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Disinfection of Treated Sewage by Chlorine Jets

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Outline

1. Harbour Area Treatment Scheme (HATS) – disinfection for protection of public health
2. Field scale model for study of mixing and rapid chlorine demand in disinfection of primary treated (CEPT) effluent
3. Theoretical modelling of chemically reacting dense chlorine jet – optimal chlorine dosing strategies
4. Conclusions

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Cross-harbour Swimming Race revived after introduction of disinfection for CEPT treated sewage

New World Harbour Race – **16 October, 2016**
(1.5 km; 2,400 participants)

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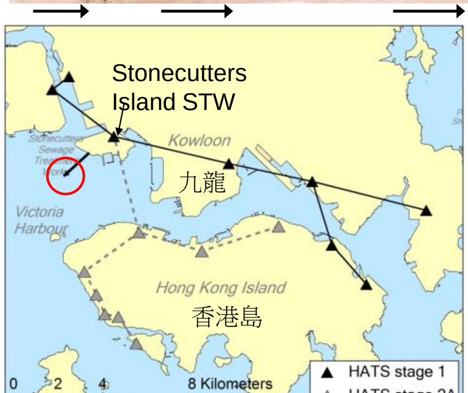
Harbour Area Treatment Scheme (HATS) 香港淨化海港計劃



Chemically Enhanced Primary Treatment (CEPT) since 2001; 23.6 km of deep tunnels; disinfection since March 2010

Stage 1: $Q = 1.4 \times 10^6\ m^3/d$

Stage 2A: $Q = 2.0 \times 10^6\ m^3/d$

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Hong Kong's beach grading system
香港海灘水質評級系統

Grading	Beach water quality 泳灘水質	E. coli * (counts /100 mL) 大腸桿菌	Minor illnesses rate ** (cases per 1000 swimmers) 發病率	Water Quality Objective Compliance/ Exceedance
1	Good	≤ 24	Undetectable	Compliance
2	Fair	25 - 180	≤ 10	
3	Poor	181 - 610	11 - 15	Exceedance
4	Very poor	> 610	> 15	

***Weekly Beach Grading**: Geometric Mean *E. coli* level of the 5 most recent samplings (C_{lnEC5})
Annual Beach Ranking: Geometric Mean *E. coli* level of all samplings in bathing season (March - October)

** Skin and Gastrointestinal illnesses (Cheung et al. 1990)

Water Quality Objective: E.coli < 180 counts/100 mL

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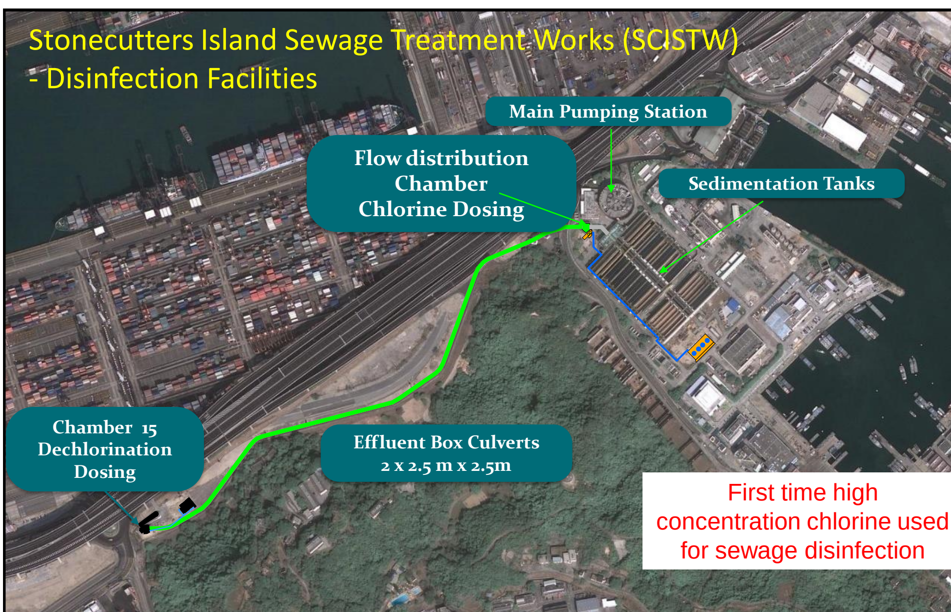

300 tonnes/day of 10% sodium hypochlorite solution
Mysterious high chlorine consumption!

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Engineering turbulent mixing

- *Chlorine disinfection* is essential to protect beach water quality in Hong Kong
- *Turbulent mixing* is the key to the large scale chlorine disinfection
- Chlorine disappears due to fast chemical reactions (~0.1 seconds) in complex turbulent shear flow
- Effective dosing (how much, where, how) can be *engineered* to ensure sustainable operation of HATS

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Motivation for Chlorine Dosage Optimization

1. Chlorine has to be imported from mainland China - subjected to uncertainties in supply, export regulations, safety during transport.
2. Large storage tanks are required to store the concentrated chlorine (NaOCl) .
3. Chlorine dosage optimization is necessary to ensure sustainability: reduce energy/chemical consumption and cost
4. Excessive Total Residual Chlorine (TRC) and Disinfection by-products (chlorinated organics) are harmful to environment

NaOCl day tanks

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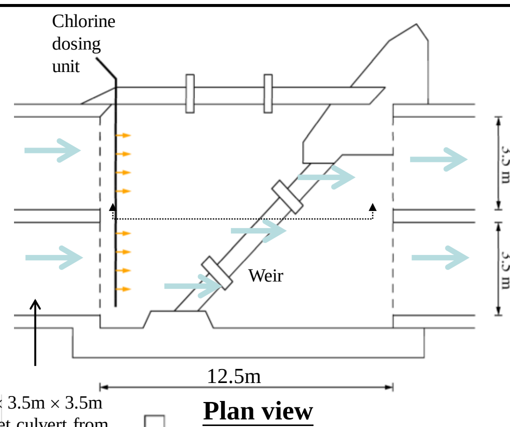
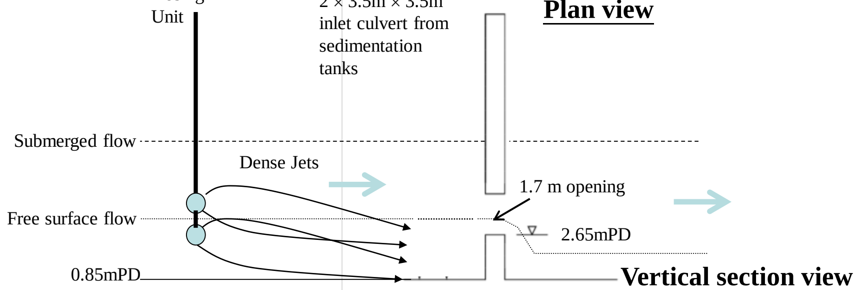
Flow Distribution Chamber (Chlorine dosing unit)

- *An inclined weir of 1.8m height in the middle of FDC*
- *10% chlorine solution is injected into the sewage flow through an array of dense jets (sp.gr.=1.2) in two rows*

Q = 25 m3/s





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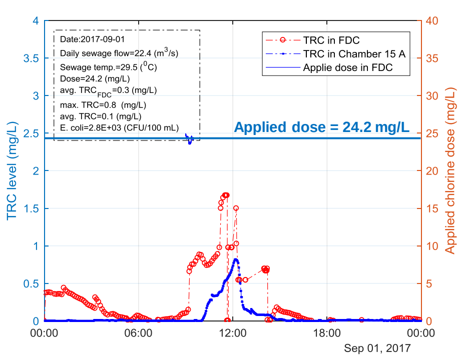
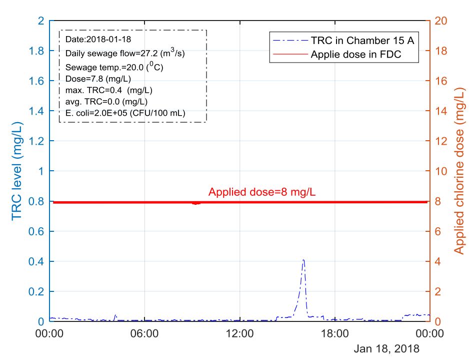
Mysterious Chlorine Consumption

Measured TRC levels very low despite high dosage level





Summer winter

Typical daily TRC level variations in FDC / Chamber 15A

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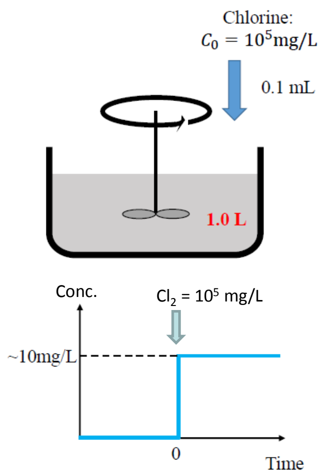
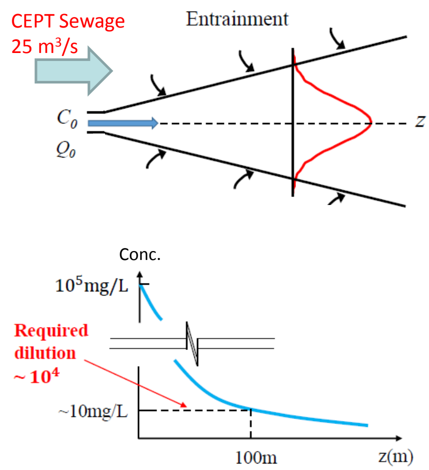
Beaker Test vs Field Dosing

- *Mixing in a beaker is very different from chlorine dosing in HATS field operations*
  Beaker test results do not represent the field condition

Beaker test
- Near-instantaneous mixing
- Limited reactants



Field Dosing
- Jet mixing, distance and time are required.
- Continuous supply of reactants



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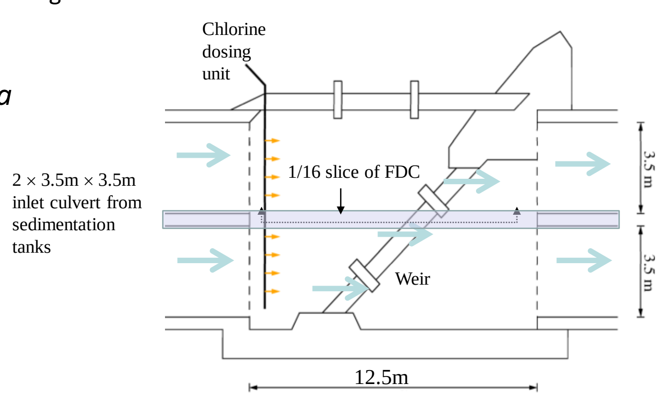
1:2 Physical Scale Model (with prototype sewage and chlorine)

The objectives are to study:
- the mixing achieved by the dosing unit in the FDC;
- chlorine demand at different key locations in the FDC;
- disinfection efficiency in the FDC; and
- degree of settling of organic solids in the FDC.

The 1:2 physical model represents a "1/16 slice" of the FDC treated sewage flow



Plan view of FDC

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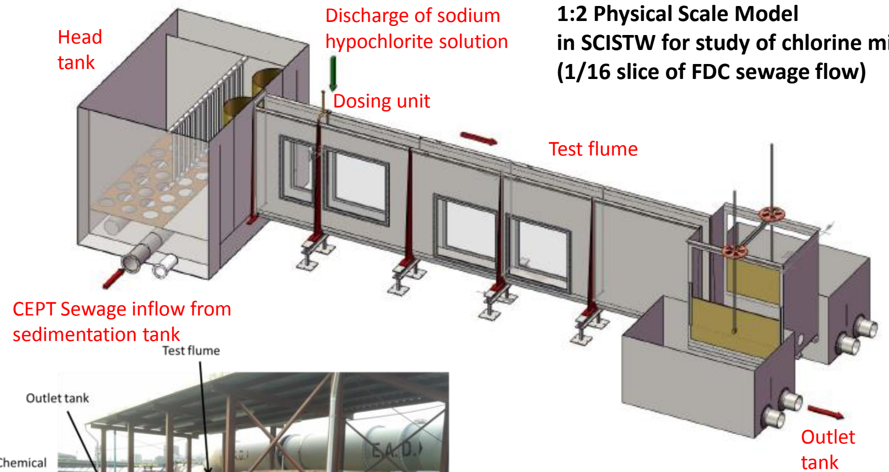
1:2 Physical Scale Model in SCISTW for study of chlorine mixing (1/16 slice of FDC sewage flow)



Prototype/model	ratio
Length L_p/L_m	2
Velocity V_p/V_m	1.41
Time t_p/t_m	1.41
Flow rate Q_p/Q_m	5.657
Density difference $\Delta\rho_p/\Delta\rho_m$	1

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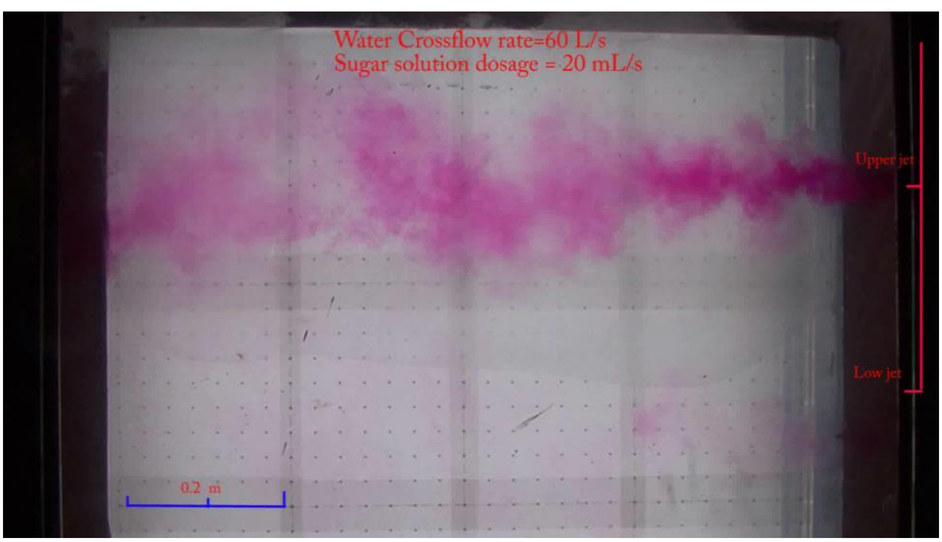
Dosing sugar solution (ρ = 1.168 g/mL) into cross flow in 1:2 model



Initial mixing of upper dosing jet with dyed sugar solution (tap water flow Qs = 60 L/s; U_a = 0.2 m/s; total jet discharge q_d = 20 mL/s)

Lee et al. *ASCE Journal of Environmental Engineering*, 2017

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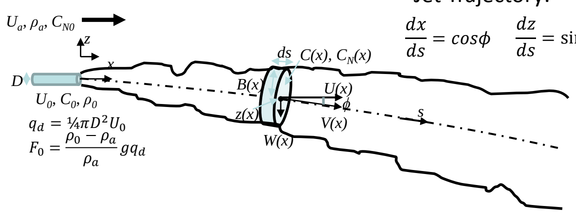
Integral model of a reacting dense chlorine jet in sewage coflow



Jet Trajectory:

$$\frac{dx}{ds} = \cos\phi \qquad \frac{dz}{ds} = \sin\phi$$

Spreading coeff.:

$\beta_s = 0.16$

$\beta_n = 0.4$

$\beta_* = 0.8$

Added-mass coeff.:

$k_n = 1$

Spreading hypothesis (top-hat):

$$\frac{dB}{ds} = \beta_s \frac{(V - U_a \cos\phi)}{V} + \beta_n \left(\frac{U_a \sin\phi}{V}\right) + \beta_* \frac{\sigma}{U_a}$$

Excess x-momentum flux:

$$\frac{d}{ds}[\pi B^2 V (U - U_a)] = 0$$

z-momentum flux:

$$(1 + k_n)\frac{d}{ds}[\pi B^2 V W] = \frac{F_0}{U_a}$$

TRC mass flux:

$$\frac{d}{ds}(\pi B^2 V C) = \begin{cases} -C_{a0} R_a \frac{dQ}{ds} & \text{for} \quad C_T/C_{a0} \ge R_a \\ 0 & \text{for} \quad C_T/C_{a0} < R_a \end{cases}$$

Ammonia mass flux:

$$\frac{d}{ds}(\pi B^2 V C_N) = \begin{cases} 0 & \text{for} \quad C_T/C_{a0} \ge R_a \\ C_{a0} \frac{dQ}{ds} & \text{for} \quad C_T/C_{a0} < R_a \end{cases}$$

Assuming instantaneous break point reaction

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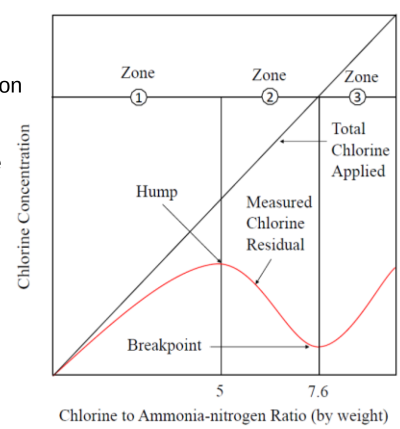
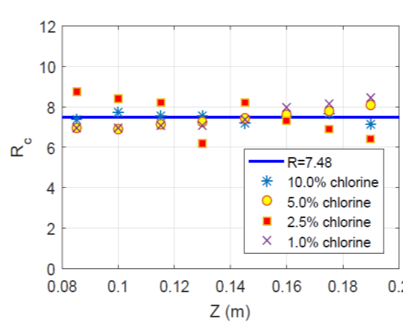
Break-point reaction of chlorine with ammonia in sewage

- When $Cl_2/NH_3 < 7.6$ (below breakpoint), chlorine reacts with ammonia to form combined chlorine (chloramines, NH_2Cl, $NHCl_2$, NCl_3) with disinfection ability;
- When $Cl_2/NH_3 > 7.6$ (beyond breakpoint): chlorine reacts *rapidly* with ammonia to form nitrogen gas, only free chlorine remains.

$$2NH_3 + 3HOCl \longrightarrow N_2 + 3Cl^- + 3H^+ + 3H_2O$$



ref. White (1992)



NH_3 in sewage ≈ 30 ppm

Breakpoint of Cl_2 ≈ 230 ppm

Chlorine/ammonia stoichiometric reaction coefficient (by mass) of a dense chlorine jet in ammonia solution

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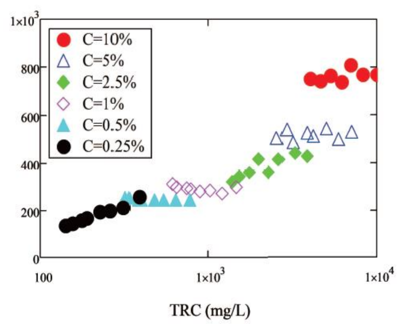
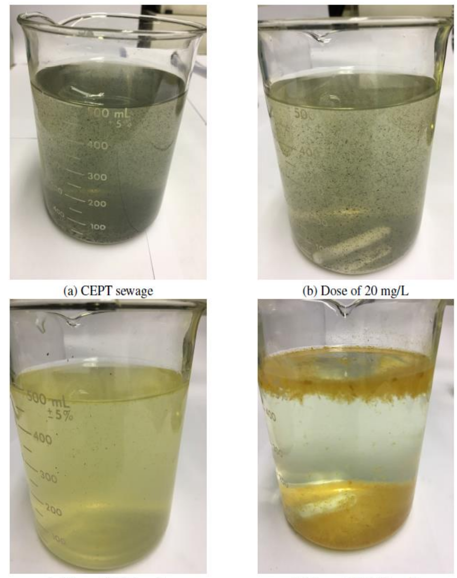
Chlorine reaction in sewage

High concentration chlorine can oxidize organic debris and sewage constituents; the chlorine demand can be 2-3 times higher at high chlorine concentration.

Chlorine consumption (mg/L) vs. chlorine conc. at jet centerline





(a) CEPT sewage

(b) Dose of 20 mg/L

(c) Dose of 1000 mg/L

(b) Dose of 10,000 mg/L

Higher chlorine concentration results in the reaction with organic debris

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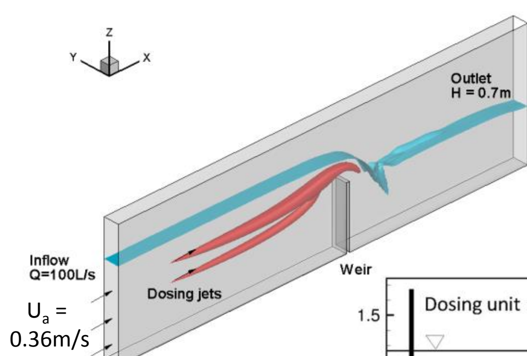
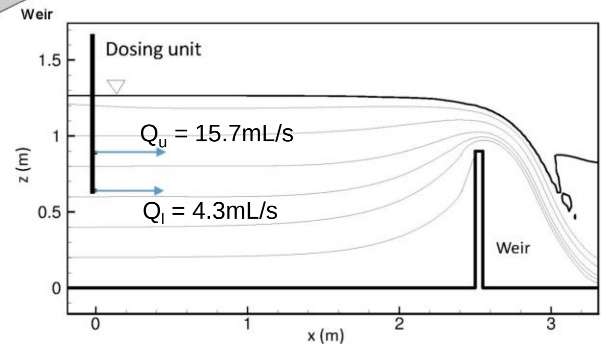
CFD modeling of the 1:2 scale FDC model



900,000 grid cells

Free surface determined by volume of fluid (VOF) method



Dosing jet flow = 20mL/s

C_0 = 100,000 mg/L

$\Delta\rho/\rho = 0.2$

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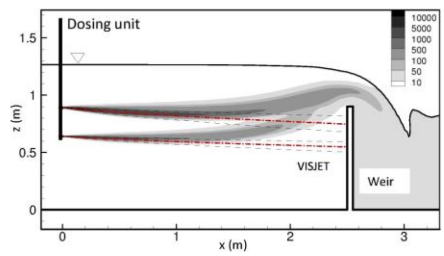
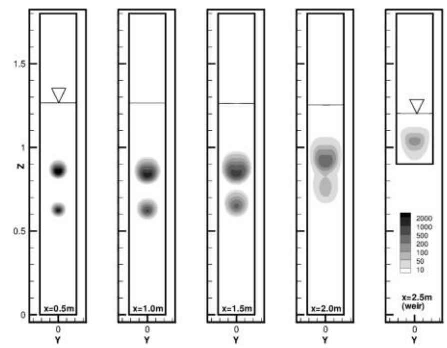
Jet mixing of the chlorine with the sewage co-flow achieves a rapid dilution in the order of 1000-2000 in the FDC. This high dilution however falls sort of the value required to achieve full mixing (i.e. a dilution of 5000-10,000). Only approximately 60-80 percent of the sewage flow over the FDC weir is chlorinated.



Flume centreline



Cross-sections

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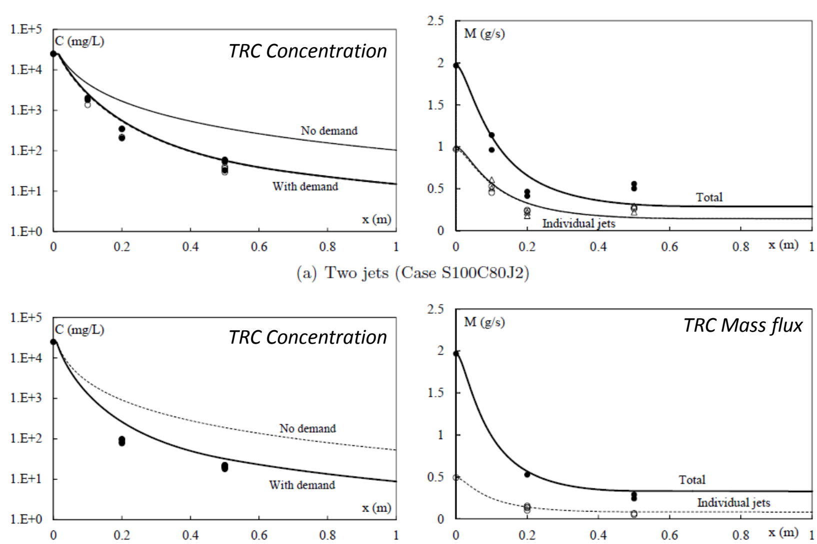
Integral model predicted chlorine jet characteristics for
2.5% chlorine jet in CEPT sewage: 15-20% reduction in chlorine demand.



(a) Two jets (Case S100C80J2)

(b) Four jets (Case S100C80J4)

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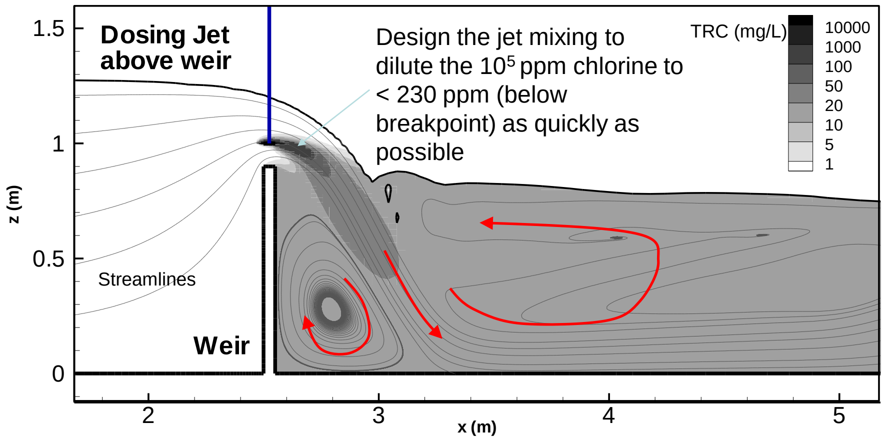
Strategy: Chlorine jet in high velocity flow

Utilize initial jet mixing in high speed flow supplemented by rapid mixing in highly turbulent recirculation flow downstream to reduce chlorine consumption by the ammonia and organics in sewage.



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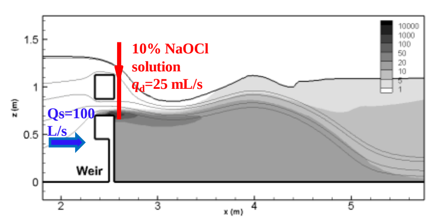
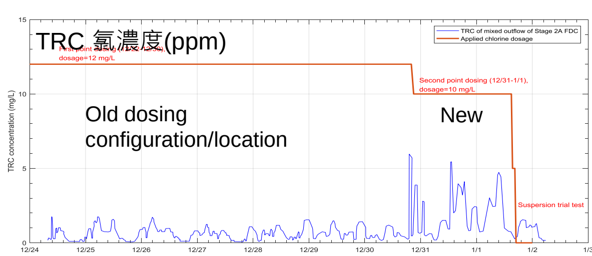
Field tests in optimizing chlorine dosage (2019)

Significant reduction in chlorine demand as seen in field tests





New dosing device for HATS 2A (Dec 2018)

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Conclusion

- The chlorine demand of CEPT effluent has been studied by theoretical modeling of a chemically reacting chlorine jet and field scale experiments using prototype sewage and chlorine dosing solution.
- Jet mixing is not able to achieve full mixing of the 10 percent chlorine solution with the sewage flow in the flow distribution chamber. Only 60-70 percent of the sewage is in contact with chlorine.
- Over 90% of the chlorine mass flux can be consumed within 5-10 seconds from the source. Most of the chlorine is used in oxidation of organic debris at the high concentrations, and not used in bacteria (pathogen) kill.
- Full scale tests have confirmed that chlorine disinfection dosage can be optimized by discharging 10% chlorine solution through an optimal diffuser design in high speed flow.

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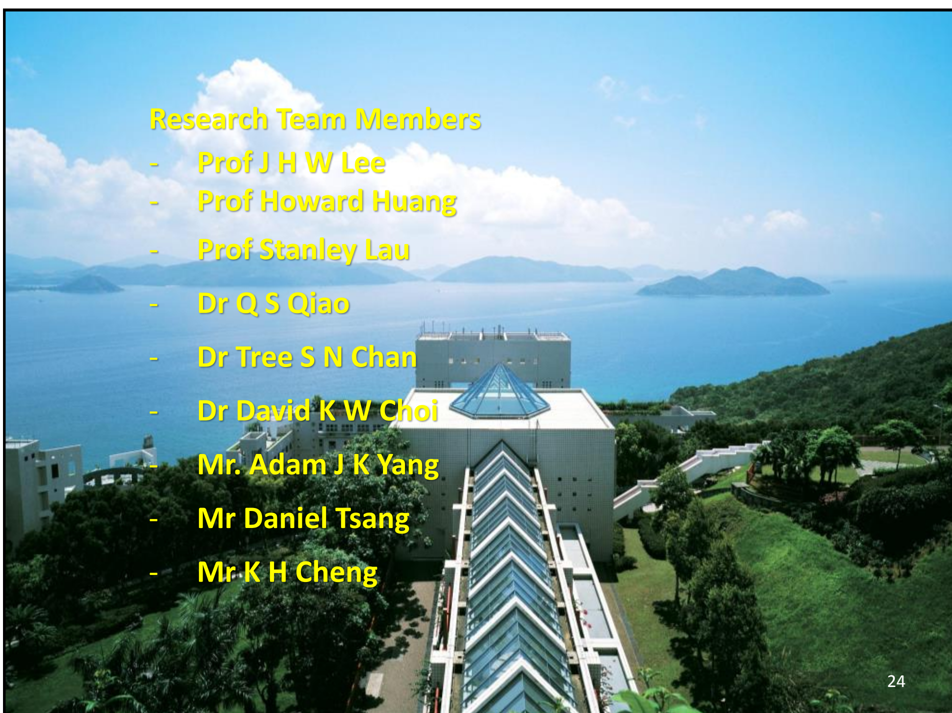

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