UNIVERSITY OF ALBERTA
SCHOOL OF PUBLIC HEALTH

Matching Water Quality to Reuse:

Rationale for performance-based targets & A systems approach to manage public health

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Re-Fresh: The Confluence of Ideas & Opportunities on Water Reuse
Alberta Water Council Symposium, Arts Hotel, Calgary, June 25th, 2014

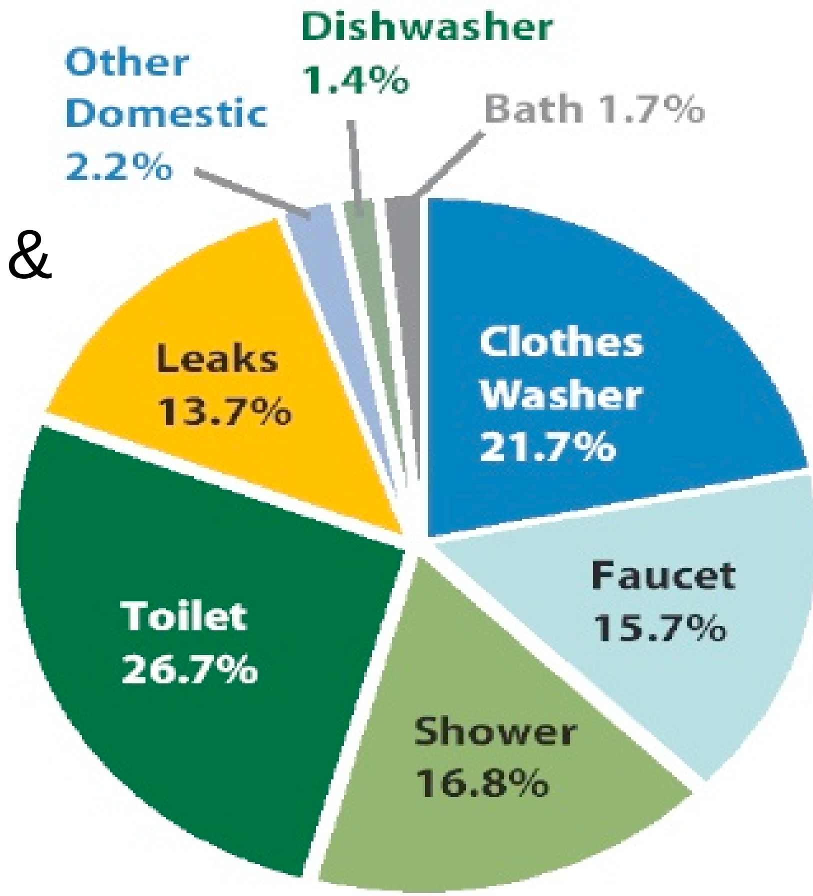
John Snow, cholera studies (1849-55): Father of epidemiology & HACCP

- Cholera introduced ~1831, but miasma theory until Robert Koch identified the bacillus agent (1883)
- English epidemics: 1832 killed 23,000, 1848-9 (53,000), 1853-4 (23,000) & the last 1866 (14,000)
  - One outbreak 1854; Snow plotted deaths & identified Broad St. pump
  - Control measure: pump handle off; but…
- Snow's work let to DW focus, yet Rev. Whitehead focus was faeces
  - Whitehead identified the problem!

http://fx.damasgate.com/john-snow-and-cholera/

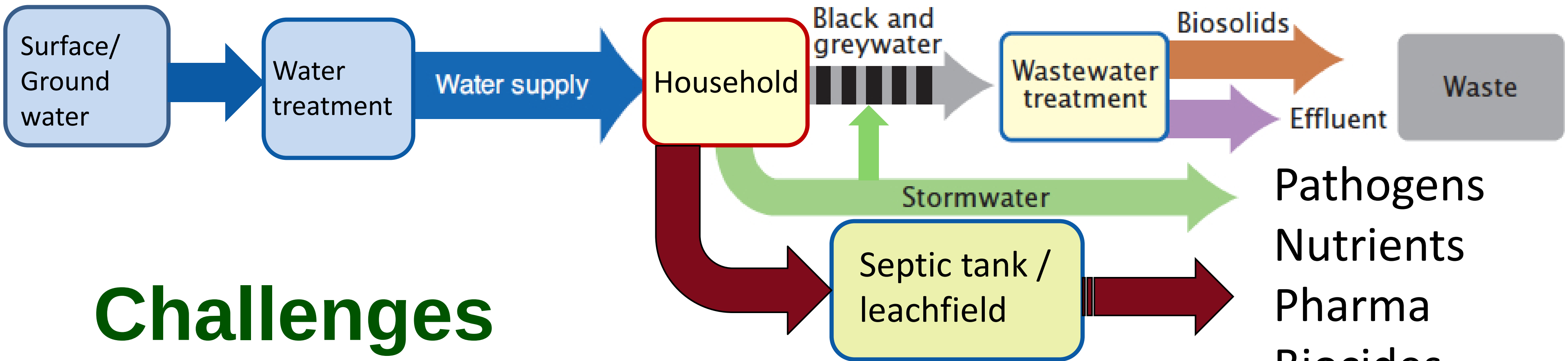
Water system issues: access & population growth, climate change, & eco-service loss

- Adaptive approaches & tools to aid in decision-making:
  - Treating water so **fit-for-purpose** & with **performance-based targets**
  - Full cost accounting for water services to be driven by **resource recovery** (energy, heat, water…) over built environ system life-time (**Integrated Resource Manag't**)
  - **Health risk assessments** for all water exposure pathways (harmonized so focus on key ones)



US Domestic water use (AWWA/AwwaRF)

Urban water service system

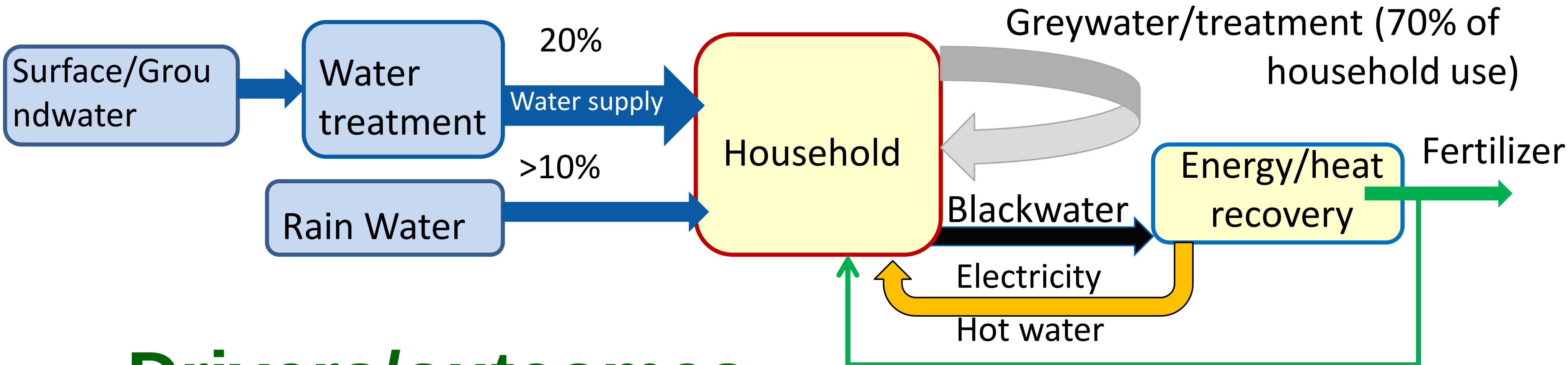


Pathogens
Nutrients
Pharma
Biocides

Challenges

- Water services utilize ~3-7% of a nation's electricity
- Insufficient nutrient and energy recovery & yield 3% GHG
- Aging water and wastewater infrastructure $trillions to maintain
- Sewer/septic system releases – major cause of eutrophication
- Neither climate/demographic resilient nor economic

Hence, alternative urban water elements for 'One-water' concept, market led

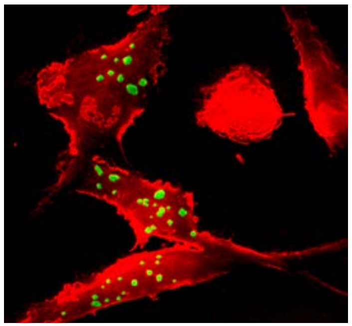


Drivers/outcomes

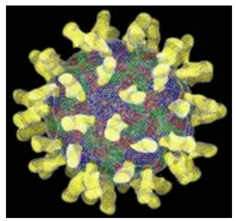
- Reduce energy use + GHG & nutrient emissions
  - Market-driven water, energy & nutrient recovery
- Climate- & demographic-resilient infrastructure
  - Decentralized, adaptable and antifragile

Human & Ecological hazards in ‘wastewaters’

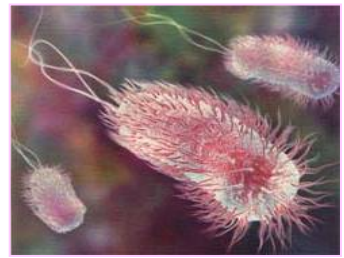
Pathogens



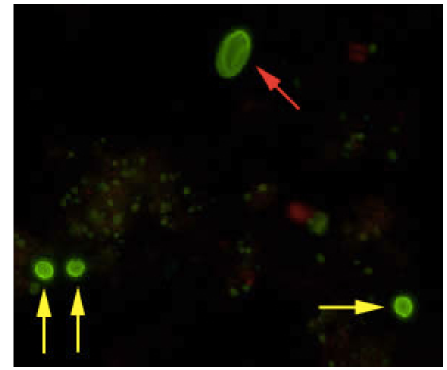
Environmental



Viruses



Bacteria

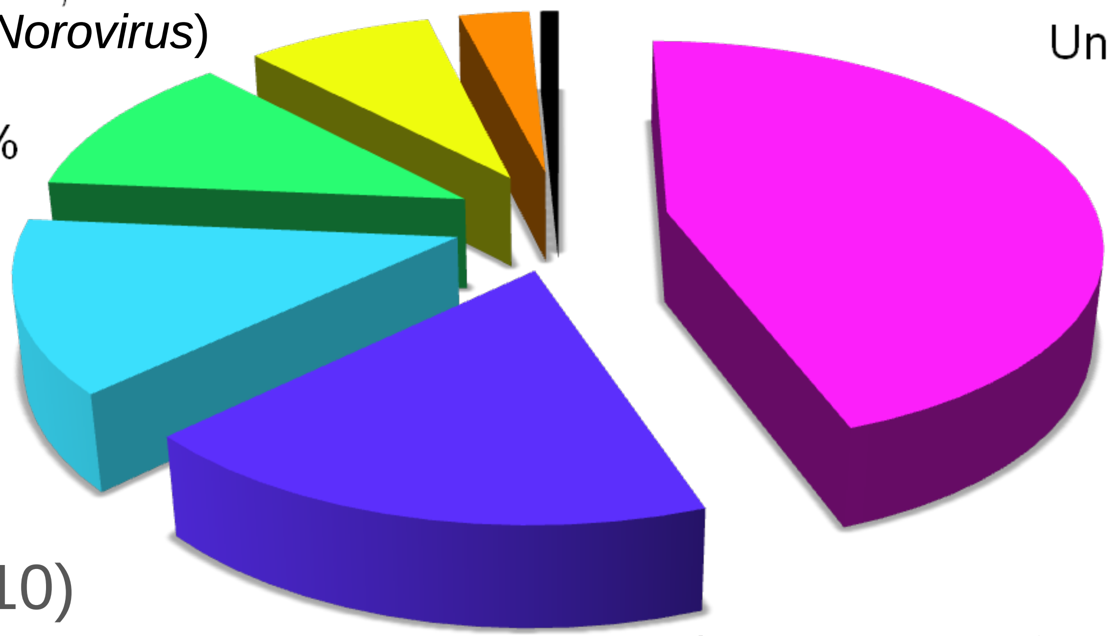


Parasitic protozoa

Chemicals

Nutrients, cleaning agents, metals, biocides & pharmaceuticals

Etiologic agents & percentages for 780 drinking water outbreaks, 1971-2006 USA



Craun *et al*. (2010)
CMR 23:507-528

Public health hospitalization costs from drinking water in the United States*

- CDC estimate drinking water disease costs > $970 m/y
  - Less so faecal pathogens, largely Legionnaires’ disease, *otitis externa*, and non-tuberculous mycobacterial (NTM) causing >40 000 hospitalizations/year

Disease	Annual costs
Cryptosporidiosis	**$46M**
Giardiasis	**$34M**
Legionnaires’ disease	**$434M**
NTM infection/Pulmonary	**$426M/ $195M**

*Collier *et al.* (2012) Epidemiology & Infection 140: 2003-2013


The Economist
AUGUST 18TH–24TH 2012
Economist.com
The Catholic church's unholy mess
Paul Ryan: the man with the plan
Generation Xhausted
China, victim of the Olympics?
On the origin of specie
Microbes maketh man
d rather not know before breakfast
How 90% of the cells in your body

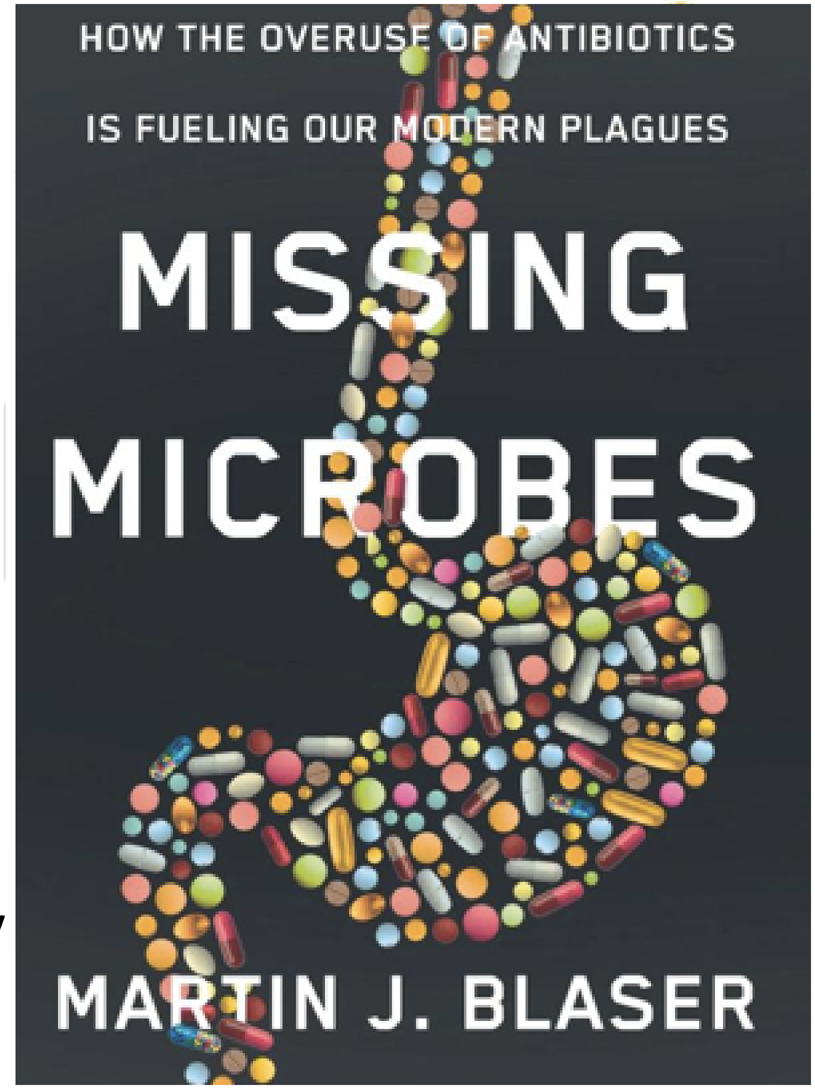
Public health & microbial roles

- 'Healthy' gut microbiome displaces pathogens/toxins
  - Production of bacteriocins, acids, H_2O_2, quorum sensor
  - Detoxication (vs detoxification) e.g. by *Lactobacillus*
- Increased diseases via some microbial metabolites
  - E.g. cardio-vascular disease via trimethylamine → TMAO[1]
- Childhood loss of gut microbiome members
  - Antibiotics & obesity[2]
  - *Antibiotics & E. coli* O104:H4 increased virulence[3]

[1]Howitt & Garrett 2012 Nature Med 18:1188-89
[2]Cox & Blaser (2013) *Cell Metabolism* 17(6): 883-94
[3]Kamada *et al.* (2012) *Nature Medicine* 18(8):1190-1191

Antibiotics & antibiotic-resistant bacteria via water exposures?

- Fat Drugs (antibiotics promote child weight)
  - Used in agriculture for weight gain
  - Part of the human obesity problem
- Primary waterborne sources include
  - Wastewater (industry & hospitals)
  - Animal production/manures
- Mass delivery via reclaimed water?
  - Water disinfectants and metal pipes known to increase gene exchange within biofilms ⟶ loss of AB efficacy



Cox & Blaser (2013) Cell Metab 17: 883-94
Gough *et al.* (2014) *BMJ 348*: g2267

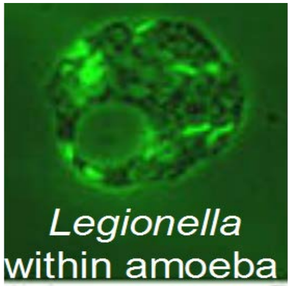
California Title 22 (1978, 2007)

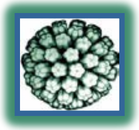
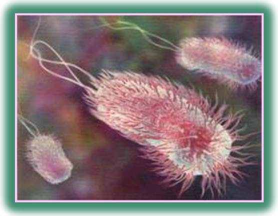
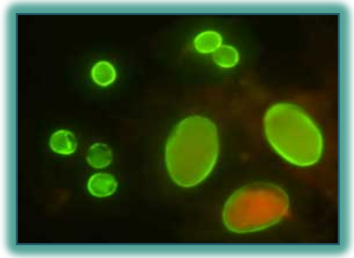
- Specifies treatment steps (with described log-reductions by unit processes), requiring:
  - 5-log_{10} virus reduction based on spiking studies*
- Total Coliforms (<2.2 MPN/100 mL) as a **[poor]** overall index of treatment performance
- NTU <2 (daily average) & chlorine 1 mg/L

*F-RNA coliphage MS2 (ATCC 15597B1, grown on *E. coli* ATCC 15597), poliovirus or other virus that is at least as resistant to poliovirus (based on Pomona Virus Study [Nellor *et al*. 1994 Health Effects Study, County Sanitation Districts of LA County])

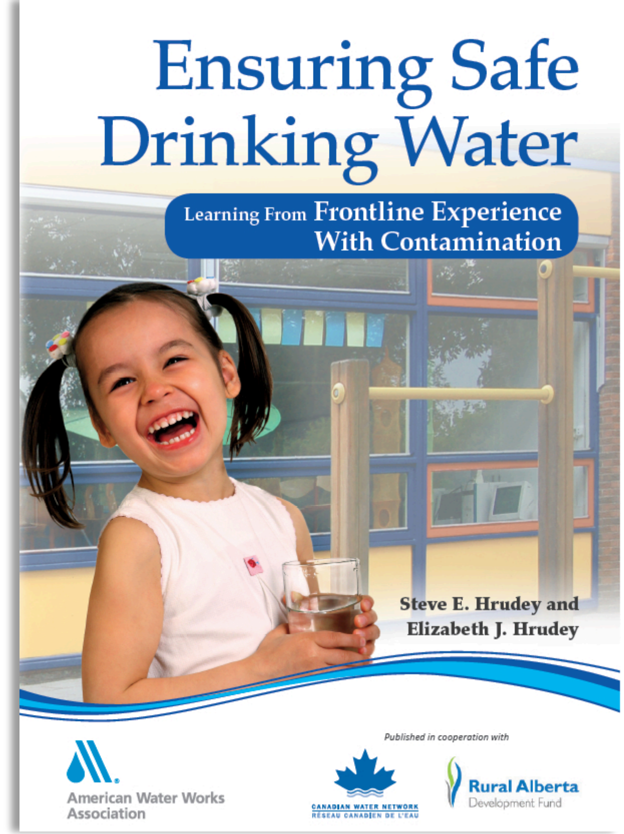
Major international microbial criteria for non-potable reuse (by 1995)

Parameter	California (Title 22)	Arizona	NSW - Australia	Israel
Designated treatment	Yes	Yes	Multiple barriers	No
Total coliforms / 100 mL	< 2.2 MPN		<10 (90%ile) into distribution <2.5 (50%ile) at point of use	< 1000
Fecal coliform/100 mL			< 1	-
Viruses	5-log_{10} reduction in spiking studies	<125/40 L restricted <1/40 L open use	<2/50 L	-
Parasites		<1/40 L	<1/50 L	< 1 ova/L
Turbidity (NTU)	<2 (daily average)		<2 50%ile <5 95%ile	-
pH	-	-	6.5-8.5	-
Color (total color)	-	-	<15	-
Chorine residual	1 mg/L	-	5 mg/L at first reservoir, 2 mg/L at customers	-



Key pathogen issues: Hazardous events & aerosolized pathogens



- System's approach to identifying & managing **environmental pathogen** risks depends on:
  - **ID and control of short-duration hazardous events throughout the system; via**
  - **Surrogate target levels (at control points)**

Quantitative Microbial Risk Assessment (QMRA): Regulatory & operational uses

- WHO & EPA set water criteria and/or treatment requirements based on QMRA (& epi) studies

  e.g. EPA 3 & 4 log treatment reductions in surface water parasites & viruses resp. for Drinking Water (DW)

- Risk-based targets (also provides a QMRA goal)
  - **Not current EPA policy:** DW < 1 infection 10^{-4}/year
  - **WHO/AUS/CAN: DW & reuse:** < 10^{-6} DALY/year
  - **EPA policy:** rec water < 32-36 NGI/1000 people.day

Failure of end-of-pipe monitoring: To verify at the 95% confidence level that failure events do not significantly add to GI risk (QMRA est.)

Nominal $\log_{10}$ reduction	#/year	Monitoring interval
0.05	1	1 year
1	30	1 week
2	300	1 day
3	3,000	3 hours
4	**30,000**	**15 min**
5	300,000	2 min
6	3,000,000	10 sec
7	30,000,000	1 sec

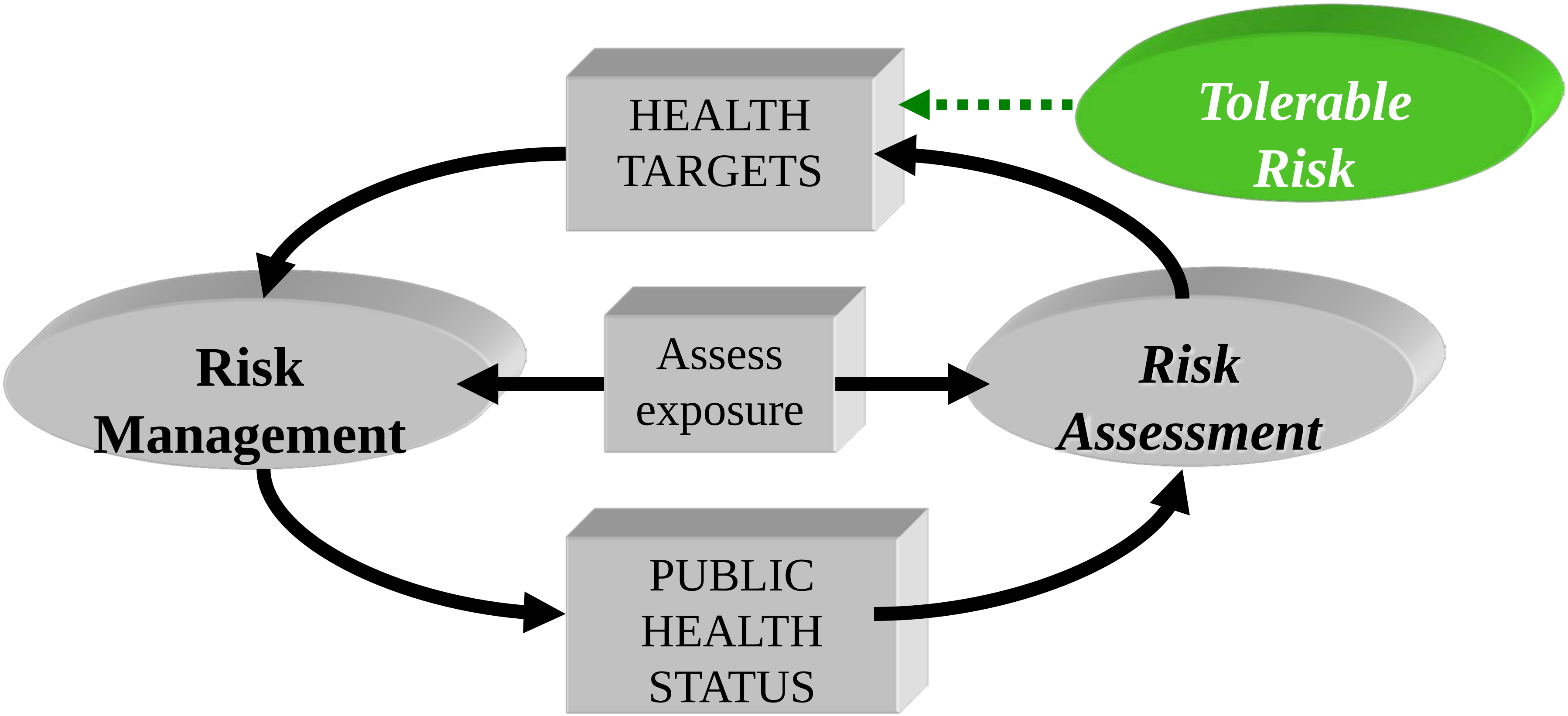
E. coli

SDWA target

i.e. a 100,000 m³/d plant treatment designed for 4 log inactivation of viruses, must monitored 3,000 L/d to be 95% confident that all drinking water was sufficiently treated

Smeets (2008) PhD TU Delft

WHO Risk management framework



Fewtrell & Bartram (2001) Water Quality: Guidelines, Standards and Health. Risk Assessment and Management for Water Related Infectious Diseases, WHO, Geneva

Quantitative microbial risk assessment (QMRA) for reclaimed water

STEP 1
SETTING

Problem formulation & Hazard identification
Describe physical system, selection of reference pathogens and identification of hazardous events

STEP 2
EXPOSURE

Source sewage
Ref pathogen densities

Treatment
Ref pathogen removals

Distribution
Pathogen loss (biofilm/death)

Environ Pathogen growth in pipes & X-connection to DW
($P_{ingress}$)

Human exposures
Vol water exposure

STEP 3
HEALTH EFFECTS

Dose-Response (P_{inf})
Selection of appropriate models for each ref pathogen and human groups exposed

STEP 4
RISK

Risk Characterisation
Simulations for each pathogen baseline and event infection risks with variability & uncertainty identified

Application of QMRA to aid performance-based target setting in water safety plan

- Given that:
  - *E. coli* (drinking water) ≠ *E. coli* (recreational water) ≠ *E. coli* (wastewater) ≠ *E. coli* (reused wastewater)
  - Viable enterococci more treatment resistant than *E. coli*
  - And faecal indicators < detection limits ≠no pathogens
- Need to select appropriate control point targets, based on QMRA derived safe level for overall risks
  - Having identified likely events and where to manage them

WSP & key questions that need quantification

What is my health target (10^{-6} DALY/y)?

System assessment

- Assemble team
- Describe water supply
- Conduct hazard analysis → What are the priority hazards and hazardous events?
- Identify Control Measures → Is my overall treatment adequate to produce safe reuse water?

Operational monitoring

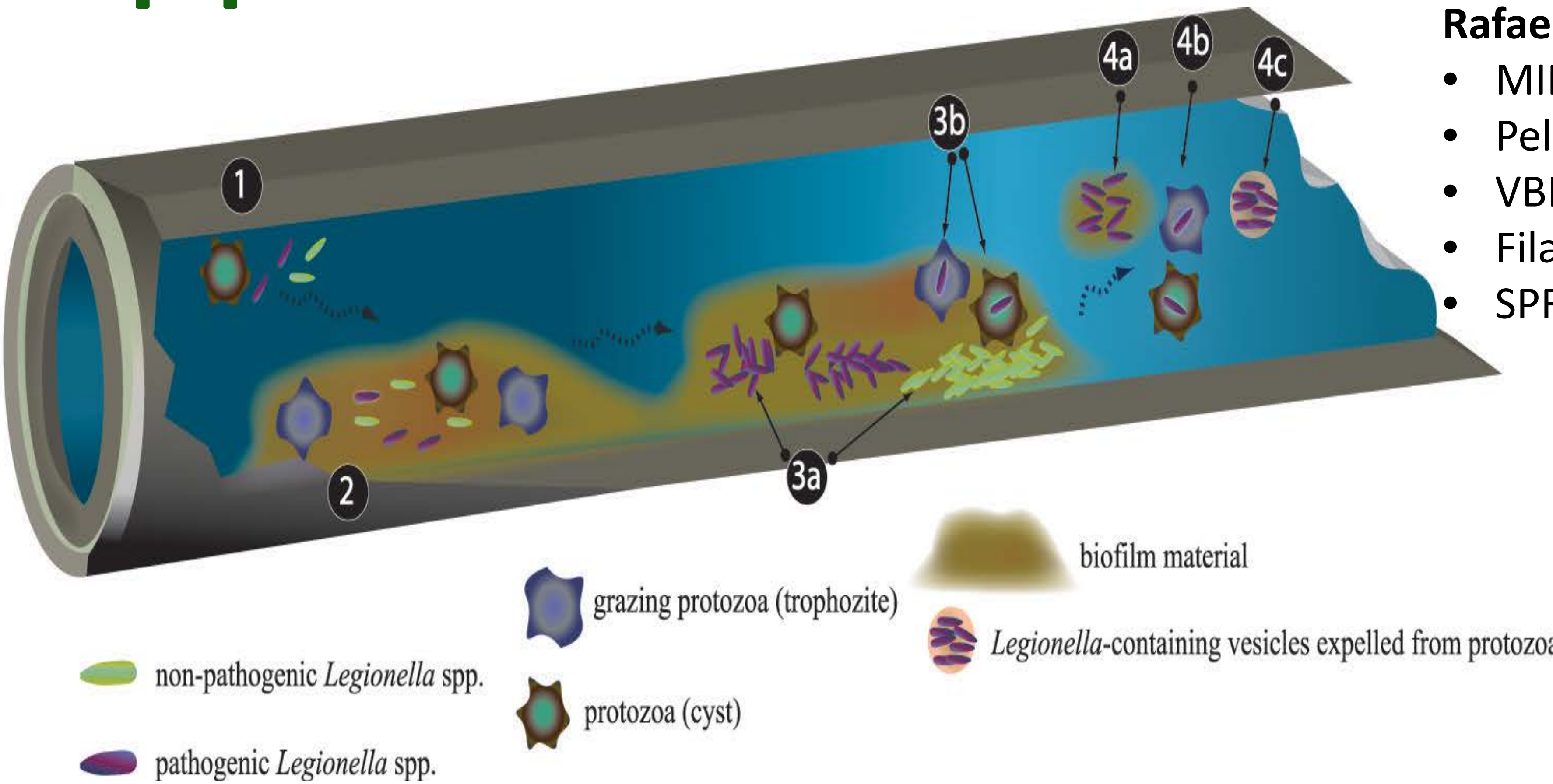
- Define Operational Limits → How much tolerance around my limits?
- Establish monitoring → Frequency of monitoring needed?

Management & communication

- Establish corrective actions → What level of corrective action is required and redundancy of barriers?
- Establish record keeping
- Establish validation + verification

Medema, G., Loret, J.-F., Stenström, T.A. and Ashbolt, N. (2006) Quantitative Microbial Risk Assessment in the Water Safety Plan. Final Report on the EU MicroRisk Project, European Commission, Brussels.

Conceptual model for *Legionella* in piped water*



Rafael Garduño

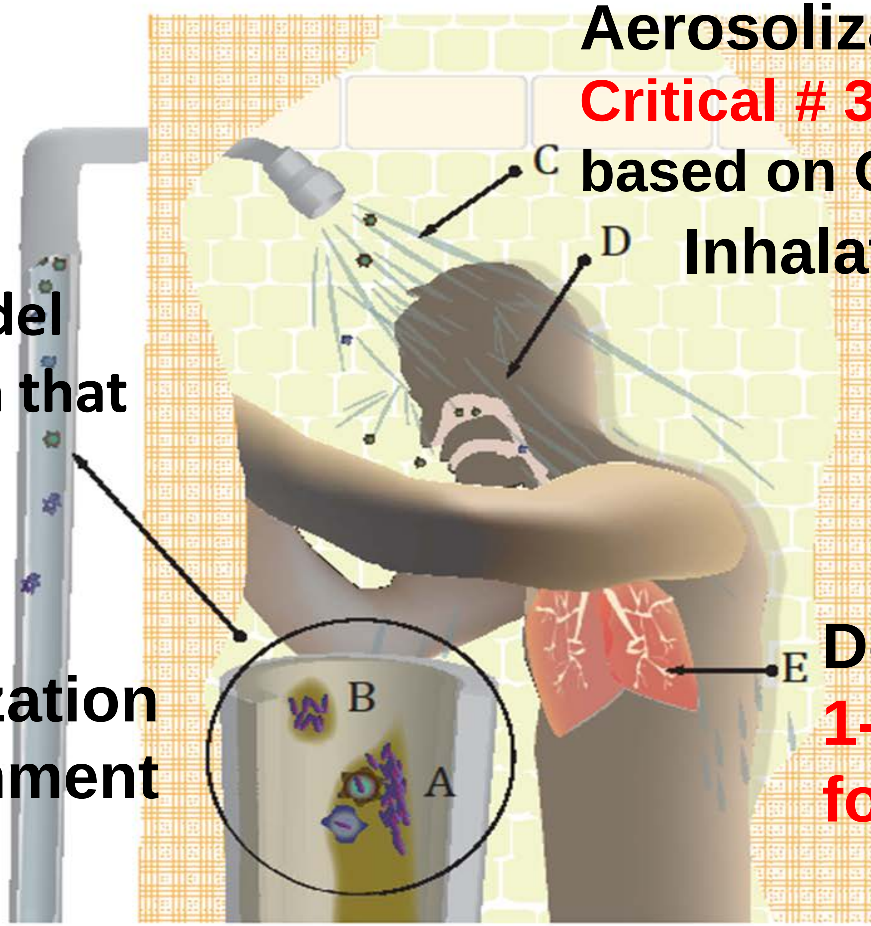
- MIFs
- Pellets
- VBNC
- Filamentous
- SPF

Garduño *et al.* (2002) *Inf Immunol* 70(11):6273-83

*Lau & Ashbolt (2009) *J Appl Microbiol* 107(3):368–378

QMRA for critical *Legionella* densities

Critical # in DW
$10^6 – 10^8$ CFU L^{-1}
based on QMRA model
Needs hosts to reach that



Aerosolization
Critical # 35 – 3,500 CFU m^{-3}
based on QMRA model

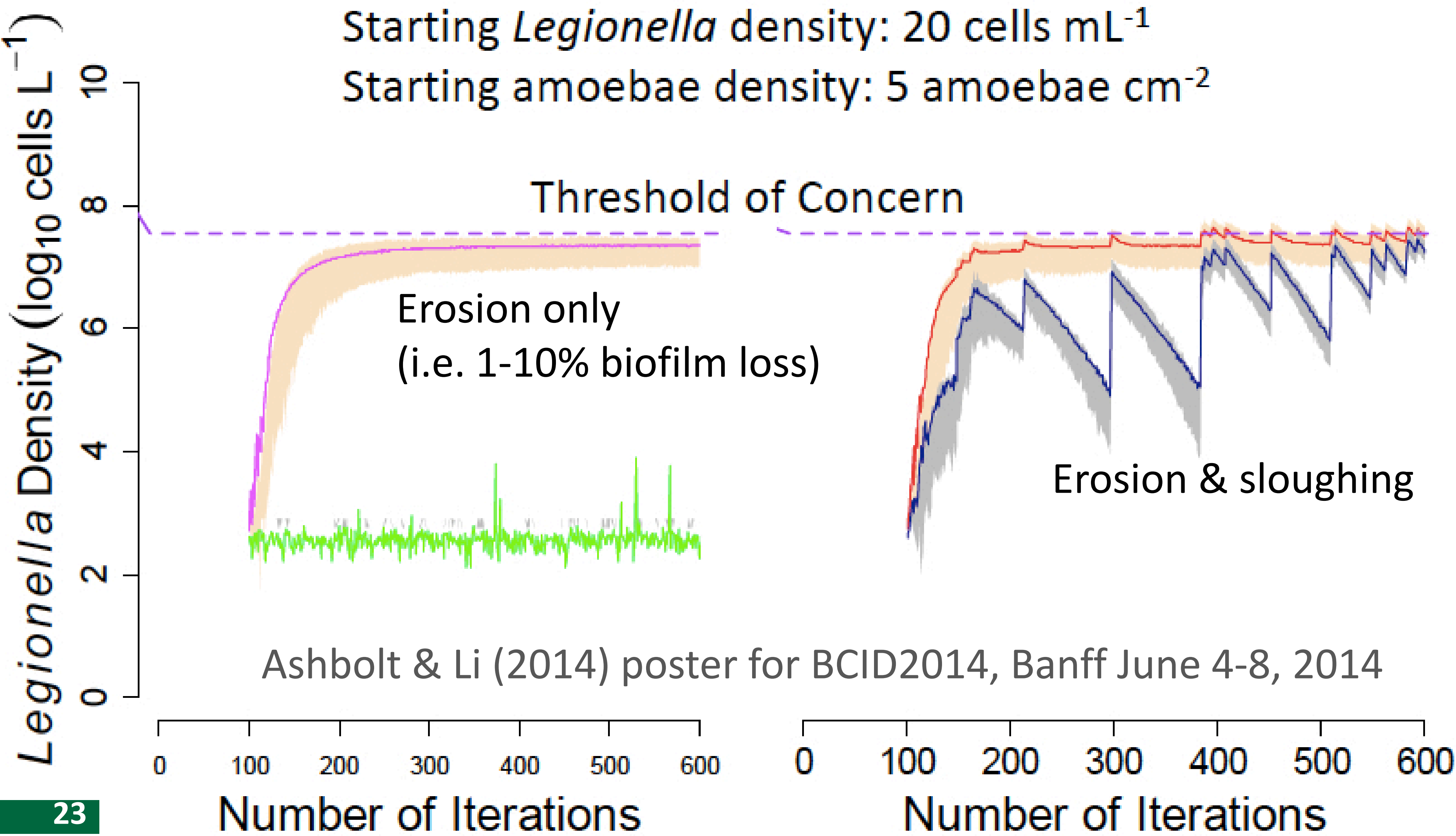
Inhalation

Biofilm colonization
and detachment

Deposition
1-1,000 CFU in lung
for potential illness

Schoen & Ashbolt (2011) *Water Res* 45(18): 5826-5836

QMRA-modelled *Legionella* densities



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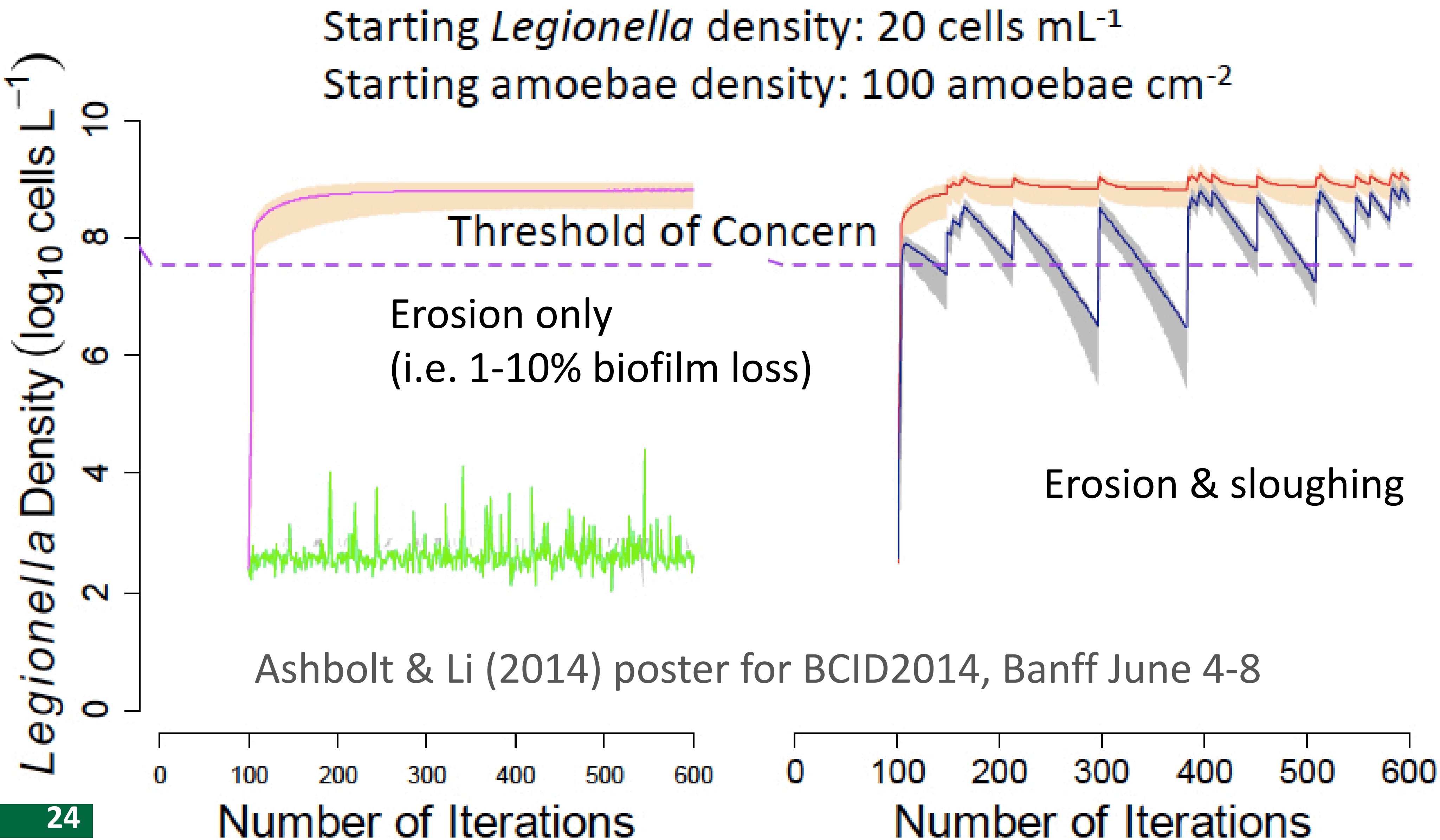


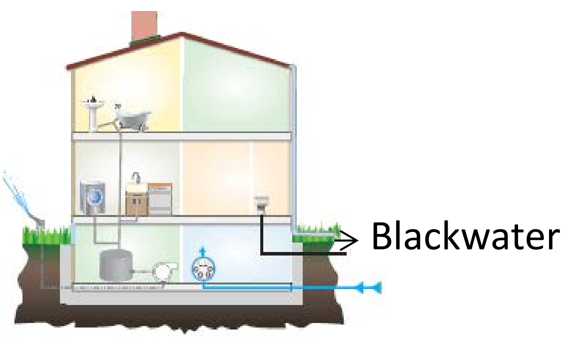
Cape Cod MA - Case Study

Systems Examined:

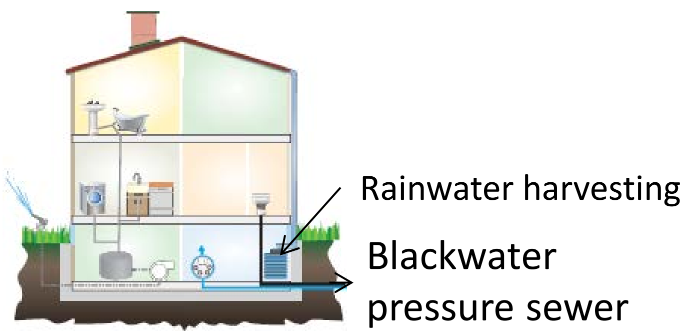
BAU: Sewer

CT-SS: Composting toilet with septic system

UD-SS: Urine-D toilet with septic system



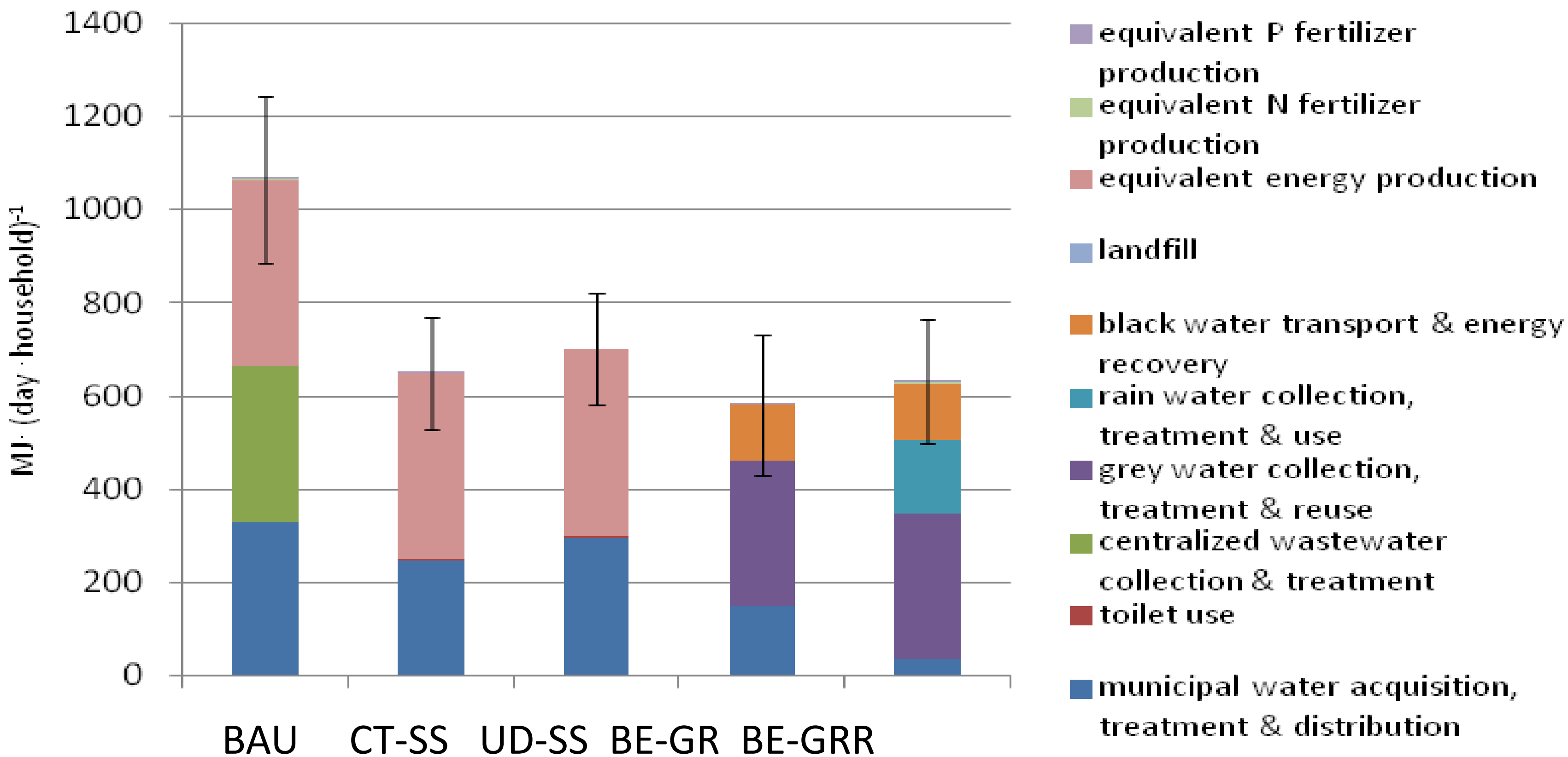
BE-GR: Blackwater sewer Greywater treat/reuse



BE-GRR: BE-GR+ Rainwater harvesting/reuse

Life Cycle Assessment

Results: LCA Energy consumption

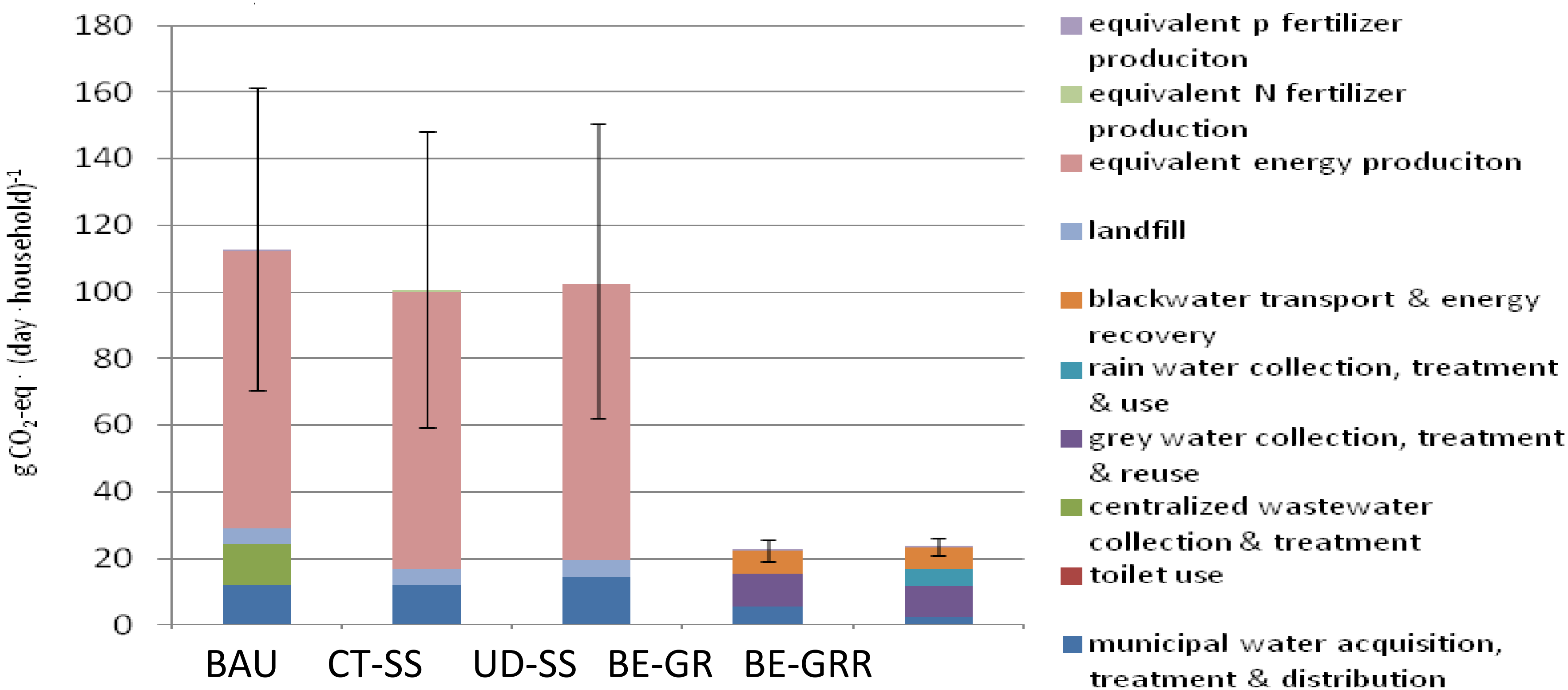


BAU: conventional centralized sewer; CT-SS: composting toilet; UD-SS: urine diverting toilet; BE-GR: onsite greywater treatment recycle +black water pressure sewer
BE-GRR: BBE-GR+ rainwater treatment

Xue *et al*. *Environ Sci Technol*, submitted

Life Cycle Assessment

LCA Global warming potential



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Xue *et al*. *Environ Sci Technol*, submitted

Human Health RA

- **Reference pathogens (Cape Cod)**
  - Human norovirus, *Campylobacter, E. coli* O157:H7, *Cryptosporidium* + *Legionella* (via rainwater system only)
  - Dose estimates: household & recreational exposure routes
  - Infection risks to disability-adjusted life years (DALYs)
- **Disinfection by-products (DBPs)**
  - The highest-risk class of chemicals associated with water & urban living (bladder cancer)
  - Focus on chloroform & bromodichloromethane
- **Most risk from recreational water**; e.g. as % of BAU
  - 63% for urine-diversion/septic, 23% composting toilet/septic, 15% for blackwater sewer, greywater reuse + RWH vs 1% without rainwater use

Schoen *et al.* (2014) *Environ Sci Technol* in press

Summary

- Performance-based targets (QMRA-derived) identified along the source-to-customer treatment train
  - Requires identified surrogates for pathogen management
- Managed within an overall water reuse safety plan with external audit (as per Alberta DWSP)
- Allows for innovation in treatment options / systems rather than specifying limited allowed components
  - And moves us on from reliance of *E. coli* verification to critical control point monitoring & performance validation

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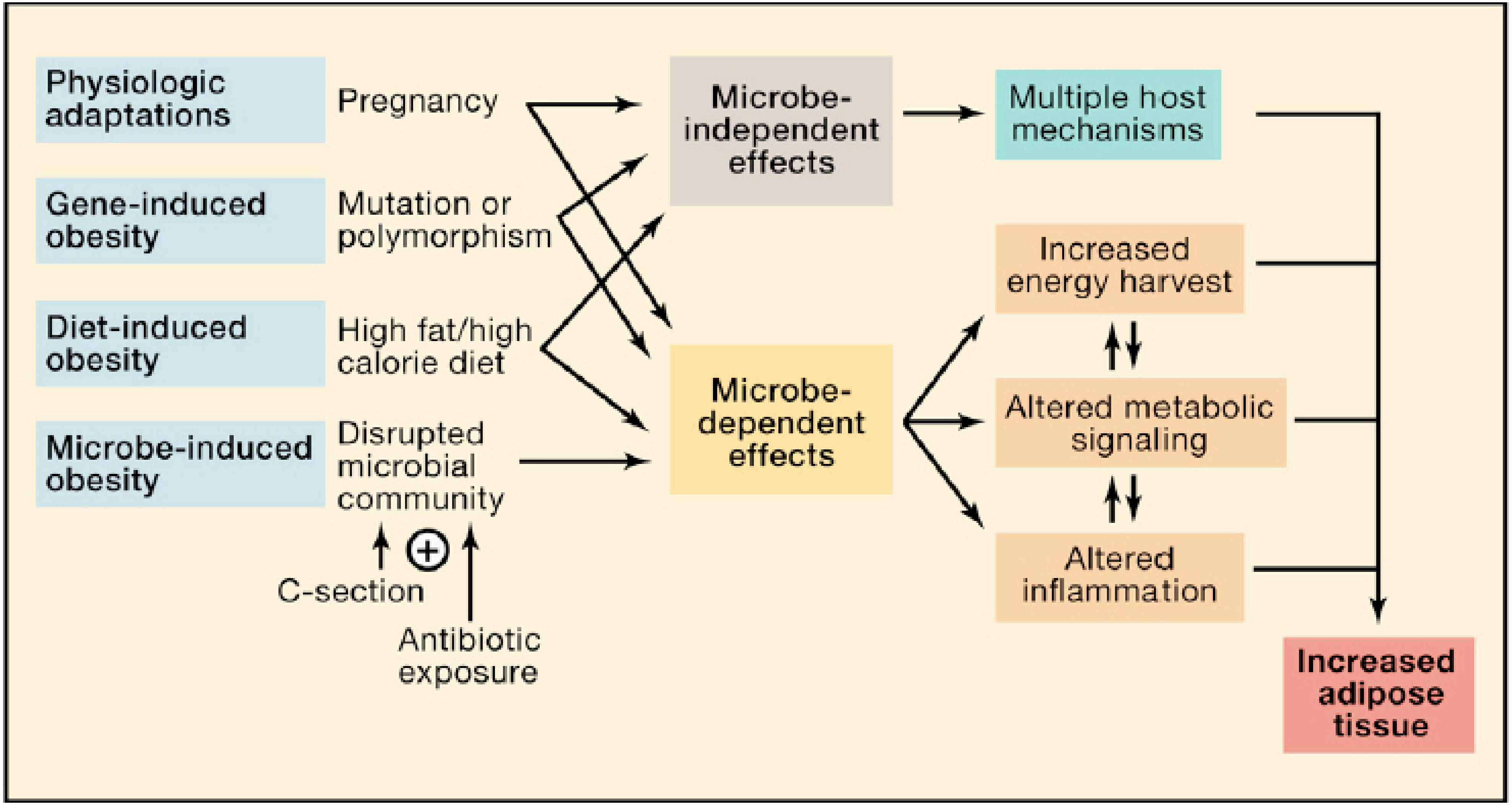
Sébastien Faucher (McGill)

Questions?

Direct potable reuse (DPR) 2013

- City of Brownwood, TX first in North America
  - Texas Water Development Board Funding approved Sept 20th, 2012
  - TCEQ approved plant construction on Dec 21st, 2012
  - Met Texas Water Development Board (TWDB) Engineering requirements and Chapter 290 of drinking water regs
  - Completed its 90 d evaluation 2013 now in use 60-80%
- DPR in Texas requires 7-9 log path removal
  - Using reverse osmosis, nano filtration, UV, activated carbon filter, NH_2Cl disinfection then DW plant
  - Yet no clear near real-time pathogen monitoring

Childhood antibiotic intake & Obesity



Cox & Blaser (2013) Cell Metabolism 7(6): 883-94

Iterative tiered approach for undertaking QMRA & asking what research is required for management