Title page

Simulating Emergencies with Transport Outcomes Sim (SETOSim): Application of an agent-based decision support tool to community evacuation planning

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Abstract

In the time since the 2004 Indian Ocean tsunami and Hurricane Katrina in 2005, an increasing number of studies have focused on developing agent-based simulations of citizen evacuation behaviours. The application of simulation to practice (*i.e.* evacuation planning, community disaster risk reduction strategy), however, is limited. This research aims to explore the effective application of agent-based evacuation simulation to better inform community evacuation planning through a collaborative process. The study developed an evacuation modelling tool focusing on the storm surge and flood evacuation behaviours of residents living in Takamatsu, Japan. The city of Takamatsu borders the Seto Inland Sea, an area where the risks from water-related disasters are increasing. The tidal flow of the Seto Inland Sea and storm surge flooding are simulated based on data from the 2004 typhoons, which seriously flooded the study area. An agent-based model exploring the relative vulnerability of residents as a function of location, demographic attributes including age, and previous experience is developed based on a questionnaire survey of residents which gathered information on their stated preference of evacuation. A visualisation of the simulation was shared with residents through workshops held in five neighbourhoods. It was also shared with government officials. The feedback from residents and governments officials on the effective applications to community evacuation planning are discussed and plans for future research are outlined.

Keywords: evacuation; agent-based model; natural hazards; disaster risk reduction; Japan; decision support tool

1. Introduction

In order to reduce disaster risk and enhance community resilience, communities must commit to promoting disaster preparedness, planning future responses, and conducting recovery exercises. These efforts can include evacuation drills, training, and the establishment of area-based support systems (UNISDR, 2015). Emergency decision-making support systems play an important role in enhancing public capacity to respond to natural hazards (Zhou, Wu, Xu, & Fujita, 2018). After the events of Hurricane Katrina in 2005, researchers have often focused on simulating evacuation behaviours to inform evacuation planning (Dixon, Mozumder, Vásquez, & Gladwin, 2017; Lämmel, Grether, & Nagel, 2010; Sadri, Ukkusuri, Murray-Tuite, & Gladwin, 2015; Weller, Baer, & Prochaska, 2016). Research in this area appears even more critical after the North East Japan earthquake and tsunami disaster of 2011 (Mas, Suppasri, Imamura, & Koshimura, 2012). In simulating evacuation behaviour, agent-based models (ABM) have proved to be highly suitable, enabling researchers to capture the interactions of diverse agents and to simulate dynamic responses in spatial environment over time (Chen, Meaker, & Zhan, 2006; Dawson, Peppe, & Wang, 2011). More recent work on hurricane-driven evacuations has seen an increase in the geographical scale of models and the application of integrated approaches, advancing the state of the art in ABM (Davidson, Nozick, Wachtendorf et al., 2020; Morss, Demuth, Lazrus et al., 2017; Watts, Morss, Barton et al., 2019; Yang, Davidson, Blanton et al., 2019). Yang et al (2019) simulated different scenarios of hurricane development and its impact on decision-making. The challenges of using ABM, however, include the simulation of human agents with potentially inappropriate behaviour and decision-making under the circumstances; in such cases, choices are affected by complex psychology (Bonabeau, 2002). Despite the complexity of real-world evacuation situations, models often assume that behaviours are relatively homogenous; for want of data, many models must rely on assumptions made about agents' behaviour (Pel, Bliemer, & Hoogendoorn, 2012; Yin, Murray-Tuite, Ukkusuri, & Gladwin, 2014). Further, integration with oceanographic or hydrological models such as tsunami and storm surge simulators is rarely undertaken, making many of the environments within which agents operate relatively unrealistic. This work presents an interdisciplinary study by researchers in the fields of marine environment/oceanography, transport planning, complexity science, and community disaster management. The study aims to:

a) develop an ABM evacuation simulation model that reflects residents' experiences and preferences in terms of emergency behaviours and

b) explore an application of the ABM simulation to community evacuation planning together with residents in a collaborative process.

In this work we base the behaviour of residents on empirical evacuation patterns of residents, as drawn from a questionnaire survey and interview. A qualitative interview and questionnaire survey with residents inform the evacuation decision-making in different stages of evacuation process (*e.g.* when to depart, where to go, and how to travel). Visualisation is applied to represent the simulation because it is a strong tool to allow community members to develop an appropriate understanding of risk. The visualised simulation, as an interactive decision support tool, was presented to residents as evacuation behaviours were discussed.

The case study area is Takamatsu city, Japan which is located in the Seto Inland Sea area. The Seto Inland Sea area is hit by more than 20 typhoons every year. The most recent disaster was Typhoon 21 in 2018; it flooded the Kansai International Airport with a storm surge that reached a maximum tide level of 233cm at the port of Kobe and 329cm at the port of Osaka (Ministry of Land, Infrastructure, Transport and Tourism, Kinki Regional Development Bureau, 2018). In Takamatsu, a series of typhoons in 2004 caused serious storm surges which flooded extensive area of the city. Historically, Takamatsu has suffered from the impact of typhoons (Nakanishi & Black, 2018). However, compared with other cities along the Seto Inland Sea, Takamatsu had not been significantly affected since the late 19th century when the city's infrastructure system was upgraded. Even at the time of the Isewan typhoon (1959), which took the lives of more than 5,000 people, the impact on Takamatsu was of a lesser scale than that on other surrounding cities. The 2004 storm surge floods were a wake-up call for residents in Takamatsu; since then, residents have expressed the opinion that the city needs enhanced awareness and preparation. In particular, the risk of a storm surge is expected to increase in the Seto Inland Sea area in the future along with the changing climate. The expected scale of storm surges in Seto Inland Sea with a return period of 100 years is estimated at 2.4 – 2.7m in the west Suo-nada Sea (the west side of the Seto Inland Sea), although this maximum height varies spatially throughout the sea (Yasuda et al., 2014). Japan understands itself as a country where residents are well-prepared for disasters, with extensive knowledge on the actions they should take in response. However the Western Japan Flood of 2018[1] and recent Typhoon Hagibis of 2019 revealed that residents' awareness of flood risks and community evacuation planning are still immature in many places, despite governmental dissemination efforts regarding hazard maps and evacuation drills.

The paper is organised as follows. In the next section, we review the existing agent-based models used for evacuation simulation and identify the limitations of current models. This is followed by a review of studies of tidal flows and storm surge simulation in the Seto Inland Sea and the application of these studies to community evacuation planning. The method section describes the study area, storm surge simulation model, and agent-based evacuation model that are applied in this research. This section also presents a summary of the residents questionnaire survey results, which are incorporated into the evacuation model. The outcome of community workshops is discussed along with research implications. The paper concludes with a brief discussion of the implications of this work and future directions.

2. A review of research on ABM models and its application to practice

When faced with a natural hazard, residents are required to make multiple, nested decisions in a few stages. First, they decide whether or not to evacuate, referring to the warnings and weather forecast. In the case of a hurricane/typhoon, residents have a few days to check the movement of the hurricane/typhoon and prepare for evacuation. Evacuation is critical if a high storm surge is predicted (Sadri et al., 2015). If the hazard is an earthquake, building fire, or nearfield tsunami, residents are required to evacuate within an hour in most cases (Wang, Mostafizi, Cramer, Cox, & Park, 2016). The second decision that residents make is the travel mode for evacuation. Private cars are the most used travel mode for hurricane evacuation in the US; some households may even take a second vehicle (Dow & Cutter, 2002). However, access to private vehicles will vary widely with geography (*e.g.* there are lower car ownership rates within cities, as well as some countries) and demography (*e.g.* car ownership related to income and age). In Japan, many conduct their evacuation by walking (Mas et al., 2012). In fact an important lesson from the 2011 North East Japan earthquake and tsunami is that the movement of crowds (including congested car traffic) hindered the smooth evacuation (Editorial Office of The Ishinomaki Kahoku A Daily Newspaper of Sanriku Kahoku Shimpo, 2014; Nakanishi & Black, 2018).

[1] The record-breaking precipitation during the period of 28th June to 8th July 2018 claimed the lives of more than 220 people in the Western part of Japan. More than 30,000 houses were flooded and 11,000 houses completely or partly collapsed, in addition to severe damages to infrastructure.

The third decision is the choice of evacuation route. In the literature, the most common method in simulating route choice is to use shortest route algorithms: residents try to reach their destinations (often the nearest shelter) via the shortest route possible (Makinoshima, Imamura, & Abe, 2018). However, in reality this choice may be constrained by limitations in spatial knowledge and perception. Real data of how individuals travel has been used, drawing upon survey data to model evacuee movements (Arce, Onuki, Esteban, & Shibayama, 2017). Kita, Hara, and Ye (2014) used a cellular automaton, a model that simulates flows between small areas (cells), to simulate people's movements and model evacuation behaviour. A review by Zheng, Zhong, & Liu (2009) on crowd evacuation models summarised the seven methodological approaches as follows: cellular automata models, lattice gas models, social force models, fluid-dynamic models, agent-based models, game theoretic models, and approaches based on experiments with animals. They concluded that psychological and physiological elements affect individuals and must be integrated in models.

Agent-based modelling (ABM) is frequently used to represent evacuation behaviours. It enables the simulator to capture the interactions of diverse agents and their dynamic responses to the spatial environment over time (Chen et al., 2006; Crooks, Castle, & Batty, 2008; Dawson et al., 2011; Mas et al., 2015). In Japan, Mas et al. (2012) simulated a tsunami evacuation with different scenarios based on the start time of the evacuation. In one scenario, all agents begin evacuating at the same time; another assigned fixed start times to different groups or areas. A third scenario introduced psychological parameters in the form of a Rayleigh cumulative distribution. Since Mas's work, Rayleigh distributions have been used in literature to represent varied departure times (Mostafizi, Wang, Cox, Cramer, & Dong, 2017; Wang et al., 2016). This is based on the compilation by Lindell and Prater (2007) of a distribution of departure times. Makinoshima et al. (2018) used a log-normal distribution for their agent-based evacuation simulation, reflecting the higher departure rates during the early post-event period. Others have sought to integrate components of family and social ties, and how dependencies between agents lead to group decisions being made (Liu, et al. 2014) or crowd behaviour being followed (Huang, Lindell, & Prater, 2016).

Examples of interactions between elements of crowd and flood simulations exist in the literature. Dawson et al. (2011) simulated the flood-based evacuation of a coastal town in the UK, coupled with a hydrodynamic model to estimate the vulnerability of individuals to flooding under different storm surge conditions. Mas et al. (2012), Mas, Adriano, and Koshimura (2013) and Takabatake, Shibayama, Esteban, Ishii, and Hamano (2017) used a tsunami simulation model to identify potential casualties. This required a multi-disciplinary team to implement. Many studies estimate inundation level by defining hypothetical situations or drawing upon past evets. For instance, Yang, Scheffran, Süsser, Dawson, and Chen (2018) used a pre-defined rainfall scenario and a simplified gravity-driven surface runoff model to simulate pluvial flooding over a digital elevation model. Wang, et al. (2016) explored how differences in evacuee decision-making influence the ultimate mortality rate using a near-field tsunami evacuation case study.

The limitations of these existing studies are twofold. First, most use simple choice architectures which are unlikely to fully reflect evacuee behaviour. ABM can allow human agents with potentially inappropriate or unsuitable behaviour and complex psychologies (Bonabeau, 2002) to interact and influence one another, which is relevant in a disaster situation. However in many existing studies, agent decision-making is relatively homogenous, and evacuees differ only in their starting time or travel speed. A few researchers have conducted questionnaire surveys on travel mode choice and route choice and integrated these findings into evacuation simulations (for example, Dixon et al., 2017; Takabatake et al., 2017). In many studies, results obtained by computer analysis are used (for example, Chen et al., 2006; X. Chen & Zhan, 2008; Kim, Lee, & Lee, 2017; Sahal, Leone, & Péroche, 2013) or simulation is conducted based on assumptions on agents' behaviours (Goto et al., 2012; Lämmel et al., 2010). Additional components of evacuation behaviour that have received less focus within ABM (Jumadi, et al. 2017) include evacuee trust in information (Lamb, et al., 2011), risk perception (Dash and Gladwin, 2007), housing type, and exposure to prior risk (Huang et al., 2016).

ABM-based simulation is a powerful tool in raising community awareness and training (Scerri, Hickmott, Padgham, & Bosomworth, 2012). However the application of ABM-based simulation to community evacuation planning is scarce despite the increasing number of studies developing simulation models. The practical application of simulation can enable residents to understand the risks as a form of disaster education and to enhance community preparedness. The possible rewards of preparedness attracted attention after the 2011 North East Japan earthquake and tsunami, when the effectiveness of such community education was verified. Disaster education and practice drills were credited for the 'Kamaishi Miracle', which saw only 5 of 2,900 Kamaishi primary and junior high school students lose their lives - a rate 20 times lower than that of the general public (Katada & Kanai, 2016; The World Bank, 2012). In Kamaishi City, Katada and Kanai (2008) organised tsunami education forums to help residents understand the risk of tsunamis and develop an evacuation plan using a map. This research team developed an integrated simulator of tsunamis that combines hydrodynamic simulation of tsunamis with warning and human-response simulations for evacuation (Katada & Kuwasawa, 2006)[2]. Using this disaster imagination game, Katada & Kanai (2008) demonstrated that disaster simulation helps residents learn effective evacuation behaviours.

Similarly, Liu, Takeuchi, and Okada (2007) developed a multi-agent evacuation simulation system with local communities in Nagata ward, Kobe. In their simulation, they focused on mutual assistance among agents (*e.g.* rescuers helping elderly people), drawing up their simulation design based upon residents' opinions on what they think should happen. Focusing on private business entities, Manley and Kim (2012) developed an agent-based simulation model to inform emergency evacuation plans, including disability levels among agents. This research simulated evacuation within buildings but the results suggest the need for a measure to identify individuals with disabilities earlier in order to ensure their safety during crisis situations. Both studies focused on people who are less able to move quickly during natural hazards. This informs ABM simulation in Japan in particular, where ageing is a serious concern in managing evacuation (Nakanishi, Black, & Suenaga, 2019).

3. Method

3.1 Study area

The study area of this work is Takamatsu City, Japan, which is hit by an average of 20 typhoons every year. The typhoons often trigger a storm surge in the coastal areas of the Seto Inland Sea (Figure 1). Takamatsu has a population of approximately 430,000 people as of 1 February, 2019. As in many other Japanese cities, the population in Takamatsu is ageing – 27.3% of people are over 65 years old. The most recent serious disaster was a series of typhoons in 2004 which flooded an extensive area of the

[2] Their model was not an ABM model, but it was useful to represent the situation of hazard.

city. On 30 August 2004, during Typhoon 16, the water level of Takamatsu port exceeded 2.46m, the highest recorded level in its history. The high tide and the summer tidal current accelerated this phenomenon. In the city of Takamatsu, more than 15,645 houses were flooded and an area of 980ha was inundated, causing the closure of major roads. Even dedicated evacuation centres were flooded and evacuation of residents became chaotic. During the continuous typhoons, a number of landslides occurred; different areas flooded according to the difference of tides, wind, and rainfall. In particular, Typhoons 16 (Figure 2) and 23 caused serious floods.

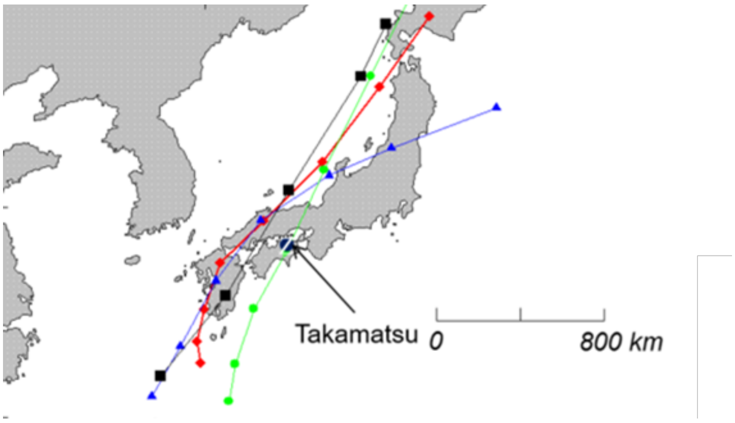

Figure 1. Location of Takamatsu, Japan and the typhoon trajectories that triggered storm surges in the last 70 years (1949 – present) (collated by authors)

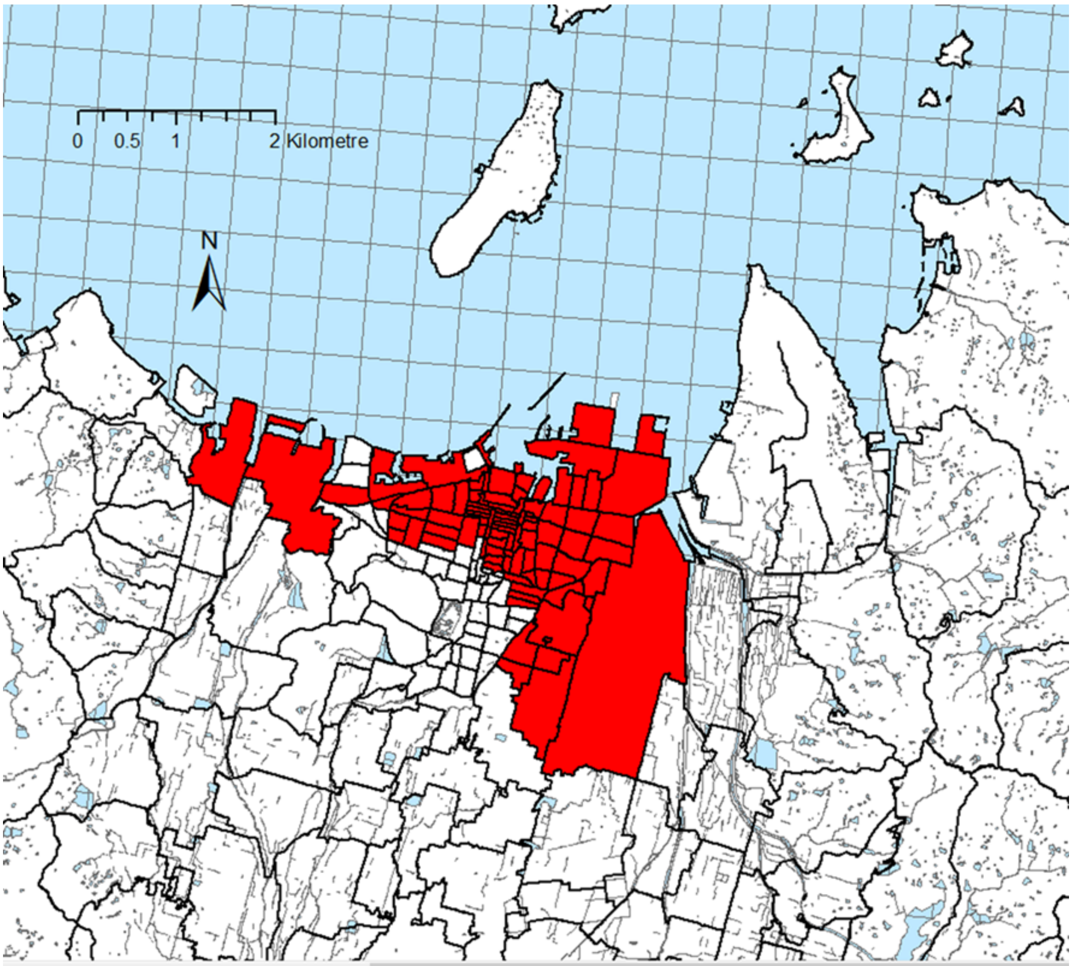

Figure 2. Flooded area (highlighted in red) during the 2004 Typhoon 16 (map made by authors)

Figure 3. Photo of flooded neighbourhood on 1 September 2004 (provided by residents)

3.2 Storm surge height simulation of the Seto Inland Sea

Studies on tidal current and storm surges in the Seto Inland Sea have been conducted since 1970 (Takeoka, 2002), with major advances during the 2000s. However studies in this area are still relatively limited.

During Typhoon 16 in 2004, a storm surge was caused by a combination of wind and the high tidal current typical of summer. The strong west and north-west wind (a speed of 26m/s was recorded) accelerated the drift effect[3], resulting in the highest recorded sea water level. Kohno, Kamakura, Minematsu, and Ueno (2009), applying their conventional two-dimensional storm surge model in the Seto Inland Sea, found that the 2004 storm surge was mainly caused by the wind setup effect. Researchers of Kagawa University developed a model and a numerical simulation based on the investigation of sea topography in their report of 2004 storm surge (Kagawa University, 2004). Kawai, Hashimoto, Yamashiro, and Yasuda (2011) discussed the need for the sea surface drag coefficient to be appropriately measured in order to consider the impact of wind. The model applied in this study is based on Kagawa University (2004), informed by Xingzhao, Tkalich, and Soon (2007) which discussed that computation of wind-waves pattern focusing on wind conditions can be applied to studies of the Seto Inland Sea. The storm surge simulation is presented below.

The suction effect due to the low atmospheric pressure is formulated in the following equation[4]:

$$\zeta_s = 0.99\Delta p \ (cm) \quad (1)$$

[3]A phenomenon whereby the mass of surface water in a part of the sea near the shoreline moves toward the shore. This occurs when a strong wind continuously blows at almost constant directions over a long period of time over a relatively shallow body of water, *e.g.* a shallow shoreline or a bay.
[4] The details of correlation between wind speed and the wind drift parameter can be seen in Appendix B.

Where Δp represents the decrease in the level of atmospheric pressure (hPa). The wind drift effect is formulated as:

$$\zeta_w = kU^2 cot\theta \ln\left({}^{h_1}/_{h_2}\right)(cm) \quad (2)$$

Where k is the wind drift parameter, U is the wind speed (m/s), $cot\ \theta$ is the slope of the sea bottom, h_1 is the water depth at the windward side, and h_2 is the water depth at the lee side (Kim et al., 2015; Mori et al., 2014; Kagawa University, 2004).

We conducted a survey of the sea bottom topography of the Takamatsu coastal area of the Seto Inland Sea to estimate the sea bottom slope. The researcher (third author) dived underwater with a 3D visualisation device and measured the gradient of sea bottom and topography. This is a common method used to estimate the sea bottom slope (see details in Appendix A). Using the estimated parameter (see Appendix B), tidal height considering the wind speed is estimated and compared with the observed tidal height. Figure 4 shows the robustness of the estimation by comparing observed tidal level and simulated tidal levels. The R-squared value of linear approximation was 0.76 and the value of exponential approximation was 0.96 (during the period of highest tide). In our simulation, we used the 3-dimensional multi-level momentum equations and changed the wind drift parameter depending on a change of the wind velocity in linear and exponential approximation, respectively. The transformation of the long wave and the kinetic effect are included in this simulation. Also, we applied a smaller mesh analysing sea bottom topography in and around the coastal area in Takamatsu city, based on Oikawa and Kyozuka (2007), whilst the parameter was re-calculated to reflect the outcome of our sea bottom topography survey. The temporal change of wind velocity and direction were simulated as in Xingzhao et al. (2007).

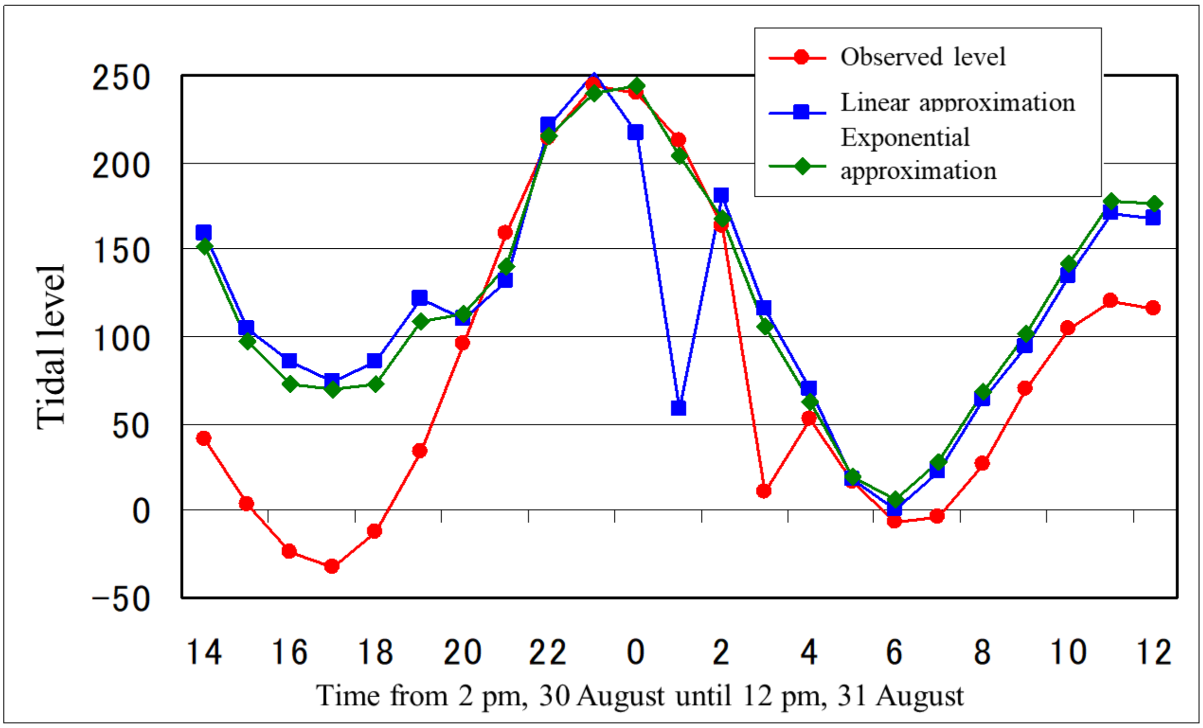

Figure 4. Comparison between observed tidal level and simulated tidal levels

Figure 4 shows that the simulation result (*i.e.* approximation) is close to the observed tidal change in the timeframe between 20 (8 pm) of 30th August and 2 (2 am) of 31st August when the tidal height reached to its peak. This demonstrates that the model is appropriate in representing the tidal height of storm surge, if wind speed is precisely informed. This simulation suggests that tidal height due to drift effect is consistent with the squared value of the change of wind speed. For example, if wind speed doubles, the tidal height may be four times as high as the base height. The inundation due to the storm surge is reflected in the agent-based model of evacuation behaviour, both in terms of rendering different parts of the environment unsafe for the simulated individuals and in terms of being observed by those individuals as part of their evacuation decision process.

3.3 Agent- based model of evacuation behaviour

The purpose of the agent-based evacuation model is to simulate the movement of individuals within an urban environment during a crisis scenario. The movements of individuals can be used to understand how effectively different configurations of shelters and evacuation instructions translate into community evacuation patterns, with particular emphasis on exploring how interventions and communication with local residents might influence evacuation success.

The model is developed in Java using the MASON Simulation Toolkit with the GeoMASON library extension. Physically, the model simulates the world at a 1m^2 resolution. Temporally the model proceeds at a resolution of 5 minutes per tick.

The following sections will introduce the data which underlies the simulation, the model environment, the major entities which are present within the model, and an overview of the simulated processes[5].

3.4 Input Data and model entities

The environment is based around a road network derived from OpenStreetMap data which was consistent with the data provided by the Geospatial Information Authority of Japan. Within this environment, census data about the city of Takamatsu is combined with OpenStreetMap building data to create a synthetic version of household distribution. Daytime activity location is selected based on tagged locations within OpenStreetMap (*e.g.* shops, offices, hospitals, schools, etc). As a precursor to running the simulation, a synthetic population is generated based on regional demographic information. In particular, individuals are endowed with evacuation preferences regarding locations and routes, as drawn from our questionnaire survey data (see section 3.5). Individuals have contextual information such as their role within the family; parents are associated with minor children, for example[6]. Drawing upon this synthetic population, the model is initialised in the morning peak hour, with individuals located in their homes and engaged in regular commuting behaviour. Starting the simulation before the crisis unfolds allows us to ensure that patterns of daily movement are captured in the real data: a crisis which begins while children are at school may produce different patterns than one which begins while all family members are located in the home. Persons begin the simulation with a knowledge of the locations of some set of shelters[7], as well as an estimate of their capacity. This knowledge can be varied as a parameter of the model and its initialisation.

The community is assumed to put out evacuation orders which indicate areas which are deemed 'at risk'. Persons travel between their homes, daytime activities, and shelters via a transportation network of roads. In the current instantiation, it is assumed that Persons can walk on all road network links as well as drive on them. Overlaying this environment is the 'crisis' layer, which is used to calculate which roads are inaccessible and which buildings are being negatively impacted by the crisis. This crisis layer is derived from storm surge simulation results (based on the model described in 3.3), as are the evacuation orders.

The model entities include Persons and Shelters (see Appendix E for details), each of which have their own behaviours which drive the simulation. Persons are demographically specific entities, having ages which influence their movement speeds. They are associated with a given home location as well as a target location for daytime activity (*e.g.* a workplace, a school, or the home). All Persons associated with the same Household are understood to be members of a small collective, the Household. Persons may also have access to a form of transportation - for example, a car or a bicycle. Finally, Persons are endowed with a knowledge of road closures, different potential evacuation targets, and shelter-related information including location, approximate capacity, and whether they are full. This knowledge is updated throughout the simulation.

[5] A full version of the model description presented in this section is available in Appendix E. Further, the full codebase is available online at https://github.com/swise5/takamatsu.
[6] See Ruin et al (2014) for a study on evacuees' contextual factors and hydrometeorological dynamics that affect crisis behavioural responses.
[7] The city councils assign shelters (usually community centres) based on their location, capacity and risk to natural hazards (Cabinet Office, 2017). Population distribution across the region affects the projected and possible populations at shelters.

In contrast, Shelters are relatively passive entities, in that they are locations in which Persons cluster during crisis situations. They are endowed with a number representing the maximum capacity for Persons, a number of vehicles which can park outside of the Shelter, and an entrance point which helps determine where Persons navigate in order to enter the Shelter. It also maintains a list of the set of Persons currently sheltering within the Shelter and a count of the number of vehicles there.

3.5 Questionnaire survey results

A resident questionnaire survey was conducted in June of 2018 to understand local knowledge/perception of disaster risk in Takamatsu. Resident experience of disasters (including the 2004 typhoons - revealed preference) and intentions of how to behave during a big typhoon in the future (stated preference) were collected to understand actual and hypothetical behaviours (Mas et al., 2012). For the purposes of this paper, the most important data obtained by the questionnaire survey was residents' evacuation route choices. The timing of conducting this questionnaire survey was selected because June is before the beginning of typhoon season; as such, the survey was conducted at a time when residents' preparedness/perceptions are in 'normal' state[8]. The questionnaire survey was conducted by both in online form (using SurveyMonkey) and paper form (for residents who are not accustomed to or comfortable with online surveys). Participants were recruited through local media (newspaper), the newsletter of the local University (Kagawa University), and the social network of the University. A paper-based questionnaire sheet was distributed at a public symposium held at Kagawa University. Residents who came to the symposium, advertised in at local newspaper and the University's website, were asked to participate in the questionnaire survey. Two hundred sixty four residents participated in the online questionnaire survey and 51 residents participated in the paper-based questionnaire survey, making 315 responses in total. After scrutinising the validity of answers, 313 responses were used for the research; the socio-demographic characteristics of respondents are shown in Appendix C. Compared with the population data obtained from the Basic Resident Register (as of 1 February 2018), our sample skews slightly disproportionately male. In terms of proportion by age group, we have a higher proportion of respondents between 20-59 years old and a lower proportion of those above 60 years old[9].

Table 1. Perception of disaster risks

	Typhoon	Floods	Earthquake	Landslide	Storm surge
Happens frequently	4.5 %	1.6 %	1.3 %	1.6 %	2.9 %
Happens sometimes	39.5 %	10.6 %	14.7 %	6.5 %	18.7 %
Happens occasionally	40.8 %	27.7 %	49.2 %	24.9 %	35.8 %
Rarely happens	15.1 %	53.1 %	33.9 %	59.5 %	36.5 %
We don't experience this	0.3 %	7.4 %	1.3 %	7.8 %	6.6 %

Our questionnaire survey results showed that many residents believe that the risk of disasters is low, as shown in Table 1. Despite the fact that Takamatsu experiences about 20 typhoons each year, and more

[8] If data were collected during the typhoon season (July – September), some residents may have biased perceptions based on whether some areas of Japan have been affected.
[9] Because of this, we encouraged the participation of male residents who are older than 60, when we organised workshops.

than half of the participants had lived in Takamatsu for over 15 years (implying that they were present during the 2004 storm surge), the perception of typhoon risk does not seem to be high. Perception of the risk of a storm surge is higher than that of floods, but not as high as typhoons. A high proportion of people think it ‘rarely happens’.

In terms of destination, participants replied that they are most willing to evacuate to ‘The shelter I feel is the safest’ (52.2% prefer) rather than ‘closest shelter’ (38.3% prefer). Stated preferences of route and travel mode are shown in Table 2. About 50% of participants answered that they will use the ‘most familiar route’ to shelters, followed by a route they ‘find on hazard map’(17%) and the shortest route (11.5%). About 53% of participants answered that they would walk to the shelter; almost everyone else said they would go by car, either as a driver (29%) or as a passenger (12%).

Table 2. Stated preference of route and mode choices

Route choice	Most familiar routes (50%)	Find on hazard map (16.7%)	Shortest route (11.5%)	Route determined by drill/training (9.4%)	Follow family/friends (8.3%)	Others (4.2%)
Mode choice	Walking (52.7%)	Car (as driver) (29.0%)	Car (as passenger) (11.9%)	Bicycle (4.3%)	Motorbike (1.1%)	Others (1.1%)

These results are incorporated into the creation of individuals in the simulation, with individuals’ choices of how to navigate through their environment being drawn from these real-life preferences.

3.6 Simulated processes

The model was developed to simulate a morning evacuation associated with the typhoon season’s tidal dynamics (*i.e.* summer tides); high tide times often occur during the night and morning with 12.42 hours cycle. The simulation models each individual resident independently, with these agents being called Persons. The activities of the Person agents drive the modelling process. Simultaneously and independently, the crisis environment is being updated based on external information (*i.e.* the storm surge model). The crisis proceeds based on the input data, with the transportation network being adjusted according to road blockages.

The Person’s regular decision flowchart is shown in Figure 5. With some frequency, Persons observe the inundation levels of their surrounding environment and any road closures, updating their knowledge of the relative safety of different locations. They then calculate a risk assessment based on their current knowledge. In the absence of a crisis situation, Persons spend their time commuting between daytime activities and their homes; at night they stay inside their homes, resting. Persons compute risk based on their knowledge (past experience and local knowledge), distance between their household and the rising floodwaters and a personal risk tolerance parameter. The risk is assessed stochastically; that is, the closer the floodwaters or the lower the risk tolerance, the more likely they are to evacuate. In this work, the perception of risk scales linearly; the framework makes it easy for more nuanced risk assessments to be substituted at a later date, if need be.

Based on their risk assessment, a Person may decide to either evacuate from their current location or to shelter there. In the former case, they will identify an appropriate evacuation target, plot a route to it based on one of a number of metrics, and attempt to move there. Parental figures will add an intermediate step of their children's locations if the members of the Household are geographically dispersed. When Persons arrive at a Shelter, they may be admitted or they may learn that it is full and be turned away to other shelters[10].

If a Person determines that the best action is to shelter in their place or where they are (*e.g.* office), they will continue to monitor the situation and to assess the risks associated with their current location. At some point, they may determine that it would be safer to move, in which case they will undertake the evacuation routine. When they move, their speed is informed by the ages of the members of the Household currently travelling together – that is, if one household member is in the 80+ age band and they are travelling on foot rather than in a vehicle, the overall speed for the Persons travelling together will be based on that Person's top speed (Gates et al., 2006, see Table 3).

Table 3. Movement speeds of various demographic groups

Group	Speed (m/s)	Speed (km/h)
Pedestrian – Default	1.5	5.4
Pedestrian – Senior or Small child	1.0	3.6
In vehicle	5.5	19.8

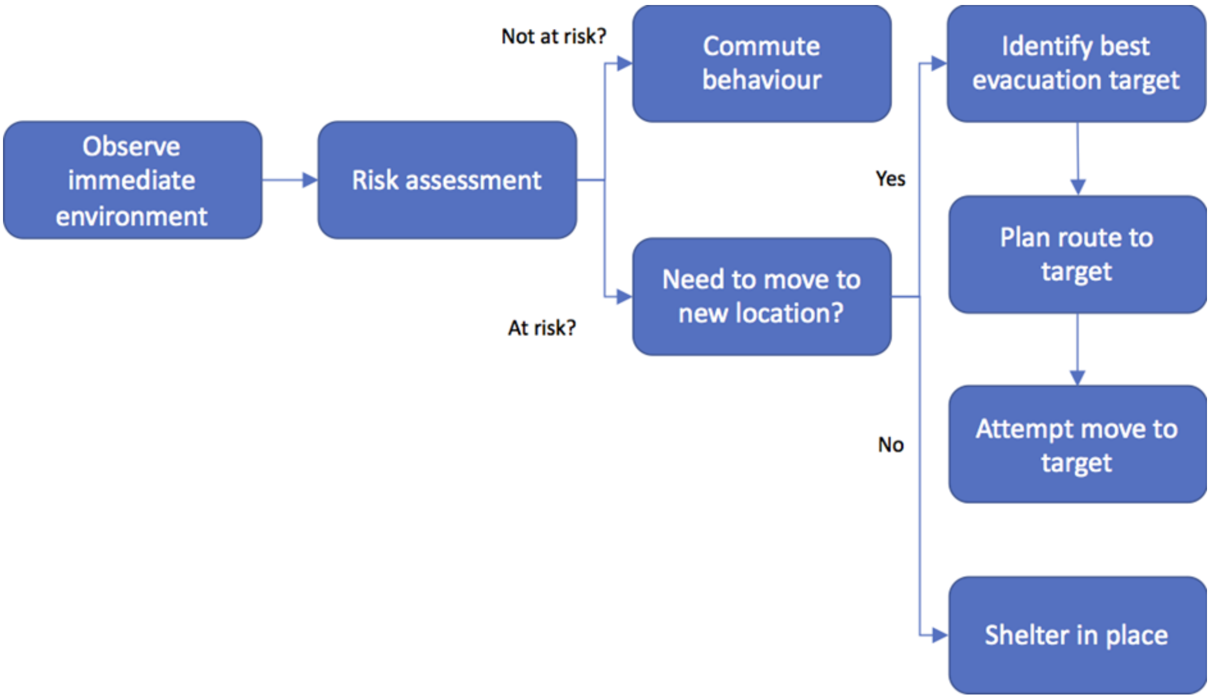

Figure 5. Simulated evacuation process

[10] As shown in Figure 9, no shelter reaches its capacity, which means that at some point, no more evacuees arrive and shelter does not become full. Therefore this situation (evacuees being turned away) rarely happens under the scenarios we explored.

The weighting of Person preferences for the route they take to evacuate is drawn from our survey data. The Person weights the candidate paths by:

a) the length of the roads (as a proxy for time cost)

b) the 'significance' of the roads (as a proxy for familiarity – for example, a motorway will be more 'significant' than a residential road, ceteris paribis)

c) the roads associated with official hazard maps or

d) a fuzzy metric which captures way finding without perfect knowledge of the road network.

These correlate to major way finding techniques identified by our survey.

a.

b.

Figure 6. Visualisation of weighting by road length (a) versus road significance (b)

From the model, we measure the relative usage of shelters; the demographics of individuals who make various choices; the overall and individual times to evacuate; and the number and population of individuals who remain sheltering in high-risk areas.

Shortest paths are found using the common A* algorithm, which calculates the shortest path in terms of a user-defined metric (Hart et al., 1968). A limited number of private vehicle is simulated based on the lessons from the 2011 tsunami disaster (many people who used cars for evacuation were caught in heavy traffic and drowned). Pedestrian movement is based on a constant value of walking speed appropriate to demographic qualities. Finally, the time to evacuate from the origin to the evacuation centre is recorded in minutes.

4. Result

4.1 Results of simulation

The scenario tested in this research was the five hour period immediately following the crisis event based on the record from 2004 storm surge and the discussion with authorities[11]. During this time, we evaluated the number of individuals who evacuated, the amount of time they took, and the arrival patterns of these individuals at shelters. Because of the significance of traffic and congestion to the movements of evacuating individuals, we simulate the behaviours of residents of the entire targeted area, approximately 14,500 individuals. Of these individuals, only a limited number evacuate – in the range of 5%. Their evacuation is driven by their perception of risk to their own homes and persons, so this number is emergent from the simulation environment. The simulation was run 30 times, with metadata about simulation outcomes suggesting low enough variance to conclude that the results were representative and analysis could proceed. We chose a five hour period as a result of our conversations with local officials and their target evacuation timeline.

[11] Our focus is rather to observe the evacuees' movement and potential traffic congestion during peak time, to inform evacuation planning, than simulation of all evacuees' behaviour.

Overall, of the approximately 970 individuals who choose to evacuate during the period, (95% CI: [969.9, 975.6] persons), approximately 85% successfully complete their evacuation (95% CI: [84.8%, 85.2%]). Their journey (from when they decided to evacuate until the time they are admitted to a shelter) takes, on average, around 84 minutes (95% CI: [83.0, 85.5] minutes). However, this is quite a biased view of the journeys individuals have to make – the median length of journey is closer to 65 minutes (95% CI of median: [64.9, 66.9] minutes), and many journeys are extremely quick. Individuals who find their homes at risk and are located near a shelter may complete their journeys almost immediately. On the other hand, some agents (those who decided to evacuate at later stage) may travel a great distance to a shelter, only to find that it has filled up during the course of their journey. In this case they must turn around and choose another shelter, continuing their search – it is not safe for people to stay outside of a full shelter (*e.g.* in a parking lot) because water level may rise. Figure 7 gives the histogram of journey times for completed journeys by evacuating agents in a typical run of the simulation.

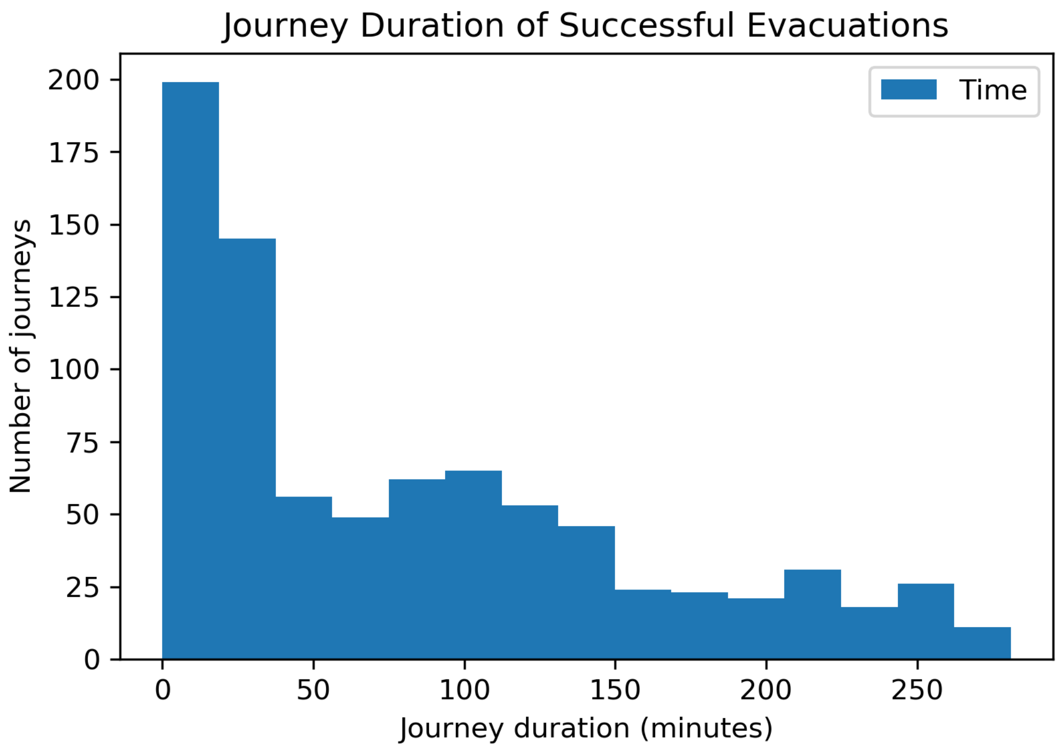

Figure 7. Duration of completed journey times for sample run of the simulation

Approximately 15% of individuals have not completed their travels by the end of the simulation. Overwhelmingly, these are individuals who have only decided to evacuate in the late stages of the simulation, or who waited until the peak period of traffic congestion had already begun, and who have longer distances to shelters (Figure 8)[12]. The average time such agents have spent travelling is around 20 minutes (95% CI: [20.4, 23.0] minutes). Thus, had the simulation continued, many would likely have successfully evacuated.

[12] Even if residents believe their house is a safe location, it may be the case that electricity etc. becomes unavailable. Residents can go to a shelter to receive basic supplies.

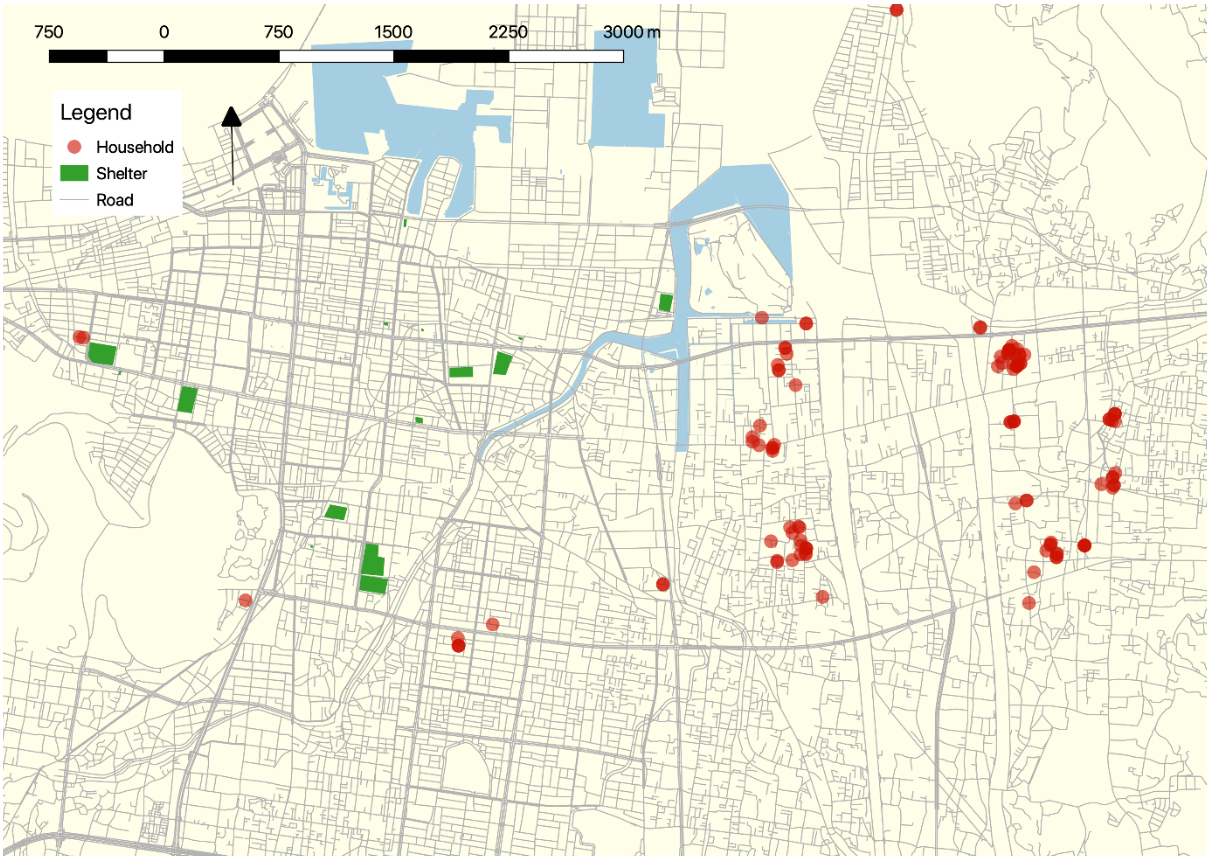

Figure 8. Households that uncompleted journey for a sample run of the simulation

We also considered the rate of arrival at shelters over the simulation period. Some shelters were almost immediately filled, with their capacity being filled in the early stages of the evacuation. The largest shelter had a steep increase in population within the first hour, but continued to accept evacuees until the end of the period. One shelter can be seen to have begun filling up its capacity only near the very end of the period, with a sudden spike in population in the final hour. This shelter-specific detail allows us to identify which areas may be oversubscribed, versus undersubscribed. Further, because we have information about the number of parking spaces associated with the shelters, we can compare the travel profile of the individuals who ultimately attempted to use a shelter and how this compares with the parking accessibility.

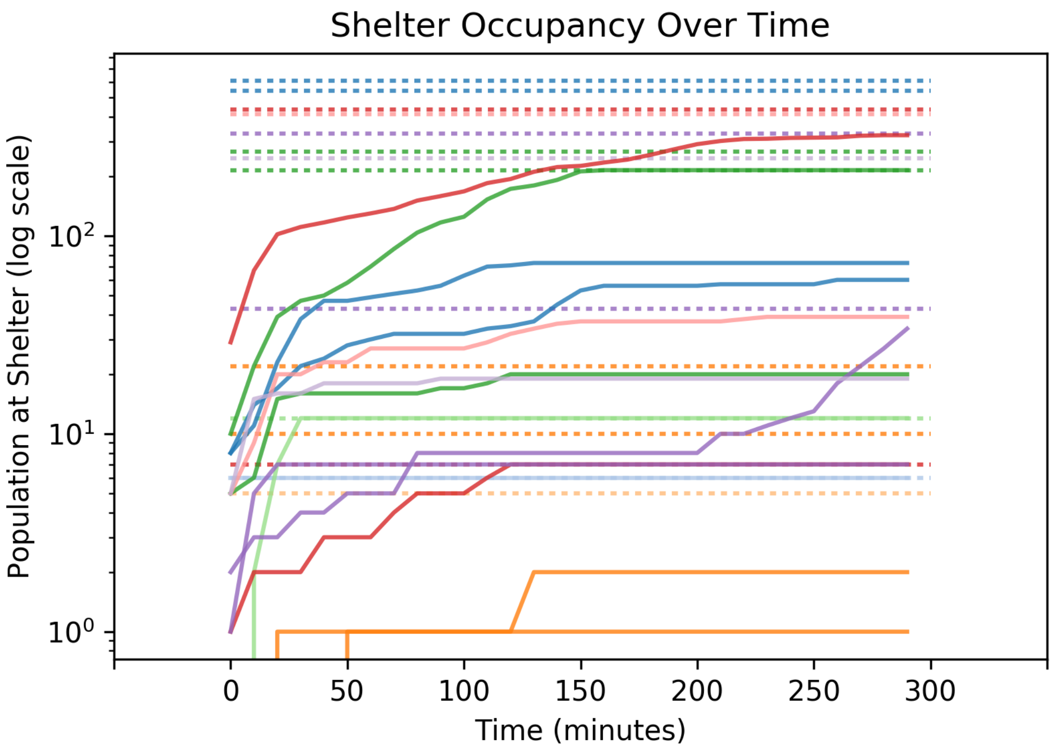

Figure 9. Arrival at shelter times. Each solid line represents a different shelter and reflects the number of Persons present at that shelter at the given point in time. The dotted lines show the maximum capacity of the shelters of the corresponding colour.

We are able to visualise the points of traffic congestion which shape and constrain individual movement within the network. Because the overwhelming majority of individuals within the simulation are choosing not to evacuate, evacuating individuals must navigate an environment largely determined by those pursuing other goals. Even if the majority of people decide not to evacuate, a majority of evacuees must start to move in a similar timeframe, leading to strains on road capacity (similar to traffic congestion during peak hours). Another hazard is that some evacuees might choose routes that have flooded. In contrast to a normal commuting situation, the set of target destinations is quite limited and traffic tends to concentrate on particular roads/routes. For those whose homes and workplaces are not impacted by the flooding, or even those who choose to shelter in place, travel patterns in the target time period will remain much the same; this is often the case in such contexts. These 'normal' traffic jams can interact with disaster-driven traffic patterns in dangerous ways for evacuees. As such, being able to use a model to explore scenarios which might include different proportions of residents being forced to evacuate is especially powerful and useful as a counterfactual to past experience. Figure 10 highlights stoppages in traffic and its impact on evacuating persons, emphasising the locations of traffic congestion. The heatmap (Figure 10) shows the locations where individuals have spent time, constructing an aggregate image of road use patterns. This, too, reflects aspects of the evacuation environment which are often opaque to citizens. In particular, this is interesting in that it can allow us to study how the timing of emergency situations influences evacuation journeys. For example, the interaction between rush hour and evacuation efforts is a dynamic that is difficult for individual citizens to understand.

Finally, the model includes a visual interface (Figure 11) which can be run together with the simulation. As the individuals make their decisions and begin to evacuate, or else pursue their daily activities, their progress can be seen relative to the overall map. This visualisation was useful in the model construction process, but was crucially necessary in building trust in and understanding of the model's workings.

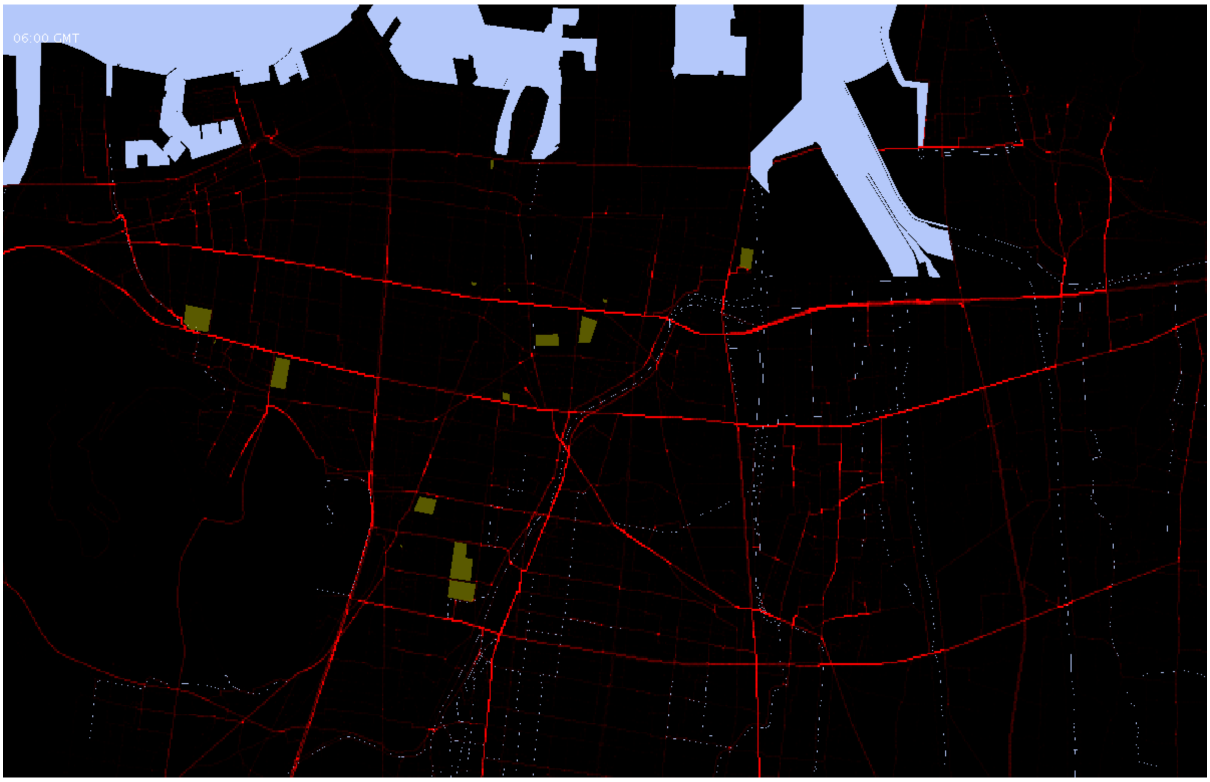

Figure 10(a) Traffic congestion heatmap

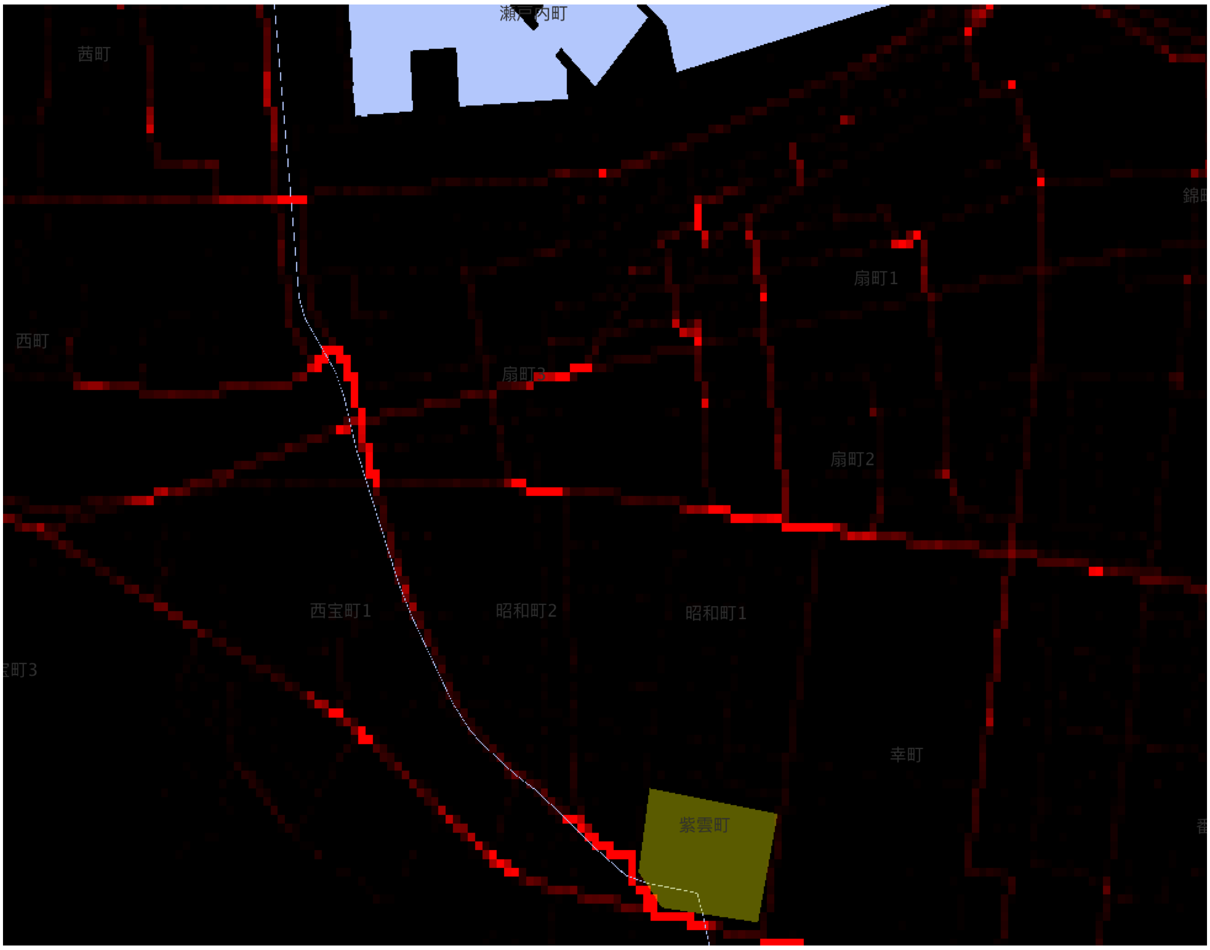

Figure 10(b) Closeup of traffic heatmap. The yellow areas indicate the location of shelters, the blue the presence of water. The rest of the environment has been separated into a raster grid which tracks the presence of Persons and scales in colour from black to red, with black being low or no activity and red being hotspots of activity. Major road intersections and points of interest (*e.g.* the entrance to the shelter) are clearly indicated by bright red traces of Person activity; the road network overall is, to a lesser extent, visible.

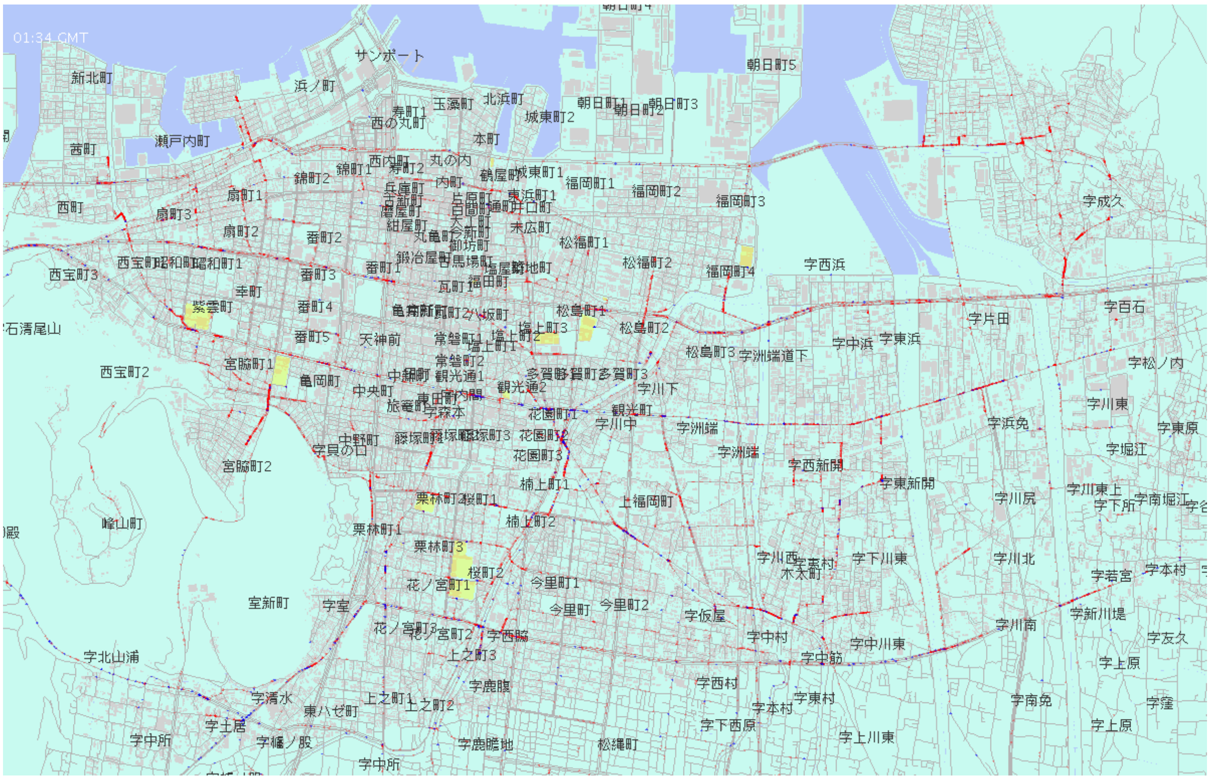

Figure 11(a) Screenshot of SETOSim simulation and traffic

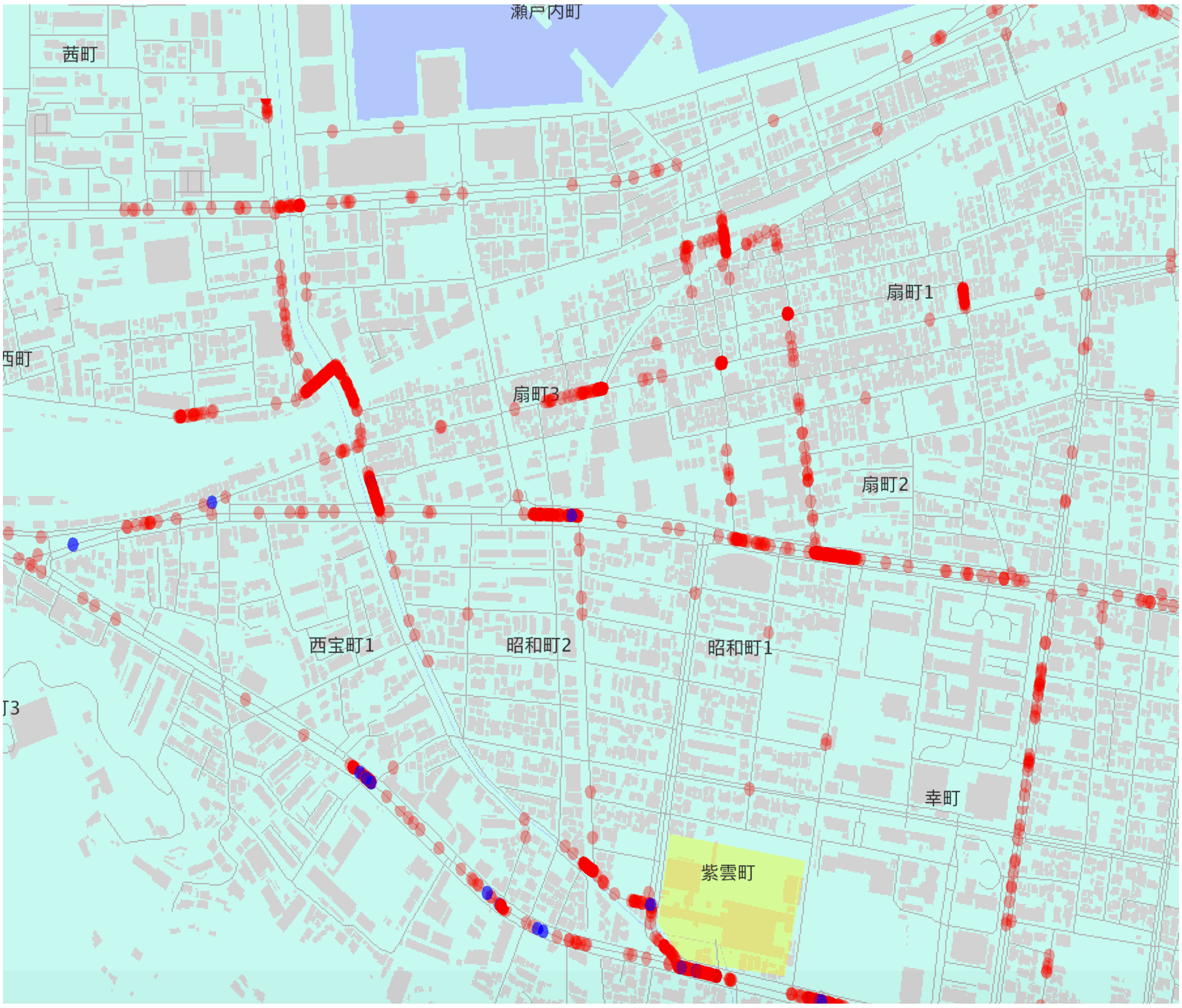

Figure 11(b) Closeup of an area within the SETOSim simulation interface. Observe the agents commuting as normal (red); the agents who are evacuating (blue); the shelters (yellow areas); and local building density. Note, also, the congestion at points where the roadways cross over the railway (visible in its absence).

4.2 Community workshops

Community workshops were held in Takamatsu from June through July, 2019. We identified the five communities most affected by the 2004 storm surge and contacted their neighbourhood association leaders through the city council. People over 65 years old were encouraged to participate to discuss the challenges of evacuation in an ageing society. We also encouraged men to join so that we could capture their perceptions, as these were less represented in the questionnaire survey. In addition, meetings with city/prefecture officials and volunteer organisation were held to receive feedback from practitioners of disaster management. The names of the communities and number of participants involved in each workshop are shown in Table 4.

Table 4. Participants of community workshops/meetings and duration

Community association/officials	Number of participants	Duration of workshop
Ritsurin town neighbourhood association	4	90 minutes
Kita town neighbourhood association	12	60 minutes

Kasuga town neighbourhood association	13	120 minutes
Matsushima town neighbourhood association	9	90 minutes
Marugamemachi neighbourhood association	2	90 minutes
Volunteer organisation	4	60 minutes
City/prefecture officials	7	60 minutes
Deputy mayor's team on disaster risk management	3	45 minutes

At each workshop, we first asked participants to share their experiences in facing and managing disasters in Takamatsu. In particular, we asked about their experience at the time of the 2004 storm surge. Some participants shared what they learned from their parents/grandparents in their childhood. We then showed our simulation on a computer (or larger screen), explaining the settings of the agents and behaviours. In each workshop, a discussion followed regarding participants' impression of/feedback to the simulation and how this could be applied to the community's evacuation plan (see Appendix E for photos of workshops). The participants started a discussion of detailed evacuation plans every time, a clear indication that the simulation tool is useful to facilitate the discussion. At all workshops, discussion continued by identifying some challenges and strategies to secure the safety of all residents of their community.

The discussions typically followed three themes: location of evacuation centres, destination of evacuees and the movement of evacuees and traffic.

Location of evacuation centres

Some participants (in particular in Kasuga and Matsushima towns) expressed concerns whether the current dedicated evacuation centres are appropriate in terms of their location, because some shelters are located alongside the river, which could flood. They agreed that it is necessary to review the appropriateness of each evacuation centre and discussed the possibility of evacuating to alternative buildings, including those that are privately owned[13]. Some participants were unsure whether all residents are aware of the location of dedicated evacuation centres; they felt that the information needs to be shared more thoroughly and regularly. There is also a need for a guidance to new residents. Participants discussed where to move their cars to avoid their being submerged (many cars were damaged/disposed of as a result of the storm surge in 2004). Residents discussed a plan to move their cars first, then walk home, and finally decide their evacuation. The location of the car parking and necessary time for this process was discussed, making it clear to the participants that they should take action early when a typhoon is approaching.

Destination of evacuees

The participants commented that they had never thought about the possibility that some residents of other towns could come to shelters of their own town, depending on the availability of shelters in other towns, the direction of water flows, and the blockage of roads. In particular, residents of Kita town do not have safe shelters in their town. For them, the only direction they can safely travel is south because there are rivers in both sides of their town and the ocean to the north. Based on the simulation, participants from Kita town started to discuss whether they should dedicate the tallest building (an apartment complex) to be used as a shelter; they concluded that they would not have enough time if the situation develops such that they need to evacuate further to the south. On the other hand, residents of

[13] The agreement between the city government and the owners of the buildings would need to be arranged.

Kasuga town noticed that some evacuees from Kita town would more naturally head toward Kasuga shelters. They now understand the possibility and have begun to discuss how they could better manage the shelter by having evacuees from different towns. They discussed whether there is enough capacity in their current local shelters and how they would deal with the unexpected number of people taking refuge, including the stock of emergency goods (*i.e.* food, water, and blankets).

Movement of evacuees and traffic

Participants were interested in observing evacuees' movements in other towns and expected traffic on main roads, as shown in Figures 10 and 11. They know which road they should take to their closest shelters but had not considered potential traffic congestion within the area. In principle, residents are expected to walk to shelters because of the limited parking space in each shelter. However this is not the case when they are assisting people who cannot walk. The simulation helped residents to reconsider which routes are most appropriate for them to efficiently move to the shelters and how they could try different routes at regular evacuation drills. They discussed working with local fire brigade members to update current evacuation procedure and reflect on evacuation drills. Related to the destination of evacuees, participants were concerned with incoming traffic to their towns and road capacity.

5. Discussion and conclusion

This research developed an agent-based simulation of residents' emergency behaviours in the context of a typhoon and storm surge in the city of Takamatsu, Japan. The simulation framework integrated a storm surge-driven inundation simulation to create the environment within which residents act. The simulation of evacuation behaviour was visualised and presented as an interactive decision support tool; it was demonstrated at residents' workshops to explore its applicability to collaborative evacuation planning. The outcomes of the workshops suggest that agent-based simulation and visualisation are useful in a) enhancing awareness of risks, not only of residents' own communities but also the risks associated with other surrounding communities; b) urging the review of current evacuation plan and drills – in particular, participants realised that currently dedicated shelters need review because some are regarded unsafe for the expected risks; and c) facilitating detailed discussion between residents on how they should behave in a survival situation. Participants also concluded that discussion not only within the neighbourhood, but across the city is critical to better manage evacuation. In particular, discussion between representatives of neighbourhoods with higher risk was deemed important. We anticipate the utility of communicating this risk to increase as extreme weather events grow more common and larger numbers of residents are impacted. By helping residents understand the dynamics of recent disasters, we can help them build the tools and community experience to survive the crises to come.

In Japan, local governments distribute 'hazard maps' to all households in their jurisdictions. These maps indicate areas that are likely to be flooded during heavy rain/typhoons. During past disasters, governments have encouraged residents to check the maps and prepare their houses relative to risk. However, being provided with an appraisal of the risks does not mean that residents are well prepared for evacuation. At workshops, residents identified making the decision about the best time to leave as the greatest challenge to evacuating. Many people wish to avoid staying at shelters if they can, although they also understand that it is sometimes necessary. However it is not easy for them to make a timely decision, despite various information from community wireless network, TV news, and social media. Governments advise citizens to evacuate as soon as possible when the evacuation advice is issued.

However the reality is that many residents stay in their homes until the last minute, which can lead in the worst case to them being left behind. It is demonstrated that the decision support tool developed in this research helps the understanding of the full context of the risk, including congestion and competition for places in shelters. Japanese governments in all levels are making efforts in raising awareness and encouraging evacuation - if more people recognise the risks, more people will evacuate, which may make traffic congestion a serious issue. Participants of workshops immediately recognised the movement of residents in different communities and potential for traffic congestion, and the resulting necessity to prepare for evacuation earlier than they initially thought. If this is reflected in their regular evacuation drills, enhanced preparedness is expected and risk could be reduced. The simulation is particularly useful in the ageing society of Japan, where many people need assistance for evacuation[14]. The challenges of the evacuation of people who need assistance is a global issue as the risks of natural hazards become more critical. It should be noted though, that the simulation and residents workshop discussed in this research is specific to the city of Takamatsu, Japan. Considerable modifications may be required if the simulation was to be applied to other parts of the world, due to differences in geography, population demographics, mode of transportation, and other relevant factors such as awareness of residents.

Future research is planned. The most obvious and immediate work deals with exploring dynamics of existing evacuation behaviour to gain a better understanding of current trends in shelter utilisation and accessibility. By creating agents who act based on the stated preferences of our interviewees, we can explore the interplay between the physical and the known psychological features of evacuation events. It will be also worth investigating the typical characteristics (*e.g.* age group, location) of Persons who make decisions/start evacuating at later stages. This understanding of the situation as it currently exists will be useful for emergency planners in an immediate sense.

Beyond helping urban/town planners, extending the visualisation to highlight the dynamic flow/speed of water would help residents to understand the crisis situation. In particular, allowing residents to explore the simulation results at the block level gives a sense of more realistic risks. At the time of Typhoon Hagibis in 2019, a survivor who was rescued by a helicopter commented that 'Although I saw [the] hazard map and [understood] that my house may be flooded, I failed to interpret the information to real threat and could not imagine "how" my neighbourhood would be flooded. Then I remained home and it was too late when I realised'. The merged visualisation of the simulations would help residents to understand the threat of the water to their towns and homes. This requires a collaboration which combines river engineering, geography, and geotechnology, as water flow reflects the characteristics of the land.

Finally, the agent-based model can also be extended. The current model considers the stated preferences of residents based on a questionnaire survey results. To make the simulation more useful for a collaborative evacuation planning, integrating a more elaborate discrete choice model would allow the simulation of evacuation movements based on different scenarios. In this way, the model can assist the discussion of alternative evacuation plans based on the understanding of residents' movements according to changes of environment (*e.g.* location of shelters, blockage of roads, reduced speeds etc.) and crisis level. As demonstrated in this research, ABM is a powerful tool to assist residents' decisions on evacuations. The more it is applied to practice, the more the model assumptions can be refined. Capacity development of local government is essential and a handbook on the application of simulation

[14] It is expected that the proportion of older people in the population will be about 40% by 2045 (National Institute of Population and Social Security Research, 2018).

to community workshops would be useful. Collaboration with interdisciplinary researchers who have local knowledge (*i.e.* local universities) is recommended to further develop the decision support tool.

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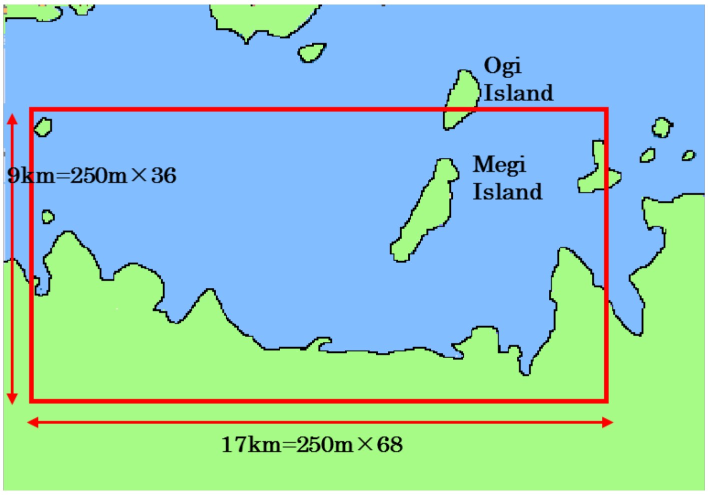
Appendix A



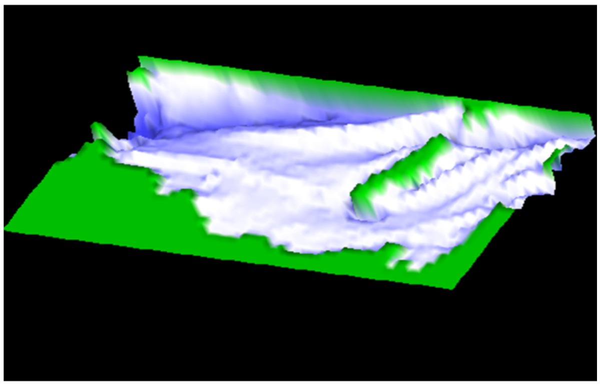


Figure A.1. The area of the sea-bottom topography survey(left) and estimated sea slope (right)

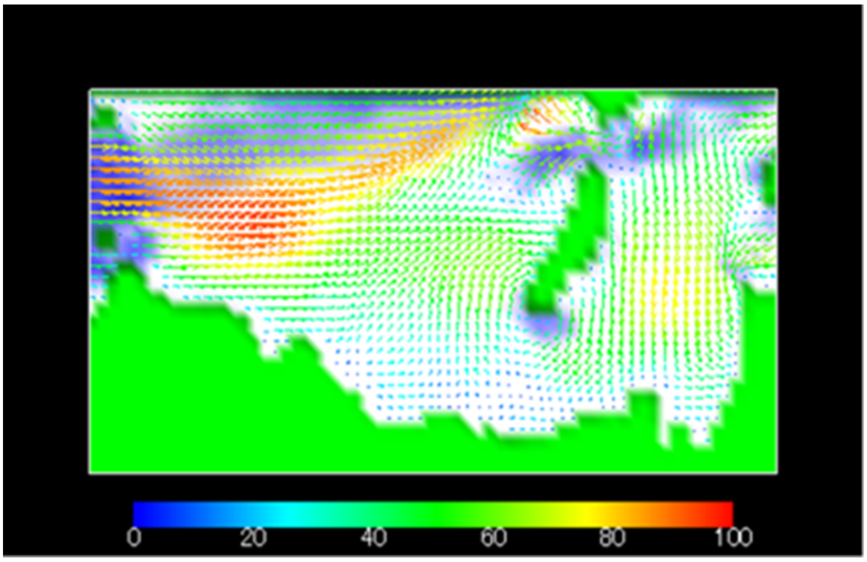
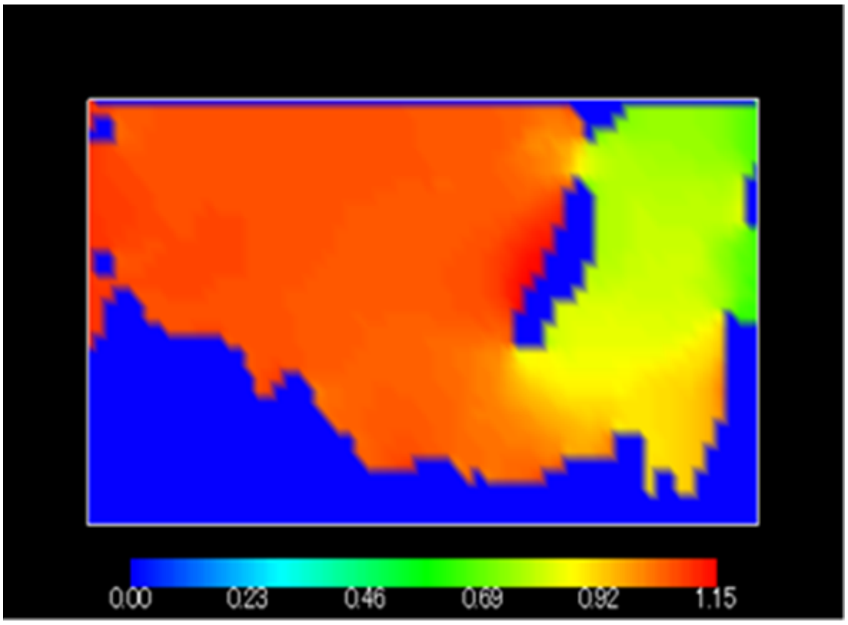


Figure A.2. Simulation of the tidal current of the Takamatsu port area (flood tide against west wind is set as 26m/s)



FigureA.3. Water level at the time of high tide when the speed of west wind is set as 26m/s

Appendix B

Correlation between wind speed and the wind drift parameter.

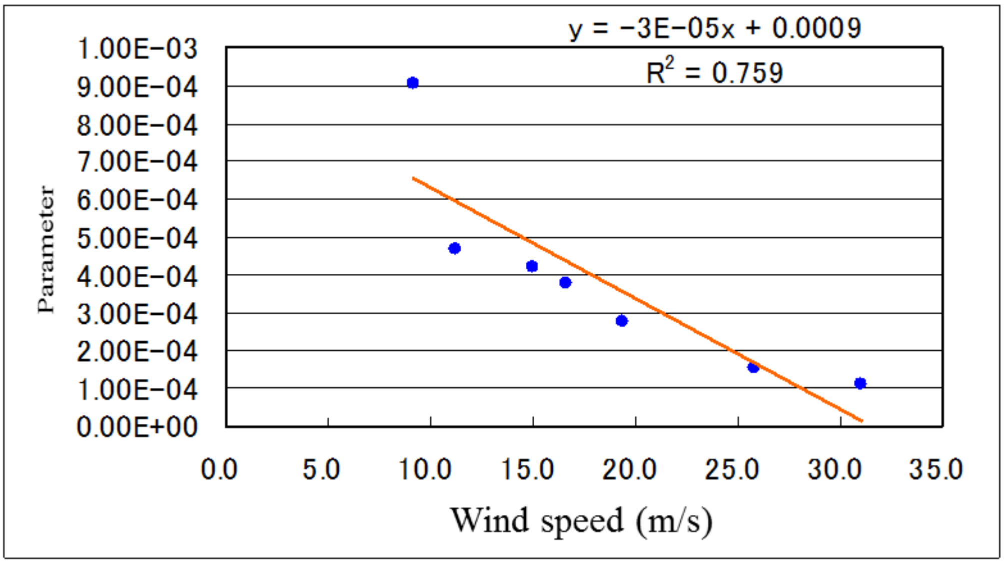


Figure B.1. Linear approximation

$y=(-3.0\times10^{-5})\ x+0.0009$

$R^2=0.76$

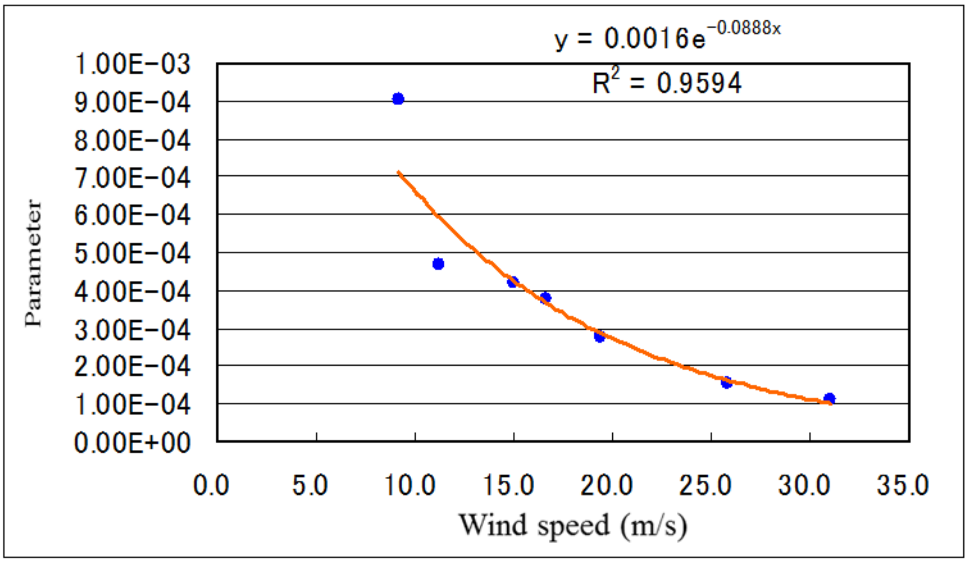


Figure B. 2. Exponential approximation

$y=0.0016\times e^{-0.0888\,x}$

$R^2=0.96$

Appendix C

Table C.1. Socio-demographic characteristics of respondents

Gender	Male	53.8 %	(48.3 %)*
	Female	46.2 %	(51.7 %)*
Age	Under 20 years old	4.7 %	(31.8 %)*
	20-29 years old	18.9 %	(9.3 %)*
	30-39 years old	17.5 %	(11.7 %)*
	40-49 years old	26.5 %	(15.4 %)*
	50-59 years old	21.1 %	(12.0 %)*
	60-69 years old	6.9 %	(12.8 %)*
	70-79 years old	3.6 %	(11.8 %)*
	Above 80 years old	0.8 %	(8.5 %)*
Occupation	Public service (full time)	14.6 %	
	Private sector (full time)	28.1 %	
	Agriculture/forestry/fishery	0.0 %	
	Self-employed (except for agriculture/forestry/fishery)	2.2 %	
	Part time/casual	16.1 %	
	Homemaker	2.9 %	
	Unemployed	4.0 %	
	Student	19.0 %	
	Others	13.1 %	
Type of house	Detached (renting)	3.8 %	
	Detached (owning)	42.9 %	
	Apartment (renting)	15.8 %	
	Apartment (owning)	11.3 %	
		24.8 %	

	Apartment (maisonette, renting) Others	1.5 %
Hometown	I am from Takamatsu I am from Kagawa prefecture I am from Shikoku Others	35.6 % 17.4 % 18.6 % 28.4 %
Length of living in Takamatsu	Less than 5 years 5 – 9 years 10-14 years 15-19 years More than 20 years	25.5 % 7.9 % 9.4 % 11.2 % 46.1 %

*Proportion of population obtained from the Basic Resident Register as of 1 February 2019 (Source: Takamatsu city website http://www.city.takamatsu.kagawa.jp/kurashi/shinotorikumi/tokei/jinko/toroku/index.html)

Appendix D

Figure D.1. Photo of Workshop at Ritsurin town community centre

Figure D.2. Photo of Workshop at Matsushima town community centre

Appendix E

EVACUATION MODEL OVERVIEW[15]

Purpose

The purpose of the model is to simulate the movement of individuals within an urban environment during a crisis scenario. In particular, it is designed around the case study of a storm surge context in the city of Takamatsu, Kagawa Prefecture, Japan. The movements of individuals can be used to understand how effectively different configurations of shelters and evacuation instructions translate into community evacuation patterns, with particular emphasis on exploring how interventions and communication with local residents might influence evacuation success and timing.

Entities, state variables, and scales

The model entities include Persons and Shelters.

Persons: Persons are demographically specific entities, having ages which influence their movement speeds. They are associated with a given home location as well as a target location for daytime activity (*e.g.* a workplace, a school, or the home). All Persons associated with the same Household are understood to be members of a small collective, the Household. Persons may also have access to a form

[15] Referring to Grimm et al. (2006)

of transportation - for example, a car or a bicycle. Finally, Persons are endowed with a knowledge of road closures, different potential evacuation targets, and shelter-related information including location and whether they are full. This knowledge is updated throughout the simulation.

Person		
Attribute	**Description**	**Representation**
Location	Location of Person in environment	Coordinate
Age	Age of Person	Bands of 10 years
Home location	Location of home in environment	Coordinate
Daytime activity location	Location of daytime activity within environment	Coordinate
Household	List of other Persons associated with this Person and their decision-making	List of Persons
Transportation	Whether the Person has access to a vehicle, such as a car or a bicycle	String
Knowledge	Store of information about road segments, risk areas, and Shelters (location, fullness)	Object: integer pairs
Evacuation policy preferences (location, routing)	Weighted list of preferred evacuation locations, e.g. home, family friends, shelter	Object: Double pairs

Shelters: Shelters are relatively passive entities, in that they are locations in which Persons cluster during crisis situations. They are endowed with a number representing the maximum capacity for Persons, a number of vehicles which can park outside of the Shelter, and an entrance point which helps determine where Persons navigate in order to enter the Shelter. The Shelter also maintains a list of the set of Persons currently sheltering within it and a count of the number of vehicles there.

Shelter		
Attribute	**Description**	**Representation**
Entrance point	Location of entrance point for Shelter in environment	Coordinate
Capacity	Total number of Persons which can be accommodated within the Shelter	Integer
Vehicle capacity	Total number of vehicles which can be accommodated within the Shelter's parking area	Integer
Current occupants	List of all Persons currently sheltering in Shelter	List of Persons
Current number of vehicles	Total number of vehicles currently present	Integer

The environment of the model includes the physical environment within which individuals travel as well as the developing crisis. As a part of the developing crisis, the community is assumed to put out evacuation orders which indicate areas which are deemed "at risk". Persons travel between their homes, daytime activities, and shelters via a transportation network of roads. In the current instantiation, it is assumed that Persons can walk on all road network links as well as drive on them. Overlaying this environment is the "crisis" layer, which is used to calculate which roads are inaccessible and which buildings are being negatively impacted by the crisis. This crisis layer is derived from either real data or storm surge simulation results, as are the evacuation orders.

Physically, the model simulates the world at a 1m^2 resolution. Temporally the model proceeds at a resolution of 5 minutes per tick.

Process overview and scheduling

The Person agents are the core of the simulation, with their activities driving the model process. Simultaneously and independently, the crisis environment is being updated based on external information. The crisis proceeds based on the input data, with the transportation network being adjusted according to road blockages.

With some frequency, Persons observe their surrounding environment, updating their knowledge of the relative safety of different locations. They then calculate a risk assessment based on their current knowledge (often based on their experience and local knowledge) and information of immediate environment. In the absence of a crisis situation, Persons spend their time commuting between daytime activities and their homes. Based on a risk assessment, however, they may decide to either evacuate from their current location or to shelter there. In the former case, they will identify an appropriate evacuation target (*i.e.* shelter), plot a route to it based on one of a number of metrics, and attempt to move there. When Persons arrive at a Shelter, they may be admitted or they may learn that it is full and be turned away to go another shelter.

If a Person determines that the best action is to shelter in place, they will continue to monitor the situation and to assess the risks associated with their current location. At some point, they may determine that it would be safer to move, in which case they will undertake the evacuation routine, which is explained above.

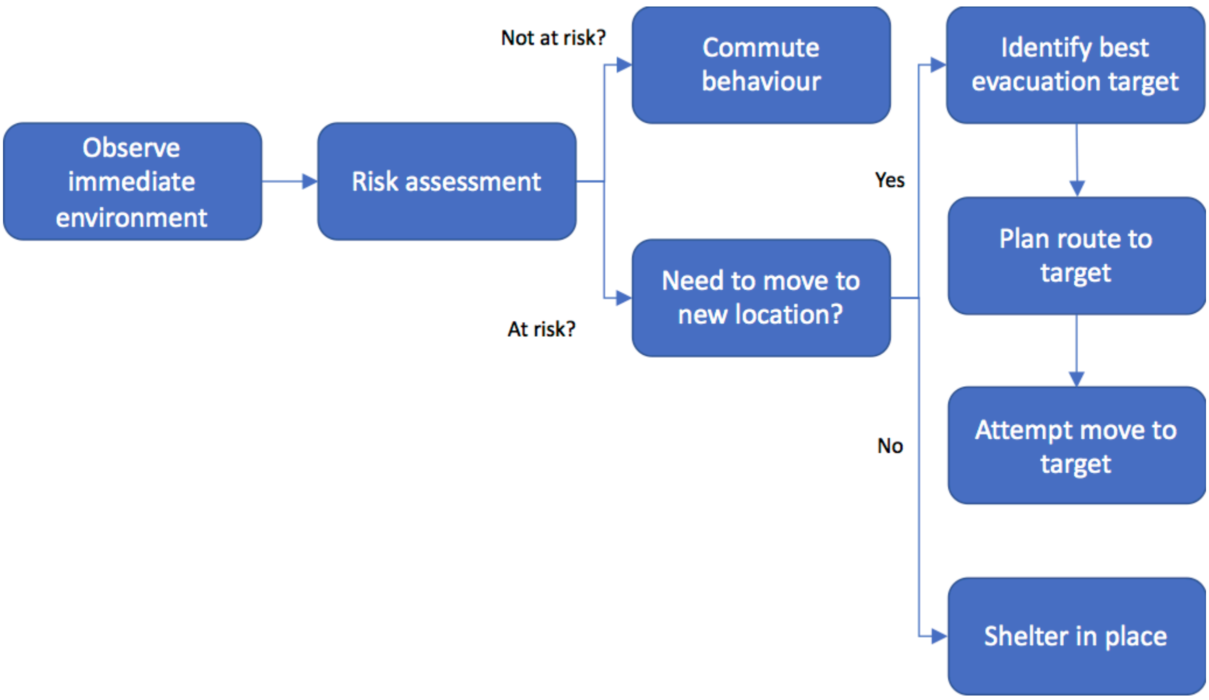


Figure E.1. Flowchart of Person's evacuation decision-making process

DESIGN CONCEPTS

Emergence: crowding dynamics may emerge from the arrival of individuals at the shelters. These dynamics emerge from the locations of homes, the timing of evacuation orders relative to the time of day, and evacuation behaviour preferences. This is one of the major features we intend to measure within the model

Adaptation: Persons adapt their goal location based on the crisis, the information they have about the road network, and their knowledge of shelters.

Objectives: Individuals attempt to avoid risk, rather than maximise safety - thus individuals may make the choice to shelter at home rather than leaving for the greater safety of a Shelter.

Learning: Persons learn about the road network as well as the capacity/current population associated with Shelters. Further, they take in information gleaned from evacuation orders. They store this information and use it in future decision-making.

Prediction: The model as implemented is designed to allow for more nuanced predictions to inform agent behaviours. At this point, however, the prediction is limited to an assumption about the current population of individuals at a Shelter and how it will persist.

Sensing: Persons sense the crisis situation developing around them. They also can sense road blockages and evacuation orders.

Interaction: Interaction in the model occurs largely in terms of competition between Persons for space at the shelter and room on the road network. Shelters can accommodate only a certain number of Persons, so this competition reshapes the environment within which individuals make their decisions. The other important source of interaction is the way family groups make choices based on all members – this interdependence causes individual Persons to modify their behaviours, e.g. group speed of movement.

Stochasticity: Stochasticity is an important feature in a model which attempts to capture the rapidly varying environment of a crisis situation. In particular, it is a feature of the risk assessment process, with agents probabilistically adjusting their willingness to evacuate based on the distance between their household and the floodwaters. Stochasticity is further present within the model in the "wayfinding" evacuation route choice, which reflects the agent's uncertainty of its path. Finally, randomnessmanifests in the synthetically generated population, with individuals having varying likelihood of selecting different evacuation targets and evacuation routing metrics.

Collectives: Persons are unified into Households, which influence the behaviours of all of the Household members.

Observation: From the model, we measure the relative usage of shelters; the demographics of individuals who make various choices; the overall and individual times to evacuate; and the number and population of individuals who remain sheltering in high-risk areas (as informed by the storm surge model).

DETAILS

Initialisation

As a precursor to running the simulation, a synthetic population is generated based on regional demographic information. In particular, individuals are endowed with evacuation policies drawn from our survey data. Drawing upon this synthetic population, the model is initialised in the morning, with individuals located in their homes and engaged in regular commuting behaviour. Starting the simulation before the crisis unfolds allows us to ensure that patterns of daytime movement are captured in the real data: a crisis which begins while children are at school may produce different patterns than one which begins while all family members are located in the home. Persons begin the simulation with a knowledge of the locations of some set of shelters, as well as an estimate of their capacity. This knowledge can be varied as a parameter of the model and its initialisation.

Storm surge information is similarly externally calculated and scheduled to be inserted into the model according to its progression over time.

Input Data

A number of sources of data inform the model. In particular, the environment is based around a road network derived from OpenStreetMap data. Within this environment, census data about the city of Takamatsu is combined with OpenStreetMap building data to create a synthetic version of household distribution. Daytime activity location is selected based on tagged locations within OpenStreetMap (e.g. shops, offices, hospitals, schools, etc).

The storm surge progression data is taken from the work of Kagawa University, (2004). Individual evacuation preference data is taken from the residents questionnaire survey by the authors.

Submodels

Shelter: Admission

Shelters will admit Persons as long as there is room to admit them. When they are full, they will turn away Persons. If a Shelter's vehicle lot is full, Persons travelling in vehicles will not be able to stop there. Otherwise, Persons arriving in a vehicle will increment the counter of vehicles present.

Person: Observation

Observation occurs every time a Person is activated - that is, when moving, when changing activities, or periodically during the daytime. Persons can perceive their direct surroundings as well as the public broadcasts about evacuation areas. Thus, if they are on a road which has been rendered impassable by the crisis, they can make future routing decisions with the knowledge that the road is inaccessible. Similarly, they will update their knowledge of shelter usage if they arrive there, or if the public broadcast includes this information.

Person: Risk Assessment

Based on their set of knowledge, Persons will assess whether the locations of their Household is at risk from the ongoing crisis. Persons compute risk based on the distance between their household and the rising floodwaters, normalising this distance by a personal risk tolerance parameter. The risk is assessed stochastically: that is, the closer the floodwaters or the lower the risk tolerance, the more likely they are to evacuate. Persons who determine that they are by their own standards too close to the area impacted by the crisis will determine that they are at risk and will switch to either evacuation or sheltering behaviours, depending on whether their own current location is at risk. In this work, the perception of risk scales linearly; the framework makes it easy for more nuanced risk assessments to be substituted at a later date.

Person: Commuting

The commuting behaviour simply consists of moving between the home location and daytime locations at the beginning of the work day, remaining at that location until the evening, and then returning to the home location. In each movement case, individuals are assumed to use any transportation resources available to them and to take the shortest path between the two locations.

Person: Identify best evacuation target

Based on the policy settings of the Person and their knowledge of Shelters in the environment, they will select the most attractive target location for evacuation. They will also be aware of another Household, to whose home they may choose to evacuate if that Household has not evacuated.

Person: Plan route to target

Based on the Person's evacuation policy, they may choose a shortest path weighted by

a) the length of the roads (as a proxy for time cost)

b) the size of the roads (as a proxy for familiarity)

c) a fuzzy metric which captures way finding without perfect knowledge of the road network.

These correlate to major way finding techniques identified by our survey.

Person: Movement

The movement submodel is initiated by either commuting or the need to evacuate. Following a path calculated by their initiating process, Persons will move with a speed determined either by demographics or else by the speed of any vehicle they have. Their progress along the road network is slowed by the presence of other Persons on the same road segment. They may also attempt to move down a road segment and find it blocked by the developing crisis - in this case, they are forced to observe their environment, learn about the road blockage, and calculate another risk assessment.