Development of a real-time analysis method for inland flooding during heavy rainfall in urban areas and its application to evacuation and disaster mitigation

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1. Introduction

In watershed flood management, it is necessary to share the concept of collaboration among the main river basin, tributary river basins, and urban areas in a multi-layered watershed scale, according to each basin. The first priority is to explain the forms of rainfall-runoff, flood discharge, and inundation in an easy-to-understand manner to disaster prevention officials and local residents, and to discuss how to prepare for future river development, land use, and inundation. Fukuoka[1] proposed a basin water balance distribution map as a technical study method, and showed the significance of its application based on studies in various river basins of different sizes.

Considering the high frequency of inland flooding in recent years and the magnitude of damage caused by overlapping disasters of inland and river flooding, it is an important issue for basin flood control to construct a highly explanatory inland flooding analysis model and a basin water balance distribution map based on the model, even for inland flooded areas in urban areas. During the torrential rainfall in July 2020, Hitoyoshi City was severely damaged by internal flooding followed by external flooding. The evacuation of residents in areas at high risk of internal and external flooding, as well as the internal flooding forecasting technology that supports this evacuation, is an urgent issue.

Figure 1 shows the two methods used in this study to investigate inland flood disasters. The first is to develop a method for analyzing inland flooding (2D Inundation Model for Evacuation and Community planning: 2D-IMEC) that can precisely analyze inland flooding phenomena in Hitoyoshi city during the July 2020 heavy rainfall. The The second is the Real-time Inundation Model for Evacuation and Community planning (RIMEC). The city water balance distribution map based on RIMEC will be constructed using 2D-IMEC as teacher data, and will be used for future evacuation and disaster reduction planning.

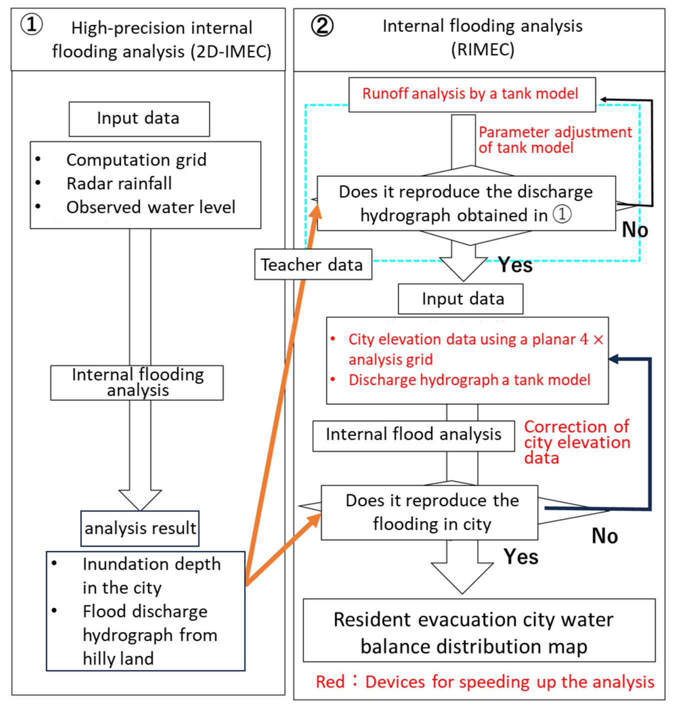

Figure.1 Overall picture of this study

2. Mechanism of internal flooding in Hitoyoshi city during heavy rainfall

2.1. Overview of the target urban area and the torrential rainfall in July 2020

The left figure in Figure 2 shows the target urban area of Hitoyoshi (approximately 10 km²).The area is shown in the left of Figure 2. In this area, rainwater is discharged into the Kuma River and other rivers through a 4-meter-wide channel indicated by the sky blue color. Rainwater is drained to the Kuma River Mae River and others through a 4-meter-wide channel shown in light blue. In the torrential rainfall in July 2020, the Kuma River was flooded from around 6:00 a.m. on July 4, 2020. The floodwaters of the Kuma River and Mae River flowed into the urban area from around 6:00 a.m. on July 4, 2020. One-fifth of all households were inundated, and as many as 21 people were dead.

The right figure in Figure 2 shows the result of the flooding in the city center. The right diagram in Figure 2 shows the time distribution of the July 2020 torrential rainfall.

The intensity of the downpour was about 60 mm/h in the urban areas. The northern hilly areas were more severely hit than the southern urban areas. In the hilly areas in the north, about 70 mm of rain fell in a short period of time compared to the southern urban areas.

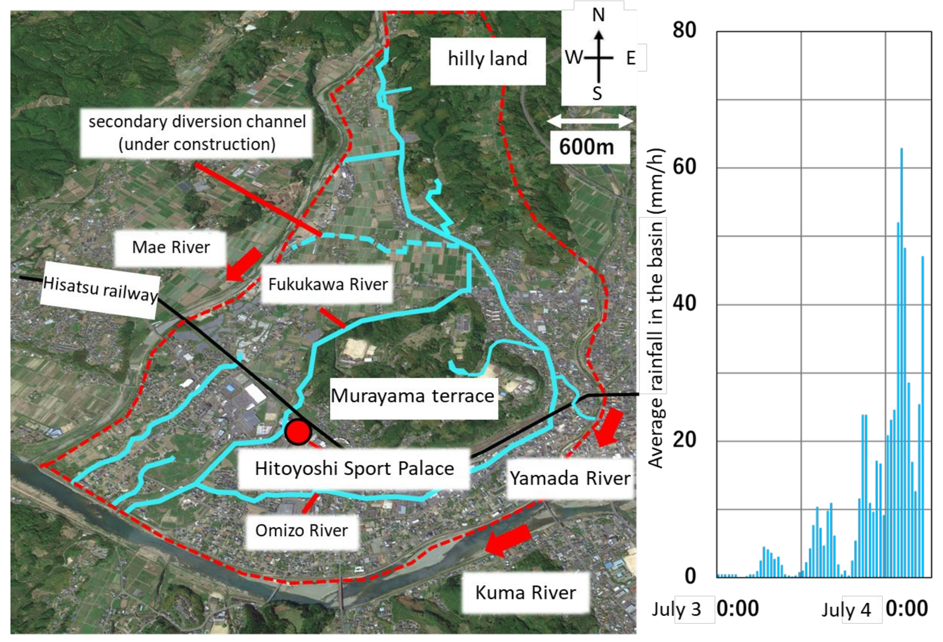

Figure.2 Outline of the target area and Hitoyoshi city torrential rainfall in July 2020

2.2. 2D Inundation Model for Evacuation and Community Planning (2D-IMEC)

Figure 3 shows a calculation method of the 2D-IMEC for the calculation of spatiotemporal distribution of inundation depth.

Creation of topographic and urban area model
①Lowland
Prefecture managed rivers and sewers surveying data, other small rivers, loads and buildings LP data (30 cm intervals)
②Hillsides · Terrace
DEM data (5m intervals)
Topographic and urban area models are created using the data ① and ②.

Upstream boundary conditions
JMA radar analysis rainfall(every 30 minutes at 1 km intervals)

Downstream boundary conditions
(Kuma R., Mae R., Yamada R.)
Water level by flood flow analysis

Spatiotemporal distribution of inundation depth

Figure.3 Outline of 2D-IMEC

2.3. Internal flooding machanism in Hitoyoshi city during the torrential rainfall in July 2020

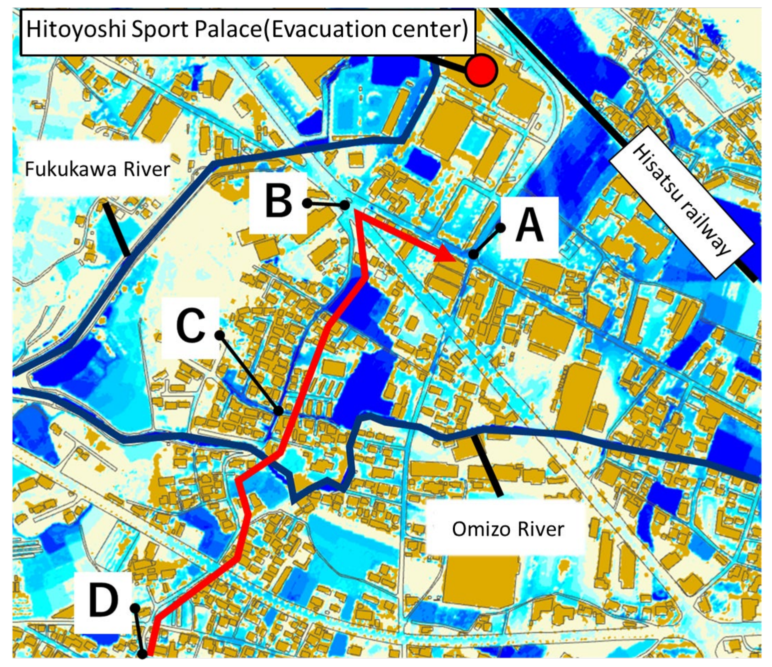

Figure.4 Inundation depth contour (2D-IMEC) at the time of the torrential rainfall in July 2020 (3:00 a.m. on July 4)

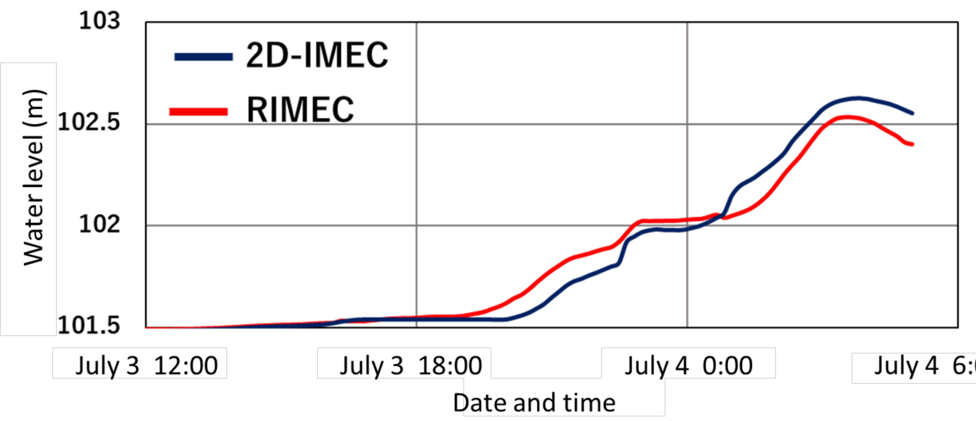

Figure.6 Inundation depth hydrograph at Point C

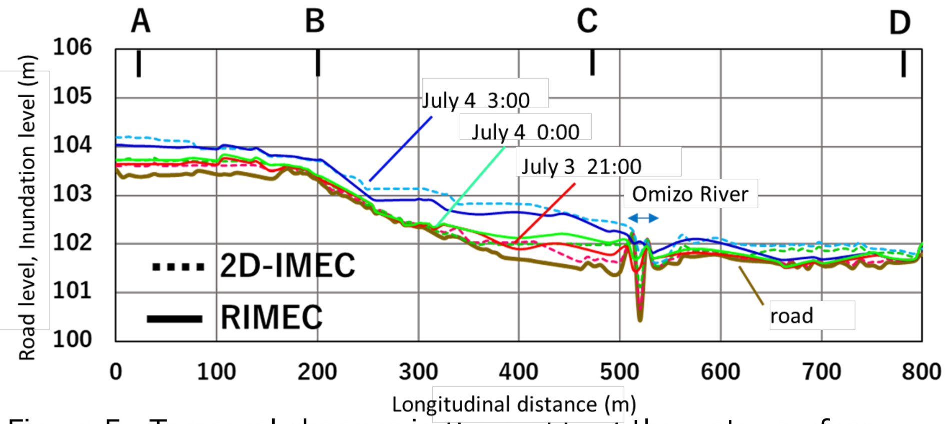

Figure.5 Temporal changes in the profile of the water surface along the evacuation route during the torrential rainfall in July 2020

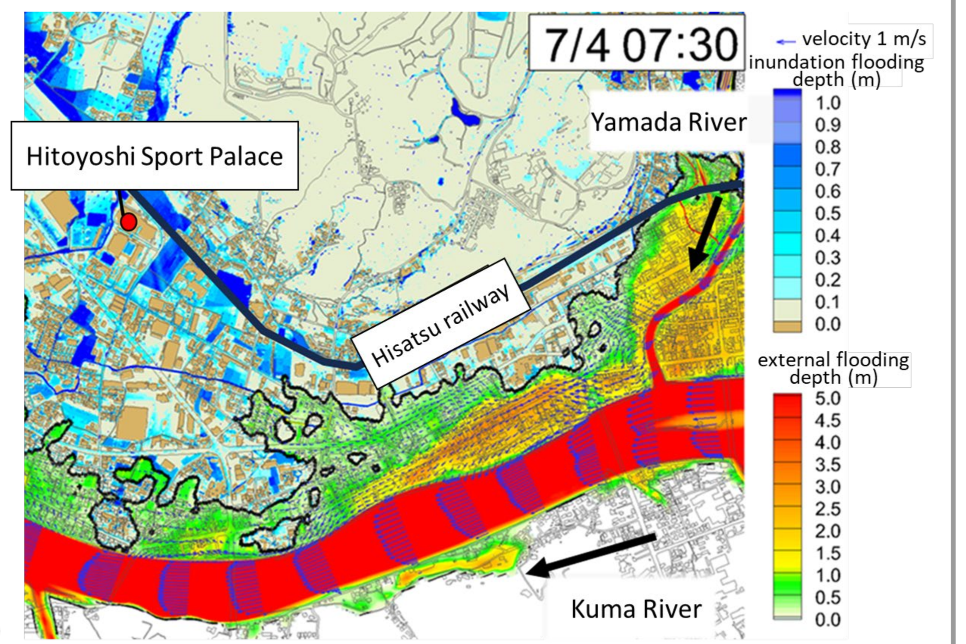

Figure.7 Overland map of internal flooding and external flooding analysis results from the torrential rainfall in July 2020.

Figure 4 shows the waterlogging depth contour around the evacuation center (Hitoyoshi Sports Palace) obtained from 2D-IMEC. In addition to waterlogging caused by the torrential rain, flooding from the Omizogawa River and Fukugawa River caused flooding of roads throughout the city. In particular, the roads leading to the evacuation centers (points A to D) are topographically prone to collect rainwater and flood waters, and as shown in Figures 5 and 6, the flood levels rose rapidly after midnight on the 4th when rainfall intensified. As a result, the inundation depth and velocity exceeded 1 m and 1 m/s, respectively, at 3:00 a.m. on the 4th day before the external flooding occurred, making evacuation difficult.

As shown in Figure 7 at 7:30 a.m. on the 4th, the situation of inundation due to internal flooding, which made it difficult to move around, was combined with external flooding, resulting in extensive damage. Therefore, in the event of a heavy rainfall that causes external flooding following internal flooding, evacuation of residents in the early stages of internal flooding and forecasting technology to support this evacuation are necessary.

3. Real-time analysis method for inland flooding (RIMEC) and its application to evacuation of residents

3.1. Real-time analysis method for inland flooding (RIMEC)

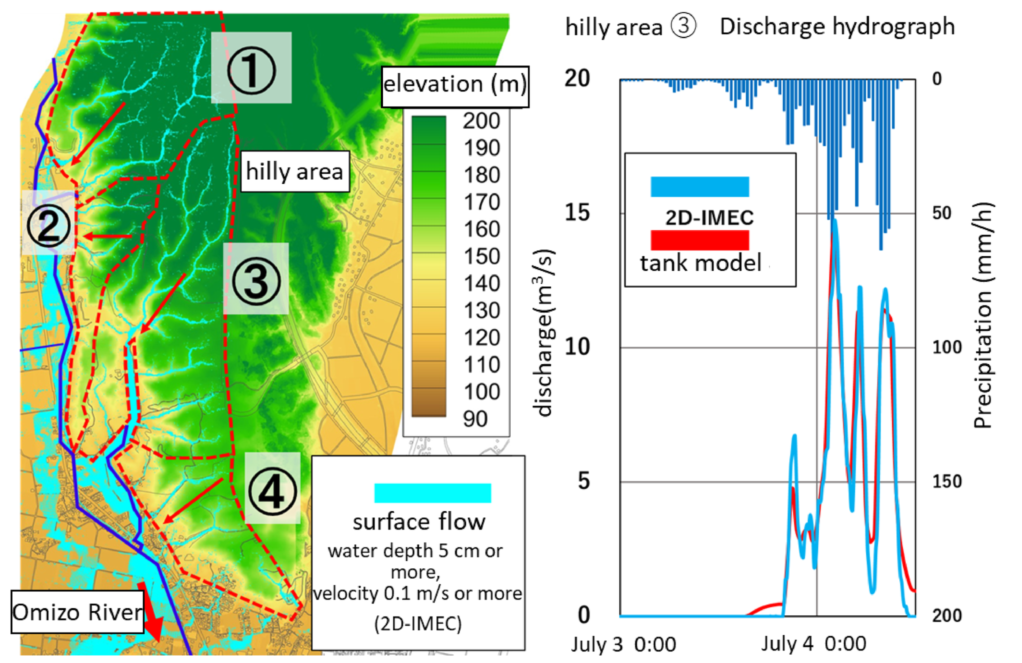

Figure.8 2D-IMEC-based subwatershed division and calculation of tank model flow rate

- 2D-IMEC requires about one week of analysis time for a one-day heavy rainfall analysis, making it difficult to apply to forecasting technology that supports the evacuation of residents. Therefore, we developed a real-time analysis method for internal flooding (RIMEC) that uses the analysis results of 2D-IMEC as teacher data (Figure 1).
- Two speed-up measures for the computation were taken to construct RIMEC. The first is the subdivision of hilly land and Murayama terrace into subwatersheds based on the results of the 2D-IMEC analysis and the application of the tank model to them. The left figure in Figure 8 shows the rainwater flow obtained from 2D-IMEC overlaid on the elevation contour in sky blue. Based on this, the hilly terrain is divided into subwatersheds as shown in the red line. The tank model parameters are identified so that the discharge hydrographs for each subwatershed obtained from 2D-IMEC, a high-precision analysis method, are consistent with the hydrographs obtained from the tank model as shown in the right diagram of Figure 8
- Second, the analysis grid size was enlarged. The grid size was enlarged four times in the plane, and the urban area and topography model was modified to account for the actual conditions such as inundation depth and inundation velocity in 2D-IMEC.
- The analysis time was reduced to about 19 hours for a one-day heavy rainfall analysis. As shown in Figures 5 and 6 , the model was able to reproduce the inundation conditions in the urban area and the rise of the inundation depth, which is important for evacuation.

3.2. Utilization of RIMEC for evacuation of residents

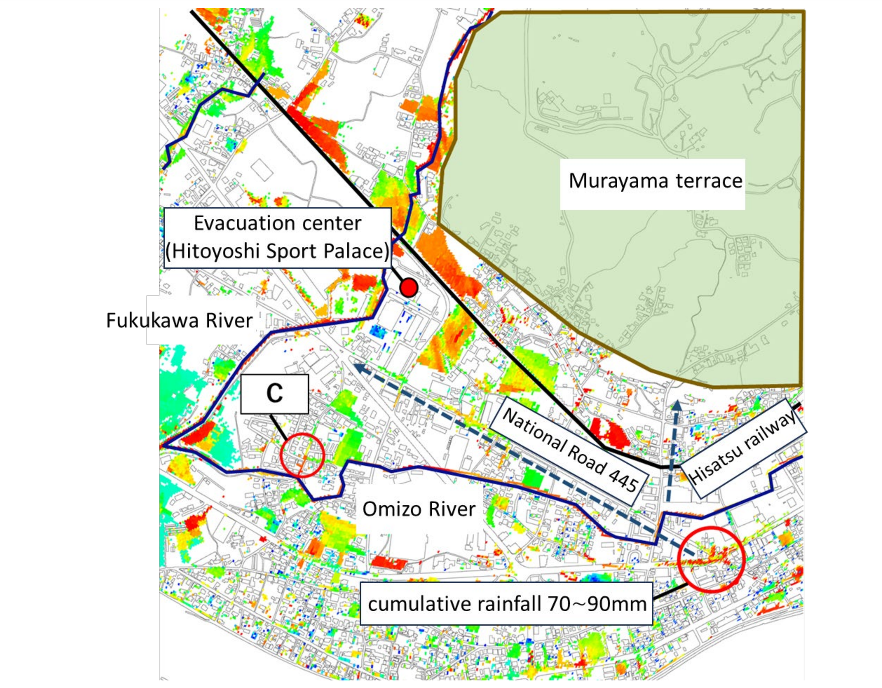

Figure.9 distribution of evacuation difficulty points and cumulative rainfall at the time of Typhoon No.14 in 2022

- The application of RIMEC to the evacuation of residents is shown for the July 2020 heavy rainfall event in Hitoyoshi city and the top six heavy rainfall events with the highest 24-hour rainfall at the Hitoyoshi Rainfall Observatory.
- Figure 9 shows the results of the analysis for Typhoon No. 14 in 2022. Due to the topographical characteristics of the flooded area, National Road 445 was inundated when the cumulative rainfall reached 70 to 90 mm, making evacuation difficult.
- The same study was conducted for each heavy rainfall event, and it was found that this road was inundated when the cumulative rainfall reached 80 mm in any rainfall event. However, the time required for the accumulated rainfall to reach 80 mm depended on the intensity of the rainfall, ranging from 4 hours for rainfalls of 10 to 20 mm in intensity to 2 hours for higher intensity rainfalls.
- In addition, the evacuation road at point C in Figures 4 and 9 became dangerous because the water depth and velocity increased early in any heavy rainfall event due to flooding and the overflow of the Omizo River and other rivers. In this area, vertical evacuation and early evacuation are especially important in urban areas. When considering evacuation, including the choice of vertical evacuation and early evacuation, evacuation decisions are made based on the relationship with the external water level as well as internal flooding.
- It was found that when cumulative rainfall reaches 200 to 300 mm in the Kumariver basin upstream of the Hitoyoshi city, the water level rises close to the flooding hazard level. It is important to estimate the time required for evacuation and inundation conditions by referring to the accumulated rainfall and rainfall intensity related to internal and external flooding.

4. Construction of watershed water balance distribution map in urban areas and study for damage mitigation

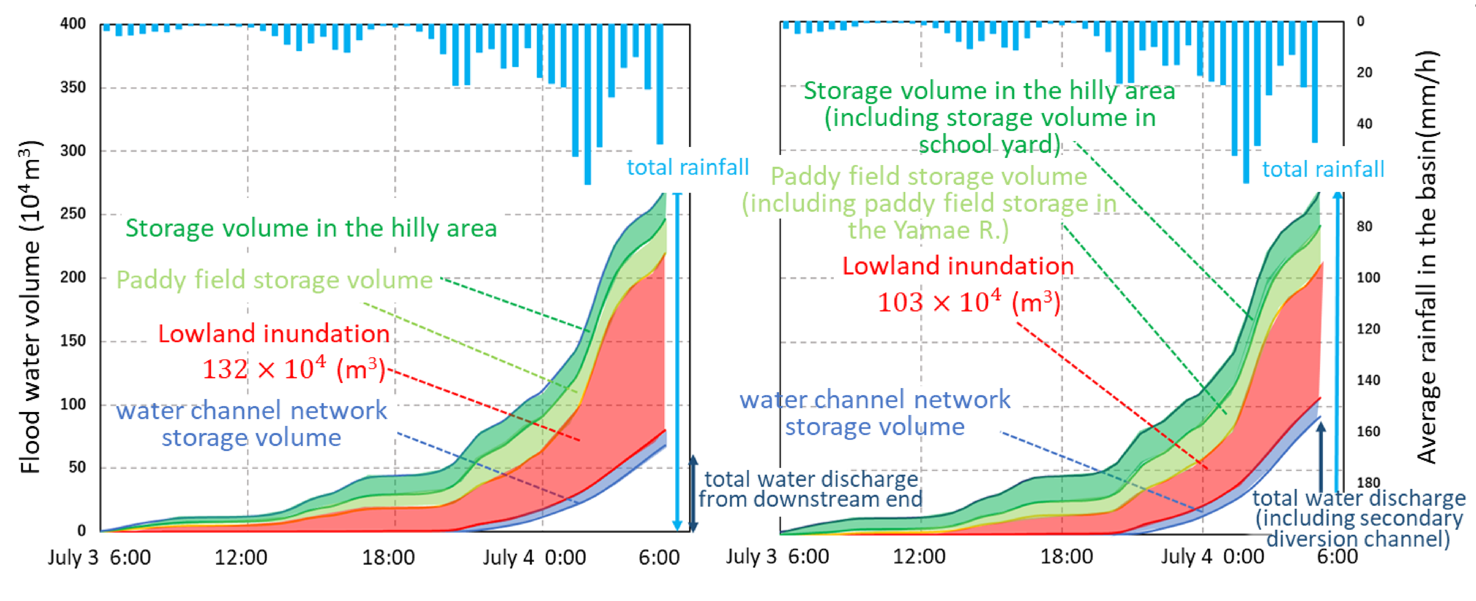

Figure.10 water balance distribution map in Hitoyoshi city basin during the torrential rainfall in July 2020 (left: without considering countermeasures, right: considering countermeasures)

4.1. Visualization of inland water hazards using urban water balance distribution maps

- The urban water balance distribution map visualizes when, where, how much and under what conditions rainfall occurs by obtaining the amount of water and its spatiotemporal distribution of water storage in urban areas based on the distribution of heavy rainfall and inundation analysis.
- The left explanatory daigram in Figure 10 shows the water balance distribution in the urban area during the July 2020 heavy rainfall based on RIMEC. The red color indicates a rapid increase in the amount of flooding in the urban area due to the rapid increase in rainfall during the July 2020 heavy rainfall event. This is considered to have caused a major problem because the evacuation time was short. In the future, it will be necessary to reduce the amount of inundation in low-lying areas or to delay the peak of inundation by controlling the runoff from hillsides and paddy fields shown in green and yellow-green, and by diverting water through drainage channels..
- The creation of a water balance distribution map for urban areas will make it possible to visualize the overall picture of internal water-related disasters and share ideas on how to mitigate damage.

4.2. Study for damage mitigation

- The urban water balance distribution map can be used to visualize internal water disasters and to estimate their effects by comparing before and after countermeasures.
- Countermeasures include a secondary drainage channel currently under construction, paddy field storage in hilly areas (storage depth: 50 cm), storage at public facilities on a terrace (storage depth of school yards and tennis courts: 30 cm), and the use of reservoirs for flood control. The results of these considerations are shown in the right-hand diagram of Figure 10. It is estimated that the amount of flooding will be reduced from 1,320,000 m³ to 1,030,000 m³ due to an increase in drainage volume by the secondary drainage canal (approx. 220,000 m³) and an increase in storage volume on hillsides and plateaus by the watershed measures (approx. 70,000 m³).
- In conjunction with this result, it is important to clearly demonstrate the significance of the countermeasures by showing the reduction in the area of inundation above floor level and the number of houses in the urban area.
- Thus, the visualization of the phenomenon of internal flooding and the effects of countermeasures using a city water balance distribution map will be useful for residents' evacuation planning and future consideration of community planning for disaster mitigation.