# Early Career Award: Framework for Quantifying Microbial Risk and Sustainability of Potable Reuse Systems in the United States

**Funding Opportunity Number:** EPA-G2014-STAR-F1

**EPA Grant Number:** R835823

**Project Period:** 8/2015 – 7/2018

**Dr. Daniel Gerrity**

Assistant Professor

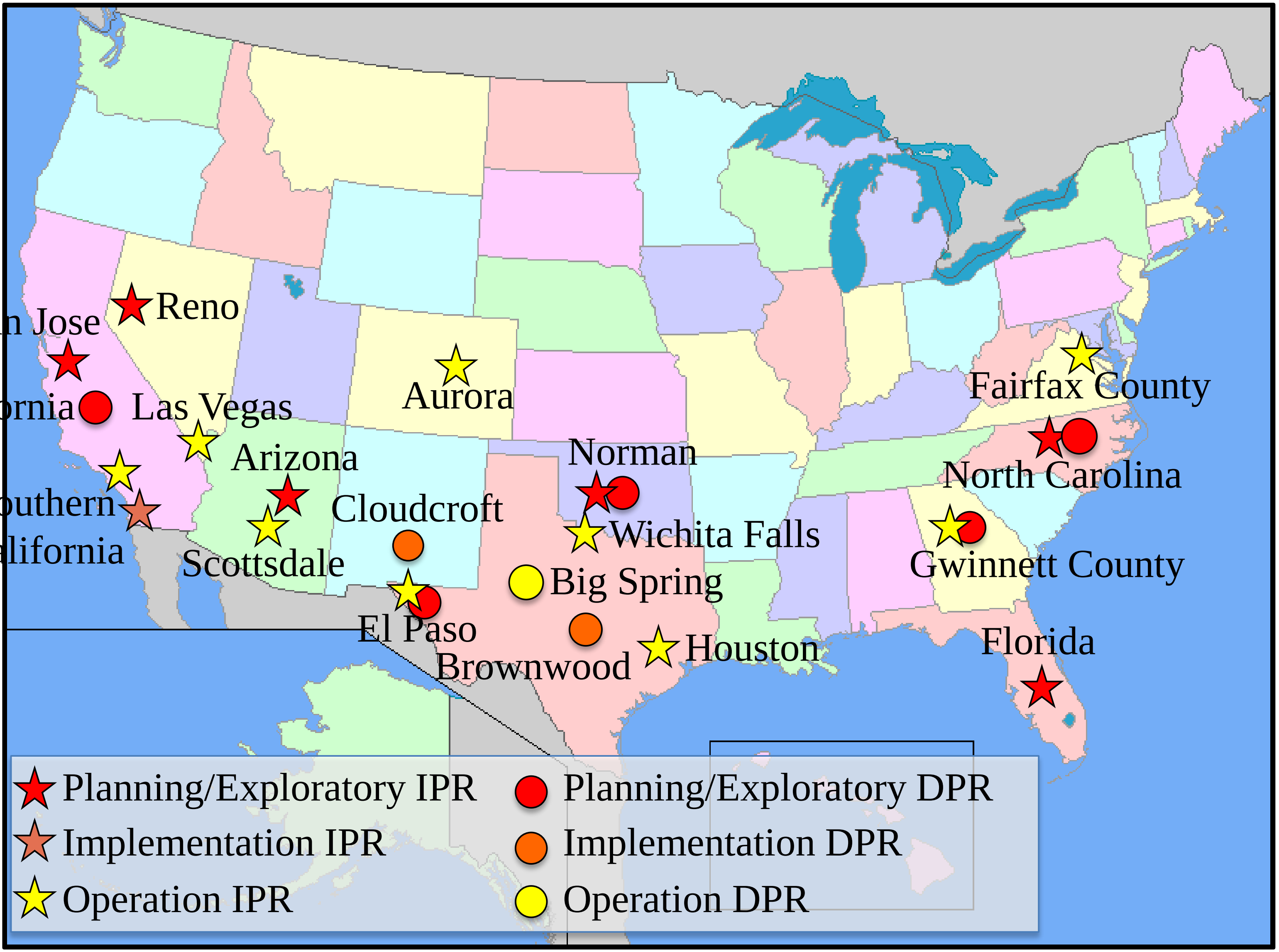
Department of Civil & Environmental Engineering and Construction

Email: Daniel.Gerrity@unlv.edu

Website: http://faculty.unlv.edu/wpmu/dgerrity/

UNLV

# Potable Reuse Systems in the U.S.




National Water Reuse Institute (NWRI), WateReuse Association, and WE&RF critical for the success of these projects

# Project Overview

- **Quantitative Microbial Risk Assessment (QMRA)**
  - Dr. Joseph Eisenberg (University of Michigan)
  - Dr. Brian Pecson (Trussell Technologies)
  - Erfaneh Amoueyan (Ph.D. Student at UNLV)

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  - Cory Dow (M.S. Student at UNLV / Carollo Engineers)
- **Potable Reuse Treatment with Ozone Biofiltration**
  - Dr. Eric Dickenson (Southern Nevada Water Authority)
  - Mayara Aquino (M.S. Student at UNLV) → THMs/HAAs
  - Fernanda Bacaro (M.S. Student at UNLV) → NDMA

# UNLV Film Department Collaboration

**Brett Levner**

- MTV, VH1, A&E, The History Channel, Animal Planet, Discovery, Atlantic Records, Coca-Cola, Greenpeace…
- Develop a short film to educate students/general public about potable reuse and the Las Vegas water system
- Collaboration begins in the Spring 2017 semester

**Motivation for Collaboration**

- ***Last Call at the Oasis*** trailer
- Research and experience indicates that public outreach and education are critical to the success of potable reuse
- Increase interest in environmental engineering in Southern Nevada

# RESEARCH TOPIC 1: QMRA

# Quantitative Microbial Risk Assessment

- **Evaluation of potable reuse treatment scenarios**
  - *de facto* Reuse
  - Indirect Potable Reuse
  - Direct Potable Reuse

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  - Viral Pathogen → future
  - Bacterial Pathogen → future

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  - Viral Pathogen → future
  - Bacterial Pathogen → future
- **Research Questions**
  - How do public health risks compare in different potable reuse systems under typical operational conditions?
  - How do failures in a treatment process impact the performance of the overall treatment train and ultimately public health risks?
  - What are the critical variables affecting public health risk in potable reuse systems?

# Model Objectives

- **Provide a template for adaptation to real-world systems**
  - Water quality (e.g., total organic carbon, $UV_{254}$ absorbance)
  - Dosing conditions (e.g., ozone dose, UV dose)
  - Baseline conditions (e.g., residence time, temperature)
  - Critical pathogens (e.g., dose response, survival)
  - Limits on log removal credits (e.g., 6-log max in California)

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  - Current: fault tree analysis from Windhoek studies
  - Current: ozone failure rate from Melbourne, Australia
  - Current: arbitrary failure rate for UV system (1%)

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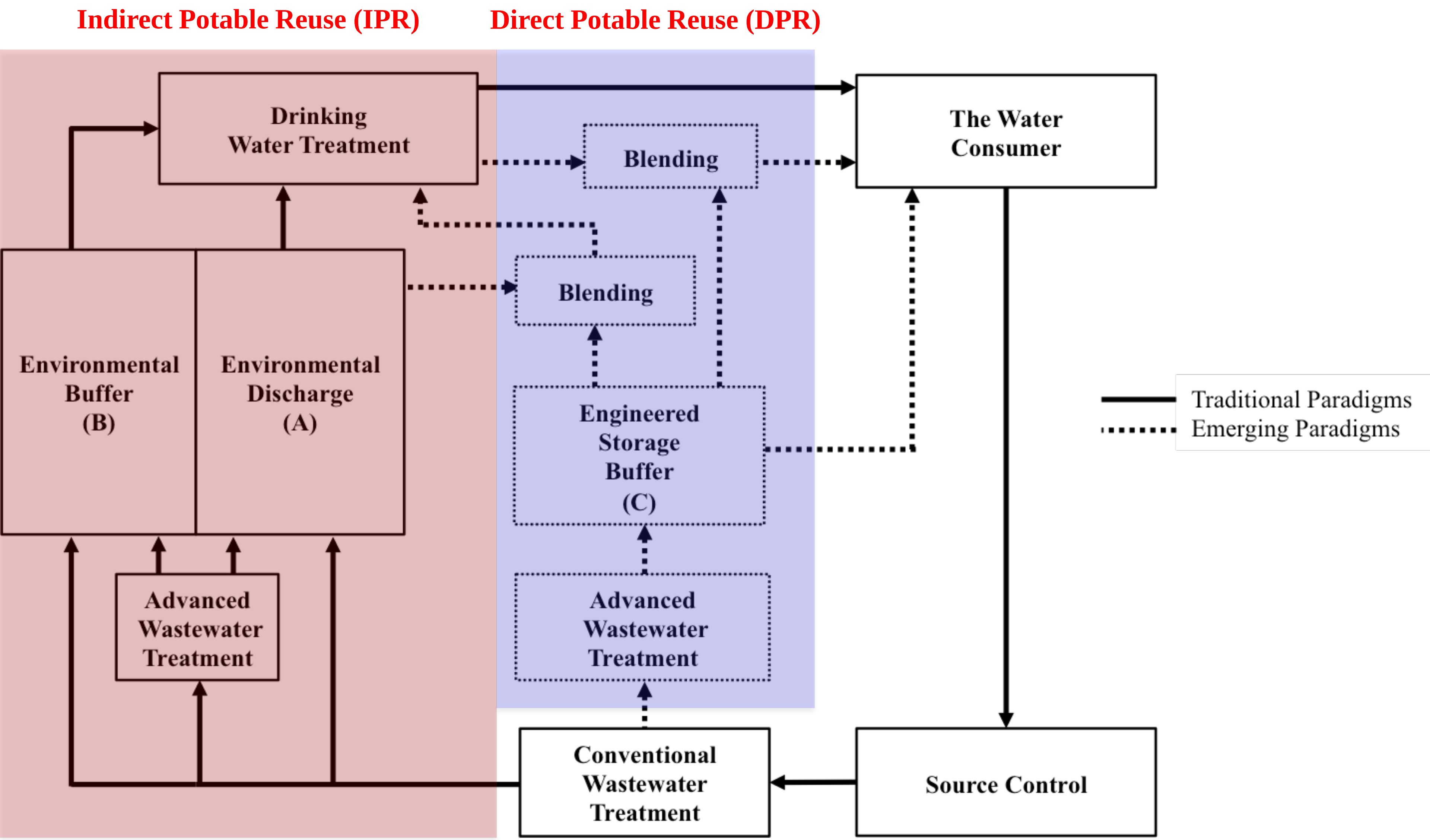
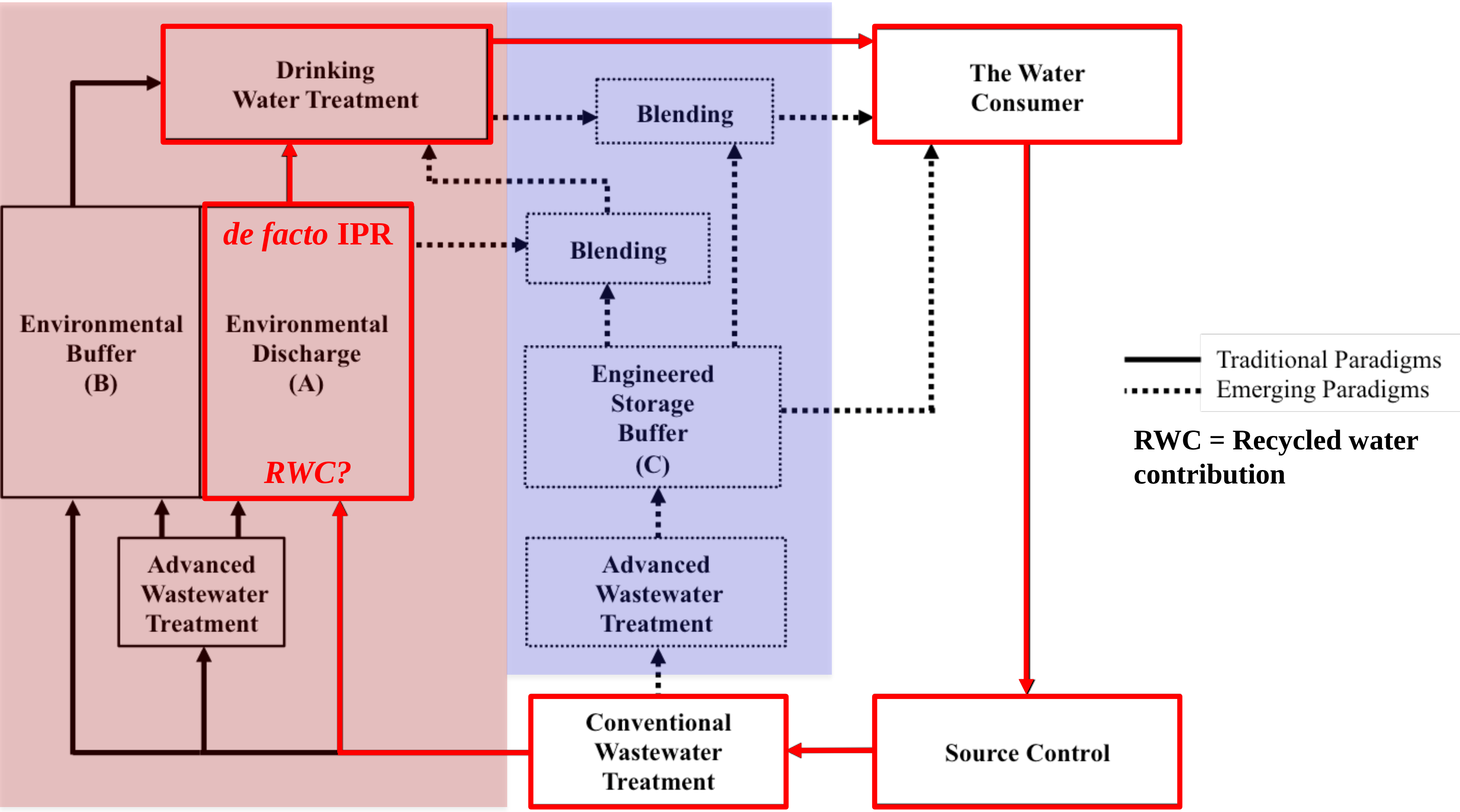
  - Current: ozone failure rate from Melbourne, Australia
  - Current: arbitrary failure rate for UV system (1%)
- **Allow for sensitivity analyses on model parameters**
  - Critical residence times in environmental buffers
  - Significance of failures (i.e., failure rates and 'domino effects')

# Potable Reuse Paradigms




**Source:** Gerrity et al. (2013) AQUA 62(6), 321-337

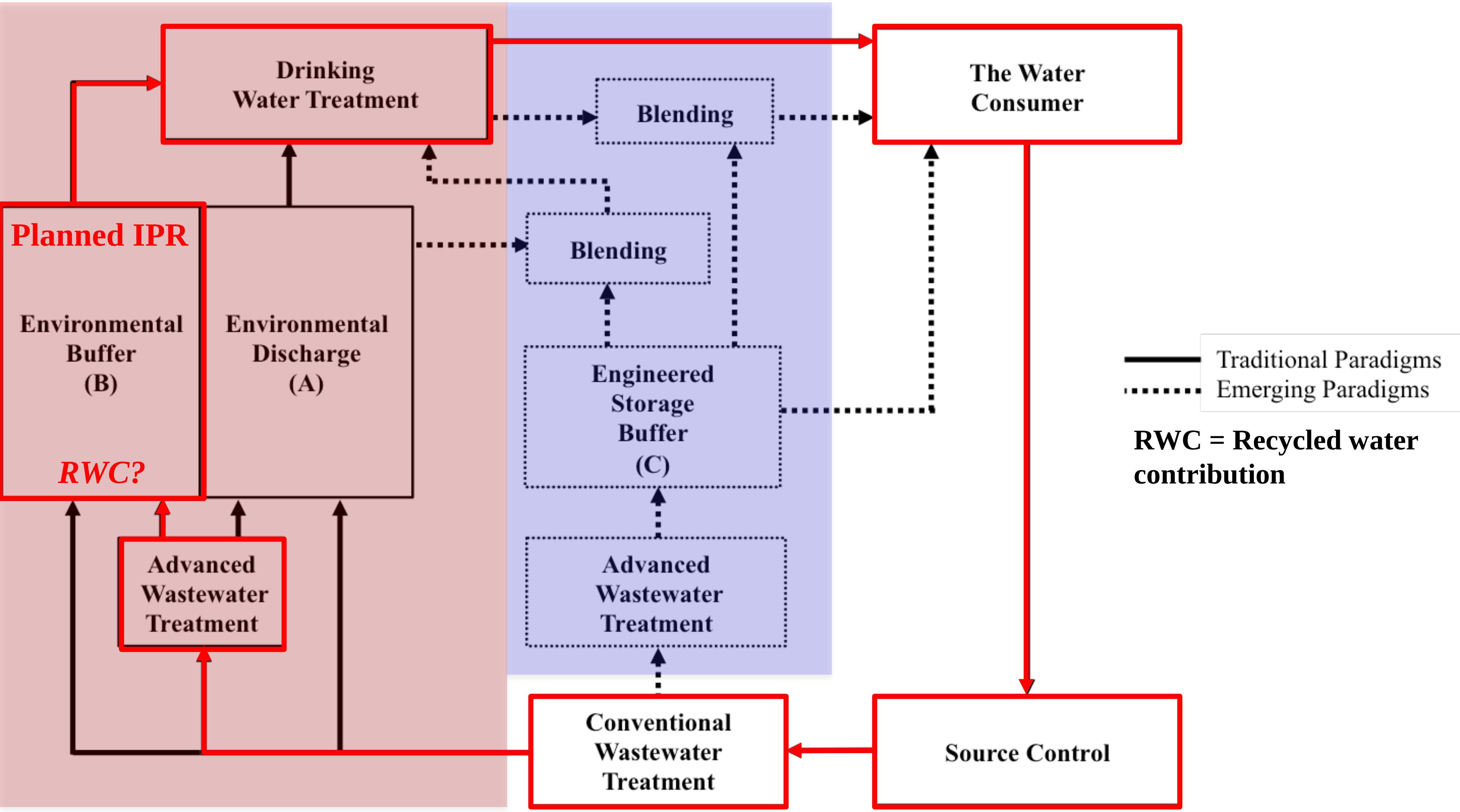
# Potable Reuse Scenario 1: *de facto* IPR




**RWC = Recycled water contribution**

**Source:** Gerrity et al. (2013) AQUA 62(6), 321-337

# Potable Reuse Scenario 2: Planned Indirect Potable Reuse

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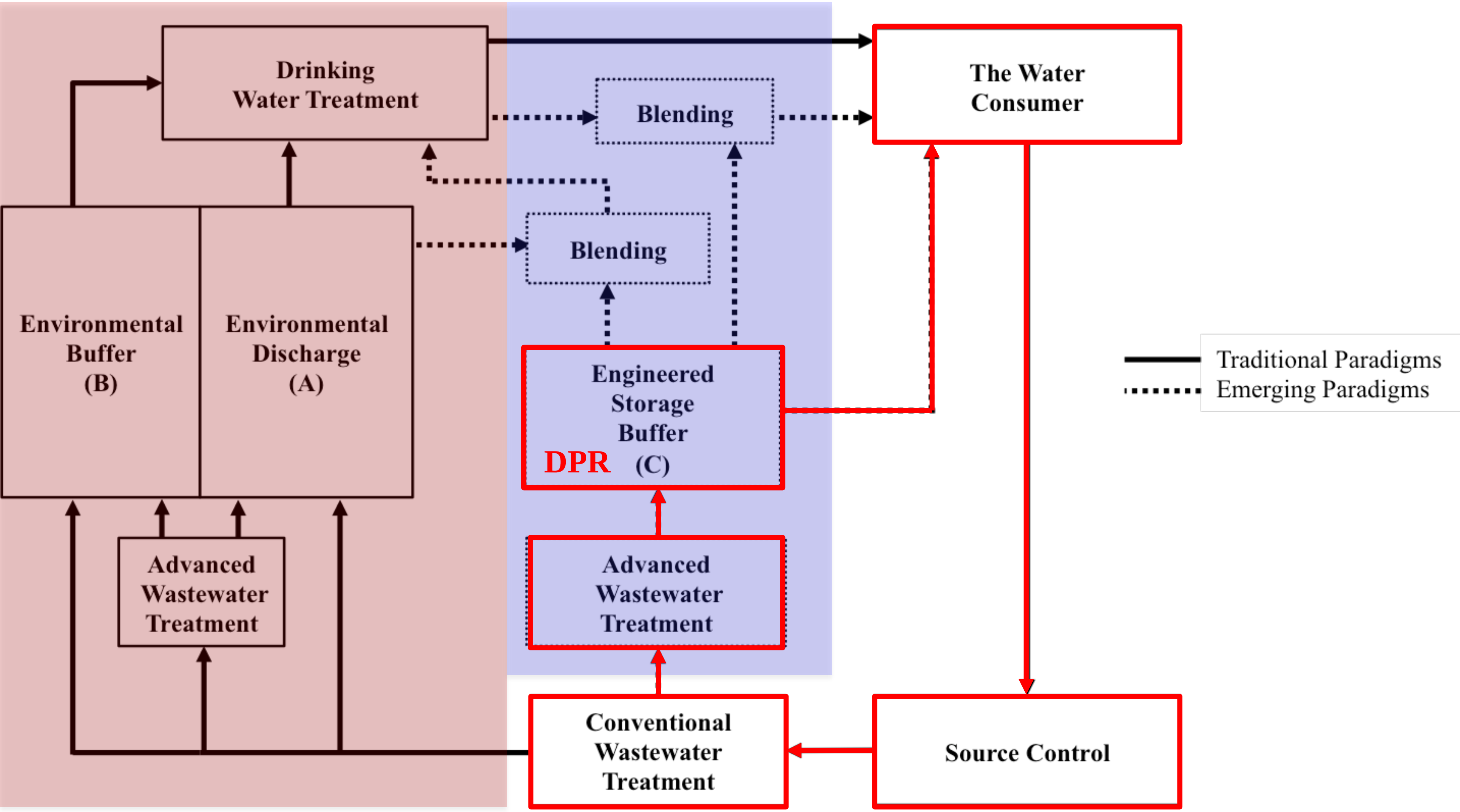
# Potable Reuse Scenario 3: Direct Potable Reuse



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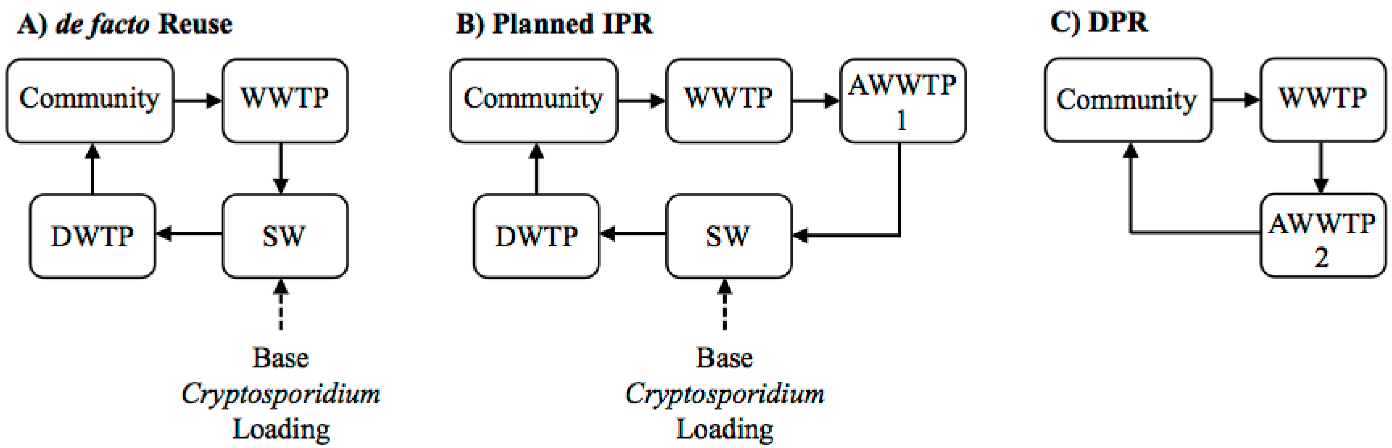
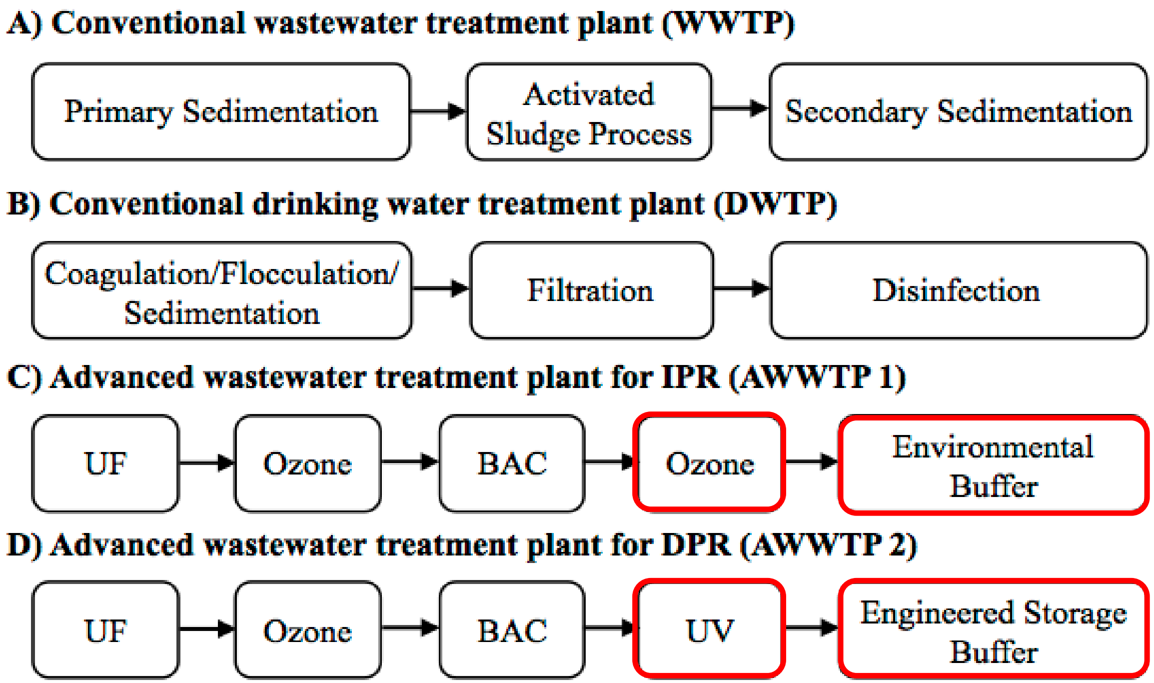
# Treatment Scenarios

**Scenarios:**




**Treatment Trains:**



# Methodology

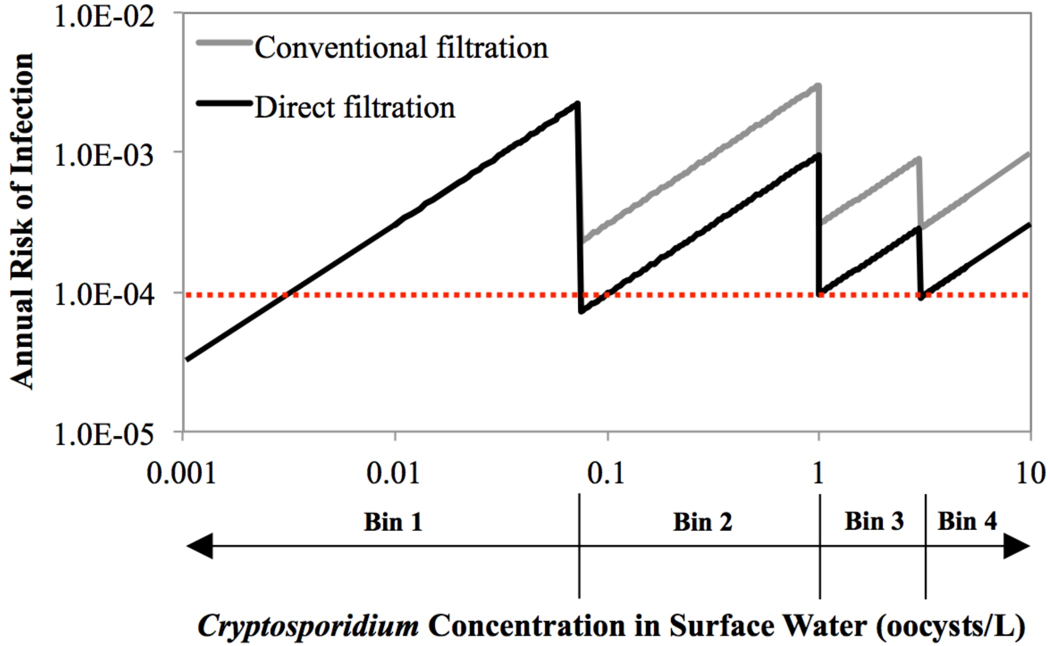
- **Model Framework**
  - STELLA 10.1 System Dynamics Software
  - 3 different *Cryptosporidium* scenarios based on LT2ESWTR
    - Affects upstream *Cryptosporidium* concentration and DWTP log removals
    - Model: Bin 1, Bin 2, and Bin 4

| Bin Classification | *Cryptosporidium* Concentration (oocysts) | DWTP (Conventional Filtration) |
|---|---|---|
| **Bin 1** | *Cryptosporidium* $< 0.075/L$ | No additional treatment |
| **Bin 2** | $0.075/L \leq$ *Cryptosporidium* $< 1.0/L$ | 1 log treatment |
| **Bin 3** | $1.0/L \leq$ *Cryptosporidium* $< 3.0/L$ | 2 log treatment |
| **Bin 4** | *Cryptosporidium* $\geq 3.0/L$ | 2.5 log treatment |

# Methodology

- **Public Health Benchmarks**
  - World Health Organization: $10^{-6}$ DALYs/person-year
  - California: 10-log removal/inactivation of *Cryptosporidium*
  - General: $10^{-4}$ annual risk of infection

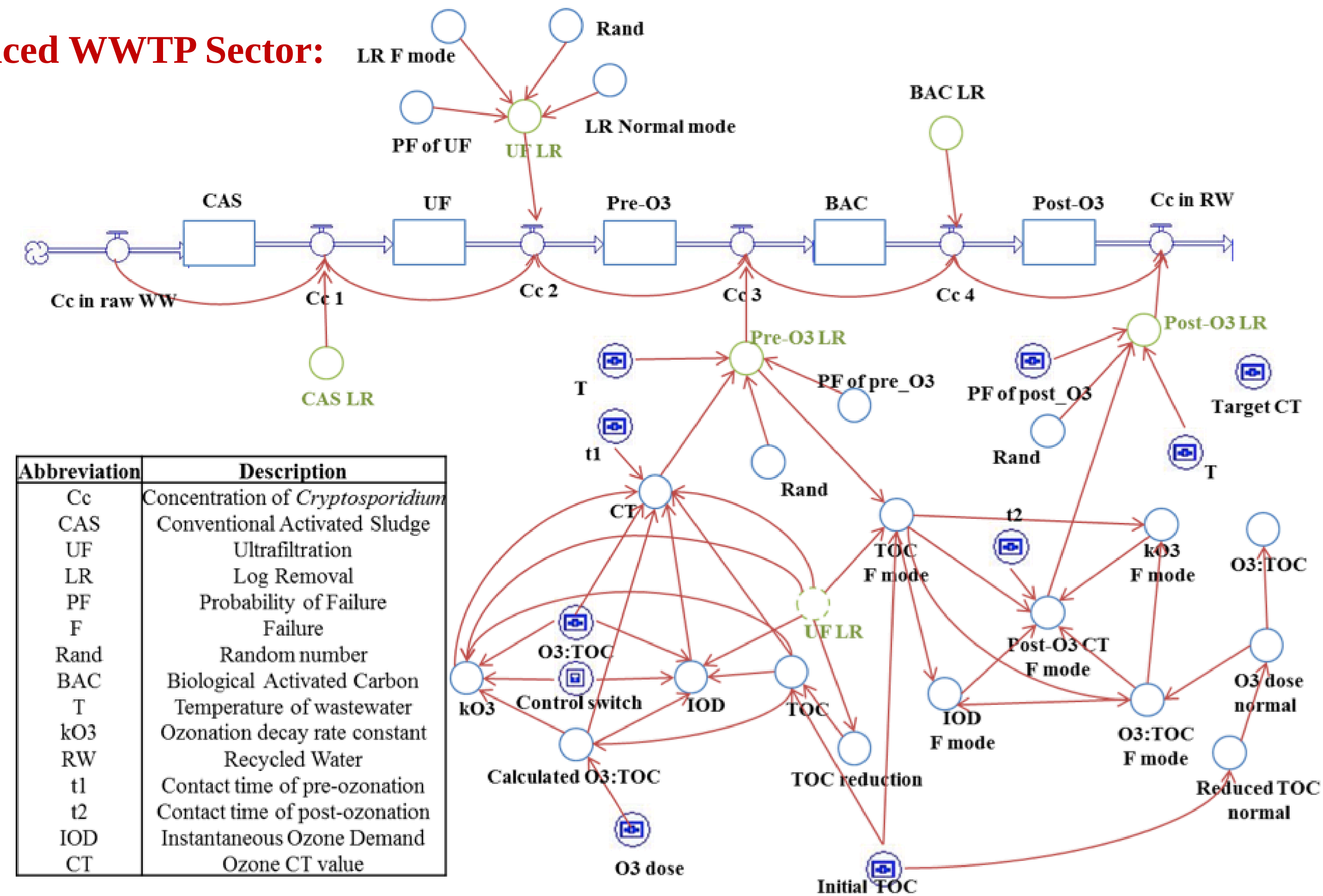
LT2ESWTR Framework and Infectivity Calculations from Literature



# STELLA System Dynamics Software

- A mathematical simulation methodology that describes the complex effects of system elements and their interrelationships using stocks, flows, convertors, and arrows.


**IPR Advanced WWTP Sector:**




| Abbreviation | Description |
|---|---|
| Cc | Concentration of *Cryptosporidium* |
| CAS | Conventional Activated Sludge |
| UF | Ultrafiltration |
| LR | Log Removal |
| PF | Probability of Failure |
| F | Failure |
| Rand | Random number |
| BAC | Biological Activated Carbon |
| T | Temperature of wastewater |
| kO3 | Ozonation decay rate constant |
| RW | Recycled Water |
| t1 | Contact time of pre-ozonation |
| t2 | Contact time of post-ozonation |
| IOD | Instantaneous Ozone Demand |
| CT | Ozone CT value |

# Planned IPR Model – Critical Steps and Parameters

- **WWTP**
  - 1-log removal of *Cryptosporidium*

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- **Ultrafiltration (UF)**
  - 4-log removal of *Cryptosporidium*
  - 0.3% failure rate → 0-log *Cryptosporidium* removal
  - Achieves reduction in $UV_{254}$ absorbance and total organic carbon (TOC)

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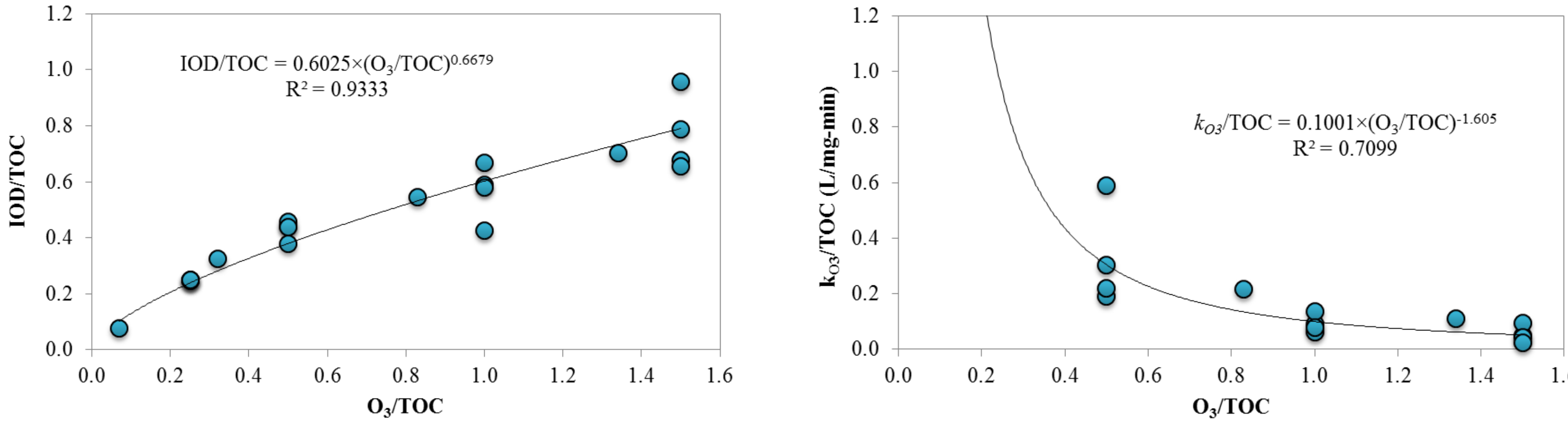
- **Pre-Ozone**
  - Dosing based on $O_3$/TOC ratio of 1.1 and inactivation based on ozone CT
  - Models developed to predict ozone demand/decay, CT, and $\Delta UV_{254}$ vs. $O_3$/TOC
  - 0.2% failure rate for ozone process → 0-log *Cryptosporidium* inactivation
  - Upstream failure of UF increases $UV_{254}$ and TOC → decreased $O_3$/TOC and CT



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  - Upstream failure of ozone → Assumes 5% TOC removal

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- **Environmental Buffer**
  - Considers upstream *Cryptosporidium* loading and recycled water contribution (i.e., dilution)
  - Considers *Cryptosporidium* die-off based on reservoir residence time and temperature

# Baseline Conditions for Model

| Parameter | | Description | Value | Units | Reference |
|---|---|---|---|---|---|
| **Risk calculations** | I | Proportion of symptomatic illness | 0.7 | Unitless | (Zhang et al., 2012) |
| | S | Susceptible proportion of population | 100% | Unitless | (Zhang et al., 2012) |
| | ω | Severity weight of *Cryptosporidium* | 0.0017 | DALYs/case | (Zhang et al., 2012) |
| | r | Infectivity parameter | 0.00419 | $oocysts^{-1}$ | (Ryu et al., 2007) |
| | w | Daily water consumption rate | 2 | L/per-day | (WHO, 2011) |
| **Wastewater** | $C_c$ | Influent oocyst concentration | Normal (74, 30) | Oocysts/L | (Kitajima et al., 2014) |
| **Pre-ozone** | $O_3$/TOC | $O_3$/TOC ratio | 1.1 | $mgO_3$/mgC | (Gerrity et al., 2014) |
| | TOC | Total organic carbon concentration | 7.2 | mgC/L | (Gamage et al., 2013) |
| | IOD | Instantaneous ozone demand | 4.0 | mg/L | See Text S2 – draft manuscript |
| | $k_{O3}$ | First order ozone decay rate constant | 0.54 | $min^{-1}$ | See Text S2 – draft manuscript |
| | $t_{O3}$ | Ozone contact time | 5 | min | (Au, 2004); See Text S2 |
| | T | Temperature | 25 | °C | (USEPA, 2010) |
| **Post-ozone** | $O_3$ CT | Target ozone CT | 5.0 | mg-min/L | (LeChevallier & Au, 2013) |
| | T | Temperature | 25 | °C | (USEPA, 2010) |
| **Environmental buffer** | $k_{oocyst}$ | Oocyst decay rate constant at 4°C | 0.0093 | $day^{-1}$ | (Peng et al., 2008) |
| | λ | Dimensionless temperature modifier | 0.095 | Unitless | (Peng et al., 2008) |
| | $T_{sw}$ | Temperature of surface water | 20 | °C | (Peng et al., 2008) |
| | RWC | Recycled water contribution | 20% | Unitless | (Rice et al., 2013) |
| | $t_{EB}$ | Storage time | 270 | days | (Wu, 2015) |
| **UV** | $I_{max}$ | UV incident (maximum) intensity | 25 | $mW/cm^2$ | Based on commercial UV system |
| | $x$ | UV path length | 10 | cm | (Lee et al., 2016) |
| | $k_A$ | UVA of nitrified effluent | 0.250 | $cm^{-1}$ | (Metcalf & Eddy, 2007) |
| | $k_A$ | UVA of filtered nitrified effluent | 0.175 | $cm^{-1}$ | (Metcalf & Eddy, 2007) |
| | $k_{UV}$ | Oocyst inactivation rate constant | 0.243 | $(mJ/cm^2)^{-1}$ | (Hijnen et al., 2006) |

# Risk Equations

## General Risk Framework:

$$P_{inf,d} = 1 - e^{-rCw}$$

$P_{inf,d}$ = daily probability of infection
r = infectivity parameter, $\text{oocysts}^{-1}$
C = oocyst concentration, oocysts/L
w = daily water consumption rate, L

$$P_{inf,a} = 1 - \prod_{i=1}^{365}(1 - P_{inf,d})_i$$

$P_{inf,a}$ = annual probability of infection

## Disability Adjusted Life Year (DALY) Framework:

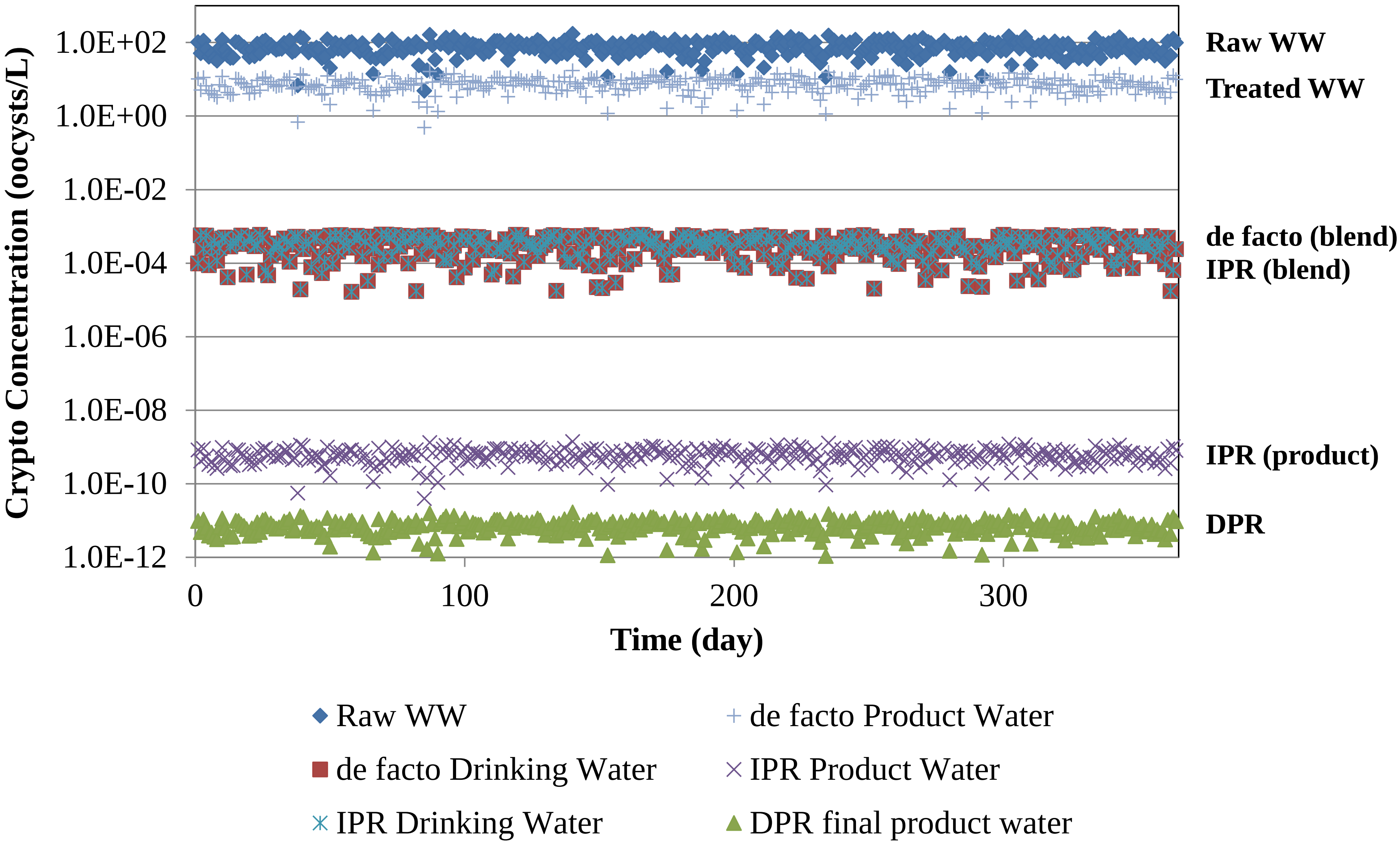
$$R = P_{inf,a} \times S \times I$$

R = annual risk of illness
S = susceptible proportion of population
I = symptomatic proportion of illnesses

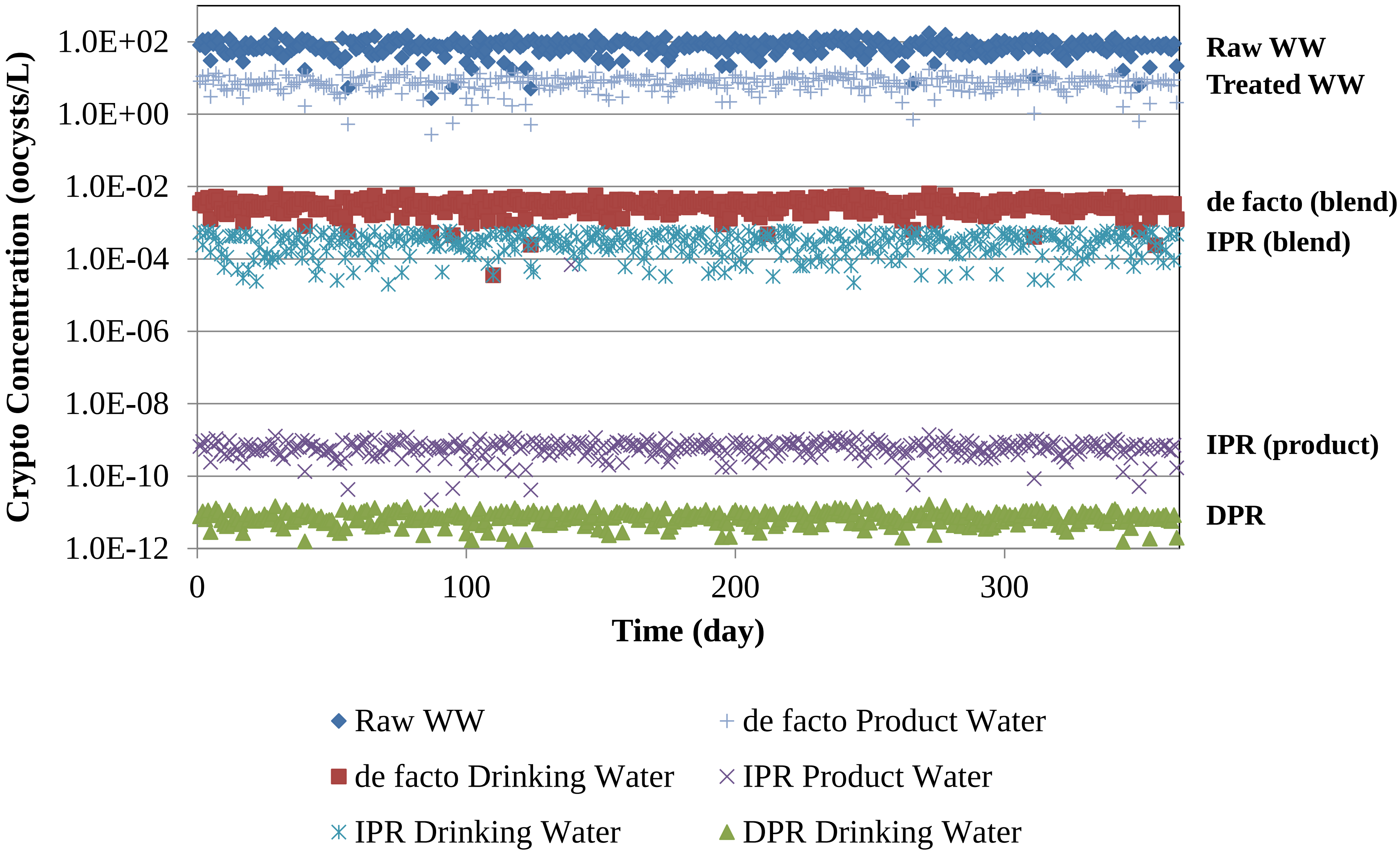
$$D = R \times \omega$$

D = disease burden, DALYs/person-year
ω = severity weight, DALYs/case

# Preliminary Data: Storage Time = 270 Days



# Preliminary Data: Storage Time = 45 Days



# Preliminary Conclusions

- **de facto vs. IPR vs. DPR**
  - Risk of infection significantly lower for advanced treated wastewater
  - Risk is generally controlled by RWC and environmental buffer
  - Failures are not particularly significant for these treatment trains/operational conditions when targeting *Cryptosporidium* → robust and redundant

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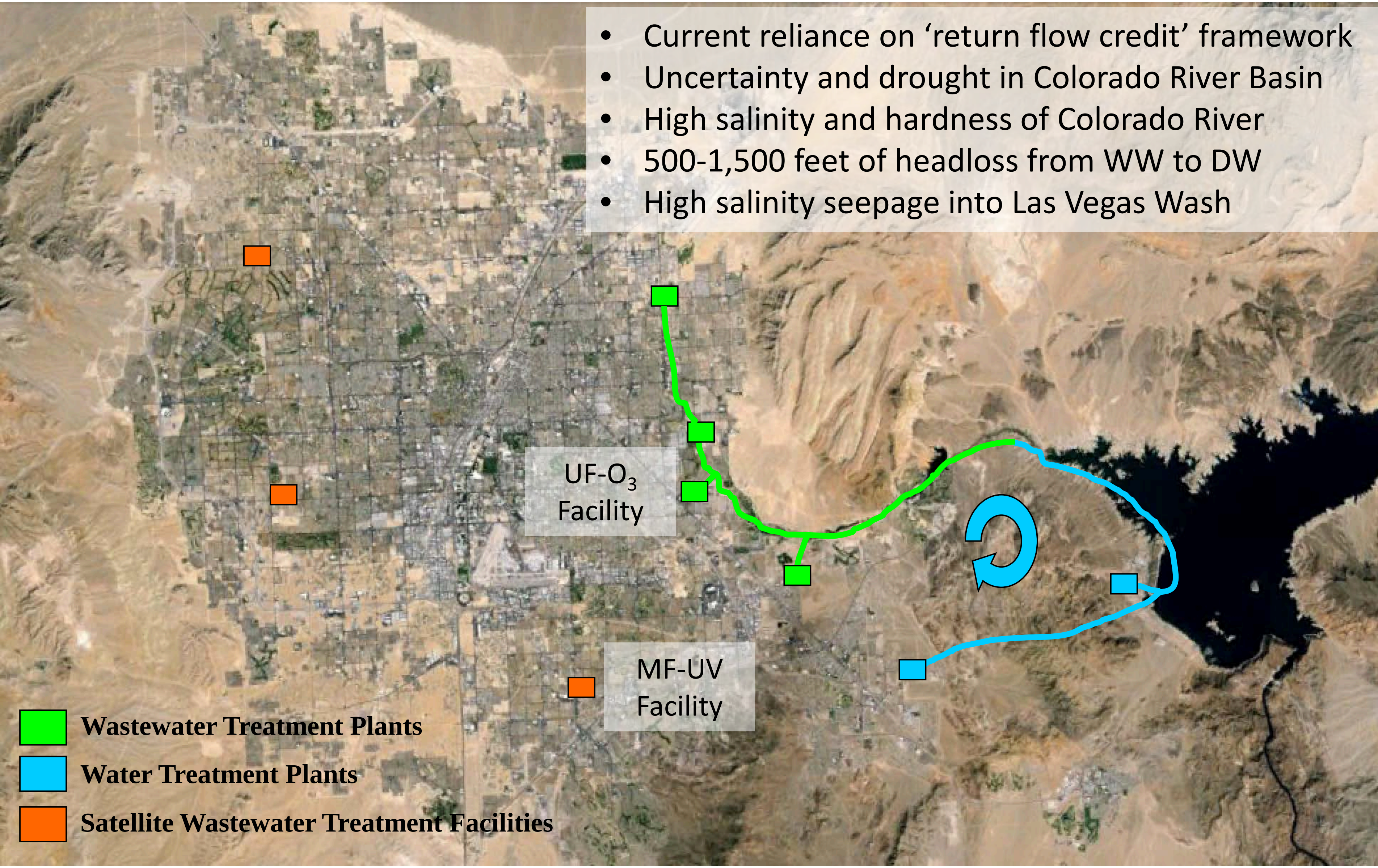
  - Failures are not particularly significant for these treatment trains/operational conditions when targeting *Cryptosporidium* → robust and redundant
- **Critical variables**
  - Retention time in the environmental buffer
    - No significant difference between de facto and IPR at 270 days
    - Critical threshold ≈ 60 days
  - Temperature in the environmental buffer
    - Significant when combined with shorter reservoir residence times
  - Recycled water contribution (RWC)
    - Higher RWC leads to decreased probability of infection
    - Impact varies with DWTP scenario (i.e., loading and bin classification)

# RESEARCH TOPIC 2: SUSTAINABILITY OF POTABLE REUSE

# Justification for Direct Potable Reuse – Las Vegas

- Current reliance on 'return flow credit' framework
- Uncertainty and drought in Colorado River Basin
- High salinity and hardness of Colorado River
- 500-1,500 feet of headloss from WW to DW
- High salinity seepage into Las Vegas Wash



# Sustainability of Potable Reuse in Las Vegas

- **Develop System Dynamics Model**
  - Water Flows (also Las Vegas Wash Ecosystem)
  - Water Quality (Salinity Loads)
  - Energy Consumption and Greenhouse Gas Emissions
  - Capital and O&M Costs

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- **Evaluate Scenarios**
  - Status Quo: Return Flow Credits / Indirect Potable Reuse
  - Direct Potable Reuse → Compare RO vs. Ozone-Biofiltration
  - Nevada Groundwater Pipeline

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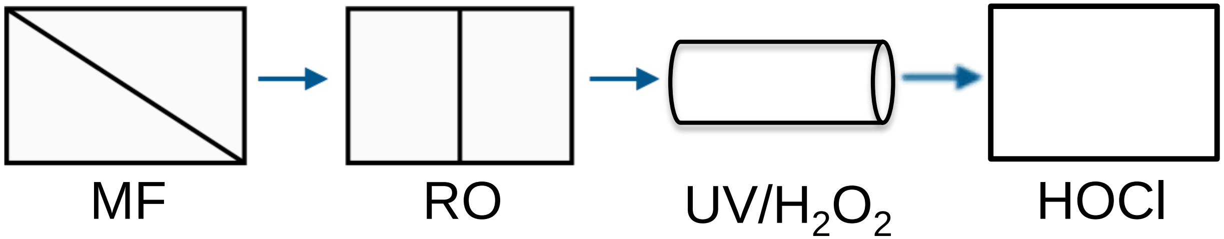
  - Status Quo: Return Flow Credits / Indirect Potable Reuse
  - Direct Potable Reuse → Compare RO vs. Ozone-Biofiltration
  - Nevada Groundwater Pipeline
- **Research Questions**
  - At what point (if any) is DPR economically viable considering the additional treatment that would be required?
  - What are the water quality and risk implications?

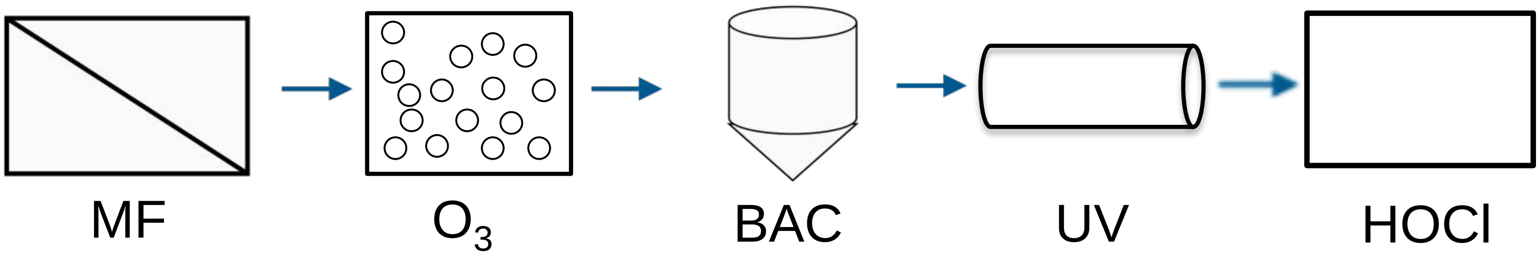
# RESEARCH TOPIC 3: OZONE BIOFILTRATION

# Potential DPR Treatment Trains

**Full Advanced Treatment:**




**Alternative based on Ozone-BAC:**




**Advantages of $O_3$-BAC**

- **Nearly complete TOrC removal**
- **Eliminates concentrated brine stream**
- **Reduced capital and O&M costs**
- **Reduced energy consumption**

**Disadvantages of $O_3$-BAC**

- **No reduction in TDS and higher TOC**
- **Disinfection byproduct uncertainty**
  - **Total trihalomethanes (TTHMs)**
  - **Haloacetic acids (HAA5s)**
  - **N-nitrosodimethylamine (NDMA)**

# Total Organic Carbon (TOC) Removal Criteria

$$TOC_{max} = \frac{0.5 \text{ mg/L}}{RWC}$$

(RWC = Recycled Water Contribution)

**Source:** CDPH (2014)

***Full advanced treatment with RO can achieve TOC < 0.5 mg/L:***

Expected TOC < 0.5 mg/L → RWC = 1.0

***Ozone-BAC can achieve 30-50% removal of TOC (multiple studies and full-scale plants):***

Expected TOC = 2.5 – 5.0 mg/L → RWC = 0.10 – 0.20

***Ozone-SAT can achieve more than 80% removal of TOC (Nishimura et al., 2013):***

Expected TOC = 1.0 – 2.0 mg/L → RWC = 0.25 – 0.50

The question is whether this TOC requirement is appropriate considering that the median TOC concentration of treated drinking water is ~3 mg/L (Trussell et al., 2013)

# Objectives of Research Topic 3

- **Chlorine Disinfection Byproduct Formation Potential (Ongoing)**
  - What is the relationship between $O_3$ dose, empty bed contact time, and TOC removal?
  - Can we use THM/HAA formation potential as a guide for TOC removal (similar to Stage 1 D/DBPR)?

| Source Water TOC (mg/L) | Alkalinity: 0 - 60 mg/L as $CaCO_3$ | Alkalinity: 60 - 120 mg/L as $CaCO_3$ | Alkalinity: > 120 mg/L as $CaCO_3$ |
|---|---|---|---|
| 2.0 – 4.0 | 35.0% | 25.0% | 15.0% |
| 4.0 – 8.0 | 45.0% | 35.0% | 25.0% |
| > 8.0 | 50.0% | 40.0% | 30.0% |

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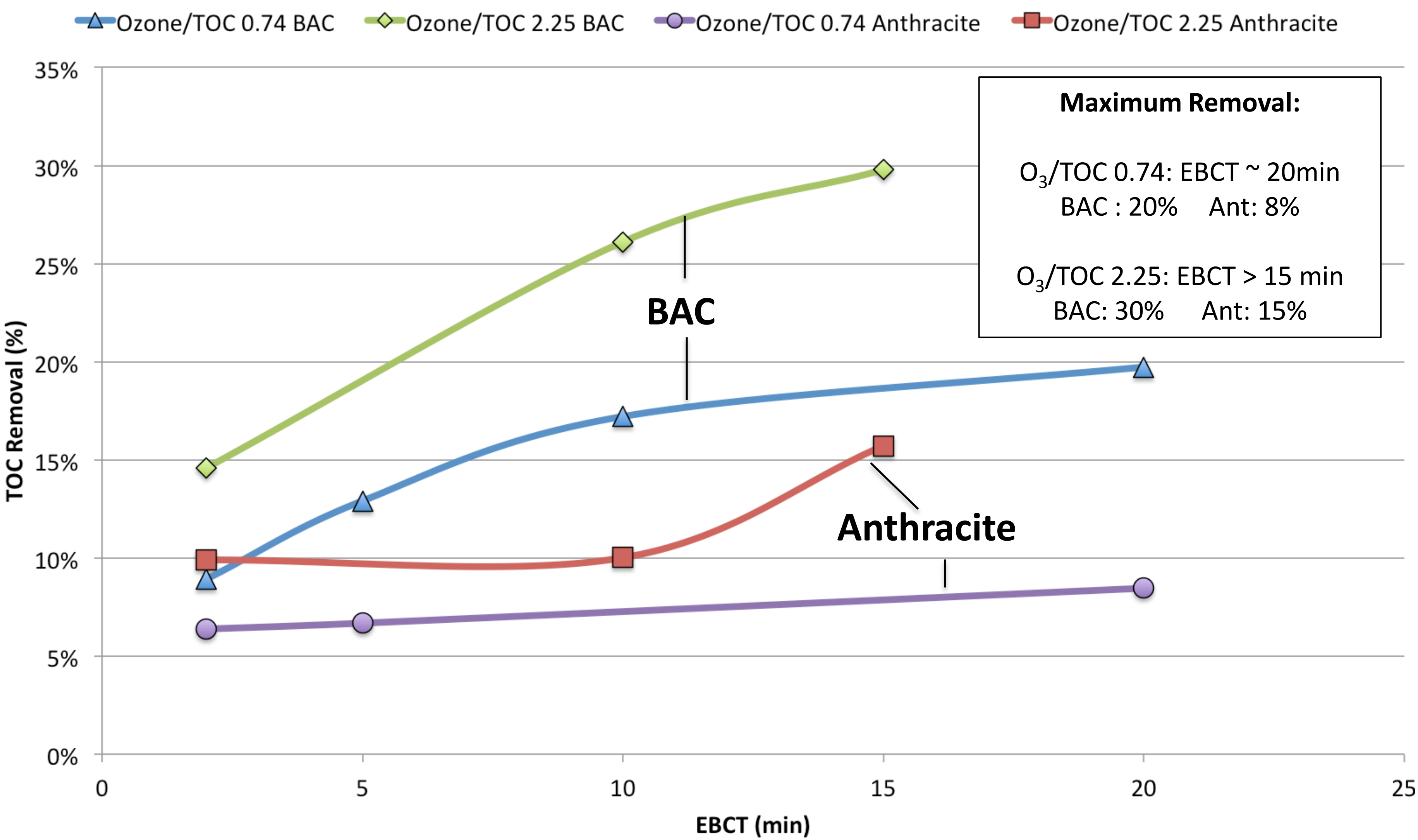
| > 8.0 | 50.0% | 40.0% | 30.0% |

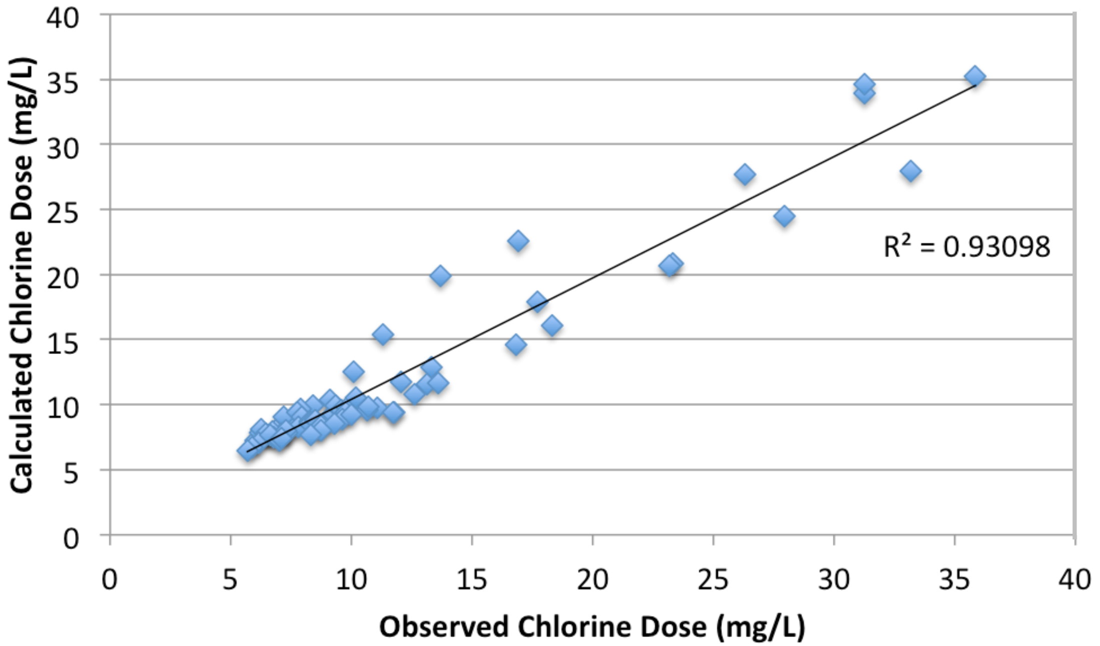
- ***N*-nitrosodimethylamine (NDMA) Formation and Mitigation (Future)**
  - What is the relationship between $O_3$ dose, empty bed contact time, and NDMA mitigation?
  - How can we optimize the biofiltration process to more reliably control NDMA mitigation?

# Current Progress: TOC Removal



# Current Progress: Chlorine Dose Correlation

- Residual ammonia was detected in some ozone-biofiltration samples (*Bradyrhizobium spp.*)
- Chlorine dose had to account for demand due to TOC and $NH_3$
  - Uniform Formation Conditions (UFC) = 1 mg/L free chlorine residual after 24 hours
- Empirical chlorine dosing requirements:




**Multivariate Linear Regression:**

Chlorine Dose (mg/L) = 8.2 × $NH_3$-N (mg/L) + 1.2 × TOC (mg/L)

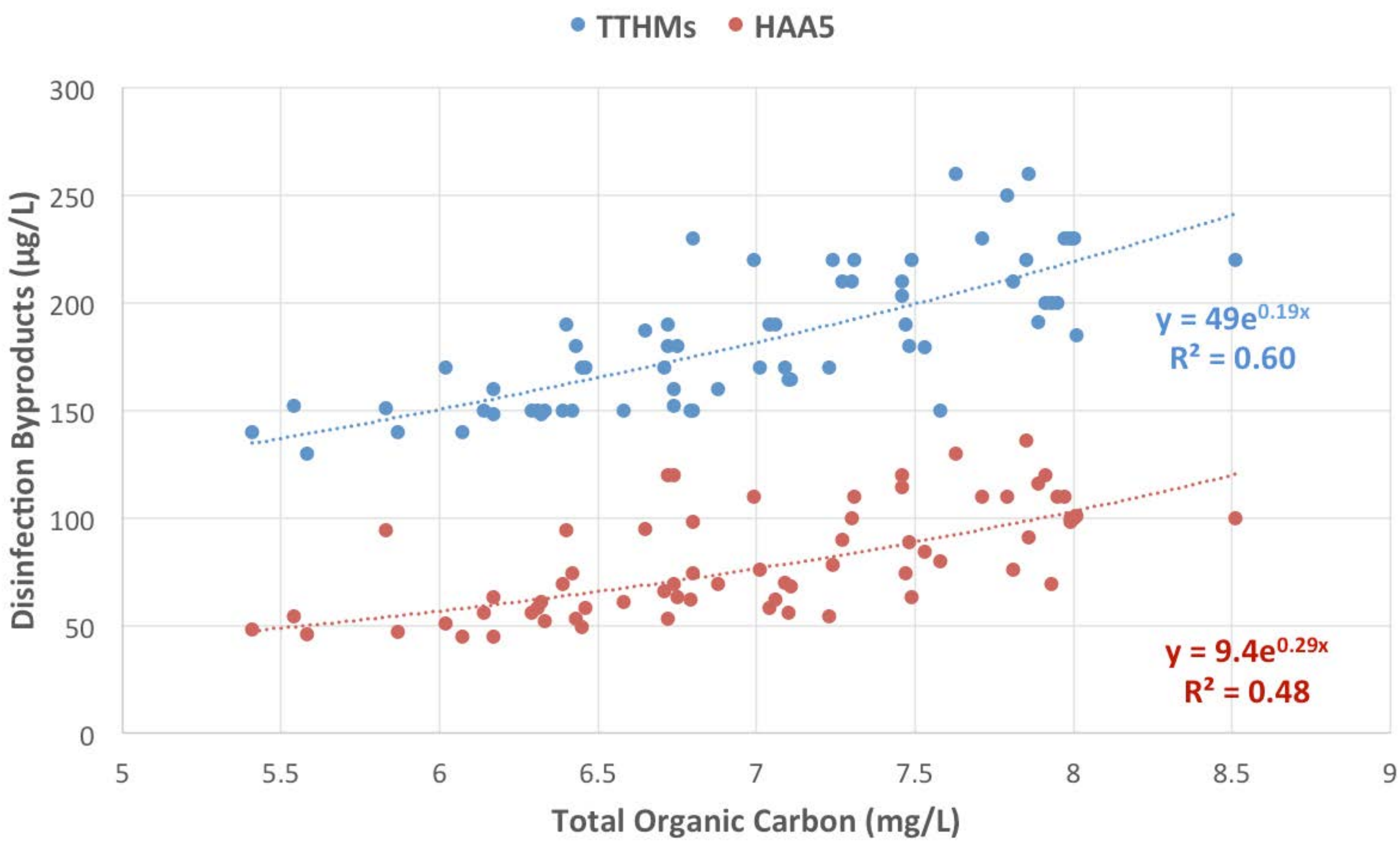
# Current Progress: DBP Summary

| | TTHMs (µg/L) | % Reduction | HAA5s (µg/L) | % Reduction |
|---|---|---|---|---|
| w/o Chlorine | <5 | <5 | <5 | <5 |
| MBR Filtrate | 226 | -- | 139 | -- |
| BAC | 206 | 9% | 102 | 27% |
| Ozone | 200 | 12% | 92 | 34% |
| Ozone+Anthracite | 168 | 26% | 70 | 50% |
| Ozone+BAC | 160 | 29% | 63 | 55% |
| EPA MCL | 80 | -- | 60 | -- |

Chlorinated (MBR Filtrate through Ozone+BAC)

***On average, all treated effluents would require further polishing to reliably achieve U.S. EPA MCLs for TTHMs (80 µg/L) and HAA5s (60 µg/L)***

# Current Progress: DBP/TOC Correlation




***Estimated TOC to achieve U.S. EPA MCLs:***

***TTHMs: TOC = 2.6 mg/L***

***HAA5s: TOC = 6.4 mg/L***

# Current Accomplishments

- **Research Topic 1: QMRA**
  - 1 Ph.D. student
  - Nearly complete system dynamics model for *Cryptosporidium*
  - Aiming for draft of first publication by end of Fall 2016
- **Research Topic 2: Sustainability of Potable Reuse**
  - 1 M.S. student
  - Significant progress on system dynamics model for Las Vegas
  - Aiming for complete model by end of Fall 2016
- **Research Topic 3: Ozone-Biofiltration**
  - 2 M.S. students
  - Significant progress on TOC removal and TTHMs/HAA5s
  - Microbial community characterization of biofiltration columns

# Next Steps

- **Research Topic 1: QMRA**
  - Expand model to address viral and bacterial pathogens
  - Expand model to include reverse osmosis
  - Expand model to include disease transmission
  - Compare relative risks of trace organics vs. pathogens
- **Research Topic 2: Sustainability of Potable Reuse**
  - Complete model and evaluate policy/water resource scenarios
    - ‘Return Flow’ vs. DPR vs. Groundwater Pipeline
- **Research Topic 3: Ozone-Biofiltration**
  - Evaluation DBP formation with different blending ratios
  - Restart ozone-biofiltration system to evaluate NDMA mitigation
  - Evaluate trace organic compound (TOrC) mitigation (PFOS/PFOA)
- **UNLV Film Department Collaboration**
  - Create short film related to potable reuse