Application of the WATERMAN Real Time Coastal Water Quality Management System to Environmental Engineering and Control

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Outline

1. Overview of Harbour Area Treatment Scheme
   - Disinfection Control and Dosage Optimization
2. WATERMAN real time beach water quality forecast system - setting of effluent discharge bacterial standard
3. Emergency response in pollution accidents
4. Disinfection performance and fluid mechanics of chlorine mixing by multiple dense jets
5. Conclusions
Overview of HATS and WATERMAN real time water quality forecasting system

Hong Kong Special Administrative Region, China
Challenges of Coastal Water Quality Management

- Coastal water quality prediction is a challenging multi-scale and multi-disciplinary problem
- Pollution sources located in close proximity to sensitive receivers
- Dynamic marine environment with complex currents; highly nonlinear biochemical process
- Water quality data are typically sparse and costly
- Uncertainty in rate coefficients, loading and boundary conditions
- Need for public accountability and public engagement

Harbour Area Treatment Scheme (HATS)

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

Stage 1: \[ Q = 1.4 \times 10^6 \text{ m}^3/d \]
Stage 2A: \[ Q = 1.8 \times 10^6 \text{ m}^3/d \]
HATS Stage 1

- Chemically-enhanced primary treatment at Stonecutters Island STW
- Stops 600 tonnes/yr of sludge from entering the harbour
- Pollutants removal rate:
  - 70% organics (BOD)
  - 80% suspended solids
  - 60% heavy metals
  - 25% total nitrogen
  - 50% phosphorus
- *E. coli*:
  - before disinfection: 50%
  - after disinfection: $10^7 \rightarrow 10^5$ cnt/100mL
Hong Kong’s beach grading system
香港海灘水質評級系統

<table>
<thead>
<tr>
<th>Grading</th>
<th>Beach water quality</th>
<th>E. coli* (counts/100 mL)</th>
<th>Minor illnesses rate ** (cases per 1000 swimmers)</th>
<th>Water Quality Objective Compliance/Exceedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Good</td>
<td>≤ 24</td>
<td>Undetectable</td>
<td>Compliance</td>
</tr>
<tr>
<td>2</td>
<td>Fair</td>
<td>25 - 160</td>
<td>≤ 10</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Poor</td>
<td>181 - 610</td>
<td>11 - 15</td>
<td>Exceedance</td>
</tr>
<tr>
<td>4</td>
<td>Very poor</td>
<td>&gt; 610</td>
<td>&gt; 15</td>
<td></td>
</tr>
</tbody>
</table>

*Weekly Beach Grading: G. Mean E. coli level of the 5 most recent data (C_{MEC})
Annual Beach Ranking: G. Mean E. coli level of all bathing season data (Mar-Oct)

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

*Beach grading based purely on past sparsely sampled data*

The need for a better beach WQ management system

- Resource-intensive for sampling and analysis of E. coli data (41 beaches x 4-5 times/month x 8 months per year)
- At least 24 hr to obtain E. coli measurement results – delayed response for pollution events
- Represents the average WQ over the past 1 month - cannot capture the dynamic beach E. coli variation; no forecast ability!

Big Wave Bay June-July 2007

![Graph showing E. coli levels and rainfall](image)
HK Water Quality Criteria for Sensitive Receivers

• **Bathing beaches**
  – *E.coli* < 610 counts/100mL for annual geometric mean
  – *E.coli* < 1600 counts/100mL for single sample

• **Fish culture zone**
  – *E.coli* < 610 counts/100mL for annual geometric mean

• **flushing sea water intakes**
  – *E.coli* < 20,000 counts/100mL at any time

• **Secondary Contact Zones**
  – *E.coli* < 610 counts/100mL for annual geometric mean

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**Environmental discharges in the form of buoyant jets**

- **Single buoyant jet**
- **Rosette jet group**
- **Dense jets**
- **Sediment jets**
Mixing and Transport Processes

Near field + Intermediate field
Multiple length & time scales

Far field
Length: 10-500m
Time: min

Length: km
Time: hr
Secondary Contact Recreation Zone

Plan view
ambient current
Submarine Outfall
sewage plume
Beach

Integral jet model
Experiments
CFD

Shallow water circulation model
Particle tracking

Beach

Side view
ambient current
entrainment
sewage plume
turbulent dispersion, bacterial decay
Submarine Outfall

Project WATERMAN

Hydrological model

Data-driven models

Data assimilation

Meteorological data

Beach water quality forecast

Field studies

Laboratory studies

Past data
Environmental factors affecting beach water quality
 影響水質的環境因素

Studies on E. coli decay rate (Chan et al, JHER 2014)
 大腸桿菌衰亡率研究 (實驗和野外研究)

\[ k(z) = (0.68 + 0.017 \times S) \times 1.07^{(T-20)} + 1.1 \times I_A \times e^{-0.1z} \]

Decay rate
Salinity Water temp. Sunlight intensity

Laboratory studies
Field studies (during storms)
Real-time WQ forecast of Tsuen Wan beaches

Gemini beach
Length: 20m
Slope = 7%

Ma Wan and Tung Wan beach
Length: 140m
Slope = 1%

Ting Kau
Tsuen Wan
Harbour
Submarine outfalls

Complex Bathymetry
Disinfection on HATS sewage since 2010 March (Removal of 99% E.coli)

Project WATERMAN
3D Hydrodynamic Model of Hong Kong waters
(Water Research, Chan et al. 2013)

Submarine outfalls
Near-field model
JETLAG
Bacterial Loading
Current, Turbulent Mixing
E. coli concentration
(Bacterial decay modeling

Dynamic coupling (DESA)
Far-field Hydrodynamic Model

潮汐流、紊流混合
(大腸桿菌含量)
Input for deterministic forecast

**Pearl River flow**
- Estimated using rainfall with ANN model

**Boundary Tide**

**Wind** 風速、風向
- Weglein daily mean
  (except for Tuen Wan)

**Boundary Salinity** 體積

**Solar radiation** 太陽輻射

**Water Temp.** 水溫
- Meas. North Point

**Bacterial decay rate** 細菌消亡率

**Rainfall induced E.coli loading** 降雨引發的細菌污染
- Empirical correction using previous 3-day rainfall

Near-far field coupling

**Velocity/salinity**

**3D jet trajectories**

**Computed E.coli profile** by far field model

**Longitudinal transect of computed E.coli concentration field**
GIS-based 3D Visualization System

Marine WQ Validation: 2010 (Average-Wet Year)

Annual Mean, Depth Avg.
Pre-disinfection: 2006

Vertical structure, annual mean
**Diurnal Variation: Beach WQ better for diurnal tides**

*Gemini*

27-Oct-2011, sunny day, semi-diurnal

4-Nov-2011, sunny day, diurnal

*Ma Wan Tung Wan*

26-Nov-2011, overcast day, semi-diurnal

19-Nov-2011, overcast day, diurnal

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**Diurnal Beach E. coli Variation**

- Beach WQ depends on tidal variation and solar radiation
- Beach WQ better under strong solar radiation; lower bacterial counts during low tide
- During diurnal tides beach WQ is relatively better than during semi-diurnal tides
- Longer travel time (from HATS to TW beaches) during diurnal tide, allows for more bacterial decay by solar radiation (Chan et al, 2013).
Application of WATERMAN system in coastal water quality management

- Definition of mixing zones
- Daily beach water quality prediction
- Setting of effluent discharge standards
- Emergency response/disaster mitigation
- Optimal disinfection dosage control

Forecast Accuracy* in 2010-2012
20 Key Beaches

* Accuracy for forecasting the compliance/exceedance of beach water quality objective (180 cnt/100mL)
(N ~ 100 per beach)
WATERMAN Beach Water Quality Forecast System: setting of effluent *E.coli* standard

**Stage I, ADF** \( (Q = 1.4 \times 10^6 \text{ m}^3/\text{d}) \)
- Monthly G-mean \( E.coli \) < \( 2 \times 10^5 \text{ counts/100mL} \)

**Stage 2A** \( (Q = 1.8 \times 10^6 \text{ m}^3/\text{d}) \)
- Monthly G-mean \( E.coli \) < \( 2 \times 10^4 \text{ counts/100mL} \)

Previous studies based on typical average wet/dry season conditions - without beach water quality field data validation

*The assimilative capacity should be assessed by accounting for entire range of discharge & ambient conditions – only thus can standards be set that are not excessively severe*

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### Predicted daily beach grading distribution – bathing season

- **Stage 1 ADF** \( C_2 = 2 \times 10^6 \text{ count/100mL} \), current license standard
- **Stage 2A** \( C_3 = 2 \times 10^5 \text{ count/100mL} \), current license standard
- **Stage 2A** \( C_3 = 2 \times 10^5 \text{ count/100mL} \), relaxed standard

**N = 245**
Flushling/Sea Water Intakes

- Criteria: *E. coli* < 20,000 count/100mL at any time

Predicted *E. coli* (depth-average, hourly data, N = 2880)

<table>
<thead>
<tr>
<th>Column: Geometric mean <em>E. coli</em> conc.</th>
<th>Error bar: Max <em>E. coli</em> conc.</th>
</tr>
</thead>
</table>

Ma Wan fish culture zone

- Criteria: *E. coli* < 610 count/100mL for annual geometric mean

Predicted depth-average *E. coli* (hourly data, N = 5880)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>E. coli standard (count/100mL)</th>
<th>Geometric mean (count/100mL)</th>
<th>% &gt; 610</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADF Current license</td>
<td>200,000</td>
<td>53</td>
<td>0%</td>
</tr>
<tr>
<td>HATS-2A 2014 License standard</td>
<td>20,000</td>
<td>32</td>
<td>0%</td>
</tr>
<tr>
<td>HATS-2A 2014 Relaxed license</td>
<td>200,000</td>
<td>45</td>
<td>0%</td>
</tr>
</tbody>
</table>

- The geometric mean of *E. coli* level in Ma Wan FCZ are well below 610 count/100mL
- There would be some improvement in the bacterial level after Stage 2A (license and relaxed conditions).
Secondary contact zones

- Criteria: Annual mean $E. coli < 610$ count/100mL

Predicted depth-average geometric mean $E. coli$

Recommendation on effluent $E. coli$ standard

- Under HATS-2A ($Q = 1.8 \times 10^6$ m$^3$/d), HATS effluent $E. coli$ standard in bathing season can be relaxed from the current license level of $2 \times 10^4$ count/100mL to $2 \times 10^5$ count/100mL. This will help reduce chlorine consumption, save energy and operational cost whilst protecting the environment.

- A less restrictive effluent $E. coli$ standard (e.g. $8 \times 10^5$ count/100mL) can be adopted for diurnal tides without violating the WQO.

- More understanding on the disinfection system is required for optimizing disinfection dosage:
  - Hydraulics and mixing of the ADF
  - Relation between chlorine dosing and effluent $E. coli$ concentration
Application of WATERMAN System in Emergency Response Incidents

Emergency Sewage Overflow, Pillar Point Sewage Treatment Works, 25-26 August 2014

- Malfunction of the fine screens at the Pillar Point Sewage Treatment Works (PPSTW) on August 25, 2014,
- a total 95,000 m³ of raw sewage was discharged through an emergency bypass outfall for 11 hr.
- All 14 beaches in Tuen Mun and Tsuen Wan were closed immediately on August 25.
Pillar Point outfall parameters

<table>
<thead>
<tr>
<th></th>
<th>Main</th>
<th>Bypass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffuser length (m)</td>
<td>425</td>
<td>50</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>No. of riser (ports per riser)</td>
<td>9 (6)</td>
<td>3 (4)</td>
</tr>
<tr>
<td>Jet diameter (m)</td>
<td>0.26</td>
<td>1.05</td>
</tr>
<tr>
<td>Jet velocity (m/s)</td>
<td>0.701</td>
<td>0.193</td>
</tr>
<tr>
<td>Densimetric Froude number Fr</td>
<td>3.14</td>
<td>0.43</td>
</tr>
<tr>
<td>Typical current $u_a$ (m/s)</td>
<td>0.15-1.10</td>
<td>0.07-0.40</td>
</tr>
<tr>
<td>Near field dilution</td>
<td>50-115</td>
<td>15-40</td>
</tr>
</tbody>
</table>

25-27 August 2014

- Impact of bypass discharge results in elevated beach E.coli levels on Tuen Mun beaches but no impact on Tsuen Wan beaches
- The effect of pollution is dissipated in about 8-10 hours
Optimization of Disinfection Performance & Fluid Mechanics of Chlorine Mixing
Flow Distribution Chamber
(Chlorine dosing unit)

- Chlorine conc = 100,000 ppm
- Target well-mixed chlorine concentration = 10-20 ppm
- Required dilution ~ 10,000

$Q \sim 10 - 20 \text{ m}^3/\text{s}$

Chlorine dosing in flow distribution chamber

Chlorine dosing unit (2 rows of jets)
Dense jet in chlorine dosing (lab experiment)
$\Delta p / \rho = 0.2 \quad V_j = 0.155 \text{ m/s}$ and $Fr = 2.0$

1:2 scale model for studying chlorine demand in the Harbour Area Treatment Scheme Advance Disinfection Facility (HATS-ADF)

CEPT effluent

10% chlorine solution
dosing unit

weir
• Onsite field monitoring on a 1:2 Froude scale model of a slice of the sewage treatment plant flow;
• The jet mixing of the chlorine with the sewage flow will be simulated;
• The exertion of chlorine demand through the interactions of chlorine with effluent impurities including both soluble and settled particles can be studied; and
• To determine of total residual chloride (TRC) fluctuations at various locations along the test flume to understand the effects of the dosing unit and the weir upon the mixing of the chlorine;

**CFD prediction of dosing jets**

Computed 3D surface of dilution 100 and 1000 contour for the present dosing unit design

Velocity (medium flow/high dosage):
Upper jet = 2.0 m/s
Lower jet = 2.0 m/s
Ambient = 0.65 m/s

Average chlorine conc. (C/Cₘ) at x = 60m

<table>
<thead>
<tr>
<th>CASP</th>
<th>Sewage flow (m²/s)</th>
<th>Chemical flow (L/s)</th>
<th>Chemical Left culvert C/Cₘ</th>
<th>Chemical Right culvert C/Cₘ</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH</td>
<td>25.0</td>
<td>4.17</td>
<td>1.19</td>
<td>0.90</td>
</tr>
<tr>
<td>MH</td>
<td>16.0</td>
<td>2.67</td>
<td>1.21</td>
<td>0.89</td>
</tr>
<tr>
<td>LL</td>
<td>7.0</td>
<td>0.58</td>
<td>1.10</td>
<td>0.95</td>
</tr>
</tbody>
</table>

ₘₚ = well mixed conc. = 20mg/L

Uneven distribution of chlorine
Full-scale Experiments of Internal Hydraulics of Dosing Jets

Water jets into air (Δρ/ρ = 1.0) - Limiting case of dense jet

Side view of water jets into air experiments
Conclusions

1. Real time water quality forecast systems can be used for environmental engineering and control and management – in particular setting of a sensible sewage effluent discharge standard and the planning of emergency response in pollution accidents/disasters.

2. The environmental impact on nearby beaches and sensitive receivers can be managed by optimizing operation strategy and disinfection dosage.

3. Optimal disinfection dosage control depends on the mixing of chlorine with the saline sewage flow - localized high chlorine concentration may lead to more chlorine demand and less *E. coli* kill.

Thank you!