AN INVESTIGATION OF FLOOD DISASTER OF THE AKIYAMA RIVER CAUSED BY REIWA FIRST YEAR EAST JAPAN TYPHOON

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Flooded areas along the Akiyama River were investigated after Typhoon Hagibis in 2019. The areas that experienced severe flood damage and the two levee failures that occurred were all areas where the river became narrower, and both levee failures occurred upstream of the foot of a bridge. The particularly severe damage to the levee on the right bank of the Kairiku Bridge in Akasaka-cho might have been the result of multiple compounding factors, including its location on the outer bank of a curve and risks, such as the angle at which the girders were built relative to the downstream current. The times when the levee failures occurred were determined through interviews with residents of the damaged areas, and a numerical analysis that took each of the relevant conditions into account indicated that the severe damage to downtown Sano City might have been caused not only by the flooding that resulted from the overflow from the Akiyama River and failures of the levees, but also by multiple compounding factors including the effects of the flooding from nearby rivers, such as the Kikusawa River.

Key Words: Akiyama river, flooding, field observation, numerical analysis

1. OVERVIEW OF THE DAMAGE FROM THE AKIYAMA RIVER

Typhoon Hagibis caused severe flooding across a large area of eastern Japan from the 11th to the 13th of October 2019. Two levee failures occurred in a prefecturally managed area of the Akiyama River, a branch of the Watarase River with a total area of 87.9km², a length of 39.8km and an average bed slope of 1/400, causing severe flooding in Sano City (Tochigi Prefecture) and areas downstream.

Fig. 1 shows the location of the Akiyama River and its levee failures; **Fig. 2** shows a close-up map of the location of the Akiyama River and its levee failures relative to the Watarase River; and **Fig. 3** shows an

oblique aerial photo of the area during the flooding.

The Akiyama River flows roughly north to south (top to bottom of the figures), passing through Sano City and merging with the left side of the Watarase River. The levee failure that is further upstream (upper levee failure in the figures) is referred to as the Ohashi levee failure and the one that is further downstream is referred to as the Akasaka levee failure. Both levee failures occurred upstream of the feet of bridges on the Akiyama River.

The Ohashi levee failure occurred upstream of the Ohashi bridge, while the Akasaka levee failure occurred upstream of the Kairiku Bridge. Both occurred on the right bank. A total of 1,411 buildings were damaged by flooding above floor level,

Fig.1 Location of the Akiyama River and its levee failures.

Fig.3 Oblique aerial photo of the flooding from the Akiyama River (photo provided by the Watarase River Office).

Fig.2 Close-up map showing the location of the Akiyama River and its levee failures relative to the Watarase River.

636 were damaged by flooding below floor level, 5 were completely destroyed, and 641 were partially destroyed. Some 899 ha of land used as rice fields and other purposes, were destroyed (Source: Report by the Ministry of Land, Infrastructure, Transport and Tourism¹⁾).

We will now provide an overview of the rainfall in the area that caused the water damage in the area around the Akiyama River. **Fig. 4** shows hourly rainfall at the Kuzuu, Sano, Ashikaga and Tochigi AMeDAS stations, while **Fig. 5** shows the cumulative rainfall. The location of all four AMeDAS stations can be seen in **Fig. 1**. At all of the stations, rainfall increased from 8:00 am on October 12, and rainfall of around 30 mm/h occurred continuously from 3:00 pm to 10:00 pm. Particularly heavy rainfall occurred

Fig.4 Hourly rainfall at Kuzuu, Sano, Ashikaga and Tochigi AMeDAS stations.

Fig.5 Total rainfall at Kuzuu, Sano, Ashikaga and Tochigi AMeDAS stations.

at Kuzuu, in the upper reaches of the Akiyama River, with hourly rainfall of 47.5 mm/h observed at 7:00 pm and rainfall of 40 mm/h or more for four hours. This caused the Osodo River, a branch of the Akiyama River (see **Fig. 1**), to overflow, resulting in 27 buildings damaged by flooding above floor level, 70 dam-

Fig.6 Hourly river depth (Kuzuu-Ohashi, Ohashi, Ogoyabashi, Ibouchi-Shimbashi).

aged by flooding below floor level, 1 completely destroyed, and 26 partially destroyed (source: Report by the Ministry of Land, Infrastructure, Transport and Tourism¹⁾).

Fig. 5 shows the cumulative rainfall until 11:00 pm, when rainfall abated. The totals are 416.5 mm for Kuzuu, 305.0 mm for Tochigi, 266.5 mm for Sano and 256.9 mm for Ashikaga. Kuzuu, Sano, and Ashikaga's 24-hour rainfall figures of 410 mm, 261.5 mm, and 253 mm, respectively, are the highest on record.

Next, we will explain how the river depth changed over time as a result of the flooding. **Fig. 6** shows the hourly water depths measured at each water-level measurement station along the Akiyama River. The stations, in order from upstream to downstream, are Kuzuu-Ohashi, Ohashi, Ogoyabashi, and Ibouchi-Shimbashi. Ohashi is located in the area of the upper levee failure, Ogoyabashi is located in the lower reaches of the prefecturally managed area on the area boundary, and Ibouchi-Shimbashi is located further downstream in the next area of the city. The locations of the latter three stations can be seen in **Fig. 2**, while the Kuzuu-Ohashi station can be seen in **Fig. 1**. Data on the depth at Ohashi are intermittent from 7:00 pm on October 12. The intermittent data is thought to be because the water level reached the maximum intended height of the water-level indicator and damaged the indicator, thus making it difficult to estimate the times at which water overflowed in the area where the levee failed.

If we focus on the increase in depth at Ogoyabashi and Ibouchi-Shimbashi, located downstream from the Akasaka levee failure, we can see that the depth increased more slowly at Ogoyabashi between 8:00 pm and 9:00 pm and at Ibouchi-Shimbashi between 7:00 pm and 8:00 pm (**Fig. 6**). From this and the time of the Akasaka levee failure, which we will cover later in this paper, we can presume that the volume of water increased more slowly at this time due to multiple

Fig.7 Oblique aerial photo of the Ohashi levee failure (photo provided by the Watarase River Office).

levee failures along the Akiyama River, including the Akasaka levee failure.

If we now focus on the maximum depth, the investigation of damage after the flood revealed that the depth at Ogoyabashi and Ibouchi-Shimbashi was highest between 1:00 am and 2:00 am on October 13. At Ibouchi-Shimbashi, the depth reached 8.87 m, exceeding the level at which a flood risk occurs (7.90 m), at 1:50 am and falling only 13 cm short of the estimated high-water level of 9.00 m.

We will now explain how the levee failures are thought to have occurred. **Fig. 7** shows an oblique aerial photo of the Ohashi levee failure. Around 20 m of the levee on the right bank upstream of the foot of the bridge was washed away. Large volumes of debris, such as driftwood, gathered at both ends of the bridge, and the afflux created by the bridge caused water to overflow from both ends, breaking the levee on the right bank. Many similar cases of levee failure caused by overflow created by a bridge have been reported in the past.²⁾ This is thought to be because narrow areas of rivers tend to be chosen when building bridges as they enable more efficient construction. The accumulation of driftwood around the pier and girders of a bridge then makes that stretch of the river even narrower and the afflux that results causes river water to come into contact with the foot of the bridge, eroding areas, such as road and eventually causing the levee to fail. It is this process that is thought to have led to the Ohashi levee failure.

Nakabashi Bridge, around 1.2 km downstream from the Ohashi Bridge, has collapsed. **Fig. 8** shows the damage. The center of Nakabashi Bridge was washed away and driftwood were found to have accumulated around the pier of the bridge.

Fig. 9 and **Fig. 10** show oblique aerial photos of the area around the Akasaka levee failure. Around 50 m of the levee on the right bank upstream of the foot of

Fig.8 The damage to Nakabashi Bridge (photographed from upstream on the right bank).

Fig.9 Oblique aerial photo of the area around the Akasaka levee failure (provided by Shimotsuke Shimbun, 2019/10/13).

Fig.10 Oblique aerial photo of the Akasaka levee failure (photo provided by the Watarase River Office).

the Kairiku Bridge was washed away. Like the Ohashi levee failure, the afflux caused by the bridge girders is thought to have caused water to overflow.

Fig.11 Levee failure and flood damage relative to the width of the Akiyama River (2.1 km–6.1 km).

Fig. 11 shows the width of the Akiyama river in the stretch of around 4 km where the two levee failures occurred. Around 1 km from a comparatively wide area measuring 6.0 km across, the river sharply narrows by around 60 m. The Ohashi levee failure occurred at the narrowest point in this stretch of river, which measures 5.2 km. Further downstream, the river briefly widens and then sharply narrows once again to around 3.7 km at the point where the Akasaka levee failure occurred. It narrows by a further 60 m at a point 200 m downstream. This indicates that a factor in the two levee failures was the point where the Akiyama River narrows in some areas, making it more difficult for water to pass through.

The arrows at the bottom of **Fig. 11** indicate areas where significant flood damage was found on the levee crown on both banks during the investigation. The horizontal axis is scaled to the stretch of the river that was investigated, with the length of the arrows indicating the size of the area where flood damage was found. Where overflow from the left and right bank was roughly the same in the area where the river sharply narrows from 6 km to 5 km, significant flood damage was found only by the right bank, upstream of the Akasaka levee failure.

Fig. 12 is a close-up overhead aerial photo of the area around the Akasaka levee failure. Above, the Akasaka levee failure occurred on the right bank upstream of the foot of the Kairiku Bridge. Severe flood damage was found in the area where the Akasaka levee failure occurred, indicated by the arrows in **Fig. 11**, the exact area where the river narrows and the right bank is almost in the center. **Fig. 13** shows the flood damage to the levee crown on the right bank where the Akasaka levee failure occurred, while **Fig. 14** shows the upper reaches of the same flood damage, photographed from the same direction a short way upstream from where the photo in **Fig. 13** was taken. **Fig. 13** and **Fig. 14** were taken from the point indicated by P in **Fig. 12**. The arrow shows the direction

Fig.12 Overhead aerial photo of the area around the Akasaka levee failure.

Fig.13 Flood damage on the levee crown of the right bank upstream of the Akasaka levee failure.

Fig.14 Perimeter of the flood damage on the levee crown of the right bank upstream of the Akasaka levee failure.

the photographer was facing.

The white arrow in **Fig. 14** shows the distribution of flood damage across the levee crown and the direction

Fig.15 Areas of flood damage investigation and interview-based survey.

of the flood waters. The flood damage extended diagonally across the levee crown, matching the direction of the waters from the Akiyama River upstream of the Akasaka levee failure.

The direction of the waters on the left bank, meanwhile, was not significantly different from the longitudinal direction of the levee from upstream. This indicates that there is a high flood risk in this area of the river due to the way the river becomes narrower and the way the right bank is on the outside of a curve. Additionally, the angle of the girders of Kairiku Bridge relative to the downstream current means that afflux from the girders is concentrated on the upstream side of the right end of the bridge. From these details, we can deduce that the Akasaka levee failure was caused by three concurrent risk factors: the narrowing of the river, the location on the outer side of a curve, and the angle of the bridge girders relative to the downstream current. However, it has not yet been possible to investigate the details of these risk factors. This will be addressed later.

2. FLOOD DAMAGE INVESTIGATION AND INTERVIEWS IN THE AFFECTED AREAS

On October 17, 2019, flood damage in the affected areas around the Akiyama River was investigated, and residents in these areas were interviewed. The investigation and interview-based surveys took place in three main areas, indicated as A-C in **Fig. 15**. Area

Table 1 Flood announcements for the Akiyama River (as a designated river) and reports from interviews.

	Area	Announcement/report from interview
10/12		
6:50 pm	Meteorological Office	Dangerous levels of flood waters
7:00 pm	B(m)	"Waist-deep flooding from irrigation canal. Extremely strong current flowing south."
	C(n)	"The Akiyama River reached the top of the levee."
7:05 pm	Meteorological Office	Prefectural Road 67 closed on Ohashi Bridge over Akiyama River
7:30 pm	Meteorological Office	Evacuation order for Sano, Ueno and Horigome areas
8:00 pm	A(c)	"The tatami in my home were floating. There was water about 30 cm deep on the floor."
	B(j)	"There was water about waist deep. The current wasn't too strong to walk in. The waters receded immediately."
	B(k)	"There was water flowing from the Akiyama River and from the east at the same time."
	B(k)	"There was a whirlpool on the road in front of the tackle shop."
	B(l)	"Sewage came up."
	B(l)	"There was knee-deep water. I saw someone's furniture that had been washed away."
8:30 pm	C(n)	"Someone in the neighborhood called me and told me it had broken."
	C(o)	"The Kikusawa River flooded."
9:00 pm	C(n)	"My floor flooded. The waters rose quickly."
	C(n)	"The Akiyama River reached the top of the banks. It stayed that way until about 1:00 am."
	C(n)	"All the roads around my home were like rivers."
10:00 pm	A(c)	"The waters of the Akiyama River rose and flooded Prefectural Road 67."
	B(j)	"There was knee-deep water at Sano City Library."
10:30 pm	C(o)	"There was water flowing from the south and then the north."
10/13		
12:00 am	A(c)	"The current got stronger and there was debris in the water."
12:00–1:00 am	B(l)	"The water was knee-deep from 12:00 to 1:00am."
12:00–1:00 am	C(n)	"The water didn't recede from 12:00 to 1:00am."
2:00 am	A(c)	"It was confirmed that the Ohashi levee had failed."
	A(e)	"The waters around Ohashi Bridge

		suddenly changed direction and flowed south instead of north."
2:30 am	B(l)	"Nakabashi Bridge collapsed. Cars were washed away by the river."
	B(l)	"The current was so strong that it swept away the stone wall of my home."
	C(n)	"The waters stopped rising."
	C(o)	"The waters rose to the bottom of the bridge on Prefectural Road 270."

Table 2 Water depths determined from flood damage investigation.

Location in Fig. 15	Depth (based on flood damage)
A	
a	80 cm
b	150 cm
c	120 cm
d	50 cm
e	130 cm
f	140 cm
g	70 cm
h	50 cm
B	
i	100 cm
C	
n	100 cm
o	50 cm
p	40 cm
q	40 cm
r	50 cm
s	80 cm

A was around the point where the Ohashi levee failure occurred, Area B was an area of the city center on the left bank of the Akiyama River where no damage from levee failures occurred, and Area C was around the point where the Akasaka levee failure occurred. The nomenclature of Areas A-C is also used in **Table 1**, which shows information gained from the interviews. Information for which the time was confirmed is arranged in chronological order in **Table 1**. "Meteorological Office" in the "Area" column indicates orders issued by the Utsunomiya Local Meteorological Office. Flood damage and water depths for which the time cannot be confirmed are indicated in **Table 2**. The specific points of the investigation, a-s, are shown in **Fig. 15**.

From **Table 1**, we can see that there were waist-deep flood waters at point m in Area B, the area by the left bank of the Akiyama River where there was no damage caused by the levee failures, from 7:00 pm on October 12, and that these were dangerous conditions where residents were aware of an extremely strong current.

Our interviews revealed that the waist-deep water

was caused by flooding of an irrigation canal, so we can presume that major inundation was occurring in the levee even before the failures. Reports from our interviews were primarily in Area B (left bank of the Akiyama River) until about 8:30 pm, but after this point, the reports from Area B were outnumbered by those from Area C, where the Akasaka levee failure occurred. Since the residents became aware of the Akasaka levee failure at 8:30 pm, we can presume that it occurred between 8:00 pm and 8:30 pm. Reports from the area of the Ohashi levee failure become frequent from 12:00 am on October 13. Interviewees in this area mentioned that the water current from Ohashi Bridge suddenly changed direction at around 2:00 am, and that the levee was washed away at this time, so we can presume that this was when the Ohashi levee failure occurred.

We have therefore been able to confirm that of the two levee failures that occurred along the Akiyama River, the Akasaka levee failure occurred first at around 8:30 pm on October 12 and the Ohashi levee failure occurred 5.5 hours later. We have also confirmed that Nakabashi Bridge was broken at around 2:30 am, around 30 minutes after the Ohashi levee failure.

While a damage investigation like this does not provide exact information on the time sequence, the investigation of the depth based on the flood damage revealed that flooding around 1.5 m deep occurred in areas around 500 m upstream from the Ohashi levee failure, and vehicles and furniture were swept tens of meters away. As these damaged areas are further upstream from the Ohashi levee failure, the further upstream of the two, this indicates that we cannot determine the full extent of the damage to the area around the Akiyama River solely from the flooding outside the levees that resulted from the levee failures. Additionally, while the specific time was unclear, multiple interviewees mentioned that the flooding first started from the drainage canal of the Kikusawa River upstream of the Ohashi levee failure.

3. CONCLUSIONS ON THE NATURE OF THE FLOODING FROM THE NUMERICAL ANALYSIS

(1) Conditions of analysis

In addition to qualitative deductions about the nature of the flooding, a numerical analysis was performed based on the information gained from the damage investigations and interviews to determine more details.

There were no basic data such as regular cross-sectional measurements for medium and small rivers managed by prefectures, including the Akiyama

Fig.16 Analyzed area.

River, and there were also no data on flow rate, a parameter that needed to be known for the purpose of this analysis. Therefore, for the purposes of this study, tendencies were reproduced based on limited information on the topography of the river and a flow rate and roughness coefficient were assigned through trial and error, with a focus on the reproducibility of the flood damage determined by the investigation, to narrow down the nature of the flooding to that which resulted from the overflowing and failures of the levee.

A large area was flooded, from the area upstream of the Ohashi levee failure to the area around the point where the Akiyama River merges with the Watarase River, but for the purposes of comparison with the investigation results, we analyzed the area shown in Fig. 16. The area includes the areas around the two levee failures and extends 2,070 m north to south and 1,100 m east to west.

Topographical conditions were indicated using numerical altitudes from base map information³⁾ provided free of charge by the Geospatial Information Authority of Japan. A 5 m grid was created with iRIC^{4),5)} based on DEM data in 0.2-second (approximately 5 m) intervals. For the river itself, where topographical measurements have not been taken, riverbed heights automatically extrapolated by iRIC were compared with the actual deepest riverbed heights at the Ohashi cross-section (location shown in Fig. 16), which is a key cross-section for the conclusion of this study. The comparison results indicated that the actual deepest riverbed height was 1.89 m lower than the riverbed height automatically generated by iRIC. In order to achieve fully accurate re-

Fig.17 Ohashi cross-section.

production of the river's topography, it would have been ideal to measure the cross-section at each 5 m grid division used for the analysis, as the topography of the river differs for each cross-section. However, this would have been too labor-intensive to be realistic, and even if we had obtained this information, the information would have reflected the topography of the river after the flooding, and therefore may not have been an accurate reproduction of the topography during the flood.

Thus, we prioritized accurately reproducing the Ohashi cross-section, as this was a key area, and subtracted 1.89 m, the discrepancy in the simulated and actual deepest riverbed heights in the Ohashi cross-section, from the deepest riverbed heights in the areas where no measurement was taken. We will consider whether the river topography generated through this process deviates significantly from the actual topography based on reproducibility in the results of investigations of the flooded areas, which we will discuss later.

Fig. 17 shows the altitude at the Ohashi cross-section, which was used as the baseline altitude for the analysis grid. The altitude of the reference point, near the levee crown on the right bank at Ohashi Bridge (point 10B06) is 32.039 m (indicated in Fig. 17). This is near the levee crown in the generated cross-section and the levee crown height is roughly the same on both banks, confirming that there is a high degree of reproducibility between the actual site and the simulation.

We considered using two roughness coefficients (0.030 and 0.035) for the river, but ultimately used only 0.030 as the two values showed no significant difference in reproducibility of the flooded area. For the levee, a series of roughness coefficients from 0.030 to 0.060 were considered. The highest value, 0.060, was selected as there was minimal difference between the analysis results and the actual depth measured in the investigation (we will provide more de-

Table 3 Specifications of analysis.

Analysis solver	Nays2DFlood version 5.0
DEM data	Numerical altitudes at 0.2-second intervals from the Geospatial Information Authority of Japan
Analyzed area	2,070 m × 1,100 m
Analysis grid	5 m (dx = dy)
Number of divisions in grid	414 × 220 (total 91,080 squares)
Analysis time intervals	0.01 sec
Total analysis time	120 min
Flow rate of influx	430 m ³ /sec (constant influx from upstream end)
Roughness coefficient (river)	0.030
Roughness coefficient (levee area)	0.060

tails on this later). The effect of the simulation in residential areas was not considered.

Similar trial and error method was used to confirm the reproducibility of the flow rate of the flooding, with a constant influx simulated from the upper reaches of the Akiyama River in the analysis area. Table 3 shows the specifications of the analysis.

(2) Analysis results and observations

Fig. 18 (1) to (6) show the inundation height distribution in 15-minute intervals from the start of measurements until 75 minutes later. The orange areas of each figure show the deepest inundation based on damage found in the investigation, which is presumed to have been caused by the flooding. The black lines along the levees indicate the severely damaged areas mentioned earlier. The inundation height is indicated with a color scale from blue (lowest) to red (highest). As the color bar shows, the heights are divided into eight divisions 10 cm or larger from 0.0100 m to 2.00 m. While the analysis results showed that flooding around 4 m deep occurred in some areas, this only occurred in a few areas, such as in the river itself and at some underpasses, so the analysis focused on the depths in areas that were important for this study.

Fig. 18 (2) shows the color contours of inundation heights 15 minutes after the influx from upstream began. By then, the higher waters had reached the downstream end and flooding had occurred from multiple areas of the river. While the flooding in the center of the analyzed area did not appear to be consistent with the severe flood damage that was found, there was a good match between the simulation and the distribution of flood damage found in the investigation in the areas around the Ohashi and Akasaka levee failures, which were the key areas in this study.

Fig.18 Analysis results. (1)-(3): $t = 0, 15 \text{ min}, 30 \text{ min}$, (4)-(6): $t = 45 \text{ min}, 60 \text{ min}, 75 \text{ min}$.

Fig.19 Change in inundation height over time near Akasaka levee failure.

In **Fig. 18** (3), we can see that the flooded area is growing, mainly on the right bank of the Akiyama River, and the flood waters are flowing downstream along the contours of the levee. A large area by the right bank is now flooded, and the growth of the limited areas of flooding by the left bank is consistent with the damage found in the investigation. The areas deeper than 2 m to the left of the Ohashi levee failure are the result of flooding in the underpass.

In **Fig. 18** (4)–(5), we can see that while the flooding on the right bank is spreading, this occurs at a roughly constant rate.

In the location of the Akasaka levee failure, the Akiyama River has almost reached the top of the banks. Interviewees told us that the levee failure occurred when the flood waters in this area had been around 1 m high for one to two hours. In **Fig. 18** (5), the inundation height is below 1.5 m in the location of the Akasaka levee failure. The conditions of the levee failure can be considered to have been reproduced.

The flooding from the river and the distribution of flood waters along the levee can be considered a reproduction of the early stages of the levee failures, so the behavior of the flood waters in the 50-m stretch of the right bank where the Akasaka levee failure occurred at $T = 60$ min was verified.

In **Fig. 18** (5) and (6), the red X in the area of the Akasaka levee failure indicates the point where the levee failed, and the red dot to the southwest (bottom left) of the levee failure indicates the point where the inundation height changed over time. **Fig. 19** shows the change in inundation height over time at the focal point marked by the red dot in **Fig. 18**. Around 900 seconds after the flood waters reached the area, the inundation height rose sharply to around 90 cm and gradually increased until the Akasaka levee failure occurred, around 3,600 seconds after the flood waters reached the area. The levee failure caused the inundation height to rise sharply to around 1.2 m. The waters remained at this height thereafter. If we return to **Table 2** and check the depth based on the flood damage around the focal point, we can see that a depth of

Fig.20 Change in inundation height over time at greatest inundation height.

Table 4 Comparison of water depths determined from flood damage investigation and depths calculated in the numerical analysis.

Location in Fig. 20		Depth based on flood damage	Depth based on analysis
	A		
a		80 cm	90 cm
b		150 cm	90 cm
c		120 cm	80 cm
d		50 cm	10 cm
e		130 cm	130 cm
f		140 cm	80 cm
g		70 cm	50 cm
h		50 cm	50 cm
	B		
i		100 cm	90 cm
	C		
n		100 cm	140 cm

around 1.0 m was estimated at point n, indicating that the actual depth has been reproduced well.

Fig. 20 shows the maximum inundation height. The points in **Fig. 15** where depth was investigated based on flood damage are included in **Fig. 20**. **Table 4** compares the depths estimated from the flood damage that were presented in **Table 2** and the depths calculated in the numerical analysis (accurate within 10 cm). While the analysis results tend to be somewhat lower than the actual results of the damage investiga-

tion in the area around the Ohashi levee failure, overall, the maximum inundation heights calculated in the analysis are an approximate quantitative match for the results of the damage investigation. With that said, we can see that the actual disaster was not reproduced correctly in some ways.

- 1) The largest flooding area upstream of the Ohashi levee failure was not sufficiently reproduced, particularly in the northwest (top left). Additionally, while the greatest inundation height estimated from the flood damage was at point b upstream of the Ohashi levee failure on the right bank, with a depth of 150 cm, the analysis result at this point deviated significantly, with only 90 cm calculated. The main reason for this discrepancy is thought to be because the influx conditions were limited to the upstream end of the analyzed area. The Kikusawa River connects to the Akiyama River further upstream from the influx boundary of this analysis, and the interview and investigation results indicated that there was highly likely to have been a large influx of flood waters from there.
- 2) The analysis results for the flooded area of the left bank around the Ohashi levee failure were also lower, failing to reproduce some of the results of the damage investigation. This is thought to be because the topography used for the analysis was not necessarily an accurate reproduction of the actual topography.
- 3) The actual damage was more severe than the results of the analysis, and more detailed information on the topography and flow rate of the Akiyama River needs to be obtained. This is a common and urgent issue in the maintenance and management of small and medium rivers throughout Japan due to insufficient budget.

4. CONCLUSION

The following main conclusions were reached through this study.

- 1) Typhoon Hagibis caused two levee failures to occur along the Akiyama River. Interviews with residents in the affected areas revealed that the first, the Akasaka levee failure, occurred at around 8:30 pm on October 12 and the second, the Ohashi levee failure further upstream, occurred at around 2:00 am on October 13.
- 2) Both levee failures occurred on the upstream side of a bridge. Additionally, both occurred in areas where the river narrows sharply. The location of the Akasaka levee failure on the outer side of a curve in the river and the angle at which the girders of the bridge were installed relative to the current may have increased the risk of levee failures

on the right bank. The detailed mechanisms by which the levee failures occurred need to be investigated.

- 3) In the areas of the city center around the levee failures on the Akiyama River, evidence of severe flooding over 1.5 m deep was found not only by the right bank where the levee failures occurred, but also by the left bank and across a wide area further upstream.
- 4) A numerical analysis effectively simulated the flooding around the levee failures, but there were discrepancies between some of the results and the actual damage, indicating a need for improvement. With that said, the analysis effectively reproduced the distribution of the flooding compared to the actual damage investigation. However, there were areas where the severe flooding that occurred were not properly reproduced by the analysis, including some areas where the inundation heights generated by the analysis were lower than those estimated from the damage investigation. The results of the interviews and damage investigation indicated a high likelihood that the flood damage that occurred in the areas of the city center around the levee failures on the Akiyama River were not only the result of the levee failures and flooding from the Akiyama River; there were additional, compounding factors, such as flooding from the nearby Kikusawa River and its drainage canal.

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