Research article

Estimation of Flooded Areas and Water Levels after the Heavy Rain in July 2018 in Okayama

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Abstract Paddy fields in the Osaka Prefecture were heavily flooded by heavy rain in July 2018 due to levee breaches. To estimate the flooded area and water level, it was necessary to combine aerial- and ground-based surveying. Accordingly, aerial photographs of the flooded area were taken on the day after the heavy rain. In this study, we developed a digital surface model (DSM) of the flooded area using the structure-from-motion (SfM) software, which can produce three-dimensional (3D) models based on multiple aerial photographs and multiple ground control points (GCPs). Using the global navigation satellite system (GNSS), we surveyed the target area to observe the 3D coordinate values of the GCPs. The DSM of the flooded area could be made by the SfM with the aerial photographs and GCPs. The DSM was input into the geographic information system to analyze the flooded area and water level. The water levels were calculated from the differences between the DSM and the digital elevation model (DEM). We used airborne laser surveying to build the DEM because it provides higher accuracy than the SfM software. To check the accuracy of the DSM, we compared the elevations of the DSM on the ground points of non-flooded areas with those of the DEM, and the differences were found to be less than 0.2 m. Then, the water levels on the actual water level observation points were compared to verify their accuracy, and the differences were found to be less than 0.4 m. The flooded area was found by overlaying the water level on the existing map.

Keywords structure-from-motion, digital surface model, digital elevation model, geographic information system, paddy field

INTRODUCTION

Heavy rain in July 2018 seriously affected the Okayama Prefecture in the west of Japan (particularly the paddy fields) due to levee breaches. As a result, nearly half of harvest of the paddy fields was lost.

A combination of aerial- and ground-based surveys was necessary for a prompt understanding of the complete picture of the damaged area (Kubodera et al., 2017). Therefore, we conducted an aerial photogrammetry and a global navigation satellite system (GNSS) survey. Aerial photogrammetry is a surveying technology that utilizes three-dimensional (3D) ground-based models, which are constructed from aerial photographs, camera coordinate values, and coordinate values of ground control points (GCPs). Based on the aerial photogrammetry, we also built orthophoto mosaics and a digital surface model (DSM), which captures the land surface elevations, including the heights of buildings and vegetation. An orthophoto mosaic is a single aerial photograph on which several orthographically projected aerial photographs are assembled. To obtain the coordinate values of the GCPs in the devastated areas, we conducted a GNSS survey (Yamazaki et al., 2019), which is a method to determine the positions using signals from positioning satellites, such as the global positioning system (GPS), global navigation satellite system (GLONASS), and Galileo. The accuracy of these satellites ranges from several meters to several millimeters. In this research, we conducted a network-based real-time kinematic (RTK) GNSS survey to determine the coordinate values of the GCPs with an accuracy of several millimeters. We used the geographic information

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system (GIS) to determine the difference between the DSM and digital elevation model (DEM), which captures the ground elevations (excluding the heights of buildings and vegetation), to analyze the flooded area and water level in the paddy fields quantitatively.

We considered that aerial photogrammetry by airplane would be preferable than by satellite or drone for the analysis of the flooded area and water level. The aerial photographs used were captured from an airplane immediately after the heavy rain. The Geospatial Information Authority of Japan (GSI) has built a detailed database of Japan's land surface from photographs taken from airplanes and has released the DEM (5 m mesh) from airborne laser surveying throughout Japan. Furthermore, the GSI has released aerial photographs of Okayama taken immediately after the heavy rain in July 2018.

METHODOLOGY

Figure 1 shows the target area of the survey and analysis. The Okayama Prefecture is located to the west of Osaka and Kyoto. Of the large area damaged by the heavy rain, we selected Mabi City to focus on the damage to paddy fields. Figure 2 shows the levee breach at the Oda river in Mabi City that caused the flooding of the paddy fields. The first author took the picture on November 10, 2018.

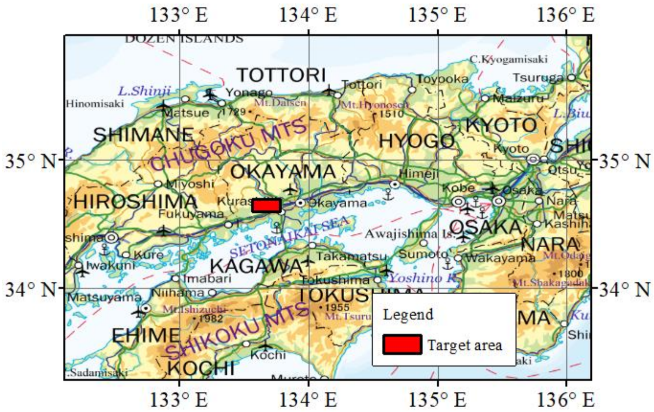

Fig. 1 Target area in Okayama

Fig. 2 Levee breach at Oda River in Mabi City

The first author took the picture in Novemeber 10, 2018.

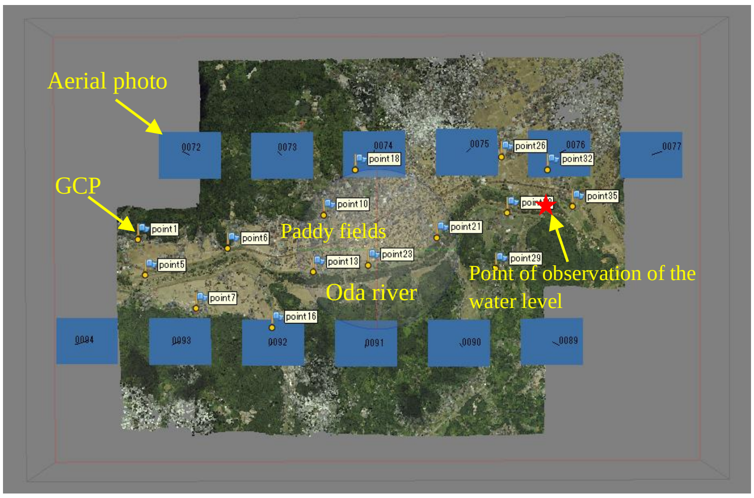

Fig. 3 3D model by aerial photogrammetry

Fig. 4 GNSS surveying

We used the photogrammetry structure-from-motion (SfM) software PhotoScan Professional, which allows the aerial triangulation based on multiple aerial photographs and multiple GCPs. It is used to build DSMs through image matching and create orthophoto mosaics automatically. Figure 3 shows the 3D model built in this study. The Oda river and paddy fields are in the center of Fig. 3; the point of water level observation, which was performed every hour, is in the right of Fig. 3. The twelve blue rectangles in the sky show the 3D positions from which the aerial photographs were taken. The 15 circles on the ground surface indicate the 3D positions of the GCPs where we conducted the GNSS survey. AS coordinate system, we used the Japanese geodetic datum (JGD) 2011 plane-rectangular coordinate system Area 5 (Matsumura et al., 2004; Tsuji and Matsuzaka, 2004; Imakiire and Hakoiwa, 2004; Geospatial Information Authority of Japan, 2011). We successfully set a group of 3D points on the ground surface through aerial photogrammetry. The aerial photographs were taken at 12:00 on July 9, 2018, immediately after the heavy rain with a well-calibrated digital aerial camera. Using the RTK GNSS surveying and inertial measurement unit (IMU) technology, we set the coordinate axes and altitudes of the digital aerial camera with an accuracy of several tens of millimeters.

As shown in Fig. 4, we conducted a network-based RTK GNSS surveying at GCPs in Okayama on November 10, 2018. We used the Trimble R10 for the GNSS surveying, and three types of satellites: GPS, GLONASS, and the quasi-zenith satellite system (QZSS). In addition, we used two frequency bands: L1 (1575.42 MHz) and L2 (1227.60 MHz). We used the geoid model GSIGEO2011 (Miyahara et al., 2014; Kubodera et al., 2016). For the GNSS survey at the GCPs, we selected the fifteen points enclosing the flooded area and the point of observation of the water level, sites accessible by car, and pavements to obtain clear photographs.

We conducted aerial triangulation based on the 3D coordinate values of the camera and the GCPs. Table 1 shows the standard deviation (SD) values of the residual errors of the most probable values of fifteen GCPs. The SD values for the X and Y coordinates and elevation H were lower than 0.10 m, indicating high accuracy.

We created a DSM with 0.4 m mesh to determine the differences between the DSM and DEM. Furthermore, we created orthophoto mosaics to obtain more information on the flooded area.

RESULTS AND DISCUSSION

Specifying the Position of Levee Breaches with Orthophoto Mosaics

Figure 5 shows the orthophoto mosaic developed on the GIS. For the aerial photogrammetry, we used the coordinate axis JGD2011 Plane-rectangular Coordinate System Area 5. The GIS software used was ArcGIS 10.7. By comparison with an existing map, we confirmed that the mosaic was developed on the designated positions correctly. The black areas in Figure 5 were either not in the aerial photograph field of view or covered by cloud or water, because SfM could not create the clouds and water. As shown in Figure 6, we successfully specified the exact positions of the levee breaches, and the orthophoto mosaic indicates that the paddy fields were flooded.

Table 1 SD values of the residual errors of the most probable values of fifteen GCPs

	X [m]	Y [m]	H [m]
SD	0.097	0.061	0.078

DSM accuracy verification

We compared the elevation values of the DSM to those of the actual water surface at the point of water level observation to verify the accuracy of the constructed DSM. Figure 7 shows a photograph of the instrument used to observe the water level in Yakatabashi, which observed the actual water level every hour during the heavy rain in July 2018. The first author took the picture on October 29, 2018. Figure 8 shows the DSM of the area around Yakatabashi. The areas of not-heat-map were those that PhotoScan Professional could not create the DSM.

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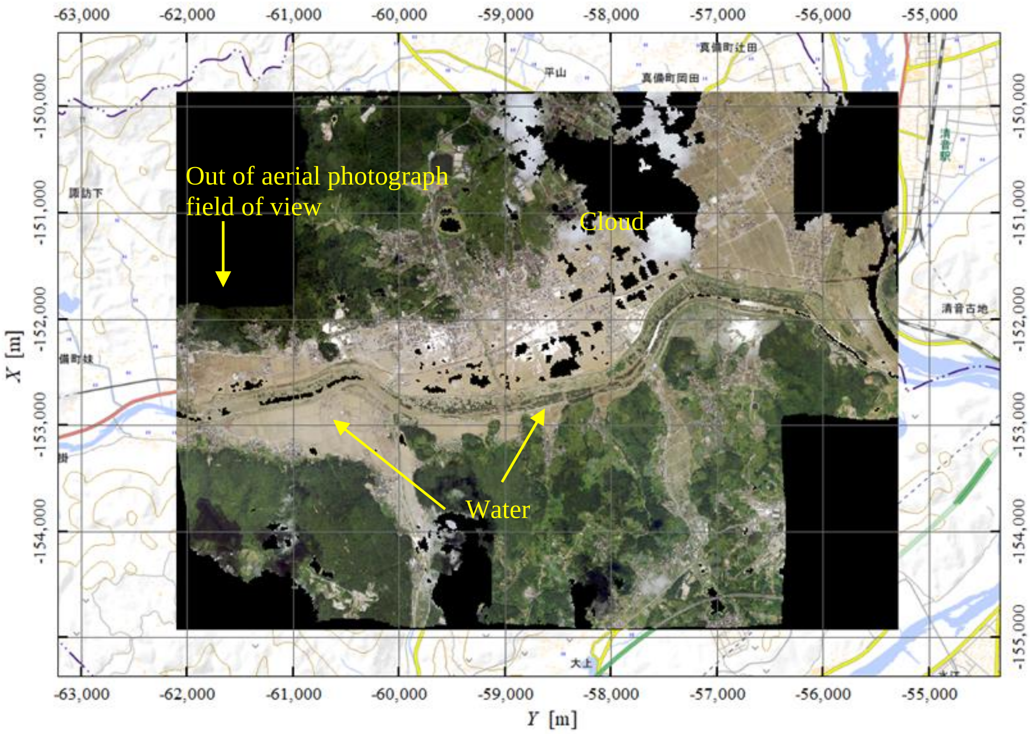

Fig. 5 Orthophoto mosaic developed from the GIS

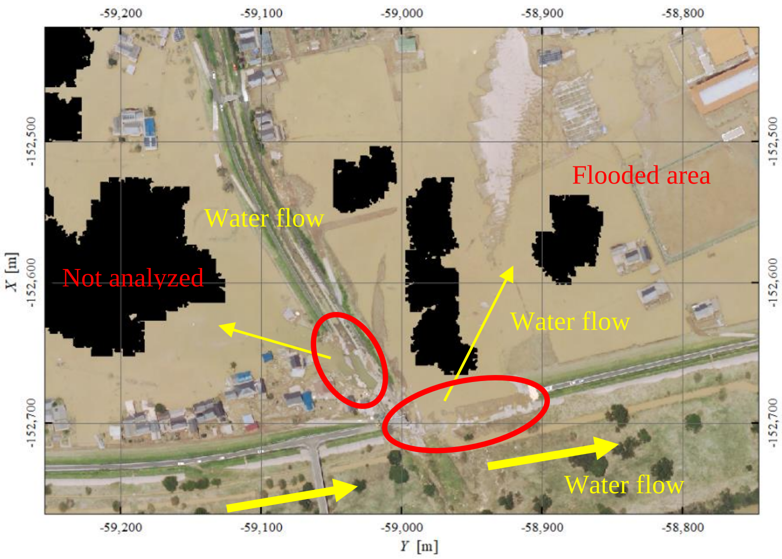

Fig. 6 Levee breaches and flooded paddy fields based on the GIS

Table 2 shows the elevation values in the DSM around Yakatabashi at 12:00 on July 9, 2018. The aerial photographs were taken at 12:00 on July 9, 2018. So, this DSM was at 12:00 on July 9, 2018. The elevation values of DSM were measured at 10 points in the water surface of the verification area of Fig. 8. The average and SD of the ten elevation values were 8.208 and 0.096 m, respectively. Table 3 shows the elevation values of the actual water surface at Yakatabashi on July 9, 2018. As shown in the table, the elevation values of the actual water surface at 12:00 was 8.167 m. Therefore, the difference between the elevation values of the DSM and those of the actual water surface was +0.041 ± 0.096 m.

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Fig. 7 The water level observation in Yakatabashi

The first author took the picture on October 29, 2018.

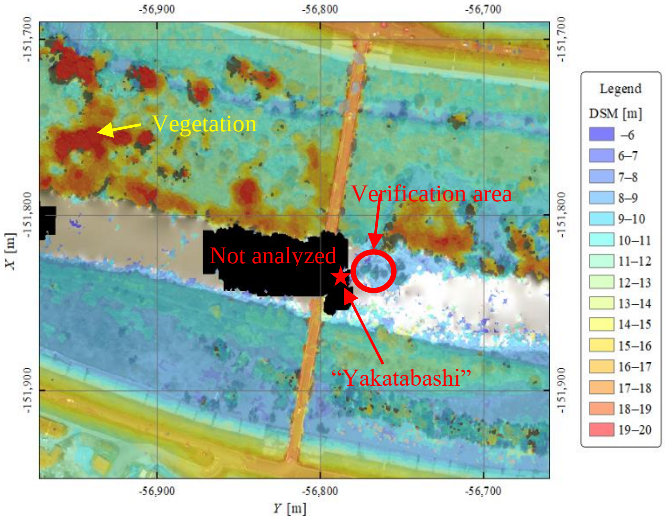

Fig. 8 DSM around Yakatabashi

Table 2 Elevation values in the DSM around Yakatabashi at 12:00 on July 9, 2018

No.	1	2	3	4	5	6	7	8	9	10	Ave.	SD
Elevation [m]	8.122	7.923	8.514	8.220	8.125	7.731	8.024	8.318	8.799	8.302	8.208	0.096

Table 3 Elevation values of the actual water surface at Yakatabashi on July 9, 2018

Time	09:00	10:00	11:00	12:00	13:00	14:00	15:00
Elevation of water surface [m]	8.507	8.357	8.247	8.167	8.107	8.047	7.987

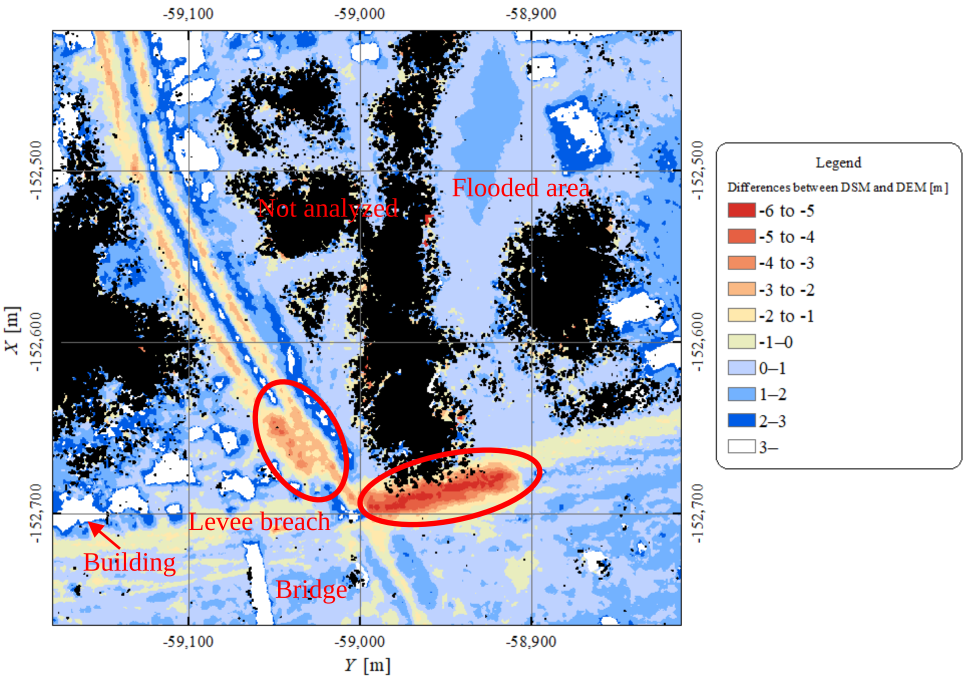

Fig. 9 Differences between DSM and DEM

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Differences between DSM and DEM

To build the DEM before the heavy rain, we used the results (5 m mesh, elevation value in units of 0.01 m) obtained from the GSI. We deducted the elevation values of the DEM before the heavy rain from those of the DSM after the heavy rain to obtain the differences. Figure 9 shows the results of the analysis in the same area as that shown in Fig. 6. The black areas indicate areas for which the PhotoScan Professional software could not create the DSM. We whited out the objects with a height difference greater than 3 m because these were assumed to be buildings or vegetation. The analysis results indicate that the vertical water level was 0‒2 m and vertical levee breaches levels were between -5 and -6 m. Based on the analysis of the differences between the DSM and DEM, we successfully clarified the vertical water level both dimensionally and quantitatively.

CONCLUSION

The contributions of this study are as follows:
(1) The exact levee breach in flooded paddy fields was specified based on the orthophoto mosaic.
(2) We compared the elevation values of the DSM and those of the actual water surface at the point of water level observation to verify the accuracy of the constructed DSM. We determined that the difference between the elevation values of the DSM and those of the actual water surface was +0.041 ±0.096 m.
(3) The analysis of the differences between the DSM and DEM indicated that the vertical water level was 0‒2 m and the vertical levee breaches levels were between -5 and -6 m.

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