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Research Article

Modeling of Combined Sewerage Overflow Induced *Escherichia Coli* and Adenovirus Transport in the Tokyo Bay

M M Majedul Islam[1], Muhammad Shahid Iqbal[1]* and Yukio Koibuchi[2]

[1]Environmental System Analysis Group, Wageningen University and Research, The Netherlands

[2]Department of Socio-Cultural Environmental Studies, The University of Tokyo, Japan

***Corresponding Author**: MM. Majedul Islam, Environmental System Analysis Group, Wageningen University and Research, The Netherlands.

Received: February 20, 2017; **Published:** March 16, 2017

Abstract

Fecal coliform and some other bacteria have been used worldwide to indicate coastal water quality for a long time. Some numerical modeling has been done currently to investigate the fate and transport of fecal bacteria in coastal water. However, no such efforts have been made for viruses. In this study, a virus (adenovirus) was included as an indicator along with fecal bacteria, *Escherichia coli*. A three-dimensional hydrodynamic model coupled with a pathogen model was used to understand the processes affecting pathogen transport in Odaiba area of Tokyo bay after a sewerage overflow event. The model was validated with the observed pathogen data. The model results show the typical two to three-day wet weather effect of storm water discharges whereas observed data shows that the effects remain longer in surface water. Storm induced discharge from pumping stations and tidal influence was identified as the dominant factor. Modeling result also shows that high pathogen levels are not necessarily tied with amount of rainfall. Even in small precipitations (< 5mm), pathogen concentration can increase significantly. Though higher viral plume observed right after every storm events like that of bacteria, the viral concentration was not always consistent with bacteria. Therefore, the traditional bacterial indicators are not adequate to reflect the presence of pathogenic viruses, in managing coastal water.

Keywords and Phrases: *Combined Sewerage Overflow (CSO); Pathogen Model; Escherichia coli (E. coli); Adenovirus (AdV); Rainfall*

Introduction

Tokyo bay is a semi-enclosed coastal sea, surrounded by one of the world's most urbanized areas (the Tokyo Metropolitan area) with a population of approximately 26 million. Annually, approximately 2 km3 of sewage effluents drain into the inner part of the bay directly or via rivers [1,2]. Thus, Tokyo bay receives huge pollutant load via both sewers and rivers and is considered the most polluted bay of Japan. Effluents released into the bay water pose a risk of pathogen contamination and human disease. This risk is heightened specially for the water body like Tokyo bay that receives Combined Sewer Overflows (CSO's) during storms.

Tokyo's Bureau of Sewerage employs a combined system in which both storm water and sanitary water flows through the same pipelines. During storms, enormous amounts of raw sewage have been overflowing directly into Tokyo bay without being treated at the Sewage Treatment Plants (STPs). This is because the transient but vast amount of waste water during storms exceeds the capacity of sewerage system. This overflowed sewage contains pathogens that are unhygienic for beach swimmers and cause many illnesses. To decrease the risk from introduced pathogens, routine and well designed monitoring is essential.

Although studies have examined the influences of storm water and CSO in terms of the release of microbial pathogens and anthropogenic compounds into Tokyo bay, routine water quality monitoring has been conducted only under clear weather conditions. Therefore, little is known about the influences of storm water or CSO on the aquatic environment of Tokyo bay. Moreover, it is difficult to accurately estimate CSO and the consequent flux of the pollution load into Tokyo bay, because there is no system in place to measure water levels and flow rates of overflowed sewers during transient storm events [3].

In addition, the physical environments of urban coastal zones vary widely depending on time and location. Their complicated geographical features border both inland and outer oceans, and so both inland and outer oceans affect them. For example, tidal currents, a dominant phenomenon in this area, oscillate according to diurnal periods. Even if the emitted levels of pathogens were constant and we could monitor the levels of pathogens at the same place, they would fluctuate according to tidal periods. Moreover, sea water contains numerous pathogens, measuring them is difficult and time consuming - not least because such pathogens usually exist in a "viable but non-culturable" (VBNC) state. Consequently, the frequent measurement of pathogens is needed to discuss the risk pathogens pose in urban coastal zones. However, this kind of frequent monitoring appears to be impossible [4].

Current laboratory methods for monitoring bacterial indicators require at least 24h of incubation, which results in delayed results and recent studies showed that there is a poor correlation between pathogen concentration on the sampling date and the next day when the results are available. The past studies demonstrated the utility of modeling for estimating pathogen indicators. They also showed that concentration of the indicator organisms is typically a function of a multitude of interacting fate and transport processes. These processes operate at time and space scales not resolved by typical monitoring programs. So, modeling can be a good alternative to solely monitoring [5].

Recent studies have shown that the fecal indicator bacteria currently used to indicate coastal recreational water quality throughout the world may be inadequate to reflect human viral contamination [6]. Coliform standards often fail to predict the occurrence of many waterborne human pathogens, such as pathogenic bacteria, the protozoan parasites and enteric viruses, which are most often the cause of disease from recreational exposure. Furthermore, traditional bacterial indicators generally die off quickly in marine water compared to viruses and protozoa [7]. Therefore, viruses are suspected to be important causative agents of waterborne illness along with coliforms.

Enteric viruses are more resistant than many other sewage-associated pathogens and bacterial indicators to extreme environmental conditions and conventional wastewater treatment, such as chlorination, UV radiation, and filtration [8]. Moreover, human adenoviruses are the only human enteric viruses that contain double-stranded DNA instead of RNA, potentially are more stable in various environments, and are more resistant to UV irradiation and other water purification treatments than other human enteric viruses, because they are able to use the host cell DNA repair mechanism to repair damage in their DNA caused by UV irradiation [9]. Therefore, adenovirus (AdV) is an important indicator to study coastal water quality.

The past studies on pathogen modeling were based solely on *E. coli*, fecal coliform or any other bacteria as an indicator [4,5,10,11]. No modeling work has done so far using any virus as an indicator of pollutant. This paper presents a case study of *E. coli* and AdV transport after CSO events in the inner Tokyo bay. The goal of the research was to determine and understand the important dynamic processes and modeling approach to support public health risk management (i.e. beach closing) for sailors, sea surfers and beach swimmers.

To achieve the goal, a three-dimensional hydrodynamic and water quality model coupled with a pathogen model at comparable resolution was applied. Field observations were also conducted to characterize the variability and patterns of *E. coli* and AdV and to validate the model.

Materials and Methods

Study site and sampling

The study site is the upper area (Odaiba) of Tokyo bay (Figure1) which is located at the central part of main island (Honshu), Japan. The bay stretches 50 kilometers north to south, 20 kilometers east to west and its average depth is 18 m. Its size (960 km^2) is forth in Japan [12]. Total twelve rivers discharge into Tokyo bay with major discharge from Tama, Edo and Ara rivers all located along upper western area of the bay.

The sampling locations in Odaiba area of Tokyo bay are shown in Figure 1. To characterize the rainfall effects on the levels of pathogen (*E. coli* and AdV) 5 days sampling was done at November, 2007 (11^{th} 12^{th} 14^{th} 21^{th} 28^{th}) just after 26.5 mm rainfall on November 10^{th}. Due to lack of observed data required for model validation, observed pathogen data from the same sampling location were also collected from Onozawa., *et al* [3]. The rainfall data were collected from Japan Meteorological Agency website (http://www.jma.go.jp).

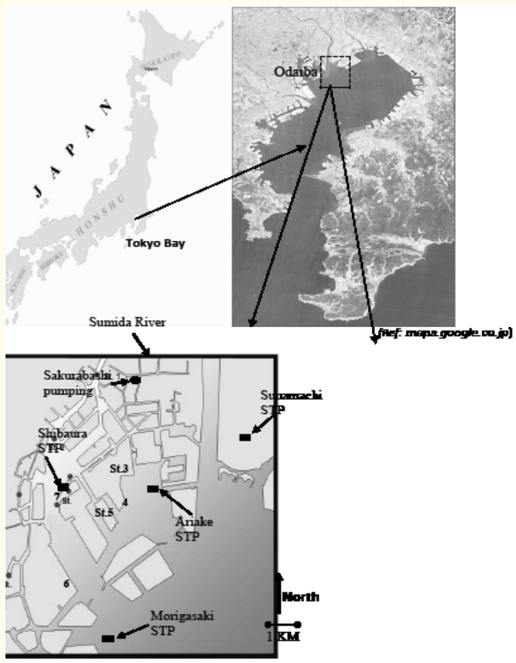


Figure 1: *Study site and sampling locations of Tokyo bay.*

Analytical methods

The methods used for analysis of *E. coli* and AdV were described by Haramoto., *et al* [13]. Briefly, samples were held on ice during sampling and transport to the laboratory. Afterward, samples were kept in the refrigerator at 4°C. *E. coli* was determined by colony forming unit (CFU). Sea water sample (10 mL) was passed through an m-Coli Blue broth filtration membrane. After 24h of incubation at 37°C blue colonies of *E. coli* was counted. For AdV firstly 1,000 mL of the sample was membrane filtered and concentrated. The concentration of AdV was quantitatively determined by the real-time PCR using the ABI PRISM 7000 sequence detection system (Applied Biosystems, Tokyo, Japan). Five microliters out of 200 µL previously extracted DNA was mixed with 45 µL of a reaction buffer [14]. Then the plate was added to a well of a 96 well micro plate. Afterwards the plate was placed in the ABI PRISM 7000 SDS and incubated at different temperature and duration. In order to draw a standard curve, DNA of AdV of serotype 40 was diluted by 10-fold serial dilution. The seawater samples and the standard samples were applied to the real-time PCR. Subsequently, analysis was done using the SDS software (version 1.1; Applied Biosystems) to obtain the quantitative data on the concentration of AdV (PDU/mL) in a well. Three wells for each sample were used and the average was used for the subsequent calculation.

Numerical Modeling

Model framework

The selection of the model that is apt for a given system is influenced by factors such as the scale and geometry of the system, the time scale of the processes, the driving forces in the system, and the physical processes occurring in the system. The present numerical model, WESTech was selected considering its applicability to the coastal environments similar to Tokyo bay. The model was first developed by

Sasaki and Isobe [15] and then later by Koibuchi and Isobe [16]. This is a three-dimensional, time-variable, hydrodynamic model which solves equations for Navier-Stokes, conservation of mass, momentum, temperature, salinity, turbulence kinetic energy and turbulence macro-scale. This hydrodynamic model is also used by Rasmeemasmuang and Sasaki [17] with some modification where details of the governing equations and boundary conditions of this model are presented [18].

Model Input

Modeling was performed with two nested domains to fit the complex geographical feature around the Odaiba area (Figure 2). The two computational domains cover the whole region of Tokyo bay (50 km × 66 km) and the Odaiba area (5 km × 12.7 km) with grid resolutions of 2 km and 100m, respectively. The first domain size is 25x33 grid points and the second domain has 50x127 grid points. All of the domains have 10 vertical sigma layers. These nested grids are able to represent vertical density gradients and hydrodynamics.

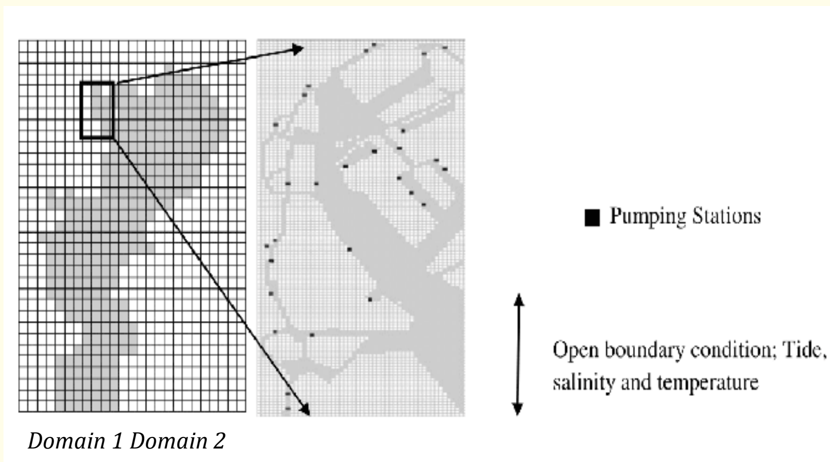


Figure 2: *Two nested computational domains. Left domain 1, whole bay area and right domain 2 with pumping station distributions around the Odaiba area.*

The hydrodynamics in the Bay-wide model (domain 1, large grid) were first simulated and the results of temperature, salinity and water surface level elevation were used as an open boundary to simulate domain 2 (fine grid). The detail of the model set up and calibration are described in Islam, M.M.M. [19].

Modeling of Pathogen

The modeling of major pathogens of concern is not usually conducted due to the difficulty of modeling and the lack of observational data in the study area. Modeling of *E. coli* and AdV was done by using experimental data in the study site. The model that is discussed above has customized and coupled with a pathogen model [3] to simulate *E. coli* and AdV.

Fecal bacteria are subject to a number of fate and transport processes. Fate processes include die-off, which depends on temperature, pH, nutrients, toxins, salinity and sunlight intensity, death by predation, as well as growth (cell division) and recovery of non-culturable cells. Transport processes include advection and dispersion, as well as settling to and resuspension from the sediment bed [5].

The mathematical framework employed in the Pathogen model to reflect the fate and transport process of E. coli and AdV is expressed as follows:

$$\frac{\partial C}{\partial t} + u_i \frac{\partial C}{\partial x_i} + (-Sink)\frac{\partial C}{\partial z} = \frac{\partial}{\partial x_i}\left(\varepsilon_i \frac{\partial C}{\partial x_i}\right) - sal \cdot C$$

Where C denotes concentrations of Pathogen and t is time. Sink represents the sinking speed of Pathogen. u_i denotes flow speed for the calculation of the advection term. ε_i denotes the diffusion coefficients. sal denotes the salinity-dependent die-off rate (/ppt-day).

Sunlight is generally recognized to be one source by which bacteria are inactivated, due to UV damage to the bacterial cell [20]. However, this particular target area has high turbidity that rapidly absorbs UV rays at the sea's surface. Hellweger and Masopust [5] reported that high turbidity in the near-shore areas of the Charles River, Boston increased light extinction and counteracted the effect of the shallower water column. They found that making *E. coli* die-off a function of sunlight intensity did not improve their model results. Sokolova., *et al*. [21] also ignored light dependent die-off rate of E. coli in their modelling study in Sweden due to no significant differences between the light and dark incubations. Again, AdV can tolerate much greater exposure to UV radiation than others, because AdV possess the cell repair mechanisms. As a result, sunlight-dependent die-off process has been ignored in this model. Resuspension effect was not also taking into account for the present study. Because it depends mainly on wind speed and water depth. As the depth of the particular area (11-14m) was very high and wind force was not so strong during study period, resuspension might not happen in the study area, especially during the particular period of study.

Input Boundary Conditions for Pathogen

The treatment plants and pumping stations around the study area discharge huge amount of pathogen into the bay. There are 4 treatment plant stations (Shibaura, Sunamachi, Ariake and Morigasaki) in the study area which have a total of 28 pumping stations. Each pumping station have different discharge rate. Pathogen input data from all the pumping stations were collected from Onozawa., *et al* [2]. They estimated discharge from each pumping station by the volume of polluted water, total discharged water and the area of each Pumping stations.

The *E. coli* concentration in CSO was assigned 33 × 106 CFU/ 100 ml which is similar to that was used by Onozawa., *et al.* [3], Carlos Ja., *et al*. [22] and Sokolova., *et al* [21]. Griffin., *et al*. [23] found virus levels in coastal water 9.2 ×104 liter-1. Based on this, in the present model the used AdV concentration is 1.0 ×104 per 100 ml. However, this concentration will be diluted with rain water runoff (shown in the formula below) and eventually finds its way into the bay.

The formulas that were used to estimate pathogen discharge are as follows:

Water flowing time + 5 min (time takes to start water flowing) = Reach time

Flowing time= Length of pipe ÷ Flow velocity (1 m/s)

Length of pipe= $\sqrt{\text{Treating area}\times 3/2}$

Rain water runoff= Rainfall Amount× Treating Water Area (ha) × Water Flow co-efficient (0.8)

E. coli (CFU/100ml) = (33×10^6) × (Dry weather sewage) ÷ Rain Water Runoff)

Q= A×B/ 24*3600

A= Total treating polluted water volume (ton/day)

B= Area (each pumping station)

Q= Water discharge

Based on the above formula the result found was used as the model input.

Results and Discussion

Model validation

E. coli

The present model predictions have generally shown good agreement between measured field data and calculated data in all three stations. Figure 3 shows a comparison between modeled and measured *E. coli*. The *E. coli* concentrations appeared to be significantly different among the stations. However, St. 3 and St. 5 show relatively higher concentration than St. 4. It may be due to the enclosed bathymetry of St.4. As St. 4 located comparatively more land locked position, in this place wind force is not so strong like St. 3 and 5.

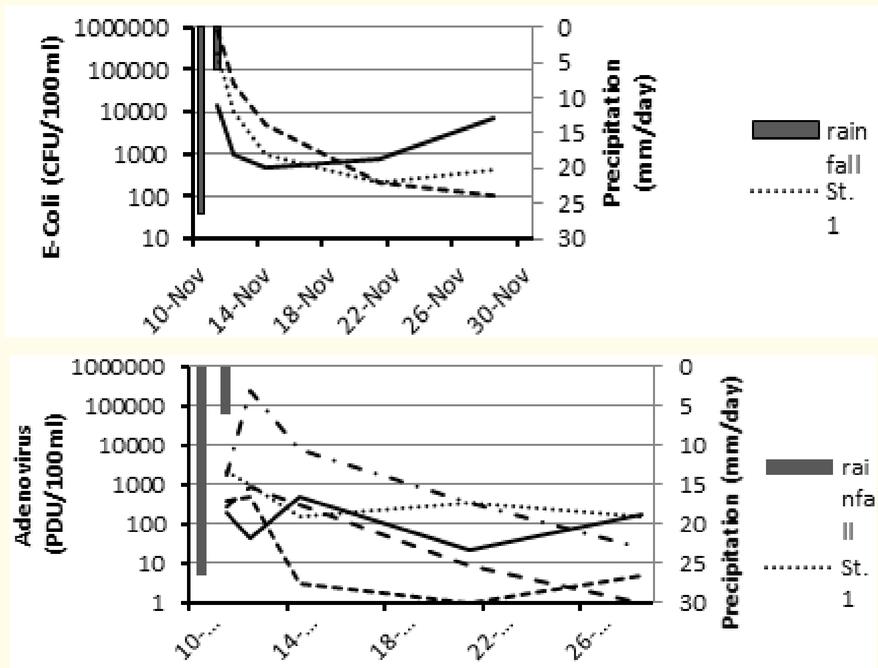


Figure 3: *Spatial and temporal variation of pathogen observed in 2007.*

Again, concentration also depends mainly on the river discharge, pumping station discharge and discharge from sewage treatment plant (STP). St. 3 and 5 contains higher discharge from river and STPs, due to their closest proximity and open position.

Thus, it can be said that concentrations of Pathogen vary widely according to space and time. The density distributions produced by the balance of tides and discharges from river and STPs have very complex effects. The big storms with CSO discharge were occurred on August 15 (32 mm), August 29 (17 mm), August 31(16 mm), September 4 (106 mm), September 27 (43 mm), October 5 (65 mm) and the biggest one on October 9 (180 mm) leaded to higher concentrations of pathogen. In contrast, a significantly higher plume was also found after a small rainfall (4 mm) of August 23rd. This is significant, because it shows that high pathogen levels are not necessarily tied with amount of precipitation. Even in small precipitations, pathogen significantly increased. Hellweger and Masopust [5] also found the same type of result during their *E. coli* modeling.

Adenovirus

To verify the model, the AdV concentrations from the field and that generated by the model were presented graphically (Figure 4). There are some significant discrepancies. The model captures that concentration decreases faster than the observed data. Calculation results shows usually after 2 days concentration decrease 1 order of magnitude, whereas observation data shows that the higher plume sometime remains about a week (Figure 5,6). Ackerman and Weisberg [24] also found similar result after observation in Santa Monica bay, California, US. They found bacterial concentrations returned to background levels in 5 days for all size of rain events. It may be because the increase is due to a more local effect, CSO discharge from upper river continues for longer time not included in the model.

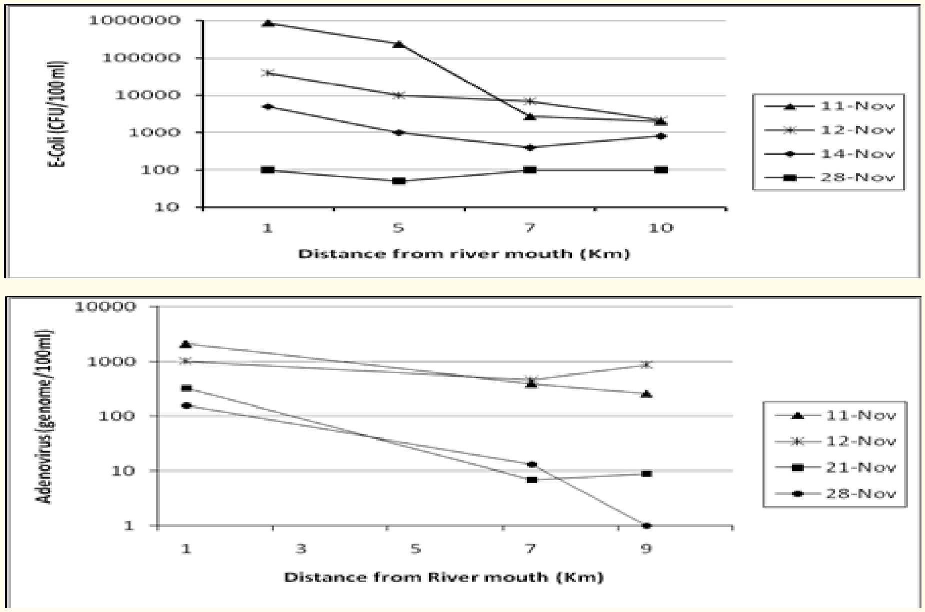


Figure 4: *Distribution of pathogen with distance from Sumida river mouth in 2007.*

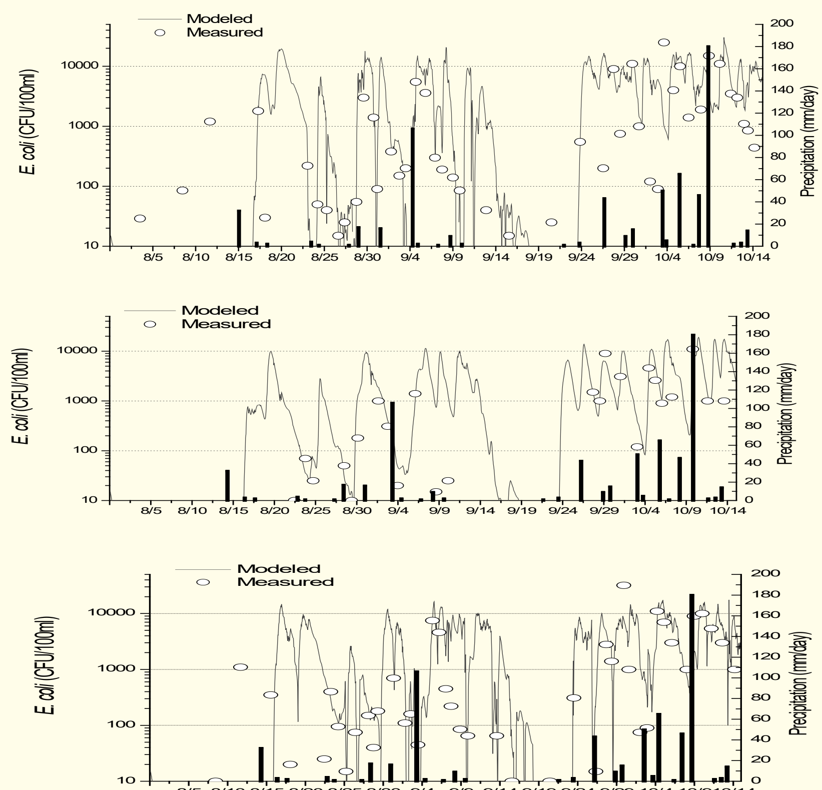


Figure 5: *Comparison between modeled and measured E. coli at surface water of Odaiba .*

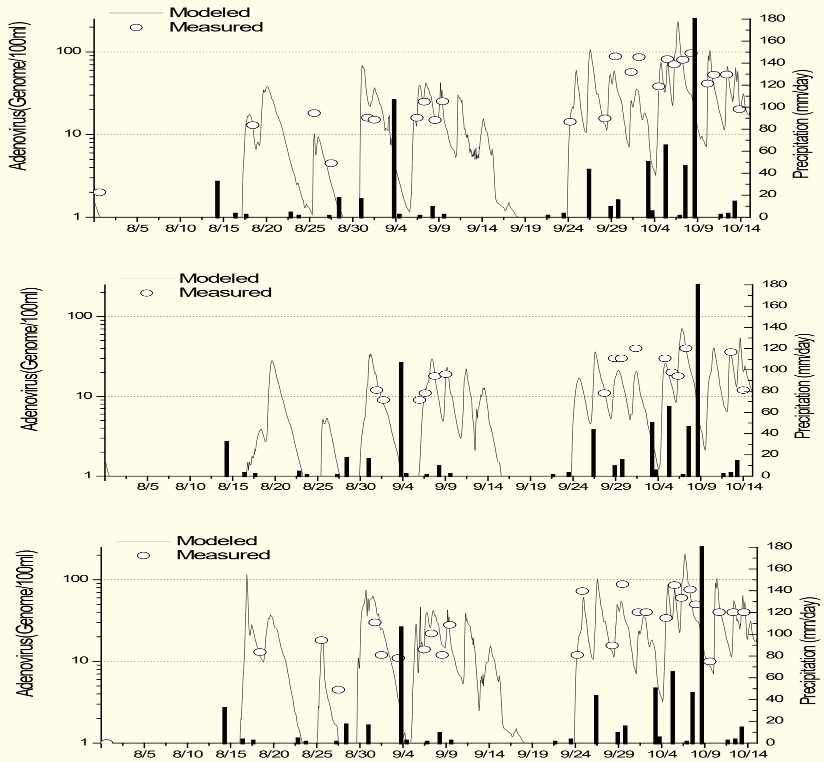


Figure 6: *Comparison between modeled and measured AdV at surface water of Odaiba.*

Understanding the effects of physical factors is important to know the fate and distributions of pathogens. Such an understanding is in turn highly related to the assessment of sanitary risks in urban coastal zones. Occasional elevated pathogen level due to storm induced CSO have been causing the bathing waters of Odaiba failed to comply with the mandatory water quality standards. These failures have become one of the major threats to the local tourist industry. The current standard for acceptably safe beaches for swimming set by of the Ministry of the Environment of Japan is a fecal coliform rate of 1000 coliforms unit per 100 mL (CFU/100 mL). According to US EPA this rate is even lower, 235 CFU/100 mL. However, if we use a value of 1000 CFU/100 ml *E. coli* as the standard for the safety of swimming in the sea, the calculation results reveal that most of the time of the storm prone period (August-September) of Japan violates standard for swimming.

Numerical experiment

Variations in levels of *E. coli* are directly correlated with the discharge from pumping stations, tidal currents, river discharges, wind velocity and density distributions. Death rate also affects pathogen concentration significantly. As a result, the distributions of CSO differ according to timing, even when the level of discharge is the same [3].

Numerical experiments were performed considering without death rate and no wind action case. The model captures the increase in pathogen concentration when the death rate was omitted (Figure 7) and concentration decrease when there was no wind velocity (Figure 8). But without wind case that means when wind force is absent concentration decrease significantly, whereas omitting death rate did not affect the concentration so much. So it is clear that wind has a strong effect on pathogen distribution and considered as a dominant factor.

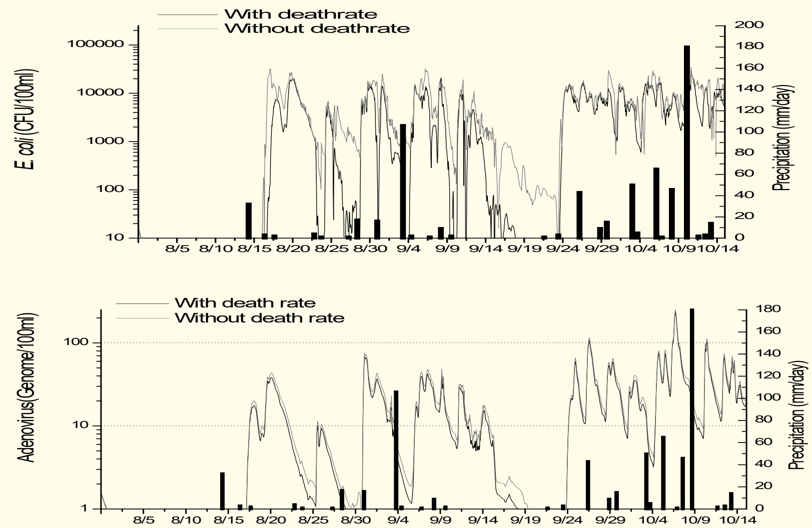


Figure 7: *Comparison between with and without death rate result of modeled E. coli and AdV conc. at st. 3.*

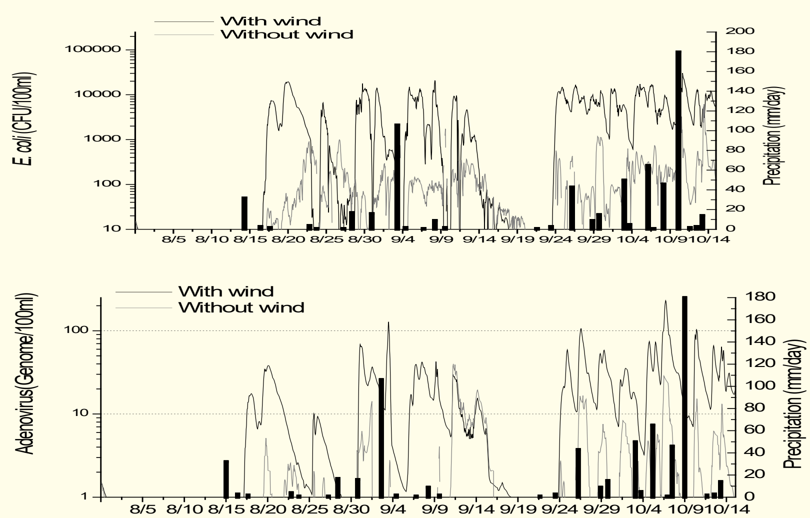


Figure 8: *Comparison between with and without wind action result of modeled E. coli and AdV conc. at St.3.*

Forecast simulation of pathogen

Figure 9 shows temporal variations tidal levels and Pathogen concentrations. Pathogens come in Odaiba area from three different treatment plant areas. Shibaura and Sunamachi area are located at the upper bay location from the Odaiba area. Whereas, Morigasaki located in the lower bay (See Figure1). In this spring tide period, small precipitation (16 mm/hr) was measured at August 29th. The levels of *E. coli* and AdV increased rapidly after the rainfall event, due mainly to discharges from all the 3 STPs. As it was spring tide period tidal ranges was reached 200 cm. So, effluent from Morigasaki also reached the Odaiba area.

In contrast, figure 10 shows a large precipitation (180 mm/hr) case under the neap tide period. In this period, only the upper bay's CSO's arrived at the Odaiba area. No contributions from the Morigasaki area took place. So, it is found that pathogen concentrations reached maximum levels after small precipitation events, but did not increase that much under large precipitation events due to mixing and tidal force. These kinds of results would be impossible to understand only from observation. The model successfully captured complex distributions of pathogen and helped our understanding of pathogens contaminations.

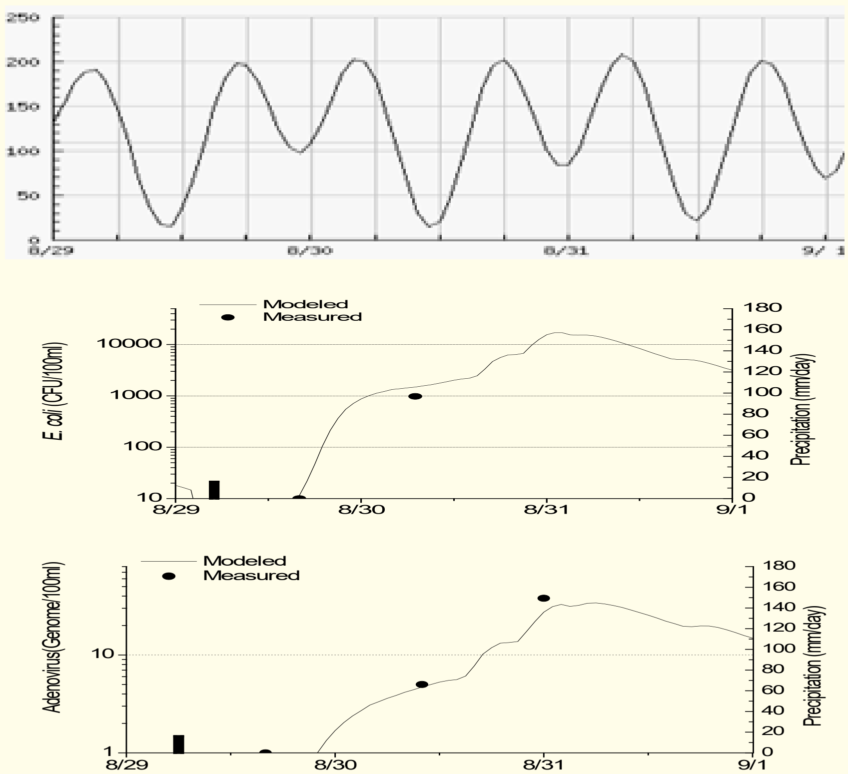
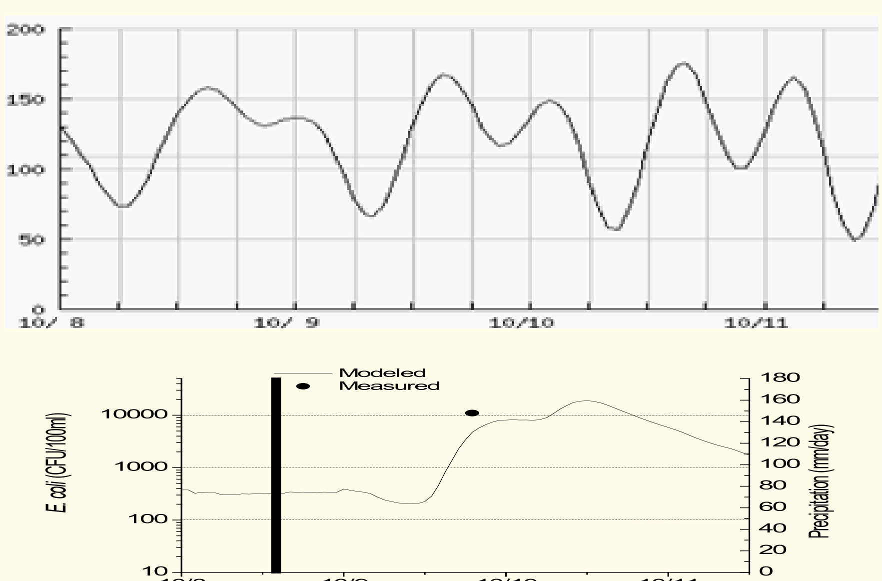


Figure 9: *Effect of rainfall and tides for Pathogen variations under the small storm event at St.4.*



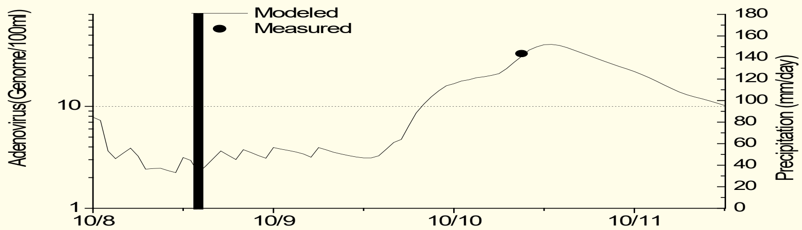


Figure 10: *Effect of rainfall and tides for Pathogen variations under the large storm event at St.4.*

The predicted pathogen levels were higher for spring tides than for neap tides. During a spring tide, the effluent plume from the lower bay spread faster and reaches Odaiba area. Even in a dry weather conditions an increased concentration occurred for a spring tide, whereas for wet weather conditions, the neap tide results showed an increase in the pathogen concentrations at all the stations. For dry weather conditions, the pathogen loads originated mainly from the river Sumida, whereas for wet weather conditions, the main load came from the pumping stations. In a dry weather conditions, the predicted pathogen concentrations were significantly below the bathing water standard. Kashefipour., *et al.* [25] were also found that during dry weather conditions, the predicted fecal coliform concentrations at the three compliance points were all significantly below the mandatory standard required to comply with the EC bathing water directive.

Relation between *E. coli* and AdV

The modeled result (Figure 11) shows that occurrence of *E. coli* did not correlate well with that of AdV. It may be due to the difference in discharge input and survival rate in water column. This is also consistent with the findings of Jiang., *et al* [26]. They found in their study that occurrence of human entroviruses did not correlate with that of Fecal Indicator Bacteria. Fong., *et al.* [7] also pointed out that Coliform standard often fail to predict the occurrence of many waterborne human pathogens.

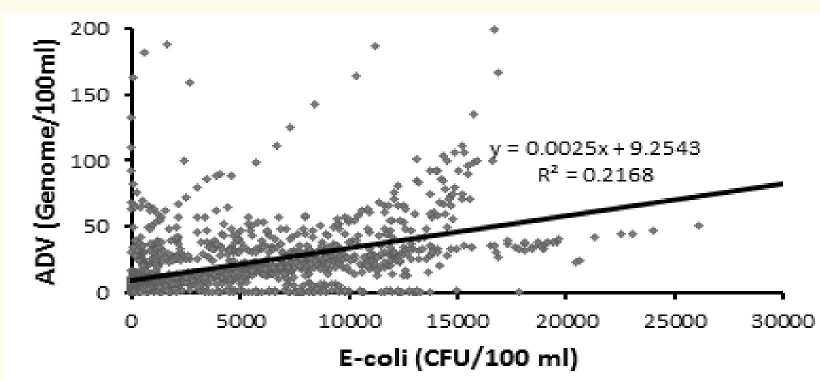


Figure 11: *Relationship between simulated E. coli and AdV.*

After every rainfall event high *E. coli* and AdV plumes appeared. But the timing is little bit different and sometime AdV peak appears and fall down sharply. It may be mainly due to the limited AdV supply in compare with *E. coli*. This is why the correlation between *E. coli* and AdV was found not so strong. However, after every storm event concentration of both *E. coli* and AdV increased significantly. So, it can be said that though some small differences observed in terms of timing of the peak, higher pathogen plume observed for both virus and bacteria following every storm event.

Potential Model Improvements

Although the model reproduces the major features of the spatial and temporal pathogen patterns, there is room for improvement. Major uncertainties are likely in the time-variable inflow concentration (i.e., first flush), other sources (direct runoff), variable die-off rate (solar radiation), settling and storage in the sediment bed. In this model a constant input of pathogen and constant die-off rate is used for lack of time-variable data.

As there was no evidence of resuspension in the study area, the model does not include resuspension effect due to currents and wind waves. However, to use this model in the other area with a broader aspect, some model development would be required to account for sediment transport linked with pathogen component. Incorporating sunlight-dependent die-off will also likely require accounting for spatially and temporally variable light extinction. Additional calibration and / or validation over a longer period would also be beneficial, which would require more data collection. This should include additional pathogen density surveys as well as hydrodynamic data.

Conclusion

The present study observed the spatial and temporal patterns of pathogen in the Odaiba area, Tokyo bay. The pathogen levels in the water column were found to be quite variable spatially and temporarily. And there is no consistent relationship between rainfall or input and elevated pathogen concentrations.

The model applied in this study can successfully reproduce the general spatial and temporal patterns of *E. coli* and AdV in the Tokyo bay. The model demonstrated that discharge from the pumping stations located near the study area is the predominant source of pathogen to the bay. The distributions and dynamics of pathogen were found very complex. Modeling result shows that high pathogen levels are not necessarily consistent with amount of rainfall. Even small precipitations (< 5 mm) can cause significant increase of pathogen concentration especially in the near shore areas. Larger storm event is not so frequent and loadings from larger storms usually represent only a small fraction of the total annual CSO. So, small precipitation event should also be considered in developing management plan of coastal waters. Though, concentration of both *E. coli* and AdV increased significantly after every storm event, correlation between them was found not so strong. So, virus should also consider in managing coastal water body.

This study demonstrated the utility of hydrodynamic and water quality modeling for predicting spatial and temporal patterns of *E. coli* and AdV in the water body of Odaiba. The factors affecting pathogen concentration will vary from system to system, but this study demonstrated that high-resolution spatial and temporal patterns observed in *E. coli* and AdV can be explained using present modeling technology. This technology should be considered as a potential alternative to the nearly impossible intensive monitoring, when constructing management systems.

Utilization of relatively small size of low cost storage tank can be effective in retaining pollutant loadings from small and frequent storm events. Which is also effective to treat the polluted most first flush. As for example, the Kisshoin Trunk Sewer in Kyoto, Japan have a storage capacity of 13000 m3 can store 5 mm/hr rainfall [27,28]. And for big storm case, awareness should create to avoid swimming. All kind of beach activities should be restricted until at least 3 days following a larger storm event. Once the small rain can be protected by installing reservoir facilities, then only have to consider about big storms. Otherwise, people have to restrain from swimming both after small and big size of storms.

Acknowledgements

The authors acknowledge Professor Furumai and former student Mr. Onozawa, Department of Urban Engineering, University of Tokyo for providing data and suggestions.

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Volume 6 Issue 5 March 2017