GENERATION AND FLOATING BEHAVIOR OF SCUM IN AN URBAN TIDAL RIVER IN OSAKA, JAPAN

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In urban rivers where combined sewer overflows occur, scum appears several days after rainfall, causing bad odor and adverse effects on the landscape and ecosystem. To clarify the generation and floating behavior of scum, we conducted a detailed observation of scum using multiple fixed-point cameras and sediment surveys in the Hirano River, an urban tidal river in Osaka, Japan. Organic mud derived from sewage was deposited in two separate areas, of which the upstream was the main source of scum in the river. The floating behavior of scum was mainly dominated by tide, and scum accumulated at the stagnant point at rising tide. Scum was frequently observed at the bend of the river channel, suggesting that the local flow structure had a considerable influence on the behavior of scum over a wide area of the river.

Key Words: scum, urban tidal river, fixed-point camera, U-net, Hirano River

1. INTRODUCTION

In urban rivers where combined sewer overflows (CSOs) occur, organic mud called “scum” appears on the water surface after a few days of rainfall. It has become a serious problem due to its bad odor and adverse effects on the landscape and ecosystem. Scum is an organic mud that emerges when organic suspended solids contained in sewage flow into a river during rainfall, accumulate on the riverbed surface, and then become buoyant due to the generation of anaerobic gas by microbial action1-4. However, the dynamics of scum is still unclear because of the complex physical, chemical, and biological effects involved.

Recently, Miura et al.5-7 formulated each process involved in scum generation in the Nomi River and modeled the series of phenomena from sewage inflow to scum generation. Okuyama et al.8 and Cashila et al.9 clarified the relationship between scum generation and water quality and odor in the Shakujii River and Sumida River. However, since the properties and transport characteristics of scum vary from river to river, it is necessary to clarify the generation and floating behavior of scum in the target rivers in order to take effective and efficient measures.

The purpose of this paper is to clarify the generation and floating behavior of scum in the Hirano River, a tidal river in Osaka, Japan. In a previous study10, the authors constructed a scum observation system consisting of multiple fixed-point cameras in the river and analyzed the behavior of scum. However, incomplete information was obtained due to the limitation of the number of observation points. In this work, more detailed data in space and time were obtained by adding multiple observation points, and a bottom sediment survey was conducted to understand the accumulation of bottom mud, which was the source of scum. Based on the data obtained from
these investigations, the location of scum generation and the spatio-temporal floating behavior of the entire river channel were clarified.

2. METHODS

(1) Study area

The Hirano River and its surrounding area are shown in Fig. 1. The Hirano River is a 17.4 km long river that flows through Kashiwara, Yao, and Osaka cities in Osaka Prefecture. The river flows in a northwesterly direction after splitting from the Yamato River and divides into the Hirano River Diversion Channel. From Sta.15, the flow changes to the north and finally joins the Second Neya River.

The longitudinal riverbed profile in the Hirano River is shown in Fig. 2. The riverbed height changes abruptly at the junction with the Hirano River diversion channel (near outlet i) and around Sta.15. The riverbed slope is about 1/1000 upstream of Sta.15 and about 1/3000 downstream of Sta.15. The area up to the junction with the Hirano River diversion channel is a tide-sensitive area. However, there is no seawater in the area and the entire area is freshwater.

Most of the basin is sewered by a combined sewer system. Because of the low-lying area, CSOs are drained by pumps, and the CSO outlets around the Hirano River are limited to the 11 points shown in Fig. 1. The amount of rainwater discharged from each CSO outlet (actual values for FY 2017) is shown in Fig. 3. CSO often occurs when the daily maximum hourly precipitation exceeds 2 mm/h. Although the Hirano River receives wastewater directly from the plant, the amount of wastewater is only about 0.50×10^6 m^3/year, which is negligible compared to the CSO.

(2) Observation of scum using fixed-point cameras

Multiple fixed cameras (MAC200DN, manufactured by Brinno) were installed on the riverbanks of
the Second Ney and Hirano Rivers (Sta.1-15) to observe scum by continuously photographing the water surface at one-minute intervals. The resolution of the images was 96 dpi and the size was 1280 × 720 pixels. However, for Sta.8 and Sta.15, images from the camera installed by the Osaka Prefectural River Office (resolution: 96 dpi, size: 640 × 480 pixels) were used\(^\text{11}\). The survey was started in November 2018 and is still ongoing as of February 2022. Initially, only eight sites were observed, but a number of sites have been added sequentially, and data for all sites are available since July 2019.

(3) Sediment survey

Sediment samples were collected at ten sites (Sta. 3, 4, 6, 7, 9, 10, 11, 12, 13, 14) in the Hirano River on October 8, 2019. The surface mud was collected using a grab-type mud sampler and analyzed for ignition loss (IL) and n-hexane extracts.

The results of sediment-quality surveys conducted by related organizations\(^\text{12},\text{13}\) were also collected and used for analysis. These mud-sampling surveys were conducted at three sites on February 5, 2018, and at four sites on September 17, 2019. Each site is shown in Fig.5.

(4) Scum detection model

We developed a deep learning model that can automatically evaluate the water surface coverage of scum continuously and quantitatively from camera images, and analyzed the spatio-temporal distribution characteristics of scum and the long-term appearance of scum in the Hirano River.

The developed model is based on U-Net\(^\text{14}\), a semantic segmentation method that classifies images into categories by pixel. U-Net is one of the deep learning models used for image recognition tasks. For details, please refer to the previous paper\(^\text{15}\).

By training the original image as the input and the image labeled with the scum as the output, we constructed a model that can detect the scum pixel by pixel. The model was trained using 1,000 camera images (8,000 images in total) of eight locations where scum was frequently observed, including relatively large-scale events, as supervisory data. The images were acquired in December 2018 and June–October 2019, and only data from daytime (7:00-19:00) were used.

As an example of the evaluation of the detection accuracy, Fig.4 shows a comparison between the results of manual visual extraction of the water surface coverage of scum and the results of estimation by the model. Although the accuracy was evaluated only for images that could be extracted manually, the detection accuracy was good with an RMSE (Root Mean Squared Error) of about 1.47%, and it was confirmed that the water surface coverage could be quantified with high accuracy for images in which a large amount of scum was floating. However, there was a tendency for misidentification when ripples were instantaneously generated on the water surface due to wind, etc. Therefore, the effect of ripples was removed by detecting only cases where the water surface coverage of scum exceeded 5% for five consecutive minutes.

3. RESULTS AND DISCUSSION

(1) Sediment conditions

Figure 5 shows the longitudinal distribution of ignition loss and riverbed height, and Fig.6 shows the relationship between ignition loss and n-hexane extracts. In Sta.6 and Sta.7, we tried to collect mud several times but could not do so because no mud was deposited. The bottom sediment was black in color and had a strong sewage smell. A strong positive correlation was observed between the n-hexane extracts,
which were high in untreated sewage\textsuperscript{16}, and the ignition loss, suggesting that the organic mud deposited was mainly derived from sewage.

In Sta.9 to Sta.11, the riverbed gradient suddenly slowed down, and it is inferred that organic matter derived from sewage discharged from the CSO outlet (i and/or k) located upstream was deposited. In Sta.3 and Sta.4, organic matter from the upper Hirano River may have been deposited due to backwater effect caused by the confluence with the Second Neya River, or organic matter from the Second Neya River may have been deposited.

(2) Long-term appearance of scum

The daily variation in water surface coverage of scum estimated by the deep learning model and daily maximum hourly precipitation for the year 2019 is shown in Fig.7. As reported in previous studies\textsuperscript{10}, scum appeared throughout the year, but occurred more frequently from June to October when rainfall frequency was higher. Large-scale events with water coverage exceeding 70\% were observed eight times during the year, six of which occurred during the summer. In addition, scum often appeared several days after rainfall, which is consistent with reported cases in other rivers\textsuperscript{5,8}, suggesting that this is a general characteristic of scum and not limited to the Hirano River. The scum did not appear during the period of no rainfall, and there was no clear relationship between the daily maximum hourly precipitation and the water surface coverage of scum.

(3) Occurrence and floating status of scum

For the seven relatively large scum events that occurred between August 1 and December 29, 2019 (see Fig.7), the relevant information at the time of occurrence is shown in Table 1. The time between the last rainfall and the onset of the scum event was generally dependent on the air temperature, which may be due to the fact that the rate of anaerobic gas production varies with temperature\textsuperscript{5}.

In tidal rivers in Tokyo, scum generation is reported to occur during the pressure drop at low tide\textsuperscript{17}. In the Hirano River, however, no relationship was found between the timing of scum generation and the

\textbf{Table 1} Related information on the large scum events.

| Event No. | Date and time of scum generation | Hourly maximum precipitation of last rainfall (mm/h) | Time from the onset of the most recent hourly maximum precipitation to scum generation (h) | Daily average air temperature (\degree C) | Tide at the time of scum generation |
|-----------|--------------------------------|----------------------------------------------------|---------------------------------------------|----------------------------------------|-----------------------------------|
| 1         | 2019/8/20  22:00                | 4.0 mm/h                                            | 29 h                                        | 28.4 \degree C                         | high tide                         |
| 2         | 2019/8/28  9:00                 | 10.0 mm/h                                           | 15 h                                        | 26.9 \degree C                         | falling tide                      |
| 3         | 2019/9/13 23:00                 | 11.0 mm/h                                           | 20 h                                        | 23.3 \degree C                         | low tide                          |
| 4         | 2019/10/4 16:00                 | 6.0 mm/h                                            | 23 h                                        | 25.1 \degree C                         | falling tide                      |
| 5         | 2019/10/23 9:00                 | 3.5 mm/h                                            | 37 h                                        | 20.7 \degree C                         | low tide                          |
| 6         | 2019/11/1 10:00                 | 2.5 mm/h                                            | 49 h                                        | 17.6 \degree C                         | high tide                         |
| 7         | 2019/12/24 20:00                | 2.5 mm/h                                            | 50 h                                        | 9.5 \degree C                          | falling tide                      |

Fig.6 Relationship between ignition loss and n-hexane extracts.

Fig.7 Daily variation in water surface coverage of scum at Sta.6 and daily maximum hourly precipitation. The numbers in the figure correspond to the event numbers in Table 1.
tide. In order for scum to emerge from the riverbed, the surface layer of the bottom sediment must be flocculated to a certain strength so that it can retain gas. However, whether the pressure drop associated with water-level fluctuations is a sufficient condition for scum to emerge depends on the erodibility of the bottom sediment due to floculation. Considering that the floculation effect is affected by the adsorption of extracellular polymers produced by microorganisms and the physical entanglement of filamentous algae and fibrous materials, it is not surprising that the conditions for scum flotation vary depending on the characteristics of the bottom mud in each river.

The occurrence and floating status of scum were organized for these seven scum events. First, the number of times scum was generated (surfaced) at each location by visually checking the camera images is shown in Fig. 8. Nighttime data were also used as long as visibility was possible. The occurrence of scum was judged based on the floating conditions at points upstream and downstream, and when the occurrence point could not be identified at one point, multiple points were counted as the occurrence point. Figure 8 shows that scum was generated only upstream of Sta. 9, and not downstream of Sta. 3 to Sta. 8. The occurrence of scum in Sta. 3 to Sta. 8 was not observed. Therefore, it is inferred that the scum suspended in the Hirano River originated from the sediment deposited in the section from Sta. 9 to Sta. 13. Based on these results, it is considered that measures to improve the bottom sediment quality in Sta. 9 to Sta. 13 (such as dredging and improvement of bottom sediment quality by chemicals) are effective in reducing the generation of scum in the Hirano River.

Next, Fig. 9 shows the results of counting the number of times the scum was found to be floating in each location during the same period using the scum detection model. In this figure, scum was judged to be floating when the one-hour maximum value of the water surface coverage was 15% or more. Sta. 8, Sta. 10, and Sta. 14 were excluded from the figure because of insufficient detection accuracy of the model. In addition, there was a missing data period for Sta. 5 and Sta. 13. Therefore, when scum was observed floating in the vicinity of either upstream or downstream, it was assumed that it was also floating in the missing points, and the number of times it was floating in the missing period (shaded area in the figure) was estimated. Figure 9 shows that scum is suspended in a wide area from the upper to the lower reaches of the Hirano River, especially in Sta. 5 to Sta. 7. As shown in Figs. 5 and 8, there is no organic matter deposited on the riverbed in this section, and it is not a scum-generating point, suggesting that scum generated upstream of Sta. 9 flows down and stays there. In this section of the river, there are many bends in the channel, and it was observed several times that scum was trapped near the river bank by the eddy structure formed at the bends. This suggests that the flow due to the local channel shape has a non-negligible influence on the behavior of scum at the scale of several kilometers.

(4) Spatio-temporal behavior of scum

Figure 10 shows the results of the spatio-temporal behavior of scum based on the camera images for three events where scum occurred on a large scale. The camera images were visually checked every minute for each location, and the hourly maximum coverage was classified into four levels: 0-10%, 10-45%, 45-75%, and 75-100%. Large scum movements are indicated by arrows in the figure, and the astronomical tide level at Osaka Port is also shown.

Events I, II, and III occurred during neap tide, spring tide, and half tide periods, respectively. In Events I and III, the scum was finally destroyed by the passage of ships and disappeared. The scum was mainly generated near Sta. 11 to Sta. 12 in the upper reaches of the river, and was observed to stay for a long time near Sta. 7. There was no clear relationship between the wind direction and speed observed at AMeDAS Osaka and the behavior of scum. In all events, scum flowed upstream during the rising tide and downstream during the falling tide, indicating...
that the behavior of scum was mostly controlled by the tide. The maximum advection velocity was estimated to be about 7 to 10 cm/s from the slope of the arrows shown in the figure. In addition to the diurnal and semi-diurnal tides, the flow in the Hirano River is known to include velocity components with a 1/5-1/6 day cycle. However, as far as the present results are concerned, the velocity components do not have a significant influence on the behavior of scum.

Because Event I was during a period of large daily tidal inequality with neap tide, large movements of scum occurred only during the rising tide from lower low tides and the falling tide from higher high tides. From 16:00 on June 28 to 1:00 on the next day, the tidal fluctuation was small, so the scum stayed for a long time near Sta.6 and Sta.7 in the middle part of the river, and it is thought that damage such as bad smell occurred in the vicinity.

Event II was a period of large daily tidal inequality with spring tide, and as in Event I, scum moved significantly during the rising tide from the lower low tide and the falling tide from the higher high tide.

In Event III, scum occurred in the upstream area for several hours from around 18:00 on October 4, and small scum masses spread and flowed from upstream to downstream. Then, during the high tide from around 6:00 on October 5, scum accumulated at the bend of the river channel near Sta.5 to Sta.7, and at Sta.12, scum accumulated due to the balance between tidal backwash and freshwater flow and formed two large clumps. After that, the scum flowed down significantly during the lowering tide, and finally disappeared when a ship passed by around 14:00 on October 6.

As described above, the floating behavior of the scum was basically controlled by the tide, and it was also strongly affected by the accumulation at the bend of the river channel and the destruction by ships. In addition, it was found that the scum disappeared from the Hirano River within two days after its appearance by settling or flowing down, although it slightly varied depending on the tide time when the scum appeared.

4. CONCLUSIONS

In this study, continuous observation of scum using multiple fixed-point cameras and a bottom sediment survey were conducted in the Hirano River, an urban tidal river, to clarify the occurrence points and spatio-temporal behavior of scum. The main conclusions obtained are as follows:

1) In the Hirano River, sewage-derived organic mud was deposited in two separate areas, and the upstream area from Sta.9 to Sta.13 was identified as the main scum-generating area. Measures to improve the bottom sediment quality in this area were considered to be effective in reducing the occurrence of scum.

2) Scum frequently appeared between June and October, when rainfall frequency was high. Scum often appeared a few days after rainfall, which was
considered to be a general characteristic of scum and not limited to the Hirano River.

3) In the Hirano River, there was no relationship between the timing of scum occurrence and the tide.

4) The frequency of floating scum is high around Sta.5 to Sta.7. This is because the scum generated upstream flows downstream and is trapped on the river bank by the eddy structure caused by the bending of the river channel, and it is inferred that the flow due to the local channel shape has a non-negligible effect on the floating behavior on a scale of several kilometers.

5) The floating behavior of scum was mainly dominated by the tide. However, it was also strongly influenced by the accumulation at the point where the tide and freshwater flow were in balance, the shape of the river channel, and the destruction caused by the passage of ships.

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