Model evaluation of faecal contamination in coastal areas affected by urban rivers receiving combined sewer overflows

T. Shibata, K. Kojima, S. A. Lee and H. Furumai

ABSTRACT

Odaiba seaside park is one of the most popular waterfronts in Tokyo Bay, but is easily affected by wet weather pollutant loads through combined sewer overflows (CSOs). The monitoring data of *Escherichia coli* clearly showed high faecal contamination after a rainfall event on 9–11 November 2007. We estimated the amounts of discharge volume and *E. coli* pollutant loads of urban rivers receiving CSO from rainfall chambers as well as pumping stations and primary effluent discharge. The result suggested that Sumida River and Meguro River were more influential to the Odaiba coastal area than other sources including the nearest wastewater treatment plant. Subsequently, we simulated the dynamic behaviour of *E. coli* by a three-dimensional (3D) hydro-dynamic and water quality model. The model simulation reproduced that *E. coli* concentration after the rainfall event increased rapidly at first and later gradually decreased. The simulations with and without inflow pollutant loads from urban rivers suggested that the *E. coli* concentration can be influenced by the Meguro River just after the rainfall event and Sumida River about 1 week later. From the spatial and temporal distribution of surface *E. coli* concentration, after at least 6 days from the rainfall event, high faecal contamination spread to the whole of the coastal area.

Key words | coastal area, CSO, *E. coli*, simulation, urban river

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INTRODUCTION

Odaiba seaside park is one of the largest and most popular waterfronts in Tokyo Bay, and is expected to become a swimmable beach. However, the park is easily affected by wet weather pollutant loads through combined sewer overflows (CSOs). The concentration of faecal indicators such as *Escherichia coli* and enteric viruses were found to increase during and after rainfall events at Tokyo Bay (Katayama *et al.* 2004; Haramoto *et al.* 2006). Therefore, CSO control measures are being actively implemented by the Bureau of Sewerage Works, Tokyo Metropolitan Government (TMG). In 2002, the Ministry of Land, Infrastructure, Transport and Tourism amended the sewerage enforcement ordinance to accelerate control measures for water pollution derived from CSOs. By 2011, the CSO control and water quality improvement projects in Japan had already been implemented in more than half of 119 municipalities having combined sewer systems. As public health risk caused by exposure to pathogens in waterfront beaches has become a social concern, its effective management is to be done through quantitative evaluation of faecal contamination.

For quantitative evaluation of the contamination, several studies on model simulation have been done to date. For example, Aström *et al.* (2009) especially focused on a calculation of pollutant discharge loads from urban sewerage systems along the river. Hellweger & Masopust (2008) and Harris *et al.* (2004) tried to simulate the contamination level by time-dependent hydro-dynamic models at rivers in Boston and along the South Wales coast, respectively. Moreover, dynamic simulation models were practically applied to issue a warning against faecal contamination and to conduct real-time management of sewer systems (Sørensen & Anderson 2005; Suñer *et al.* 2008). However, the previous studies have considered a limited number of CSO discharge points, while in the coastal area of the Tokyo Bay there are numerous pollutant discharge locations. These include CSO from rainfall chambers and

doi: 10.2166/wst.2014.225

pumping stations as well as primary effluent discharge from wastewater treatment plant (WWTPs). Kojima & Furumai (2012) conducted urban runoff simulation in the whole Tokyo drainage area, and estimated CSO volumes to urban rivers from hundreds of rainfall chambers and direct CSO discharge volumes to the coastal area from pumping stations. They reported that CSO volumes from the rainfall chambers accounted for 57% of the total CSO volumes for an event in November 2007. Therefore, it is necessary to consider inflow pollutant loads of urban rivers receiving CSO from rainfall chambers as well as pumping stations and primary effluent discharge, so that dynamic change of *E. coli* concentration could be estimated in the coastal area after rainfall events.

The purpose of this study is to evaluate the spatial and temporal behaviour of *E. coli* as faecal indicator quantitatively using a three-dimensional (3D), hydro-dynamic and water quality model in Odaiba coastal area, Tokyo, Japan. After confirming that the model could reproduce the observed *E. coli* concentration level and its trends, the model was used to simulate two cases without inflow pollutant loads of two key urban rivers. In addition, we investigated the influence of the pollutant discharges on faecal contamination around the coastal area.

SIMULATION AND METHOD

3D hydro-dynamic and water quality model

The complete model used in this study is composed of a 3D hydro-dynamic sub-model and a water quality sub-model, which are for expressing tidal flow and *E. coli* behaviour, respectively. The hydro-dynamic model was originally developed by Koibuchi & Sato (2010), in which the Navier–Stokes equation was solved under hydrostatic and Boussinesq approximations to express the flow dynamics in coastal waters of Tokyo Bay considering density effect by temperature and salinity. The water quality model solved the mass conservation equation and advective diffusion equations.

For expressing the behaviour of *E. coli*, the constant settling rate (3.47×10^{-6} m/s) and decay rate were considered. The decay rate coefficient was given as 3.76×10^{-5} (sec^{-1}) under freshwater conditions after Omura *et al.* (1982) with consideration of salinity-dependent features. To conduct the model simulation of the spatial and temporal behaviour of *E. coli*, several input data are required. The meteorological data and tidal levels at the Tokyo reference point were obtained from the Bureau of Construction, TMG, and the Japan Meteorological Agency. The water level, temperature and salinity were given as boundary conditions, following the procedure proposed by Onozawa *et al.* (2005). The used input rainfall event has a total rainfall amount of 33 mm and it rained for 3 days, 9–11 November 2007. The initial *E. coli* concentration was given as 100 CFU/100 ml in the entire coastal water, which reflects the typical level under fine weather conditions.

Locations of pollutant discharge in study area

Figure 1 shows the locations of pollutant discharge, which are inflow and discharge points of urban rivers, WWTPs and pumping stations, in addition to the whole study area for model simulation. The two computational domains cover the whole region of Tokyo Bay and the Odaiba region with grid resolution of 2 km and 100 m, respectively. The first domain (Figure 1(b)) size is 25×33 grids and the second domain (Figure 1(c)) has 60×290 grids horizontally. All of the domains have 10 vertical sigma levels. The water depth is illustrated in Figure 1(b) and used for 3D vertical level simulation. Numerical simulation was conducted to evaluate *E. coli* behaviour in the nested domain covering the coastal area near Odaiba seaside park with complex geographical features.

The computational domain of the Odaiba region was expanded to the upstream of Sumida River by Kojima *et al.* (2011), compared with the original model, so that we could consider the ebb and flood tides in Sumida River receiving pollutant loads from inflowing urban rivers. In the study area, there are 29 pumping stations and six WWTPs. Shingashi River and Kanda River each receive the discharge from two WWTPs. Therefore, we took into account the discharge from the additional four WWTPs into river flows. In addition, our effort was directed towards considering the CSO discharge from about 800 rainfall chambers in Tokyo's 23 Wards. We estimated the flow volume and *E. coli* loads in each inflowing river, considering CSO from the chambers. The estimation method will be discussed in the following section. At the upper end of Sumida River, a part of the Ara River water flows through the water gate. Based on this assumption, discharge volume from the Ara River was 79.4 m^3/s during 2 days from the rain initiation in the simulation period of this study (8–27 November 2007).

Source inflow condition

As shown in Figure 2, the gravity flow system and pumped system should be considered to calculate the CSO discharge in a drainage area with a combined sewer system. During wet

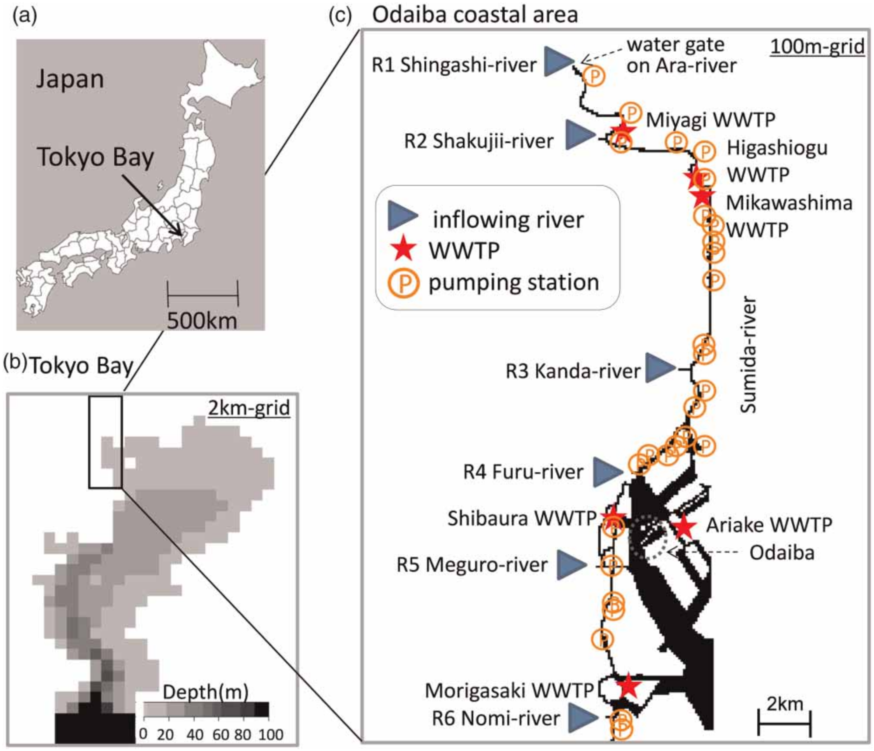

Figure 1 | Schematic of the study area: (a) Japan area, (b) Tokyo Bay area and (c) Odaiba coastal area including location of rivers, WWTPs and pumping stations.

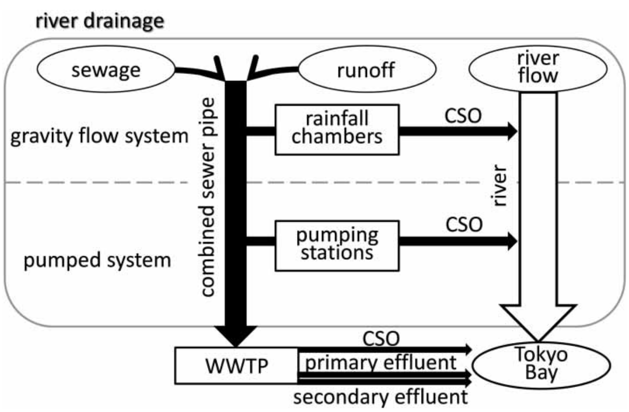

Figure 2 | Conceptual diagram of CSO discharge in combined sewer system.

weather, sewage and runoff are collected in combined sewer pipes, and CSO discharge occurs at rainfall chambers in a gravity flow system and at pumping stations in a pumped system. The intercepting flow of wet weather sewage is directed and treated at the downstream WWTPs. Since the intercepting volume is designed as three times that of maximum dry weather flow in Tokyo, the WWTPs discharge not only secondary effluent but also primary effluent on a rainy day.

Considering that there are eight drainage systems in the study area, we calculated the total dry weather flow, total CSO volume and *E. coli* concentration for each drainage system using Equations (1), (2) and (5). The average dry weather flow was based on population and unit flow per capita. The change in dry weather flow rate was considered by multiplying the hourly fluctuation coefficient with the average rate. The drainage runoff hydrograph was calculated by rational formula depending on drainage area and travelling time (30, 60, 90, 120, 180 and 240 min). Intercepting flow is defined as three times that of the hourly maximum flow rate in Tokyo. Then the CSO volume was divided into the discharge from pumping stations and rainfall chambers in the drainage system as Equations (3) and (4). If there are several pumping stations in the drainage area, we need to estimate CSO flow from rainfall chambers by subtracting the sum of the CSO volume through each pumping station from the total CSO volume. Inflow volume to WWTPs was regarded as the total of intercepting flow

$$Q_{\mathrm{DWF}} = \text{drainage area} \times \text{population density} \times \text{dry weather flow per capita} \quad (1)$$

$$Q_{\text{CSO-total}} = \text{drainage runoff} + Q_{\mathrm{DWF}} - \text{intercepting flow} \quad (2)$$

$$Q_{\text{CSO-p}} = Q_{\text{CSO-total}} \times (\text{pumped system area}/\text{whole drainage area}) \quad (3)$$

$$Q_{\text{CSO-c}} = Q_{\text{CSO-total}} - \sum Q_{\text{cso-p}} \quad (4)$$

$$C_{\text{CSO-total}} = C_s \times Q_{\text{DWF}}/(\text{drainage runoff} + Q_{\text{DWF}}) \quad (5)$$

where Q_{DWF}, $Q_{CSO\text{-}total}$, $Q_{CSO\text{-}p}$ and $Q_{CSO\text{-}c}$ are total dry weather flow, total CSO flow, and CSO flows from a pumping station and rainfall chambers in a drainage area, respectively. $C_{CSO\text{-}total}$ and C_s are *E. coli* concentration in CSO and in dry weather flow.

In the simulation, the average of C_s was given as 9.6×10^6 CFU/100 ml. The *E. coli* concentration in primary treatment was regarded as 30,000 CFU/100 ml, which is equivalent to the effluent standard, while the concentration after the secondary treatment was given from 30 to 2,240 CFU/100 ml, which appeared as average concentrations in the annual report of the Bureau of Sewerage Works, TMG.

RESULTS AND DISCUSSION

Monitoring of *E. coli* concentration distribution after a rainfall event

Water sampling was conducted at seven points for more than 2 weeks after the rainfall event (33 mm of total precipitation) when it rained for 3 days, 9–11 November 2007. *E. coli* concentrations were measured by a single agar layer method using Chromocult® coliform agar (Merck) and its detection limit was 50 CFU/100 ml. Figure 3 shows the distribution of *E. coli* concentration in the surface layer (0.5 m from water surface). On 11 November, all monitoring data clearly showed high faecal contamination compared with the background level of *E. coli* of less than 10^2 CFU/100 ml. Until 12 November, *E. coli* concentration level was higher than a swimmable water quality, 10^3 CFU/100 ml, which was given as the criterion of faecal coliform counts in open coastal areas. We assumed that the high faecal contamination continued at ebb tides because the ebb tides moved toward the Tokyo Bay. Eventually, after the rainfall event, it took more than 13 days for *E. coli* to decrease to the ordinary level of around 10^2 CFU/100 ml. There are several CSO discharge points which have an influence on the water quality, and yet the overall origin of the pollutant load of Odaiba is not clear.

Amount of pollutant loads from sources

We compared three inflowing rivers (Sumida River, Furu River and Meguro River) and a WWTP (Shibaura WWTP), which are large pollutant sources near Odaiba seaside park. Regarding the four sources, the total amount of discharge volume and *E. coli* was calculated after the rainfall event for 20 days from 8 to 27 November. Of the four pollutant sources, total inflow discharge volume was the highest in Sumida River, followed by Shibaura WWTP (Figure 4 (left)). On the other hand, the total amount of *E. coli* in Shibaura WWTP was much lower

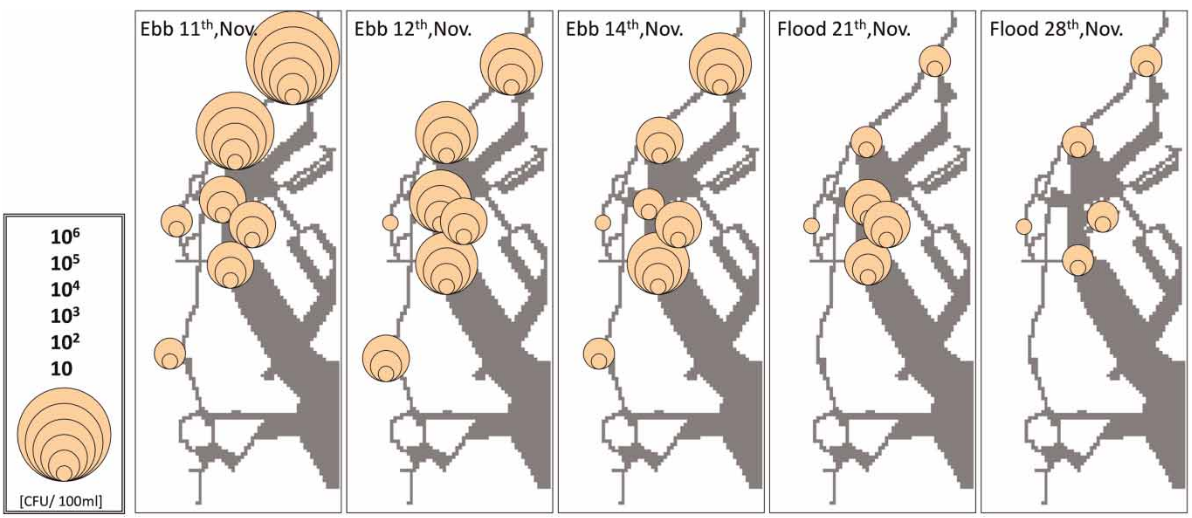

Figure 3 | The monitoring results of *E. coli* concentration after the rainfall event (rainfall precipitation: 33 mm, 9–11 November 2007).

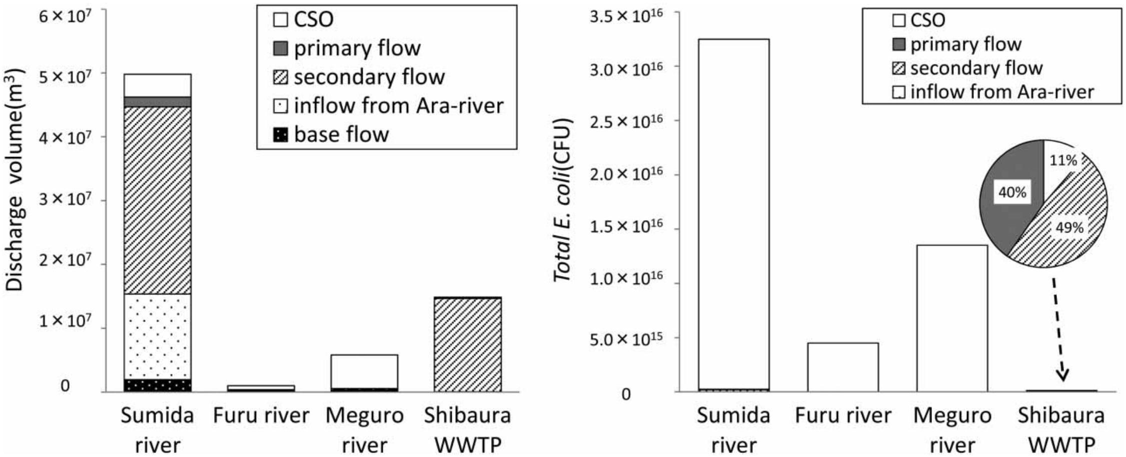

Figure 4 | Total discharge volume (left) and *E. coli* (right) from Sumida River, Furu River, Meguro River and Shibaura WWTP during 20 days (8–27 November).

than the other sources, because most of the pollutants were treated by WWTPs (Figure 4 (right)). Therefore, it can be said that Sumida River and Meguro River are more influential in faecal contamination than the other sources around the Odaiba coastal area, because these two rivers receive CSO from many rainfall chambers and pumping stations.

Effect of Sumida River and Meguro River on *E. coli* behaviour

Considering the above-mentioned inflow pollutant loads of urban rivers receiving CSO from rainfall chambers as well as pumping stations and primary effluent discharge, *E. coli* concentration was calculated during the monitoring period by the 3D hydro-dynamic and water quality model. In addition to the base case considering all discharges, simulations were conducted for two cases, in which the discharges from Meguro River (Case 1) and Sumida River (Case 2) were omitted, respectively.

Figure 5(upper) shows the simulated surface *E. coli* concentration and the monitoring data of *E. coli* concentration in the surface layer at the Odaiba seaside park point, which are expressed by lines and dots. The simulation reproduced a general trend that the *E. coli* concentration increased rapidly after a rainfall event and then decreased gradually. It took more than 10 days for *E. coli* concentration to decrease to the swimmable criteria level (10^3 CFU/100 ml). The simulation results in the base case are about 1-log order of magnitude higher than the observed data from 11 to 15 November, while the gradual decrease in concentration was reproduced well. Just after the rainfall started, *E. coli* concentration in Case 1 was the lowest but, after 18 November, *E. coli* concentration in Case 2 was the lowest in the three cases. The result suggests that *E. coli* concentration at Odaiba coastal area can be influenced by Meguro River just after the event, while the effect of Sumida River discharge appears about 1 week later. Figure 5(lower) shows the spatial and temporal distribution of the surface *E. coli* concentration in the three cases at 9:00 and 15:00 on 10 November and at 0:00 on 16 November. The *E. coli* concentration increased rapidly at 15:00 on 10 November in the north of Odaiba except for Case 1 without pollutant discharge from Meguro River. It also indicates that the pollutant load from Meguro River was essential for faecal contamination just after the rainfall. Although the concentration levels are lower in Cases 1 and 2 than the base case in which all pollutant discharges are considered, high *E. coli* concentration spreads to the whole coastal area at 0:00 on 16 November in all cases.

CONCLUSION

The water quality monitoring data clearly showed high faecal contamination after a rainfall event in comparison with the background level of *E. coli* of less than 10^2 CFU/100 ml. We estimated the total amount of discharge volume and *E. coli* for 20 days from inflowing urban rivers as well as the nearest WWTP to the Odaiba coastal area. The estimated *E. coli* loads suggested that Sumida River and Meguro River were much more influential regarding the coastal area from the viewpoint of faecal contamination than the nearest WWTP. We evaluated the spatial and temporal behaviour of *E. coli* after the rainfall event in Odaiba coastal areas by a 3D hydro-dynamic and water quality model, considering inflow pollutant loads of urban rivers receiving primary effluent discharge and CSO from rainfall

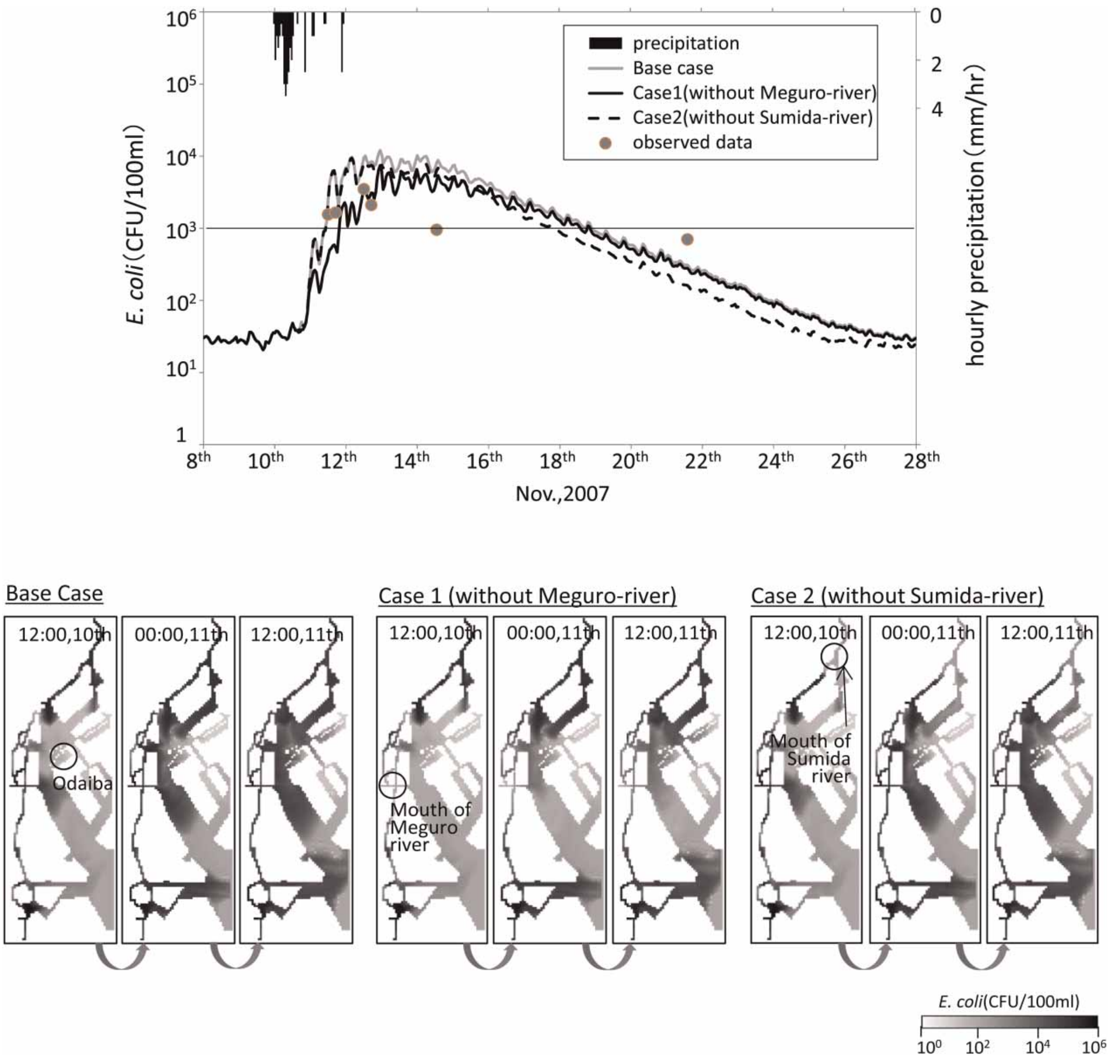

Figure 5 | Simulation results and monitoring data at Odaiba point (left) and spatial and temporal distribution (right) of *E. coli* concentration in the surface layer.

chambers and pumping stations. Comparing the simulation and monitoring results of *E. coli* concentration indicated that the model reproduced well the general trend that *E. coli* concentration rapidly increased after a rainfall event and then decreased gradually. The model predicted that it took more than 10 days for *E. coli* concentration to decrease to the swimmable criteria level (10^3 CFU/100 ml). The simulation results with and without pollutant discharge from Meguro River and Sumida River showed that *E. coli* concentration can be influenced at the Odaiba coastal area by the Meguro River just after the rainfall event, while the effect of Sumida River discharge appeared about 1 week later. The simulation results on spatial and temporal distribution of the surface *E. coli* concentration indicated that Meguro River discharge was essential for faecal contamination in the coastal area just after the rainfall. In addition, the high faecal contamination region spread to the whole coastal area by tidal actions after around 6 days. Our model can be useful to discuss effective CSO control measures and to provide an alarm system for faecal contamination. It is recommended that the model be improved with accurate estimate discharge volume and *E. coli* loads from pumping stations and rainfall chambers.

ACKNOWLEDGEMENT

This work was financially supported by JSPS (Japan Society for the Promotion of Science) Grant-in-Aid for Scientific Research (A) Number 24246090.

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First received 28 November 2013; accepted in revised form 6 May 2014. Available online 28 May 2014