-0.14	0.04	-0.05
Temp	0.30	0.10	0.22	-0.12	-0.60	0.19	-0.26	-0.01	0.60	-0.11	0.06	-0.05
DO	-0.22	-0.39	-0.30	0.14	-0.28	-0.09	-0.58	-0.40	0.32	0.02	-0.03	0.07
Total.Cl	-0.12	0.01	-0.63	-0.18	-0.42	0.30	-0.27	-0.05	0.44	-0.12	-0.06	-0.07
TCC	0.37	-0.40	-0.05	0.04	0.03	-0.12	0.09	0.00	-0.20	-0.41	0.09	-0.68
HPC	0.39	-0.31	-0.01	-0.19	0.02	-0.21	-0.02	-0.09	-0.18	-0.25	-0.50	0.56
Leg.sp	0.37	-0.31	-0.02	-0.09	0.13	-0.20	0.25	-0.40	0.11	0.56	0.37	0.14
TOC	0.32	0.18	-0.07	0.42	0.12	0.30	-0.19	-0.65	-0.11	0.23	0.22	0.05
Alka	0.30	-0.18	-0.17	-0.27	0.07	-0.76	-0.32	-0.24	0.07	0.11	0.14	0.03
TTHM	0.23	-0.01	0.14	0.67	0.29	-0.23	0.03	0.24	0.39	-0.06	-0.33	0.01
vol.events	-0.27	-0.42	0.37	-0.10	-0.12	-0.13	-0.28	-0.20	0.10	0.45	-0.39	-0.29
mtsl	0.29	0.42	-0.31	-0.15	-0.19	-0.05	-0.24	-0.02	-0.10	0.38	-0.52	-0.32
Standard deviation	2.01	1.34	1.19	1.08	0.98	0.80	0.74	0.69	0.62	0.50	0.43	0.42
Proportion of Variance	0.34	0.15	0.12	0.10	0.08	0.05	0.05	0.04	0.03	0.02	0.02	0.01
Cumulative Proportion	0.34	0.49	0.60	0.70	0.78	0.83	0.88	0.92	0.95	0.97	0.99	1.00



PC1 Loading Factors	
HPC	0.392
TCC	0.373
Leg.sp	0.373
TOC	0.320
Temp	0.296
Alka	0.295
mtsl	0.294
vol.events	-0.266
TTHM	0.235
DO	-0.221
pH	0.125
Total.Cl	-0.119

Principal Component Analysis

PC1 – Water Age (34% of variance)

- Microbes increase
  - Reproduce in plumbing (Falkinham et al. 2015)
- Carbon concentrations increase
  - PEX leaching (Proctor et al. 2017)
- Temperature increases
  - Home is warmer than service line (NRC, 2006)
- Alkalinity increases
  - Perhaps produced by denitrification in biofilm
  - Slight increase in pH
- TTHMs increase
  - Chlorine reacts with organics (NRC, 2006)
- DO and Cl are consumed (weak)
  - Aerobic respiration & chlorine decay

Principal Component Analysis

PC2 Loading Factors	
vol.events	-0.421
mtsl	0.417
TCC	-0.396
DO	-0.389
HPC	-0.314
Leg.sp	-0.306
pH	0.270
Alka	-0.181
TOC	0.181
Temp	0.100
Total.Cl	0.013
TTHM	-0.006

PC2 – Biofilm Detachment (15% of variance)

- Detachment increases with infrequent use
  - Detachment driven by erosion (drag) and sloughing (structural failure) (Schrottenbaum et al. 2009)
  - Sloughed-off biofilm is replaced as the surface is re-colonized (time dependent)
- Microbes reduced
  - Removed via washout (Falkinham, 2015)
- DO decreases
  - Low DO can induce sloughing (Applegate & Byers, 1991)
  - Oxygen demand of recently detached biofilm
- pH increases

Principal Component Analysis

PC3 Loading Factors	
Total.Cl	-0.625
pH	0.416
vol.events	0.375
mtsl	-0.315
DO	-0.303
Temp	0.224
Alka	-0.166
TTHM	0.140
TOC	-0.069
TCC	-0.051
Leg.sp	-0.020
HPC	-0.006

PC3 – Biofilm development and possible denitrification (12% of variance)

- Decreases with chlorine
  - Chlorine inhibits microbial growth
- Increased pH
  - Possible evidence of denitrification
- Decreases with frequent water use
  - Possible consequence of biofilm detachment
- Increases with temperature
  - Accelerated growth

Principal Component Analysis

PC4 Loading Factors	
TTHM	0.669
TOC	0.417
pH	-0.394
Alka	-0.274
HPC	-0.195
Total.Cl	-0.181
mtsl	-0.151
DO	0.140
Temp	-0.125
vol.events	-0.102
Leg.sp	-0.091
TCC	0.037

PC4 – Bulk water growth and possible nitrification (10% of variance)

- TTHM formation
  - Formation in bulk water
  - Chlorine too reactive to penetrate deep into biofilm
- TOC
  - Required for TTHM production
  - Encourages bulk-phase microbial growth
- Potential for nitrification in bulk water
  - Decreased pH and alkalinity

Conclusions

- Water age
  - Decreases: DO and chlorine
  - Increases: Carbon, TTHMs, microbial growth/Legionella
- Biofilm detachment
  - Caused by erosion and sloughing
  - Requires time for regrowth
- TTHM formation
  - Occurs over time
  - PEX leaching may provide carbon source
- Alkalinity and pH appear to increase with time in plumbing
  - Possible denitrification in anoxic biofilm
  - Possible nitrification in oxygen-rich bulk water
  - Resulting alkalinity may act as an indicator of water age

Questions?

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