The comparison of the damaged houses estimation method caused by heavy rainfall in July, 2020 Kuma river flood and heavy rainfall in August, 2021 in Rokkaku river flood using aerial photographs and inundation simulation

Daichi Nakata. 1*, Yoshiyuki Imamura.2, Keiichi Kajiwara.3 and Hideo Amaguchi.4

[1,3]Student, Civil and Environmental Engineering, Tokyo Metropolitan University,

1-1, Minamiohsawa, Hachioji city, Tokyo, Japan

[2]Proffessor, Civil and Environmental Engineering, Tokyo Metropolitan University,

1-1, Minamiohsawa, Hachioji city, Tokyo, Japan

[4]Assistant Professor, Civil and Environmental Engineering, Tokyo Metropolitan University,

1-1, Minamiohsawa, Hachioji city, Tokyo, Japan

*d-nakata@river.or.jp

Abstract *In Japna, typhoons and torrential rainfalls frequently cause large-scale floods in urban areas. By the August 2019 torrential rainfall, the Rokkaku River in Takeo City, Saga Prefecture, inundated approximately 1,500 houses. Since the river has a very gentle slope, it repeatedly causes pluvial flooding. By the July 2020 torrential rainfall, the Kuma River, which flows through Hitoyoshi City, Kumamoto Prefecture, caused a fluvial flood that inundated approximately 3,000 houses, breaching levees. The river is one of the steepest rivers in Japan. Aerial photographs include the boundary between inundated and non-inundated areas (the edge) have possibility to determine the extent of inundation effectively. In this study, the number of damaged houses and the depth of inundation were estimated in the two inundated rivers using aerial photographs and inundation simulation analysis. The inundation simulations were differently set up as follows: (a) Discharge data from the upstream of the Rokkaku River and precipitation were used. (b) Discharge data from the upstream of the Kuma River, and the breaking levee point was set. The results showed that the difference between the numbers of observed and estimated damaged houses was about 10%. It was difficult to estimate the number of inundate houses under floor level in the Rokkaku River, while the Kuma River caused more inundation above floor level and destructed houses. The results indicate the developed method can be used for rapid damage assessment in different types of rivers and floods.*

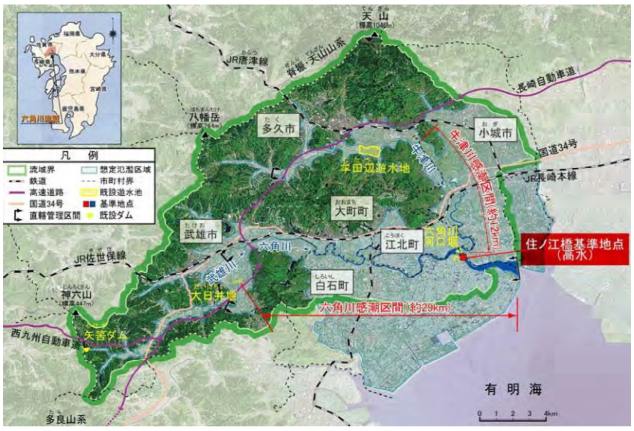
Keywords: Aerial Photograph, August 2019 Rokkaku river flood, July 2020 Kuma river flood, Inundation simulation, Damaged house estimation

1. Introduction

Record-breaking heavy rains have caused floods in many cities of Japan, resulting in a series of floods in urban areas due to breaking levees and overflows. In recent years, the Chikuma River overflowed in Nagano City, Nagano Prefecture, due to Typhoon No. 19 in 2019, the Kuma River overflowed in Hitoyoshi City and Kuma Village, Kumamoto Prefecture, due to the July 2020 torrential rains, and the Rokkaku River overflowed in Takeo City and Omachi Town, Saga Prefecture, due to the August 2019 and August 2021 torrential rains, causing serious damage to houses. The amount of flood damage and the number of houses damaged by depth of inundation are published annually by e-Stat, Japanese statistical information system, however, the burden on municipalities to conduct the survey is heavy. The number of damages caused by torrential rains is increasing, and the survey process is taking longer than usual. The damage assessment method using inundation simulation can estimate the inundation depth of each house in the computational mesh. However, in the statistical survey of flood damage, inundation is classified into six categories: inundation under the floor, inundation above the floor (1-49 centimeter above the floor, 50-99 centimeter above the floor, inundation depth of 1 meter or more), partial destruction, and total destruction. Then, we attempted to improve the estimation accuracy by clarifying the relationship between the inundation depth and flow velocity for each damaged house and by taking into account the flow velocity acting on the house during a flood.

1.1 Rokkaku river flood

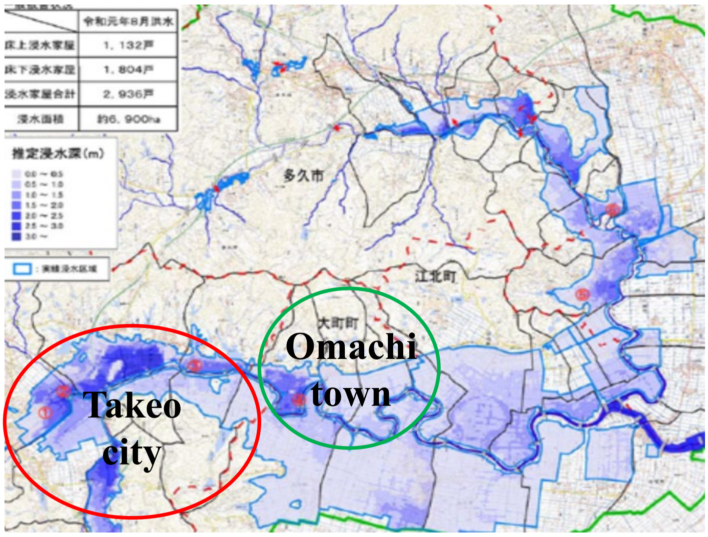
In this study, two cases of flood damage were analyzed and compared: the first was the Rokkaku River flood damage caused by the August 2019 torrential rainfall. Figure 1 shows a map of the Rokkaku River basin.



Source:Ministry of Land, Infrastructure, Transport and Tourism, Japan(MLIT)

Figure 1: Watershed map of the Rokkaku River

The Rokkaku River watershed is surrounded by hilly mountainous terrain, and the Shiraishi Plain extends downstream. The riverbed gradient is approximately 1/60 in the upper reaches, 1/150-1/1,000 in the middle reaches, and 1/1,500-1/45,000 in the lower reaches. A major characteristic of the Ariake Sea is the relatively long tidal zone (29 kilometer), which is affected by tidal fluctuations due to the large tidal range characteristic of the Ariake Sea, extending into the middle reaches of the river. Because of this long tidal zone and low-lying land, the area is prone to both external and internal flooding, and has suffered severe damage from flooding many times in the past. The objective flood is caused by the torrential rainfall in August 2019. The stagnation of the autumn rain front from late August 2019 caused record-breaking heavy rainfall mainly in northern Kyushu from around August 27, 2019. Overflow from branch rivers and internal flooding caused flood damage over a wide area. The maximum depth of inundation reached approximately 3 meters at the deepest point. Figure 2 shows a map of inundated areas published by the MLIT. Of the inundated areas, the analysis targets two municipalities, Takeo City and Omachi Town, which were particularly heavily damaged by the main Rokkaku River. The number of damaged houses in Takeo City and Omachi Town published by Saga Prefecture was compared with the results of the inundation simulation.



Source:Ministry of Land, Infrastructure, Transport and Tourism, Japan(MLIT)

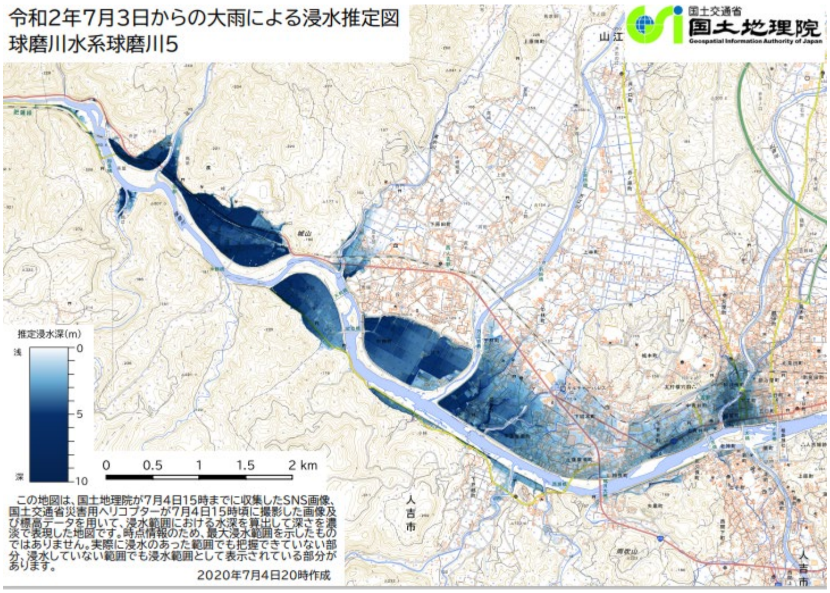
(Some additions to the figure)

Figure 2: Flooded area of the Rokkaku River due to the torrential rainfall in August 2019

1.2 Kuma river flood

The second case is the damage caused by the flooding of the Kuma River due to the torrential rainfall in July 2020. Figure 3 shows the estimated inundation of the Kuma River. The Kuma River, one of the three steepest rivers in Japan, is thought to have a large impact on damage to houses due to its steep river.

The objective of this study was to apply a quick and simple method for determining the number of houses damaged by inundation to these two large-scale inundation cases, and to compare the estimation results.



Source: from the Geospatial Information Authority of Japan(GSI)

Figure 3: Estimated inundation of the Kuma River

1.3 Flooding and damaged houses

Sato et al. found that damage began to occur when the maximum flow force exceeded 1.5 m^3/s^2 and that some houses became uninhabitable when the maximum flow force exceeded 2.5 m^3/s^2. Various studies have been reported on the damage caused by the flooding of the Kuma River due to the torrential rainfall in July 2020. Hirakawa et al. analyzed the inundation characteristics in the Watari area of Kum village, Kumamoto Prefecture, and confirmed that the areas where the hydrodynamic forces became large coincided with the areas where houses were concentrated. Kuroki also analyzed oblique aerial photographs of the flooded Kuma River and mapped the velocity and direction of flow in the Arase and Fujimoto areas, the Kamihagi and Shimohagi areas, and the Sakamoto and Matsuzaki areas in Sakamoto Town, Yatsushiro City, to analyze the magnitude of flow velocity and extent of damage. However, the relationship between damaged houses and flow velocity over a wide area inundated by flood waters has not been fully investigated. Furthermore, Nakata analyzed the relationship between the number of damaged houses and the depth of inundation in the Chikuma River flooding caused by Typhoon No. 19 in 2019, and pointed out that the number of totally or partially destroyed houses cannot be evaluated only by the depth of inundation.

2. Methodology

2.1 Inundation simulation

In this study, the maximum inundation depth, maximum flow velocity, and inundation area were estimated by plane two-dimensional inundation simulation analysis using International River Interface Cooperative (iRIC), and the validity of the estimates was verified by comparing them with the edge of aerial photographs, inundation estimation maps by GSI, and Hitoyoshi City published data. The validity of the estimates was verified by comparing them with aerial photographs, inundation estimates from GSI, and data published by Hitoyoshi City. The continuous equation of the basic equation is shown in Equation (1), and the equations of motion are shown in Equations (2) and (3), referring to the iRIC software manual.

$$\frac{\partial h}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}=0 \tag{1}$$

$$\frac{\partial (uh)}{\partial t}+\frac{\partial (hu^2)}{\partial x}+\frac{\partial (huv)}{\partial y}=-hg\frac{\partial H}{\partial x}-\frac{\tau_x}{\rho}+D^x \tag{2}$$

$$\frac{\partial (vh)}{\partial t}+\frac{\partial (huv)}{\partial x}+\frac{\partial (hv^2)}{\partial y}=-hg\frac{\partial H}{\partial y}-\frac{\tau_y}{\rho}+D^y \tag{3}$$

However,

$$\frac{\tau_x}{\rho}=C_f u\sqrt{u^2+v^2} \qquad \frac{\tau_y}{\rho}=C_f v\sqrt{u^2+v^2} \tag{4}$$

$$D^x=\frac{\partial}{\partial x}\left[v_t\frac{\partial (uh)}{\partial x}\right]+\frac{\partial}{\partial y}\left[v_t\frac{\partial (uh)}{\partial y}\right] \tag{5}$$

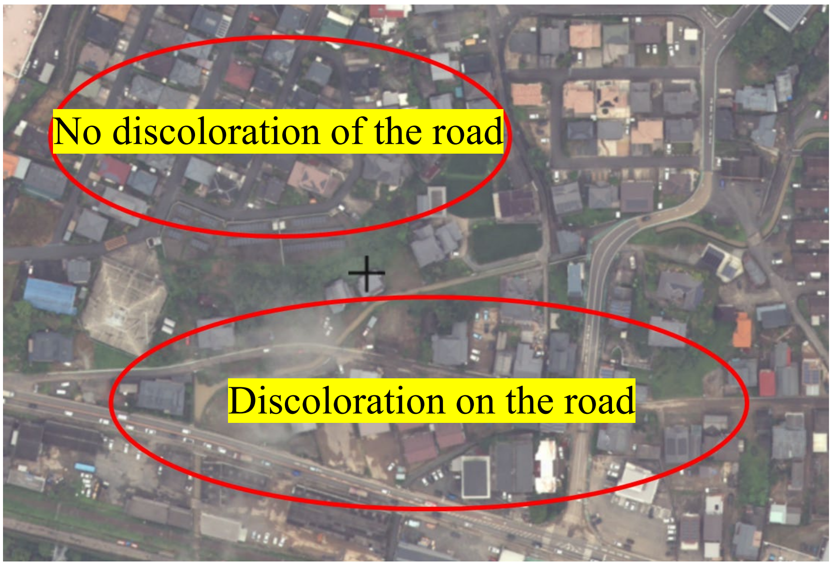
$$D^y=\frac{\partial}{\partial x}\left[v_t\frac{\partial (vh)}{\partial x}\right]+\frac{\partial}{\partial y}\left[v_t\frac{\partial (vh)}{\partial y}\right] \tag{6}$$

where h: water depth (m), t: time (s), u: velocity in x direction (m/s), v: velocity in y direction (m/s), g: gravity acceleration (m/s^2), H: water level (m), τ_x: river shear force in x direction (N/m^2), τ_y: river shear force in y direction (N/m_2), C_f: river shear coefficient, v_t: eddy viscosity coefficient (m^2/s), ρ: density (kg/m^3)

The edges of the aerial photographs were visually identified as inundated and non-inundated areas, and the latitude and longitude information were identified using Google earth Pro based on surrounding roads, houses, signs, and landscapes. The target number of flood damaged houses was 3572, including the fringe area within the inundation area obtained from the inundation simulation. The latitude and longitude of the center of each of these houses were identified using a clear Google earth Pro satellite image taken on September 16, 2016, before the inundation occurred.

2.2 Aerial photograph information on the Rokkaku River

First, we attempted to extract the inundation area using aerial photographs published by GSI and helicopter videos published by MLIT on YouTube channel. The aerial photographs published by GSI (Figure 4) were taken on August 30, two days after the peak of the flooding, so the floodwaters had receded. Although it is not impossible to distinguish between flooded and non-flooded areas by the presence or absence of road discoloration, we investigated images other than GSI's aerial photographs because of the risk of misjudging the extent of flooding.



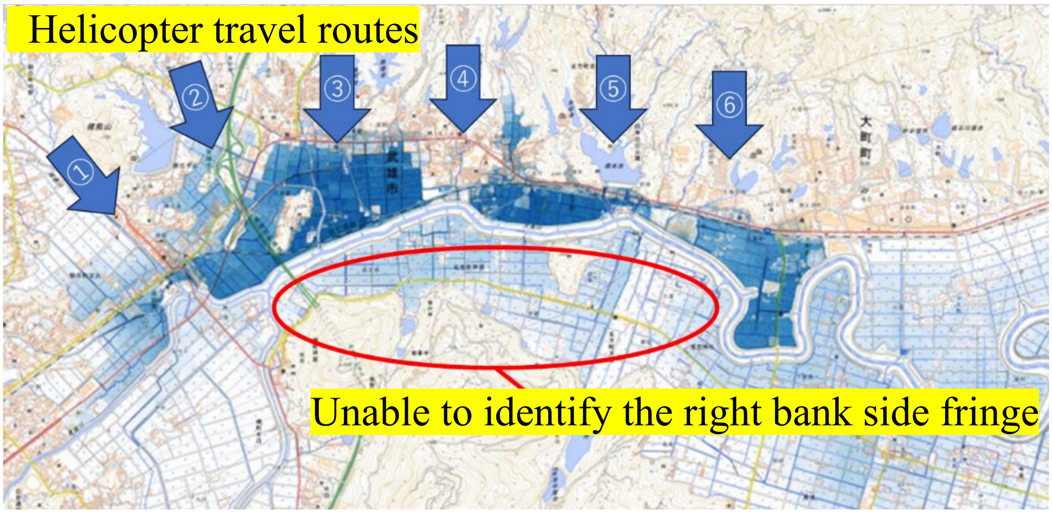
Source: The aerial photograph of GSI taken on August 30, 2019

(Some additions to the figure)

Figure 4: Aerial view of the Rokkaku River flooding

Next, a study was conducted using a video taken by a disaster prevention helicopter, which is available on YouTube from the Kyushu Regional Development Bureau of MLIT.

This video was shot at around 14:00 on August 28, the day of peak flooding, and the floodwaters had not receded. Figure 5 shows the route taken by the helicopter, and Figure 6 shows the image of the helicopter on the right bank of the Rokkaku River taken from the sky over Takeo City. Since the helicopter was moving along the north side of the Rokkaku River, the right bank edge could not be confirmed, but some of the edge on the bank side could be read.



Source: from the Geospatial Information Authority of Japan(GSI)

(Some additions to the figure)

Figure 5: The travel routes of the disaster prevention helicopter

Source: from the Geospatial Information Authority of Japan(GSI)

(Some additions to the figure)

Figure 6: Image of the right bank side of the Rokkaku River over Takeo City

Figure 7 shows the flood edge of the Rokkaku River as observed from the disaster prevention helicopter image. Part of the fringe was observed on the left bank of the Rokkaku River in the middle and upstream areas of Takeo City.

Source: from a satellite photograph by Google earth Pro Imageⓒ2024 Airbus)

(Some additions to the figure)

Figure 7: Edge area (red line) confirmed by disaster prevention helicopter image

2.3 Aerial photograph information on the Kuma River

Next, five aerial photographs (Table 1) published by newspapers and other media organizations were collected from the Internet on July 4, 2020, when the Kuma River was estimated to have reached its peak flood discharge and the urban area was inundated. The collected aerial photographs and location maps are shown in Figure 8.

Table 1: Detail of Aerial Photographs

No	position	Shooting time
Aerial photograph 1	**Kuma village**	**7月4日12時36分**
Aerial photograph 2	**Kuma village**	**7月4日11時44分**
Aerial photograph 3	**Hitoyoshi city**	**7月4日15時43分**
Aerial photograph 4	**Hitoyoshi city**	**7月4日11時48分**
Aerial photograph 5	**Hitoyoshi city**	**7月4日11時49分**

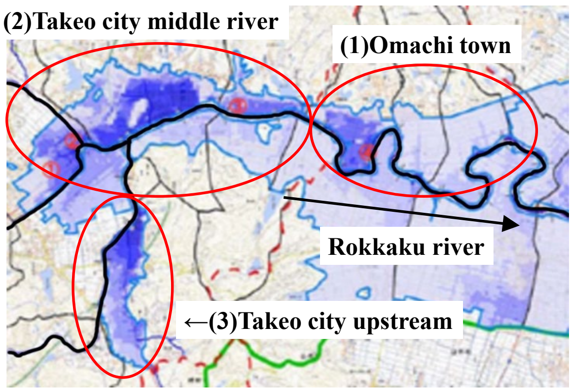
(Aerial photograph 1 is provided by The Nishinippon Shimbun. From Aerial Photograph 2 to 5 refers to references.)

Source: from The Nishinippon Shimbun Co., Ltd. and a satellite photograph by Google earth Pro Imageⓒ2024 Airbus (Some additions to the figure)

Figure 8:Identifying inundation edge by aerial photographs

2.4 Conditions for Rokkaku River flooding simulation

First, for the Rokkaku River inundation, the target area was divided to shorten the computation time for the inundation simulation. This is because the main Rokkaku River does not overflow from the river, and the main cause of inundation was internal flooding, so dividing the target area did not affect the results. Based on the inundation maps published by MLIT, the inundation area in Takeo City and Omachi Town was divided into three parts: (1) Omachi Town, (2) the middle part of Takeo City, and (3) the upper part of Takeo City. Figure 9 shows the location of each area.



Source:Ministry of Land, Infrastructure, Transport and Tourism, Japan(MLIT) (Some additions to the figure)

Figure 9: subject area of calculation

The topographic data used was a 5 meters mesh numerical elevation model (DEM5A) from GSI. Flow and precipitation data were obtained from the Hydrologic Quality Database of MLIT, and data for 12 hours from 0:00 to 12:00 on August 28, 2019, the period covered by the calculations, were used.

Three rivers were considered for the flow: the main Rokkaku River, and the Takeo and Takahashi Rivers, which are particularly large tributaries of the Rokkaku River. The locations of the rivers and the observatories are shown in Figure 10. For the Rokkaku River, a hydrograph was created using data from the Mizonoue observatory upstream, and for the Takeo River, data from the Takeo River observatory upstream (Figure 11). The Takahashi River hydrograph was created using rainfall data from the Suginodake rainfall observatory located in the river basin and iRIC's SRM (a solver that can calculate hydrographs from rainfall data) because there was no flow observatory upstream (Figure 11). In order to reproduce internal flooding, rainfall was applied to the entire computational grid. The rainfall data was measured at the Takeo river observatory closest to the target area from 0:00 to 12:00 on August 28, 2019 (Figure 11).

Source:ⓒGoogle(Some additions to the figure)

Figure 10: Location map of water level and rainfall observation stations

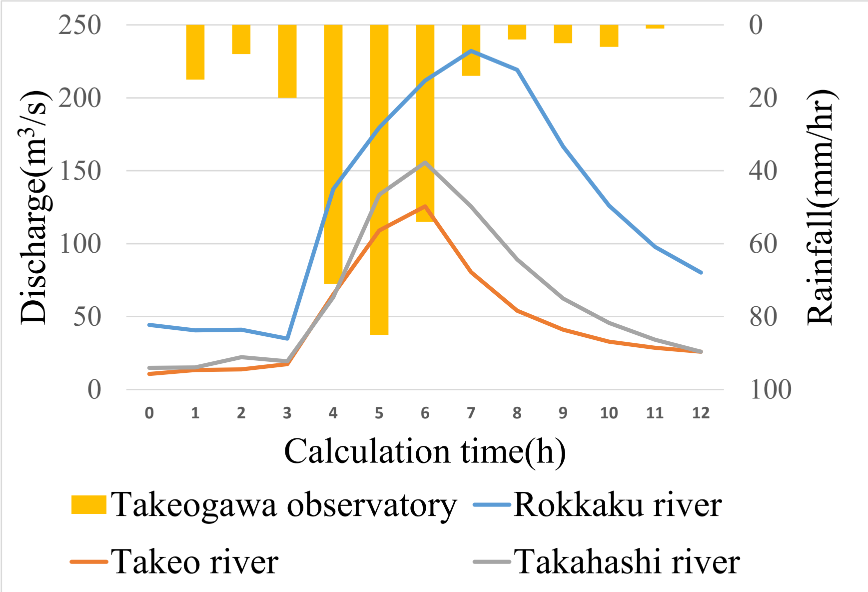


Figure 11: Hydrograph of each river and precipitation data

2.5 Conditions for Kuma River flooding simulation

Next, for the analysis of the Kuma River inundation, inundation simulations were performed using iRIC for Hitoyoshi City and the Watari area of Kuma Village. As a preliminary preparation before the calculations, topographic data was checked. iRIC imported topographic data for the Hitoyoshi City area, and DEM data within the river channel was found to be missing, so the missing data was interpolated from distance marker data and cross-section data from the Kuma River second bridge (around 52.5k) to the Kuma River fourth bridge (around 66.2k). The ground elevation in the river channel was interpolated by Triangulated Irregular Networks (TIN) using Geographic Information System (GIS) software and combined with the ground elevation in the floodplain. The topographic point cloud data was created so that the ground elevation of the river channel (DEM) could be connected to the ground elevation of the channel transect survey.

The computation time was 10 hours from 4:00 to 14:00 on July 4, 2020, including the peak of the flooding. The mesh size is 25 meters and 25 meters, based on the Flood Inundation Area Mapping Manual 4th edition. The ground height near the break points in the point group data was modified to 80.0 meters, which is the same level as the ground inside the embankment, and the width and length of the break were set to 50 meters and 25 meters, respectively. The embankment was set up to cover the breach area. The breached block was set to be a barrier to prevent floodwaters in the river channel from moving into the embankment, and the conditions of the breach were reproduced so that floodwaters in the river channel would flow out into the embankment after the breach. The peak time of the water level at the Ohashi point in Hitoyoshi City was around 9:50 a.m. on July 4, and the estimated time of the breach was unknown as far as data was collected. The minimum inundation depth was set to 0.01 meters, the calculation time step to 0.1 seconds, and the number of parallel calculation threads to 8. Roughness coefficients were set to 0.03 for the outside of the embankment and 0.025 for the inside of the embankment, and the riverbed slope was set to 1/500, based on a report by the Japan Society of Civil Engineers (JSCE). The standard model constant for the drag force of buildings was set to 0.383, taking into account the influence of houses, in reference to the Manual for Mapping Assumed Inundation Zones revised edition.

Hydrographs were created from the hydrologic database, referring to the flow data from the Ichitake hydrograph observatory upstream of the main river and the Yanase hydrograph observatory on the Kawabe River, a tributary of the main river. The flow data from Ichibu was missing for four hours from 8:00 to 11:00 on July 4, so it was necessary to compensate for the missing data. The estimated maximum peak flow rate of the Kuma river was set to 7400 m^3/s because the estimated flow rate of the Hitoyoshi Observatory was reported as 7400 m^3/s in the reference material of the second meeting of the Kuma River Torrential Rainfall Verification Committee in July 2020. Since the maximum observed flow rate at the Yanase observatory of the Kawabe river, a tributary river, is 3400 m^3/s, the maximum flow rate of Ichibu was assumed to be 4000 m^3/s (= estimated maximum peak flow after confluence 7400 m^3/s - maximum observed flow rate at Yanase 3400 m^3/s), assuming no influence from other tributaries. The water depth situation in Hitoyoshi city where Aoiaso Shrine is located was assumed to have reached its maximum flow at 9:42 a.m. on July 4 at the Ichitake station upstream of the Kuma river, because the Kuma river began to pull back into the main Kuma river at 9:42 a.m. on July 4. The iRIC calculations also show that the depth of inundation near Aoiaso Shrine reached its maximum at 9:50 a.m. on July 4, which is in good agreement with the iRIC calculations. The 4 hours of missing measurements at the Ichibu observatory were interpolated between the previous and following observations and 4,000 m^3/s to produce a hydrograph. The hydrograph is shown in Figure 12.

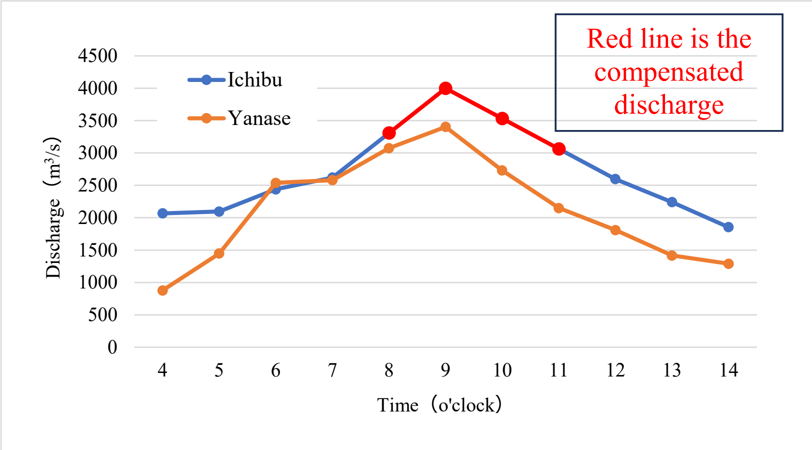
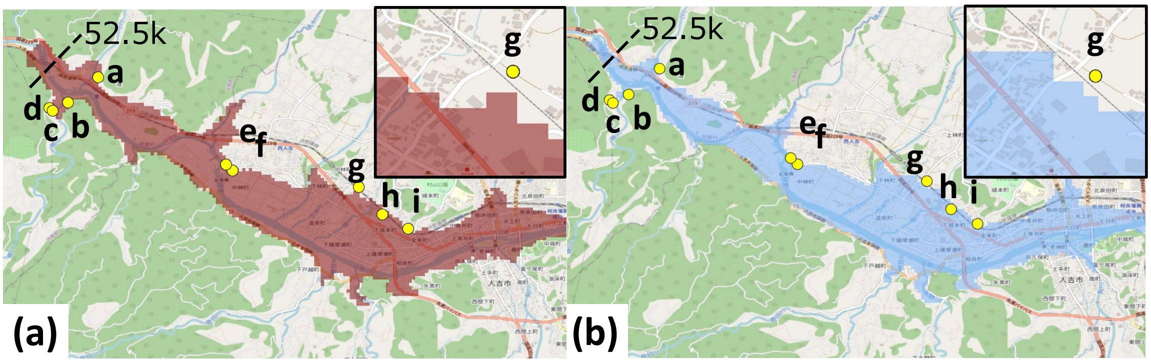


Figure 12: Hydrograph of the main Kuma river and its tributary Kawabe river

Figure 13 shows the overlap of the edge of the aerial photograph and the results of the inundation simulation. The nine points on the edge identified in the aerial photograph represent the edge of the inundation area in the inundation simulation. The calculation conditions were reviewed in detail, including changing the mesh size from 40m and 40m (Figure 13(a)) to 25m and 25m (Figure 13(b)), so that the difference between the inundation area and the edge of each aerial photograph is reduced. As a result, the difference was reduced by an average of 3.2 meters in the direction of the fringe. Figure 13(b) shows the modified results



Source:ⓒOpenStreetMap contributors

Figure 13: Comparison of aerial photographs and inundation simulation results a) before modification b) after modification

3.Results and Discussion

3.1 Results of inundation simulation in the Rokkaku River

The results of the Rokkaku river inundation simulation are described.

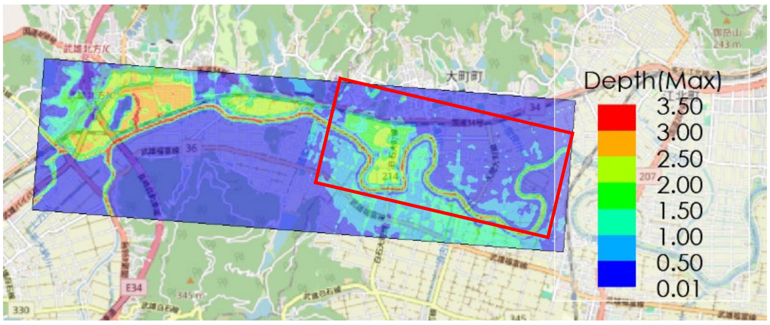
3.1.1 Calculation of estimated maximum inundation depth

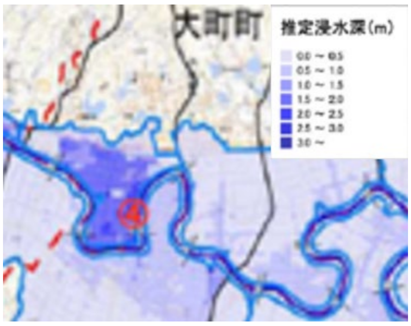
The calculation period was 12 hours from 0:00 to 12:00 on August 28, including 7:00 on August 28 when the water level of the Rokkaku River reached its peak. iRIC requires the inflow rivers to be set at the edge of the grid, so the grid was extended from Omachi-cho and was made to touch the Rokkaku River, Takeo river and Takahashi river. The grid size was 20 and 20 meters. The lateral (right bank) boundary condition was set as an inflow due to the presence of the Rokkaku river, and the lateral (left bank) boundary condition was set as a “wall” because there was no large river inflow. Rainfall was applied to the computational grid, and the roughness coefficient was set to 0.03 for the river channel and 0.05 for the urban area. The number of cores for parallel computation was set to 5 to reduce computation time. Other calculation conditions are summarized in Table 2. The PC used for the calculations was an Intel Core i7-1260P with 32 GB RAM.

Table 2: Calculation conditions (Omachi Town)

The mesh size (meter)		**20 and 20**
Mesh number		**470 and 130**
boundary condition	**Side(right bank)**	**Inflow**
	Side(left bank)	**Wall**
	Water level at the down stream end	**Free discharge**
precipitation		**on**
Time step (second)		**0.01**
River bed gradient		**0.001**
roughness cofficient	**river**	**0.03**
	downtown	**0.05**
Number of threads for parallel computation		**5**

Figure 14 shows the calculation results for the maximum inundation depth in Omachi Town, displayed at 50 centimeters intervals. The calculation time was approximately 11 hours. The maximum inundation depths ranged from 2.5 meters to 3 meters. Comparison with the inundation map published by the Takeo River Office (Figure 15) confirms that the inundation area and distribution of inundation depths were generally consistent.





Source:ⓒOpenStreetMap contributors

Figure 14:Calculation results (Omachi Town)

Figure 15:Flooding Situation Map

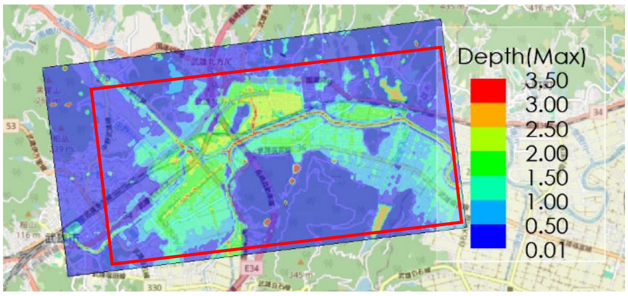
(The part of Figure 9)

Next, for the middle part of Takeo City, the calculation period was 12 hours from 0:00 to 12:00 on August 28, as was the case for Omachi Town. The Rokkaku River, the Takeo River, and the Takahashi River were selected as inflow rivers, and the computational grid was created so that the grid was tangential to each of the three rivers. The lateral boundary conditions were set as inflow for both the Rokkaku River and the Takahashi River. Other computational conditions, such as grid size, were set equal to those in Omachi Town (Table3).

Table 3: Calculation conditions (Takeo midstream area)

The mesh size (meter)		**20 and 20**
Mesh number		**240 and 100**
boundary condition	**Side(right bank)**	**Inflow**
	Side(left bank)	**Inflow**
	Water level at the down stream end	**Free discharge**
precipitation		**on**
Time step (second)		**0.01**
River bed gradient		**0.001**
roughness cofficient	**In the river**	**0.03**
	downtown	**0.05**
Number of threads for parallel computation		**5**

Figure 16 shows the calculation results for the maximum inundation depth in the middle reaches of Takeo City. The calculation time was approximately 26 hours, and the maximum inundation depth was approximately 3 meters. Compared to the inundation situation map published by the Takeo River Office (Figure 17), it was confirmed that the approximate inundation area and distribution of inundation depths were consistent even in the middle reaches of Takeo City.



Source:ⓒOpenStreetMap contributors

Figure 16:Calculation results (Takeo midstream)

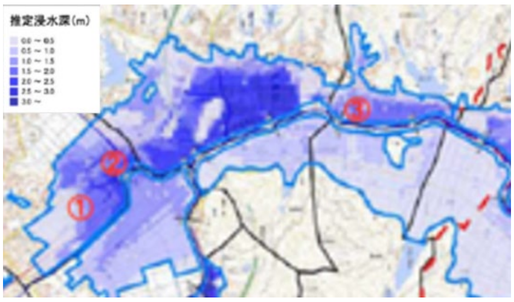


Figure 17:Flooding situation map

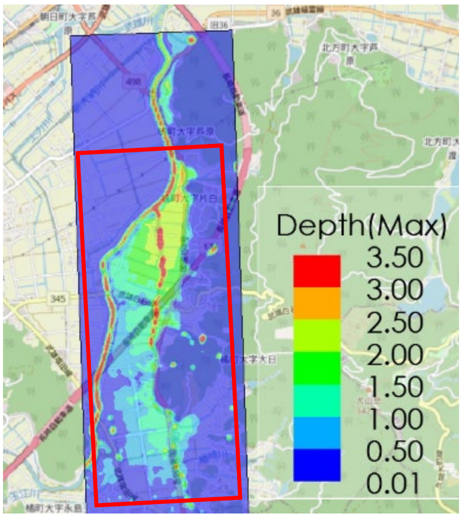
(The part of Figure 9)

Next, for the upper reaches of Takeo City, the calculation period was set to 12 hours from 0:00 to 12:00 on August 28, as in Omachi town and the middle reaches of Takeo City. Since the upper reaches of Takeo City are located before the confluence of the Takeo and Takahashi rivers, only the Rokkaku River is assumed to flow into the city, and the computational grid was made to be tangential to the Rokkaku River. The lateral (left bank) boundary condition was assumed to be an inflow because of the Rokkaku River, and the lateral (right bank) boundary condition was assumed to be a wall because there is no river. Other computational conditions, such as grid size, were the same as those used in the Omachi town and the middle part of Takeo City (Table 4).

The results for the maximum inundation depth in the upper reaches of Takeo City are shown in Figure 18. Compared to the inundation map published by the Takeo River Office (Figure 19), the approximate extent of inundation and the distribution of inundation depths in the upper reaches of Takeo City were consistent.

Table 4: Calculation conditions (Takeo city upper stream department)

The mesh size (meter)		**20 and 20**
Mesh number		**238 and 80**
boundary condition	**Side(right bank)**	**wall**
	Side(left bank)	**Inflow**
	Water level at the down stream end	**Free discharge**
precipitation		**on**
Time step (second)		**0.01**
River bed gradient		**0.001**
roughness cofficient	**river**	**0.03**
	downtown	**0.05**
Number of threads for parallel computation		**5**



Source: ⓒ OpenStreetMap contributors

Figure 18:Calculation results(Takeo City Upstream)

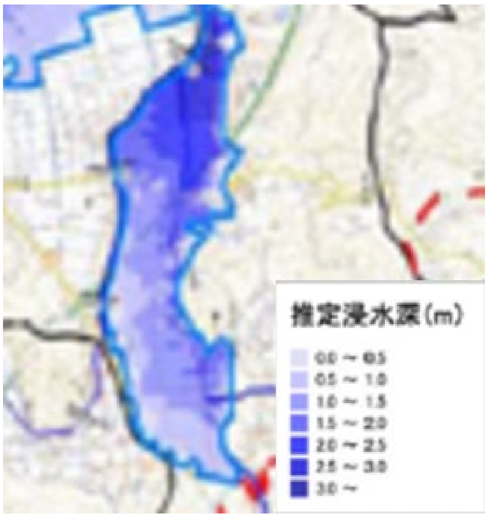


Figure 19: Flooding situation map

(The part of Figure 9)

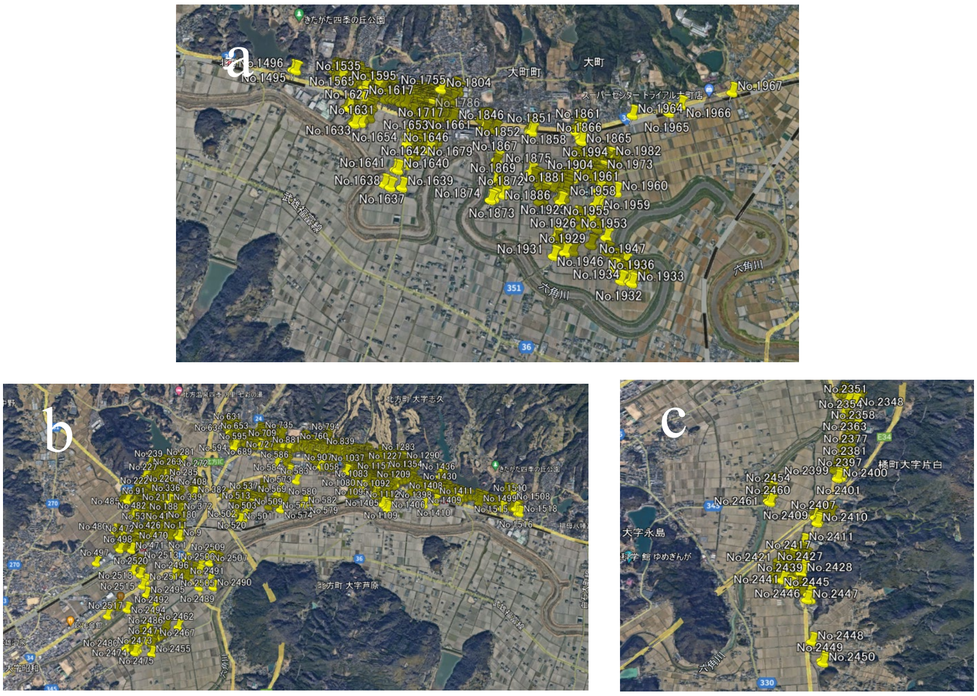
3.1.2 Identification of house location

Google earth Pro and Google Map Street View were used to locate houses. First, we switched to the Google earth Pro pre-flood image (April 27, 2019, etc.) to identify houses located within the flood zone. Figure 20a) is a portion of the image. In (1), there appears to be a house, and in (2), there appear to be two houses. However, when viewed from the street view, (1) is actually a carport (Figure 20b) and (2) is actually one large house (Figure 20c). Thus, there was a risk that the houses could be mistakenly identified from an aerial view, so we used Google Map Street View of the same location as a supplemental method to identify the location of the houses.

Source:ⓒ2024 Google

Figure 20: Identification of houses "a") Before enlargement "b") ①Carport easily misidentified as "a" house (red area in "a") "c") General house (orange area in "a")

Figure 21 shows the Google earth Pro image after locating the houses. We mapped 482 houses in Omachi town, 1,921 houses in the middle part of Takeo City, and 121 houses in the upper part of Takeo City.



Source:ⓒ2024 Google

Figure 21: a) Omachi Town, b) middle part of Takeo City, c) upper part of Takeo City.

3.1.3 Result

Using GIS software, the number of inundated houses was aggregated in 50 centimeters segments by linking the point data of the identified houses with the maximum inundation depth value from the inundation simulation at that location. Figures 22 show the results. The results for Takeo City include inundated houses in the middle and upper reaches of the city. 0 to 0.49 m inundated houses are considered to be inundated under the floor, and houses inundated more than 0.50 m are considered to be inundated above the floor, and the results are compared with the data published by Saga Prefecture.

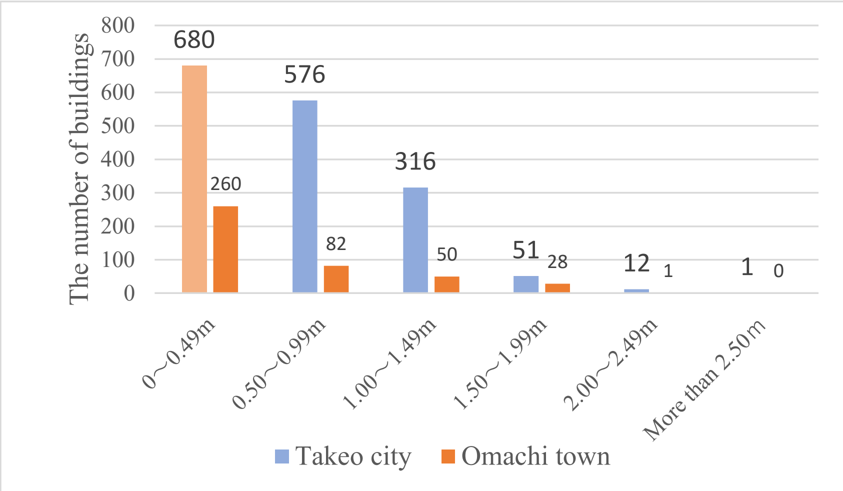


Figure 22 Number of houses by depth of inundation

3.1.4 Comparison with published data from Saga Prefecture

The number of houses that were totally, largely, or partially destroyed was also included in the number of houses inundated above floor level in the "The number of damaged houses" (Table 5) published by Saga Prefecture. The comparison results are shown in Figures 23 and 24.

Table 5: The number of damaged houses by flooding in Takeo City and Omachi Town

	Totally destroyed	Largely destroyed	Partially destroyed	inundated above floor level	inundated below floor	total
Takeo city	**2**	**34**	**712**	**202**	**332**	**1282**
Omachi town	**79**	**71**	**4**	**18**	**131**	**303**

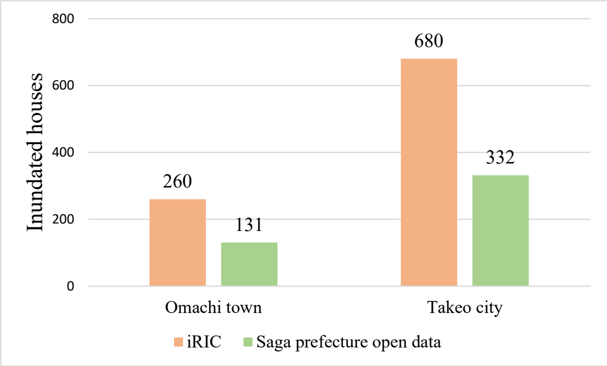


Figure 23: Comparison of the number of damaged houses flooded under the floor

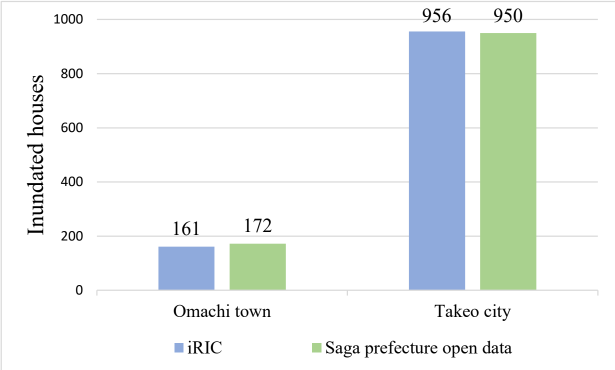


Figure 24 Comparison of number of buildings damaged houses above floor level

The number of damaged houses inundated above floor level was 6% higher in Omachi town and 1% higher in Takeo City than in the published data. On the other hand, the number of damaged houses inundated under the floor was about twice as large in both Omachi town and Takeo City.

The reason for the large difference in the number of damaged houses flooded under the floor is considered to be that iRIC's minimum flood depth setting was set to 0.01 meter or greater. In this study, rainfall was applied to the entire calculation grid in order to reproduce internal flooding, but the distribution of inundation depths below from 0 to 0.5 meters is assumed to be larger because rainfall was uniformly applied to all calculation grids. Therefore, we believe that the difference between the number of damaged houses flooded under the floor and the published data is large because the iRIC results include houses that were flooded to a depth of about 0.1 meter and may or may not have actually been determined to be flooded under the floor. In fact, when the number of houses with a maximum inundation depth of less than 0.5 meter is compared for each 0.1 meter section (Figure 25), the number of houses with smaller inundation depths is larger, and it is possible that the number of houses included in this category was overcalculated. Therefore, it is necessary to examine in detail the aggregation of inundation under the floor by local governments, and to redefine the criteria of houses considered to be inundated under the floor.

It is also necessary to review the rainfall conditions that were set to reproduce internal flooding. In a previous study on the inundation damage caused by Typhoon Chikuma on the Chikuma River in Nagano Prefecture in 2019, inundation simulations were conducted in the same way as in this study. The cause of the flooding in the Chikuma River was external flooding due to a levee breach. iRIC calculations do not take precipitation into account, but only the flow of the Chikuma River. The difference from the published data of Nagano prefecture is shown in Figure 26. The difference from the published data of inundation under the floor is 24%, which is smaller than the result of the Rokkaku River. The fact that the difference was small in the analysis for external flooding and the difference for under floor inundation was large in this study for internal flooding suggests that the effect of rainfall on the calculations was significant. Therefore, it is necessary to revise the conditions in order to make the inundation depth due to internal flooding closer to the measured values in the future.

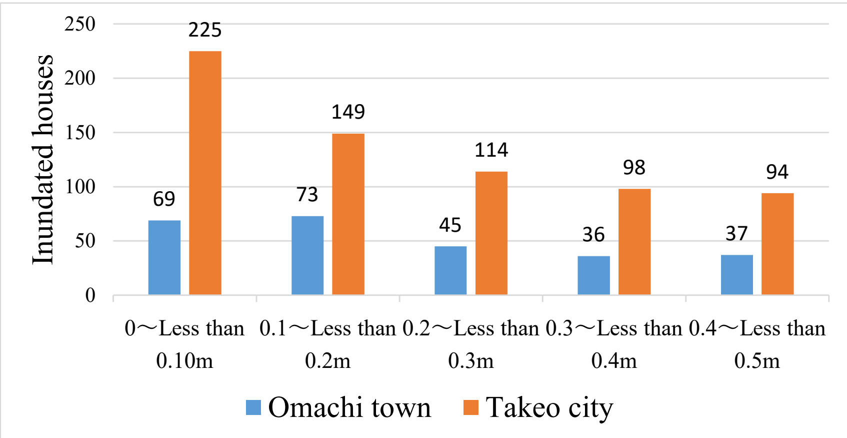


Figure 25 Distribution of number of houses inundated by less than 0.5 m

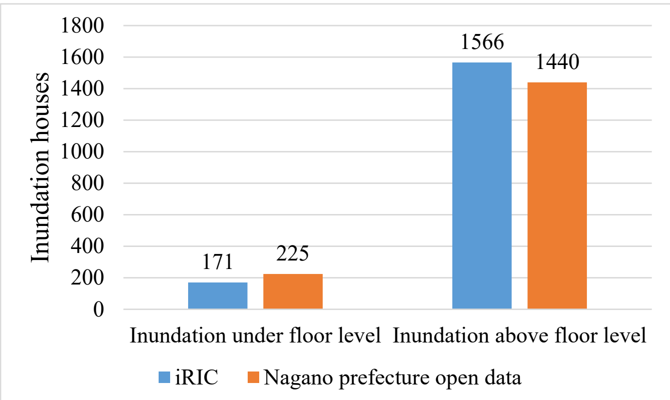


Figure 26 Results of study on the Chikuma River

In addition, we believe that the development of residential land has also had an impact on the area. When confirming houses on the street view, some houses were built a little higher than the ground level due to stone walls. This may have caused the difference from the published data to be larger. Table 6 shows the number of houses damaged when the height of the houses from the ground was 0 cm, 5 cm, 10 cm, 15 cm, and 20 cm. The number of houses damaged was calculated by subtracting the height from the ground of the house from the maximum inundation depth in iRIC for each case.

Table 6: Comparison of number of damaged houses based on assumed height of houses from the ground

	Inundation classification	Height of the house from the ground (centi meter)					Published value (buildings)
		0 cm	5 cm	10 cm	15 cm	20 cm	
Takeo city	Inundated below floor level	680	632	580	565	557	332
	Inundated above floor level	956	885	832	774	706	950
	Inundation classification	Height of the house from the ground (centi meter)					Published value (buildings)
		0 cm	5 cm	10 cm	15 cm	20 cm	
Omachi town	Inundated below floor level	260	247	221	191	176	131
	Inundated above floor level	161	147	127	117	104	172

The higher the height of the house from the ground, the smaller the difference from the published number of houses inundated under the floor, but the larger the difference in the number of houses inundated above the floor. Simply subtracting the same value from the inundation depth of all houses results in a uniformly smaller inundation depth, and thus a smaller number of houses flooded above the floor level. We expect that the difference will become smaller if the height of each house is totaled, but since this is not a simple estimation, further study is needed in the future.

3.2 Simulation results of flooding in the Kuma River

The results of the Kuma River inundation simulation are described below. The peak time of the Kuma River flooding is estimated to be around 9:42 a.m. on July 4, around the Aoiaso Shrine. Aerial photographs 2 and 4 are close to the area of maximum inundation, and aerial photograph 3 was taken approximately six hours after the peak of inundation. Figure 27 shows the location information, ground elevation, and distance from the reference point (Kuma Village Office) of 10 measurement points read from the five aerial photographs. Figure 27 shows that the maximum difference in inundation level at the edge of the target area of approximately 8 kilometer is 9.3 meters (maximum value: 104.9 meters - minimum value: 95.6 meters).

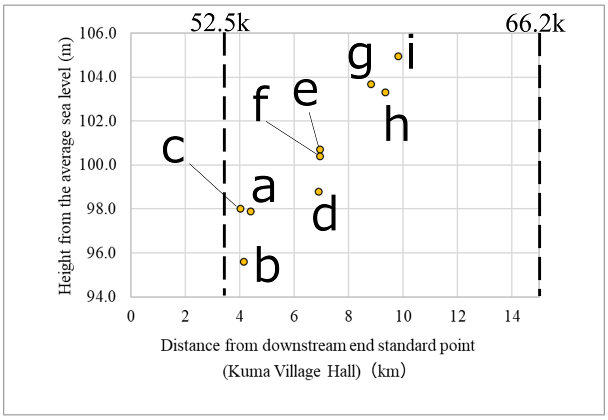
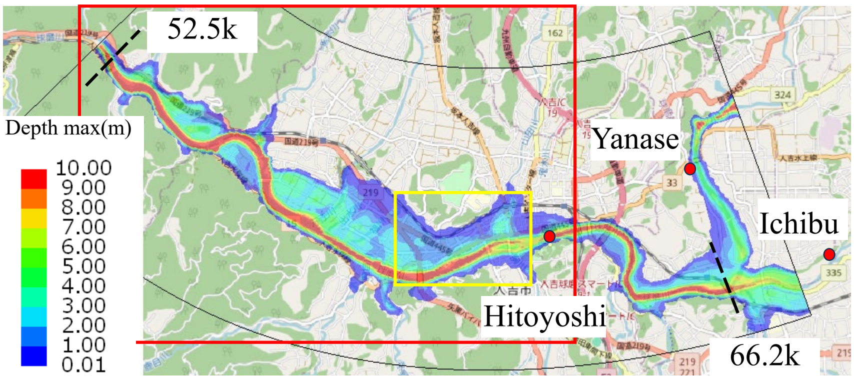


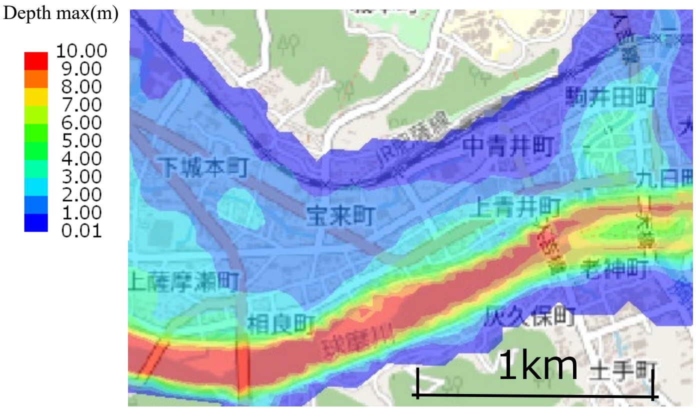
Figure 27: Ground elevation at the edge

Figure 28 shows the results of the maximum inundation depth calculations. In the urban area of Hitoyoshi city, the inundation depth was 1 to 2 meters. The actual calculation time was 77.5 minutes. The actual calculation time was 77.5 minutes. Compared with the GSI's inundation estimation map (Figure 30), the inundation area and depth were generally reproduced. Figures 29 and 31 show enlarged images of the Hitoyoshi urban area (yellow box) in Figures 28 and 30, respectively. Of the 3572 houses in the inundation simulation area, 2891 were inundated. Figure 32 shows a contour plot of the maximum flow velocity at intervals of 1 m/s. The red boxes in Figures 28 and 32 indicate the area covered by the GSI data (Figure 30).



Source:ⓒOpenStreetMap contributors

Figure 28 Calculation results (maximum inundation depth)



Source:ⓒOpenStreetMap contributors

Figure 29 Hitoyoshi urban area (Figure 28 enlarged)

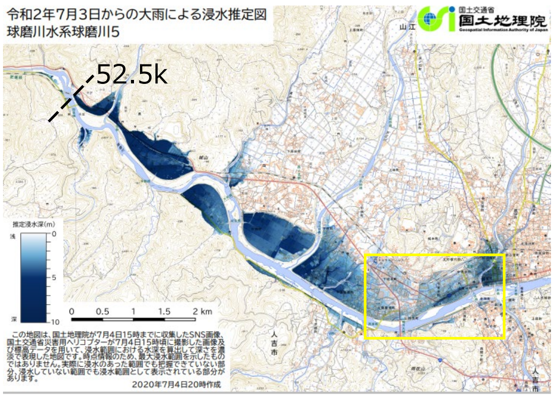


Figure 30: Estimated inundation of the Kuma River

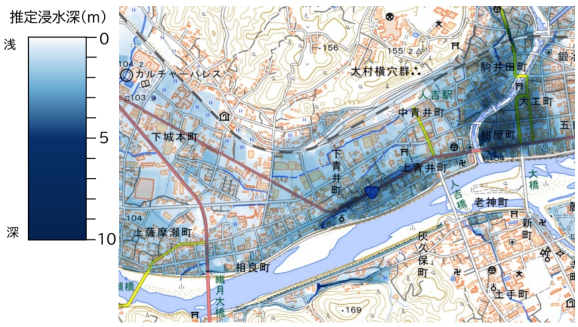
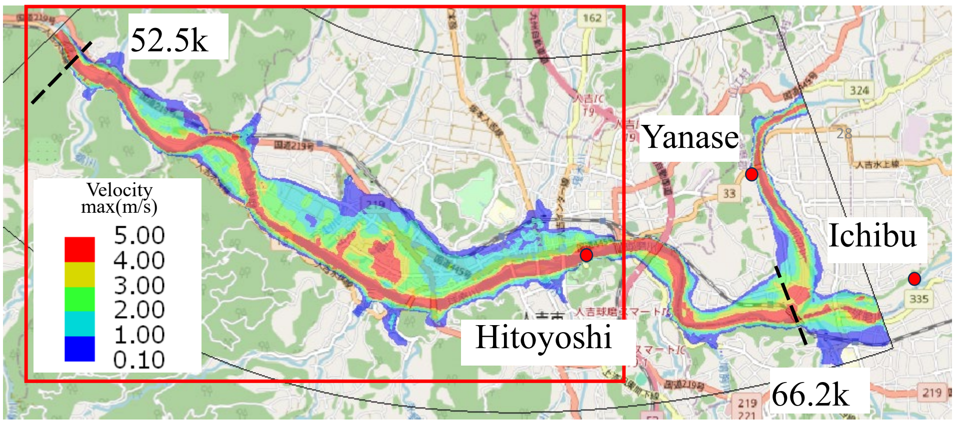


Figure 31: Hitoyoshi urban area (Figure 30 enlarged)



Source:ⓒOpenStreetMap contributors

Figure 32 Calculation results (maximum flow velocity)

Figure 33 shows the relationship between inundation depth and flow velocity for each of the 2891 houses within the inundation area based on the inundation simulation results. Previous studies have classified damaged houses as partially or totally destroyed based only on the estimated inundation depth, but in this study, the correlation between inundation depth and flow velocity was found to be weak (correlation coefficient 0.508), so the number of damaged houses was classified based on the maximum flow velocity and the number of houses at the maximum flow velocity of 0.1 meter pitch was calculated. The classification results are shown in Figure 36. The total number of damaged houses according to the Hitoyoshi City data was 2,662, of which 2,643 were subject to the inundation simulation. Comparison of the two data sets shows that the velocity classification of Hitoyoshi City is generally consistent with the published data, with total destruction classified as having a velocity of more than 2.4 m/s, large partial destruction as more than 1.7 to less than 2.4 m/s, partial destruction as more than 0.4 to less than 1.7 m/s, and partial damage as less than 0.4 m/s. From the viewpoint of simpler estimation, we focused on the maximum flow velocity for each mesh for each house in the entire inundation area rather than examining the complex fluid forces acting on each house individually, and evaluated the effectiveness of this method as a method to quickly grasp the damage situation and classify each damage. The location information for each damaged house is not publicly available, so it is difficult to obtain the breakdown shown in Figure 33. In order to improve the accuracy of damage assessment, it is necessary to clarify the relationship between the damage to individual houses and the hydrodynamic forces acting on them as a future task. The hydrodynamic forces are expressed in terms of the depth of inundation, flow velocity, density of soil particles, and reaction coefficient acting on the house. Since these factors greatly affect the accuracy of the estimation method of damaged houses using hydrodynamic forces, it is necessary to carefully consider how these factors should be set.

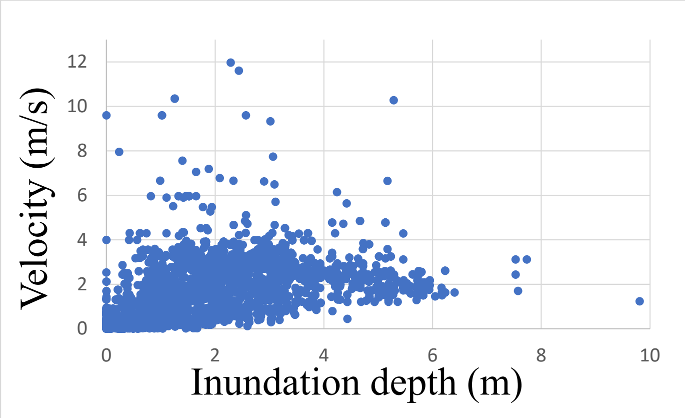


Figure 33: House locations within the inundation area

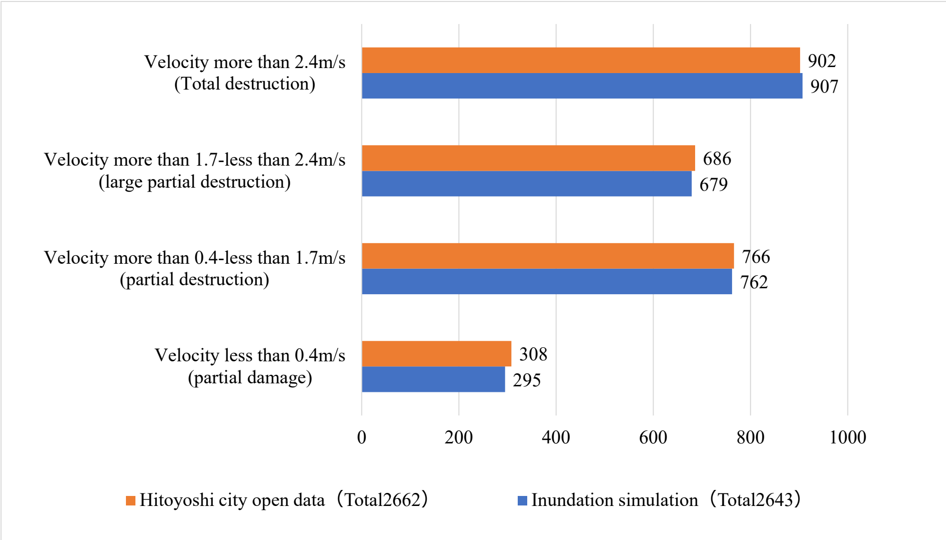


Figure 34: Optimal flow velocity for the number of damaged houses in Hitoyoshi City

3.3 Comparison of flood damage between the Rokkaku River and the Kuma River

Comparing the two flood damage estimation results, the extent of inundation was generally estimated using aerial photographs for both floods, but there was a difference in the estimation results for understanding the damage. In the case of the Rokkaku river flood, the difference in the estimation of inundation below floor level was larger than that of inundation above floor level. On the other hand, in the Kuma River flooding, the number of houses inundated above floor level was larger, and the difference in the maximum velocity that houses were subjected to was also larger. The estimated results reflect the results for the houses affected by the velocities and are close to the published values. These results suggest that the Kuma river has a steep topography with a river gradient of 1/200 to 1/600 in the Hitoyoshi basin, which has a large impact on flood velocities, and thus the damage to the houses in the published data was close to that in the published data. The difference between the published and estimated total number of houses damaged by flooding was also small. However, in contrast to the Kuma River, the Rokkaku River is closer to the mouth of the river and has a gentle gradient that makes it difficult for the river to drain, resulting in widespread shallow flooding rather than rapid flooding. Accurate identification of damage from under-floor flooding is important for determining the total number of damaged houses. However, since it is difficult to clarify the criteria for determining under-floor flooding, caution must be exercised in analyzing inundation caused by internal flooding. However, it has become clear that the published and estimated numbers of damaged houses generally difference about 10%, and the verification of the two representative rivers treated in this study, which are very different in their river environments, has made it possible to apply a method using aerial photographs and inundation simulations to determine the number of houses damaged when large scale flooding occurs. This study has shown that the application of the method using aerial photographs and inundation simulation is effective in quickly identifying damaged houses in various types of inundated rivers when large scale inundation damage occurs.

4. Conclusion and Recommendation

A simple estimation of the number of houses flooded by the Rokkaku river in the August 2019 heavy rainfall in Saga prefecture, using a flooding simulation, showed that the number of houses flooded above floor level was almost the same as that in the published data, while the difference in the number of houses flooded below floor level was almost twice as large in both Omachi town and Takeo city. The reasons for this difference could be due to the effects of rainfall when reproducing internal flooding, etc. Therefore, it is necessary to review the setting of inundation under the floor and to examine the total number of inundation under the floor in each municipality in detail. In the case of the Kuma river flooding caused by the July 2020 heavy rain, the extent of inundation, the number of damaged houses, the maximum depth of inundation for each house, and the maximum flow velocity were estimated using inundation simulations and aerial photographs. The results of the inundation area generally agreed with the estimated inundation map by GSI, and the number of damaged houses in Hitoyoshi City generally agreed with the data published by Hitoyoshi City, where the flow velocity was 2.4 m/s or higher for total destruction, 1.7 to 2.4 m/s or lower for large partial destruction, 0.4 to less than 1.7 m/s for partial destruction, and 0.4 m/s for partial damage. The proposed method, which includes the effect of flow velocity, has the potential to be an effective method of surveying damaged houses. However, since the durability of houses depends on the structure and age of the houses, the effect of flow velocity may be smaller in rivers with different river gradients and inundation patterns, it is necessary to confirm the relationship between inundation depth and flow velocity in other inundation cases. Therefore, it is necessary to confirm the relationship between inundation depth and flow velocity in other inundation cases. In the future, it is necessary to extensively study the improvement of estimation accuracy to establish a methodology for advanced survey methods.

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