Wave-Induced Mass Transport Affects Daily Escherichia coli Fluctuations in Nearshore Water

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ABSTRACT: Characterization of diel variability of fecal indicator bacteria concentration in nearshore waters is of particular importance for development of water sampling standards and protection of public health. Significant nighttime increase in Escherichia coli (E. coli) concentration in beach water, previously observed at marine sites, has also been identified in summer 2000 from fixed locations in waist- and knee-deep waters at Chicago 63rd Street Beach, an embayed, tideless, freshwater beach with low currents at night (approximately 0.015 m s\(^{-1}\)). A theoretical model using wave-induced mass transport velocity for advection was developed to assess the contribution of surface waves to the observed nighttime E. coli replenishment in the nearshore water. Using average wave conditions for the summer season of year 2000, the model predicted an amount of E. coli transported from water of intermediate depth, where sediment resuspension occurred intermittently, that would be sufficient to have elevated E. coli concentration in the surf and swash zones as observed. The nighttime replenishment of E. coli in the surf and swash zones revealed here is an important phase in the cycle of diel variations of E. coli concentration in nearshore water. According to previous findings in Ge et al. (Environ. Sci. Technol. 2010, 44, 6731−6737), enhanced current circulation in the embayment during the day tends to displace and deposit material shoreward, which partially sets up the system by the early evening for a new period of nighttime onshore movement. This wave-induced mass transport effect, although facilitating a significant base supply of material shoreward, can be perturbed or significantly influenced by high currents (orders of magnitude larger than a typical wave-induced mass transport velocity), current-induced turbulence, and tidal forcing.

INTRODUCTION

Characterization of the transport and fate of fecal indicator bacteria (FIB) is critical to understanding and predicting microbial water quality in coastal waters, including those for recreational uses, the protection of public health, and remediation for heavily contaminated sites. One problem that is of particular importance is the diel variability of FIB concentration in the nearshore water, which is potentially important for developing water quality monitoring protocols and predictive models. Specifically, it is well-known that the ultraviolet (UV) component of solar radiation tends to considerably decrease E. coli concentration in nearshore water throughout a day (e.g., by 34−99% in southern Lake Michigan), but the concentration of E. coli is often observed to increase overnight at the same location.3,4 In a monitoring project in year 2000, for instance, we observed at Chicago 63rd Street Beach a 3-fold increase in mean E. coli concentration from the afternoon (14:00 h) to the next morning (07:00 h) in both 90-cm (waist) and 45-cm (knee) deep waters throughout the summer beach season. (More details will be given in the Results section.)

Recovery of E. coli from solar inactivation at night appeared to be a natural postulate for explaining this phenomenon.7 As a matter of fact, nighttime resuscitation or regrowth of FIB has never been unambiguously observed in nearshore Lake Michigan waters. On the contrary, laboratory studies have demonstrated an extremely low dark DNA repair rate (approximately 0.01%) for E. coli at a nearly constant temperature of 23 ± 1 °C after UV disinfection.5 Therefore, microbiological mechanisms such as bacterial resuscitation are unlikely to be a major cause for a quick increase in E. coli concentration in nearshore water. Previous studies explaining the diel cycling in FIB concentrations at marine beaches revealed the importance of tidally driven discharge of contaminated groundwater.6,8 Onshore currents generated by anthropogenic activities in Avalon Bay, California, were also found to contribute to the higher FIB concentration in the daytime compared to that at night along the shoreline.7 These
mechanisms, however, are not directly applicable to our tideless, freshwater beach with little boat traffic. Intuitively, if a nighttime increase in E. coli concentration is found significant in a statistical sense, this phenomenon must be realized by a statistically stable factor, which occurs with a high certainty. In our case, the surface wave in the beach water that always travels onshore due to refraction appears to be a likely factor. Longuet-Higgins significantly extended Stokes’ classical theory of wave-induced mass transport to accommodate the effect of the bottom and surface boundary layers in the wave field. The modified mass transport velocity profile tends to have a positive (i.e., in the direction of wave propagation) value near the bottom that moves mass forward, which has been widely observed in the laboratory and in natural waters. This forward velocity near the bottom has a typical magnitude of a few centimeters per second. This pattern of mass transport velocity can result in a stable net transport of E. coli toward the beachfront. Because the onshore propagation of waves is ubiquitous in nearshore waters, the associated onshore concentration of E. coli should be equally so. In open nearshore waters, current velocity often has a higher order of magnitude than that of the wave-induced mass transport velocity, which significantly alters or, at least, obscures the effect of the onshore waves. In a relatively quiet embayment such as Chicago 63rd Street Beach, the most probable current velocity at night was observed to be only 0.015 m s$^{-1}$, similar to that of the wave-induced mass transport velocity at the bottom (detailed in Results). The onshore E. coli movement thus becomes conspicuous during the night. In what follows, a theoretical model that describes the temporal and spatial variation of E. coli due to an onshore wave field at a sloping beach is proposed in order to explain the quick increase in E. coli concentration observed in situ.

**MATERIALS AND METHODS**

**Study Site.** Chicago 63rd Street Beach is partially enclosed by two breakwaters along the north and the south, with an opening directed roughly toward the northeast (Figure 1). For water sampling, five transects were selected to be centered at the beach house and approximately 100 m apart from one another. In the summer of 2000 (from April to September), water samples were taken at both 07:00 h and 14:00 h on three consecutive days per week (usually from Tuesday through Thursday) 20 cm below the water surface in both 45-cm-deep (knee-deep) and 90-cm-deep (waist-deep) waters at each transect. Beneath the 45-cm-deep water, sediment samples were collected from the submerged sand. Water and sediment samples were transported back to the laboratory and analyzed for E. coli concentration within 3 h. Membrane filtration mTEC method (EPA/600/4-85 076) was adopted for analyzing water samples. Additional preparation for sediment samples included estimation of the total sample volume with the core liner, dilution of the test sediment, and shaking of the sample bottles for 5 min at 210 rpm on an Eberbach platform shaker. Results were reported as colony forming units per 100 mL of water (CFU 100 mL$^{-1}$). E. coli concentrations averaged over the five transects for the 90-cm-deep and 45-cm-deep waters and for the submerged sediment were used in the present study. More details about the sampling project in year 2000 can be found elsewhere.

Hourly incident (deep-water) wave parameters were obtained from the Great Lakes Observing System (GLOS, www.glos.us) at the nearest grid point, approximately 1 km from the beach (Figure 1). Because the hydrodynamic characteristics, especially current velocity, can be significantly different in intermediate or small depth nearshore waters than those in 5–6-m-deep water, an Acoustic Doppler Current Profiler (ADCP, Nortek Aquadopp current profiler, Nortek USA) was deployed close to the shoreline at 41.7831° N and 87.5727° W (location indicated in Figure 1; water depth approximately 1.4 m) from late July through early August 2009 to provide a supplemental examination of the general characteristics of the nearshore current flow. The ADCP, mounted upward looking on a bottom frame to place the transducer 15 cm above the bed, profiled current velocity every...
12 min with a sampling frequency of 1 Hz and averaging over 3 min. Four cells (cell size 0.3 m) in the profiles were used for further analysis.

**Model Domain.** For simplicity, we only examined an idealized transect approximately perpendicular to the shoreline, shown as the domain ABC (main part of Figure 1), where A is the offshore face in the water of 2.7 m deep, BC is the onshore face with a water depth of 1.0 m, AB is the lake bed, and the boundary C is the still water surface with a length of 180 m. (The effect of wave setup was neglected here, so that C is level.) A coordinate system is established at point o with the x-direction on the still water surface directed toward the shore and the z-direction positive upward. The trapezoidal domain ABC was extended onshore to form an additional triangular domain BDC, of which point D is the beachfront, to represent the surf and the swash zones. The beach slope is assumed to be constant, approximately 0.0094, and hence the length of CD is 106 m.

**Wave-Induced Velocity Field for Mass Transport.** It was first shown by Stokes that in a wave water fluid particles possess a second-order, steady drift velocity, often called the mass transport velocity, besides their circular or elliptic orbital motions. Longuet-Higgins further considered the existence of the bottom and surface boundary layers in the wave field and derived a modified velocity profile, which has been supported by various field and laboratory experiments, in the form of

\[
U(z) = \left(\frac{H}{2}\right) \omega F(p) \left(\frac{z + h}{h}\right)
\]

for the interior of the fluid under a progressive wave. In eq 1 \(\omega\) and \(\kappa\) denote cyclic frequency and wavenumber, respectively; \(H\) denotes wave height; \(h\) is the still water depth; and the function \(F(p)\) is given as

\[
F(p) = \frac{1}{4\sinh^2 \kappa h} \left[ 2\cosh 2\kappa h (\mu - 1) + 3 + \kappa \sinh 2\kappa h (3\mu^2 - 4\mu + 1) \right]
\]

Equations 1 and 2 were derived based on the assumption of zero net mass transport, such that \(U(z)\) roughly (neglecting the contributions from the boundary layers) satisfies the condition

\[
\int_{-h}^{0} \rho U(z) \, dz = 0
\]

(3)

where \(\rho\) is the density of the fluid being studied. Considering water has a constant \(\rho\), \(U(z)\) must have both positive and negative values throughout the depth to accomplish a zero integral. This is applicable to water waves near a beach where there normally is no net water mass pushed to the shore.

However, it is of critical importance to note that the mass flux of any passive scalar with a nonuniform concentration profile can have a nonzero net mass transport through a vertical face, namely, the integral \(\int_{-h}^{0} C(z) U(z) \, dz\) can be nonzero if the concentration profile \(C(z)\) is not constant throughout the depth.

**Wave-Induced E. coli Transport in Beach Water.** The spatial and temporal variations of E. coli concentration in our domain \(\partial ABC\) due to a wave-induced mass transport velocity field can be represented by

\[
\frac{\partial C}{\partial t} + \frac{\partial (UC)}{\partial x} + \frac{\partial (WC)}{\partial z} = w_{s}\frac{\partial C}{\partial z} + \frac{\partial}{\partial x} \left( \varepsilon_{sz} \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial z} \left( \varepsilon_{sz} \frac{\partial C}{\partial z} \right) - kC
\]

(4)

where \(U(x,z)\) is the steady mass-transport velocity as in eq 1 and changes gradually with the decreasing water depth toward the shore; \(W(x,z)\) is its associated vertical velocity field to satisfy the continuity equation

\[
\frac{\partial U}{\partial x} + \frac{\partial W}{\partial z} = 0
\]

(5)

as indicated in ref 8. Because the beach slope is small, we assumed that the mass transport velocity can adapt to the local water depth quickly as if the local area was constant depth, for which eqs 1 and 2 were originally derived. In eq 4, \(w_{s}\), \(\varepsilon_{sz}\) and \(\varepsilon_{sz}\) denote the settling velocity and the wave-induced diffusivity (in the x- and z-directions, respectively) of the sediment particles to which E. coli are most likely to attach. As E. coli are typically attached to particles with a diameter ranging from 2 to 10 \(\mu m\) (i.e., from clay to fine silt), a median value of the settling velocity for such fine particles found in natural waters is approximately \(1.65 \times 10^{-5}\) m s\(^{-1}\); the vertical diffusivity \(\varepsilon_{sz}\) due to surface waves, with no turbulence, is determined by wave frequency, size of the particle being diffused, and the nearshore wave orbital amplitude.

The value was estimated to be \(2.8 \times 10^{-5}\) m\(^2\) s\(^{-1}\) for the case in the present work. The horizontal diffusivity coefficient \(\varepsilon_{sz}\) was assumed to be of the same order of magnitude. It is noted that this diffusivity is as small as that of molecular diffusion, as a result of the no-turbulence assumption. Also in eq 4, \(\kappa\) denotes the first-order dark decay rate of E. coli, estimated to be 0.0324 h\(^{-1}\) by a previous mesocosm study conducted in Lake Michigan beach water. In using the mass transport velocity field to replace the oscillatory wave field, the time scale for eq 4 should be larger than, for example, several wave periods, over which this second-order mass transport effect becomes appreciable.

**Wave-Induced Turbulence.** The orbital motions of water due to a nonbreaking surface wave often generate turbulence, which might significantly enhance the mixing of the flow field. A wave Reynolds number, based on the wave-induced orbital motion at each locus of the field, can be defined as

\[
Re = \frac{\omega (H/2)^2}{\nu} \left( \frac{\sinh \kappa(z + h)}{\sinh \kappa h} \right)^2
\]

(6)

where \(\nu\) denotes kinematic viscosity of water. It has been confirmed by multiple laboratory and field observations that turbulence can be generated in a wave field where wave Reynolds number is above 2000–3000. To account for the additional mixing effect due to this surface-wave induced turbulence, Dai et al. estimated the wave-induced turbulent diffusivity as

\[
B = \left( \frac{H}{2} \right)^3 \kappa U_{o} \left( \frac{\sinh \kappa (z + h)}{\sinh \kappa h} \right)^3
\]

(7)

to be added to the background molecular diffusion coefficient. Therefore, we further added \(B\) to the vertical diffusivity \(\varepsilon_{sz}\) in eq 4 to account for the wave-induced turbulence effect. The same adjustment was assumed for \(\varepsilon_{sz}\).
because the horizontal range of wave-induced orbital motions of water particles has the same order of magnitude as the vertical range.

Therefore, eqs 4 and 5 adjusted with eq 7 constitute our base case, in which only steady effects caused by nonbreaking surface waves are considered; other factors such as wind stressing and current (as well as current-generated turbulence) are neglected. Adjusting the diffusivity for wave-induced turbulence also implies that $U$ and $W$ in eqs 4 and 5 now represent the mean mass transport flow field where turbulence is present.18

Although the incident wave field from deep water is typically composed of a whole spectrum of waves, a monochromatic wave was considered in the present simple model. In this case, significant wave height $H_s$ and peak period $T_p$ observed or estimated at the GLOS grid point was used as the wave height and period of the incident monochromatic wave. For the ideal transect of beach water as shown in Figure 1, variation of wave height toward the shore due to refraction can be estimated (Supporting Information).

**Bed Shear Stress and Sediment Resuspension.** Bed shear stress is the controlling factor for the occurrence of sediment resuspension. The method for estimating bed shear stress in a combined wave–current boundary layer flow was given in the classical work by Grant and Madsen.19 Bed shear stress induced only by a surface wave field, considered in the present work, is simply a special case to which the same method can be applied.1

**Numerical Solution of Wave-Induced E. coli Transport.** Equation 4 was solved numerically in domain aABC as shown in Figure 1. Lacking the knowledge of the detailed process of sediment resuspension at the beach, we simply imposed a high $E. coli$ concentration $C_0$ at boundary AB (lake bed) during resuspension. When resuspension ceases, the boundary condition at AB becomes $\partial C/\partial n|_{z=h} = 0$, where $n$ is a direction normal to the boundary. The condition $\partial C/\partial n|_{z=h} = 0$ is always held at the mean free surface Co. Boundary values for $C$ at the offshore face aA were extrapolated from interior points of the domain if the local $U$ was negative (seaward) or set to zero if $U$ was positive (shoreward); boundary values for $C$ at BC were extrapolated from the interior if $U$ was positive, or otherwise the mean $E. coli$ concentration $C_{BC}$ for the surf and swash zones (domain BDC) was imposed. Therefore, $E. coli$ can be transported in both directions between domain aABC and the surf and swash zones BDC. More details about the numerical methods are given in the Supporting Information.

**E. coli Loading into the Surf and Swash Zones.** $E. coli$ fluxes through both faces, aA and BC, were monitored by integrating the product of $C(x,z)$ and $U(x,z)$ along the boundaries. Because the water in the triangular domain BDC is very shallow (less than 1 m), possibly with wave breaking as well as longshore transport,20 only mean $E. coli$ concentration $C_{BC}$ in the domain BDC was examined. Based on the actual observations of $E. coli$ concentration in 90- and 45-cm deep waters, both of which were in domain BDC, we assumed an exponential decay of $E. coli$ concentration from the shoreline (point D in Figure 1) toward the water of 1 m deep with no vertical variability (i.e., particles assumed to be well mixed vertically in such shallow water).

## RESULTS

**Nighttime Increase in E. coli Concentration Was Significant.** In year 2000, there were 43 days with observed $E. coli$ concentration both in the afternoon and the next morning. A paired samples $t$ test indicated that (log-transformed) $E. coli$ concentrations in the 90-cm (location P1 in Figure 1) and the 45-cm (location P2 in Figure 1) deep waters both underwent a significant increase overnight ($P < 0.001$ and $P = 0.003$, respectively). Specifically, mean $E. coli$ concentration was 35 in the afternoon and 118 CFU 100 mL$^{-1}$ the next morning in the 90-cm deep water. The mean in the 45-cm deep water was 126 in the afternoon and 317 CFU 100 mL$^{-1}$ on the next morning. They both had an increase of over 3-fold if it is considered that the lowest level of $E. coli$ concentration in a day typically occurs not at 14:00 h but later. The distributions of the nighttime increase of $E. coli$ concentration in waters of both depths are shown in the Supporting Information (Figure S1). The mean $E. coli$ concentration $C_{BC}$ in domain BDC (the surf and swash zones) deduced from the observed values in waters of these two depths assuming an exponential decay cross-shore, as described previously, was approximately 84 in the afternoon versus 228 CFU 100 mL$^{-1}$ the next morning. Additionally, mean $E. coli$ concentration in the submerged sediment was 1585 CFU 100 mL$^{-1}$ for these 43 days.

For the same 43 days, histograms of the nighttime significant wave height and peak wave period from the GLOS, averaged from 22:00 through 06:00 h the next day, showed random association with the occurrences of overnight increase in $E. coli$ concentration (Figure S2 of the Supporting Information). This implies that the nighttime increase in $E. coli$ concentration at the study site can occur under a wide range of wave conditions and it is therefore a general phenomenon.

The GLOS data showed that the mean significant wave height and peak wave period at 21:00 h (night) was 0.229 m and 2.078 s, respectively. These two parameters increased slightly to 0.259 m and 2.147 s, respectively, at 07:00 h (morning) of the second day. Taking these parameters as the conditions of incident waves, we estimated the distributions of wave height and bed shear stress as the waves propagated shoreward (Figure S3 of the Supporting Information). It is evident that both night and morning wave fields had a bed shear stress in excess of the threshold value, 0.06 Pa, for sediment resuspension in water shallower than 1.8 m.1,15,21 Hence, sediment was constantly subject to resuspension in the nearshore beach water up to 1.8 m deep in this mean wave state.

Current velocity data near the shoreline were only available in 2009. Based on observations from the ADCP, the mean current velocity (magnitude) was 0.038 m s$^{-1}$ with a standard deviation 0.027 m s$^{-1}$ ($N = 204$) at night (averaged from 19:00 h to 06:00 h the next day). The probability distribution was highly skewed toward zero with the most probable current velocity being only 0.015 m s$^{-1}$. In contrast, the mean current velocity increased to 0.055 m s$^{-1}$ with a standard deviation 0.027 m s$^{-1}$ and a reasonably symmetric probability distribution ($N = 201$) in the day (averaged from 07:00 h to 18:00 h). Therefore, a general character of the current pattern in the nearshore beach water, although inferred from a different year of data, is that the magnitude of current velocity tends to increase significantly from the night to the next day, implying significantly enhanced longshore transport$^1$ in the day.

**Theoretical Mass Transport Velocity.** Horizontal mass-transport velocity $U(x,z)$ for three typical water depths, 2.6, 1.6, and 1.3 m, are plotted in Figure 2 based on eqs 1 and 2. The surface drift velocity is always positive (shoreward) for the depths considered, whereas the mass transport velocity near the
bed is only significantly positive where the water is shallower than, e.g., 1.6 m. The small difference between the wave parameters for the night and the morning did not result in significant difference in the estimated mass-transport velocity profiles.

Diffusion Due to Wave-Induced Turbulence. Distribution of the total vertical diffusivity $B_v + \varepsilon_{sz}$ in the model domain is shown in Figure 3 for the average wave condition between 21:00 h and 07:00 h of the following day (Figure S3 of the Supporting Information). Apparently, the correction of diffusivity for wave-induced turbulence was significant in the water near the surface. The contours for $Re = 2000$ and 3000 divided the domain into two parts: Flow above the contour for $Re = 2000$ (i.e., the upper layer) tended to be turbulent, while the part below (i.e., the lower layer) had intermittent to negligible turbulence. It should be noted that $Re = 2000$ and 3000 are used here only for reference because these critical Reynolds numbers were originally obtained in deep-water waves.

**Dimensional Analysis of Transport Equation.** Contribution of each term in eq 4 can be better revealed by a dimensional analysis. The characteristic horizontal mass transport velocity $U_m$ was chosen to be 0.01 m s$^{-1}$ (Figure 2). Because wave-induced mass transport is primarily in the direction of wave propagation, the characteristic vertical mass transport velocity $W_m$ was assumed to be an order of magnitude smaller than $U_m$, namely, 0.001 m s$^{-1}$. The characteristic time $T$ was 30 min as we were interested in the variation of E. coli concentration during a 10-h period at night. These scales resulted in a characteristic horizontal length $X$ of 18 m and a vertical $Z$ of 1.8 m. A characteristic E. coli concentration was arbitrarily chosen.

Equation 4 then became

$$\frac{\partial C'}{\partial t'} + U' \frac{\partial C'}{\partial x'} + W' \frac{\partial C'}{\partial z'} = \frac{w_z'}{P_e x} \frac{\partial^2 C'}{\partial z'^2} + \frac{1}{Pe_x} \frac{\partial^2 C'}{\partial x'^2} - Da C' \quad (8)$$

where the primed variables are nondimensional by dividing the original ones by their respective characteristic scales; Péclet numbers, reflecting the ratio of advection to diffusion, are defined as $Pe_x = (U_m x) / (\varepsilon_{sx} + B_v)$ and $Pe_z = (W_m z) / (\varepsilon_{sz} + B_v)$, in which $B_v$ has been assumed to be constant only for the convenience of dimensional analysis; Damköhler number $Da = kT$ reflects the contribution of the dark decay of E. coli. Since 1/$Pe_x$ is always 2 orders of magnitude larger than 1/$Pe_z$, horizontal diffusion can be neglected from the equation compared to its vertical counterpart. The contribution of vertical diffusion of E. coli (given by 1/$Pe_z$) can range from 0.56, for $B_v$ of approximately $10^{-3}$ m$^2$ s$^{-1}$ (near the surface; see Figure 3), to $5.6 \times 10^{-6}$, for $B_v$ of $10^{-8}$ m$^2$ s$^{-1}$ (near the bed). Therefore, the contribution of vertical diffusion has the same order of magnitude as advection in both directions (the left side of eq 8) in the turbulent upper layer and becomes negligible in the laminar lower layer. Substituting the characteristic scales also resulted in $w_z' = w_z/W_m \approx 0.017$ and $Da \approx 0.016$. Hence, settling and dark decay of E. coli contribute similarly to the rate of change of E. coli concentration over a time scale considered here (30 min), which are both small compared to the advection terms. Although contributions of these two terms can still be comparable to that of vertical diffusion where $B_v + \varepsilon_{sz}$ is near the level of $10^{-3}$ m$^2$ s$^{-1}$ (indicated in Figure 3), they are invariably larger than that of horizontal diffusion, which ranged from $5.6 \times 10^{-3}$ (water surface) to $5.6 \times 10^{-8}$ (near bed), throughout the model domain.

The analysis above was based on the choice of $T$. There are cases where both settling and dark decay of E. coli become comparable to advection. Such cases are discussed in the Supporting Information.

**Simulated Wave-Induced E. coli Transport.** The two-dimensional model of E. coli transport and fate, eq 4, was solved numerically in the oABC domain. The effect of 10 episodes of sediment resuspension in the first 40 min of each hour was simulated by imposing a steady $C_0$ of 300 CFU 100 mL$^{-1}$ during resuspension along the nearshore half of boundary AB.
for water shallower than 1.8 m. Because \( E. coli \) concentration at the sediment–water interface can be comparable to that in the submerged sediment,\(^{2,3} \) the assumed \( C_0 \) of 300 CFU 100 mL\(^{-1} \) at resuspension was reasonable compared to the season-mean \( E. coli \) concentration of 1585 CFU 100 mL\(^{-1} \) in the sediment. The duration of each sediment resuspension, 40 min, was selected based on previous observation that resuspension tends to be intermittent and each event rarely lasts for more than 1 h.\(^{13} \)

\( E. coli \) concentration distributions in the model domain at \( t = 6.99 \) and 9.99 h (immediately before a new period of sediment resuspension) are shown in Figure 4. Vertical profiles of \( E. coli \) concentration appeared to be very uniform in the upper part of the water column due to turbulent mixing. At depths close to the bed, a vertical gradient can be pronounced (e.g., at \( t = 6.99 \)), which likely resulted in a nonzero net mass transport cross-shore.

The net flux of \( E. coli \) through boundary BC was mostly onshore, while that through \( \omega A \) was offshore throughout the entire 10-h period (Figure 5). Therefore, both onshore and offshore faces of the domain were outlets for \( E. coli \). A time history of the total \( E. coli \) number within the domain \( \omega ABC \), compared to the accumulated \( E. coli \) numbers that have been transported through both faces (negative value for leaving the domain) are plotted (Figure 5a). The mean \( E. coli \) concentration in the surf and swash zones \( C_k \) clearly increased appreciably over time (Figure 5b). If the initial \( C_k \) was set to 84 CFU 100 mL\(^{-1} \) (observed season mean in the afternoon), the total \( E. coli \) number transported through BC was sufficient to raise \( C_k \) to about 250 CFU 100 mL\(^{-1} \) within 10 h, higher than the season mean, 225 CFU 100 mL\(^{-1} \), of the next day. Moreover, the increase of \( C_k \) during the final 2 h was slow compared to the beginning 8 h, signifying the attainment of a stable state on the early morning.

A simulation with all conditions unchanged but a uniform diffusivity of \( 10^{-5} \) m\(^2\) s\(^{-1} \) was also conducted in order to examine the sensitivity of the mechanism to a different range of diffusivity. This uniform value chosen was typical of vertical eddy diffusivity observed in similar environments such as bays in the summer.\(^{3–5} \) This case hence considered the effect of background turbulence that is not necessarily generated by

![Figure 4. Distribution of \( E. coli \) concentration in the nearshore beach water at (a) \( t = 6.99 \) h and (b) \( t = 9.99 \) h during a 10-h simulation.](image)

![Figure 5. Summary of a 10-h simulation with sediment resuspension occurring for the first 40 min of each hour. (a) Time histories of the total \( E. coli \) number that is within domain \( \omega ABC \) (black curve), that had entered the domain through the onshore face BC (red curve) and through the offshore face \( \omega A \) (blue curve) (negative value means exiting the domain) and (b) instantaneous mean \( E. coli \) concentration \( C_k \) in domain BDC (the surf and swash zones) due to \( E. coli \) loading through face BC.](image)

**DISCUSSION**

An onshore \( E. coli \) transport mechanism has been investigated. This type of transport is only facilitated by shoaling waves, whose ubiquity in nearshore waters assures the ubiquity of \( E. coli \) concentrating toward the shore. Due to the complexity of events during a night and the lack of knowledge of detailed spatial and temporal behavior of sediment resuspension in water of intermediate to small depths, we were only able to simulate \( E. coli \) transport under simple and ideal conditions. But the 10-h simulation of an intermittent series of resuspension episodes (Figures 4 and 5) appeared to be sufficiently representative to demonstrate the strength of wave-induced \( E. coli \) loading into the surf and swash zones.

Considering the bed shear stress (Supporting Information) can be even larger in the knee-deep water (domain BDC), the locally resuspended \( E. coli \) can be a more direct cause for \( E. coli \) concentration surge observed in the morning than those transported from deeper water. However, the strength of this local source was not anticipated to be large, because most of these resuspended \( E. coli \) had been inactivated by solar radiation during the day before they were settled into the sediment and overnight recovery in the submerged sediment was unlikely under typical, natural conditions.\(^{5} \) In this sense, the observed high \( E. coli \) concentration in the submerged sediment (mean value 1585 CFU 100 mL\(^{-1} \)) underneath the knee-deep water was more likely to be a result of early morning deposition of \( E. coli \) from deeper water than an original source. The local input of \( E. coli \) in the knee-deep water, even if significant to some extent, does not necessarily weaken the contribution of nighttime wave-transported \( E. coli \) onshore.
The base case studied in the present work, in which only wave effects are considered, can often be perturbed by other factors such as additional mixing due to wind forcing and current-induced turbulence and the interaction of nearshore beach water with anthropogenic currents, shallow groundwater, and tides at marine sites.4,6,7 We assume that strong perturbations to the base case, especially high currents (e.g., magnitude larger than 0.15 m s−1) or current-induced turbulence, could have resulted in a smaller wave-induced nighttime increase, or even a decrease, in E. coli concentration as observed on particular days (Figure S1 of the Supporting Information). Because the theoretical model presented here correctly explained the season-mean level of nighttime increase in E. coli concentration, we believe that our base case is robust in describing nighttime transport of E. coli in the nearshore water in an embayed, tideless, low-current environment similar to our study beach. At marine beaches, nevertheless, further analysis should be carried out to elucidate the issues of how well the wave effects can be separated from those of tides and to what extent our base case is representative in describing the ambient environment.

The nighttime replenishment of E. coli in the knee-deep beach water identified here is an important link in the diel cycle of E. coli concentration variability. An ideal cycle of events can be deduced from previous findings and the present study. Generally, this nighttime onshore transport of E. coli is perturbed or destroyed later in the morning when wave height gradually increases (Figure S3 of the Supporting Information), wave breaking line moves offshore, and the current velocity near the beach, whose direction is typically alongshore roughly following the wave depth contours, is increased by 2–3 times (as observed from ADCP in 2009), significantly surpassing the strength of the wave-induced mass transport. Part of the E. coli accumulated overnight in the knee-deep water is inactivated by the UV radiation in the sunlight throughout the day until the early evening.2,4 The other part of the E. coli is transported longshore by the enhanced daytime current circulation, including rip currents, and are eventually carried back to the deeper water or out of the embayment.1,5,6 Unlike the E. coli that remain in the shallow water, a significant portion of the E. coli transported back to the deeper water (still inside the embayment) are more likely to survive from solar inactivation by settling or vertical mixing in the water column.15 The system is thus restored by the early evening when current quiets down, wave height is slightly lower, and the knee-deep water is ready to receive E. coli input from deeper water by sediment resuspension and wave-induced mass transport. Analysis and experiments have been planned to provide further evidence for this deduced cycle of diel E. coli variation patterns in nearshore beach water.

**ASSOCIATED CONTENT**

Supporting Information
Details about the observed nighttime increase in E. coli concentration in the beach water, the observed wave parameters during the same period at Chicago 63rd Street Beach in 2000, the estimated variation of wave height and bed shear stress in model domain 0ABC due to wave refraction, further discussion on dimensional analysis and model sensitivity. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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