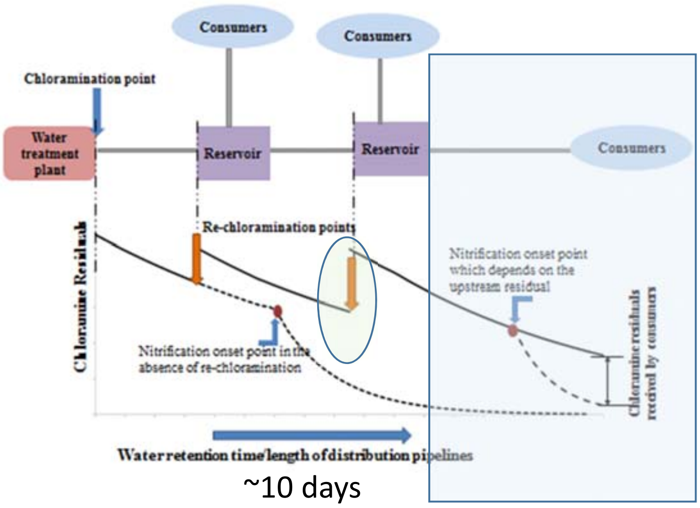
Achieving disinfection in engineered systems with minimal side effects

(Sathaa) Arumugam Sathasivan
School of Engineering;
Western Sydney University
s.sathasivan@westernsydney.edu.au

WSU Water Group

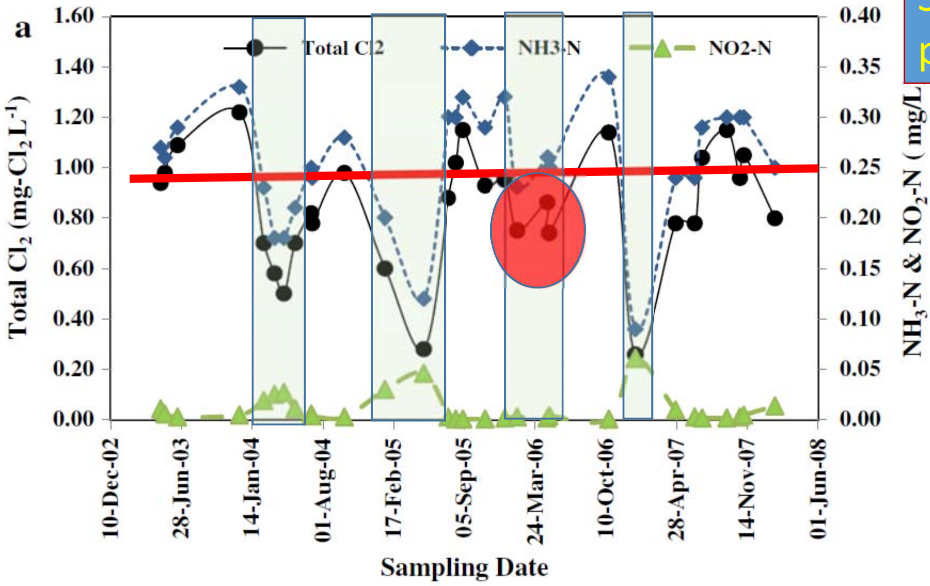
Chloramine profile along the system



WSU Water Group

Current status in many reservoirs

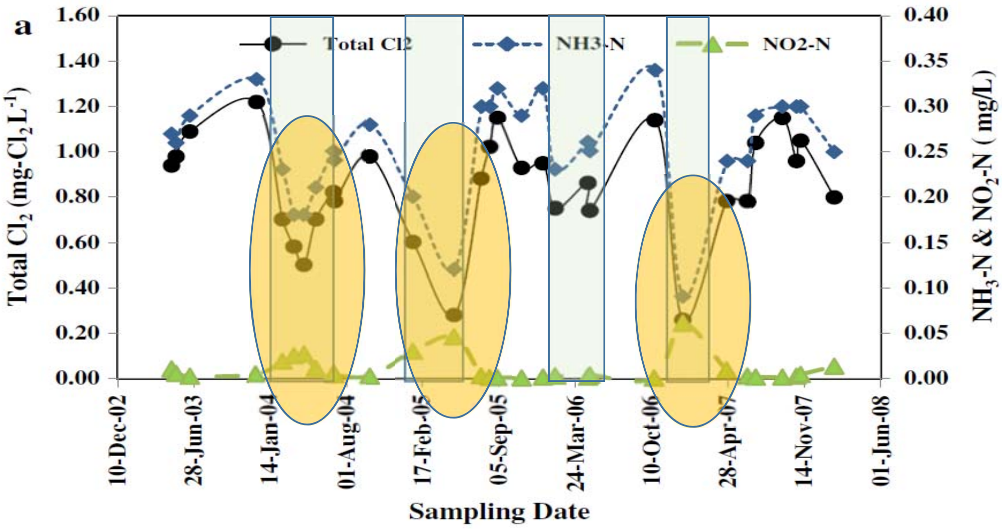
Summer is problematic.



Chlorine addition does not always help or it cannot always be added.

WSU Water Group

Traditional approach



Monitor parameters associated with nitrification, study and research solely about nitrifiers and their control for the last 100 years!!

WSU Water Group

Problem of traditional method

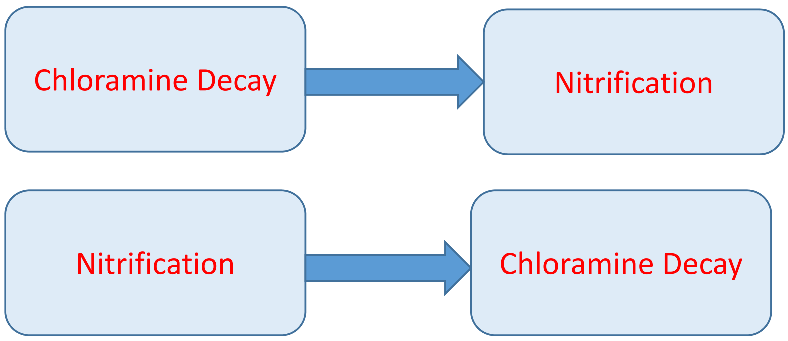
- No quantification, no prediction and hence no warning!!
- Always do their best to control the food to near zero level (Cl2/NH3 ratio close to 4 – if we go more than that chlorine chemically disintegrate)!! OVER/UNDER REACTION ???

WSU Water Group

Is traditional approach right?

Which occurs first?

Is decay from only nitrifiers?



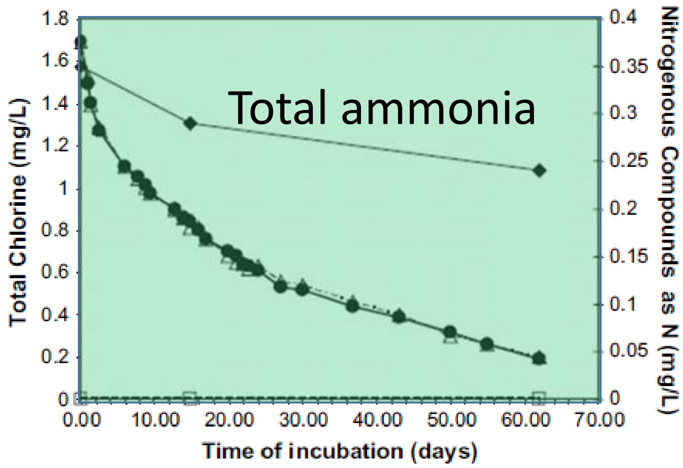
Is the decay microbial or chemical?

Developed microbial decay factor (F_m) method

Sathasivan, Fisher, Kastl (2004);
Environmental science & technology 39 (14), 5407-5413

WSU Water Group

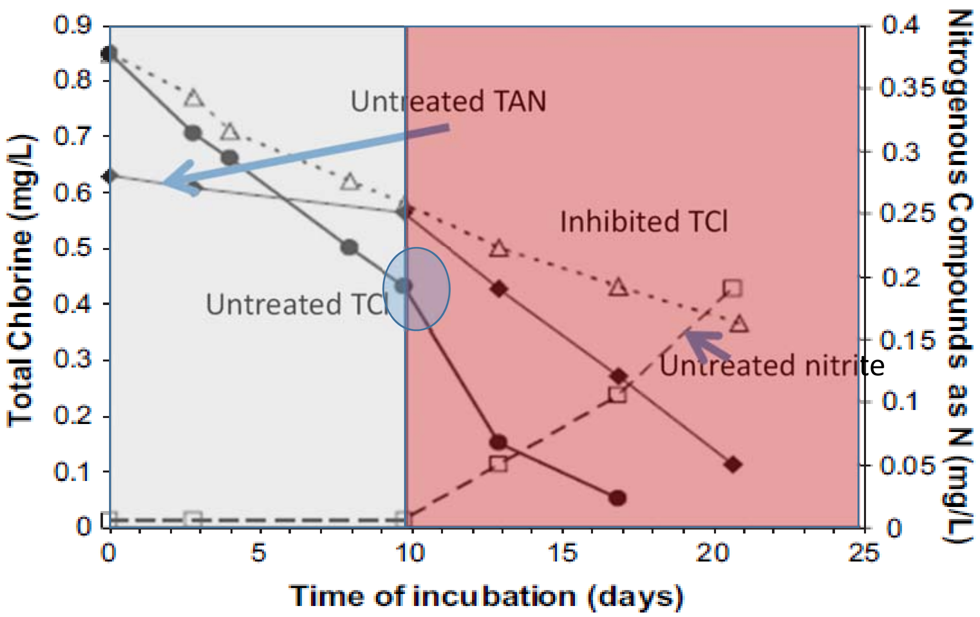
Water from filtration plant (all chemical decay)



Sathasivan, Fisher, Tam (2008)
Water research 42 (14), 3623-3632

WSU Water Group

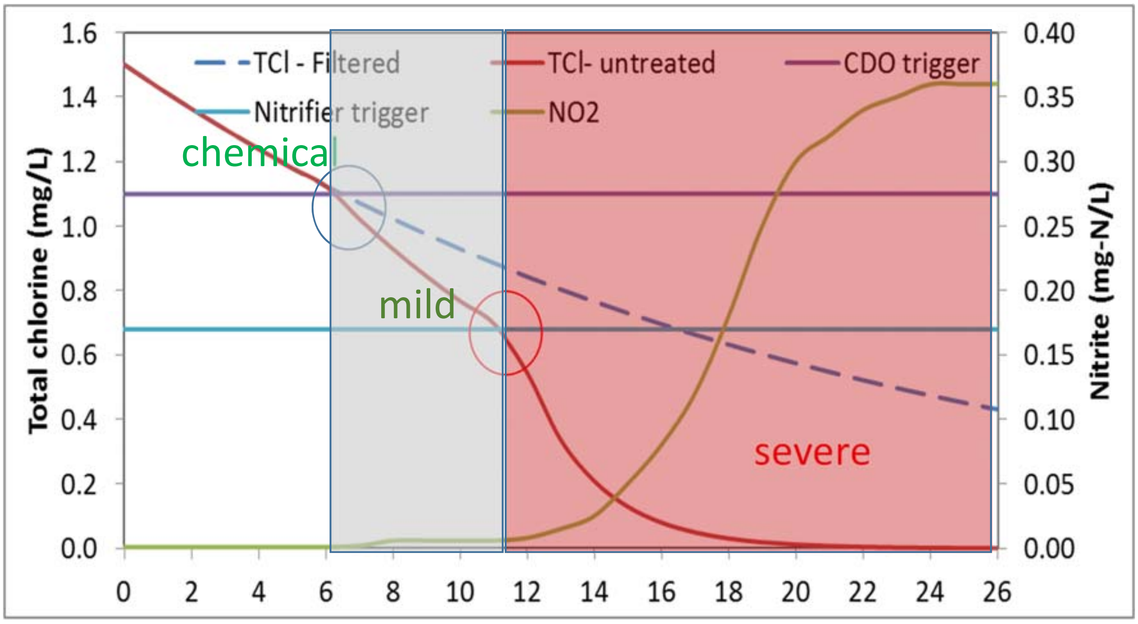
Water from retic system (mild and severe)



Sathasivan, Fisher, Tam (2008)
Water research 42 (14), 3623-3632

WSU Water Group

What did F_m method reveal?



WSU Water Group

Biostable residual concentration (BRC) concept?

- Disinfectant (Chlorine) tries to kill
  - Kill rate α disinfectant concentration

  ➔Kill rate r_d= k.Cl
- Growth rate, $r_g = \mu_m \frac{S}{Ks+S}$
- If $r_g = r_d$, bacterial number remains constant
- If $r_g > r_d$, bacterial number increases
- If $r_g < r_d$, bacterial number decreases
- A chlorine concentration at which $r_g = r_d$ is called BRC

In a chloraminated system

- For nitrifiers, free ammonia is the substrate

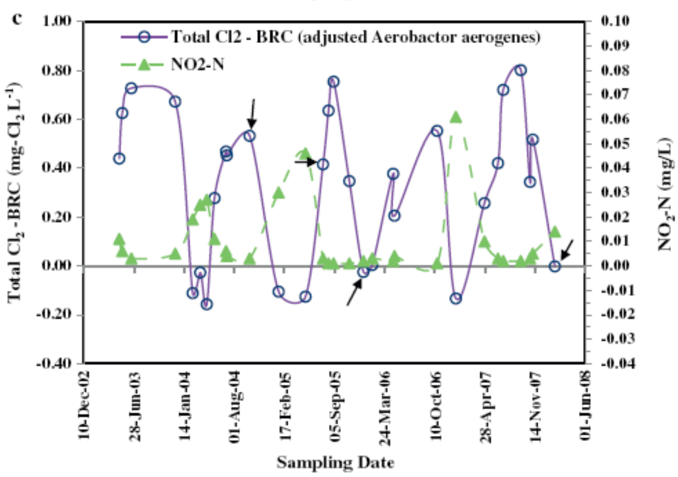
$$\frac{\mu_m (\text{free ammonia})}{(K_s + \text{free ammonia})} = k_d \times \text{BRC}$$

TCl>BRC killing
TCl<BRC growth

Sathasivan, Fisher, Tam (2008)
Water research 42 (14), 3623-3632

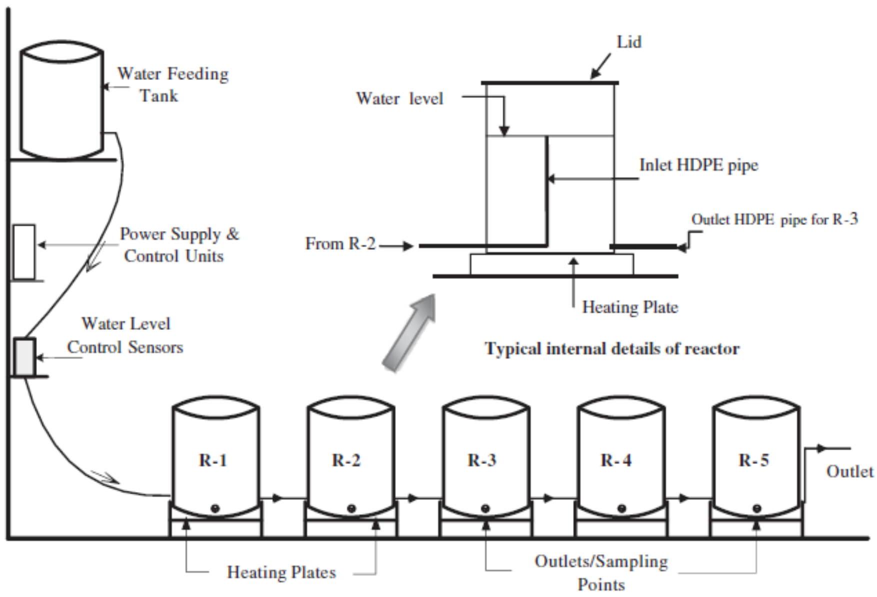
μ_m, k_d are functions of temperature

The model predicts the problems of growth



DC Sarker, A Sathasivan, CA Joll, A Heitz
Science of the Total Environment 454, 88-98

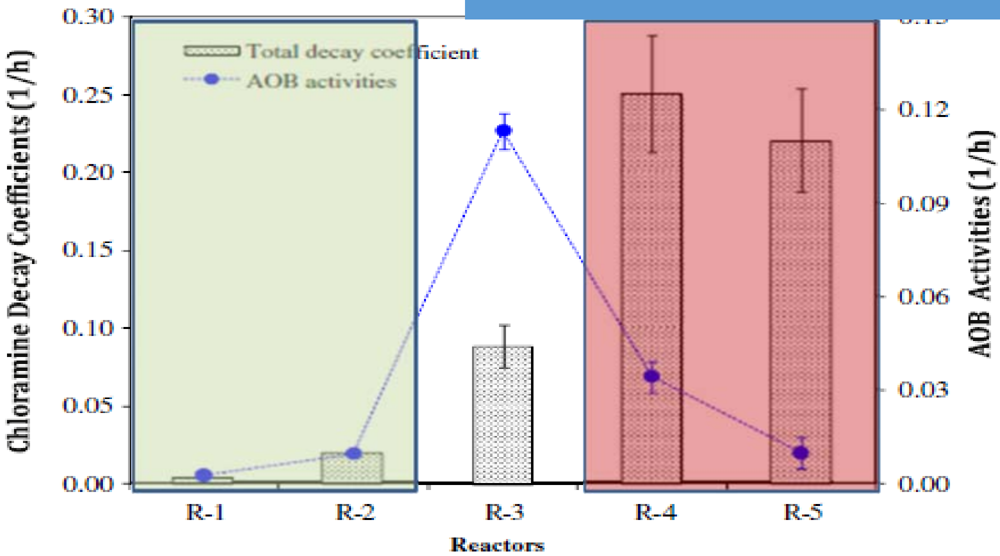
Reactors simulating various phases



WSU Water Group

Initially NOx production correlates decay, but later it d

Is that chemical decay from nitrite?

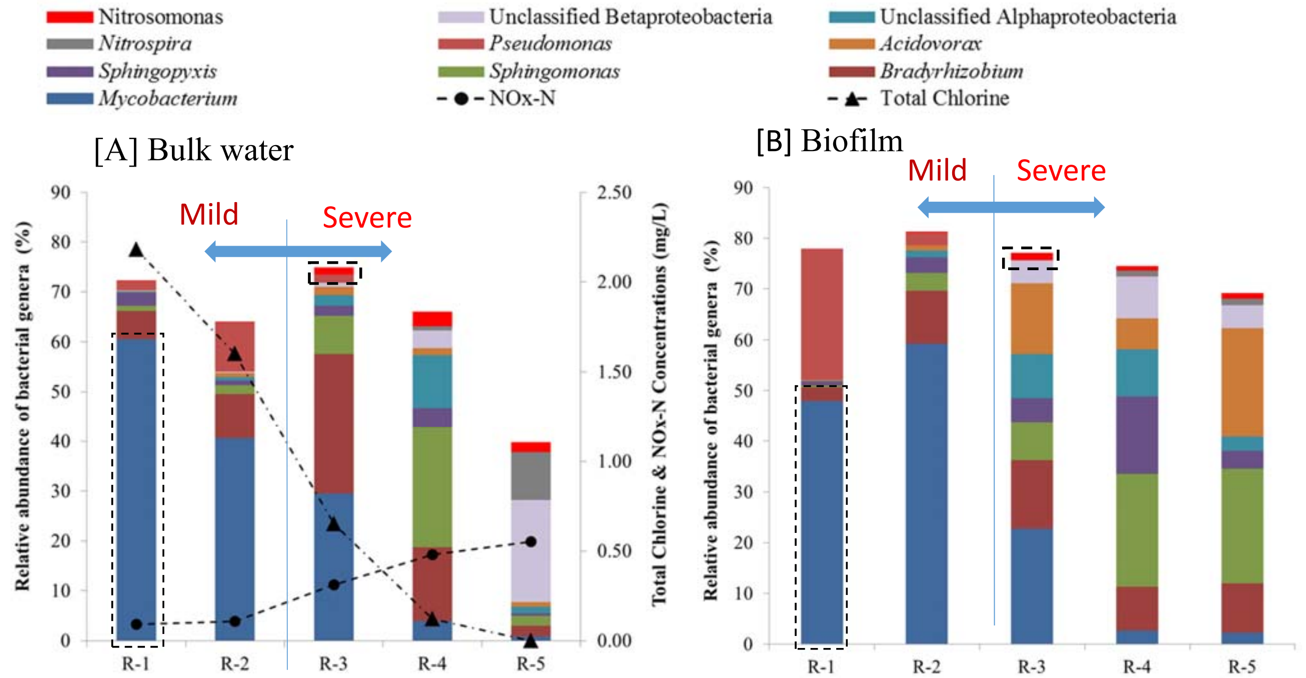


Bal Krishna et al., 2013

WSU Water Group

WESTERN SYDNEY UNIVERSITY

WSU Water Group



Origin of Samples

KCB Krishna, A Sathasivan, MP Ginige

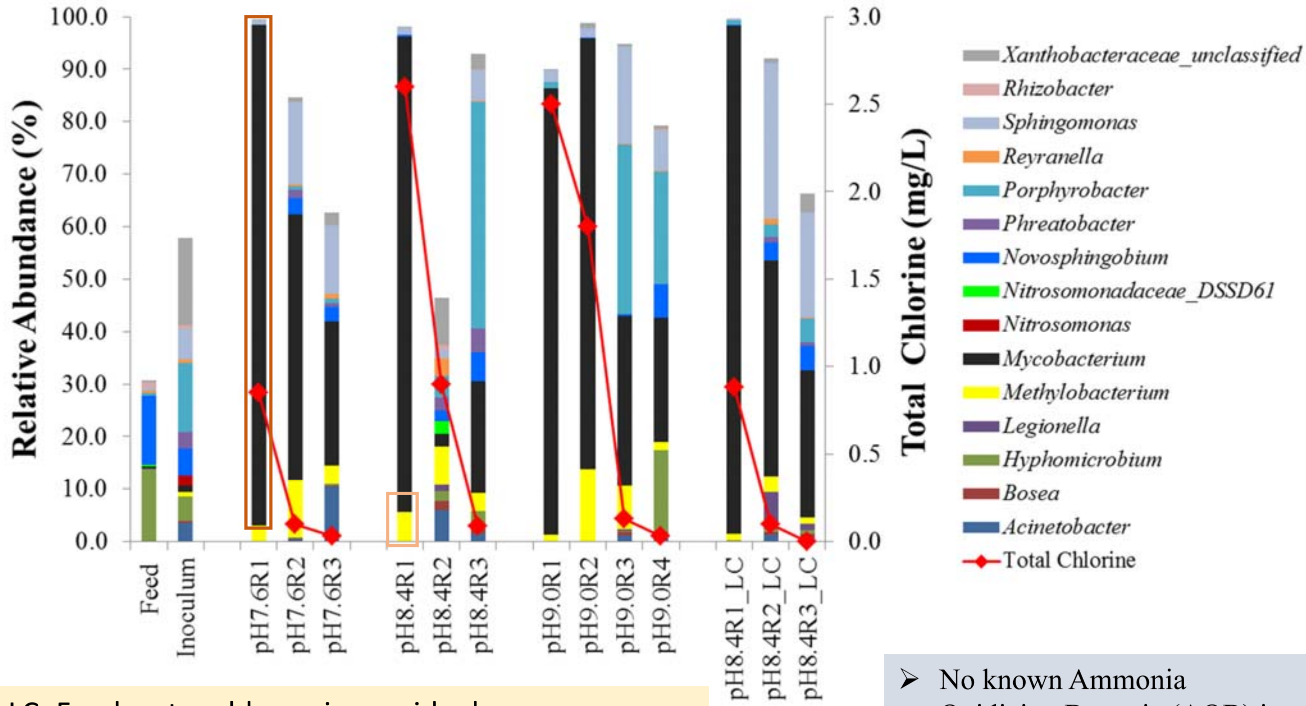
Water research 47 (13), 4666-4679

WESTERN SYDNEY UNIVERSITY

WSU Water Group

Bacterial Community Composition:

Bulk Water



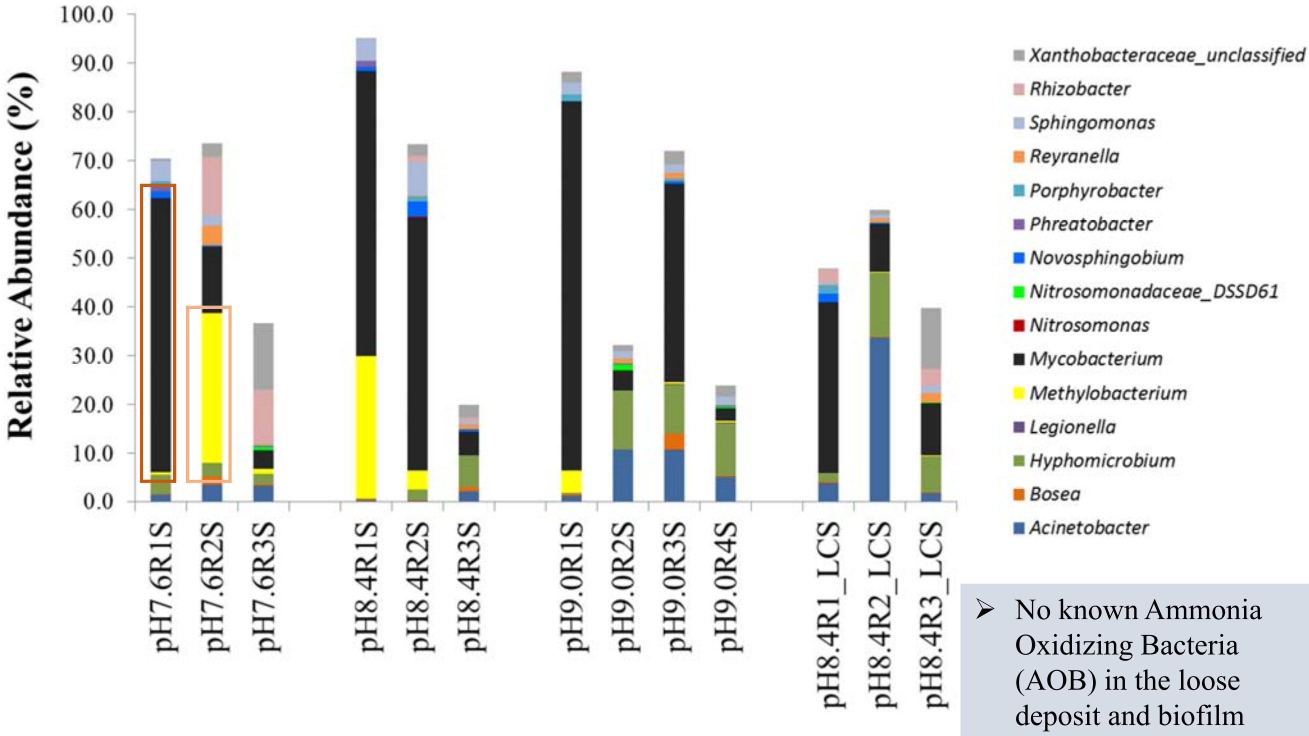
LC: Feed water chloramine residuals of 2.6 mg/L and others: 3.8 mg/L

- No known Ammonia Oxidizing Bacteria (AOB) in the bulk waters

WESTERN SYDNEY UNIVERSITY

WSU Water Group

Bacterial Community Composition: Loose deposit & Biofilm

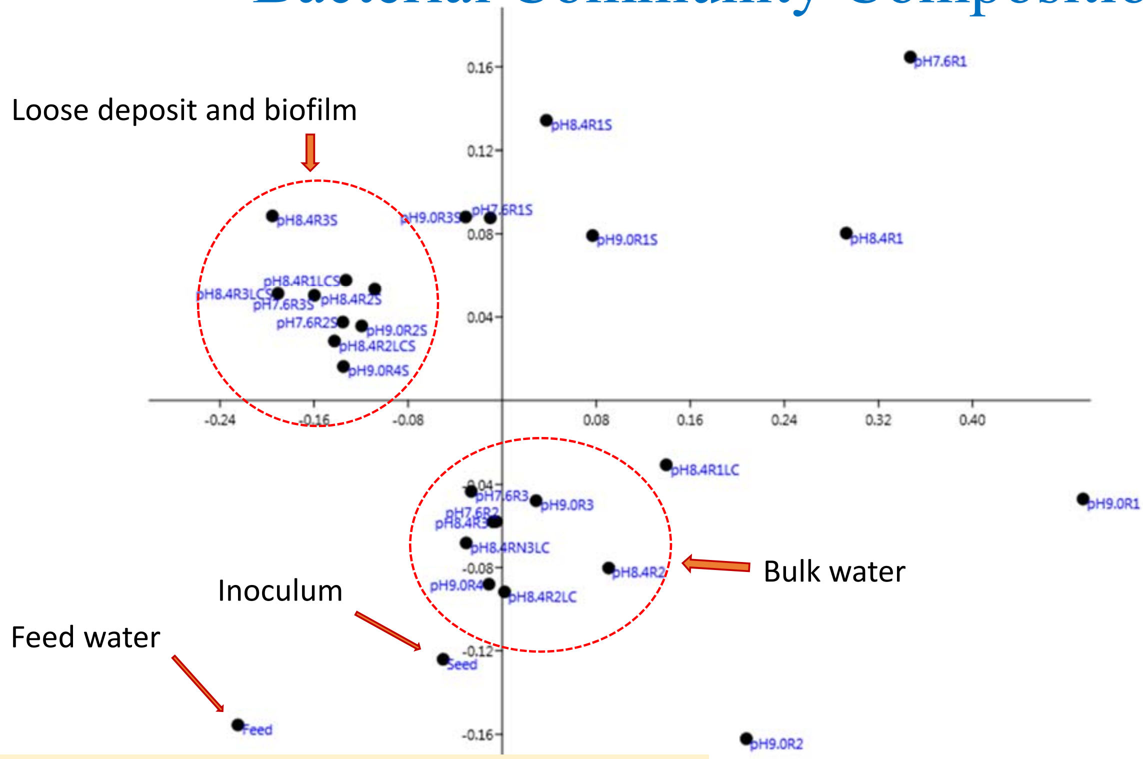


- No known Ammonia Oxidizing Bacteria (AOB) in the loose deposit and biofilm

WESTERN SYDNEY UNIVERSITY

WSU Water Group

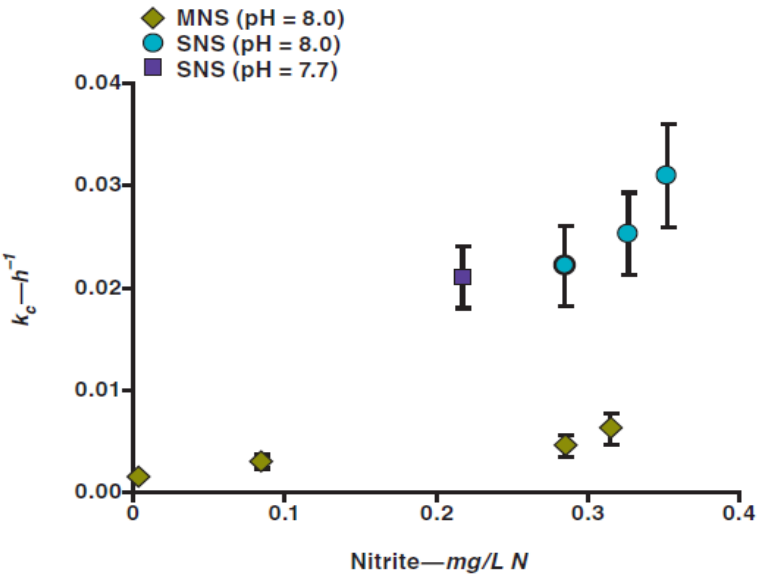
Bacterial Community Composition



LC: Feed water chloramine residuals of 2.6 mg/L and others: 3.8 mg/L

S= Loose deposit and biofilm

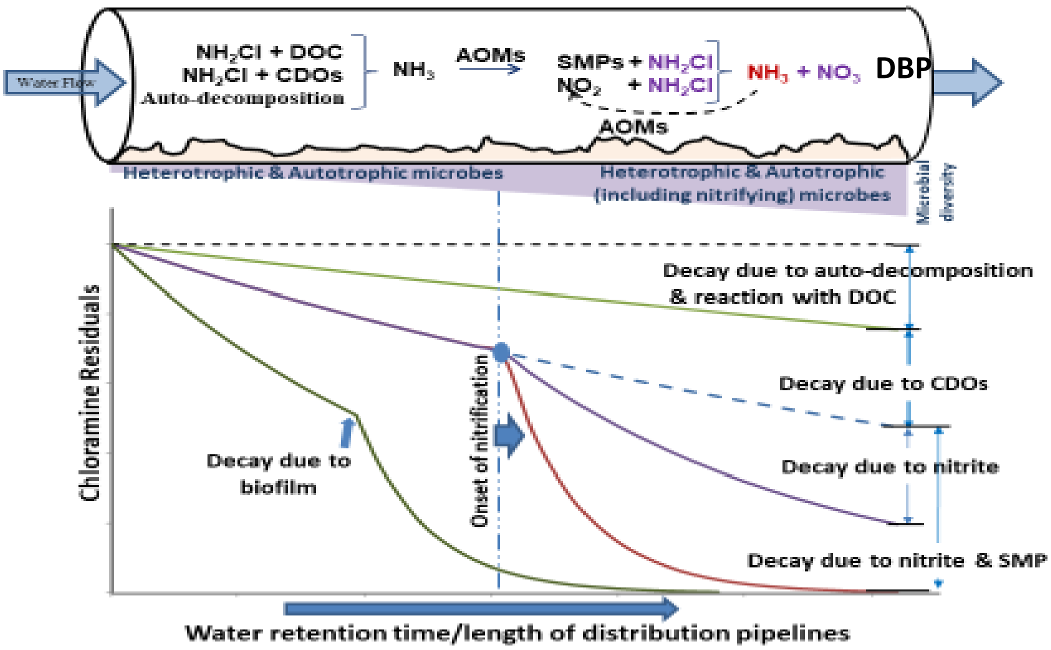
Mild vs severe nitrifying filtered samples



KC Bal Krishna, A Sathasivan, S Garbin
Water Science and Technology: Water Supply 13 (4), 1090-1098

WSU Water Group

Actual situation is much more complex

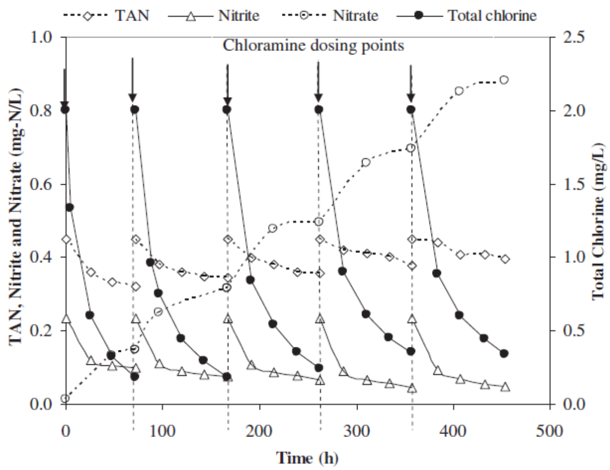


Sathasivan et al., 2016 :

WSU Water Group

Some interesting facts about SMP

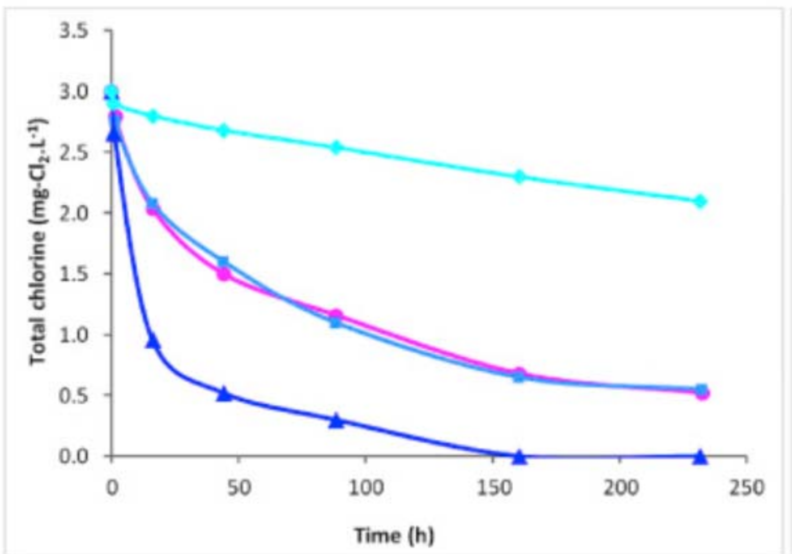
- They are proteins of molecular weight 30-50 KDa
- They catalyse the disinfectant decay



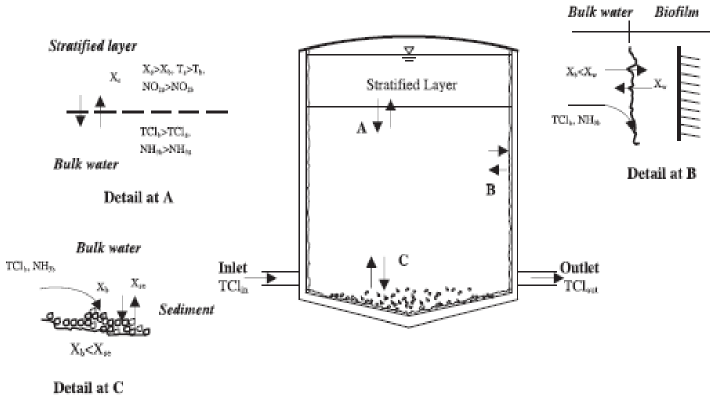
BS Herath, A Torres, A Sathasivan (2018) Chemosphere 212, 744-754

KCB Krishna, A Sathasivan, DC Sarker (2012)Water research 46 (13), 3977-3988

CDPs are formed as a stress response



Things at play in a service reservoir



$$TCl_{out} = \frac{TCl_{in}}{(1 + k_{Rt}\theta)}$$

$$F_{Ra} = \frac{k_{Rt} - k_{bc,T}}{k_{bc,T}}$$

Fig. 1 – Conceptual representation of factors affecting chloramine residual. **X** is the bacterial number and subscripts b, w, s and se represented bulk water, biofilm (wall), stratification and sediment, respectively.

A Sathasivan, KCB Krishna, I Fisher
Water research 44 (15), 4463-4472

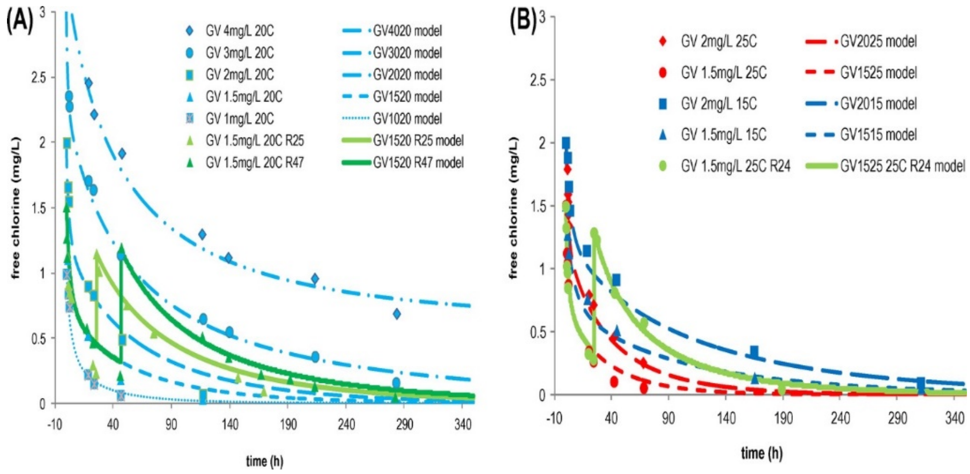
Chlorination

- 2R model - Fast reacting and slow reacting agents (Fisher et al., 2016; 2017)
- $\frac{dCl}{dt} = (k_f.FRA + k_s.SRA).Cl$
- $k_T = k_{20}.\exp\left(-\frac{E}{R}.(\frac{1}{273+T} - \frac{1}{293})\right)$
- Analytical solution (Kohpae and Sathasivan, 2011)

$$C_{Cl}(t) = \frac{C_{cl_{FRA}}(t) - c}{1 - \frac{c}{C_{cl_{FRA}}(t)} e^{-(C_{cl_{FRA}}(t) - c)k_{SRA}t}} \quad (37)$$

Application

- With one set of parameters
  - different dosing,
  - different temperature,
  - rechlorination



I Fisher, G Kastl, A Sathasivan
Urban Water Journal 14 (4), 361-368

Can apply for successive rechlorination

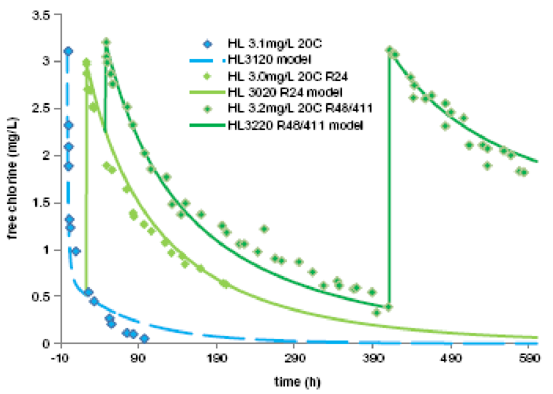


Figure 2. Chlorine concentrations from 2R model of Harsh Lake 2 water, calibrated against data set comprising a single ID and successive rechlorinations to 3 mg/L after 24, 48 and 411h (data from Boccelli *et al.* 2003). Markers, curves and legend are as defined in Figure 1.

I Fisher, G Kastl, A Sathasivan
Urban Water Journal 14 (4), 361-368

Can apply for bend of two sources

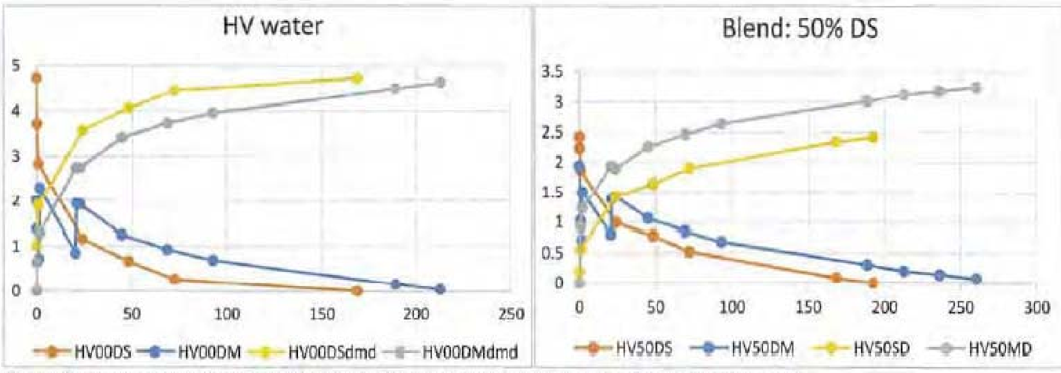
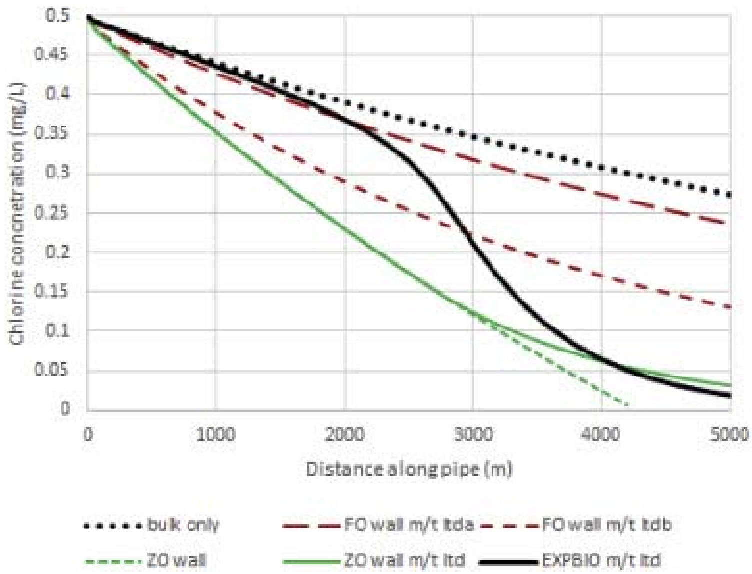


Figure 2. Single- (brown) and multiple-dose (blue) decay test data for: A – HV water alone; and B – HV blended with 50% DS water. Data source: Byrne *et al.* (2013). Corresponding demand curves (yellow and grey respectively) were constructed as shown in Figure 1.

I Fisher, G Kastl, F Shang, A Sathasivan (2018) Journal American Water Works Association 110 (11)
I Fisher, G Kastl, A Sathasivan, D Cook, L Seneverathne (2015) Journal of Environmental Engineering 141 (12), 04015039
I Fisher, G Kastl, A Sathasivan (2014) Water: Journal of the Australian Water Association 41 (8), 32

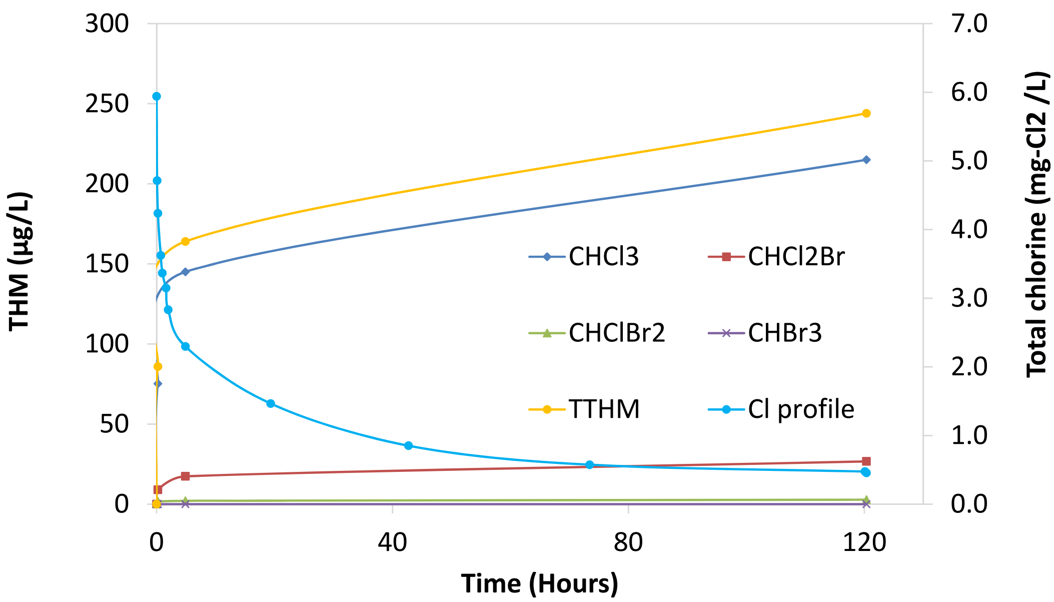
Full scale application – evidence of microbial chlorine decay



I Fisher, G Kastl, A Sathasivan Water research 125, 427-437

How about THM?

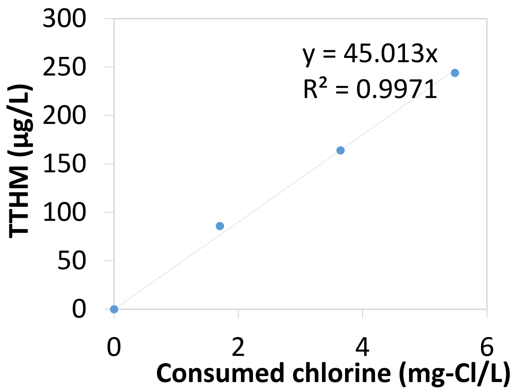
Behaviour during chlorine decay (Nepean Dam water, Australia)

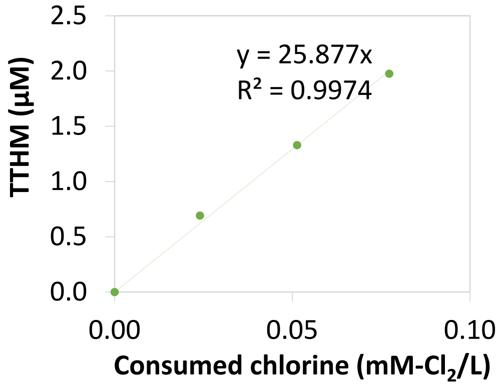


Sathasivan et al., 2019; NOM 7 conference proceedings

WSU Water Group

Yield calculation (Nepean Dam water, Australia)





This implies that if we know what chlorine we dosed and the concentration at a given point (predicted or measured), we can calculate the TTHM confidently

Sathasivan et al., 2019; NOM 7 conference proceedings

WSU Water Group

Comparison

Raw water or treatment details	DOC (mg/L)	UV_{254} (/cm)	SUVA	Br (µg/L)	pH	Cl_2 dose mg-Cl_2/L	TTHM mass yield (mg THM /mg-Cl_2 consumed) (R^2)	TTHM molar yield (µmol THM /mmol Cl_2 consumed) (R^2)
Nepean , Aus	5.44	0.0828	1.52	43	7.4	5.9	45.0 (0.997)	25.9(0.997)
Wyong, Aus	8.99	0.3154	3.51	187-159	7.3	6.9	40.9(0.980)	22.5(0.976)
Petrie, Aus	9.88	0.3408	3.45	48	7.3	8.3	43.7 (0.999)	25.4 (0.999)
North Pine, Aus	6.58	0.1418	2.15	81	7.6	4.9	45.0 (0.963)	25.0 (0.964)
Lake Gaillard WTP, USA[1]	1.91	0.03	1.57	30-50	7.3	2.5 4.0	28.8 (0.988) 29.6 (0.982)	15.9 (0.964) 16.2 (0.97)
Lime softened Lake Gailard(?)[1]	-	-	-	30-50 (?) +100	7.5	2.5	44.7 (0.992)	16.5 (0.990)

[1]McClellan, 2000 PhD Thesis

Gallard & Gunten, 2002 - molar yield 19.6±4.9 µM TTHM/mM of Cl_2 reacted R^2>0.92 in eight different raw water samples with SUVA 0.6-2.1

Sathasivan et al., 2019; NOM 7 conference proceedings

WSU Water Group

Molar fractions

$$n_{CHCl_3} = \frac{C_{CHCl_3}}{MW_{CHCl_3}}$$

$$n_T = n_{CHCl_3} + n_{CHCl_2Br} + n_{CHClBr_2} + n_{CHBr_3}$$

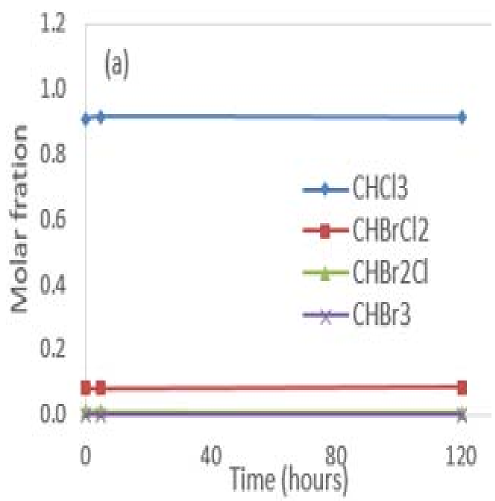
$$f_{CHCl_3} = \frac{n_{CHCl_3}}{n_T}$$

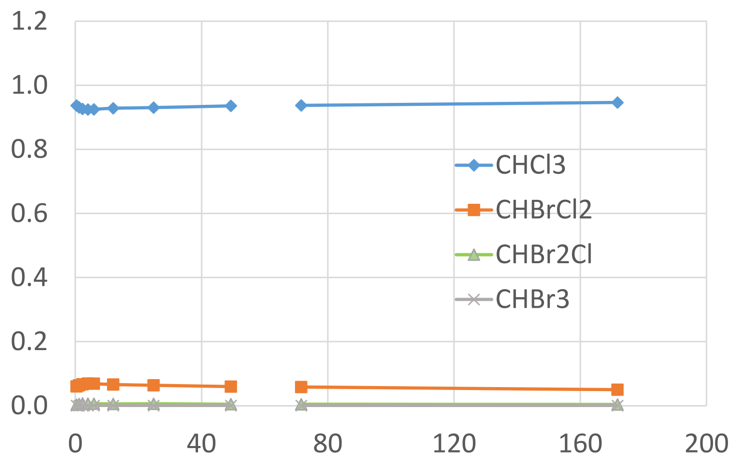
Sathasivan et al., 2019; NOM 7 conference proceedings

WSU Water Group

Molar fractions of THM species in low Br waters

Nepean water (~40 µg-Br/L) Lake Gaillard WTP (30-50 µg-Br/L), McClellan, 2000 PhD Thesis





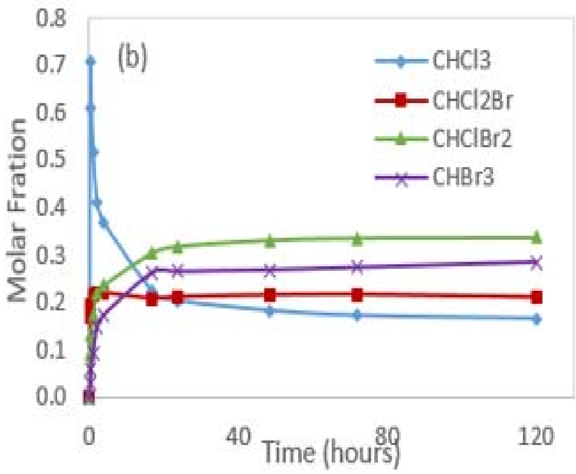
Sathasivan et al., 2019; NOM 7 conference proceedings

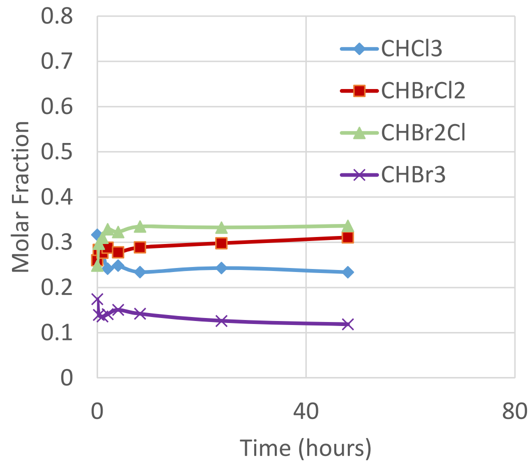
WSU Water Group

Molar fraction of THM species in high Br waters

DOC = 2.22 mg/L; 159 µg-Br/L

Lime softened water, US
DOC ?, >100 µg-Br/L
McClellan, 2000 PhD Thesis





Sathasivan et al., 2019; NOM 7 conference proceedings

WSU Water Group

Model of THM species

- Now chlorine decay can be described for a given water
- Yield (mass as well as molar) remains relatively constant
- Molar (mass) fraction of each species remains relatively constant for ret time, t > 24 h in raw waters
- In treated water, constancy t > 4 h

Sathasivan et al., 2019; NOM 7 conference proceedings

Model

$$\frac{dTTHM}{dt} = \alpha_{mass}(k_f.FRA + k_s.SRA).Cl$$

$$\frac{dC_{CHCl_3}}{dt} = \alpha_{mol}.f_{CHCl_3}(k_f.FRA + k_s.SRA).Cl.MW_{CHCl_3}$$

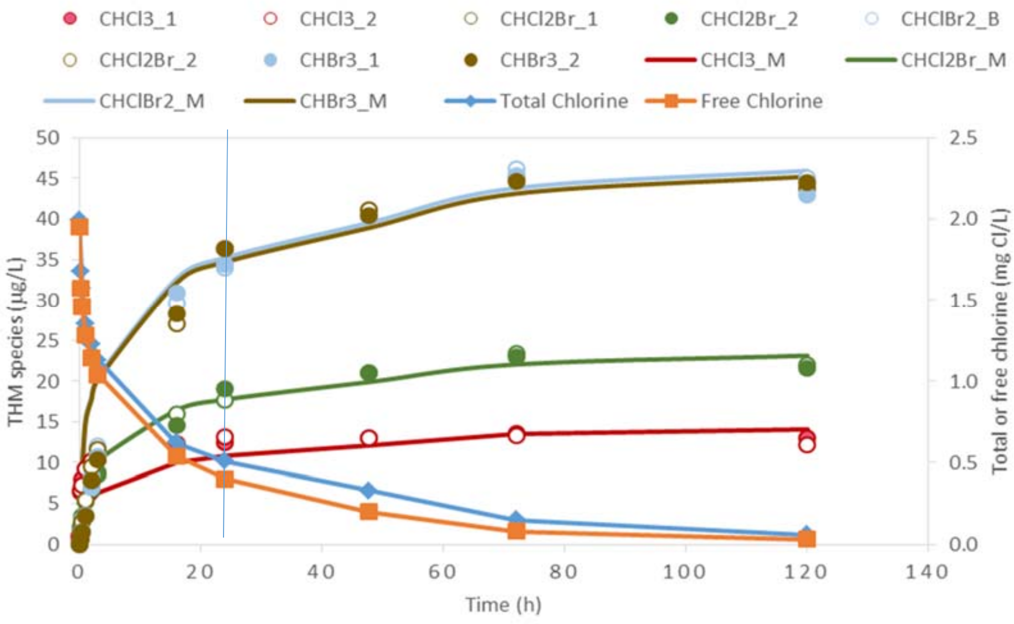
Or simply

$$C_{CHCl_3} = \alpha_{mol}.(Cl_o - Cl_t).f_{CHCl_3}.MW_{CHCl_3}$$

Sathasivan et al., 2019; NOM 7 conference proceedings

WSU Water Group

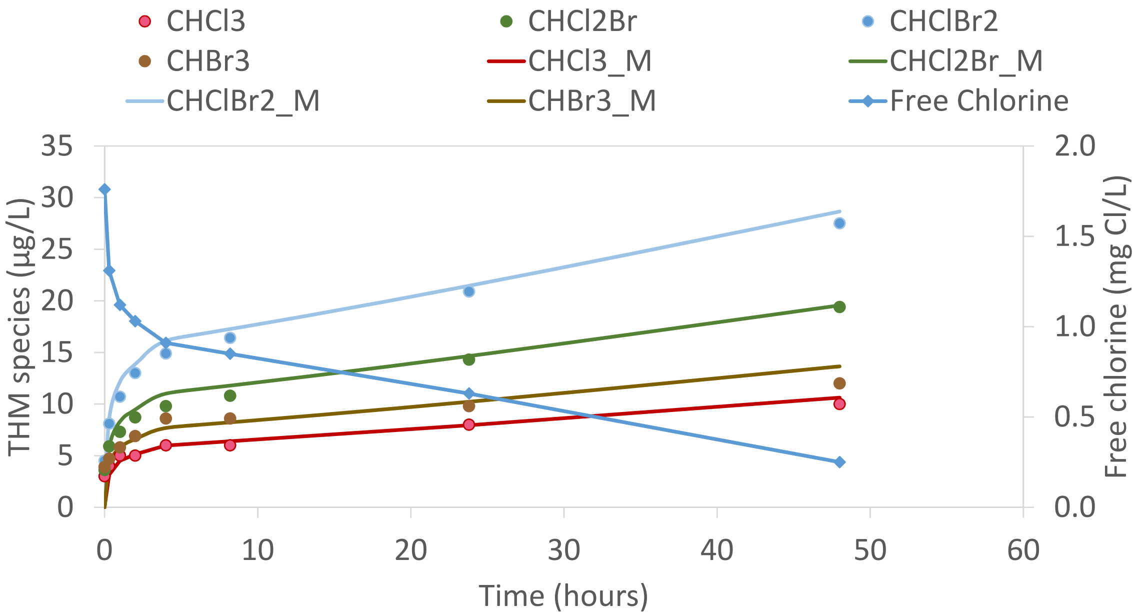
Model agreement, our data



Sathasivan et al., 2019; NOM 7 conference proceedings

WSU Water Group

Model agreement, US lime softened water[1]



[1] >100 µg-Br/L ; McClellan, 2000 PhD Thesis

Sathasivan et al., 2019; NOM 7 conference proceedings

WSU Water Group

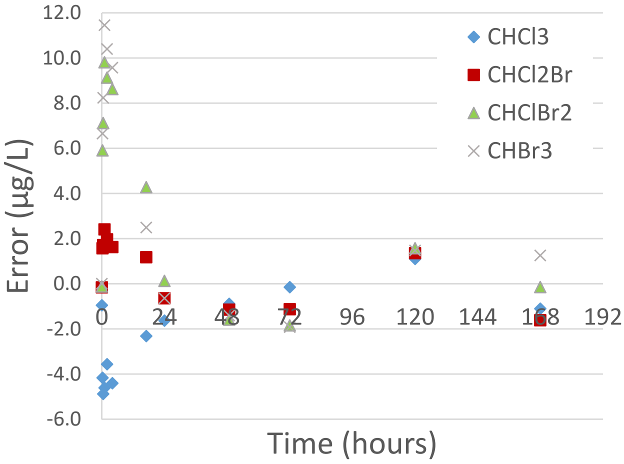
Error in prediction

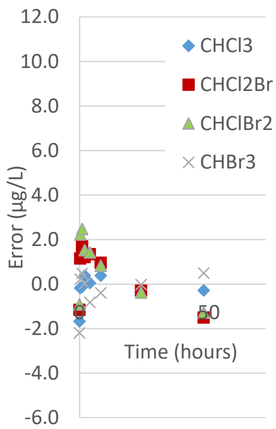
DOC = 2.22 mg/L; 159 µg-Br/L

Lime softened water, US

DOC ?, >100 µg-Br/L

McClellan, 2000 PhD Thesis





Sathasivan et al., 2019; NOM 7 conference proceedings

WSU Water Group

Comparison of best models with the developed model

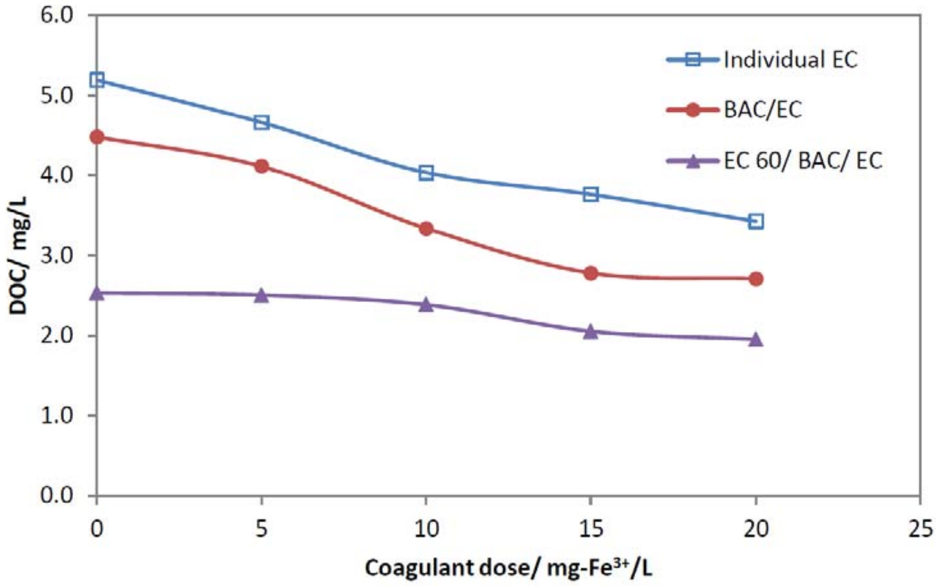
	Standard error of best models (µg/L)	Max error, raw water t>24 h (µg/L)	Max error Lime softened water, t > 0h
$CHCl_3$	14.4	<2	<2
$CHCl_2Br$	8.7	<2	<2
$CHBr_3$	4.1	<2	<2
$CHClBr_2$	>35	<2	<2
TTHM	68.8 – 76.8	<5	<5

Yield & fixed molar fraction approach minimizes the error to below measurement error.

Sathasivan et al., 2019; NOM 7 conference proceedings; Water Research under review

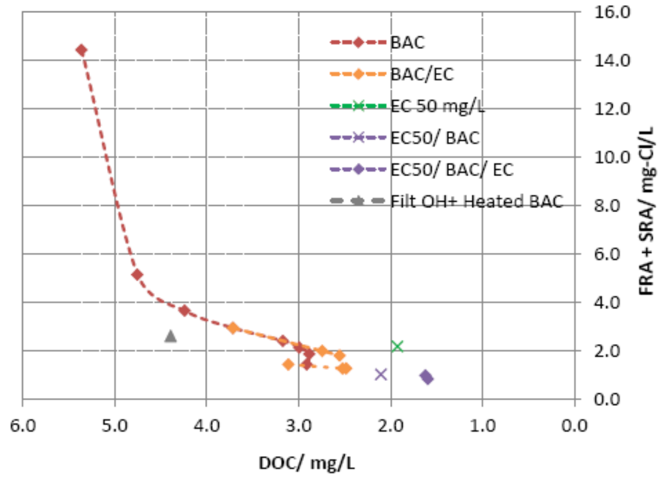
WSU Water Group

BAC/Coagulation



Shashika Krotta Gamage (2019) PhD Thesis

Is DOC good predictor of chlorine decay?



Shashika Krotta Gamage (2019) PhD Thesis

Thank you

Any questions??

WSU Water Group