Survey Report:

Scenario Analysis of Sluice Gate Operations for Evaluating Inland Flood Damage

Hiromichi Muroi†**, Kensuke Mine, and Yoshiki Eguchi**

Waterworks Bureau, City of Kawasaki
1 Miyamoto-cho, Kawasaki-ku, Kawasaki, Kanagawa 210-8577, Japan
†Corresponding author, E-mail: 80gkeika@city.kawasaki.jp
[Received October 1, 2020; accepted November 26, 2020]

Typhoon Hagibis, which hit Japan directly on October 12, 2019, caused great damage, including the flooding of rivers, across various parts of Japan. The Tama River, which flows north of Kawasaki City, also experienced flooding which exceeded the designed high water level; although it did not cause fluvial flooding, river water flowed into the urban areas through the sewerage system, causing unprecedented inundation damage. This damage was reproduced with the inland flood simulation model. Furthermore, we performed simulations in which the water level, precipitation, and sluice gate operation of the Tama River differed from actual conditions, and compared them with the actual damage. Based on these results, we examined methods for reducing inundation damage, such as improving the operation method of sluice gates, and confirmed their effects.

Keywords: Typhoon Hagibis 2019, sewer, sluice gate, inland flood simulation model, Tama River

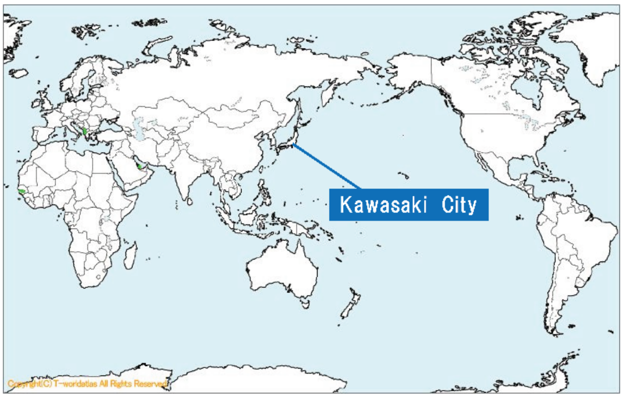


Fig. 1. Location of Kawasaki City.

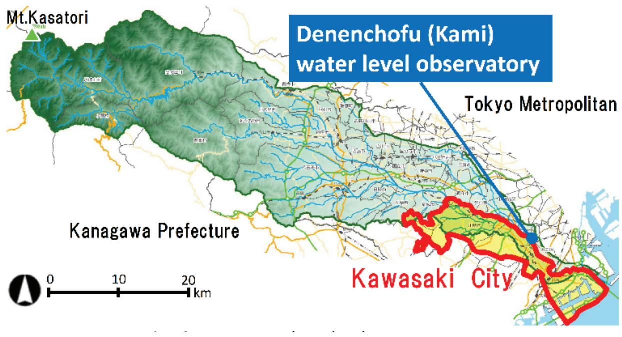


Fig. 2. Tama River basin map.

1. Introduction

Kawasaki City is located in the eastern part of Kanagawa Prefecture, with the Tama River running to the north of the city (**Fig. 1**).

The Tama River originates from Mt. Kasatori in Koshu City, Yamanashi Prefecture, and flows down from the western part to the southern part of Tokyo, along with many tributaries such as the Aki River and Asa River, and flows through the prefectural border between Tokyo and Kanagawa Prefecture to Tokyo Bay. The Tama is a first-class river with a trunk channel length of 138 km, a basin area of 1,240 km^2, and a basin population of an estimated 3.8 million (**Fig. 2**). In addition, with the urbanization of the basin, the riverbed is used for various purposes [1].

The main flood damage caused along the Tama River includes that of September 1947 – when approximately 100,000 houses were inundated, and September 1974 – when 19 houses were washed away. During the flooding of September 1974, the highest-recorded water level was noted at the Denenchofu (Kami) water level observatory at A.P. +9.07 m (the water level in this paper is described in A.P.: Arakawa Peil).

In the "River Improvement Plan for the Tama River System," the aim is to safely accommodate the flow of the largest flood volume recorded after World War II; as such, the flooding of September 1974 has been recognized as a benchmark. The plan's target designed flow rate is set at 4,600 m^3/s at the Denenchofu (Kami) water level observation station, which currently does have this flow capacity.

In Kawasaki City, which faces Tokyo Bay, inundation damage tends to occur quite easily, with huge expected storm-surge damage being attributed to climate variability [2].

A survey report [3] notes that Typhoon Hagibis caused

© Fuji Technology Press Ltd. Creative Commons CC BY-ND: This is an Open Access article distributed under the terms of the Creative Commons Attribution-NoDerivatives 4.0 International License (http://creativecommons.org/licenses/by-nd/4.0/).

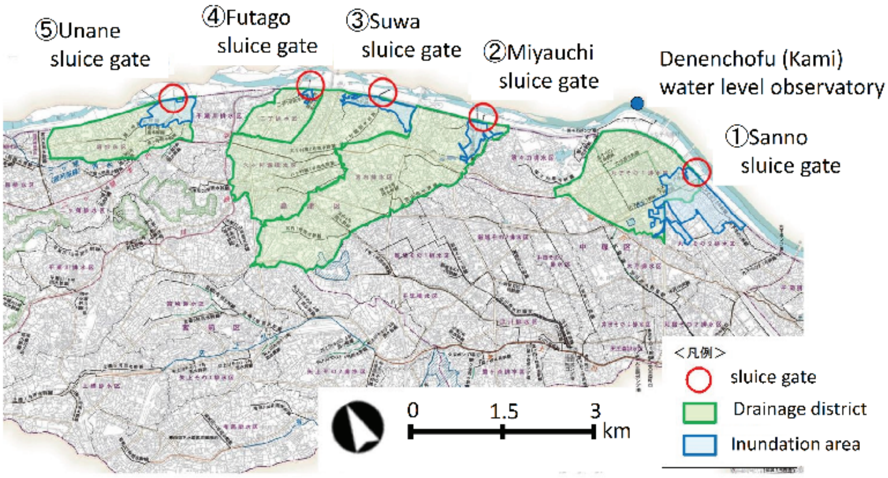


Fig. 3. Inundation areas in Kawasaki City.

relatively little damage to the populous area around Tokyo Bay when the storm surge reached its peak at low tide, despite extreme sea level abnormalities.

Construction on Kawasaki City's sewerage system started in 1931 as a countermeasure against flooding in the southern part of the city. The project has been promoting the construction of sewer pipes and rainwater pumping stations as a response to hourly rainfall of 52 mm (five-year return period rainfall) or 58 mm (10-year return period rainfall) in some areas. During Typhoon Hagibis, large-scale damage from water inundation was caused by the Tama River, which overflowed and spilled out of the sewerage system along five areas via sluice pipes (also located along the Tama River). In order to clarify the mechanism leading to this flooding damage, inundation simulations were conducted across the five areas.

In this paper, we report the results of the survey on inundation damage in the Sanno area, which requires special considerations in light of the area being subject to both natural water flows and pump drainage (due to the combined sewerage system). First, the results of the inundation simulation (for reproducing the actual inundation) are described for the purpose of clarifying the inundation mechanisms; then, the results of inundation damage are described, in which the rainfall, the water level of the Tama River, and the gate operation methods of the sluice gate are changed. Finally, the estimated effects of the countermeasures (taken after experiencing typhoon damage) are also described.

2. Inundation Damage Caused by Typhoon Hagibis

2.1. Overview of Damage in the Area Around the Sluice Pipe

The Typhoon, which landed in Japan on October 12, 2019, passed through the Kanto and Tohoku regions, recording the largest volume of rainfall on record over a wide area (which includes the Koshin region). In the Tama River, the water level at the Denenchofu (Kami) water level observatory reached A.P. +10.81 m, which exceeds its highest water level (A.P. +9.07 m) and the designed high-water level (A.P. +10.35 m).

Under the influence of the water level of the Tama River, which we had never experienced before, inundation occurred in the areas around the five sluice pipes in Kawasaki City (Sanno, Miyauchi, Suwa, Futago, and Unane); this led to the inundation of an estimated 110 ha area, along with approximately 2,500 houses (**Fig. 3**).

Of the five areas, the Sanno area is a combined sewer system, and rainwater is drained naturally or by pump (according to the amount of rainfall). In addition, the other four areas are separated sewer systems, with rainwater being drained naturally.

In the Sanno and Suwa areas, inundation damage occurred when the water level at the Denenchofu (Kami) water level observatory exceeded the flood danger water level (A.P. +8.40 m) in the past. However, the event of a backflow of river water (as happened in this instance) has not been confirmed. There are no records of previous inundation damage in the other three areas.

2.2. The Damage in the Sanno Area and the Situation Concerning Sewerage Facilities

The result of the damage survey in the Sanno area estimated that an area of 60 ha was inundated (**Fig. 4**). At that time, it was also confirmed that the manholes in the vicinity overflowed as the water level of the Tama River rose.

The Sanno area is divided into the Maruko No.1 and the Maruko No.2 drainage districts, with sewerage facilities having been developed (**Fig. 5**). The Maruko No.1 drainage district is a combined sewer system covering an area of 177 ha; sewage generated in the Maruko No.1 drainage district is sent to the wastewater treatment plant via the Maruko No.2 drainage district and the downstream Maruko pumping station. Rainfall in the Maruko No.1

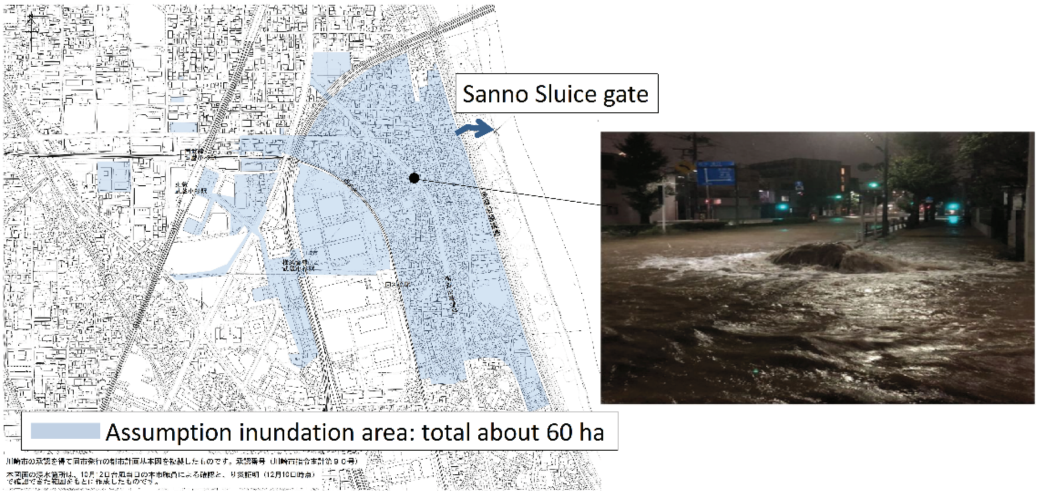


Fig. 4. Inundation at the Sanno area.

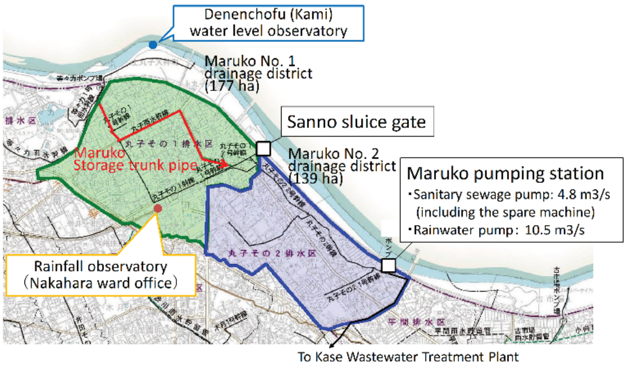


Fig. 5. Sewage facilities at Sanno area.

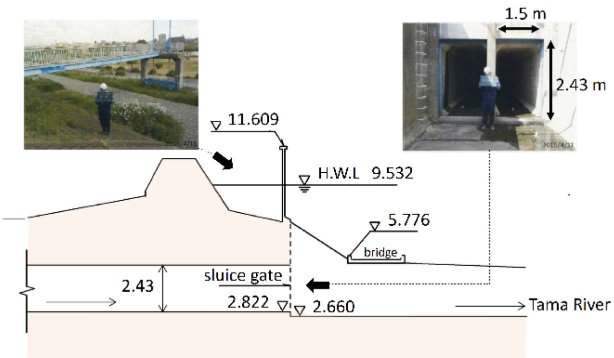


Fig. 6. Overview of the Sanno sluice gate.

drainage district will be sent to the wastewater treatment plant, together with the sewage, if the amount of rainfall is relatively small. When the amount of rainfall exceeds the treatment capacity of the wastewater treatment plant, a part of the sewage mixed with rainwater is discharged into the Tama River through the Sanno sluice pipe (**Fig. 6**). In addition, rainwater is stored in the Maruko storage trunk pipe (2.4 m inner diameter, 1,800 m extension, 8,200 m^3 storage capacity) in the drainage district. As a result, the Maruko No.1 drainage district can handle an hourly rainfall of 58 mm (10-year return period rainfall), and on-floor inundation does not occur for an hourly rainfall of 92 mm (maximum rainfall in the past) as per the designed level.

The Maruko No.2 drainage district is a combined sewer system covering an area of 139 ha, and both sewage and rainwater are sent to the Maruko pumping station. In addition, the Maruko No.2 drainage district is designed to handle an hourly rainfall of 52 mm.

The Maruko pumping station has the role of sending the sewage from the Maruko Nos.1 and 2 drainage districts to the Kase Wastewater Treatment Plant, draining the rainwater from the Maruko No.2 drainage district to the Tama River. The capacity of the sewage pump is 4.8 m^3/s, including when the spare machine is employed, whereas the capacity of the rainwater pump is 10.5 m^3/s.

3. Reproduction of Inundation Damage by Inundation Simulation

3.1. Inundation Simulation Conditions

In order to investigate the cause of the inundation caused by Typhoon Hagibis, an inundation simulation was carried out using InfoWorks ICM (which is a runoff analysis model) using the methodology shown in **Table 1**. The model conditions for the Sanno area are shown in **Table 2**. The sewer pipe (approximately 86 km) in the drainage district, the Sanno sluice pipe, and the Maruko pumping station (shown in **Fig. 5**) were all modeled.

3.2. Reproduction of Results and Considerations

In order to reproduce the inundation scenario, the actual measurement data of the nearby rainfall observatory (Nakahara Ward Office) was used to model the rainfall in this model. In addition, since there is no water level gauge at the Sanno sluice pipe point, and given that the

Table 1. Overview of the simulation.

Run off analysis model	Software	InfoWorksICM ver9.5
	Rainfall loss model	Runoff coefficient model
	Surface runoff model	Double linear storage method
	Sewer hydraulic model	Full Saint Venant equation (Dynamic Wave method)
	Flood analysis model	Two-dimensional unsteady flow model
Mesh data		5 m mesh data (Geographical Survey Institute)
Ground surface model		10 m mesh

Table 2. Conditions and parameters in the simulation.

Analysis area	315.9 ha
Runoff coefficient	0.68 in Maruko No.1 drainage district 0.66 in Maruko No.2 drainage district (0.20 on railway)
Modeled sewer network links	Maruko No.1 drainage district: Pipe diameter ϕ150–2,400 mm $\times$ 2,400 mm, extension 53,030 m Maruko No.2 drainage district: Pipe diameter ϕ150–5,000 mm $\times$ 4,500 mm, extension 32,974 m
Number of nodes/ number of sewer network links	2,220/2,396
Maruko pumping station setting	Sewage pump 4.8 m^3/s (include the spare machine) Rainwater pump10.5 m^3/s
Precipitation conditions	Total rainfall 219 mm (October 12 0:00–24:00) Maximum hourly rainfall 22 mm (October 12 7:30–8:30)

actual water level is unknown, the assumed water level data were created. The highest water level is assumed to be the peak water level (A.P. +9.70 m, 22:30 on the 12th), as visually confirmed by the Sanno sluice pipe and the water level hydrograph created based on observed data from the nearby Denenchofu (Kami) water level observatory. The rainfall and river water level used in the simulation conditions are shown in **Fig. 7**.

In addition, due to the rise in water level in the Tama River, the gate of the Sanno sluice pipe started to close at 22:52 on the 12th of October, whereas the sluice gate was closed at 10:50 the next day. In the simulation, the operation of the Sanno sluice gate was set to the same parameters.

The water level conditions of the well where the rainwater pumps of the Maruko pumping station operate were set to the same parameters as the actual ones.

Under these conditions, the reproduced maximum inundation depth map of the Sanno area is shown in **Fig. 8**. Furthermore, the water level's fluctuation within the Maruko storage trunk pipe is shown in **Fig. 9**. It can be confirmed that the measured water level at each point in **Fig. 8** and the results of the simulated water level are almost the same. Furthermore, the water level fluctuation of the Maruko storage trunk pipe in **Fig. 9** is almost the same as both the measured water level and the simulated water level, confirming that a highly accurate model was built. The mean absolute error (Eq. (1)) of the time-varying values from 1:00 to 17:00 on the Maruko storage trunk pipe (as shown in **Fig. 9**) was 0.669, and the mean relative error (Eq. (2)) of the time-varying values was 1.522.

$$E_w = \frac{1}{n}\sum_{i=1}^{n}|O(i) - C(i)|, \qquad (1)$$

$$E_w = \frac{1}{n}\sum_{i=1}^{n}\frac{|O(i) - C(i)|}{O(i)}. \qquad (2)$$

E_w: Error, $O(i)$: Measured value at time i,
$C(i)$: Calculated value at time i.

According to this reproduced result, the peak amount of flooding at the ground surface level of the Sanno area was estimated to be 173,000 m^3, while the area that was flooded by 50 cm or more was estimated to be 151,000 m^2.

3.3. Model Evaluation Regarding Inundation Damage Under Different Conditions

Since the reproducibility of the simulation model has been confirmed, this model will be used to determine trial calculations of inundation damage under different conditions (using actual conditions as reference point). In analyzing this event, the following three issues can be considered.

The first issue is how different the inundation damage would have been if the river's water level had risen to its previously recorded highest water level (A.P. +9.07 m at Denenchofu (Kami) water level observatory). For this typhoon, the water level of the Tama River recorded its highest water level, and the river water flowed back inland through the sluice pipe as a result. Although the Tama River has reached a relatively high-water level in the past, no backflow of river water like this has been confirmed. Therefore, a water level scenario was created in which the Tama River's water level has risen to the previously recorded highest level as "assumed water level." In the scenario, the actual water level is used until 15:00 on the 12th; thereafter, the water level will reach the previously recorded highest water level by 19:00 on the 12th. In the "assumed water level," the water level at the Sanno sluice pipe point was estimated when the Denenchofu (Kami) water level observatory set A.P. +9.07 m.

The second issue concerns how different the inundation damage would have been if the heavy rainfall (as predicted by the weather service) had occurred. The weather forecast for the day predicted that Kawasaki City would experience 300 mm total rainfall between 6:00 on the 12th to 6:00 on the 13th and that the maximum hourly rainfall

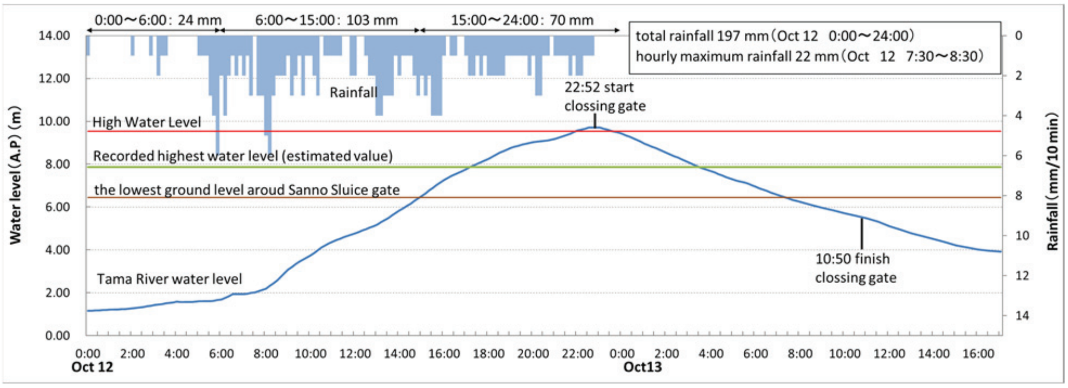


Fig. 7. Rainfall and Tama River water level at the Sanno sluice gate.

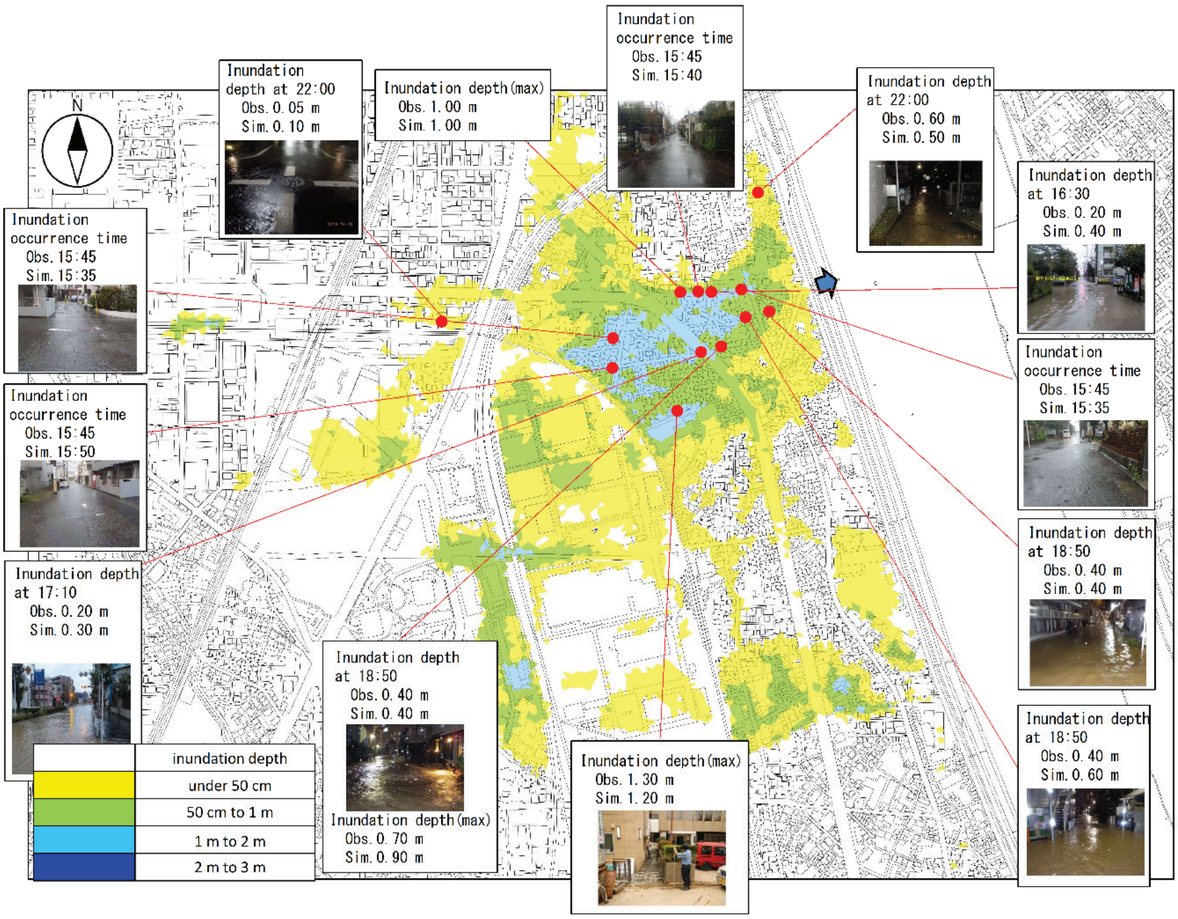


Fig. 8. Inundation depth (max) map by the simulation.

would be 50 mm; however, the actual rainfall was less than these amounts. Therefore a “hypothetical rainfall” scenario was created in which the actual rainfall occurs until 15:00 on the 12th (the actual amount was 103 mm), after which the total rainfall reaches 197 mm (the actual amount was 70 mm) while hourly rainfall between 18:30 to 19:30 proceeded at a rate of 50 mm (by stretching the actual precipitation waveform).

The third issue is how the inundation damage would have differed if the sluice gates were closed earlier. In the operation procedures for the Sanno sluice gate, when the water level of the Denenchofu (Kami) water level observatory reaches A.P. +7.6 m, and if there is no rainfall or risk of rainfall, the sluice gate will be closed; if it rains, or it is likely to rain inland, the top priority becomes the removal of inland water, requiring a decision to be made as to whether or not keep the sluice gate open. In addition, the opening and closing of the sluice gate will be judged comprehensively based on the situation of the Maruko pumping station.

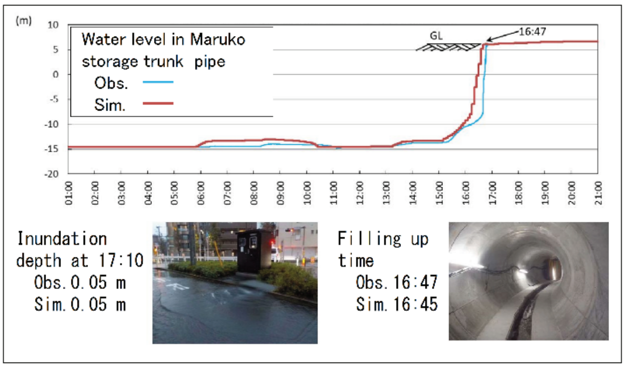


Fig. 9. Water level in Maruko storage trunk pipe.

At that time, the water level at the Denenchofu (Kami) water level observatory reached A.P. +7.6 m at 15:00 on the 12th; however, no water level gauge was installed in the sewerage system. Because of this, it was difficult to grasp the volume of the backflow of river water. Furthermore, there was a risk that a typhoon would land in Japan after 15:00 and that heavy rainfall would occur, so the sluice gate was kept open. After that, the water level in the Maruko pumping station rose, posing the risk of the station becoming submerged. Subsequently, the sluice gate started to close at 22:52. Therefore, the change in inundation damage will be checked by immediately closing the gate at 15:00 on the 12th.

In order to verify these issues, simulations were carried out across the following three scenarios (**Table 3**). In all scenarios, the water level conditions of the well where the pumps at the Maruko pumping station operate were set to the same as that of the actual settings.

Scenario 1: The river's water level is at the "assumed water level (rising to the highest recorded water level)," while rainfall is that of the "assumed expected rainfall (precipitation according to the weather forecast)." The gate operation remains the same as that of the real-life scenario.

Scenario 2: The sluice gate was closed at 15:00 on the 12th. The river's water level is set at the same level as was actually experienced until 15:00. The river's water level is not affected after 15:00, as the sluice gate is closed. Rainfall is that of the "assumed rainfall" parameter (as used in Scenario 1 as well).

Scenario 3: The sluice gate was closed at 15:00 on the 12th. The river's water level is that of the actual water level until 15:00. Since the sluice gate is closed after 15:00, the river's water level will not be affected. The rainfall pattern is that of the actual rainfall which was experienced.

The maximum inundation depth map of each simulation scenario is shown in **Fig. 10**.

Firstly, by comparing Scenario 1 to 2, it was found that, if heavy rainfall was experienced (as the weather forecast predicted), and if the river's water level was at the highest recorded level, then the inundation scale would be almost the same, regardless of the sluice gate's operation status.

Furthermore, by comparing the actual situation of the day with that of Scenario 3, it is seen that the inundation scale grows smaller due to the closing of the sluice gate at 15:00. The Maruko pumping station does not assume that the rainfall in the Maruko No.1 drainage district will be drained, but it was found that if the volume of rain approximately matched this level, the inflow of river water would be prevented by closing the gate of the Sanno sluice pipe. Subsequently, the rain in the Maruko No.1 drainage district will be drained at the Maruko pumping station, contributing to the reduction in inundation.

4. Evaluation of Countermeasure Effect

One of the problems with analyzing this typhoon is that there were no instruments that could measure the inland and river water levels; as such, it impossible to grasp the reality concerning the river's potential backflow. Therefore, as a countermeasure after the typhoon, an internal water level gauge, an external water level gauge, and a flow direction gauge were installed in the sluice pipe so that the status of its water flow could be ascertained. This made it possible to close the sluice gate when backflow in the sluice pipe was confirmed. In addition, a drainage pump truck (drainage capacity: 30 m^3/min, total head 10 m) was introduced as a means of draining the rainfall that fell inland when the sluice gate was closed. In order to confirm the effect of these measures, simulations were carried out under the conditions of Scenario 4.

Scenario 4: The sluice gate is closed when backflow in the sluice pipe is detected. The river's water level is the actual water level until the sluice gate is closed (the water level is not affected after the sluice gate's closure). Precipitation is the actual rainfall experienced. After the sluice gate is closed, 30 m^3/min is drained from the drainage district to the Tamagawa River via a drainage pump truck. The conditions for the water level in the well where the pumps at the Maruko Pump Station operate are the same as their actual settings.

Table 4 shows the situation on the day, the conditions of Scenario 4, and the maximum inundation depth maps.

The area flooded by 50 cm or more was estimated to be 151,000 m^2 in the situation on the day, while Scenario 4 resulted in 0 m^2 of flooding more than 50 cm deep. Thus, it became clear that the inundation damage can be significantly reduced.

5. Conclusions

Throughout this survey, the inland flood simulation model was constructed to mimic the drainage area of Kawasaki City, which operates a pumping station along the Tama River and a sluice gate for rainwater management. Following the models' completion, the flooding caused by Typhoon Hagibis was reproduced. This model was, therefore, used to evaluate inundation conditions across different scenarios. As a result of the model's abil-

Table 3. Conditions for each scenario.

Conditions	Actual situations	Scenario 1	Scenario 2	Scenario 3
Tama River water level	Actual water level	Assumed water level	Actual water level before gate closed (No influence of water level after gate closed)	
Rainfall	Actual rainfall	Assumed rainfall		Actual rainfall
Gate operation	Actual operation (12th 22:52 start closing, 13th 10:50 finish closing)		Assumed operation (12th 15:00 start and finish closing)	

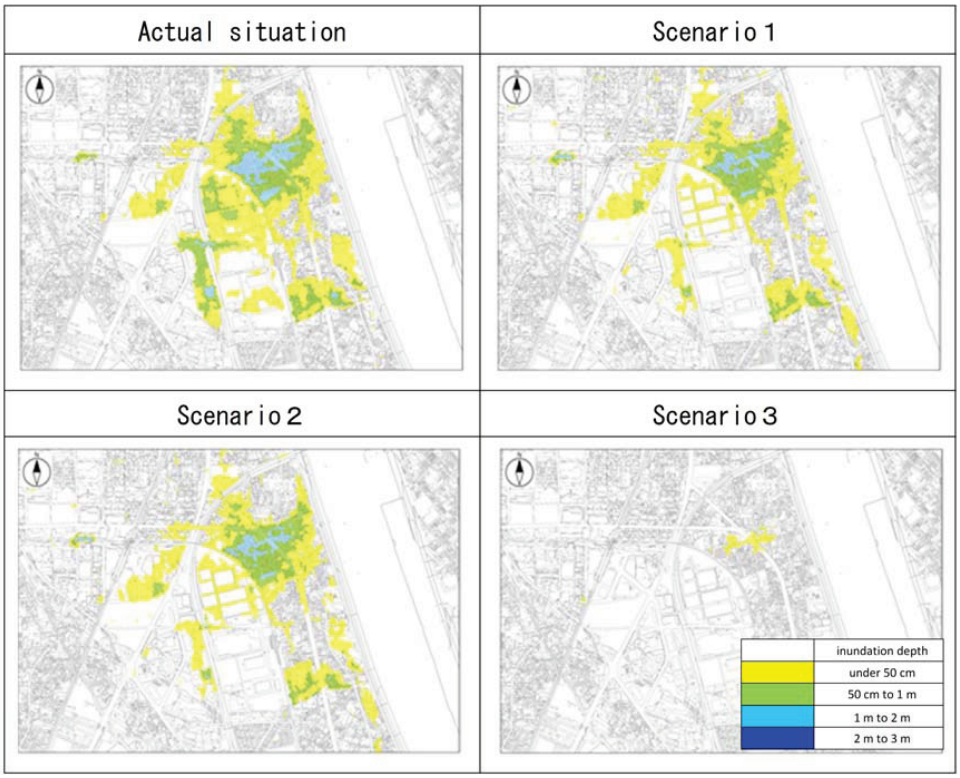
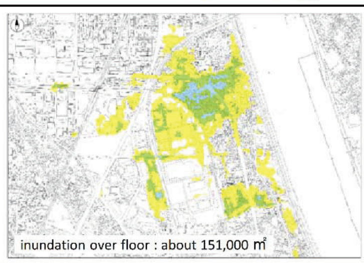
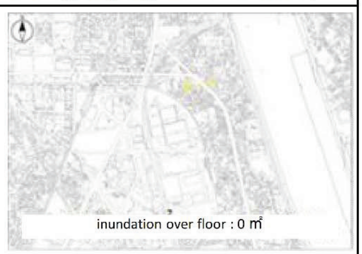


Fig. 10. Inundation depth (max) map for each scenario of the simulation.

Table 4. Comparison of the situation of the day and Scenario 4.

Conditions	Actual situation	Scenario 4
Tama River water level	Actual water level	Actual water level before gate closed (No influence of water level after gate closed)
Rainfall	Actual rainfall	
Gate operation	Actual operation (12^{th} 22 : 52 start closing 13^{th} 10 : 50 finish closing)	Assumed operation (start and finish closing when grasping the backwater)
Inundation depth (max) map		

ity to reproduce conditions and analyze scenarios, the following conclusions were reached.

By comparing the scenarios in which the sluice gate's operation was changed, no decrease in the inundation area was observed, even if the sluice gate was closed at 15:00 on October 12th and when 300 mm of rainfall was expected (greatly exceeding the actual rainfall of 173 mm experienced between 6:00 on the 12th to 6:00 on the 13th).

However, in a simulation using the actual rainfall that was experienced on the day, the flooded area decreased due to the early closing of the sluice gate and the drainage effect from the downstream pumping station.

It is important to understand the backflow dynamics at the sluice gate and make decisions regarding the gate's operation. In the case of Typhoon Hagibis, inundation damage may have been reduced if the sluice gate was closed when the backflow began. Therefore, we planned to install water level gauges and flow direction gauges at all sluice gates along the Tama River. Then, a sluice gate operation manual was created that utilizes the information learned from the observation instruments.

Finally, research is currently underway to predict damage in real time from past flood damage [4]. By applying these technologies and improving the accuracy of precipitation forecast, there is a possibility that the sluice gate can be operated more effectively.

References:

[1] K. Mitsui, K. Kodera, and T. Inoue, "Change of Land Use in Tama River Bed in Kanto District, Japan," J. Japan. Soc. Hydrol. and Water Resour., Vol.7, No.3, pp. 204-213, 1994.

[2] S. Hoshino, M. Esteban, T. Mikami, H. Takagi, and T. Shibayama, "Estimation of increase in storm surge damage due to climate change and sea level rise in the Greater Tokyo area," Nat. Hazards, Vol.80, No.1, pp. 539-565, 2016.

[3] T. Shimozono, Y. Tajima, K. Kumagai, T. Arikawa, Y. Oda, Y. Shigihara, N. Mori, and T. Suzuki, "Coastal impacts of super typhoon Hagibis on Greater Tokyo and Shizuoka areas, Japan," Coastal Engineering J., Vol.62, No.2, pp. 129-145, 2020.

[4] L. Moya, E. Mas, and S. Koshimura, "Learning from the 2018 Western Japan Heavy Rains to Detect Floods during the 2019 Hagibis Typhoon," Remote Sens., Vol.12, No.14, p. 2244, 2020.

Name:
Hiromichi Muroi

Affiliation:
Manager, Sewage Waterworks Planning Section, Sewerage Administration Department, Waterworks Bureau, City of Kawasaki

Address:
1 Miyamoto-cho, Kawasaki-ku, Kawasaki, Kanagawa 210-8577, Japan

Brief Career:
1992- City of Kawasaki

Name:
Kensuke Mine

Affiliation:
Associate Manager, Sewage Waterworks Planning Section, Sewerage Administration Department, Waterworks Bureau, City of Kawasaki

Address:
1 Miyamoto-cho, Kawasaki-ku, Kawasaki, Kanagawa 210-8577, Japan

Brief Career:
2012- Ministry of Land, Infrastructure, Transport and Tourism
2018- City of Kawasaki

Name:
Yoshiki Eguchi

Affiliation:
Assistant Manager, Sewage Waterworks Planning Section, Sewerage Administration Department, Waterworks Bureau, City of Kawasaki

Address:
1 Miyamoto-cho, Kawasaki-ku, Kawasaki, Kanagawa 210-8577, Japan

Brief Career:
2001- City of Kawasaki