Examining the operational aspect of pedestrian evacuation modeling, a case study of Ras-Baalbek flash floods – Lebanon

Rita Der Sarkissian^{1,2,3, a}, Chadi Abdallah³, Jean-Marc Zaninetti⁴, Rachid Nedjai⁴

¹ Lab'Urba/Université Gustave Eiffel, Ecole des Ingénieurs de la Ville de Paris, Université Paris-Est Creteil, France

² Laboratoire d'Economie Orléans (LEO) – Université d'Orléans – Orléans, France

³ National Council for Scientific research, Remote sensing Center, Natural Hazard, Beirut, Lebanon

⁴ Centre d'études et de Développement des Territoires et de l'Environnement, Université d'Orléans, France

Abstract. A number of evacuation models exist in literature, but investigations of their operational aspects and efficient implementation are rare. The purpose of this paper is to critically assess the operational aspect of pedestrian evacuation models for flash floods mitigation. Through a detailed real-life case study in Ras-Baalbek village-Lebanon, the efficiency of evacuation models when it comes to saving lives was examined. Potential evacuation times were established using an anisotropic least-cost-distance (LCD) approach combined with an exploratory geospatial analysis. The next step was a field verification of the obtained results and accordingly, a detailed evacuation plan that would allow evacuees for a quick departure before flash floods arrival was established. Based on the modeling results, evacuation signs were proposed to be installed on roads along with building vertical-evacuation structures to enhance the evacuation time. The obtained evacuation-modeling outcomes showcased to have multiple operational implications: flood risk outreach, educating and training (preparedness and response), reducing risk and casualties, long-term land use/land cover zoning and, ultimately, improving communities' resilience to floods.

1 Introduction

Floods, among other hydro-meteorological hazards, are the most prevalent (Arrighi et al., 2019) affecting more people worldwide than any other natural event (EC, 2017; Guerreiro et al., 2018). Floods have the potential to cause extreme property damage and great loss of life. During flood events, according to Arrighi et al. (2019), the majority of fatalities occur outdoors when people attempt to escape by driving or walking in floodwaters (FitzGerald et al., 2010; Kellar & Schmidlin, 2012; Salvati et al., 2018). Despite developments in terms of early flood warning systems, studies have also demonstrated that the impact of floods is intensifying over time (Ferreira et al., 2011; Stevens, 2012). Besides being key components of the Sendai Framework (UNISDR, 2015), preparedness and planning play a pivotal role in reducing the impact of floods on lives, livelihoods and societies (Petrucchi et al., 2017). Emergency evacuation is often one of the most effective preparedness strategies that can be undertaken in response to floods (European Commission, 2003; Hector Lim et al., 2013; Na et al., 2012; Zhai & Ikeda, 2006). However, confusing and contradicting evacuation information can aggravate flood situations. Field investigations in Thailand reported that due to late decision and limited information many people lost the chance to

evacuate (Jamrussri & Toda, 2018). Knowing exactly where to go during an evacuation is crucial to the survival of people in a flood prone zone. Siebeneck and Cova (2012) found that people are motivated to evacuate when the level of risk to their homes is displayed on maps. Decision-makers, in turn, are more active when they see their region mapped as prone to hazards.

This fact calls for efficient and operational flood evacuation models. Although the need for models to assist facilitating evacuation under flooding scenarios is becoming increasingly sought (Johnstone & Lence, 2009), evacuation planning and modeling studies that specifically consider flood hazards are still limited in number (Hector Lim et al., 2013). In literature, relatively few approaches were tackled in studies to model flood evacuation, e.g., a heuristic and implicit enumeration algorithm (Sherali et al., 1991), a telephone survey and face-to-face interviews (Pfister, 2002), timeline modeling (Oppen ESM et al., 2010), inundation analyses (Oppen ESM et al., 2010), Geographic Information System (GIS) (Masuya et al., 2015), a logit model (Lim et al., 2016), dynamic modeling approaches (Dawson et al., 2011; Dressler et al., 2016; Lumbroso et al., 2010; Mordvintsev et al., 2014; Southworth & Chin, 1987; Wang et al., 2010) and integrated micro-level multi-models for simulating human behaviour and routing (Wolshon & Dixit, 2010). These

^a Corresponding author: rita.der-sarkissian@civp-paris.fr
DOI 10.3311/FLOODRisk2020.18.8

evacuation models serve also for exposure assessment. Basic population exposure numbers do not reveal the full risk story. Distances to safe zones of each evacuee show variations in population exposure as a function of pedestrian travel times to safety (temporal exposure). Exposure functions based on these evacuation micro-models can be used to estimate life loss and identify the effects of response management (Dawson et al., 2011). Preparing a community for future floods requires not only an understanding of the hazards faced, but how residents are exposed to those hazards.

Human factors and socio-demographic characteristics of evacuees influence the effectiveness of the above-mentioned evacuation models and question their assumptions and operational applicability. A lack of sociological and psychological literature on evacuation behaviour is claimed on many levels (Wood et al. 2016). Some studies have determined indicators that impact the decision of evacuation: 1) Irwin and Hurlbert (1995) focused on factors like awareness, perception of risk and being hurt if not evacuating, the perceived ability of the home to resist to the hazard, past disaster experience, gender, marital status, education, age, and race of the owner, 2) the presence of children in household plays an important role in the decision to evacuate or not according to Wilmot and Mei (2004), and 3) Regional Development Service (RDS) (1999) stressed on indicators like whether an evacuation order had been issued or not, the announced intensity of upcoming hazard, whether the neighbours evacuated or not, and the home structure type. Xu et al. (2012) proved that the “perception-reaction time” during emergency situations is lower compared to that during normal situations. To date, a significant literature lack resides in revealing social and psychological factors impact on evacuation behaviours and implementing them in evacuation models (Zheng et al., 2017). In the midst of this lack, evacuation models effectiveness should be critically reassessed through detailed case studies.

Flash floods in Lebanon, eastern Mediterranean country, are frequent especially in Ras-Baalbek a relatively dense village with buildings not exceeding one or two floors. The region's semi-arid lands along with the limited vegetation cover hamper the absorption of the excess water and increase the runoff. Flash floods, the most catastrophic of which occurred as recently as 2018, caused considerable damages to the road network, infrastructure, crops and livestock, severe soil erosion in addition to, and most importantly, casualties. Structural flood protection measures were taken in the forms of reservoirs and walls to intercept flood waters. It was notable that relying only on such structural measures is not a proper way for reducing flash floods risk in Ras-Baalbek, as they are not consequently maintained (Abdallah and Hdeib 2018). Raising awareness, preparing and planning for these catastrophic and sudden hazards that arrive within a short lag of time is of ultimate importance to reduce life losses and mitigate the negative impacts of floods. Among these risk preparedness measures, a detailed flood evacuation planning for the population of Ras-Baalbek is required, especially that no studies on flood evacuation have been conducted and no evacuation plan exists in this highly exposed and vulnerable area. Due

to the suddenness of flash floods, lack of early warning system, the relatively small floodplain and limited road network in study site, as in other similar region of the world, evacuation is self-initiated by walking/running across the landscape without any routing restrictions (Wood and Schmidtlein 2012). Vehicle use, which may lead to road congestion, represents a potential threat to the physical safety of pedestrians, drivers and passengers alike, which should be highly discouraged (Trindade et al., 2018).

According to all the above, Ras-Baalbek village can serve as a case study to respond to the aim of the study. This work investigates the operational aspect of evacuation modeling, choosing an ArcGIS extension “The Pedestrian Evacuation Analyst” (PEA) developed by USGS (Wood et al. 2014; Wood and Schmidtlein 2012, 2013). Employing anisotropic least-cost-distance (LCD) modeling and exploratory geospatial analysis approaches, this paper addresses the need for evacuation maps in the region for supporting evacuation outreach, emergency response, relief planning, and disseminating a culture of risk (Wood et al. 2016). Modeling pedestrian evacuations from natural hazards by using LCD approaches is a fairly new yet developing subject in the literature with numerous growing techniques for examining and modeling pedestrian travel costs like travel time (Graehl, 2009; Laghi et al., 2006; Post et al., 2009), probability functions based on existing routes (Pingel, 2009), energy expenditure (Jobe & White, 2009), cellular automata (Zheng et al., 2017) and agent-based model focusing on individual evacuee behaviour (Pluchino et al., 2015; Rendón Roza et al., 2019). Aiming to understand the spatial distribution of evacuees over time within Ras-Baalbek community and taking into consideration the availability of data, the LCD-based approach was chosen over the other cited methods. The adopted method and detailed analysis of potential evacuation times necessitate an important amount of high-resolution data and several processing steps. In opposition to many other pedestrian evacuation analysis (Girres et al., 2018), the LCD takes into account the elevation changes (i.e. how steep the path is) and the different types of land use /land cover (maintained road, sand, grass, forest, buildings, rivers, etc.) that a person would encounter on his/her way, along with travel speed of the evacuee (walking, running, etc.).

The remainder of this paper is structured as follows: The next section presents the study area characteristics (Ras-Baalbek village), focusing on elements that would serve the assessment of evacuation potential and the organization of an evacuation planning. The third section describes the used materials and the adopted methodological approach, highlighting the scale and resolution of used data. The fourth section presents the revealed results, discussing the approach and its applicability, along with field-verification results. The fifth section develops the gaps of the adopted model and the uncertainties that influence its effective implementation. The final section offers concluding insights and highlights further research works.

The flash flood hazard zone used in this study is based on the “Flood Hazard Assessment and Mapping for Lebanon” study conducted in 2013 by the National Center for Remote Sensing (NCRS)-Lebanese National Council for Scientific Research. The worst possible flash flood scenario was considered despite its low 0.01 exceedance probability (or return period $T=100$ years). This decision is related to the fact that the worst-case scenario provides a clear indication of the maximum area that will be affected by the flooding. Therefore by adopting this

scenario, the less severe scenarios are inherently safeguarded. Furthermore, no Early Warning System exists to predict the intensity of the upcoming flash flood. Concerning the available time for evacuation, although the flash floods lag time in the concerned watershed is estimated to be 2 hours, due to the lack of early warning system, people are warned by seeing the floods flowing down the mountains only 10 minutes before the waters reach the village.

3.1.2 DEM

DEM (Digital Elevation Model) is used to derive slope. High/safe ground can be reached usually by moving away from the river bed and climbing the hillside. The degree of slope is one of the most important components for determining evacuation speed in an anisotropic LCD approach which is slope dependent (Laghi et al., 2006). Anisotropy incorporates the influence of a given slope on the direction of travel (uphill or downhill). Moreover, the model uses the slope information to detect possible changes in travel speeds. The spatial resolution of the DEM has a large impact on the results of the computed pedestrian travel-time map. Wood and Schmidtlein (2012) have shown, in a model sensitivity analysis, that varying elevation data resolutions from 1- to 10-m grid cells had a significant impact on evacuations times and, eventually, on the number of people to reach a safe zone on time. Therefore, a 20-cm DEM, conducted by CNRS-L via drone imagery was utilized in the current study. More than 5000 raw images were captured from several drone photography surveys covering the whole floodplain. These raw images were acquired in strips with adjoining photographs having an overlap of 80% in the flight direction and 70% between parallel flight tracks (Hdeib et al., 2018). To generate the 20 cm-resolution DEM, the images were integrated and processed in the Pix4DMapper software following criteria provided by the American Society of Photogrammetry and Remote Sensing (Mikhail et al., 2004).

3.1.3 LULC

LULC (Land use/Land cover) map is another important component of anisotropic LCD modeling. The study of Wood and Schmidtlein (2012) has proved that LULC resolution also greatly influences travel times and the use of higher resolution LULC datasets is highly recommended for more accurate results. In this context, drone aerial photos were used to manually map and classify a 1/100 resolution LULC for the Ras-Baalbek. A total of 319 residential structures were delineated in the studied floodplain.

3.1.4 Population

Data about population distribution and characteristics is necessary to separate each time step by geographic unit and indicate the population by time and location during every phase of the evacuation. High resolution population datasets are also essential for accuracy of outputs. For this purpose, and having elaborated a 1/100 resolution LULC for Ras-Baalbek floodplain, the population data were obtained by applying an intelligent dasymetric method

(Der Sarkissian et al., 2019). Disaggregating population homogenously to residential structures is bound by uncertainties but determining exact population counts at each household was considered beyond the scope of this study.

After gathering, preparation and treatment, all of these inputs were converted to raster grid formats.

3.2 Reclassifying LULC into SCV

This step consists of defining the relationships between LULC types and movement/walking speeds of a human. Each class of the produced LULC was given a new value describing its capability to modify or conserve the speed of a person's movement. These values are "speed conservation values" (SCV) based on the inverse of the landscape-energy coefficients discussed in Soule and Goldman F. (1972). SCV reveal the proportion of a maximum speed that could be reached across the given LULC type. Table 1 shows the land-cover types delineated for Ras-Baalbek community, PEA simplified LULC classes and their associated SCVs. Values range from zero, indicating that travel is not possible, to 1.0 indicating that pedestrian evacuation speed is 100 percent of the base travel rate. Consequently, LULC_SCV layer was generated and converted to a cost-inverse raster implying the friction of the evacuation movement.

Ras-Baalbek Land-use/Land-cover types	PEA Land-cover classes	Speed-conservation values (SCV) (fraction of maximum travel speed)
Not available	Water	0 (No through travel possible)
Industrial /Urban	Buildings	0 (No through travel possible)
Bare rocks/ outcrops	Unconsolidated Beach (sand)	0.5556
Forests/fruit trees	Heavy Brush	0.6667
Grasslands /crops	Light Brush	0.8333
Urban sprawl/open space	Developed	0.9091
Paved areas/Roads	Roads	1

Table 1 Ras-Baalbek Land-use/Land-cover types, PEA land-cover classes and their corresponding Speed Conservation Values (SCV). Source: adapted from Soule and Goldman F. 1972.

3.3 Slope reclassification into SCV

Slope, derived from 20-cm DEM, is combined with a table based on Tobler's (1993) empirical hiking function converting slope to inverse "speed conservation values" (SCV) following the empirical Equation 1:

$$\text{Walking speed} = 6e^{-3.5*|\text{slope}+0.05|}$$

Equation 1 Walking speed as function of slope (Tobler, 1993)

SCVs herein represent the fraction of maximum travel speeds expected on areas with different slopes. Consequently, a SCV surface for slope is obtained and used as vertical factor to retrieve the anisotropic cost. The direction of the inverse slope SCV table is then reversed because the search direction in the LCD path algorithm is opposite to the direction of evacuation, beginning from safe zones (set as the origin) and expanding to floodplain (set as destination) for easier means of search for the shortest paths.

3.4 Calculating path distance to a safe zone and creating Least Cost path surface

In respect to anisotropy, travel cost distances are calculated using Path Distance geoprocessing tool allowing for both the calculation of three-dimensional distances between cells of changing elevations and different LULC types in the floodplain, as well as the path from a given cell to each of its adjacent cells reaching out the nearest safe zone (Wood and Schmidtlein 2012). All artificial structures like buildings, walls, etc. are automatically removed from the model, considered inaccessible. The model considers detours during evacuation to avoid these structures.

3.5 Calculating Evacuation Speeds

Human walking speeds vary with multiple factors. Several authors addressed evacuation speed issues and suggested speed values that widely range from 1.0 m/s (González-Riancho et al., 2013; YAGI et al., 2006) to 2.80 m/s (Post et al., 2009). In this study, 1.1 m/s is adopted as the fixed average value considered for the normal speed of an adult (United States Department of Transportation, 2009). This speed, though seen as conservative (Wood et al. 2014), is considered to be appropriate for the floodplain mixed population with ranges in age and physical mobility. Demographic data show that 16% and 7% of the population in Ras-Baalbek are children and elderly, respectively (Population Explorer, 2019). This value is a simplification of actual travel speed, especially for children, elderly people, and evacuees with special needs. These groups may encounter more difficulties evacuating flood-prone areas and influence evacuation response (Heller et al., 2005; Schiff, 1977). Moreover, fatigue also affects the travel speed. To quantify, in our study area, the interrelation between travelled distance, land cover conditions and fatigue, additional physiological research is required.

To obtain SCVs, speeds were then divided by the greatest potential walking speed, a universal calculation across the full extent of the slope-based, walking-speed surface (Wood and Schmidtlein 2012).

Overall, the use of a lower travel speed is justified by the probability of individuals moving faster due to risk perception motivation but also likely to be delayed for various reasons (Wood et al. 2014).

3.6 Generation of Least Evacuation Time map

To illustrate the time, in minutes, it would take to walk to the closest flood-safe evacuation site, the LCD surfaces were converted to pedestrian least-evacuation-time pixels, multiplying it by the inverse of the previously fixed base travel speeds.

Flood Vertical-evacuation (FVE) structures, such as buildings, replace natural heights in a flood zone, designed to tolerate flash floods and provide safe shelters for neighbouring population evacuation. If the least-evacuation time exceeds the flood arrival time lag, it is important to consider hypothetical FVE structures in the modeling and test their efficiency in decreasing the evacuation-time. Therefore, two potential FVE1 and FVE2

structures were considered in the floodplain, as safe zones, and placed in the revealed “hotspots of evacuation” zones (to enhance evacuation time) and empty areas where construction may be possible. Consequently all the previous steps were executed to lead to the generation of Least Evacuation Time map with FVE.

3.7 Generation of Population spatio-temporal exposure and travel times to a safe zone

After generation of Least Evacuation Time maps, spatial joins are performed to integrate evacuation results (transformed to vector formats) with various population data. This geospatial function results in portraying the number and distribution of populations as a function of minimum travel time to safe areas.

3.8 Model validation

To test the accuracy of the computed evacuation time maps and their operational efficiency, a field model verification was performed. Ras-Baalbek community was visited and a subset of road-based routes were walked and time-recorded, then compared to the model results.

4 Results and discussion

4.1 Pedestrian evacuation potential under baseline conditions

The LCD approach has led to understand the spatial distributions of required evacuation times within Ras-Baalbek community under current conditions. Figure 3-a) demonstrates the baseline evacuation-modeling outputs. Assuming an average travel speed for evacuees of 1.1 m/s, the resulting pedestrian-evacuation travel times vary from less than a minute to more than 13 minutes in some locations. Although the flash floods lag time in the concerned watershed is estimated to 2 hours, due to lack of early warning systems, the “available time” to evacuate is estimated at 10 minutes. Locations with required pedestrian evacuation time exceeding 10 minutes, showed in red on the map, represent “hotspots of evacuation”. This is probably due to the steep slopes in the northern parts of the floodplain and the haphazard and unorganized urbanization with some buildings too close to each other and not directly connected to roads or paved areas.

It is important to know the number and distribution of people along these evacuation time land surfaces to point out the evacuation challenges. Therefore, evacuation travel time maps were merged with the obtained population data. Population distribution as a function of travel time to safe zones in baseline conditions were plotted in orange (Figure 4). Accordingly, the model shows that a considerable number of people may encounter problems evacuating before the flash floods arrival at 10 minutes. These people, representing 12% of the initially exposed community, would be probably located in “hotspots of evacuation” at floods arrival, and thus they won’t be able to reach safe zones at time. It is noteworthy that this percentage should not be translated as definitive estimates of the number of victims for many components that may delay evacuation

and influence travel times. These components include the time needed to take the decision of evacuation, to leave a car or a building, to navigate unfamiliar environments, to have mobility issues, etc. Some individuals in flood-hazard zones may also completely refuse to evacuate. To better account for these factors, assuming that some people in the 8-10 min window of time may delay their evacuations, it may be more appropriate to summarize “hotspots of evacuation” to areas that would require more than 8 min. In our study area, this assumption allowed to increase the percentage of the population potentially unable to evacuate before floods arrival from 12 to 20%.

4.2 Changes in pedestrian evacuation landscapes with FVE options

Planning for efficient solutions is necessary to reduce potential casualties. Building FVE has as primary objective to maximize the number of lives saved from future flash floods is Ras-Baalbek.

Based on the disclosed “hotspots of evacuation” zones representing significant challenges and empty areas for construction site, two FVE were proposed. To test the efficiency of each of these proposed FVE options, they were introduced to the modeling of the potential evacuation time to safe zones in the floodplain and geospatial efforts focused on two major factors. The first factor depicts spatial variance in evacuation potential. The variations in the evacuation landscape with the introduction of FVE1 and FVE2 are shown in Figure 3 b) and c) respectively. Again, people in the area are assumed to start evacuating approximately 10 minutes before the arrival of flash floods is predicted. At a glance, the area of “Hotspots of evacuation” zones (where required evacuation time is higher than 10 minutes) represented in red, decreased compared to the baseline (Figure 3-a) after introduction of FVE1 (Figure 3-b) and even more after the introduction of FVE2 (Figure 3-c). A second set of parameters aimed to describe changes in population exposure as a function of travel time to safe zones based on the FVE alternatives. The spatial distribution of the population as a function of travel time to safety if FVE1 and FVE2 existed are plotted respectively in yellow and green in Figure 4. This figure shows that while there were approximately 190 people at locations that would require only 1 minute to reach safe zones under baseline conditions, this number increases to 205 and 210 after installation of FVE1 and FVE2 respectively. Moreover, this figure shows that the number of people who may encounter problems evacuating before the flash floods arrival are decreasing with these FVE options. The main evaluation criterion is the additional number of people who can reach a proposed FVE in less than 10 min. The efficiency of an individual FVE was measured by changes in the exposure of the population relatively to current landscape conditions. While 88% of the residents may have enough time to successfully evacuate from Ras-Baalbek floodplain under current conditions, this percentage increases to 94 % and 97% after introduction of FVE1 and FVE2 respectively (Figure 5). In other words, FVE1 and FVE2 reduced the percentage of people

potentially not being able to reach safe zones at time to its half and to its quarter respectively (from 12% to 6% to 3%).

All the above results demonstrate that FVE2 may be a preferred option. Furthermore, red “Hotspots of evacuation” zones, denoting areas where timely evacuations are improbable, decrease but do not completely disappear in scenarios with FVE1 and FVE2. This shows that each FVE option could only serve evacuees near its proposed construction site, but that a single FVE option cannot constitute the unique solution and help the evacuees of the entire floodplain. Decisions based on tradeoffs and compromises would need to be made, especially that Ras-Baalbek population exposed to flash floods was estimated at approximately 1550 individuals. These exposed individuals represent half of the total community of the village. The relatively high percentage suggests that, although the total losses may not be as high as in other larger communities, this small community may be less likely to cope with those losses and have greater difficulty recovering. However, as mentioned earlier, this basic population exposure approach doesn’t tell the full risk story since it ignores the physical/mental ability of at-risk individuals to evacuate before flash floods arrive. This ability needs preparedness and planning. It is important to convince people that not only they have higher chances of survival if they evacuate, but also that they can lose their lives if they refuse to.

Figure 3. a) Pedestrian evacuation times map under current conditions and b) with vertical evacuation solution VE1 and c) with vertical evacuation solution VE2.

Figure 3. Distribution of Ras-Baalbek residents as a function of travel time to reach safe zones in Baseline conditions (red), after installation of proposed FVE1 (yellow) and after installation of FVE2 (green).

Figure 4. Percentage of Ras-Baalbek residents to reach safe zones with less than 10 minutes travel time in current conditions (baseline), after introduction of FVE1 and FVE2.

4.3 Results verification and validation

One of the main purposes of this paper was to critically reassess the operational applicability of the PEA results. A first step was to validate the model. Underestimating travel time or overestimating it in other locations is a civil protection concern. Underestimation of travel times can promote a false sense of security, making evacuees believe they have more time than they really do to evacuate. Travel time overestimation can mislead emergency managers and first-responders actions during response time. Given the specifications of the current case study, with the absence of early warning systems and short time periods to evacuate, even few seconds of inaccuracy may lead to death of many individuals. In response to the importance of model validation, field model verification was performed in Ras-Baalbek community. 22 routes to evacuate from different starting points covering all obtained evacuation time classes were tested. Relative walked distances, average walking speeds and field measured walking times were all recorded and listed in Table 2. Comparison of computed values to on-field measured values of egress time from floodplain allowed for calculation of error (Equation 2) and subsequently for revealing the accuracy level (Equation 3) of the model.

$$\text{Error} = \frac{|\text{Modeled time} - \text{Field measured time}|}{\text{Field measured time}} * 100$$

Equation 2. Error percentage calculated from comparison of field and modeled measures

$$\text{Accuracy level} = 100 - \text{Average}(\text{Error}).$$

Equation 3. Accuracy level calculated from average error.

The model showed an accuracy level of around 91%, and is thus believed to be relatively precise and reliable (table 2). However, zooming into individual errors, the highest error percentages were found for the longest and for the shortest distances of evacuation. Physical and psychological factors are believed to be the causes behind these errors. These high percentages of errors can be explained during long distances by the fatigue that influences the speed and tends to decrease it. Concerning high percentage of errors in shortest distances of evacuation, it can be explained by the motivation considering risk perception and knowing the small time remained to reach safety, which can induce an increase in walking speed. Furthermore, people present at point 3 and 4 were modelled to be able to reach safe grounds before

the arrival of flash floods. Although the model proved a good level of accuracy, the records from field measurements show that these evacuees will take more than 10 minutes to reach safety. Thus, the model may be giving evacuees, emergency managers and first responders, a false sense of security.

Starting Point	Coordinates	Walked distance (meters)	Average walking speed (m/s)	Field measured walking time (minutes)	Modeled time (minutes)	Error
1	36°25'29.961"E 34°15'33.775"N	695	0.81	14.25	12.70	10.88%
2	36°25'16.261"E 34°15'34.883"N	623	0.73	14.30	13.00	9.09%
3	36°25'29.051"E 34°15'34.907"N	559	0.91	10.20	9.10	10.78%
4	36°25'8.61"E 34°15'36.335"N	517	0.84	10.25	9.30	9.27%
5	36°25'23.822"E 34°15'35.971"N	465	0.89	8.70	8.10	6.90%
6	36°25'12.302"E 34°15'38.283"N	444	0.80	9.30	8.60	7.53%
7	36°25'34.907"E 34°15'32.018"N	394	0.82	7.99	7.50	6.13%
8	36°25'6.41"E 34°15'38.448"N	367	0.77	7.90	7.40	6.33%
9	36°25'18.346"E 34°15'37.318"N	328	0.75	7.30	6.90	5.48%
10	36°25'7.811"E 34°15'34.827"N	259	0.73	5.90	6.20	5.08%
11	36°25'29.224"E 34°15'36.433"N	263	0.78	5.65	5.30	6.19%
12	36°25'27.92"E 34°15'29.734"N	222	0.72	5.15	5.50	6.80%
13	36°24'57.476"E 34°15'40.901"N	198	0.76	4.35	4.60	5.75%
14	36°25'26.918"E 34°15'29.579"N	201	0.84	4.00	4.40	10.00%
15	36°25'14.413"E 34°15'39.418"N	179	0.81	3.69	3.80	2.98%
16	36°25'24.124"E 34°15'28.861"N	159	0.85	3.10	3.20	3.23%
17	36°25'2.142"E 34°15'35.046"N	105	0.85	2.05	2.30	12.20%
18	36°25'29.055"E 34°15'37.723"N	89	0.71	2.10	2.40	14.29%
19	36°25'8.583"E 34°15'40.226"N	66	0.99	1.11	1.20	8.11%
20	36°25'4.76"E 34°15'31.392"N	52	0.91	0.95	1.00	5.26%
21	36°24'53.486"E 34°15'40.706"N	48	1.00	0.80	0.90	12.50%
22	36°25'26.414"E 34°15'28.104"N	32	1.40	0.38	0.50	31.58%
Average error						8.93%

Table 2. Comparison of collected values on-field with modelled values.

4.4 Operational applicability of the model and strategic implementation of flood Evacuation signage

The above obtained pedestrian evacuation-modeling results have several implications and applications. First of all, the pedestrian evacuation potential maps produced have a primary purpose, which is to raise awareness among the community of Ras-Baalbek. People will be aware of the danger they face if they do not evacuate before the arrival of the floods, and thus initiate them to pedestrian self-evacuation. From the perspective of risk psychology, model results suggesting successful evacuations could be used as part of flash flood outreach to raise positive outcome expectancy (i.e. the degree to which people believe there is a way to reduce risk to hazards). For instance, Ras-Baalbek population is more likely to prepare and plan for future flash floods and take

action if they believe that successful evacuations are possible and that their actions will have positive outcomes. The produced maps also apply to education and training (for the community, emergency managers, community planners and first responders) for effective and successful evacuation. Efforts should focus on educational campaigns to help Ras-Baalbek residents read the produced maps correctly and know the most effective evacuation route from their residence or from any possible location they can be at when flash floods arrive.

Second, results strongly support preparedness, evacuation planning efforts and response procedures on a community-based level. Evacuation strategy planning includes a mix of measures to help people evacuate in a flash flood emergency. The obtained pedestrian evacuation maps directly serve the evacuation strategy in Ras-Baalbek by guiding the production of flood evacuation road signage and their distribution along the floodplain to safe zones. Although residents are familiar with the region, during the sudden flash flood, they may be confused and panicked and will need guidance to evacuate. Signalling evacuation directions is therefore imperative, and must be made with easy to read signs. The pedestrian evacuation times shown in **Error! Reference source not found.-a)**, were used to propose four types of flash flood evacuation signs. It is noteworthy that no methodologies or international standards have been found related to the flash flood evacuation route signage, thus the followed methodology to the flood evacuation signage and their colours was inspired by tsunami evacuation route signage (Girres et al., 2018). These proposed evacuation signs (Figure 5), on which information is written in both Arabic (mother tongue) and in English languages (for potential presence of foreigners) will guide Ras-Baalbek residents to the direction they should follow to evacuate successfully, and will indicate the needed time to reach a safe zone at an average pedestrian travel speed. The four types are related to the time required to reach safe zones. Green signs represent 3 min required to reach a safe zone and should be strategically installed in green colour regions (Figure 3a). Yellow signs represent 6 min needed to reach a safe zone and should be strategically installed in yellow colour regions in map. While, orange signs denote that 9 min are necessary to get to a safe zone and should be strategically installed in orange colour regions. Consequently, Red signs indicate that 13 minutes are needed to reach safe zones and should be strategically installed in red colour, considered as “Hotspot evacuation zones”. Setting these evacuation roads signs should be done carefully and with the consent of residents and landowners to prevent conflicts. Many landowners may oppose the installation of these signs, especially the red ones, seen as an indicator of the flash floods risk threatening their lands and thus lowering its per capita value in the real estate market. Therefore, the education campaigns previously discussed are of key importance for the acceptance of these evacuation signs and make best use of their role in Ras-Baalbek community. Additional blue signs (Figure 5) were proposed to indicate when evacuees are in a safe area from flash floods, encouraging them to carry on to a final destination as opposed to stopping where the routing signage ends leading to assemblies build-up in

the floodplain threatened area. These signs are believed to psychologically assist evacuees and motivate them to continue their road. People tend to speed up when knowing that little distance remains to reach safety demonstrating that motivation can play a crucial role in walking speed.

Figure 5. Proposed flash flood evacuation road signage for Ras-Baalbek community.

Another measure for efficient evacuation strategy planning, provided by the obtained pedestrian evacuation maps, is the potential of FVE structures (**Error! Reference source not found.-b,-c)**. The elaborated evacuation models can serve as a decision-support tool through comparisons of FVE1 and FVE2 options and their effect on evacuation times. Results showed that FVE2 would save more lives and is therefore more favourable. The construction of FVE should also be carefully studied, well-planned for and designed to meet several requirements. Engineering studies are necessary to design FVE able to resist to the floating debris and heavy objects transported by the floods waters. These structures may remain flooded in waters for a period of time. Therefore, they must also have access to basic livelihoods needs such as food, drinking water, sanitary, emergency kits and means of communication.

5 Gaps and challenges

This study discussed the applicability and implementation of pedestrian evacuation modeling. Evacuation in response to any particular event is a unique, complex, and uncertain response. This evacuation model has been completed using the best information available. However, some known limitations and unknown uncertainties and probabilities may exist and should be pointed out. Preparedness actions in Ras-Baalbek, as for other regions in developing countries, are often ignored. Societal challenges behind preparing for intensive hazards is to cope with risk uncertainty and its low probability. The field of evacuation planning necessarily entails uncertainties. These uncertainties form a considerable debate, especially when considering the costs of associated preparedness measures. These uncertainties present many challenges and lead to increased vulnerabilities. The faced gaps, challenges and uncertainties in this study reside in:

5.1 Hazard uncertainties

The utilized flood hazard, on which the modeling was performed, was conducted on a scale of 1/20000. Further analysis needs to be done to perform a new flood hazard map on a larger scale, which would lead to the implementation of the dynamics of the flood in time of the evacuation. Implementing dynamics of flash floods would lead to more detailed and more accurate evacuation time maps. Moreover, Climate Change should be considered in flood hazard assessment.

5.2 Population characteristics and behavioural uncertainties

There are aspects of individual behavioural issues and mobility that require consideration before localized evacuation may be realistic. The conducted modeling simplified actual travel resulting from a generalization of speeds for the entire population. Individuals will not travel at similar speeds and won't maintain a steady speed, especially as fatigue sets in for those with longer travel distances and different demographic groups with different mobility (elderly, children or people with special needs) who need assistance. More data is needed to assess the fatigue-motivation influence on speed, believed to be the driver of found error during field-validation, and to be able to study different demographic groups, their relative vulnerability and their location in order to increase the accuracy of the model.

It is of key importance to seek to drive down uncertainty as much as possible but inevitably it must be accepted that uncertainty will always exist especially in the field of evacuation preparedness. Uncertainty is believed to be inherent in risk and knowledge is not complete.

6 Conclusion

This study comes in an attempt to examine the operational aspect of pedestrian evacuation models and their ability to efficiently assist the organization of evacuations.

The methodology presented in this study employed anisotropic least-cost-distance (LCD) modeling and exploratory geospatial analysis approaches, and implemented it in Ras-Baalbek. The latter is a village with a long history of flash floods.

The evacuation modeling showed to have multiples preparedness implications and application to flood-evacuation outreach, educating and training (for the community, emergency managers, community planners and first responders to understand likely evacuation corridors), response procedures, mitigation (reducing the risk or even the loss of life of people living in Ras-Baalbek high flood risk areas), and long-term land use/land cover zoning leading to a resilient Ras-Baalbek community. One of their most important applications is to initiate Ras-Baalbek population to self-evacuate and prepare and plan for this evacuation. Moreover, the elaborated evacuation model can serve as a decision-making support tool through differentiation between the proposed vertical evacuation options. Some gaps of the proposed modeling like hazards uncertainties and population characteristics and

behavioural uncertainties, believed to be behind the percentage of error revealed, were highlighted for further research development.

Acknowledgments

This research is part of a PhD thesis funded by the National Council of Scientific Research- Lebanon (CNRS-L). Authors thank CNRS-L for their funding. Thanks is also extended to editor and reviewers for their valuable comments in leveraging the scientific quality of work.

References

- 1 Abdallah, C., Chorowicz, J., Boukheir, R., Dhont, D., 2007. Comparative use of processed satellite images in remote sensing of mass movements: Lebanon as a case study. *Int. J. Remote Sens.* **28**, 4409–4427. <https://doi.org/10.1080/01431160701241761>
- 2 Abdallah, C., Hdeib, R., 2018. Detailed assessment of flood risk in Ras-Baalbek. Lebanon.
- 3 Arrighi, C., Pregolato, M., Dawson, R.J., Castelli, F., 2019. Preparedness against mobility disruption by floods. *Sci. Total Environ.* **654**, 1010–1022. <https://doi.org/10.1016/j.scitotenv.2018.11.191>
- 4 Dawson, R.J., Peppe, R., Wang, M., 2011. An agent-based model for risk-based flood incident management. *Nat. Hazards* **59**, 167–189. <https://doi.org/10.1007/s11069-011-9745-4>
- 5 Der Sarkissian, R., Zaninetti, J., & Abdallah, C. (2019). Adaptive contribution to Intelligent Dasymeric mapping for estimation of daytime and nighttime populations at risk from natural disasters, case study Baalbek-Hermel-Lebanon. *EGU General Assembly*, 21, 3555. <https://doi.org/Vol. 21, EGU2019-3555-2>, 2019
- 6 Dressler, G., Müller, B., Frank, K., Kuhlicke, C., 2016. Towards thresholds of disaster management performance under demographic change: exploring functional relationships using agent-based modeling. *Nat. Hazards Earth Syst. Sci.* **16**, 2287–2301. <https://doi.org/10.5194/nhess-16-2287-2016>
- 7 EC, 2017. Eu agricultural outlook for the agricultural markets and income 2017-2030, EU Agricultural outlook for the agricultural markets and income 2017-2030.
- 8 European Commission, 2003. Best Practices on Flood Prevention, Protection. Ec.Europa.Eu 1–29.
- 9 Ferreira, S., Hamilton, K., Vincent, J., 2011. Nature, socioeconomics and adaptation to natural hazards: new evidence from floods. Policy research working paper.
- 10 FitzGerald, G., Du, W., Jamal, A., Clark, M., Hou, X.-Y., 2010. Flood fatalities in contemporary Australia (1997-2008). *Emerg. Med. Australas.* **22**, 180–186. <https://doi.org/10.1111/j.1742-6723.2010.01284.x>
- 11 Girres, J., Leone, F., Péroche, M., Gustave, G., Gherardi, M., 2018. Analysis of tsunami evacuation maps for a consensual symbolization rules proposal. *Int. J. Cartogr.* **4**, 4–24. <https://doi.org/10.1080/23729333.2018.1440711>

- 12 González-Riancho, P., Aguirre-Ayerbe, I., Aniel-Quiroga, I., Abad, S., González, M., Larreynaga, J., Gavidia, F., Gutiérrez, O.Q., Álvarez-Gómez, J.A., Medina, R., 2013. Tsunami evacuation modeling as a tool for risk reduction: application to the coastal area of El Salvador. *Nat. Hazards Earth Syst. Sci.* **13**, 3249–3270. <https://doi.org/10.5194/nhess-13-3249-2013>
- 13 Graehl, N., 2009. Using a GIS to model pedestrian evacuation times for Newport, OR. California.
- 14 Guerreiro, S.B., Dawson, R.J., Kilsby, C., Lewis, E., Ford, A., 2018. Future heat-waves, droughts and floods in 571 European cities. *Environ. Res. Lett.* **13**. <https://doi.org/10.1088/1748-9326/aaaad3>
- 15 Hdeib, R., Abdallah, C., Colin, F., Brocca, L., Moussa, R., 2018. Constraining coupled hydrological-hydraulic flood model by past storm events and post-event measurements in data-sparse regions. *J. Hydrol.* **565**, 160–176. <https://doi.org/10.1016/j.jhydrol.2018.08.008>
- 16 Hector Lim, J., Bernadeth Lim, M., Piantanakulchai, M., 2013. A Review of Recent Studies on Flood Evacuation Planning. *J. East. Asia Soc. Transp. Stud.* **9**, 147–162. <https://doi.org/10.11175/easts.10.147>
- 17 Heller, K., Alexander, D.B., Gatz, M., Knight, B.G., Rose, T., 2005. Social and Personal Factors as Predictors of Earthquake Preparation: The Role of Support Provision, Network Discussion, Negative Affect, Age, and Education. *J. Appl. Soc. Psychol.* **35**, 399–422. <https://doi.org/10.1111/j.1559-1816.2005.tb02127.x>
- 18 Irwin, M., Hurlbert, J.S., 1995. A behavioral analysis of hurricane preparedness and evacuation in southwestern Louisiana. LA.
- 19 Jamrussri, S., Toda, Y., 2018. Available Flood Evacuation Time for High-Risk Areas in the Middle Reach of Chao Phraya River Basin. *Water* **10**, 1871. <https://doi.org/10.3390/w10121871>
- 20 Jobe, R.T., White, P.S., 2009. A new cost-distance model for human accessibility and an evaluation of accessibility bias in permanent vegetation plots in Great Smoky Mountains National Park, USA. *J. Veg. Sci.* **20**, 1099–1109. <https://doi.org/10.1111/j.1654-1103.2009.01108.x>
- 21 Johnstone, W.M., Lence, B.J., 2009. Assessing the value of mitigation strategies in reducing the impacts of rapid-onset, catastrophic floods. *J. Flood Risk Manag.* **2**, 209–221. <https://doi.org/10.1111/j.1753-318X.2009.01035.x>
- 22 Kellar, D.M.M., Schmidlin, T.W., 2012. Vehicle-related flood deaths in the United States, 1995-2005. *J. Flood Risk Manag.* **5**, 153–163. <https://doi.org/10.1111/j.1753-318X.2012.01136.x>
- 23 Laghi, M., Cavalletti, A., Polo, P., 2006. Evacuation routes tools ArcGIS toolbox user's manual.
- 24 Lim, H.R., Lim, M.B.B., Piantanakulchai, M., 2016. Determinants of household flood evacuation mode choice in a developing country. *Nat. Hazards* **84**, 507–532. <https://doi.org/10.1007/s11069-016-2436-4>
- 25 Lumbroso, D., Johnstone, W., Bruijn, K. De, Mauro, M. Di, Tagg, A., 2010. Modelling mass evacuations to improve the emergency planning for floods in the UK, The Netherlands and North America., in: Paper Presented at International Conference on Emergency Preparedness, University of Birmingham.
- 26 Masuya, A., Dewan, A., Corner, R.J., 2015. Population evacuation: evaluating spatial distribution of flood shelters and vulnerable residential units in Dhaka with geographic information systems. *Nat. Hazards* **78**, 1859–1882. <https://doi.org/10.1007/s11069-015-1802-y>
- 27 Mikhail, E., Bethel, J.S., McGlone, J.C., American Society of Photogrammetry and Remote Sensing, Imaging & Geospatial Information Society (2004). Mikhail, Edward M & Bethel, James S. (James Samuel) & McGlone, J.C. & A.S. of P. and R.S., Imaging & Geospatial Information Society, 2004. Manual of photogrammetry (5th ed). American Society of Photogrammetry and Remote Sensing, Bethesda.
- 28 MoE, 2002. National Action Programme Interventions and Operational Guidelines 71.
- 29 Mordvintsev, A.S., Krzhizhanovskaya, V. V., Lees, M.H., Sloot, P.M.A., 2014. Simulation of City Evacuation Coupled to Flood Dynamics, in: Pedestrian and Evacuation Dynamics 2012. Springer International Publishing, Cham, pp. 485–499. https://doi.org/10.1007/978-3-319-02447-9_40
- 30 Na, L., Xueyan, S., Mingliang, Q., 2012. A Bi-objective Evacuation Routing Engineering Model with Secondary Evacuation Expected Costs. *Syst. Eng. Procedia* **5**, 1–7. <https://doi.org/10.1016/j.sepro.2012.04.001>
- 31 Oppen ESM, S., Cinque OAM, P., Davies, B., 2010. Timeline modelling of flood evacuation operations. *Procedia Eng.* **3**, 175–187. <https://doi.org/10.1016/j.proeng.2010.07.017>
- 32 Petrucci, O., Caloiero, T., Pasqua, A.A., Perrotta, P., Russo, L., Tansi, C., 2017. Civil protection and Damaging Hydrogeological Events: comparative analysis of the 2000 and 2015 events in Calabria (southern Italy). *Adv. Geosci.* **44**, 101–113. <https://doi.org/10.5194/adgeo-44-101-2017>
- 33 Pfister, N., 2002. Community response to flood warnings: the case of an evacuation from Grafton, March 2001. *Aust. J. Emerg. Manag.* **17**, 30.
- 34 Pingel, T., 2009. Modeling slope as a contributor to route selection in mountainous areas., in: UCGIS 2009 Summer Assembly.
- 35 Pluchino, S., Tribulato, C.M.G., Caverzan, A., McQuillan, A., Cimellaro, G.P., Mahin, S., 2015. Agent-Based Model for Pedestrians' Evacuation after a Blast Integrated with a Human Behavior Model, in: Structures Congress 2015. American Society of Civil Engineers, Reston, VA, pp. 1506–1517. <https://doi.org/10.1061/9780784479117.129>
- 36 Population Explorer, 2019. Population explorer [WWW Document]. URL <https://www.populationexplorer.com/> (accessed 9.21.18).
- 37 Post, J., Wegscheider, S., Mück, M., Zosseder, K., Kiefl, R., Steinmetz, T., Strunz, G., 2009. Assessment of human immediate response capability related to tsunami threats in Indonesia at a sub-national scale. *Nat. Hazards Earth Syst. Sci.* **9**, 1075–1086. <https://doi.org/10.5194/nhess-9-1075-2009>

- 38 Regional Development Service (RDS), 1999. Executive summary of a socioeconomic hurricane impact analysis and a hurricane evacuation impact assessment tool (methodology) for coastal North Carolina: A case study of Hurricane Bonnie. Greenville, N.C.
- 39 Rendón Rozo, K., Arellana, J., Santander-Mercado, A., Jubiz-Díaz, M., 2019. Modelling building emergency evacuation plans considering the dynamic behaviour of pedestrians using agent-based simulation. *Saf. Sci.* **113**, 276–284. <https://doi.org/10.1016/j.ssci.2018.11.028>
- 40 Salvati, P., Petrucci, O., Rossi, M., Bianchi, C., Pasqua, A.A., Guzzetti, F., 2018. Gender, age and circumstances analysis of flood and landslide fatalities in Italy. *Sci. Total Environ.* 610–611, 867–879. <https://doi.org/10.1016/j.scitotenv.2017.08.064>
- 41 Schiff, M., 1977. Hazard Adjustment, Locus of Control, and Sensation Seeking. *Environ. Behav.* **9**, 233–254. <https://doi.org/10.1177/001391657792005>
- 42 Sherali, H.D., Carter, T.B., Hobeika, A.G., 1991. A location-allocation model and algorithm for evacuation planning under hurricane/flood conditions. *Transp. Res. Part B Methodol.* **25**, 439–452. [https://doi.org/10.1016/0191-2615\(91\)90037-J](https://doi.org/10.1016/0191-2615(91)90037-J)
- 43 Siebeneck, L.K., Cova, T.J., 2012. Spatial and Temporal Variation in Evacuee Risk Perception Throughout the Evacuation and Return-Entry Process. *Risk Anal.* **32**, 1468–1480. <https://doi.org/10.1111/j.1539-6924.2011.01781.x>
- 44 Soule, R.G., Goldman F., R., 1972. Terrain coefficients for energy cost prediction. *J. appl. Physiol.* 706–708.
- 45 Southworth, F., Chin, S.-M., 1987. Network Evacuation Modelling for Flooding as a Result of Dam Failure. *Environ. Plan. A Econ. Sp.* **19**, 1543–1558. <https://doi.org/10.1068/a191543>
- 46 Stevens, M., 2012. Cities and Flooding: A Guide to Integrated Urban Flood Risk Management for the 21st Century by Abhas Jha, Robin Bloch, Jessica Lamond, and other contributors. *J. Reg. Sci.* **52**, 885–887. https://doi.org/10.1111/jors.12006_6
- 47 Tobler, W., 1993. Three presentations on geographical analysis and modeling: Non-isotropic geographic modeling speculations on the geometry of geography global spatial analysis, Technical report (National center for geographic information and analysis).
- 48 Trindade, A., Teves, P., Catita, C., 2018. A GIS - based analysis of constraints on pedestrian tsunami evacuation routes : Cascais case study (Portugal). *Nat. Hazards*. <https://doi.org/10.1007/s11069-017-3152-4>
- 49 UNISDR, 2015. The Sendai Framework for Disaster Risk Reduction 2015-2030: the challenge for science. *R. Soc. Meet. Note* **9**. <https://doi.org/A/CONF.224/CRP.1>
- 50 United States Department of Transportation, 2009. Manual on uniform traffic control devices for streets and highways.
- 51 Wang, H., Andrews, S., Ni, D., Collura, J., 2010. Scenario-based analysis of transportation impacts in case of dam failure flood evacuation in Franklin county, Massachusetts., in: Paper Presented at the Transportation Research Board 89th Annual Meeting.
- 52 Wilmot, C.G., Mei, B., 2004. Comparison of Alternative Trip Generation Models for Hurricane Evacuation. *Nat. Hazards Rev.* **5**, 170–178. [https://doi.org/10.1061/\(asce\)1527-6988\(2004\)5:4\(170\)](https://doi.org/10.1061/(asce)1527-6988(2004)5:4(170))
- 53 Wolshon, B., Dixit, V., 2010. State-of-the-Art Modeling and Analysis for Evacuation Planning and Operations. *J. Transp. Saf. Secur.* **2**, 85–87. <https://doi.org/10.1080/19439962.2010.490155>
- 54 Wood, N., Jones, J., Schelling, J., Schmidtlein, M., 2014. Tsunami vertical-evacuation planning in the U.S. Pacific Northwest as a geospatial, multi-criteria decision problem. *Int. J. Disaster Risk Reduct.* **9**, 68–83. <https://doi.org/10.1016/j.ijdr.2014.04.009>
- 55 Wood, N., Jones, J., Schmidtlein, M., Schelling, J., Frazier, T., 2016. Pedestrian flow-path modeling to support tsunami evacuation and disaster relief planning in the U.S. Pacific Northwest. *Int. J. Disaster Risk Reduct.* **18**, 41–55. <https://doi.org/10.1016/j.ijdr.2016.05.010>
- 56 Wood, N.J., Schmidtlein, M.C., 2013. Community variations in population exposure to near-field tsunami hazards as a function of pedestrian travel time to safety. *Nat. Hazards* **65**, 1603–1628. <https://doi.org/10.1007/s11069-012-0434-8>
- 57 Wood, N.J., Schmidtlein, M.C., 2012. Anisotropic path modeling to assess pedestrian-evacuation potential from Cascadia-related tsunamis in the US Pacific Northwest. *Nat. Hazards* **62**, 275–300. <https://doi.org/10.1007/s11069-011-9994-2>
- 58 Xu, Z., Kuan Yang, X., Hua Zhao, X., Jie Li, L., 2012. Differences in Driving Characteristics between Normal and Emergency Situations and Model of Car-Following Behavior. *J. Transp. Eng.* **138**, 1303–1313. [https://doi.org/10.1061/\(asce\)te.1943-5436.0000434](https://doi.org/10.1061/(asce)te.1943-5436.0000434)
- 59 Yagi, S., Hasemi, Y., Takai, S., Mizuochi, H., 2006. Requirements and verification methodology for the design performance of “tsunami-hinan buildings” (buildings for temporary refuge from tsunami)(Architectural Planning and Design). *AJ J. Technol. Des.* **12**, 299–304. https://doi.org/10.3130/aijt.12.299_1
- 60 Zhai, G., Ikeda, S., 2006. Flood Risk Acceptability and Economic Value of Evacuation. *Risk Anal.* **26**, 683–694. <https://doi.org/10.1111/j.1539-6924.2006.00771.x>
- 61 Zheng, Y., Jia, B., Li, X.-G., Jiang, R., 2017. Evacuation dynamics considering pedestrians’ movement behavior change with fire and smoke spreading. *Saf. Sci.* **92**, 180–189. <https://doi.org/10.1016/j.ssci.2016.10.009>