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

Joseph H. W. Lee
Department of Civil and Environmental Engineering
Hong Kong University of Science and Technology, Hong Kong, China

S. N. Chan
School of Civil and Environmental Engineering
Nanyang Technological University, Singapore

K. W. Choi
Department of Civil and Environmental Engineering
Hong Kong University of Science and Technology, Hong Kong, China

P. K. Chan
Drainage Services Department
Hong Kong Special Administrative Region Government, Hong Kong, China

ABSTRACT

Bathing beaches are invaluable marine resources for Hong Kong and the protection of public health is of utmost importance. The Harbour Area Treatment Scheme (HATS) is the sewage collection and treatment scheme that serves the urban areas of Hong Kong on both sides of Victoria Harbour. The sewage receives Chemically Enhanced Primary Treatment (CEPT), and the treated sewage flow (1.4×10^6 m^3/d) is discharged through a 1.2km outfall in the western Victoria Harbour. Since March 2010 the additional provision of chlorination to the treated effluent has brought significant water quality improvements to the neighbouring Tsuen Wan beaches.

The WATERMAN Real-Time Coastal Water Quality Management System has been applied to formulate a disinfection dosage control strategy. A comprehensive investigation on the relationship between beach water quality, bacterial standard of effluent discharge and environmental conditions has been carried out using the extensively validated WATERMAN 3D hydrodynamic model. Detailed numerical simulations for an entire average wet year demonstrate that the Water Quality Objectives (WQO, *E.coli* < 180 count/100mL) can be met in the coastal receiving waters for an effluent *E.coli* standard of 200,000 counts/100mL for HATS Stage 2A (Q = 1.8×10^6 m^3/d). The setting of an appropriate discharge standard will help to optimize the chlorine dosage, reduce energy consumption and operation cost whilst preserving the protection of the water quality of beaches, seawater intakes and other sensitive receivers. The WATERMAN system has also been applied for emergency response in pollution accidents and development of operational strategies.

1. INTRODUCTION

1.1. Hong Kong Harbour Area Treatment Scheme (HATS)

The Hong Kong Harbour Area Treatment Scheme (HATS) (Fig. 1a) is the sewage collection and treatment scheme that serves the urban areas of Hong Kong on both sides of Victoria Harbour (Fig. 1). Stage 1 of HATS consists of a 23.6 km-long system of deep tunnels that conveys sewage from Kowloon and the north-eastern part of Hong Kong Island to a centralized sewage treatment plant at Stonecutters Island (SCISTW). The sewage receives Chemically Enhanced Primary Treatment (CEPT), and the treated sewage flow (1.4 million m^3/d or 16 m^3/s) is discharged via a 1.2 km long submarine outfall diffuser into western Victoria Harbour at a mean depth of around 12 m. Stage I of HATS serves a population of around 3 million and treats 75% of the sewage from the harbour catchment. In Stage 2A of HATS, additional flows from Hong Kong Island and the rest of the catchment will be collected; the daily average sewage flow of SCISTW will be increased to 1.8 million m^3/d (21 m^3/s).

Since the full commissioning of HATS Stage 1 in 2001, the water quality in Victoria Harbour has notably improved - with increase in dissolved oxygen and decrease in ammonia nitrogen concentrations. The overall bacteria (*E.coli*) levels in eastern and central Victoria Harbour have also been reduced by about 50%. However, due to the significantly more concentrated and larger sewage flow from HATS, bacterial water quality in the adjacent western harbour and coastal waters has notably deteriorated, resulting in closure of seven gazetted beaches along the Tsuen Wan coast in 2003 (Fig. 1b – e.g. Gemini (GEM), LIDO and Approach (APP)).

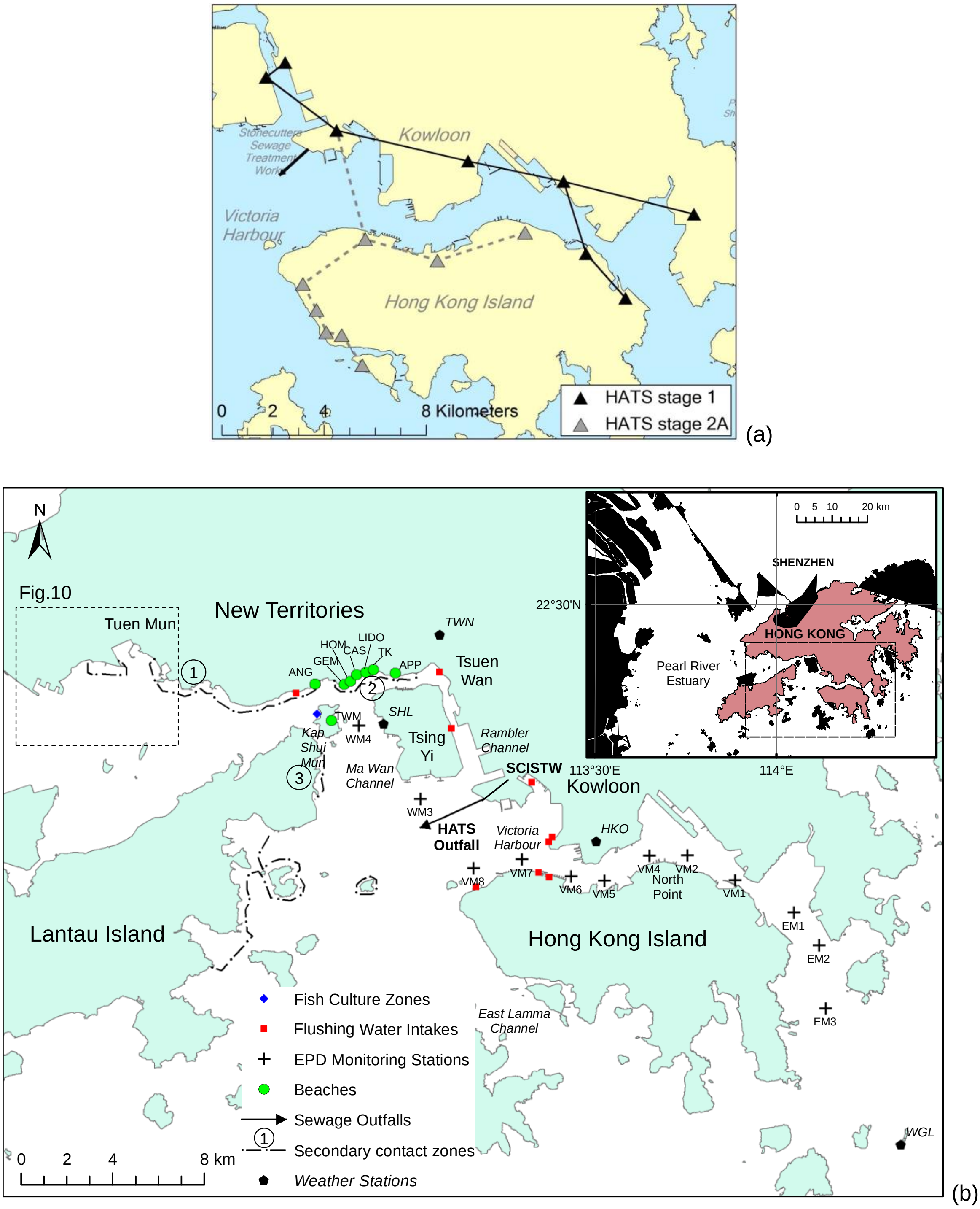


Figure 1: (a) The Hong Kong Harbour Area Treatment Scheme (HATS), Stages 1 and 2A. (b) The HATS outfall, Tsuen Wan Beaches and other sensitive receivers (WSD flushing water intakes, fish culture zones and secondary contact zones) in the region.

1.2. Disinfection of HATS Effluent

In order to improve water quality along the Tsuen Wan coast, the provision of part of the permanent disinfection facilities under HATS Stage 2A has started in advance of the completion of Stage 2A works. The Advance Disinfection Facilities (ADF) were completed in 2009 and started operation in March 2010. The key elements of the disinfection system include: a) mixing of sodium hypochlorite solution with the treated sewage in the form of multiple dense jets; b) the use of a 1km long effluent discharge box culvert as a chlorine contact tank for about 10 min of contact time; and c) provision of sodium bisulphite at the outfall chamber for controlling residual chlorine before discharge. The water quality at the Tsuen Wan beaches has notably improved over the past three years; the closed beaches were re-opened in 2011.

While chlorine is an effective disinfectant for reducing pathogen levels, it is also toxic to aquatic life. There are environmental concerns associated with the formation and toxicity of total residual chlorine (TRC), and chlorination by-products (CBPs) formed by reactions between chlorine and other substances present in the effluent. CBPs refer to chlorinated organic compounds and are generally considered of concern to human health and marine life. Although the TRC in the effluent is controlled to acceptable levels, it is desirable to optimize the chlorine dosage, reduce energy consumption and operation costs - subject to meeting effluent discharge and beach water quality standards, and protection of beneficial uses.

1.3. Beach Water Quality Objective and Setting of Effluent Standard

The Hong Kong Beach Water Quality Objective (WQO) states that the *E.coli* (EC) levels - calculated as the geometric mean of all samples collected in the bathing season within 1 calendar year - shall not exceed 180 counts/100mL. Samples are taken at least 3 times in 1 calendar month at intervals of between 3 and 14 days by the Environmental Protection Department. Beaches are classified into 4 grades each week in the bathing season, based on the geometric mean of the most recent 5 samplings ($C_{\ln EC5}$, Table 1). Beaches with $C_{\ln EC5}$ > 610 counts/100mL, or a single sample EC > 1600 counts/100mL are graded as "Very Poor" and would be closed to swimmers immediately.

Table 1 Hong Kong's beach grading system and the dependence on minor illness (skin and gastrointestinal illnesses) rate [2].

Grading	Beach water quality	*E.coli* ($C_{\ln EC5}$) (counts/100 mL)	Minor illnesses rate (cases/1000 swimmers)
1	Good	< 24	Undetectable
2	Fair	25 - 180	< 10
3	Poor	181 - 610	11 – 15
4	Very Poor	> 610	> 15

Currently the effluent standards for different stages of HATS are based on results of water quality modelling in an Environmental Impact Assessment (EIA) study [1]. The effluent discharge standards for *E.coli* are set as 200,000 counts/100 mL for HATS Stage 1-ADF and 20,000 counts/100 mL for Stage 2A. A more conservative standard is recommended for Stage 2A, considering the large variations of beach *E.coli* levels, the increased sewage flow and assuming better chlorination efficiency due to the provision of a new chlorine contact culvert to increase the chlorine contact time [1].

It must be emphasized that the water quality modelling in [1] did not account for the high variability of environmental factors including salinity, natural ultra-violet radiation, and wind that affect the fate and transport of *E.coli* (only "typical" dry and wet season conditions are considered). The model used was also not calibrated against beach water quality data, and predictions are not well supported by the field observations since commissioning of ADF. Furthermore, there is great uncertainty on the relation between chlorine dosage and effluent discharge *E.coli* concentration. There is hence a need for a more realistic re-examination of the effluent discharge standard in relation to the beach water quality actually achieved and chlorine dosage requirement.

This paper demonstrates the use of the recently developed WATERMAN system in several critical areas important for HATS Stage 2A and to the protection of coastal water quality:

- Field validation of WATERMAN system for HATS ADF operation – water quality of Victoria Harbour and Tsuen Wan beaches
- Environmental assessments of HATS ADF and Stage 2A for disinfection dosage optimization – permissible effluent bacterial standard to meet statutory requirements for beach water quality, industrial water use, and fish farming.
- Application in emergency response

2. THE WATERMAN SYSTEM

The WATERMAN Environmental Impact Assessment (EIA) system is a three-dimensional real time regional hydrodynamic and water quality model for the entire Hong Kong waters, capable of evaluating long-term water quality impact and forecasting short-term water quality variations. The simulation engine is developed based on the three-dimensional (3D) flow model with the Distributed Entrainment Sink Approach (DESA) for near and far field coupling [3] of wastewater discharges into a changing tidal ambient. The far field flow and mass transport model is based on the Environmental Fluid Dynamics Code (EFDC) that solves the free surface flow and transport problems [4].

The model covers the area of the Pearl River Estuary, the entire Hong Kong waters, and the northern South China Sea with 16,443 horizontal grid cells and 10 sigma layers (Fig. 2). The model is driven by tidal and salinity boundary conditions at the open boundaries. Daily vector-averaged wind corrected to 10 m level at Waglan Island is used, except for the area near Tsuen Wan beaches, Ma Wan and Rambler Channels, where the wind condition at Tsing Yi is used. Daily freshwater discharge from Pearl River (Fig. 3a) are estimated using a validated ANN model with daily rainfall data from 14 weather stations covering the key river basins. *E.coli* loading from submarine sewage outfalls has been estimated from the measured flow in various sewage treatment plants with reference to their treatment level. *E.coli* loading from stormwater outfalls are obtained from reported pollution loading inventory [5] and fine-tuned by calibration against EPD *E.coli* field data in 2010-12 (Fig. 4). The *E.coli* inactivation is modelled as a first order decay as a function dependent on hourly-varying salinity, temperature and solar radiation (measured data at King's Park, Fig.3b), which is specifically developed for subtropical Hong Kong coastal waters based on laboratory and field studies [6].

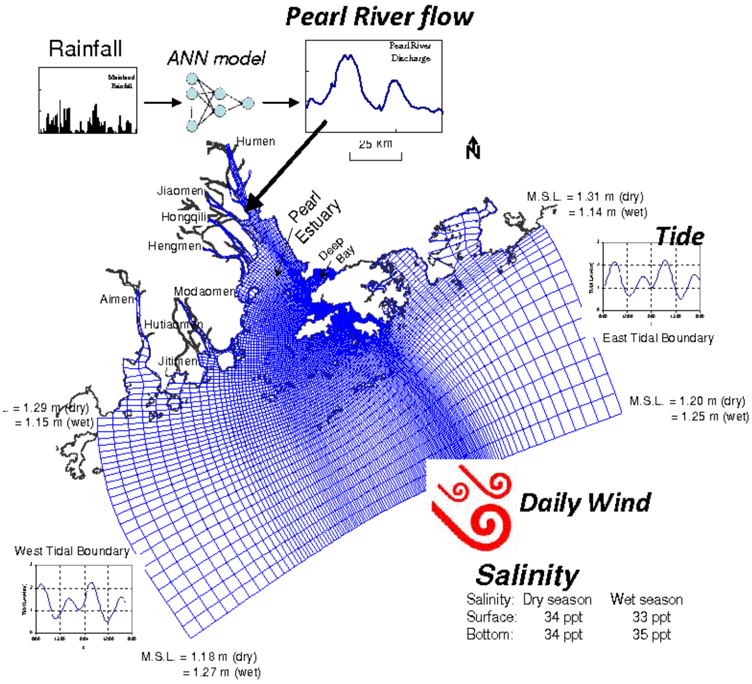


Figure 2: The model grid and boundary conditions for the WATERMAN 3D hydrodynamic and water quality model.

The 3D WATERMAN system is unique in its extensive validation against field data, including velocity and salinity data obtained in several hydrographic surveys in Hong Kong Waters between 1996 and 2007 [7], and *E.coli* levels in Tsuen Wan beaches and Victoria Harbour in 2006-2012, covering both pre- and post-disinfection conditions. For the first time the diurnal variation of beach water quality is studied through field sampling and 3D model analysis; a new understanding on the relation between beach water quality and hydro-meteorological factors has been obtained. The model has been applied for daily deterministic beach water quality forecast for Tsuen Wan beaches based on the best estimation of hydro-meteorological conditions. Since August 2011, the 3D WATERMAN system has achieved an accuracy of 75-100% in predicting the compliance/exceedance of Hong Kong beach WQO (180 counts/100mL) for the period of 2011-2012 [8]. The corresponding daily beach water quality indices or gradings are issued and disseminated to the public through the Internet (www.waterman.hku.hk) and smartphone apps.

It should be noted that the 3D deterministic model requires a minimum of model assumptions and is particularly suitable for predicting water quality of beaches affected by point source (e.g. HATS) and revealing insights into cause-effect relationships.

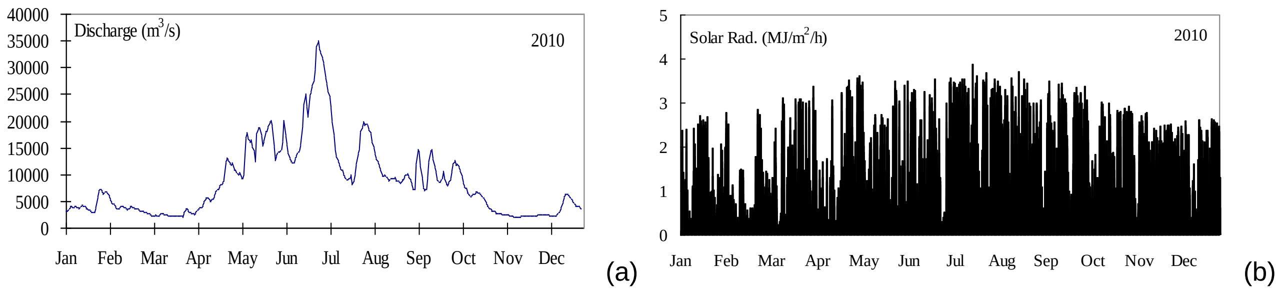


Figure 3: (a) Pearl River flow (predicted using ANN model) and (b) solar radiation conditions of 2010 used in the model scenarios.

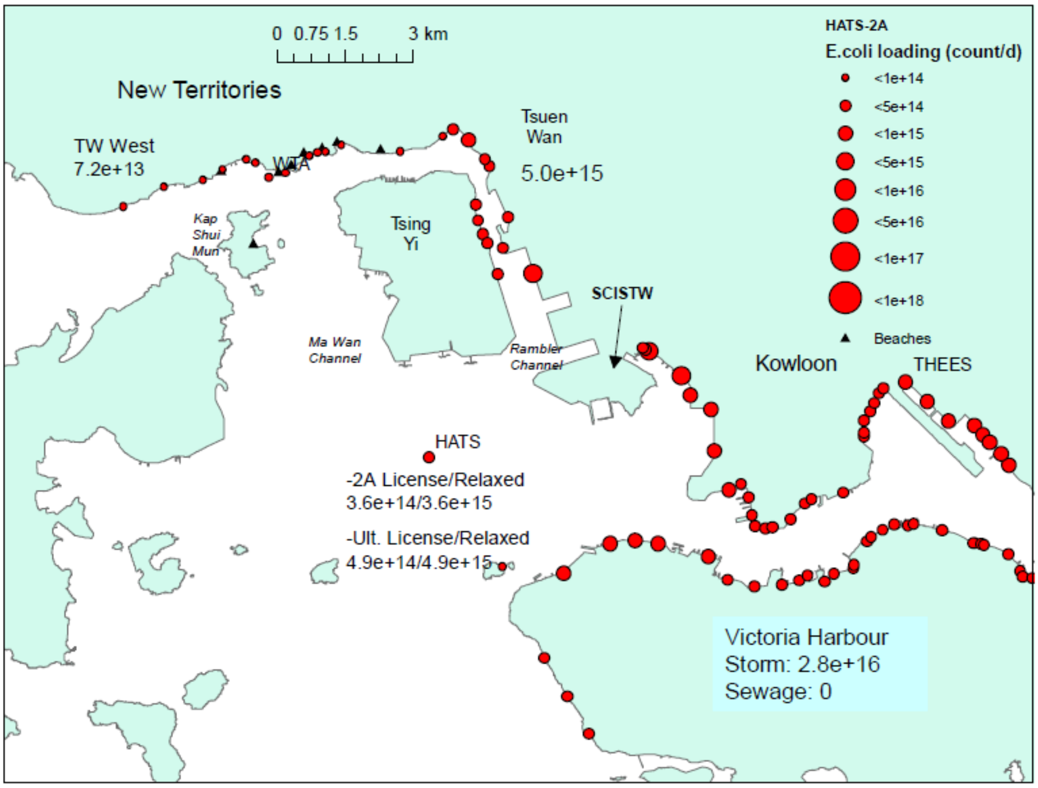


Figure 4: *E.coli* loading (count/d) from sewage and storm outfalls in Victoria Harbour, Rambler Channel and Tsuen Wan Beaches.

3. FIELD VALIDATION OF THE WATERMAN SYSTEM

3.1. Diurnal variation of beach water quality

The water quality of Tsuen Wan beaches is found to be highly dependent on hydro-meteorological conditions such as solar radiation, tide and rainfall. There is a significant diurnal variation of *E.coli* level, typically varying from the highest in the morning 6-8 am to the lowest in 3-5 pm. Fig. 5 shows example comparisons of predicted vs measured diurnal variation of beach water quality at Gemini (GEM) and Lido (LIDO) beaches in the dry season. The predicted *E.coli* level using measured hydro-meteorological conditions is shown along with the field data and predicted tidal level. It is seen that the model predictions capture the observed trends in bacterial water quality and are in good agreement with data. These and other comparisons reveal several interesting features: (i) Under sunny conditions, the beach *E.coli* level is much lower under diurnal tides than under semi-diurnal tides; water quality tends to be better under ebb tide conditions (see Fig. 5 for Gemini and Lido as an example); (ii) Similarly under overcast conditions, the beach water quality is also better under diurnal conditions. Similar differences can also be seen for the summer wet season with field data and extensive numerical simulations (not shown). The underlying reason is that the current speed during flood tide is in general stronger for semi-diurnal tides but weaker for diurnal tides, resulting in longer travel time from HATS outfall to Tsuen Wan Beaches during diurnal tides with more time for bacterial decay.

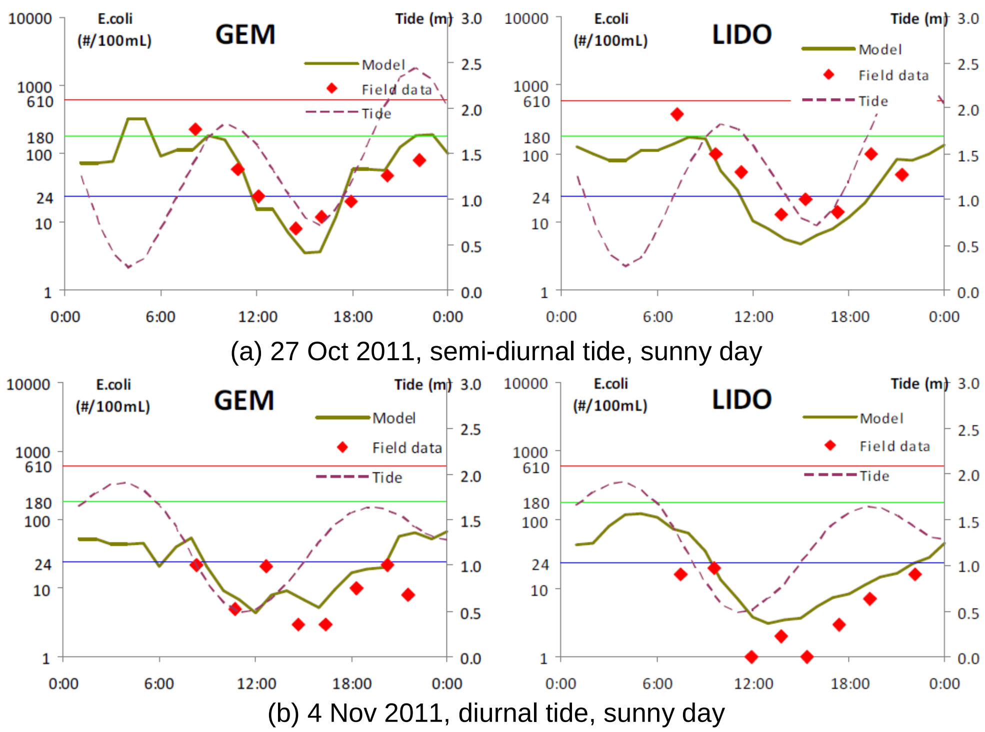


Figure 5: Predicted and measured E.coli level of Gemini and Lido beaches under different tidal conditions

3.2 Marine water quality in Victoria Harbour

To realistically reflect the impact of HATS effluent on the water quality of the receiving coastal waters, the model has also been calibrated and validated against the observed spatial and temporal *E.coli* variation in Victoria Harbour, the vicinity of HATS outfall and Rambler Channel. The dry weather storm outfall *E.coli* loadings are parameters to be calibrated.

Monthly EPD marine monitoring data in Victoria Harbour (12 stations, cf. Fig. 1b) is used for model-data comparison as they provide a long-term and consistent basis for understanding water quality trends. Water samples are taken once every month at 1 m below water surface (Surface), mid-depth (Middle) and 1 m above sea bed (Bottom). Data analysis of pre- and post-disinfection

E.coli levels shows that the positive impact of disinfection can be seen only in the western Victoria Harbour (e.g. stations VM7, VM8, WM3 and WM4), while the stations eastward from Central are unaffected by the reduction of HATS bacteria loading. The calibration is carried out for pre-disinfection years 2006 (wet year) and 2009 (dry year). Two post-disinfection years, 2010 (average-wet year) and 2011 (dry year) is used for model validation purposes. The measured hydro-meteorological conditions are used as input wherever possible.

Fig. 6 shows a comparison between predicted and observed *E.coli* levels in a post-disinfection wet year (2010); the model has been calibrated using the 2006 data. The spatial and temporal trends of *E.coli* distribution are well predicted by the model. The predicted *E.coli* level in Victoria Harbour is highly correlated with observations (N = 108, r = 0.71) (Fig.6a). The *E.coli* concentration is a maximum in Central Harbour (VM6) and decreases towards the east (Lei Yu Mun, VM2) and west (Ma Wan, WM4), showing the same trend as the observed data (Fig. 6b). The vertical structure shows that the maximum *E.coli* level is often not at the surface, especially in the western Harbour near the HATS outfall, reflecting submergence of the sewage field in a density-stratified environment (Fig. 6c, WM3 and WM4).

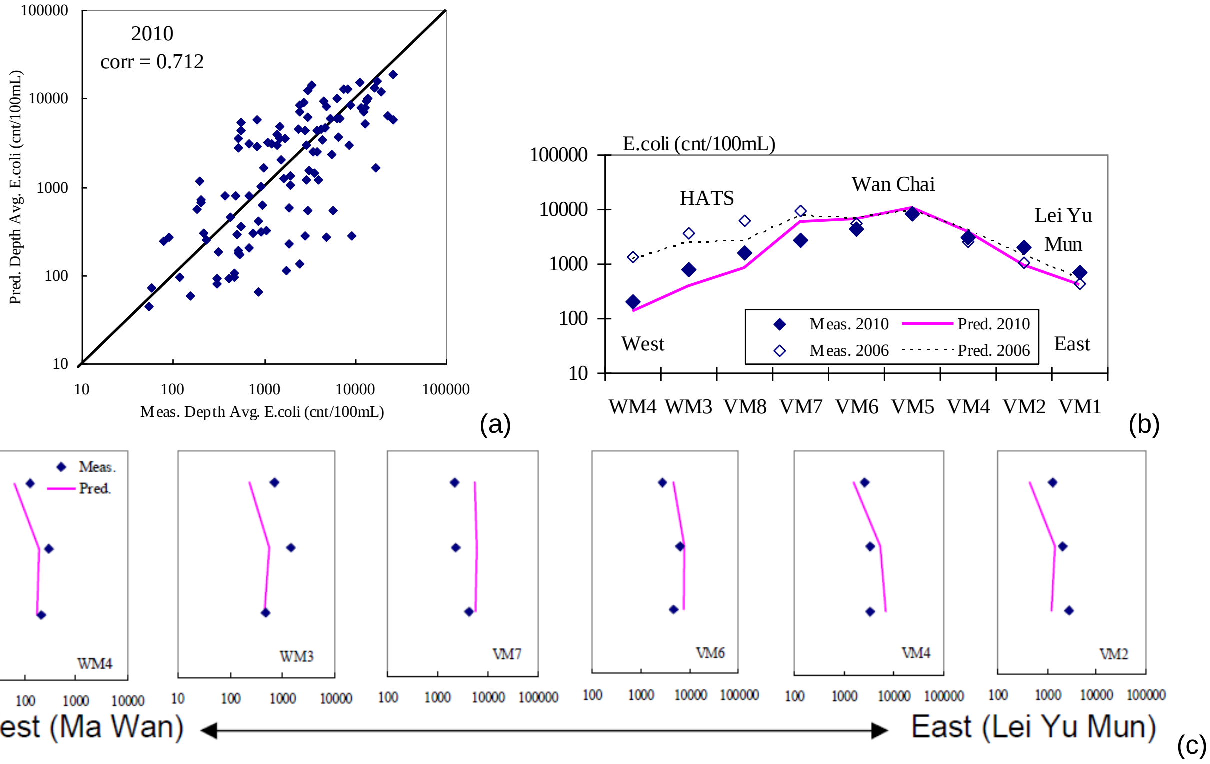


Figure 6: (a) Comparison of predicted and measured marine water *E.coli* levels (depth averaged, N = 108) of 2010 (post-disinfection). (b) Annual and depth averaged *E.coli* distribution along Victoria Harbour, pre- (2006) and post-disinfection (2010). (c) Annual averaged vertical *E.coli* distribution.

4. ASSESSMENT OF HATS STAGE 2A EFFLUENT WATER QUALITY STANDARD

4.1. Study Scenarios

Using the validated WATERMAN system, the water quality of Tsuen Wan beaches and the coastal receiving waters is studied for three representative scenarios: HATS ADF ($Q = 1.4x10^6$ m^3/d), HATS Stage 2A - 2014 ($Q = 1.8x10^6$ m^3/d) and Ultimate Stage ($Q = 2.45x10^6$ m^3/d). For each sewage flow condition, the water quality during the bathing season (March – October) is studied for different effluent *E.coli* standards. Both the current license (C_0 = 20,000 counts/100mL for HATS-2A and HATS-Ultimate) and a more relaxed effluent *E.coli* standard (C_0 = 200,000 counts/100mL) are studied. The year of 2010 (an average-wet year, with 2372 mm rainfall) is selected; the bacteria distribution in the entire Hong Kong waters is computed for the entire year (output time step of 30 min), covering a representative range of tidal and hydro-meteorological conditions. For each day the computed *E.coli* level at around the nominal EPD sampling time of 11 am (geometric mean of half-hour values between 10 am-12noon) is taken to be the daily prediction - i.e. the concentration that would correspond to a sample measurement in a standard beach water quality monitoring survey. The bacterial loads from HATS outfall and other main point sources in Victoria Harbour for HATS-2A and HATS-Ultimate are illustrated in Fig. 4. It can be seen that the contribution by local storm sources in Tsuen Wan (5.0×10^{15} counts/d) is one order higher than that of HATS-2A with current license effluent standard (3.6×10^{14} counts/d), and of the same order if the effluent license standard is relaxed by one order (3.6×10^{15} counts/d), despite the increase in sewage flow by about 30%. Victoria Harbour with a number of storm outfalls contributes a load of 2.8×10^{16}counts/d, one order higher than that of Tsuen Wan Bay. The pollution load from Tsuen Wan West (close to the beaches) is much smaller after the introduction of a number of sewage collection and dry weather flow inception measures [10]. After disinfection (compared to the pre-disinfection loading of 1.4×10^{17} counts/d), the HATS bacterial loading is comparable to that from the local storm water pollution sources in Tsuen Wan Bay and Rambler Channel.

4.2 Statistical distribution of beach water quality and implication on effluent standard

The annual bathing season geometric mean *E.coli* level serves as an important indicator for assessing the compliance of WQO of a beach. Table 2 shows the predicted geometric mean of *E.coli* level (N = 245) in the bathing season of Tsuen Wan beaches for HATS Stage 2A (license and relaxed standard). It can be seen that under the license condition, the annual geometric mean level is very similar to that in the ADF stage. The slight improvement in water quality resulted from a reduction in overall *E.coli* loading due to the closure of sewage outfalls in Victoria Harbour which currently discharge nearly untreated sewage. For the relaxed effluent standard, the mean *E.coli* level is slightly higher but still below the beach WQO of 180 counts/100mL. The model prediction indicates the relaxing of effluent standard to 200,000 count/100mL does not lead to any material deterioration of the water quality of Tsuen Wan beaches.

Statistical analysis of the daily model predictions also shows that for both HATS-2A and Ultimate conditions, the relaxing of license standard to 200,000 counts/100mL would not result in significant rise in the proportion of Poor (181-610) and Very Poor (> 610) water quality. Fig. 7 shows the percentage of predicted water quality categories (according to classification in Table 1) of four selected beaches: TWM and GEM (HATS-affected), LIDO (local village pollution) and APP (urban pollution sources) under ADF-license, 2A-license and 2A-relaxed standards. For example, for Ma Wan Tung Wan (TWM), for HATS-ADF license condition, the beach water quality is “Good” or “Fair” for 40 and 58 percent of the time respectively. For the HATS-2A with relaxed standard, the corresponding figures would be 45 and 54 percent respectively. For both scenarios, the beach water quality would meet the WQO (i.e. <180 counts/100mL) for around 98 percent of the time. It is also seen that except for Approach Beach (APP) which is affected by pollution from the Tsuen Wan Bay area, enforcing a stricter license standard for HATS-2A would reduce the occurrence of WQO exceedance by 1-3% only. Similar conclusions can be made for HATS-Ultimate condition.

Table 2 Measured geometric mean (N = 33, 32 for Ma Wan Tung Wan) of Tsuen Wan beach *E.coli* level (count/100mL) in bathing season 2010 (Mar-Oct) and model predicted geometric mean (N = 245) *E.coli* level for HATS-ADF, HATS-2A and HATS-Ultimate scenarios. License/Relaxed: 2.0E4/2.0E5 counts/100mL.

Beach	Measured (2010)	Predicted HATS-ADF	Predicted HATS-2A		Predicted HATS-Ultimate	
			License	Relaxed	License	Relaxed
Ma Wan Tung Wan	17	33	17	29	18	32
Angler’s	134	128	109	126	111	133
Gemini	137	76	59	75	60	80
Hoi Mei Wan	87	66	49	66	50	71
Casam	102	63	52	62	53	66
Lido	87	64	52	62	53	66
Ting Kau	141	156	143	155	145	159
APP	124	117	97	114	99	120

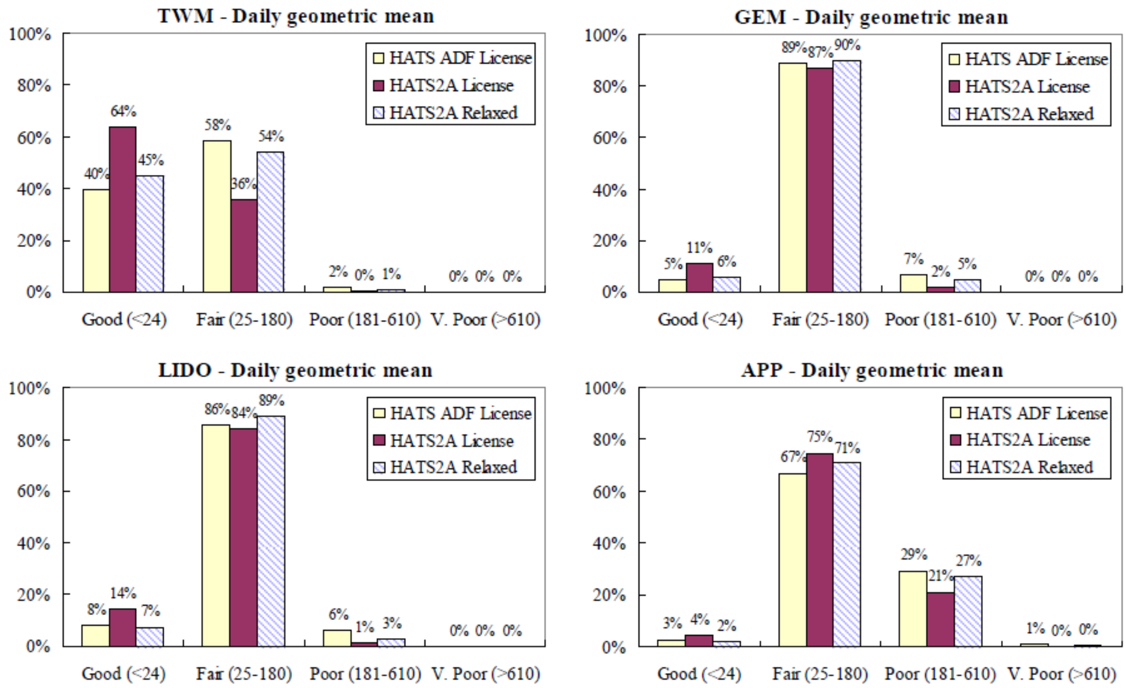


Figure 7: Percentage of predicted water quality categories for HATS 2A-2014 (2010 bathing season condition, N=245).

4.3. Diurnal *E.coli* variation and disinfection dosage optimization

A close examination of the diurnal beach *E.coli* variation reveals that the water quality is significantly poorer during semi-diurnal tides (irrespective of the weather condition) than under diurnal tides. This interesting feature is consistent with the field measurement of *E.coli* level as shown in Fig.5 and confirmed for a wide range of tidal and hydro-meteorological conditions (not shown). During semi-diurnal tides the water quality are usually in the “Fair” condition (25-180 counts/100mL) with occasional exceedance of the WQO (>180 counts/100mL) (Fig.8a). During diurnal tides the beach water quality are usually “Good” (<24 counts/100mL) or “Fair” for all scenarios (Fig.8b). The similar *E.coli* levels for the scenarios shows that the HATS discharge has minimal impact to the beach water quality if the effluent standard of HATS-2A is relaxed to 200,000 counts/100mL.

During semi-diurnal tides an effluent *E.coli* concentration of $4x10^5$ count/100mL would already result in the increase in number of “Poor” water quality. Hence it is not advised for reduced chlorine dosage during semi-diurnal tides. The beach water quality is better during diurnal tides even under overcast condition, without WQO exceedance. For a higher effluent *E.coli* level of $8x10^5$ counts/100mL, the water quality of Gemini beach would only worsen to “Poor” during the night time and the early morning. Detailed numerical studies [12] have confirmed that during diurnal tides it is possible to discharge effluent *E.coli* level of 800,000 counts/100mL without violating the beach WQO – suggesting a simple and practical operational strategy to optimize chlorine dosage while the coastal environment remains protected.

4.4. Impact on other sensitive receivers

The assessment has also considered the compliance of water quality objectives for seawater intakes in Victoria Harbour (*E.coli*<20,000 counts/100mL), Ma Wan Fish Culture Zone (annual mean *EC* < 610 counts/100mL) and Secondary Contact Zones along Tsuen Wan and Tuen Mun coast (annual mean *EC* < 610 counts/100mL). Model prediction shows that there is no significant increase in *E.coli* level for the intakes under a relaxed license condition in Stage 2A. All intakes, except one in an enclosed bay, show a maximum *E.coli* level less than 20,000 counts/100mL [11]. The geometric mean of *E.coli* level at the Ma Wan FCZ is well below 610 counts/100mL for all three conditions studied [11].

Three secondary contact zones are most critically affected by the HATS effluent: Zone 1 - along the coast from Golden Beach to Sham Tseng; Zone 2 - along the coast from Sham Tseng to Approach; Zone 3 - along part of the coast in Northern Lantau Island (cf. Fig.1b). The predicted annual geometric mean *E.coli* levels for all three zones are well below 610 counts/100mL (Fig.9 for zone 1 and zone 2). There will be some improvement in the water quality of secondary contact zones in Tsuen Wan coast under HATS 2A compared with the current ADF condition. Relaxing the Stage 2A standard by 1 order will result in rise in mean *E.coli* levels close to the ADF condition, but it still remains well below 610 counts/100mL.

In the dry (non-bathing) season (Jan-Feb, Nov-Dec) there is no statutory requirement for the water quality of bathing beaches. Detailed studies also show the water quality objectives for these sensitive receivers are satisfied for a HATS effluent standard of 700,000 counts/100mL [11].

13-Jul-10	HATS-ADF	HATS-2A 2014	
Time	License Standard	Relaxed standard	License Standard
E.coli	2.00E+05	2.00E+05	2.00E+04
0:00	**195**	**198**	**197**
2:00	**242**	**249**	**191**
4:00	**176**	**180**	**180**
6:00	**155**	**147**	**104**
8:00	**199**	**189**	**159**
10:00	**248**	**222**	**191**
12:00	**62**	**50**	**39**
14:00	**8**	**8**	**7**
16:00	**19**	**18**	**18**
18:00	**44**	**46**	**45**
20:00	**199**	**162**	**158**
22:00	**136**	**119**	**120**

Good	<24
Fair	25-180
Poor	181-610
Very Poor	>610

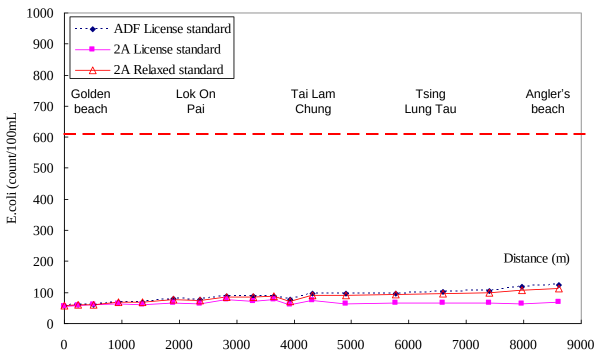
(a) 13 July 2010, sunny day with semi-diurnal tide

6-Aug-10	HATS-ADF	HATS-2A 2014	
Time	License Standard	Relaxed standard	License Standard
E.coli	2.00E+05	2.00E+05	2.00E+04
0:00	**127**	**164**	**95**
2:00	**50**	**83**	**26**
4:00	**36**	**49**	**22**
6:00	**59**	**66**	**23**
8:00	**85**	**87**	**61**
10:00	**17**	**17**	**15**
12:00	**14**	**14**	**14**
14:00	**12**	**13**	**13**
16:00	**15**	**11**	**8**
18:00	**14**	**12**	**10**
20:00	**33**	**40**	**23**
22:00	**46**	**64**	**28**

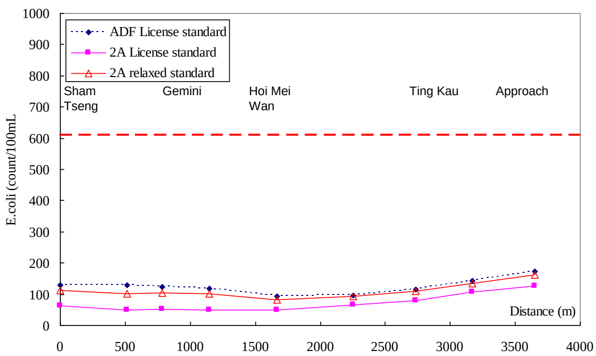
Good	<24
Fair	25-180
Poor	181-610
Very Poor	>610

(b) 6 August 2010, sunny day with diurnal tide

Figure 8: Model predicted *E.coli* diurnal variation of Gemini beach under the HATS-ADF and HATS-2A (license and relaxed standards) conditions.



(a) Zone 1 (Golden beach to Angler's beach)



(b) zone 2 (Sham Tseng to Approach beach)

Figure 9: Predicted (depth-averaged) bathing season geometric mean *E.coli* level in secondary contact zones 1 and 2 (cf. Fig. 1b) under HATS ADF, HATS-2A License and HATS-2A relaxed conditions.

5. APPLICATION OF WATERMAN SYSTEM IN EMERGENCY RESPONSE

The capability of WATERMAN system in forecasting the water quality impact of an accidental pollution discharge is illustrated. Due to a malfunction of the fine screens at the Pillar Point Sewage Treatment Works (PPSTW) in Tuen Mun on August 25, 2014, a total 95,000 m^3 of raw sewage was discharged through an emergency bypass outfall from around 15:30 hr on 25/8; all emergency repair works were completed at 02:30 hr on 26/8. All 14 beaches in Tuen Mun and Tsuen Wan were closed immediately on August 25. The 3D WATERMAN model was used for forecasting the impact on the nearby beaches.

The main sewage outfall for PPSTW is located about 2 km offshore and at a depth of 15m, while the Bypass Outfall is located about 700 m offshore, at a depth of 10m and is about 2.1 km to the nearest gazetted beach (Butterfly beach, Fig. 10). The simulated period covers three days from 25-28 August. During the incident the effluent was discharged via the Emergency Bypass Outfall (3 risers with 4 ports each) instead of the main sewage outfall for PPSTW (represented by 9 risers with 2 ports each). The effluent *E.coli* concentration is taken to be 3.3×10^7 counts/100mL for this period. Due to the much weaker tidal current near shore and shallower depth, the predicted near field dilution for the bypass outfall is only about 15-40, much lower than that of the normal discharge outfall (~ 50-115),

The predicted *E.coli* levels at the Tuen Mun and Tsuen Wan beaches agree well with the observations (Fig. 11). The model prediction shows an elevated *E.coli* level for Butterfly beach in Tuen Mun (Fig. 11a), from "Fair" water quality in normal condition to "Poor"/"Very Poor" water quality during the bypass discharge period. It is seen that the effect of the bypass discharge is dissipated in about 8-10 hours due to dilution, turbulent dispersion and bacterial inactivation. Furthermore, model prediction indicated that the incident has almost no impact upon the more distant Tsuen Wan beaches (Fig. 11b). The model predictions were confirmed by the field measurement, and the beaches were re-opened to the public on August 27. As a standard *E.coli* measurement usually takes at least 24 hours, the use of a real time water quality forecasting system would enable better beach management and planning of disaster mitigation measures. A similar application for emergency response in 2012 in Deep Water Bay was also conducted [9].

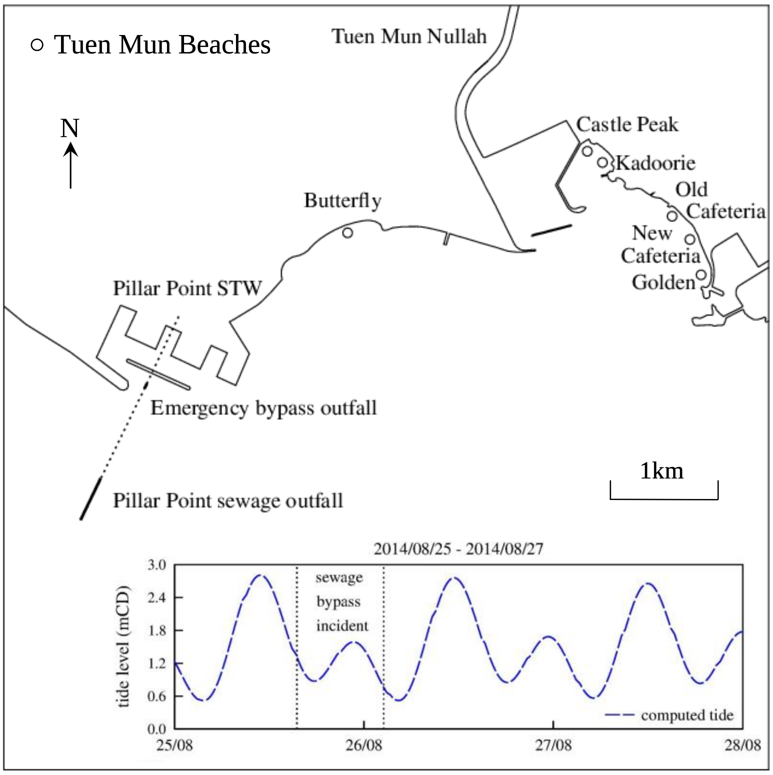


Figure 10: The outfall of Pillar Point STW for normal operation, the emergency bypass outfall and Tuen Mun beaches. Inset figure shows the tide level during the period of pollution accident.

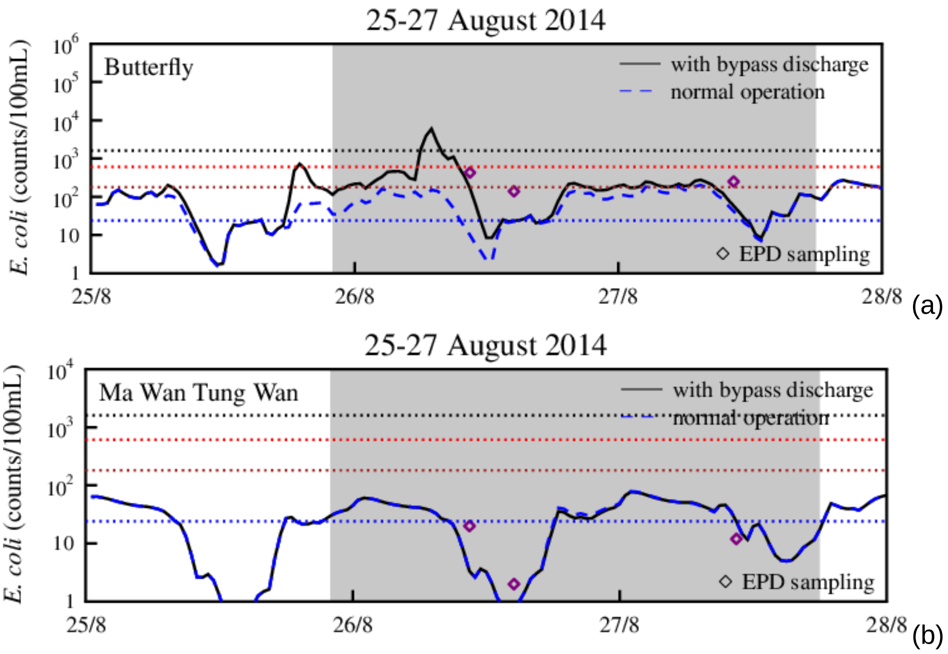


Figure 11: Model predicted *E.coli* level variation at (a) Butterfly beach (Tuen Mun) and (b) Ma Wan Tung Wan beach (Tusen Wan) after the emergency bypass discharge. Field data in symbol, period of beach closure is shaded.

6. CONCLUSION

The WATERMAN 3D deterministic environmental impact assessment and forecast system is developed based on a robust technology of hydrodynamic modelling and near-far field coupling of wastewater discharge. The system is unique in its extensive validation against field data. It is capable of predicting water quality impact of pollution discharges over a wide range of conditions.

The WATERMAN system has been employed in a comprehensive study of the relationship between Tsuen Wan beach water quality and different effluent discharge and environmental conditions. It is shown that the beach water quality response to effluent discharge concentration is highly nonlinear and complex. Extensive numerical studies has shown that the water quality of Tsuen Wan beaches will not be significantly affected for a relaxed HATS effluent *E.coli* level of 200,000 counts/100mL under the HATS-2A 2014 (Q = $1.8\text{x}10^6$ m^3/d) and Ultimate sewage flow conditions (Q=2.45 x 10^6 m^3/d). The bathing season geometric mean *E.coli* level can meet the Water Quality Objective of 180 counts/100mL without violation of the beach closure criteria (610 counts/100mL). It is hence recommended that the HATS effluent *E.coli* standard can be safely relaxed from the current license level of $2\text{x}10^4$ counts/100mL to $2\text{x}10^5$ counts/100mL – a standard that would protect the environment but not unnecessarily severe. The water quality objectives of other sensitive receivers (seawater intakes, fish culture zone and secondary contact zones) are also found to be satisfied under the relaxed standard. The WATERMAN system has also been used for optimizing chlorine dosage and supporting management actions during emergency response situations – with great benefit to the public.

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