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Paper:

Flooding Along Oda River Due to the Western Japan Heavy Rain in 2018

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The heavy rain that hit Western Japan in July 2018 triggered the worst rain-related disaster in the Heisei era, with the total of dead and missing persons exceeding 230, mainly in the Hiroshima and Okayama Prefectures. At several locations along Oda River (of the Takahashi river system) and its tributaries, dikes were breached due to large-scale flood, leaving 51 persons dead. This paper aims to shed light on the scale of inundation along Oda River and its tributaries and identify the characteristics of and critical factors for human damage. Field surveys were conducted to measure flood marks in flooded areas and river channels, and gauge the extent of damage to people and property. The surveys found that a large area was inundated on the north side of Oda River, with an inundation depth exceeding 5 m for 1 km in the south-north direction and 3.5 km in the east-west direction, which made vertical evacuation of residents difficult. The findings that about 80% of the dead were found on the first floor of their houses, with those who had lived in a one-story house and those who had lived in a two-story house accounting for 50% each of the deceased, indicate how difficult even vertical evacuation was. The findings appear to be related to the considerable inundation depth and high rate of water level increase, along with the fact that the majority of the deceased were elderly people.

Keywords: flood, inundation, Oda River, Western Japan heavy rain

1. Introduction

Influenced by the stagnation of the seasonal rain front since June 28, 2018, and the formation of Typhoon No. 7, Prapiroon, on June 29, a warm and moist air flowed in and around Japan, even as it rained heavily throughout the country, especially in the western part during the period from June 28 to July 8 [1]. The total amount of rainfall during this period exceeded 1,800 mm in some places in Shikoku Region and 1,200 mm in Tokai Region. In particular, during the period from July 5–7, a record rainfall was observed in the western part of Japan, and a special heavy rain warning was issued in the 11 prefectures of Fukuoka, Saga, Nagasaki, Hiroshima, Okayama, Tottori, Kyoto, Hyogo, Gifu, Ehime, and Kochi. Moreover, the record for the heaviest-ever rainfall was broken at 14 locations in Japan based on the one-hour precipitation rate, 48 locations based on the 12-hour precipitation rate, 76 for the 24-hour precipitation rate, 124 for the 48-hour precipitation rate, and 122 locations for the 72-hour precipitation rate [1]. The most notable feature of the 2018 heavy rain was that its intensity was not for a short duration of one to six hours, but for a longer period of 24 hours and more [2]. Thus, the 2018 flood disaster was different from the other flood and sediment disasters that have occurred in recent years in Japan, which were all characterized by heavy rains in a short time, such as the 2004 Niigata Fukui heavy rain [3], the 2012 heavy rain in Northern Kyushu [4], the 2013 Izu Ohshima sediment disaster [5], the 2014 Hiroshima sediment disaster [6], and 2017 heavy rain in Northern Kyushu [7].

The 2018 heavy rain triggered flood and sediment disasters at various places in Japan and caused serious damage. Hiroshima, Okayama, Ehime, and other prefectures saw the worst rain disaster in the Heisei era, with the total of dead and missing persons exceeding 230 [8]. The Meteorological Agency termed this heavy rain disaster as “the Heavy Rain of July 2018” [1], while it was named “the Western Japan heavy rain” in mass media. At nine locations along Oda River of the Takahashi river system and its tributaries, dikes were breached, inundating about 30% of the area of Mabi Town, Kurashiki City, Okayama Prefecture, and leaving 51 persons dead. Although the inundation of flood water began between 23:00 and 24:00 on July 6, an evacuation advisory and a special heavy rain warning were issued to the districts concerned at 22:00 and 22:40, respectively. That is to say, both the evacuation advisory and the warning were issued before the flooding. Nonetheless, serious human damage was caused. Accordingly, it is vital to identify the factors causing human damage.

This paper summarizes the findings on the inundation situation and house damage along Oda River and its tributaries, where the heavy rain-related damage was the most severe in 2018. Furthermore, this paper aims to clarify the relationship between the inundation process and the characteristics of human damage in Mabi Town, where 51 people lost their lives. For this purpose, field surveys were conducted to 1) measure the flood marks in the flooded areas; 2) measure the flood marks within the river channels in Oda River and its tributaries; 3) estimate damage to property; and 4) estimate human damage. Based on the findings of these surveys, the situation on inundation and dike breach on the left (north) and right (south) sides of Oda River was determined. By surveying the flood marks within the river channels, the influence of the backwaters from the confluence with Oda River on the tributaries is also clarified. Furthermore, this paper provides a spatial distribution of the human damage and its characteristics, while attempting to make clear the influences of inundation on human life.

2. Survey Method

2.1. Survey Site

The basin area of Oda River and that of Takahashi River, into which Oda flows, are shown in **Fig. 1**. Takahashi River originates at Hanami Mountain (1,188 m above sea level) that is located on the border of Okayama and Tottori Prefectures, flows southward where it is joined by Kumagaya River, Nishi River, Osakabe River, and Nariwa River, and incorporates Oda River before flowing into the Inland Sea. Takahashi River is a Class-A river, with a river channel length of 111 km and basin area of 2,670 km^2. Oda River, a tributary of Takahashi River, originates in Jinsekikogen Town, Hiroshima Prefecture, flows eastward through Ihara City, Kurashiki City, etc., traverses Okayama Prefecture, and flows into Takahashi River at a point that is 13 km upward from its mouth. The length of the river channel is 33 km and the basin area is 491 km^2, and the section controlled by the country ranges from the confluence with Takahashi River to a point that is 7.9 km upward from the confluence. Many Class-A rivers in Honshu, Japan flow in the north-south direction, but Oda River flows eastwards, so the riverbed slope is relatively gentle.

The contour map of the lower reach of Oda River where the inundation occurred is shown in **Fig. 2**. The tributaries of Oda River, Suemasa River, Takama River, Uchiyamadani River, Setani River, and Obutani River on the left (north) side, and Nimantani River and Madani River on the right (south) side can also be seen. On the north side of Oda River, the low ground is surrounded by dikes of Oda River and Takahashi River, while the mountains spread out in the north. The lines of the dikes of the tributaries, Suemasa River and Takama River, flowing in the low ground are clearly recognized. Accordingly, it can be understood that the dikes of not only large rivers but also the tributaries border the low ground. Moreover, the riverbed height of these tributaries is higher than that of the area surrounded by the dikes. Thus, these tributaries form raised bed rivers.

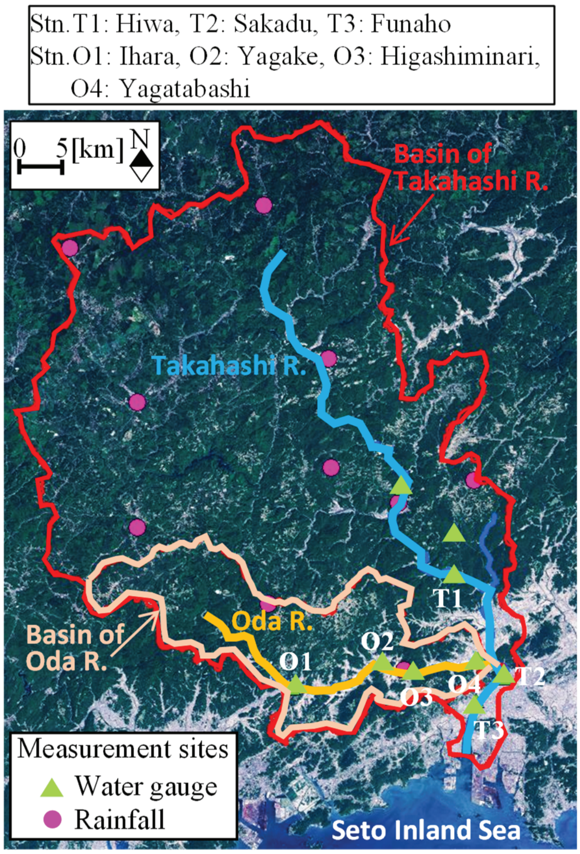

Fig. 1. Basin of the Takahashi River and Oda River and locations of measurement sites for rainfall and water level.

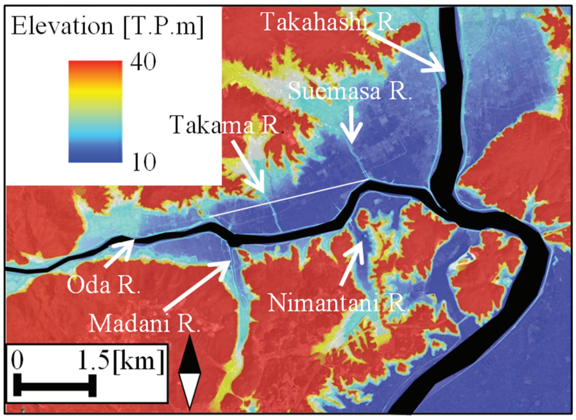

Fig. 2. Contour map of ground elevation near Oda River.

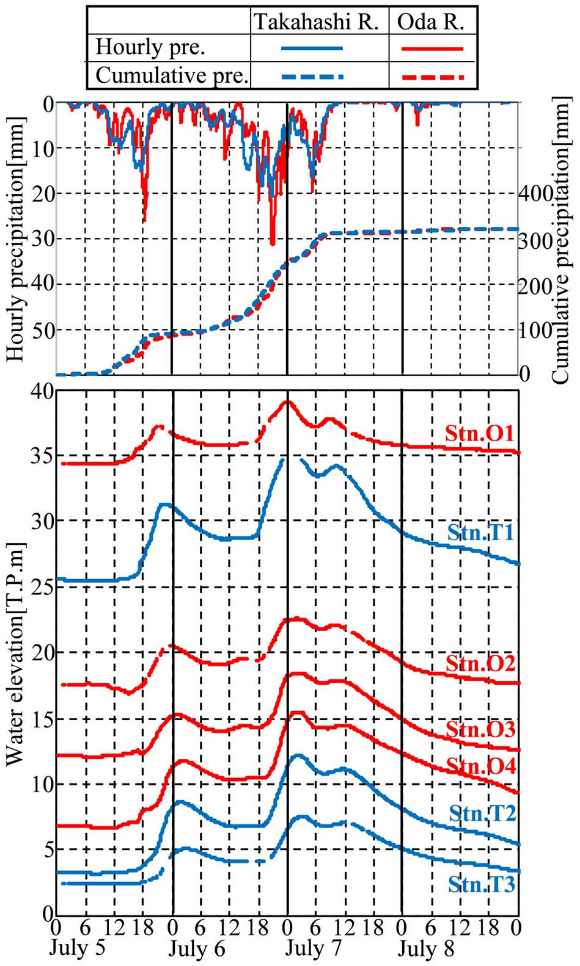

Fig. 3. Temporal change in hourly and cumulative precipitation calculated using basin average and C- and X-band radar observations, and in river water level.

2.2. Weather Conditions and River Water Level

To understand the weather conditions and river water level in the Takahashi River and Oda River basins during the flood disaster, the time series in the amount of rainfall and river water level during the period from 0:00 on July 5, 2018 to 0:00 on July 9 is shown in **Fig. 3**. For the amount of rainfall, the hourly and cumulative precipitation are shown by averaging the precipitation data observed by the C-band and X-band multi-parameter synthetic radars of the XRAIN (eXtended RAdar Information Network) rainfall observation system [9] in both river basins. **Fig. 3** also shows the river water level at seven measurement sites, namely, Ihara (25.6 kp (kilopost) upward from the confluence with Takahashi River, Station (Stn.) O1), Yagake (13 kp, Stn. O2), Higashiminari (9.6 kp, Stn. O3), and Yagatabashi (0.8 kp, Stn. O4) along Oda River and Hiwa (27.6 kp upward from the mouth of the river, Stn. T1), Sakadu (10.2 kp, Stn. T2), and Funaho (6.4 kp, Stn. T3) along Takahashi River. It can be seen from **Fig. 3** that it started to rain at about noon on July 5, 2018, but the rain eased up in the evening of the same day. However, it started to rain again at about noon on July 6, with intense rains continuing until the morning on July 7, when the total amount of rainfall exceeded 300 mm. There is no significant difference between both basins. For hourly precipitation, two large peaks can be recognized, one for the night on July 6 and the other for the morning on July 7, with the former larger than the latter.

With respect to the change in water level of Takahashi River and Oda River, two peaks can be distinctively recognized at the Ihara (Stn. O1) and Hiwa (Stn. T1) measurement sites in the upper reaches of Oda River and Takahashi River, with the first peak value greater than that of the second peak at both measurement sites. At the other measurement sites, the first peak of water level is clearly distinctive, but the second peak is not clear. This tendency is especially remarkable at the Yagatabashi site (Stn. O4) along Oda River and the Sakadu site (Stn. T2) along Takahashi River near the confluence of both rivers. It can also be seen that the water level decreased rapidly after the peak at 2 o'clock on July 7. For example, at Sakadu, a decrease in water level of 77 cm was recorded from 2 o'clock to 5 o'clock. The temporal change in water level at Yagatabashi along Oda River followed a similar pattern of change.

2.3. Outline of Field Surveys

To understand the situation on inundation and human damage, field surveys were conducted on 1) flood marks in the flooded areas, 2) flood marks within the river channels in Oda River and its tributaries, 3) damage to property, and 4) human damage. The surveys were conducted on July 11–12, 2018, July 18–19, August 1, and December 11.

In survey 1, the inundation height and depth were measured based on flood marks such as mud and vegetation deposits on houses in the flooded area around Oda River (**Fig. 4(a)**). In this survey, the ground level of a location where any flood mark was found was measured using RTK-GNSS (R6/R10, manufactured by Trimble Co., Ltd.), or the inundation height was directly measured if the flood mark was at a low level. The height from the ground to the flood mark (inundation depth) was measured to determine the inundation height (flood level) by adding inundation depth to ground level. This survey covered the entire flooded area on the left and right sides of Oda River, and the number of survey points was 170.

In survey 2, the flood mark, riverbed height, and height of the dike crest within the river channels were measured using RTK-GNSS and by leveling staff, as shown in **Fig. 4(b)**. The rivers surveyed were Oda River and its tributaries, Suemasa River, Takama River, Madani River, and Uchiyamadani River.

In survey 3 on house damage, the areas around Oda's tributaries Suemasa and Takama were surveyed. The damage was classified into one of the following six categories based on the extent of damage: "washed away," "damage to the second floor," "damage to the first floor," "partly damaged," "only inundation," and "no damage."

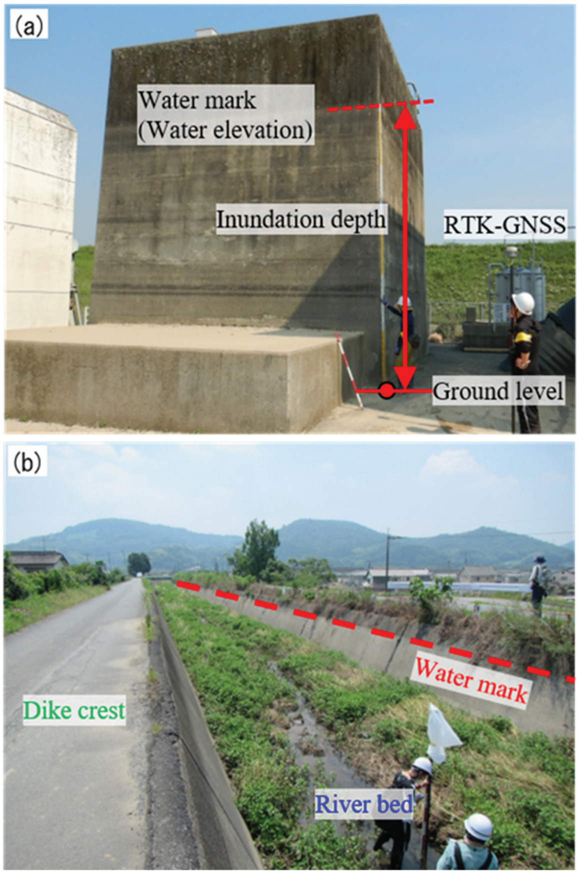

Fig. 4. Survey on flood marks in flooded area (a) and river channel (b).

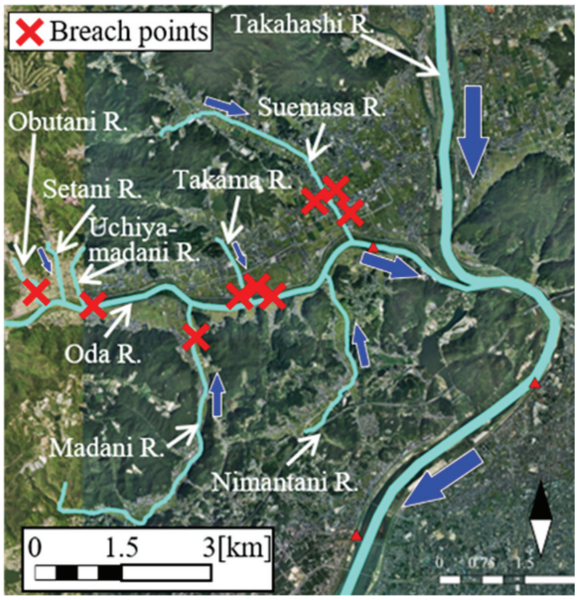

Fig. 5. Dike breach points in the lower reaches of Oda River and its tributaries.

In survey 4 on human damage, information on the dead, such as age, address, and damage situation, was collected mainly through newspaper articles and reports from residents. The materials of the investigation commission on "the Heavy Rain of July 2018" of Okayama Prefecture were also used [10].

3. Results and Discussion

3.1. Dike Damage Situation

A map of and detailed information on the dike breach points along Oda River and its tributaries are shown in **Fig. 5** and **Table 1**, respectively. The data on dike height, breach width, and breach height (= dike height − bed height) in the table were sourced from the investigation commission on dikes along Oda River of the Takahashi river system [11]. The estimated breach time was determined based on the testimonies of residents and image data from mass media. Although the damage to dikes along Obutani River was not considered as dike breach by the investigation commission [11], this location was added to the dike breaches in this paper in light of the erosion of the dike on the field.

It can be seen from **Table 1** that there were two dike breaches along Oda River at the 3.4 kp and 6.4 kp points, which were located on the left side of the river and at the downstream side of the confluences with its tributaries. The point of dike breach at 3.4 kp was located at the downstream side of the confluence with Takama River and that at 6.4 kp at the downstream side of the confluence with Uchiyamadani River. The breach width was 92 m and 54 m at the 3.4 kp and 6.4 kp points, respectively. For the tributaries of Oda River, there were three points of dike breach along Suemasa River (0.4 kp on the left side, 0.7 kp on the left side, and 0.7 kp on the right side), two points along Takama River (0.0 kp on the left side and 0.1 kp on the right side), one point along Madani River (0.5 kp on the left side), and one point along Obutani River (0.1 kp on the right side). In total, the dikes were breached at two points along the main river and seven points along its tributaries. The breach width varied, ranging from 20 m at the 0.0 kp on the left side along Takama River to 110 m at the 0.7 kp point on the left side and 150 m at the 0.7 kp point on the right side of Suemasa River.

From the estimated breach times, it can be seen that the right side of Takama River at the 0.1 kp point was breached first at around 11:30–12:00 pm on July 6, followed by the right side of Suemasa River at the 0.7 kp point at about 0:00 on July 7. Next, the left side of Oda River at the 3.4 kp point was breached at around 3:00–3:30 am on July 7, followed by the left side of Suemasa River at the 0.4 kp and 0.7 kp points at around 7 am the same day. For the other breach points, except the one along Obutani River, for which the estimated breach time is not available, it is supposed that the dikes were breached before dawn on July 7 based on the testimonies of residents and the surrounding state of inundation. The dikes were thus breached one after another over time, but it is important to note that a dike breach

Table 1. Detailed data on dike breach points (hyphen indicates that the item is neither measured nor determined).

River	Breach points	Bank	Dike height [T.P.m]	Breach width [m]	Breach height [m]	Estimated breach time
Oda R.	3.4 kp	Left	16.0	92	7.5	July 7, 3:00–3:30 am
	6.4 kp	Left	17.2	54	6.3	–
Suemasa R.	0.4 kp	Left	15.5	40	7.0	July 7, around 7 am
	0.7 kp	Left	15.4	110	3.4	July 7, around 7 am
	0.7 kp	Right	15.2	150	6.1	July 7, around 0 am
Takama R.	0.0 kp	Left	15.8	20	6.8	–
	0.1 kp	Right	15.8	55	6.1	July 6, 11:30–12:00 pm
Obutani R.	0.1 kp	Right	–	57	–	–
Madani R.	0.5 kp	Left	16.5	75	6.2	–

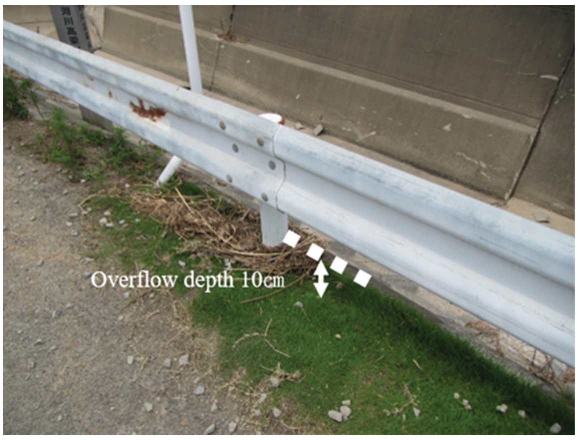

Fig. 6. Situation of overflow near the right side of Takama River at the 0.1 kp point.

occurred not only at night, but also in the morning.

A main factor of dike breach was overflow, according to the investigation commission [11]. **Fig. 6** shows a flood mark on a dike crest near the right side of Takama River at the 0.1 kp point. Although the overflow depth is 10 cm, as can be seen, a mark of overflow can be recognized.

3.2. State of Inundation of Flood Water

The measured values of inundation depth and height (flood level) obtained from the survey on flood mark are shown in **Figs. 7(a)** and **(b)** to illustrate the state of inundation. **Fig. 7(a)** shows that the area on the north (left) side of Oda River was widely inundated and points to an inundation depth exceeding 5 m were found all over this area. On the other hand, on the south (right) side of Oda River, the range of inundation was narrower than that on the north side, and inundation occurred mainly around the tributaries, with an inundation depth exceeding 4 m recorded along Madani River. The maximum value of inundation depth recorded in this survey was 5.38 m on the north side of Oda River.

Similarly, **Fig. 7(b)** on inundation height shows that on the north (left) side of Oda River, the values were higher in the west and lower in the east. The magnitude relation that upper reaches are larger than lower reaches is applied as in the case of riverbed height. Therefore, it can be generally understood that the flood flow moves from west to east. However, on the south (right) side of Oda River, the flood level was higher locally around Madani River and at other locations, but no distinctive tendency can be recognized regarding the upper and lower reaches of the river. This indicates that the inundation of flood water on the south side of Oda River occurred locally as a result of overflow around the tributaries, Madani River and Nimantani River. The lower locations of dikes on the right side of Oda River and the flood flow dose are not linked because of the topographical factor.

An aerial map of inundation depth was drawn using point data on inundation depth. **Fig. 7(c)** shows the contour of the inundation height, which was generated by interpolating point data on inundation height, as Sayama and Takara [12] did. For this purpose, natural neighbor interpolation of ArcGIS 10.3 was used. **Fig. 7(d)** shows the contour of inundation depth, which was generated by subtracting the altitude data, obtained using DEM, from the obtained inundation height. From this figure, it can be understood that an inundation depth exceeding 5 m occurred along 1 km in the north-south direction and 3.5 km in the east-west direction on the north side of Oda River. A major part of the inundated area on the north side had an inundation depth exceeding 3 m. However, it can be seen that on the south side of Oda River, the inundation depth exceeded 5 m around Madani River. The values of inundation depth are generally measured by supposing the road surface as the ground level. However, the area with

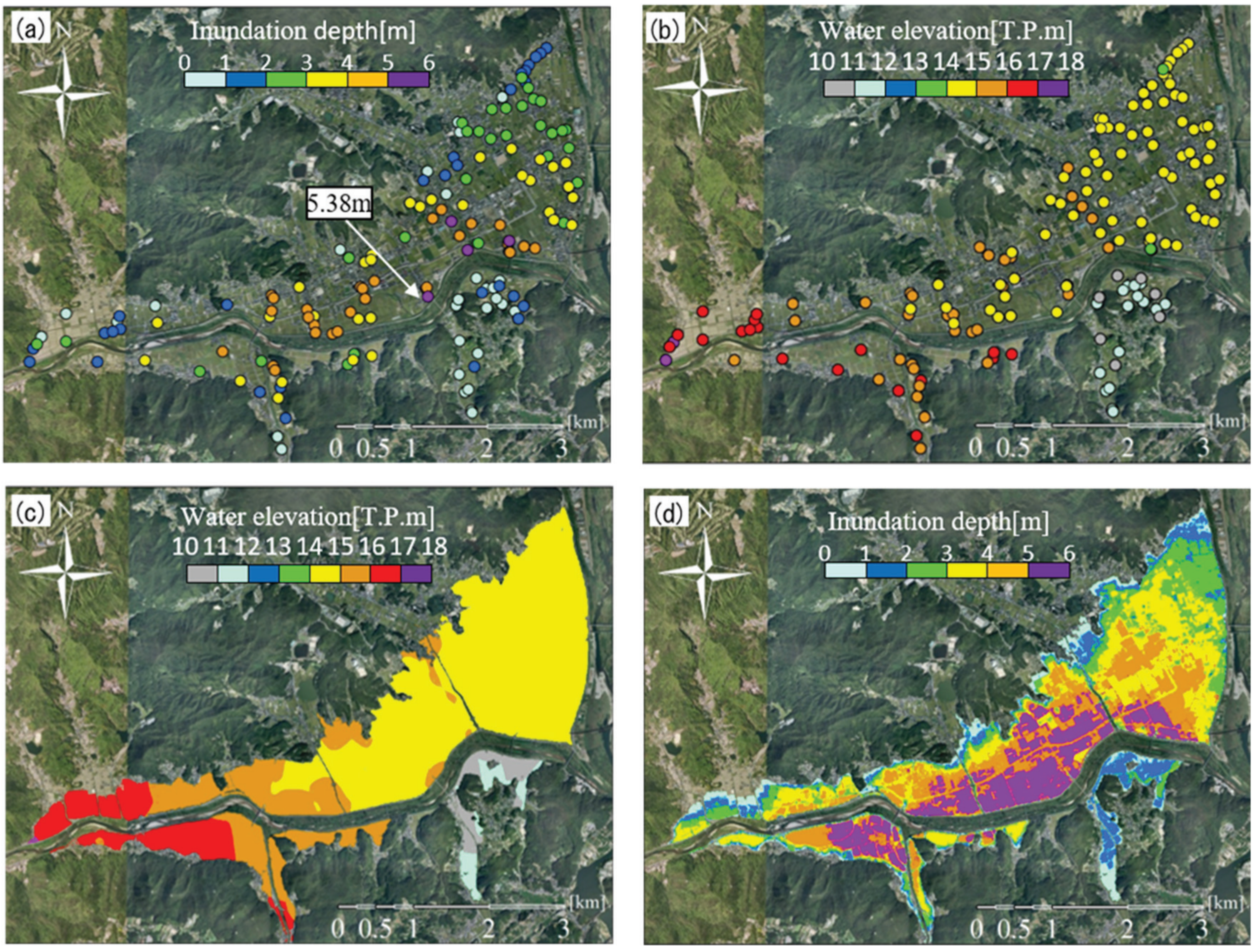

Fig. 7. State of inundation along Oda River (measured values of inundation depth (a), measured values of inundation height (b), contour of inundation height (c), and contour of inundation depth (d)).

Table 2. Comparison between the inundation situation along Oda River in 2018 and that along Kinugawa River during the Kanto and Tohoku heavy rain in 2015 [13].

Name	Western Japan heavy rain in 2018	Kanto and Tohoku heavy rain in 2015
Place	Mabi town, Kurashiki city, Okayama prefecture	Joso city, Ibaraki prefecture
Inundation area [km^2]	10.3	40
Inundation volume [10^4 m^3]	3,531	3,400
Max. of inundation depth [m]	5.38	3.01
Breach time	Nighttime	Daytime

an inundation depth of over 5 m on the north and south sides was extensive, since rice paddy fields are at a lower level than the road surface.

Table 2 shows the comparison between the inundation situation along Oda River in the 2018 heavy rain and that along Kinugawa River following the Kanto and Tohoku heavy rain in 2015 [13]. The table shows that the inundation area along Oda River was 10.3 km^2, which corresponds to about one-fourth of the 40 km^2 along Kinugawa River. However, the inundation volume was similar for both floods at 35.3 million m^3 in the case of Oda River and 34 million m^3 in the case of Kinugawa River. Thus, it appears that the inundation depth was greater in the case of Oda River, because the large volume of inundation occurred in a relatively narrow area.

3.3. Longitudinal Distribution of Flood Marks in River Channel

The longitudinal distribution of the elevation of flood marks in the river channels of the tributaries is shown in **Fig. 8** to illustrate how the flow regime influenced the inundation. The figure shows the findings for the four Oda tributaries of Suemasa River, Takama River, Uchiyamadani River, and Madani River. The longitudinal distribution of dike height and riverbed height are also shown. It can be seen from **Fig. 8** that in Suemasa River, the flood mark shifted almost horizontally in a section beginning from its confluence with Oda River and extending to a point about 1.1 km upward. The horizontal flood level was influenced by backwaters from Oda River. A simi-

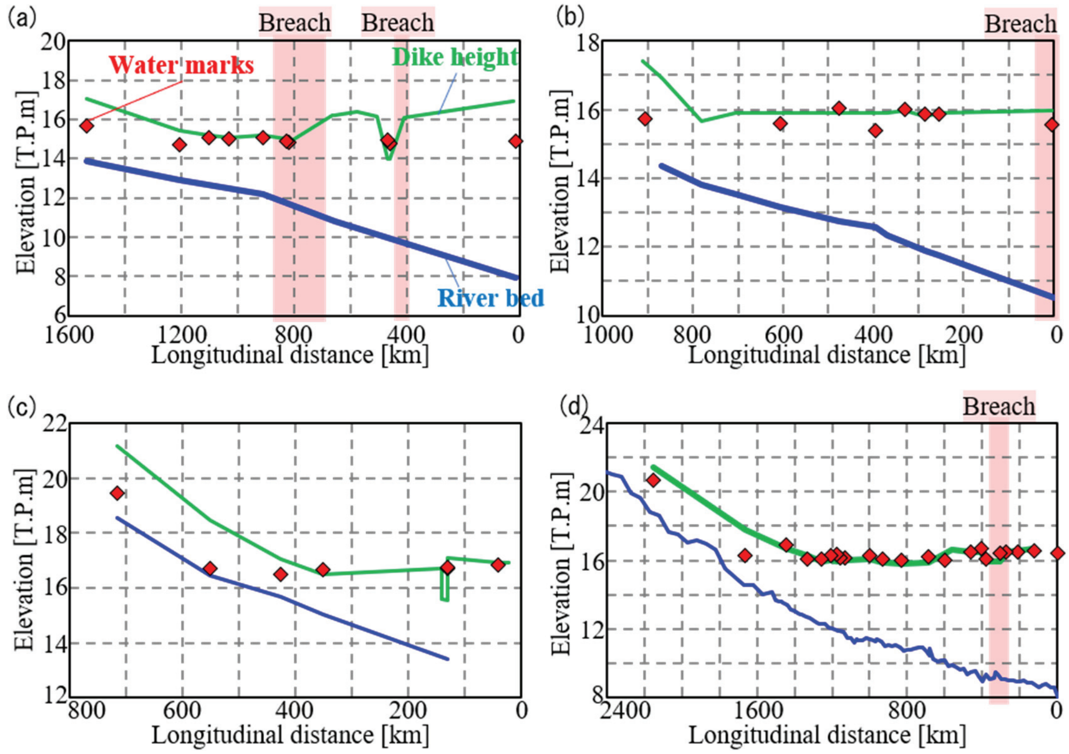

Fig. 8. Longitudinal distribution of elevation of flood marks and dike height in tributaries (Suemasa River (a), Takama River (b), Uchiyamadani River (c), and Madani River (d)).

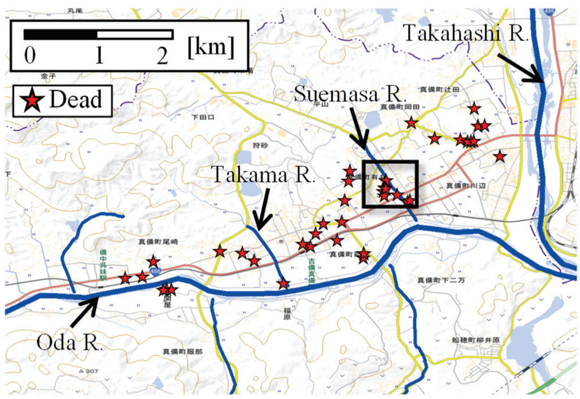

Fig. 9. Locations where persons died in Mabi Town. Square with black line is the range of **Fig. 10**.

lar tendency is seen in the other three tributaries. Such sections with an almost horizontal level of flood mark can be seen for 600–800 m in Takama River, about 400 m in Uchiyamadani River, and about 1,400 m in Madani River. It can be understood that the flood mark water level exceeded the dike height at some locations, causing overflow. For example, in Suemasa River, overflow occurred at a point about 0.8 km upward from the confluence with Oda River, where dike height was lower. It is supposed that the dike height is lower at a point about 0.4 km upward because of an intersection with a road, which triggered a dike breach.

3.4. State of Human and House Damage

The locations of the houses in Mabi Town (41 houses in all) where 51 persons died because of the flood disaster are shown in **Fig. 9**. The figure shows 38 houses in the disaster area on the left (north) side of Oda River where 47 persons died, and three houses on the right (south) side where four persons died. Specifically, there are 7 houses on the west side of Takama River, 19 between Takama River and Suemasa River, and 12 on the east side of Suemasa River. The number of houses between Takama River and Suemasa River, where the Yata and Arii districts of Mabi Town are located, is remarkably high. Thus, human damage was higher on the left side of Oda River, though the damage was concentrated not near the river, but near the shelter located on the north side of the area.

The state of house damage near the points of dike breach and the locations where human damage occurred are shown in **Fig. 10**. In this figure, the extent of house damage is represented by different colored circles, and the locations where human damage occurred are indicated with a star symbol whose color follows the same criteria as those of the circle. It can be seen from **Fig. 10** that in the vicinity of the dike breach at the 0.7 kp point in Suemasa River, there were cases of houses that were “washed away” or suffered “damage to the first floor” or “damage to the second floor,” but the majority of house damage was placed in the “only inundation” category. At the locations where human damage occurred, only two

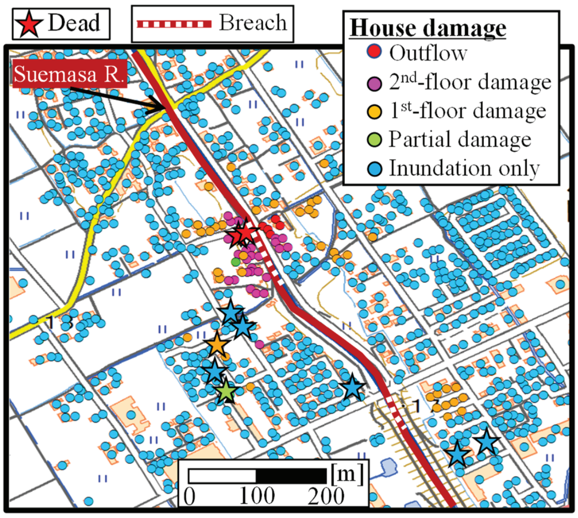

Fig. 10. Relation between the situation on house damage and that on human damage around points of dike breach in Suemasa River.

houses were placed in the "washed away" category, one house in the "damage to the first floor" category, one house "partly damaged," and six houses in the "only inundation" category. Thus, it can be seen that the extent of house damage was relatively small compared to human damage in what is a significantly different scenario from the case of sediment disaster in the mountains.

To shed light on the characteristics of human damage, the findings on the location where the dead were found and the state of home inundation (i.e., inundation depth, time when inundation started, and rate of water level increase) are shown in **Fig. 11**. The inundation depth and the time when inundation started were calculated from the findings of the field survey, while the rate of the increase in water level was calculated from the simulation on inundation of flood water in Mabi Town, which was carried out separately based on the authors' model [14]. According to the findings, 44 persons were found dead in their own houses, with 43 of them found on the first floor. The locations of the two houses (nearly 5% of the total), which were washed away, were in the vicinity of the dike breach points on the right side of Suemasa River and on the left side of Takama River. As mentioned above, the inundation, rather than the washing away of houses, had a significant influence on human damage.

In terms of inundation depth at home, 37 persons, or nearly 73% of all dead people, suffered inundation with a depth of 3 m or more, indicating submergence of the first floor, and 24 persons suffered inundation with a depth of 4 m or more. This finding highlights the difficulty in vertical evacuation. The remaining 14 persons (27% of all dead people) experienced an inundation depth ranging from 2 m to 3 m, indicating submergence of a large part of the first floor. For 38 persons (75%), inundation started at night when the dike was breached along Oda River. However, for 13 persons (25%), inundation started at daytime. Therefore, human damage occurred both at night and during day, indicating that the damage was triggered regardless of the time when inundation started. Furthermore, the water level rose at a rate of 1 m/h or more at the houses of 35 persons, which was significantly higher than the maximum rate of water level increase of 0.5 m/h in the flooded area of Kinugawa River during the Kanto and Tohoku heavy rain in 2015 [15].

About 80% of the dead were found on the first floor, of whom those who had lived in a one-story house and those in a two-story house accounted for 50% each, indicating how difficult even vertical evacuation was. The findings appear to be related to the considerable inundation depth and high rate of water level increase, in addition to the fact that 45 persons, the majority of the deceased, were those aged 65 years or more.

4. Conclusion

In this study, field surveys were conducted to assess the state of inundation of flood water along Oda River during the Western Japan heavy rain disaster in 2018, and the resultant human damage. The main conclusions are as follows:

1) Inundation with a depth exceeding 5 m occurred along 1 km in the north-south direction and 3.5 km in the east-west direction on the north side of Oda River. A major portion of the inundated area on the north side had an inundation depth exceeding 3 m.
2) The inundation area in the case of Oda River was 10.3 km^2, which corresponds to about one-fourth of that of the Kinugawa River flood in 2015, while the inundation volume was 35 million m^3, similar to that of the Kinugawa River flood. Accordingly, it appears that the inundation depth was greater in the case of Oda River, because a large volume of inundation occurred in a relatively narrow area.
3) The elevation of flood marks of the tributaries shifted almost horizontally in a section near their confluence with Oda River and was influenced by backwaters from Oda River.
4) About 80% of the dead were found on the first floor, of whom those who had lived in a one-story house and those in a two-story house accounted for 50% each, indicating how difficult vertical evacuation was. The findings appear to be related to the considerable inundation depth and high rate of water level increase, in addition to the fact that the majority of the deceased were elderly people.

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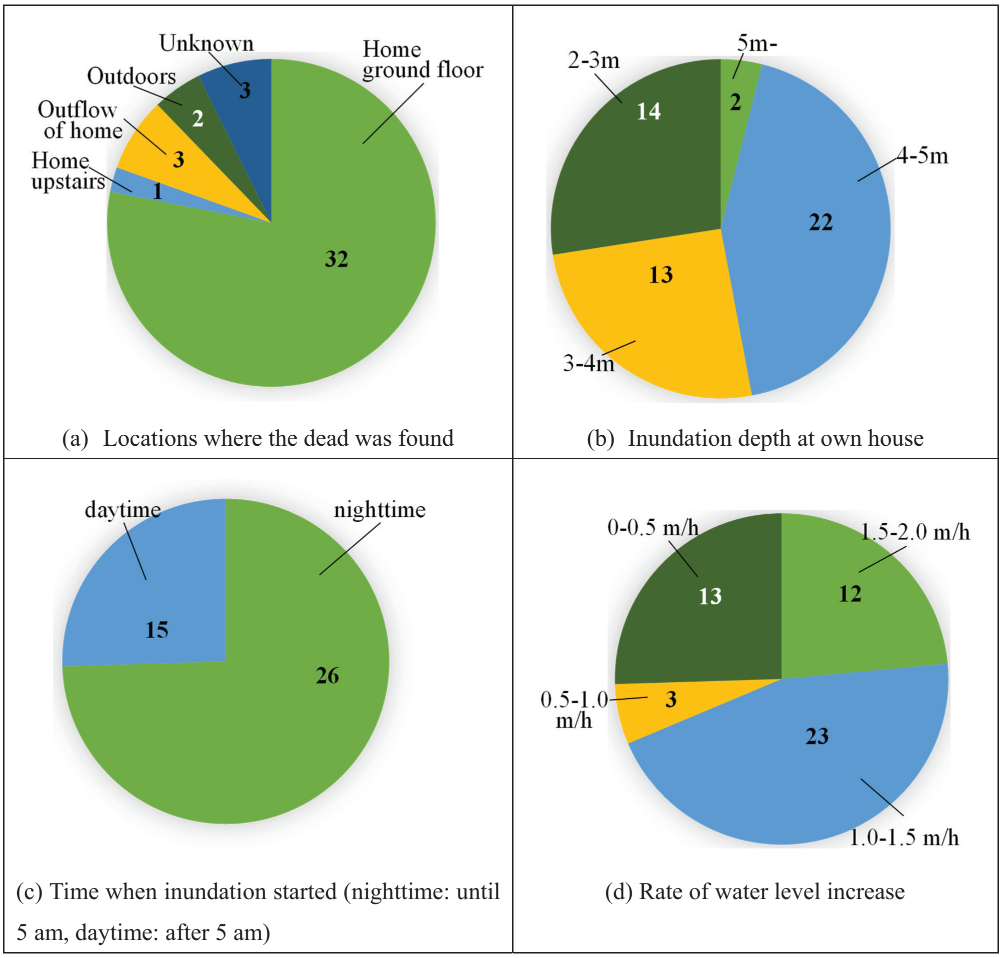

(a) Locations where the dead was found

(b) Inundation depth at own house

(c) Time when inundation started (nighttime: until 5 am, daytime: after 5 am)

(d) Rate of water level increase

Fig. 11. Summary of characteristics of human damage (Unit: people).

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