FLOOD DISASTER AND SAFE EVACUATION IN DRAINAGE AREA WITH SMALL RIVERS

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ABSTRACT

In recent years, fluvial flood damage has been mitigated by strengthening embankments, however, pluvial flood damage by heavy rainfall is increasing in mega and provincial cities. In August 2014, pluvial flood occurred in Fukuchiyama, where the drainage system includes small rivers. Such drainage system is popular in provincial cities, and small rivers cause widespread inundation. In order to enhance safety against such disasters, it is necessary to strengthen not only structural measures but also non-structural measures. The fluvial flood hazard map is mandatory, and pluvial flood hazard map should be made early. In hazard maps, the risk level is evaluated based on the inundation depth, but there are only few cases that evaluate the risk level including the flow condition. In this study, this kind of pluvial flood in Fukuchiyama is discussed with numerical results by InfoWorks ICM, which can be modelled rivers and sewerages. The inundation characteristics in this area showed that inundation started from the north and south side of the city, and spread from there. In addition, the inundation characteristics when pluvial flooding and fluvial flooding occurred at the same time were examined. The difficulty of evacuation was evaluated using specific force per unit width which can be able to consider fluid force and hydrostatic pressure simultaneously, and the time to start evacuation from small areas was discussed.

Keywords: pluvial flood, fluvial flood, safe evacuation, provincial city, drainage system with small rivers

1. INTRODUCTION

The frequency of fluvial floods has been lower than before due to flood control, but the frequency of pluvial floods becomes higher in drainage area with small rivers. Yura River, which flows through Fukuchiyama City in northern Kyoto Prefecture, Japan, has been flooding many times in the past. Fluvial floods occurred in this river basins in 2004 and 2013, and new flood controls have been promoted since then. However, in pluvial floods of 2014 and 2018 small rivers overflowed and caused severe damage. In this area, there is a risk that pluvial and fluvial flooding occur at the same time, such as Tokai heavy rain disaster that hit Aichi Prefecture in Japan in 2000. To mitigate damages of such floods, it is important to strengthen not only the structural measures but also non-structural measures.

Most risk assessments in Japanese flood hazard maps are based only on water depth and do not take into account flow conditions. Onishi et al. (2009) made it possible to evaluate the difficulty of evacuation including flow conditions using a specific force per unit width taking into account water depth and velocity. Taniguchi et al. (2018) evaluated inundation damage when pluvial and fluvial flood occurred simultaneously. Few studies have applied the difficulty of evacuation when pluvial and fluvial flooding occur simultaneously.

In this paper, the difficulty of evacuation and the time to start evacuation are discussed when pluvial and fluvial flooding occur simultaneously.

2. STUDY AREA

Figure 1 shows the study area, Fukuchiyama city. The analysis site is west and south-east area including the sewer drainage area. This area has several small rivers without levees, and is surrounded by big rivers with levees such as the main stream Yura River and its tributaries of Haze River and Waku River. The levee break point 1 in Figure 1 was broken by Typhoon No.13 in 1953. In recent years, pluvial floods caused by flooding of small rivers have frequently occurred. Pumping station is one of the measures against flooding. A, B, and D in Figure 1. are the stations for pumping flood water from the brooks to the main river, and C is a drainage pump. Rainwater in the study area flows into the small rivers from the sewer pipes, and in the case of heavy rain, it is drained to Yura River via drainage stations at the downstream end of the small rivers.

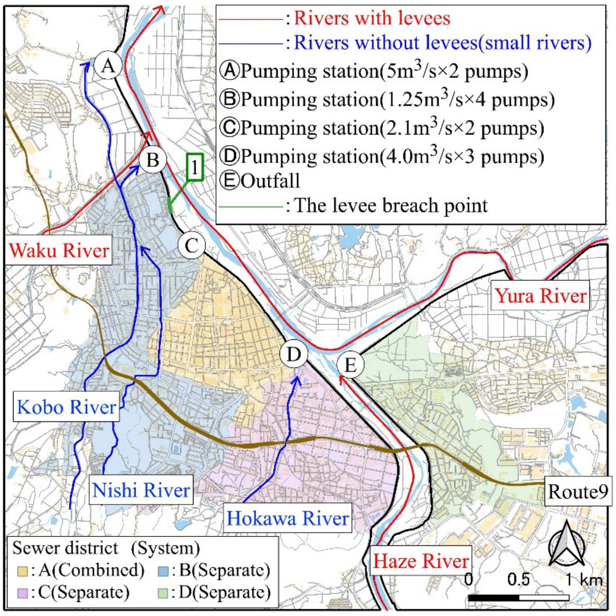

Figure 1. Study area

3. NUMERICAL METHOD

3.1 Calculation of inundation

Flood in study area is calculated using InfoWorks ICM. The flow in sewer pipe is calculated using the Saint-Venant equation, and the ground surface flow is calculated using the 2D shallow flow equation. The inflow from the ground surface to the sewer is calculated by using the weir equation at the manhole.

Topographic data used here was DEM5m published by Geospatial Information Authority of Japan, and the data collection was done with field survey results. The roughness coefficient was determined using the land use mesh data of National Land Information Division, National Spatial Planning and Regional Policy Bureau, MLIT of Japan. The sewer model consists of drainage pipes and small rivers shown in Figure 1. The small rivers were modeled by using width and bed level data. Verification of the model and determination of coefficients were done by using the data of the pluvial flooding that occurred in 2014. The effective depth of Kobo River and Nishi River downstream from Route 9 was set to 50% in order to express the impediment of small rivers flow caused by driftwood and sediment at that time. The accuracy of the calculation results is verified by comparison with Fukuchiyama pluvial flood hazard map showing inundation depth in 2014. Figure 2 shows that the inundation area and the inundation depth are almost the same. The data used for verification are the inundation depth data observed at 1813 points of the 2014 flood acquired by the local government. The accuracy of the inspection range is MAE = 0.21 (m), RMSE = 0.28 (m), and R = 0.55.

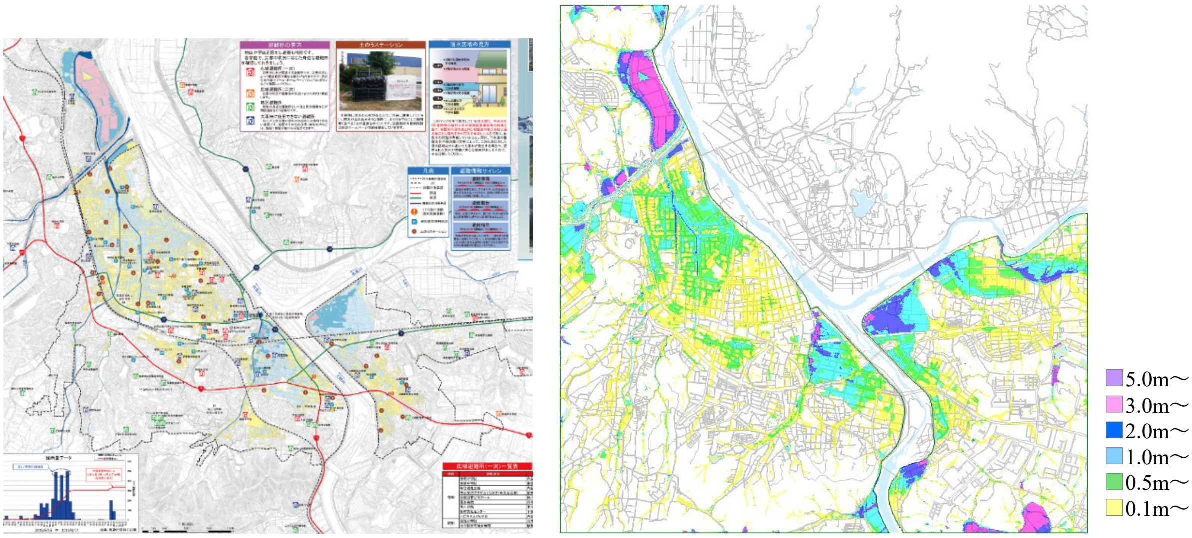

Figure 2. Fukuchiyama pluvial flood hazard map (Left) and Results of the calculation of pluvial flood in 2014 (Right)

3.2 Runoff calculation

The flood discharge was calculated by using the River Planning Simulator Runoff Analysis System of the Japan Institute of Country-ology and Engineering. The basin and river channel are modeled using the Kimura storage function method, and the effective rainfall model is determined by using the f1-Rsa method.

Figure 3 shows the upstream area of 36.6 km from the estuary of Yura River, which is the study area for runoff analysis. Figure 4 is the diagram of the runoff analysis model. Yura River basin was divided into five basins and three rivers with reference to Takasao et al. (1988). The average rainfall in each basin was calculated by weighting the area using the rain gauge boundary line (Figure 3) created using Voronoi polygons. The coefficient was calibrated using rainfall data (2013/9/15 0:00 to 9/17 23:59) at the time of Typhoon 2013, when the highest water level was recorded at the Fukuchiyama observatory at 36.6km of Yura River. In addition, 2004 and 2011 floods cases were calculated.

The accuracy was verified by the Nash-Sutcliffe coefficient (NSE) and the allowable error value (E). Nash-Sutcliffe coefficient is bigger than 0.7 and closer to 1, and the allowable error value should be less than 0.03. In the calculation results of all floods, NSE values are in 0.95 ~ 0.98, and E values are less than 0.005. These values show that the runoff model has higher accuracy.

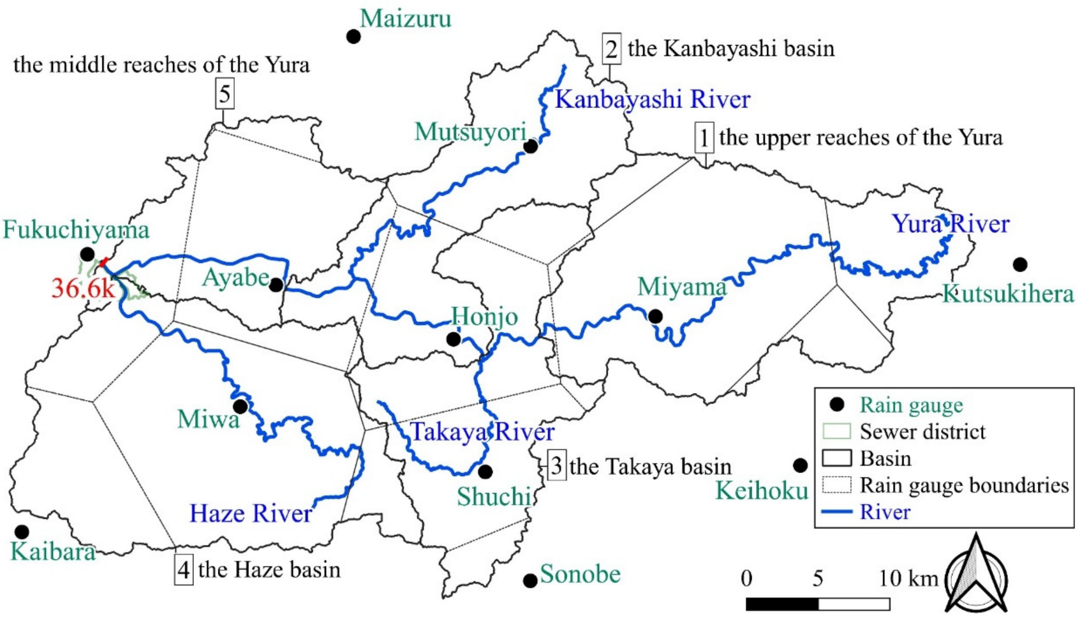

Figure 3. Study area for runoff analysis

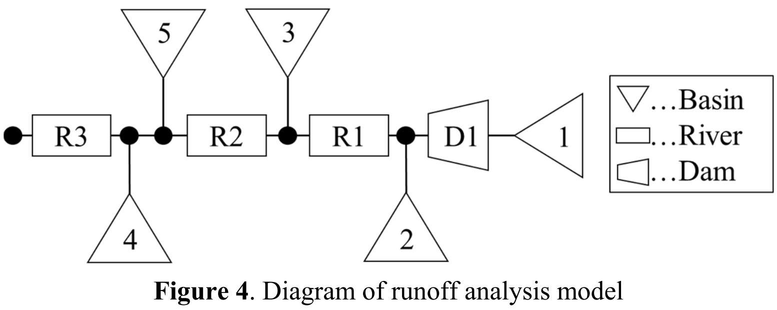

Figure 4. Diagram of runoff analysis model

3.3 Conditions for flood analysis

In this study, the extended rainfall of Typhoon 18, 2013, of which total rainfall is 494mm for two days, are used as the extreme condition. The conveyance discharge at the point 36.6km of Yura River is 6,500 m^3/s. Discharge over the conveyance is used as overtopping discharge here. Figure 5 shows the extreme rainfall hyetograph, and the conveyance discharge. It is assumed that a levee break will occur at the point shown in Figure 1 when the flow capacity is exceeded. The width of the levee break was calculated using the following formula, (1).

$$B_b = 1.6(\log_{10} B)^{3.8} + 62 \quad (1)$$

where, B_b: the width of dike break (m), B: the river width (m).

Since the river width is 480m, the width of the levee break is determined to be 130m. The discharge was converted to water level using the H-Q curve and applied to the point E in Figure 1.

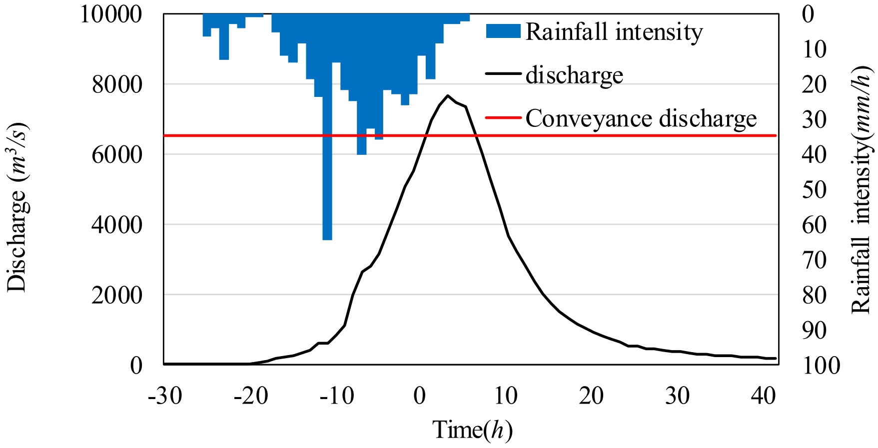

Figure 5. Hyetograph and hydrograph

3.4 Pluvial and fluvial flood simulation in case of extreme rainfall

Figure 6 shows the results of the flood analysis. In this paper, the results for levee break point 1 are shown. t=0(h) is just before the fluvial flood occurs. The result at t=0(h) in Figure 6 (a) indicates that pluvial flooding occurred before fluvial flooding started. Especially, in some areas of C and D drainage areas, the inundation depth is more than 2.0m and the first floor is almost swamped. The result of t=1(h) in Figure 6 (b) shows that floodwater spreads rapidly from levee break point to the south, and the area with inundation depth was deeper than 1m. Figure 6 (c) shows the result at t=2(h), showing that the inundation area expands over the entire area of A drainage area and north part of B drainage area. Figure 6 (d) shows the maximum depth, which is over 3m in wide area, and over 5.0m around the levee break point. Residents in flooded areas need to evacuate early because floodwaters can reach the second floor.

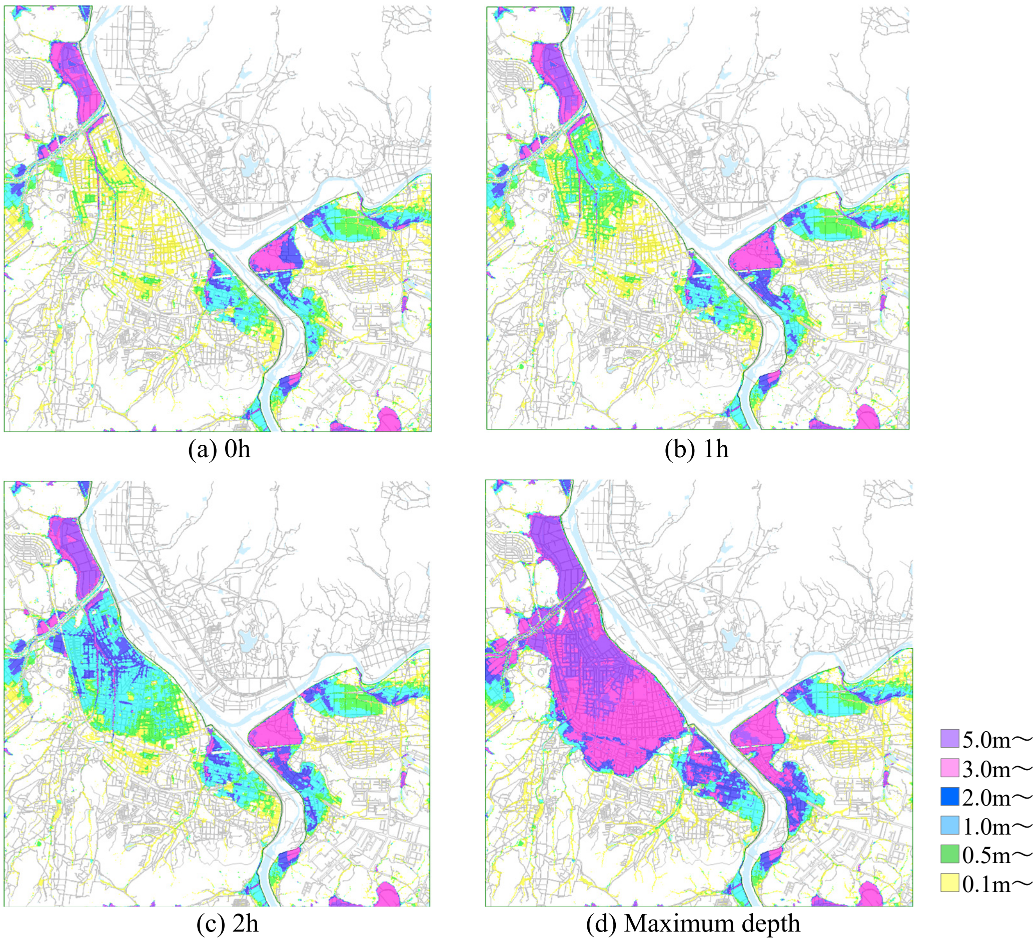

Figure 6 The results of the flood analysis

4. SAFE EVACUATION

4.1 Method

The safety of shelters in Fukuchiyama city was determined from the depth. In this paper, shelters with an inundation depth of less than 0.5 m are referred to as "safe shelters", and those that can be used upper floors are referred to as "multistory shelters".

The safety of evacuation routes is evaluated by the specific force per unit width (Onishi et al., 2009), which can evaluate fluid force and water pressure simultaneously. Equation (2) is a specific force per unit width, M_0,

$$M_0 = \frac{u^2 h}{g} + \frac{h^2}{2} \tag{2}$$

where, u: velocity(m/s), h: water depth(m), g: gravitational acceleration (m/s^2).

The time when M_0 becomes larger than 0.080(m^3/m) is defined as the evacuation difficulty time because Asai et al. (2010) clarified that the value for elderly women shows difficulty of evacuation.

In addition, the evacuation start time for each community association area was revealed using the shortest route search tool of GIS. The start points are the center point of the polygon that divides the inundation area using the small area boundary, and the goal points are safe shelter and multistory shelter. It is assumed that roads where M_0 becomes larger than 0.080(m^3/m) and bridges that cross rivers with embankments cannot be passed. The shortest route is searched every hour based on the results of the flood analysis. Evacuation is possible when the route can be searched from each starting points and the specific force per unit width of the starting points are less than M_0 = 0.080(m^3/m).

4.2 Results

The number of people who needed evacuation after the levee break was 14,530 in the area where the maximum inundation depth was larger than 0.5m.

Figure 7 shows the number of people who can evacuate. The number of people who have difficulty in evacuation increases immediately after the peak of rainfall because the number of people who can evacuate is significantly affected by pluvial flood before fluvial flooding occurs. One-third of the people who need evacuation will have the difficulty at that time. The impact of pluvial flooding must be taken seriously because pluvial flood has already occurred just before fluvial flood occurs as shown in Figure 6 (a), and about half of those who need to evacuate are already having the difficulty. It has been found that the percentage of people who have the difficulty rapidly increases after the occurrence of fluvial flooding, 60% after one hour and 86% after two hours. The number of people who can evacuate increased 20 hours after the fluvial flood occurred, because the pluvial floodwaters in the D drainage area began to draw down.

Figure 8 shows the safety of evacuation shelters, the difficulty of evacuation of roads, and the evacuation start time for each small area. It was confirmed that 14 shelters in the sewer district were submerged. Roads that are difficult to evacuate before fluvial flooding occur are widespread in C and D drainage areas, and are scattered in A and B drainage areas. In particular, the road shown in Figure 8 [a] is difficult to evacuate before fluvial flooding occurs, even though most of the inundation depth less than 0.5m as shown in Figure 6 (a). Roads that are difficult to evacuate suddenly spread from the levee break point due to flood flow after a fluvial flood. Furthermore, the evacuation start times for safe evacuation from each small area in Fukuchiyama city area were classified into three types: before the start of rainfall (t= -24(h)), before peak of the rainfall (t= -12(h)), and before fluvial flooding occurs (t= 0(h)). In addition, the evacuation start time was indicated.

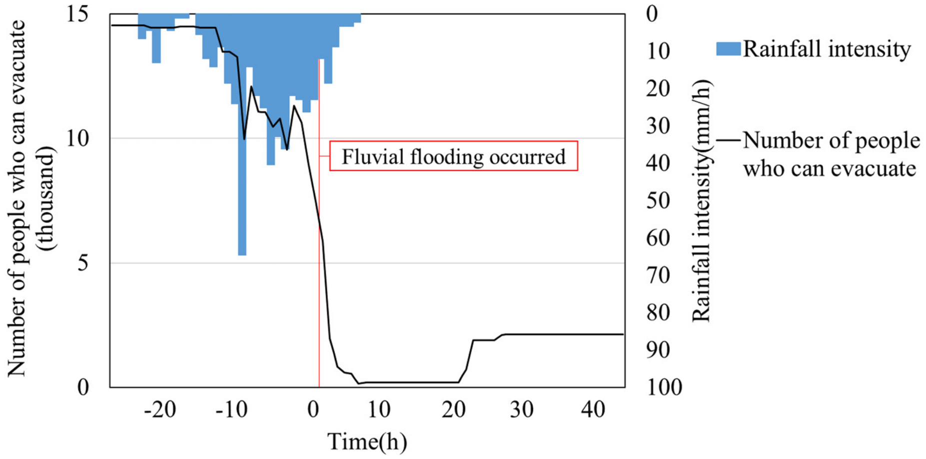

Figure 7. Number of people who can evacuate at each time

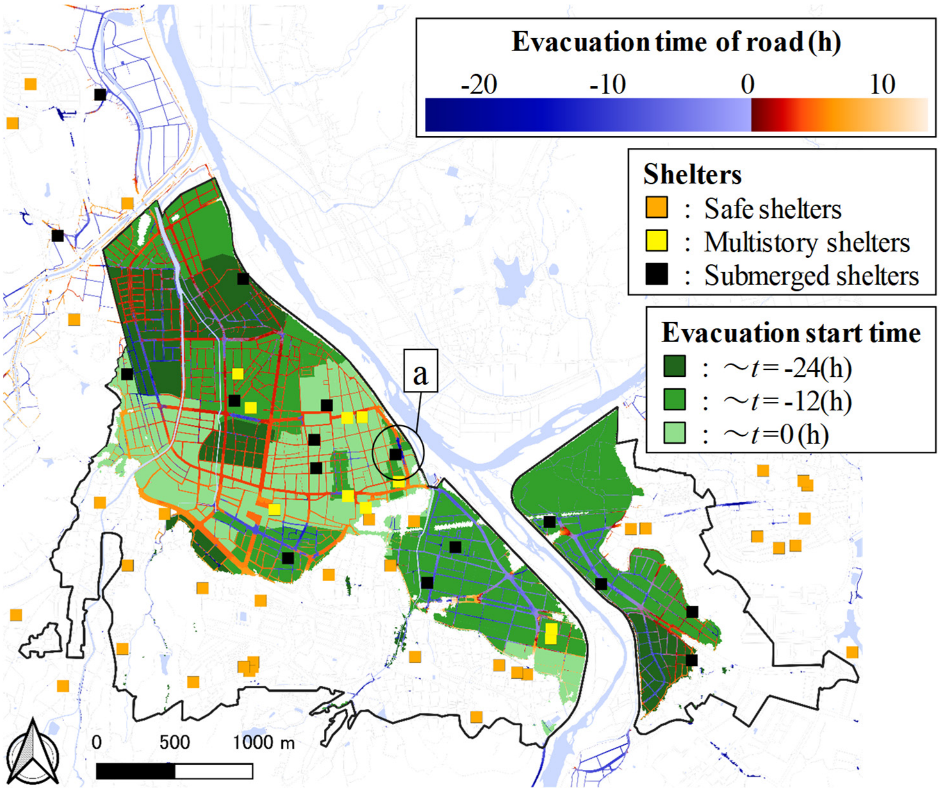

Figure 8. Number of people who can evacuate

5. CONCLUSIONS

In this study, safe evacuation was investigated by using inundation analysis results during pluvial and fluvial floods. A flood analysis model for sewerage in Fukuchiyama city and a runoff analysis model for Yura River basin were constructed. The effects of pluvial flooding before fluvial flood occurred were serious, and roads and districts where evacuation was likely to be difficult were identified. The evacuation start times for safe evacuation from each small area in Fukuchiyama city area were classified into three types: before the start of rainfall, before peak of the rainfall, and before fluvial flooding occurs. In the future, it will be necessary to use another types of rainfall and to consider the time when evacuation starts from each residential area.

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