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Research paper

Field and laboratory studies of *Escherichia coli* decay rate in subtropical coastal water

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Abstract

Escherichia coli is a commonly used bacterial indicator of water quality. Despite the significance of *E. coli* decay rate in many engineering applications, there has been scant field studies in subtropical coastal waters. In this study, laboratory experiments and field studies for *E. coli* decay rates are carried out for the first time in Hong Kong coastal waters. *E. coli* decay rates under typical ranges of light intensity, water temperature and salinity in the subtropical coastal waters are determined in the laboratory experiments. It is found that light intensity is the most significant factor affecting *E. coli* decay rate: 14.7−107 d^{-1} under light-exposure as compared to 0.85−1.50 d^{-1} in darkness. A decay formula is derived based on the laboratory results and validated against field studies of *in-situ E. coli* decay rate carried out at a coastal beach in Hong Kong. A parallel tracer method with reference to storm events is used, with the stream flow and the *E. coli* loading from the storm water runoff as the two sources of tracers. The freshwater concentration of a beach sample measures the physical dilution due to the mixing of the stream flow with the marine water. The *E. coli* concentration measures both the physical dilution and the bacterial decay; the biological decay of *E. coli* can then be determined from the measured freshwater and *E. coli* concentrations. The *in-situ E. coli* decay rates range from 1.3 to 5.1 d^{-1} for the four episodic storm events; the corresponding time required to have a 90% reduction of the initial *E. coli* level ranges from 10.8 to 42.3 h. The decay rates can be reasonably predicted by the formula derived from laboratory experiments. The present findings provide more realistic estimates of bacterial decay rate than values inferred from indirect model calibration against sparsely sampled data, and enable accurate predictions of water quality accounting for spatial and temporal variations of environmental factors.

Keywords: Escherichia coli; Decay rate; Subtropical coastal water; Parallel tracer experiment

1. Introduction

There are 41 coastal beaches in Hong Kong visited by millions of visitors every year. Coastal waters may be contaminated by faecal pollution from sewage discharge and urban runoff. Exposure to the faecal polluted beach water results in high risks of contracting swimming-associated illnesses (WHO, 2003). *Escherichia coli* (*E. coli*), a subgroup of faecal coliform bacteria, is a commonly used water quality indicator for the potential presence of pathogens, due to its high correlation with swimming-associated illnesses (Cabelli, 1983; Cheung et al., 1990). These enteric bacteria become naturalized to the environment, and gradually die off in the natural environment after leaving the intestine of human or other warm-blooded animals. The *E. coli* decay rate k (often expressed as T_{90} hours, the time required to achieve 90% reduction) is typically described by first-order kinetics ($EC(t) = EC_0 \cdot e^{-kt}$, where $EC(t)$ = *E. coli* concentration after

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decay, EC_0 = initial *E. coli* concentration and t = time for decay).

E. coli decay rate is important in many engineering applications, including outfall design for sewage disposal, environmental planning and impact assessment, and real time control of disinfection dosage (Chan et al., 2013). In a typical coastal sewage disposal scheme, treated sewage is discharged through a submarine outfall diffuser system. The sewage plume undergoes rapid initial mixing with the ambient water in the form of turbulent buoyant jets. Faecal pollutants in the mixed sewage plume are further diluted due to passive turbulent dispersion and natural bacterial decay. In many Asian Pacific coastal cities, sewage outfalls are typically located in relatively shallow waters (5−20 m deep), and are often close to sensitive receivers (5−10 km) such as beaches (Lee and Choi, 2008; Choi et al., 2009). The diluted sewage plumes can reach the nearby beaches in a couple of hours. Hence an accurate bacterial decay rate is essential to the prediction of beach water quality.

In coastal waters, various factors contribute to the mortality of *E. coli* including: photo-oxidation induced by sunlight (Davies-Colley et al., 1999), osmotic stress caused by the abrupt variation of salinity (Hrenovic and Ivankovic, 2009), infection by bacteriophages (Brüssow, 2005), and predation by protozoa (Chamberlin and Mitchell, 1978; Matz and Kjelleberg, 2005). Among all the environmental factors, sunlight has been found to be the most significant on bacteria inactivation (Fujioka et al., 1981; Gameson and Gould, 1975; Kapuscinski and Mitchell, 1983; Yang et al., 2000). The decay rate under sunlight in both laboratory and field experiments is two or more orders of magnitude greater than that in darkness. Gameson and Gould (1975) found that summer *in-situ* T_{90} during daytime is as short as 20 min. In addition, the *E. coli* decay rate is depth-dependent mainly due to rapid sunlight attenuation; this significantly decreases bacterial decay in wet seasons when sewage plumes are typically trapped in stratified coastal waters.

Mancini (1978) proposed an empirical formula to estimate decay rates of coliform bacteria (including total coliform, faecal coliform, and *E. coli*) based on field and laboratory measurements reported in approximately 100 studies, considering three key environmental factors: sunlight intensity, water temperature and salinity. This equation (Equation (1), “Mancini Equation”) estimates the average coliform decay rate in a fully-mixed water body.

$$k = [0.8 + 0.006 \times (\%\text{seawater})] \times 1.07^{(T-20)} + I_A \frac{1 - e^{-e_t H}}{e_t H} \quad (1)$$

where k = exponential decay rate (d^{-1}); T = water temperature (°C); I_A = average intensity of surface solar radiation (ly/h = cal/cm^2); e_t = light extinction coefficient (m^{-1}); H = fully-mixed water depth (m).

This simple Mancini Equation and its related forms have been incorporated in many water quality modeling tools, such as the hydrodynamic water quality model Delft3D (Deltares, 2009). However, it has some inherent limitations. First, there is a great scatter within the data (Mancini, 1978); the difference between estimation and observation can be up to one order of magnitude. Second, the Mancini Equation presumes coliform bacteria die off at a basic decay rate of 0.8 d^{-1} and 1.4 d^{-1} in darkness at 20 °C in freshwater and seawater, respectively; however, these values have not been verified. Third, the data come from various studies targeting three different groups of coliform bacteria, with many uncertainties in measurements and adjustments. Some studies reported that different groups of bacteria can have different decay rates under the same condition (Gameson and Gould, 1975; Sinton et al., 2002). In many environmental planning and assessment studies, a constant representative value is often adopted without considering significant time and spatial variations of environmental factors (e.g. solar radiation and salinity).

Whilst *E. coli* decay rate has been studied extensively especially in Europe and USA (Noble et al., 2004; Boehm et al., 2009), few studies in sub-tropical estuaries or coastal waters have been reported. One of these studies was conducted in controlled laboratory experiments in Taiwan (Yang et al., 2000). There is a great uncertainty in adopting an appropriate *E. coli* decay rate for application in sub-tropical waters including the Pearl River Estuary and the coastal waters around Hong Kong. Influenced by the subtropical monsoon climate, Hong Kong (~22°20′N) has a long and humid summer. Approximately 80% of the rain is received between May and September. Water temperature is relatively high with an annual average of about 23 °C; September has the highest water temperature of 27.5 °C, and decreases to approximately 18.0 °C in January to March. The maximum hourly solar radiation is approximately 3.0 MJ/m^2/h under clear skies in winter, and is approximately 3.5 MJ/m^2/h in summer. *E. coli* decay rates adopted in Hong Kong for environmental impact assessment purposes are usually obtained through 3D hydrodynamic modeling, calibrated against monthly marine water quality data, without laboratory or field validation. Accuracy of the k value is uncertain.

In this study, a series of laboratory experiments under typical sub-tropical environmental conditions are conducted to derive a formula to estimate the *E. coli* decay rate based on three key environmental factors: light intensity, salinity and water temperature. Field validation by means of parallel tracer experiments with reference to storm events is carried out at a coastal beach in Hong Kong − Big Wave Bay Beach, with the pulse-like stream flow and the bacterial (*E. coli*) pollution loading from the storm water runoff as the two instantaneous sources of tracers. As the freshwater stream enters the adjacent marine beach, it is diluted by tidal mixing with the seawater at the beach; the freshwater concentration of a water parcel originating from the stream hence progressively decreases (increase of salinity) with time. On the other hand, the *E. coli* concentration of the same parcel measures the decrease in bacterial concentration due to both physical dilution and biological decay. The biological decay of *E. coli* can then be determined from the measured freshwater and *E. coli* concentrations of a number of beach water samples. Application