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SCENARIO ANALYSIS FOR EVACUATION STRATEGIES FOR RESIDENTS IN BIG CITIES DURING LARGE-SCALE FLOODING

Toshitaka KATADA[1], Noriyuki KUWASAWA[2], Satoru SHIDA[3] and Masaru KOJIMA[4]

[1]Member of JSCE, Professor, Research Center for Disaster Prevention in the Extended Tokyo Metropolitan Area, Gunma University (1-5-1 Tenjin-cho, Kiryu-shi, Gunma 376-8515, Japan)
E-mail: katada@gunma-u.ac.jp
[2]Member of JSCE, Research Center for Disaster Prevention in the Extended Tokyo Metropolitan Area, Gunma University (IDA Co., Ltd.) (1-5-1 Tenjin-cho, Kiryu-shi, Gunma 376-8515, Japan)
E-mail: kuwasawa@ce.gunma-u.ac.jp
[3]Member of JSCE, River Planning Division, Water and Disaster Management Bureau, Ministry of Land, Infrastructure, Transport and Tourism (1F, Joint Government Building (Chuo Godo Chosha) No. 3, 2-1-3 Kasumigaseki, Chiyoda-ku, Tokyo 100-8918, Japan)
E-mail: shida-s2jf@mlit.go.jp
[4]Member of JSCE, River Department, Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism (16F, Saitama New Urban Center Joint Government Building No. 2, 2-1 Shintoshin, Chuo-ku, Saitama-shi, Saitama 330-9724, Japan)
E-mail: kojima-m8314@ktr.mlit.go.jp

In major cities, large populations can hinder evacuation efforts in the event of a large-scale flooding. Therefore, for investigating evacuation strategies during large-scale flooding in such cities, population size and its impact must be considered. This study aims to examine the evacuation problems that arise when big cities are subjected to large-scale flood damage. In addition, it attempts to examine strategies that can overcome the evacuation problems. In this study, we developed a scenario simulator to elaborately simulate the flooding, evacuation of residents, and status of damage due to water exposure in the Edogawa Ward, which has a population of approximately 650,000. In addition, using a simulation that reflected the intended evacuation behaviors of the residents for a scenario in which the banks of the Arakawa River overflowed, we were able to identify the inherent evacuation problems of the city, including the damage caused by the presence of a large number of evacuees. Furthermore, we analyzed scenarios including measures to reduce the extent of damage. From this information, it became clear that countermeasures such as spatial and temporal dispersion of evacuees and a reduction in evacuation demand are necessary.

Key Words: *scenario analysis, evacuation strategies, big cities, large-scale flooding, simulation*

1. INTRODUCTION

In recent years, the risk of flooding has grown because of the increased frequency of torrential downpours and stronger typhoons as a result of climate change associated with global warming. Therefore, the need for disaster-prevention measures targeting flood damage has also grown. In large cities, in particular, the frequency of exposure to water has reduced as a result of aggressive flood control measures and facilities implemented in recent years. However, at the same time, concentration of population and industries in such cities has also accelerated. Consequently, extensive damage by large-scale flooding is now a real concern. Hence, development of disaster-prevention measures targeting large-scale flood damage in big cities has become an urgent concern. In particular, demand has risen for promoting software-based countermeasures, including evacuation strategies.

In April 2010, the Expert Panel on Large-Scale Flood Disaster Countermeasures of the Central Disaster Prevention Council of the Cabinet Office made recommendations to reduce damage from large-scale flooding in the Tokyo metropolitan area[1). According to estimations by this Expert Panel, in the case of flooding of the Tone River, which would cause maximum damage to the Tokyo metropolitan area, an area of approximately 500 km^2 would be submerged in water and 2.3 million people would be exposed to flooding. The Expert Panel also indicated that evacuation policies must be examined based on the characteristics of the city to reduce the extent of damage. As highlighted in these recommendations and in a case involving the city of Nagoya, presented in the next chapter, evacuation strategies in large cities pose a difficult set of problems because a large population is affected.

Based on an awareness of the abovementioned problems, the aim of this study is to understand the evacuation problems that arise with large-scale flooding in large cities, as well as to examine appropriate countermeasures for such problems. First, to specifically identify the problems associated with a large number of evacuees present in cities with large populations, we developed a scenario simulator to simulate the evacuation of local residents necessitated by flooding in the Edogawa Ward of Tokyo, which has a population of over 650,000 people. We then used the developed simulator to analyze a scenario that assumed a washout of the banks of the Arakawa River. This information was then used to understand the status of damage based on the behaviors of the residents to examine measures to reduce damage, as well as to verify the effectiveness of such measures. Consequently, we were able to clarify the evacuation problems inherent to large cities where stereotypical evacuations cannot be promoted or derived, as well as the directionality of the strategies that should be adopted.

2. POLICY FOR EXAMINING FLOODING EVACUATION MEASURES FOR LARGE CITIES

(1) Evacuation problems during flooding of large cities

When Typhoon No. 15 was located in the southern ocean waters of Kyushu the day before it made landfall in eastern Japan and caused extensive damage in September 2011, it fed damp air to the stagnated front line on Honshu and caused intermittent, heavy downpours in the Gifu and Aichi prefectures. At the Shonai River, the watershed for this region, the torrential downpour caused the water level to rise rapidly, reaching a height of 6.23 m, thereby exceeding the previous peak caused by the Tokai torrential downpour in 2000 by approximately 50 cm. However, while excessive water was observed in some areas, the river banks did not experience washout, and fortunately, large-scale external flooding did not occur. During the largest recorded flooding of the Shonai River, the city of Nagoya issued an evacuation advisory that targeted over a million residents living in 181 school districts within the city 25 minutes after the river had exceeded the water level, which was the standard for announcing an evacuation advisory. However, the number of residents who evacuated to facilities specified by the city was limited to approximately 5,000 people. Hence, based on the evacuation percentage, only a very limited evacuation could be performed[2). If we also consider the evacuees who fled to locations other than those that were designated as evacuation shelters, the actual number of evacuees was a little higher. However, if the Shonai River had burst its banks at that time, it is not hard to imagine the large-scale damage that would have occurred. However, on the other hand, if most residents who were warned to evacuate had actually evacuated, an unprecedented large-scale flood evacuation would have unfolded. In such a scenario, it is easy to imagine that the evacuation would have resulted in serious confusion. Furthermore, if large-scale external flooding had occurred, we cannot deny the possibility that there would have been numerous casualties among the evacuees.

As can be imagined from this case, the problem of evacuating residents from large cities is a complicated concern, which, depending on the presence of a large population to be evacuated, cannot be resolved by merely promoting evacuation. Therefore, to examine appropriate evacuation strategies for large cities, rather than statically considering the regional population as the scale for a maintenance target or an evacuation target, we must also address problems that occur during evacuation, including evacuation behaviors using the way people think and act as dynamic elements that depend on the progression of the situation and the acquisition of information.

(2) Policy for examining the evacuation of residents in the event of large-scale flooding of a large city

In this study, based on an awareness of the problems described in the previous section, we developed a scenario simulator (hereinafter, simulator) to specifically determine the status of flood damage in a specific region to examine the problem of evacuation in the event of large-scale flooding in a metropolitan area.

Much of our nation's simulation research targeting the evacuation of residents focuses on confined spaces such as underground complexes[3) or targets only a portion of the given region[4]. There are only few simulations that assume the evacuation of a large population in a large city[5), 6)]. However, local municipalities are examining the evacuation of residents. In studies that target large-scale flood damage in which an extensive area is submerged in water, at the very least, the evacuation conditions of the entire area of each municipality must be considered. Furthermore, when a large city is affected, an examination specifically considering the impact of population size on the evacuation and devastation conditions is required. Other countries have also conducted simulation research that pertains to evacuations in the event of flood damage over an extensive area. This research can be classified into different types such as research to determine the time required for evacuations based on the population and size of the affected area, the attributes of its residents[7), 8)], predictions of time taken for evacuation using the number of evacuees, the OD, the network of roads[9), 10)], and micro-simulations that model the individual behavior of the evacuees and agent-based modeling[11), 12)]. Of course, much of the evacuation responses that are examined in these research areas focus on efficiently evacuating residents to areas that are not submerged by water, as typified by hurricane response in the United States, and much of this research is not in accordance with the evacuation policies of Japan, which are based on municipality units. In addition, as with this research, research that utilizes micro-simulation models to determine individual evacuation conditions focuses on evacuation by car. In fact, there is no simulation research that specifically and comprehensively models the conditions of a region in the event of a flood, such as the conveyance of disaster-related information to residents, the behavior of evacuees including walking, and the dynamic relationship with flooding.

From an awareness of such problems and from previous research, in our study, we considered the following policies as we developed a simulator and conducted the examination. We targeted an entire large city and specifically aimed at modeling large-scale evacuation based on the intended behaviors of its residents.

- To identify the specific problems with residential evacuations, the simulator was designed to not only model hazards that pertain to flooding disasters, but also to comprehensively model every aspect, including evacuation behaviors and other social response behaviors.
- From information obtained by an examination that targets a large city, the simulation models the impact that the population scale has on damage and evacuation behavior of residents.
- To conduct an examination based on the characteristics of the targeted region, the simulator elaborately models the elements that express the affected region such as its topography, road network, distribution of residents, and establishment and layout of disaster prevention facilities.
- The response behavior of residents is an element that has a major impact on the extent of damage, and therefore, the simulator reflects and models the residents' level of awareness to examine actual issues and strategies.
- To examine strategies that aim toward reducing human suffering, the priority of measures with different direct goals, such as improving information transmission and providing evacuation support, must be examined. Therefore, the simulator models human suffering, and uses the reduction numbers as common evaluation indicators for different strategies.

3. BUILDING THE SIMULATION MODEL

In this study, to develop a simulator in accordance with the policies mentioned in the previous chapter, we used comprehensive disaster scenario simulators[13), 14)] that we had developed previously as a basic model. The basic model was configured using three different models, namely, an information transmission model to express the status of transmitting disaster-related information, an evacuation behavior model to express the evacuation conditions of the residents, and a flooding model to express the hazard conditions. In this study, for the evacuation behavior model, reduction in evacuation speed in accordance with the extent of traffic jams and the level of congestion caused by evacuees on foot was considered, and improvements were made to achieve modeling with a more accurate representation of the evacuation speed and the evacuation behavior in a large city.

(1) Simulator configuration

To model the evacuation conditions of residents in the event of large-scale flood damage, a simulator configured from the computational models shown in **Fig.1** was developed. These computational models can be largely classified as models that express hazards related to flood disasters, models that express social response in the event of a flooding disaster, and models that estimate human suffering. The computational model that expresses hazards comprises a river model that expresses the change in water level of the rivers and a floodplain model that expresses the water depth and area in a flooded region within a dike area. On the other hand, the so-

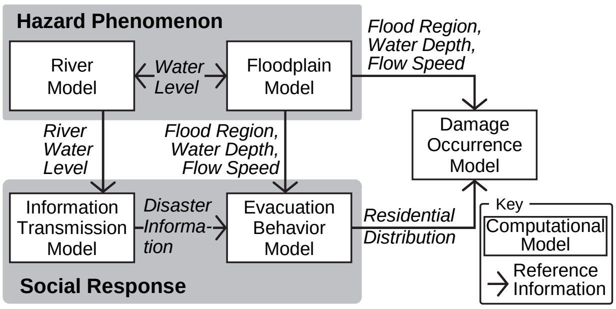

Fig.1 Configuration of the simulation model.

cial response model comprises an information transmission model that expresses the conditions surrounding the transmission of disaster information by the government to the residents in accordance with the hazard conditions, and an evacuation behavior model that expresses the decision by residents to evacuate based on the acquisition of disaster-related information and the conditions surrounding their movement to evacuation facilities. Furthermore, a damage occurrence model is used to estimate the scale of human suffering from the results output by the other two model groups.

(2) Overview of the simulation model

This section is a general overview of each computational model presented in **Fig.1**. Note that each model basically utilizes existing technology, and therefore, the details are limited to the information presented by the documents listed in the references.

a) River model

The river model expresses temporal changes in water levels and flow rates in river channels using the tidal level at the river mouth as the starting water level and the hydrograph for the flow rate applied at the upstream end as a boundary condition. Because the temporal changes in flooding conditions are expressed with this model, one-dimensional unsteady flow calculation[15] is used as the computational method. In addition, with this model, points for calculating the flow rate and flow speed are placed in a transverse cross-section of the river channel to establish the river width and hydraulic radius, and calculations of the water level are performed using an intermediate point in this cross-section. If an area of convergent flow exists in the targeted region, the flow rate at the downstream end of the area of convergent flow is calculated using a common water level calculation point for a downstream cross-section of the branch streams and a common water level calculation point for the area of convergent flow in the given river.

b) Floodplain model

The floodplain model is expressed by Cartesian coordinate system-based two-dimensional unsteady flow calculations[15] of the behavior of floodwaters flowing into a dike region due to a dike break or overflow. The dike break flow rate or overflow rate due to river flooding is calculated by the Honma lateral overflow formula[16] based on the calculated mesh water level of the floodplain, corresponding to the water level in accordance with the river model, and the relationship with the dike break height and embankment level height. Note that with this simulator, the flooding conditions within the dike area must be evaluated in conjunction with the evacuation behavior of the residents, and therefore a 10 m detailed computational mesh is used.

c) Information transmission model

The information transmission model expresses conditions surrounding the transmission of warnings, evacuation advisories, and other disaster-related information to the residents through radio communications for disaster prevention, mass media, and other such means. Moreover, to model the conditions for which information is disseminated throughout the region by word of mouth among residents, the individual behavior of residents with respect to conveying information is also considered. To implement this model, we used a disaster information transmission simulation model[17] that we developed in a previous research. The disaster information transmission simulation model consists of parameters that handle the level of information transmission behaviors between residents. Moreover, it can model the conditions of transmission behavior according to measures such as the cohesiveness of the local community at the time of a disaster. This model demonstrates information transmission in the event of a disaster by radio communications for disaster prevention and by the media based on a model of information transmission behavior of residents.

d) Evacuation behavior model

The evacuation behavior model primarily expresses the conditions of movement of the residents from their homes to their evacuation destinations via roadways. The timing at which evacuations begin is based on the timing at which such as evacuation advisories are acquired as modeled by the information transmission model. It includes the time spent on evacuation preparations. Furthermore, for the evacuation destination and route, as a general rule, the evacuation facility closest to the resident's home and the shortest route to that facility are used. Note that the modeling of this portion is described in detail in the next chapter.

During an evacuation, the position of an evacuee is determined from the time that has lapsed since evacuation first started, as well as roadway data in accordance with the travel speed. The roads of a targeted region are expressed as a network composed of links that express roads and nodes that express intersections. Each link has a changeable condition that expresses whether or not passage is possible at any given point in time. If a link that an evacuee tries to enter is not passable, the unpassable link is excluded from the network, and route searches that use the resulting network are implemented to determine the appropriate detour. Moreover, the flooding conditions expressed by the floodplain model are reflected every 10 seconds to update the road conditions, and the emergence of unpassable locations in conjunction with the spread of the flooded area and the detour behavior of evacuees in accordance with such are also modeled[14].

Both walking and the use of automobiles are modeled as evacuation measures. In the event of flood damage, evacuation is done by walking as a general rule, but for reasons such as vehicles being a valuable asset and movement by walking during a torrential downpour being difficult, evacuation by car is widely used[18]. Travel speed is based on an arbitrarily established speed. However, regarding the speed of vehicles, when an evacuee attempts to enter a link and the traffic volume of a link on which an evacuee is currently traveling changes, the change in speed is expressed in accordance with traffic volume by updating the speed using Greenshields[19] equation.

$$v_c = v_f \cdot (1 - k / k_j) \tag{1}$$

where v_c is the vehicle speed (km/h), v_f is the free travel speed (km/h), k is the traffic density (cars/km), and k_j is the saturation density (cars/km, set to 140 for calculations for this study). Free travel speed is based primarily on the scale of the roads, and therefore, in this study, expressways were set to 30 km/h and all other roads were set to 20 km/h based on surveys, such as a road traffic census of the targeted region. Moreover, traffic density was determined using an inverse number of the spacing between the front of the vehicle and the vehicle ahead. With this model, vehicle lanes and traffic signals were omitted to simplify the model, and priority was given to through-traffic at intersections. Because of evacuation behaviors in large cities, congestion resulting from pedestrian evacuees occurs; therefore, reduction in the evacuation speed must also be considered. Therefore, the following equations were used with reference to previous studies[20] to model the reduction in walking speed in accordance with the level of congestion.

$$\begin{aligned} r_d &= 1 && (d < 1.5) \\ r_d &= 1.3 - 0.2d && (1.5 \le d < 6) \\ r_d &= 0.1 && (6 \le d) \end{aligned} \tag{2}$$

where r_d is the speed coefficient in accordance with the level of congestion, and d is the level of congestion (people/m^2). The level of congestion is calculated using the surface areas of the sidewalks and the number of evacuees in the given link. If $6 \le d$, it was assumed that evacuees could not enter the given link from a separate link. Furthermore, if the evacuation took a long time, a reduction in speed due to fatigue of the residents evacuating by walking is conceivable; therefore, the speed reduction due to fatigue was considered using equation (3) [21].

$$r_f = 1 / (0.982 + e^{1.12t - 4}) \tag{3}$$

where r_f is the speed coefficient due to fatigue and t is the amount of time (hours) that has lapsed since the evacuation started. A reduction in speed in flooded areas was also considered using equation (4) [22].

$$r_w = 1 - w / w_{max} \tag{4}$$

where r_w is the speed coefficient due to flooding, w is the depth of flood water (m), and w_{max} is the depth of flood water that is the limit for walking (m, set to 1 m for calculations during this study). While the impact of flow speed should be considered with respect to decreases in speed in accordance with flooding; but because it was difficult to model the flow direction and the impact from shallow water depths, in this study, only water depths that had a more dominant impact were considered[23].

The above coefficients relating to speed decrease were considered, and the evacuation speed of pedestrian evacuees was expressed using equation (5).

$$v_w = r_d \cdot r_f \cdot r_w \cdot v_s \tag{5}$$

where v_w is the pedestrian evacuation speed and v_s is the initial value for pedestrian evacuation speed.

e) Damage occurrence model

In the case of flood damage due to river flooding, even if a resident is within the flooded area, the person will not necessarily become a victim. Therefore, with this model, the flooded population was categorized in three categories, as shown in **Table 1**, based on the evacuation conditions of the residents, the characteristics of their homes, and the flooding conditions. This information was used as evaluation indicators for the scale of human suffering. With this model, residents who were in a flooding situation that made it difficult for them to walk were considered to be residents who required rescuing. To determine walking difficulty, an equation was used from Suga et al.[23] that determined walking difficulty based on body height and hydrodynamic force.

Table 1 Classification of flooded population.

Flooded Population	Definition
Person staying within a flooded area	A person who stays in his or her own home without evacuating, and who is not personally experiencing flooding but whose home is within a flooded area. (The ground surface of the person's home is flooding.)
Person in danger within a flooded area	A person who has not evacuated or is in the process of evacuating, and while emergency rescue is not necessary, the person is located within flood waters.
Person requiring emergency rescue	A person who has not evacuated or is in the process of evacuating, is surrounded by flood waters to the extent that walking is difficult, and an emergency rescue is necessary.

4. ESTABLISHMENT OF THE BASIC SCENARIO

In this chapter, we summarize the region targeted by the study and the calculation conditions that were established (see **Fig.2** and **Table 2**).

(1) Establishing the calculation conditions

a) Targeted region

In this study, the Edogawa Ward of Tokyo was selected to examine evacuation strategies in the event of large-scale flooding. The Edogawa Ward is located in the southeastern part of Tokyo and is sandwiched between two major rivers, the Arakawa River on the West and the Edogawa River on the East. In addition, because the Edogawa Ward is located at a position furthest downstream from both rivers, if the embankments of the rivers collapse, the geographical features of the area are such that the ward is at the risk of flooding regardless of where the embankments collapse. Furthermore, because of the effects of ground subsidence, 70% of the land area is a zero-meter region below the high-tide level, and because there is no natural drainage, after flooding has occurred, an extensive area will be covered in flood waters for an extended period of time with prolonged damage. Moreover, even within Tokyo, the Edogawa Ward is a large, prominent city with a population of approximately 650,000 people, and if flooding should occur, there are concerns that a large population will need to be evacuated.

b) Conditions related to topography and population

First, a topographical map of the targeted region was prepared with 10 m mesh precision using a laser profiler. Next, the distribution and shapes of buildings were modeled using commercially available electronic residential maps. The number of stories of each building was set using residential maps and laser profiler data as a reference. Finally, network data that expresses the roadways was prepared using the road shapes contained in the residential maps as a reference.

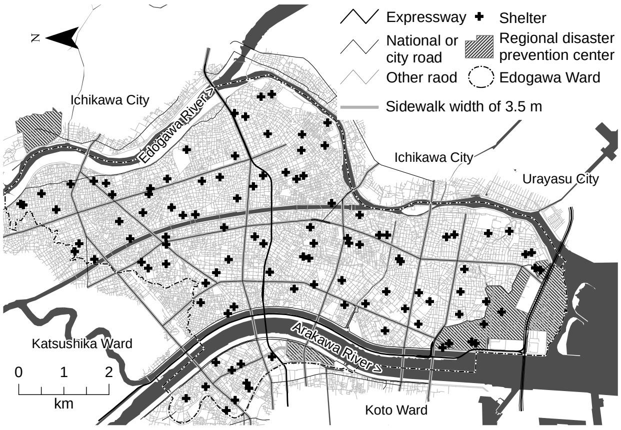

Fig.2 Region targeted by the study.

Table 2 Calculation conditions.

Classification	Item	Settings	References and thinking
Flooding	Assumed flooding	200-year probable flooding	Design flood
	Starting water level	AP + 2.2 m	High water level
	Dike break areas	Arakawa River left bank 7.0k	Maximum damage
Residents	Population households	651,733 people 303,245 households	Ward documents
	Walking speed	Walking speed based on sex and age	Statistical data
Loud-speakers	Layout	256 speakers	Ward documents
	Audio range	280 m	Ordinary value
	Hearing rate	30 %	Previous studies
Publicity cars	Number	10 cars	Ward documents
	Speed	20 km/h	Ordinary value
	Audio Range	80 m	Ordinary value
	Hearing rate	30 %	Ordinary value
Communication between residents	Communication method	By word of mouth only	Phones cannot be used due to congestion.
	Activity level	Not aggressively communicated	Survey of residents
Roads	Sidewalk width	2 m, some 3.5 m	Ward documents
	Basic vehicle speed	30 km/h on highways, 20 km/h on all other road	Ward documents
Evacuation facilities	Shelters	106 shelter	Ward documents
	Regional disaster prevention centers	3 locations	

First, to model the residents, we prepared virtual residents, based on the demographic composition as of January 2010 that was announced by the Edogawa Ward. This data included population statistics by district, age, and gender. Next, we targeted detached homes and apartment buildings shown in residential maps by district, and randomly distributed virtual households for the number of households that existed according to population statistics. We then distributed the population by randomly allocating the residents prepared for each household premised on the conditions that detached homes contained only a single household.

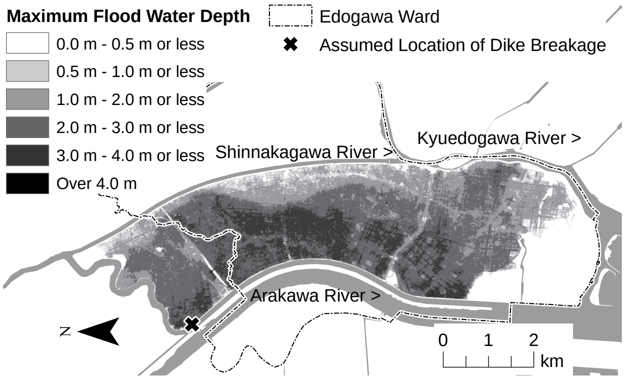

Fig.3 Assumed dike-breakage locations and maximum flood water depth distribution.

Table 3 Conditional stages during flooding presented with the survey.

No.	Conditions
1	Rain seems heavier than normal at home.
2	Heavy-rain warning or flooding warnings are announced.
3	Warnings continue for a long time, and the rain does not stop falling.
4	An evacuation advisory is announced.
5	Residents have become aware of conditions in which the embankment is likely to collapse.
6	Evacuation instructions are announced.
7	Notification has been received that the embankment collapsed.
8	Flooding reaches the area near a resident's own home.
9	A resident's own home begins to flood.

c) Conditions related to hazards

The river model was modeled based on the Arakawa River. For other rivers, topography data were utilized to model full capacity conditions. The assumed flooding was set to the flooding levels of September 1947 based on the design flood (1/200th probability) of the Arakawa River. For the dike break, a 7.0 km location along the left bank of the Arakawa River was selected, which is a location with a relatively large population that would be affected by flooding within the targeted region. The width of the dike break at the river embankment was set to 340 m based on the dike failure results along the Tone River caused by Typhoon Kathleen as a reference. In addition, the timing of the dike break at the embankment was set to the point in time at which a reference water level was reached with consideration of the current allowance height of the embankment and maintenance conditions. Flooding calculations based on these conditions provided results that indicated that a large portion of the region between the Arakawa River and the Shinnakagawa River would be flooded (see **Fig.3**).

d) Conditions pertaining to disaster-prevention facilities and disaster information

The evacuation facilities were modeled by targeting shelters such as elementary and middle schools, and regional disaster-prevention centers (higher elevation parks) designated in the regional disaster prevention plan for the Edogawa Ward. When considering shelters, we referenced usable floor space, which excluded floors of buildings that were at risk for flooding based on documentation from the Edogawa Ward, and the number of people that can be accommodated per shelter in an emergency evacuation was set based on two people per 1.65 m^2 (the size of one tatami mat). In addition, because the area has considerable floor space in its regional disaster-prevention centers to accommodate over two million people, the number of people that can be accommodated in the centers was set as limitless. According to the evacuation behavior model, if an evacuation facility had exceeded its accommodation limit, the residents were evacuated from that location to the next closest evacuation site.

Regarding radio communications for disaster prevention, the 256 outdoor loudspeakers prepared by the ward were modeled. The rate at which information was acquired from the outdoor loudspeakers was set to 30% based on a previous study[24]. Moreover, the timing at which the evacuation advisory was issued and the timing at which evacuation instructions were issued were set as the point in time at which the water level at the Iwabuchi site of the Arakawa River reached the water level determined for evacuation and when it reached a flooding risk level, respectively. Both timings were established by referencing the ward's regional disaster prevention plan. Consequently, with the assumed flooding scenario, an evacuation advisory was issued 4 hours and 44 minutes prior to the collapse of the embankment, and the evacuation instructions were issued 2 hours and 41 minutes prior to the collapse.

(2) Intentions of residents regarding flooding evacuation and method for reflecting those intentions

In this section, we discuss the results of an awareness survey that was conducted to understand the intended behavior of the residents in the event of a flood disaster and the method that was used to reflect that behavior in the evacuation behavior model.

a) Method for reflecting the intentions of the residents and an overview of the survey

In this study, we decided to consider the intentions of the regional residents in three areas: (1) determination of intent to evacuate, (2) timing at which evacuation began, and (3) behavior at the time of evacuation. We expressed these intentions in the evacuation behavior model. First, regarding the determination of intent to evacuate, we presented the conditional stages during flooding, as shown in **Table 3**, and identified the evacuation intentions of the residents at each stage. Furthermore, because the

Table 4 Overview of the resident awareness survey.

Survey period	February 19–23, 2010
Survey target	Residents 20-years-old or older of the Tokyo, Edogawa Ward
Survey method	Internet survey
No. of responses	3,000
Survey items	● Basic attributes ● Awareness regarding flooding disasters ● Behavioral intentions regarding flooding disasters

impact of persuasion to evacuate is large[25], we also decided to determine and understand the evacuation intentions when residents were subjected to persuasion. Next, for the timing at which evacuation began, we decided to add the time required for preparations after the determination of intent to evacuate was reached. Finally, regarding evacuation behavior, we also decided to identify the evacuation methods and destinations.

The abovementioned behavioral intentions of the residents in the event of a flooding disaster were determined using a survey targeting the residents of the Edogawa Ward. An overview of the survey is presented in **Table 4**. This survey was implemented using an online survey service, and responses were obtained from 3,000 residents of the Edogawa Ward. The survey asked questions regarding basic attributes, including questions regarding the presence of any family members who would have difficulty in evacuating on their own and would require support.

To use the model to determine evacuation behaviors that reflected the intentions of the residents, responses obtained in advance through the survey were randomly selected for each household, and behavior in line with the responses for each question was then applied to the given household. Rather than using the individual responses as is, another conceivable method was to model behavior based on tallied results for each question. However, this method was not adopted because it did not allow for expressing the correlation of the responses for each question, and consistency in individual behavior would be lost. Furthermore, differences were observed in the evacuation intentions between the residential areas (six districts) and the number of stories of the residence (single-family homes, single-story apartment buildings, two-story or higher single-family homes, two-story or higher apartment buildings), and therefore, the responses were divided into groups according to these two attributes. Moreover, when selecting the response to be associated with each household, the response was selected from the group for which the household matched the residential area and the number of stories of the residence.

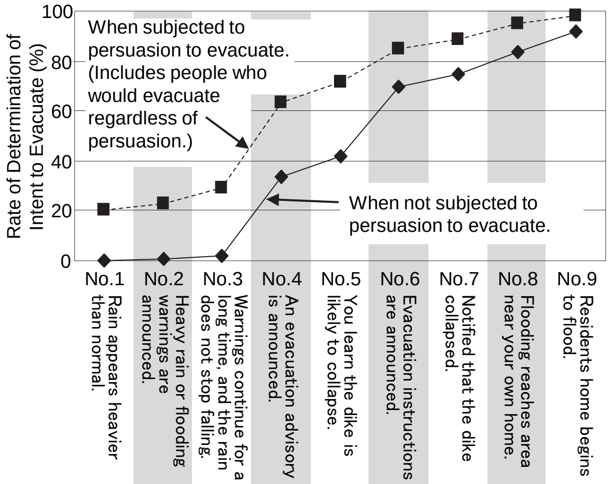

Fig.4 Rate of determination of intent to evacuate by conditions.

b) Determination of intent to evacuate

The percentages of people who decided to evacuate to a location outside of their homes at each of the stages, No. 1–9, as shown in **Table 3**, which were obtained from a survey of the residents, and the percentages for a case in which the residents were also subjected to persuasion are shown in **Fig.4**.

As shown in the figure, if we first focus on data for when the residents are not subjected to evacuation persuasion, a large increase is observed at the point in time that the residents learn about the evacuation advisory, but that percentage is limited to 34%, which is approximately one-third of all the residents. Furthermore, the evacuation percentage increases dramatically to approximately 70% when evacuation instructions are issued. We can also see that at the final point when the residents' homes are beginning to flood, the percentage of residents who have determined to evacuate reaches about 92%, meaning that approximately 8% of the people have no intention to evacuate their own homes at any of the stages.

In determining the intent to evacuate when subjected to persuasion at each stage prior to the issuing of the evacuation instructions, the percentage of residents who have determined to evacuate is about 20% higher than when they are not subjected to evacuation persuasion. However, after the evacuation instructions are issued, that difference decreases. These results show the importance of persuasion to promote evacuation in the initial stages of a disaster.

The timing of the occurrences in the simulation of each event corresponding to the conditions of **Table 3** is shown in **Fig.5**. To establish the timing of these events, we used the time difference between the evacuation advisory and the embankment failure obtained as-is from the calculation results of the abovementioned river model. Using the time difference, the timings when the flood warning and the river-related information would be transmitted were

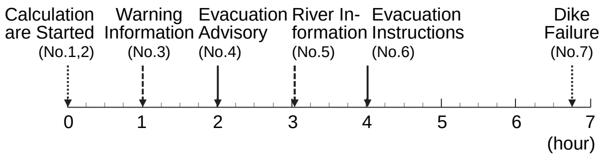

Fig.5 Event occurrence timing.

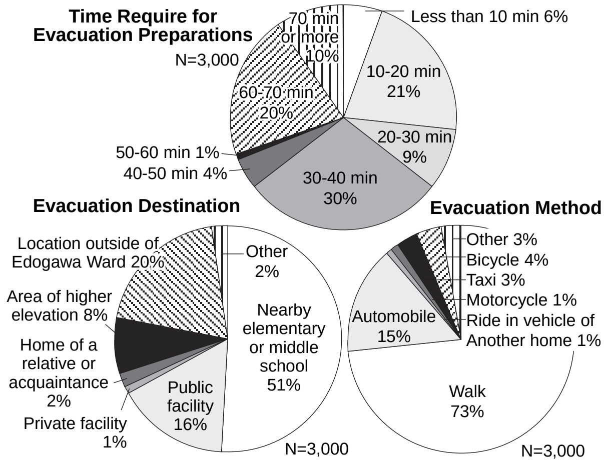

Fig.6 Time required for evacuation preparations and behavior at time of intention to evacuate.

set using a time of two hours prior to the issuance of the evacuation advisory as the calculation start time. For this situation, conditions that had already occurred prior to starting the simulation were assumed as conditions No. 1 and No. 2. In addition, condition Nos. 8 and 9 occurred at different timings for each individual depending on the location and flooding status of their homes. The timings shown in **Fig.5** actually show the start of information transmission using the occurrence of an event as the trigger, and therefore, the exact timing of the occurrence of an event is the timing at which each resident receives information via transmission by radio communications for disaster prevention, mass media, etc. Therefore, if a resident is unable to obtain information, the relevant event does not occur.

In the evacuation behavior model, the determination of intent to evacuate is decided by residents according to the conditions for receiving disaster information and evacuation persuasion. More specifically, if the information that was obtained was information that indicated a situation in which the resident responded that he or she would decide to evacuate, or was a later situation, the resident was treated as having made the decision to evacuate. Furthermore, if information was obtained from another resident who had already decided to evacuate, this was viewed as having been subjected to evacuation persuasion, and depending on the evacuation intention at the time that the resident was subjected to persuasion, the resident either decided at that point in time to evacuate or would decide to evacuate, depending on the details of the information that was received.

c) Timing at which evacuation started

Responses pertaining to the time required for preparations from the moment the decision was made to evacuate until the resident left his or her home to evacuate are shown in the top portion of **Fig.6**. According to these results, the number of households that can complete preparations within 30 minutes from the time that the decision was made to evacuate was limited to 36%. Moreover, the response that accounted for the largest percentage of responses indicated that a preparation time of 30–40 minutes would be required, and this was the case for one-third of all respondents. On the other hand, a similar number of respondents indicated that they would need one hour or longer to prepare. In the evacuation behavior model, the timing at which evacuation was started was determined by adding the time required to prepare for evacuations once the decision was made to evacuate.

d) Evacuation behavior

The tallied results for the survey items relating to behavior at the time of evacuation are shown at the bottom of **Fig.6**.

First, the ward's evacuation plan includes evacuation to both regional disaster prevention centers (higher elevation) as a basic evacuation destination and shelters (elementary and middle schools) as emergency evacuation destinations; however, inconsistencies occurred between the ward's evacuation plan and the evacuation destinations desired by the residents. More specifically, many respondents replied that they would evacuate to a nearby elementary or middle school, and when other public facilities were included, the percentage of respondents who intended to evacuate to a facility of the ward reached 67%. On the other hand, respondents who expected to evacuate to a higher elevation location was limited to 8%, which was a very limited percentage. Twenty percent of the respondents imagined broad-based evacuation to an area outside the ward.

Next, when asked about their evacuation methods, 73% of the respondents assumed that evacuation would be done by walking, which was characteristic of the group. Evacuation using an automobile also included evacuating as a passenger in someone else's car or using a taxi or motorcycle. The percentage of respondents falling into these categories was around 20%. When considered in terms of absolute numbers, it is clear that the number of automobiles used for evacuation would be large.

In the evacuation behavior model, the evacuation destination and method for residents who have started evacuation behavior were selected based on these responses. To simplify the model, if evacuation was done to a public facility, a private facility, or a home

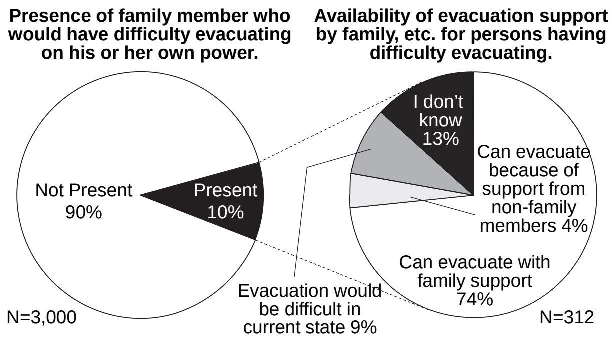

Fig.7 Presence of family members who would have difficulty evacuating on their own and availability of evacuation support by family members, etc.

of a relative or acquaintance within the ward, a condition of evacuation to a shelter was assumed. In addition, if a resident indicated that he or she would evacuate to an area outside the ward, such a case was modeled using an evacuation to virtual facilities distributed at the end points of the network of roads that led to the outside of the ward. Furthermore, the evacuation methods were selected as either walking or by car. If the response indicated that evacuation would occur by walking or by bicycle, the condition was modeled as evacuation by walking, and for all other cases, the condition was modeled as evacuation by car.

e) Persons experiencing difficulty in evacuating on their own

The two graphs shown in **Fig.7** are respective responses to questions regarding (1) the presence of a family member who would have difficulty evacuating on his or her own power and (2) whether or not evacuation support could be provided for households having family members who would have difficulty evacuating on their own. When we look at these results collectively, it is clear that 10% of all households have family members who would have difficulty evacuating on their own, and at least about 10% of such households would have difficulty in obtaining support for evacuation by other family members. Therefore, evacuation on a household unit would be difficult.

These results were reflected in the evacuation behavior model, and a condition that included the presence of a person who would have difficulty evacuating under his or her own power and for which evacuation would be difficult was modeled as a state in which evacuation to a location outside of their own home was not possible. Half of the responses of "I don't know" regarding the availability of support by family members and others for persons who would have difficulty evacuating were handled as not being capable of evacuating.

Table 5 Strategy scenarios.

Symbol	Strategy Scenario	Modeling Method
A1	Support households who would have difficulty evacuating.	Implement strategies to support households that would have difficulty in evacuation and enable evacuations based on the condition of requiring double preparation time.
A2	Take measures to ensure that all households receive information.	Improve information transmission so that all residents receive the information within one hour from the time that information transmission started.
A3	Improve evacuation timing.	Improve the awareness of residents so that all residents decide to evacuate at least by the time they hear the evacuation advisory.
A4	Improve evacuation preparation time.	Assume advance preparations during normal conditions so that evacuation can be started within 30 minutes from the moment the decision is made to evacuate.
B1	Prohibit dangerous evacuations by residents living in upper stories.	After information of a dike break has been obtained, prohibit the evacuation of residents living on the third floor or higher.
B2	Limit the number of people targeted for evacuation.	After the information of an evacuation advisory has been obtained, prohibit the evacuation of residents living on the third floor or higher. Evacuate all residents living on the second floor or lower by the time the evacuation advisory has been issued.
C	Guide evacuees to regional disaster-prevention centers.	Based on evacuation to regional disaster-prevention centers, do not evacuate to shelters other than in an emergency after flooding begins.
D1	Introduce roads for pedestrians.	After an evacuation advisory has been issued, partition a part of the roads for use by pedestrians (see **Fig.11**).
D2	Decentralize evacuation destinations.	Allow only those households with vulnerable family members to evacuate to shelters.
D3	Promote evacuation in advance.	Complete the evacuation of households with vulnerable family members two hours prior to the evacuation advisory.

5. SCENARIO ANALYSIS

To analyze scenarios for examining measures to reduce damage in the event of large-scale flooding in a large city, we first implemented simulations of scenarios that reproduced the intended behaviors of the residents, as understood from the survey (hereinafter, the current status reproduction scenario). Using that scenario, we gained an understanding of the assumed-damage scale with the current conditions and the factors thereof. Next, we implemented simulations of various scenarios that modeled damage-reduction strategies based on the factors that generated the damage (see **Table 5**), and we then verified the results and identified new issues.

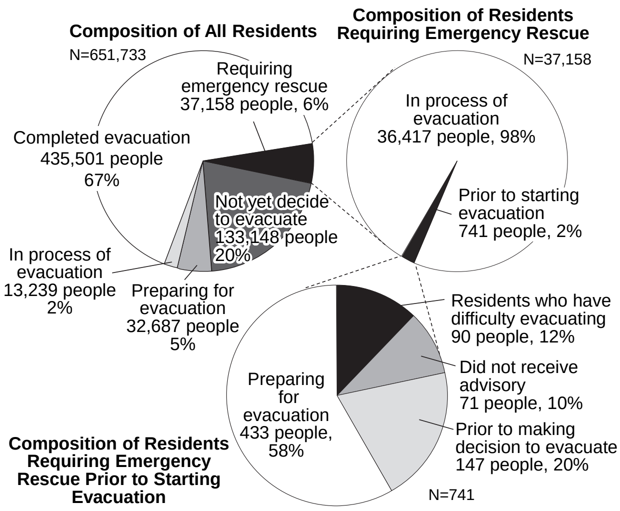

Fig.8 Results of simulation of current status reproduction.

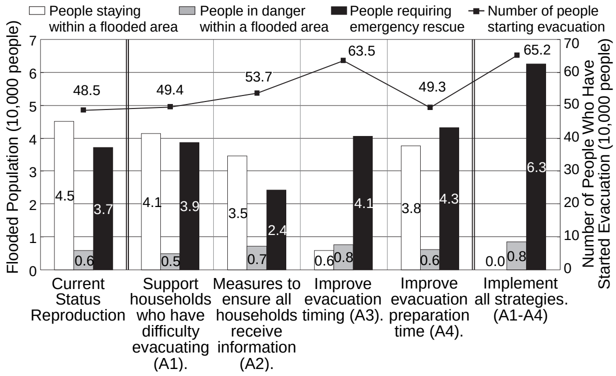

Fig.9 Flooded population and change in the number of people starting evacuations according to strategy scenarios.

(1) Assumed damage with current conditions based on the behavioral intentions of the residents

Figure 8 summarizes the conditions of each resident when 24 hours had passed since the beginning of the current status reproduction scenario. The number of residents requiring emergency rescue would exceed 37,000, and it is clear that large scale injury would result. It is also clear that 98% would be injured while evacuating and would require emergency rescue. Regarding the contributing factors, many residents decided to evacuate when the risk of flooding had increased after the evacuation advisory (see **Fig.4**). Thus, it is clear that these residents became engulfed in the flooding while they were evacuating. Further, if we look at the composition of the residents requiring emergency rescue prior to beginning evacuation, approximately 60% are in the middle of evacuation preparations, 20% do not have any intention to evacuate outside their own homes, and the rest are either residents who have not been able to receive any evacuation information or residents who would have a difficult time evacuating. From these results, with the current status reproduction scenario, it is clear that injury is caused by various factors, including a delay in the determination of intent to evacuate. It is important to note that many shelters ultimately reached an over-capacity state.

(2) Effects of improving evacuation behavior

Based on the problems identified from the current status reproduction scenario, we determined the injury reduction effects from improving the evacuation percentage and the timing at which evacuation began. The assumed strategies are the scenarios A1–A4, shown in **Table 5**.

Figure 9 summarizes the number of people who started evacuating and the flooded population for a case in which each scenario for each strategy was conducted independently with respect to the current status reproduction scenario and for a case in which all the strategies were implemented collectively. The definition of each flooded population, such as the number of people who stayed within the flooded area, is shown in the diagram in accordance with **Table 1**. From these results, if we look at the change in the number of evacuees, when each strategy is implemented independently, the evacuation percentage and the timing at which evacuation is started are improved, and as a result, more residents begin evacuating compared to the current status reproduction scenario. When all the strategies are implemented collectively, it is clear that approximately 650,000 people, a number that corresponds to the entire population, begin to evacuate. However, when we focus on the flooded population, with the scenarios other than A2, it is clear that the introduction of improvement measures has the opposite effect and results in an increase in the number of people requiring emergency rescue. In particular, with the current status reproduction scenario, 45,000 residents stayed in the flooded region; however, when all of the strategies were implemented, the number reduced to zero. However, people requiring emergency rescue due to serious injuries totaled 63,000, approximately 1.7 times more than the level estimated with the current status reproduction. This result suggests that the promotion of stereotypical evacuation behavior of all residents with current conditions has the risk of leading to an increase in injury. We also analyzed the individual implementation of scenarios for each strategy, and found that while scenario A3 involved active evacuation at the evacuation advisory stage, when the evacuation scale became very large, the evacuation facilities became overcrowded, congestion became a serious concern, and the amount of injuries increased. In addition, scenarios A1 and A4 did not involve improvements in the timing at which the decision to evacuate was made, and therefore, the number of people evacuating under dangerous conditions after the evacuation advisory increased, resulting in an increase in injuries. On the other hand, by ensuring that information was thoroughly conveyed with scenario A2, the evacuation of residents who made the decision to evacuate at an early stage was reliably started, and the evacuation timing became faster. In addition, because evacuation intentions were based on an awareness of the current state, a significant increase in the number of evacuees, as seen with scenario A3, did not occur, and as a result, the amount of injuries decreased.

From the above analysis, we were able to confirm the following problems that occur in conjunction with an increase in the number of evacuees.

Problem of risky evacuation behavior: If residents who live in high-rise buildings stay in their own homes, and if their homes become flooded, they require emergency rescue when they evacuate their homes.

Problem of the capacity of evacuation facilities: The capacity of shelters is expected to be exceeded even with the current status reproduction scenario, and is reached at an even earlier timing when the number of evacuees increases.

Problem of evacuee congestion: The increase in the number of evacuees causes serious vehicle and pedestrian congestion, resulting in a slowdown of the evacuation time.

Significantly, assuming a condition in which none of the residents evacuate, the number of people requiring emergency rescue decreases to approximately 6,000 people, which is significantly lower than the current status reproduction scenario. However, the number of people who becomes surrounded by flood waters increases to 310,000, and therefore, some response is required.

(3) Injury reduction effects from evacuation demand reduction measures

Based on the results described in the previous section, we conducted simulations that assumed strategies to reduce risky evacuation behavior immediately before flooding and after flooding. More specifically, the simulations included prohibiting evacuation by residents living on the third floor or higher after a dike break (B1), evacuating all residents living on the second floor or lower by the time the evacuation advisory was issued, and prohibiting the evacuation of residents living on the third floor or higher once an evacuation advisory was issued (B2). These scenarios also assumed that the strategies for A1, A2, and A4 had already been implemented.

If we examine the simulation results for B1 and B2 in **Fig.10**, it is clear that both scenarios significantly reduce injury when compared to the scenario in which all residents were evacuated (left side of

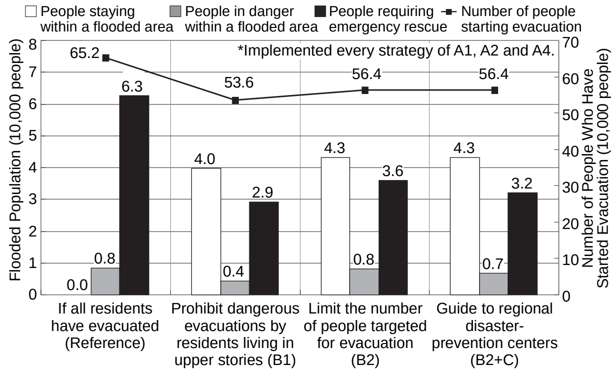

Fig.10 Effects of limiting evacuees and guiding them to regional disaster-prevention centers.

Fig.10). However, when compared to the current status reproduction scenario, the reduction in the number of people requiring emergency rescue is minimal, and it is clear that a large amount of injury still occurs. Moreover, limiting the number of evacuees resulted in 40,000 people being surrounded by flood waters, and therefore, separate measures that target these residents are required.

(4) Injury reduction effect by improving evacuation destinations

While 70% of the residents intend to evacuate to a public facility within the ward, the total capacity of shelters is approximately 270,000 people. Therefore, if a large-scale evacuation is implemented, it would be unrealistic for residents to evacuate as intended. On the other hand, regional disaster-prevention centers have enough capacity to accommodate a total of over 2 million people. In the ward's evacuation plan, these centers are stipulated as priority locations for the evacuation of residents. In the next analysis, we established a scenario (C) that used these regional disaster-prevention centers. In this scenario, regional disaster-prevention centers were stipulated as the evacuation destination according to the residential district. However, when information of a collapse of the embankment or flooding of the surrounding region was obtained, evacuation to the nearest evacuation location that included shelters was assumed as the emergency evacuation behavior.

If we examine the results of adding the conditions of C to those of B2 (right side of **Fig.10**), we can confirm that injury is reduced by stipulating the appropriate evacuation destination. However, since the decrease is approximately 4,000 people, the number of people requiring rescue still remains over 30,000.

(5) Injury reduction effect from dispersing evacuees

While a reduction in the number of injuries was observed in improving the evacuation destination, a

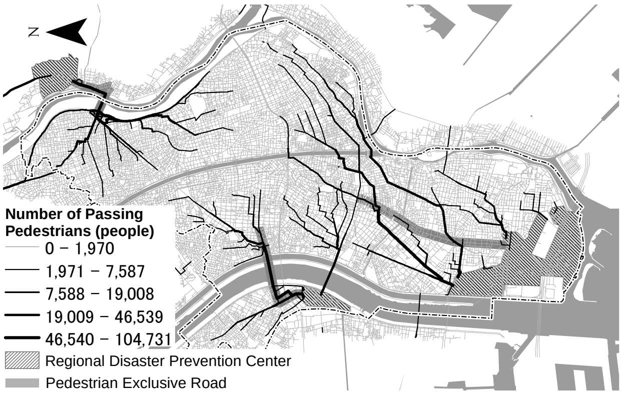

Fig.11 Number of pedestrian evacuees passing on roads and areas where pedestrian-exclusive roads are introduced.

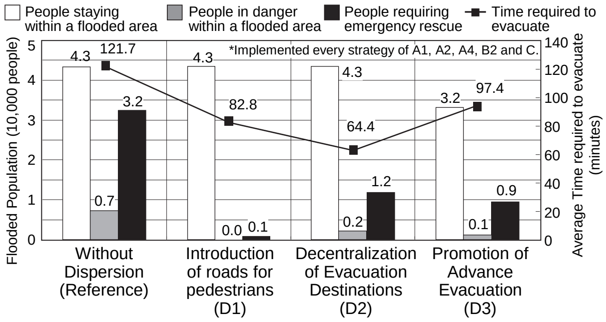

Fig.12 Effects of dispersing evacuees.

large number of evacuees were guided to a small number of regional disaster-prevention centers. Consequently, large-scale congestion occurred along some roads particularly due to pedestrian evacuees (see **Fig.11**). Congestion occurred because of evacuees converging on specific roads in numbers that temporarily exceeded capacity. Accordingly, to eliminate the congestion, a strategy that spatially and temporarily disperses evacuees is conceivable. To develop spatial dispersion strategies, first a scenario was developed in which some of the roads were designated exclusively for pedestrian use after an evacuation advisory was issued (D1, see **Fig.11** for the targeted roads), and a strategy was established in which the evacuation destinations were decentralized by selecting evacuation destinations, including shelters for vulnerable households (households with preschool-age children or elderly family members, approximately 24% of all households) and households with family members who would have difficulty in evacuating (D2), were established. With D1, it was assumed that the roads designated exclusively for pedestrian use were well known, and in the search for pedestrian courses, the roads were evaluated at half the normal cost. Next, as a temporal dispersion strategy, a case in which evacuation of vulnerable households was completed two hours prior to the evacuation advisory (D3) was established with the assumption that the prior evacuation of vulnerable households was promoted.

The flooded population and the average evacuation time of pedestrian evacuees for conditions D1 to D3 based on strategies B2 and C is summarized in **Fig.12**. From the figure, if we examine the results for strategy D1, it is clear that the evacuation time was reduced by approximately 40 minutes compared to strategy C, which required approximately 2 hours for evacuation; congestion was also alleviated. Further, a total of approximately 30,000 people requiring emergency rescue was significantly reduced to approximately 1,000 people. Next, with strategy D2, because vulnerable households could evacuate to nearby shelters, the evacuation time was reduced by another 20 minutes compared to D1. However, congestion by evacuees heading to regional disaster-prevention centers was not adequately alleviated, and the injury reduction level was limited to approximately 20,000 people. Finally, with strategy D3, the evacuation of vulnerable households was completed at an early stage. Therefore, congestion at the time of the evacuation advisory was alleviated, and the number of people requiring emergency rescue was reduced to approximately 9,000 people, with fewer experiencing injury compared to D2. However, the evacuation time of ordinary households heading to regional disaster-prevention centers was not significantly improved. When the strategies of D1 to D3 were implemented together, the number of people requiring emergency rescue was reduced to zero.

(6) Summary of scenario analysis results

In this section, we summarize the issues and strategies for reducing the number of flooding victims in large cities, as identified from the scenario analyses implemented in this study.

Improving the awareness of residents: The awareness among residents regarding flooding disasters is low, and with the current awareness levels, many residents would engage in risky behavior in the event of a flooding disaster, such as evacuating when their own homes are flooded. To reduce the number of victims, civil authorities must understand the flooding risks of cities and improve awareness to promote appropriate responses. Therefore, we must also promote disaster prevention education during normal periods.

Reducing evacuation demand: Large-scale evacuations of cities result in problems such as congestion of evacuees and evacuation facilities exceeding their capacities. Therefore, these evacuations also carry the risk of increasing the number of victims. Accordingly, measures to reduce the demand for evacuation are required, such as recommending that residents of high-rise buildings wait in their own homes. However, in zero-meter areas, flood waters could remain for an extended period of time, and therefore, secondary evacuation plans for use after human life has been secured must also be examined and implemented. This includes plans to promote reserve supplies in each home and rescue plans in the event of a flood.

Dispersion of evacuees: If evacuation is initiated once an evacuation advisory is issued, the concern is that congestion of evacuees could become serious. Therefore, an intrinsic issue is advancing with the temporal dispersion of evacuees by promoting proactive evacuation from an early stage. Achieving this requires that information be aggressively provided from an early stage using the latest technology for weather forecasts and water-level predictions. Appropriate evacuation destinations must also be specified, and strategies to alleviate congestion must be implemented to spatially disperse evacuees. The most serious concern arises when large numbers of evacuees temporarily converge in small-scale evacuation facilities. Therefore, evacuation facilities that can meet the evacuation demands of each region must be established. However, the establishment of a small number of large-scale evacuation facilities comes with the risk of congestion becoming a serious problem, and therefore, caution must be exercised. Furthermore, if the establishment of evacuation facilities is difficult, extensive evacuation that includes evacuation to higher elevations or areas outside the region must also be examined, which would require coordination with surrounding regions and measures to educate the residents. The most effective measure for cities in low-lying areas is to realize early-stage evacuation to areas outside the flood zone by promoting both types of dispersion measures.

Transmitting information to all residents, and supporting residents requiring relief in a disaster: To eliminate human suffering, it is essential to support residents who do not receive evacuation information or would require relief assistance during a disaster. It is particularly difficult for large cities to ensure that information is transmitted to every resident due to various problems such as the presence of a large, diverse population, and the lack of cohesiveness in communities. Conceivable measures to resolve this problem include diversifying the media sources used to transmit information and fostering independent efforts to obtain disaster-related information. Moreover, support for residents requiring evacuation assistance is a basic problem, which does not depend on regional characteristics. In cities with large populations, it is difficult for the government to be the sole source of support during disasters, and therefore, there is a demand to develop support organizations by engaging residents in the region.

6. CONCLUSION

In this study, our objective was to examine appropriate evacuation strategies for large-scale flood damage in a large city. To achieve this, we developed a simulator to model the spatial characteristics of the region, including its topography and evacuation facilities, as well as the current status of the residents of an area. This simulator was used to specifically model large-scale evacuations based on the behavioral intentions of the residents using an entire large city as the target. In addition, the simulator was also capable of modeling conditions, such as the disaster phenomenon, the transmission of information, and the damage in the event of large-scale flooding; thus, we were able to use it as a tool to examine evacuation measures in a large city. However, some issues remain that must be resolved to achieve a more realistic examination, such as considering the impact of inland flooding and flow speed on the evacuation of residents.

In this study, we used the developed simulator to conduct scenario analyses of the Edogawa Ward. From the analyses, we could identify the evacuation problems that are inherent in large cities, and found that the promotion of stereotypical evacuation behaviors temporarily creates a large number of evacuees, compounds the problems of congestion, and causes evacuation facilities to exceed capacity, resulting in an increase in injuries. We also confirmed that, to reduce injury in the event of a flooding disaster in a large city, it is important that a wide range of evacuation strategies be developed to improve the awareness of the residents, reduce the evacuation demand, and temporally and spatially disperse evacuees.

The results of this study are limited to indicating the framework for evacuation strategies in cities, and therefore, to devise practical evacuation plans for a specific region, examinations based on actual conditions of a region must be implemented. Furthermore, the appropriate implementation of an evacuation plan requires the understanding of the residents in the region to be evacuated, and therefore, activities to raise awareness are extremely important.

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