Combining a social science approach and GIS-based simulation to analyse evacuation in natural disasters: A case study in the Chilean community of Talcahuano

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ABSTRACT

In rapid-onset disasters the time needed for evacuation is crucial. Aside from the behaviour of the population, the road network plays a fundamental role. It serves as a medium to reach a safe area. This study analyses the entire evacuation process, from decision-making up to the arrival at an evacuation zone by combining standardised questionnaires and GIS-based simulation. Based on a case study in the Chilean community of Talcahuano, an event-based past scenario and a hypothetical future scenario is investigated, integrating the affected population in the research process. The main problem identified in past evacuations has been time delay due to congestions, which also is evident in the results of the hypothetical future scenario. A result which supports evacuation by foot. This paper argues that a combination of scientific methods is essential for analysing evacuation and to reduce the risk due to time delay, critical route and transport medium choice.

KEYWORDS Interdisciplinary approach, case study, evacuation, tsunami, recommendations, disaster risk management

INTRODUCTION

Destroyed roads and bridges, isolated road sections, past natural disasters like the Maule Earthquake and Tsunami in 2010 (Chile) and the Great East Japan Earthquake and Tsunami in 2011 illustrate the impact of natural events on critical infrastructure (Dueñas-Osorio and Kwasinski, 2012; Elnashai et al., 2010; Kadri et al., 2014; Nobuo et al., 2011). These phenomena are not isolated events. The tendency of natural disasters and their impacts on critical infrastructure are increasing (EM-DAT, 2018; Kadri et al., 2014; Munich RE, 2018; Oh, 2010). These effects are enhanced due to progressive urban development in disaster-prone areas (Chen et al., 2012). Critical infrastructure is of fundamental significance in modern societies' unobstructed functioning of day-to-day life and if disrupted, can have severe negative consequences on security and well-being (Urlainis et al., 2014). The road network, as part of the critical infrastructure, plays a crucial role in the case of natural disasters. It ensures not only the accessibility of first responders and e.g. emergency service units, but also serves as a medium for evacuation to a safe area outside the impacted area (Chen and Qiang, 2017). Hence, the importance of the road network during the evacuation is a critical issue in disaster risk management (DRM) in order to avoid loss of human life (Bunea et al., 2016).

Evacuation is the most important strategy for saving human lives, by leaving an endangered area and reaching an evacuation zone (Charnkol and Tanaboriboon, 2006; Chen et al., 2012;Shuto, 2005). Typically, natural disasters lead to the evacuation of large population masses (Buckle, 2012). Recent disasters show that the choice of transport medium in case of evacuation is the private vehicle (Lämmel et al., 2008; León & March, 2014; Pel et al., 2012; Ramos, 2016). This often leads to capacity overload and congestion on the road network (Dow & Cutter, 2002; Litman, 2006; Ramos, 2016; Rinaldi, et al., 2001). Additionally, cascading effects, occurring during tsunamis may hinder evacuation due to the blockages of intersection by the debris of destroyed buildings or collapsed electrical towers (Elnashai et al., 2010; León and March, 2014; León et al., 2018). Human behaviour in evacuation tends to be hard to predict. Many situational factors, including official warnings and instructions, time of day and day of week, the presence of family members or behaviour of the social environment, influence the decision-making process, whether to evacuate or not, and the response to an impending hazardous event. Hence, evacuation is a complex and dynamic process and may also increase the risk for the affected people (Buckle, 2012; Charnakol and Tanaboriboon, 2006; Chen, 2012; Quarantelli, 1980; Quarantelli, 1990; Ramos, 2016).

In order to execute realistic simulations and to facilitate evacuation planning, a detailed understanding of the human behaviour during evacuation, as well as an analysis of the urban environment, especially the road network, are necessary. The conditions of the road network and comprehensive knowledge about transport medium choices, elected or hypothetically elected evacuation routes and zones and the reason for the choices, may anticipate congestion and ensure effective evacuation planning (Lämmel et al., 2008; León and March, 2014; Pel et al., 2012; Ramos, 2016).

Previous evacuation studies mostly focus on either modelling approaches (Chen and Zhan, 2008; Mas et al., 2012; Pan et al., 2007) or social science approaches (Burnside et al., 2007; Dow and Cutter, 2002; Miran et al., 2018; Nakaya, et al., 2018; Perry, 1979; Shapira et al., 2018). However, the evacuation process is highly complex due to an interaction of the human factor and its urban environment. The response of the evacuees influences congestions in the road network significantly. Therefore. the evacuation process benefits from the analysis of an interdisciplinary perspective, combining different scientific methods (Chen et al., 2012; Lindell and Prater, 2007; Naster & Birst, 2010; Quarantelli, 1985). A large number of studies in the field of social science has investigated the evacuation process during hurricane events (e.g. Dash and Gladwin, 2007; Dow and Cutter 2002; Lindell et al., 2005; Smith & Mccarty, 2009; Whitehead, et al., 2000). Hurricanes have a long forewarning time. Such an evacuation differs from the evacuation process in tsunamis, where the time for evacuation decision and response is limited (Lämmel et al., 2008; León and March, 2014).

This paper addresses these limitations, linking a social science perspective and GIS (Geographic Information System) simulation, combining both fields in a stepwise research design. Besides, emphasising the value of interdisciplinary research, this paper analyses the evacuation process in a past event and hypothetical future event. The evacuation process is analysed from the decision to evacuate up to the arrival at a safe destination in case of a tsunami. The objective of the analysis is to detect issues and challenges in evacuation and to give recommendations to improve DRM at a local level. As congestion by the use of vehicles is a major problem in evacuation (León and March, 2016; Muñoz, 2014; Ramos, 2016; Riveros, 2014), evacuation by foot is simulated.

The combination of standardised questionnaires and GIS gives insight to evacuation routes and zones used and provides alternative evacuation routes by foot.

A case study is performed, investigating the district of Las Salinas, in the coastal community of Talcahuano, Chile. The community was among the Chilean coastal cities which were hardest hit by the tsunami of the 27th of February 2010 (Martínez et al., 2011).

The paper is structured as follows. The first section gives brief insight into the research area and the impacts of the earthquake in 2010 in Chile. Section 2 explains the applied methodology. In Section 3 the results are presented, followed by the discussion in Section 4. The paper finishes with a conclusion and recommendations in Section 5.

THE RESEARCH AREA TALCAHUANO

Chile is one of the countries, most prone to earthquakes due to its geographic location at the boundaries of the South American and Nazca Plates. It has a long history of tsunamis triggered by earthquakes (Bronfman et al., 2015; INE Medio Ambiente, 2010). On the 27th of February 2010, Chile was hit by an earthquake followed by a tsunami with a magnitude of 8.8 Mw, which affected about 800 km of the shoreline (Martínez, et al., 2011; USGS, 2010). According to statements of the Chilean government, more than 12.8 million people were affected by the earthquake and the subsequent tsunami, and 521 people were killed. The two most populated areas in Chile were impacted, the metropolitan region of Santiago and the central region Bio-Bío with the conurbation of Concepción-Talcahuano (CEPAL, 2010; GEER, 2010; USGS & U.S. Department of the Interior, 2011). Approximately 51% of the regional population lives in the coastal area (Martínez, et al., 2011) .

Within the region, several bridges were damaged and collapsed as a result of the earthquake. Since these bridges are critical links in the transportation network, their being damaged affected accessibility significantly. Damage to the road network was only minor. As consequences of the earthquake and tsunami, significant damage was also apparent in Talcahuano, one of the most affected communities of the tsunami in 2010 (Elnashai et al., 2010; Fritz, et al., 2010). 18.1% of the inhabitants of the community were affected and 9,173 houses were destroyed. In total, an area of 11.04 km^2 was impacted (INE, 2018; Martínez, et al., 2011). The port and the city centre were damaged severely by the tsunami, due to its low ground elevation between 5-10 m above sea level (León and March, 2014). Figure 1 illustrates the research area and an overlapping tsunami inundation map of 2010.

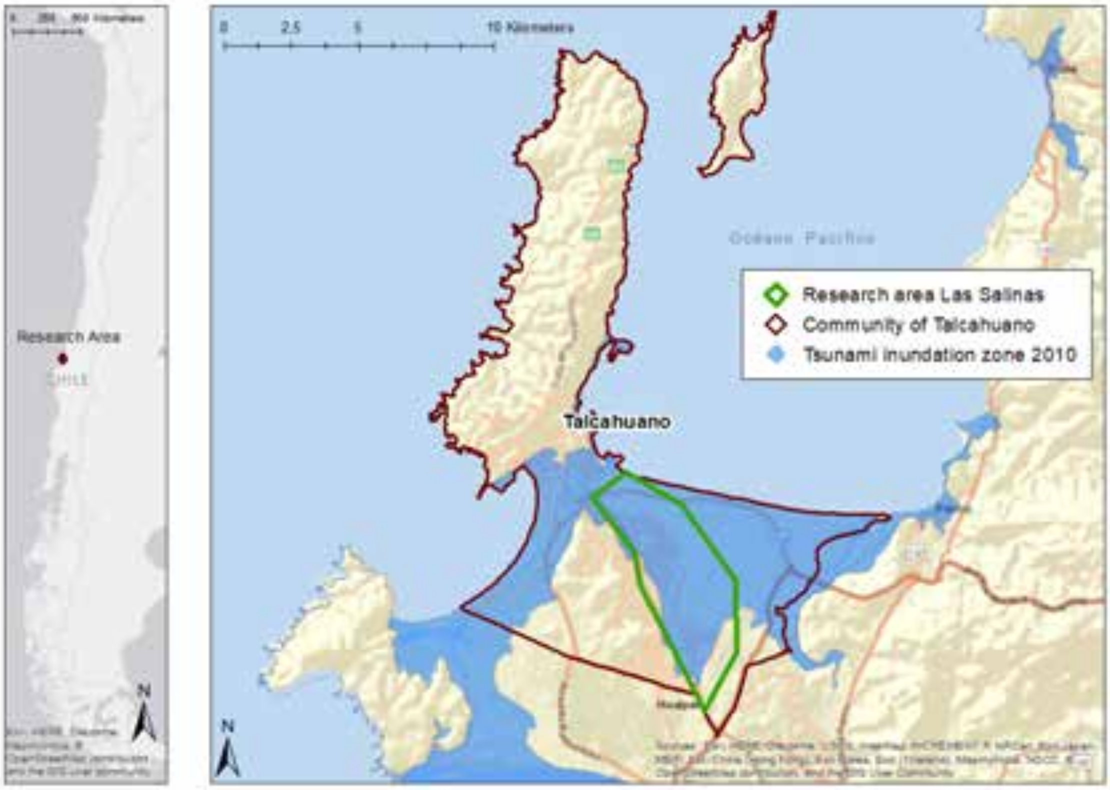

Figure 1: The Chilean territory (left), the community of Talcahuano with the research area Las Salinas and the tsunami affected area in 2010 (right).

Tsunami waves were up to 14 m high, and waves arrived between 12 to 20 minutes and 30 to 45 minutes after the earthquake, depending on the distance from the rupture zone (Vargas et al., 2010). Due to the breakdown in the communication system caused by the preceding earthquake and failures in communication between responsible institutions, no tsunami warning was released. The official institution ONEMI (Oficina Nacional de Emergencia del Ministerio del Interior y Seguridad Pública), which is responsible for the distribution of the alert, even gave a tsunami all-clear. The situation was aggravated by the centralisation of the administrative structure in Chile, which also affected the area of DRM and hindered local authorities in giving alerts. However, the majority of the coastal inhabitants left the hazard zone immediately after the earthquake (Herrmann Lunecke, 2015; León and March, 2014; Rojas et al., 2014). During that event as well as in later major earthquake and tsunami events a large part of the affected population evacuated in private vehicles. That fact led to many accidents and much congestion on the road network and impeded evacuation (León and March, 2016; Muñoz, 2014; Ramos, 2016; Riveros, 2014). The map in Figure 2 shows the official evacuation zones located 30 m above sea level and the official evacuation routes.

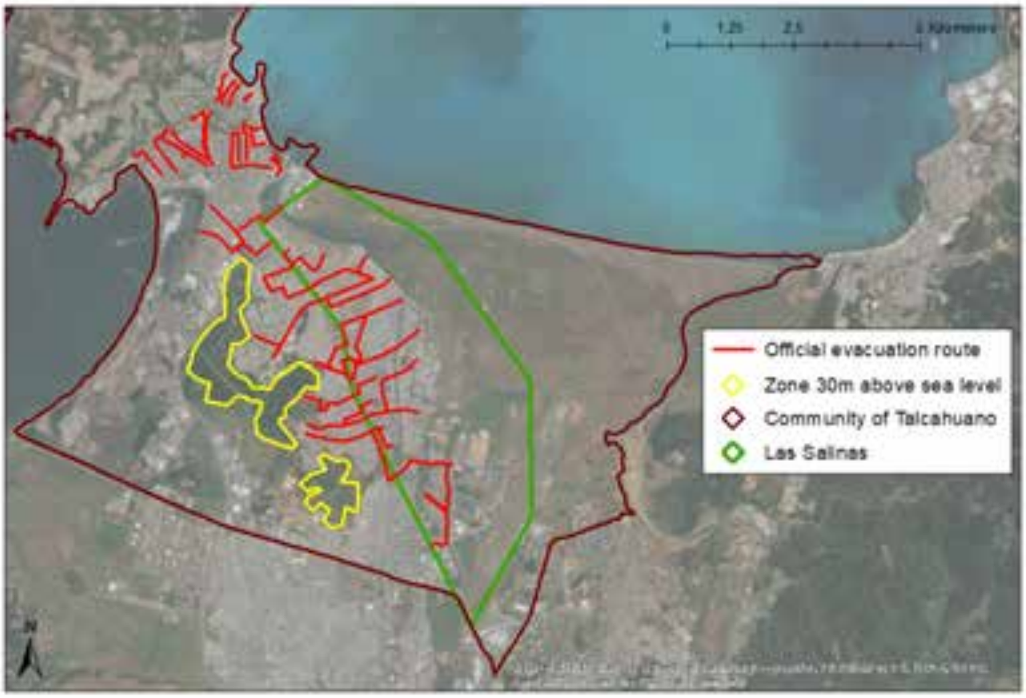

Figure 2: Official evacuation routes and zones in Talcahuano. Source: own additions based on data from Municipalidad Talcahuano (2018).

The following details are characteristics of the evacuation zones and routes of Talcahuano (see Figure 2): Evacuation zones (yellow framed area) are predominantly empty spaces and are located more or less 30 m above the sea level. An evacuation infrastructure with equipped evacuation zones is missing. The official evacuation routes and zones are marked with signs since the earthquake and tsunami of 2010. Before then, no official signposting existed (Municipalidad Talcahuano, 2018). In the following, we refer to that zone as the official evacuation zone.

METHOD

In order to analyse the evacuation process, an interdisciplinary approach was applied, combining social science and GIS simulation. We focused on the residential area of Las Salinas in the community of Talcahuano, due to the large impact there of the earthquake and tsunami event in 2010.

The research was conducted in a progressive form, the research phases were set up and linked together. Results of preceding steps were integrated in the subsequent steps. The research design can be dived in three major parts (coloured blue, green, and orange in Figure 3) with six minor phases. The first part of the social science approach represents the data collection and evaluation employing literature review, expert interviews and a standardised questionnaire. Afterwards, in the second part, a data simulation using GIS methodology was conducted. Based on the results of the preceding steps, recommendations are given.

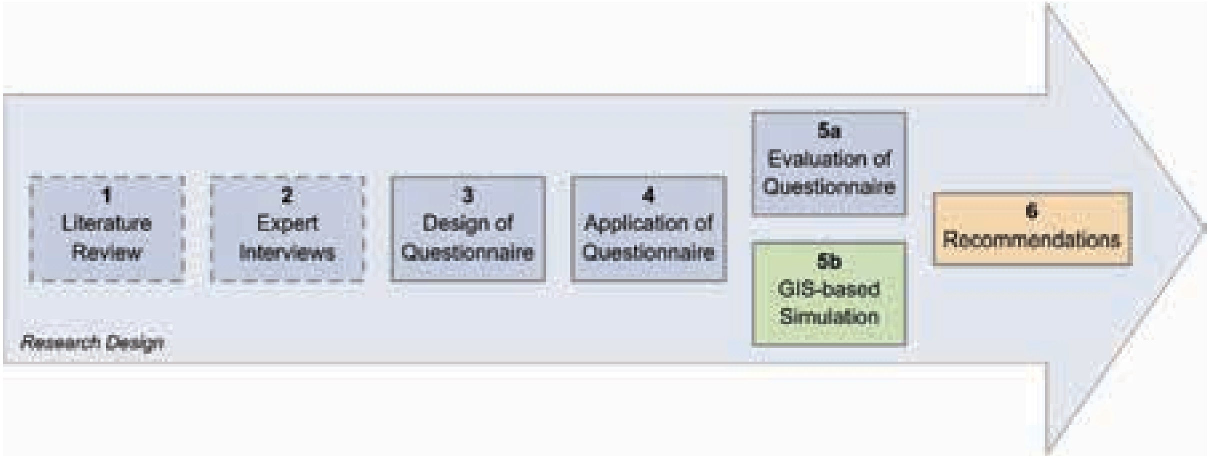

Figure 3: Overview of the research design. Steps of the social science part are highlighted in blue. The step of the GIS-based simulation is highlighted in green. Arising recommendations are highlighted in orange. Step 1 to2 in the dashed frame are not part of this paper.

Regarding the social science part of the research design, subsequent to the literature review on evacuation research, DRM, and state of the art in Chile, guided expert interviews were executed. Thereafter, Chilean experts of DRM, urban and regional planning, psychology and sociology were consulted. The results of the literature review and the expert interviews served as a basis for the design of the standardised questionnaires, which were distributed in the research area. After the application of the questionnaires, the results are statistically evaluated. The results from the marked maps, which were part of the questionnaire, were then integrated into and visualised with a GIS. In order to face the critical issues identified by means of the standardised questionnaire, further simulations were executed to perform a possible simulation by foot. On the basis of the results of both approaches, recommendation for strengthening DRM in the research area are given. In the following, the procedure of the survey, as well as the GIS simulation are explained in more detail.

The survey process

The standardised questionnaire was applied in the district Las Salinas on a household level. In total, 136 households were surveyed (N=136). The households were reached via the leaders of the *Juntas de Vecinos*, which are neighbourhood communities, uniting several times a year to discuss relevant problems and challenges within the district. The respective *Juntas de Vecinos* are spatially distributed within the district, so that the questionnaires were evenly distributed.

The questionnaire was comprised of eight parts. In the first part, socio-economic data were collected. The second part queried the experience with tsunamis and the impact on the household's property. The third and the fourth parts of the questionnaire collected data about influencing factors in the decision of evacuation and about the evacuation undertaken in the tsunami event in 2010. The fifth part requested the destination of evacuation in 2010. The sixth and the seventh parts was comprised of a combination of maps and questions. The respondents had to indicate the evacuation routes and zones they used in 2010 and respond to questions about the kind of blockages they discovered in the road network, as well as their transport medium choice. The seventh part collected data about evacuation behaviour in a possible future tsunami event, indicating possible evacuation routes and zones. The last part contained questions about the evaluation of DRM at the local and national level. The questionnaire was composed predominantly of closed questions with one or more predetermined answers possible. Respondents who did not evacuate in 2010 or had not been in the research area at the time the tsunami struck the area could mark the option "I did not evacuate".

The questionnaire, which was carried out in Spanish, was analysed with a frequency distribution using IBM SPSS Statistics 24. The results of the maps were integrated into QGIS, in order to visualise the past and future evacuation routes and zones.

GIS-based simulation of evacuation routes

For the GIS simulation, the OpenStreetMap (OSM) road network data was employed (OSM Contributers, 2018). OSM is crowd-sourced and free to use under an open license. The quality of OSM data varies between regions. A preliminary manual analysis of the road network data for the study region in Talcahuano has proven that the accuracy and completeness of the OSM data are sufficiently high.

The GIS served to evaluate and visualise the maps of the recent event-based and hypothetical future scenario of evacuation routes and zones which were marked by the respondents in the standardised questionnaire. In a further step, alternative simulations of the shortest footpaths to the nearest evacuation zones were conducted and evacuation time for walking distance to these zones was simulated for different walking speeds.

For the simulation of evacuation routes, 50 access points or roads to the evacuation zones were identified visually with the help of Google Maps satellite data. In a few cases, access points are roads that lead to the evacuation zone. In most cases, the access points to the evacuation zone are small, muddy footpaths. These points are herein called evacuation zone access points (EZAP).

The typical walking speed of pedestrians depends on multiple factors like age, disability, gender, road conditions and group size (Gates et al., 2006). In addition to these factors, the walking speed in disaster scenarios is even more unpredictable. For this simulation walking speeds were used that were observed during a simulated tsunami evacuation in Padang, Indonesia by Yosritzal et al. (2018). They observed different walking speeds for various age groups. Using their findings, three different walking speeds were applied for different age groups in this study: slow (1.35 m/s) for children under 10 years old, medium (1.4 m/s) for elderly, older than 60 years and fast (1.51 m/s) for adults between 40 and 60 years. The simulation did not consider the slope of the terrain as a factor on the walking speed.

Data on the exact location of households in Talcahuano does not exist. Thus, to obtain the starting points for the shortest path calculation to the evacuation zones, a 10 m x 10 m grid over the study region was created. The centroids of the grid cells served as starting points for the evacuation routes. Only centroids that are closer than 200 m to a road were considered for the simulation. This results in a total of approximately 180.000 starting points in the area. Then the shortest walking path via the OSM road network to the next road near an EZAP is calculated from every grid cell. For the shortest path calculation, the Dijkstra Algorithm (Dijkstra 1959) was applied. The distances from the centroid and from the EZAP to the nearest road, respectively, were added to the shortest path distance. Additionally, for every road in the network it was counted how often it is travelled. For every EZAP it was evaluated for how many starting points it is the closest.

The simulation was done using the open-source object-relational database PostgreSQL (v. 9.3) and its extension PostGIS (v. 2.3). pgRouting (v. 2.4) provides geospatial routing and other network analysis functionality. Results are illustrated with the GIS software QGIS (v. 2.18).

RESULTS

The result section is divided into two parts. According to the structure of the research design, the results of the standardised questionnaire are presented first, followed by the results of the GIS-based simulation.

Results of the survey

The results of the survey are divided into a past event and a hypothetical future scenario, and are structured in the sequence of an evacuation process, from the decision to evacuate to the arrival at the destination of evacuation. The results are based, as mentioned before, on N=136 households surveyed.

According to the results of the survey, in 2010 72.1% of the respondents evacuated, 22.8% of the interviewed person decided against evacuation or had not been in the research area at the time of the earthquake, and 5.1% did not answer the question.

The respondents were asked to indicate which factors they considered in their decision to evacuate *(multiple answers possible).* The majority specified the intensity of the previous earthquake (58.8%) as critical for the decision to evacuate. Further factors relevant for the decision were the distance to the evacuation zone (23.5%), availability of a car (19.1%), withdrawal of the sea (16.2%) and the evacuation of family and neighbours (14.7%). All relevant factors are illustrated in Figure 4.

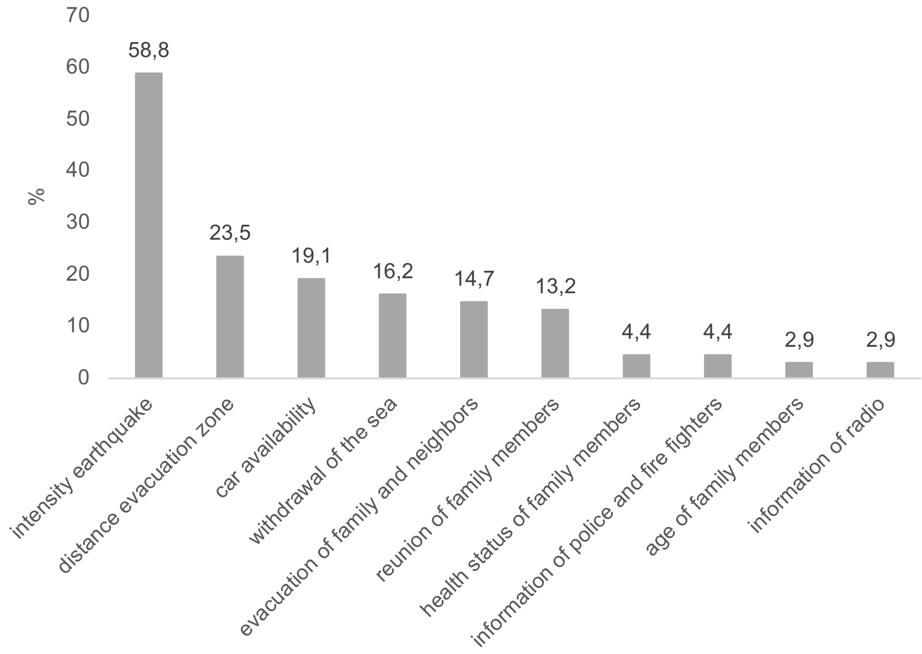

Figure 4: Factors of the decision of evacuation in 2010.

To decide whether to evacuate or not, 30.9% of the respondents indicated to have needed up to 5 minutes, 21.3% up to 10 minutes, whereas 10.3% took more than 25 minutes for their decision (Figure 5).

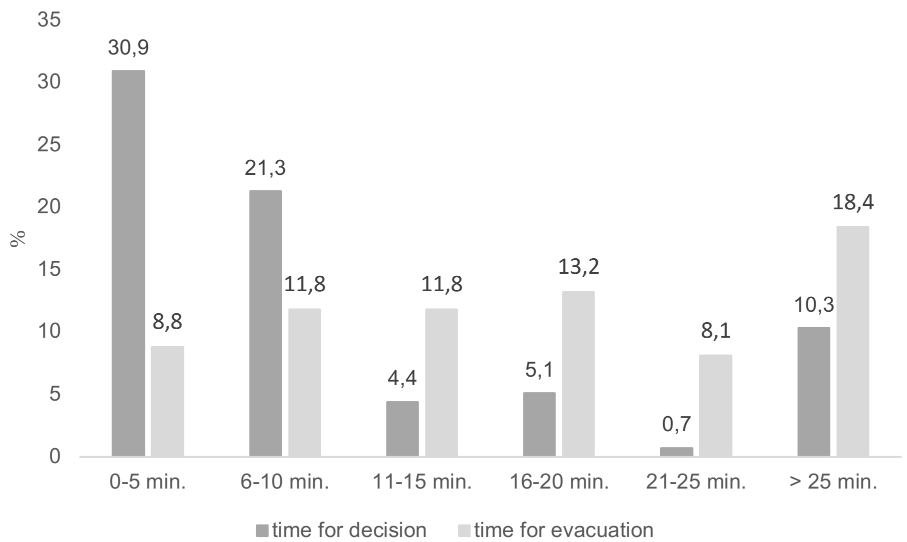

Figure 5: Time of decision-making and evacuation in the event 2010.

As a next step after making the decision to evacuate, 33.1% of the respondents collected equipment essential for survival, 27.2% tried to reunite their family and 19.9% tried to communicate with their family, and 14.7 % with their neighbours. Only 8.1% tried to get information from authorities *(multiple answers possible)*.

Finally, 59.6% evacuated with their whole family. In a hypothetical future scenario, if the family would not be together *(multiple answers possible)*, the majority (71.3%) indicated they would evacuate with present family members. Another 27.2% indicated they would bring together all family members and 27.2% retrieve their children from kindergarten or school.

The primary transport medium for evacuation in 2010 was the private car with 52.2%, and only 17.6% indicated having evacuated by foot. The primary reason for choosing the car was speed (26.5%), followed by the presence of children and older adults (24.3%). Further, the distance to the evacuation zone (20.6%) and the possibility to overnight in the car (18.4%) were mentioned. Expected blockages and congestion (10.3%) in the road network was the fifth most common answer *(multiple answers possible)* (Figure 6).

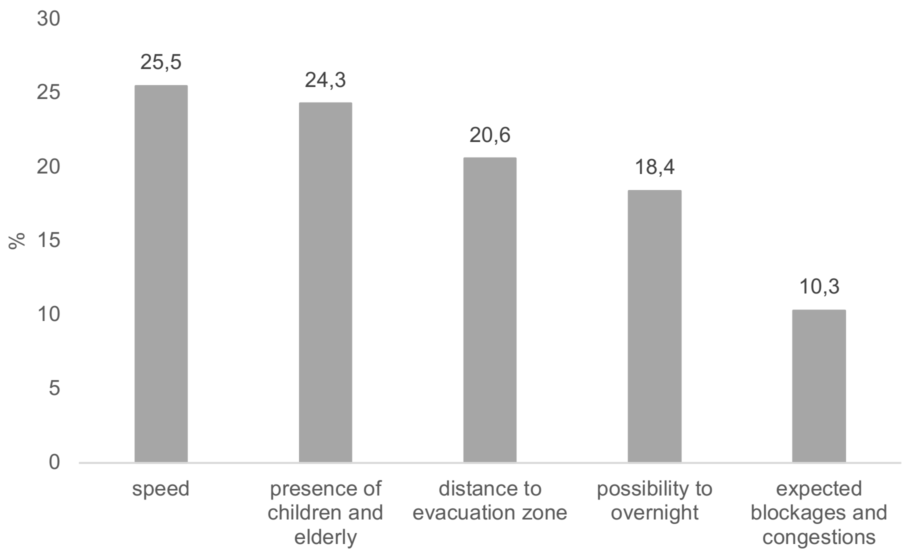

Figure 6: Reasons for the choice of transport medium.

Asking the respondents for a hypothetical future scenario, 46,3% indicated they would evacuate by car, while almost the same number (43,4%) would evacuate on foot.

Most of the evacuees (18.4%) needed more than 25 minutes to reach a safe destination, and many more needed up to 20 minutes (13.2%). Only a minority (8.8%) indicated to have needed as little as 5 minutes (Figure 5). The main reasons for the amount of time needed to evacuate were blockages (47.1%) in the road network and the distance to the evacuation zone (22.8%). The roads were mainly blocked by congestion (39.7%), persons in the street (38.3%), parked cars (21.3%) and debris (14.7%) due to the preceding earthquake *(multiple answers possible)*.

Figure 7 illustrates the evacuation routes and zones in 2010 (left) and in a hypothetical future event (right), which were indicated by the respondents on the maps. The thicker a street is highlighted the more evacuees have used it in 2010 or would use it in a hypothetical future event.

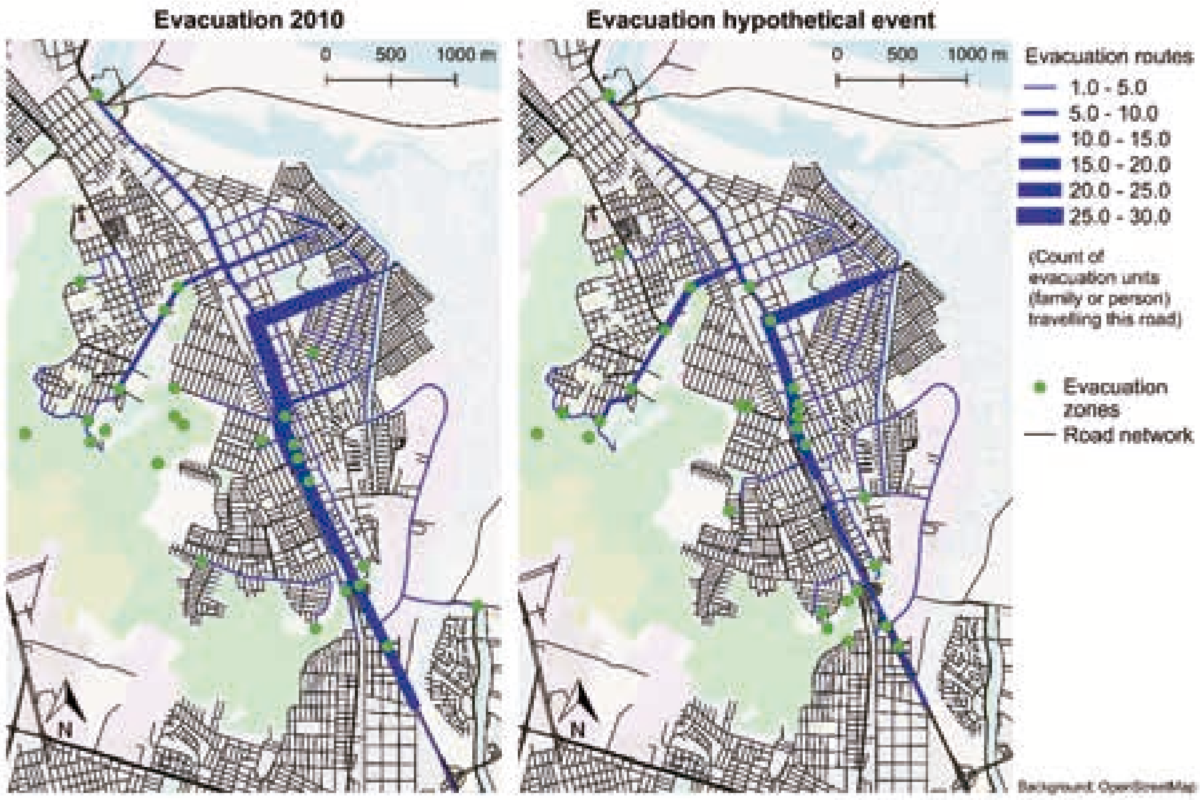

Figure 7: Evacuation routes and zones in 2010 (left), and in a hypothetical future event (right).

The majority of the evacuees indicated that they chose the route for evacuation that they are most familiar with (42.6%), or the route they consider to be the safest (17.6%), or is the shortest route to the evacuation zone (11.8%). Estimated congestion and blockages (9.6%) were not that relevant in evacuation route choice. In a hypothetical future scenario, the main reason for evacuation route choice is familiarity (58.1%). The evaluated distance to the evacuation zone (30.9%) and route security (20.6%) gain in importance for the choice, as does congestion and blockages (22.8%) *(multiple answers possible)* (Figure 8).

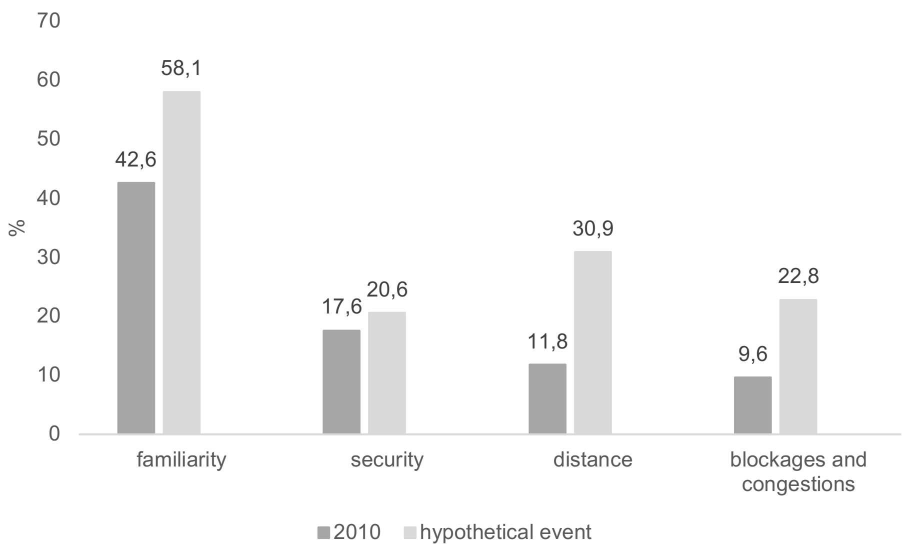

Figure 8: Reasons for the choice of the evacuation route in 2010 and in a hypothetical future event.

Regarding the destination for evacuation in 2010, most of the respondents indicated that they chose a nearby hill for evacuation (52.2%) or went to family or neighbours (8.8%). Reasons given were mainly the proximity to the house (26.5%) and accessibility (25.7%) *(multiple answers possible)*. In a hypothetical future scenario, the respondents indicated that they would go to the evacuation zones in Figure 7. Reasons are in particular the evaluation of the security of the zone (30.9%), the proximity to the house (30.1%), and evacuation zones which are recommended by authorities (22.1%). Also, accessibility (16.2%) would play a role in the choice. Recommendation by friends and family members (11%), as well as crowdedness (11%) would play a subordinate role. The facilities (shelter etc.) at the evacuation zone (2.9%) are rarely critical for the choice *(multiple answers possible)*.

Many respondents drove outside the community in 2010, so some evacuation zones are located outside the map extract in Figure 7 (left).

Results of the GIS-based simulation

The results of the walking time estimation for the three walking speeds described above are presented in Figure 9. A total area of circa 19.2 km^2 in Las Salinas was simulated. With a slow walking speed, 46.5% of the area needs an evacuation time over 15 minutes. With a medium walking speed, this decreases to 45.5% and to 43.3% with a fast walking speed. A small percentage (of 9.6% at slow speed, 7.4% at medium speed, and 4.2% at fast speed) of the area takes longer than 30 minutes (red marked area) to evacuate by foot. These results base on the assumption that the evacuees follow the shortest path to the nearest evacuation zone.

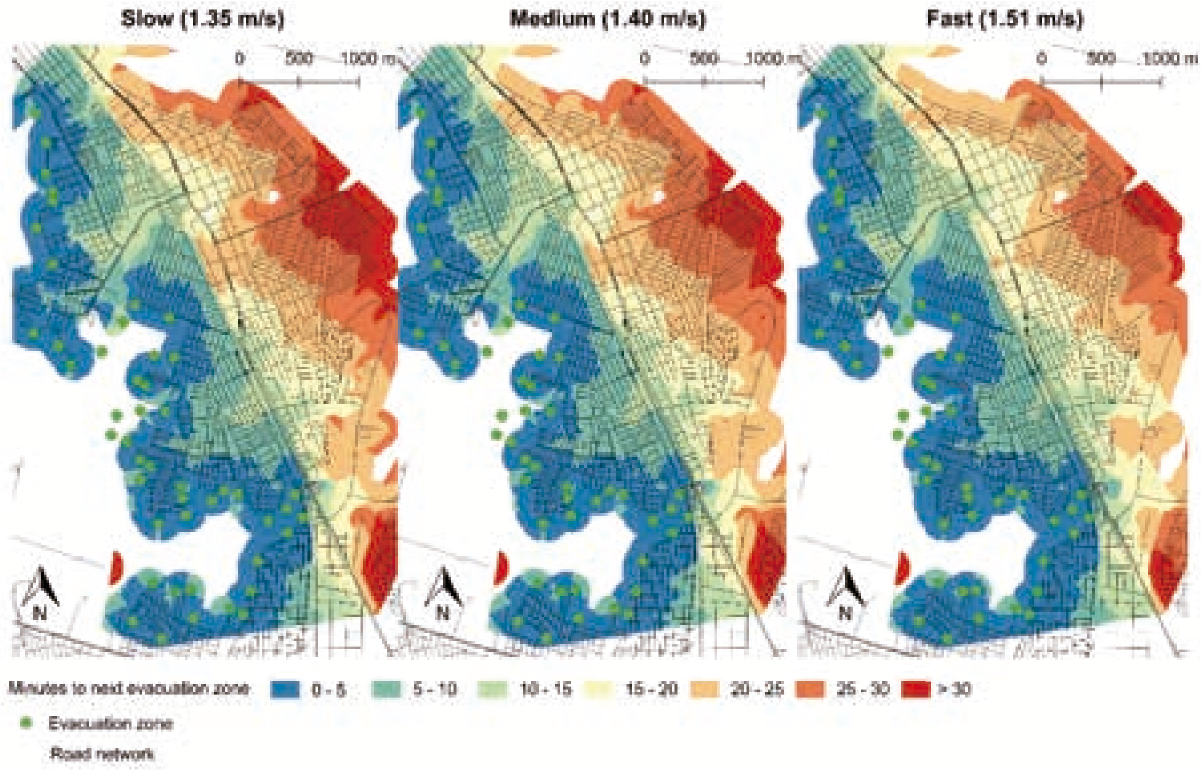

Figure 9: Evacuation times in minute for slow, medium and fast walking speed.

Figure 10 illustrates which roads and which EZAP are most used for evacuation. In total, 192.249 shortest evacuation paths were calculated. The four most often used EZAP are the nearest EZAP for 57% of the area.

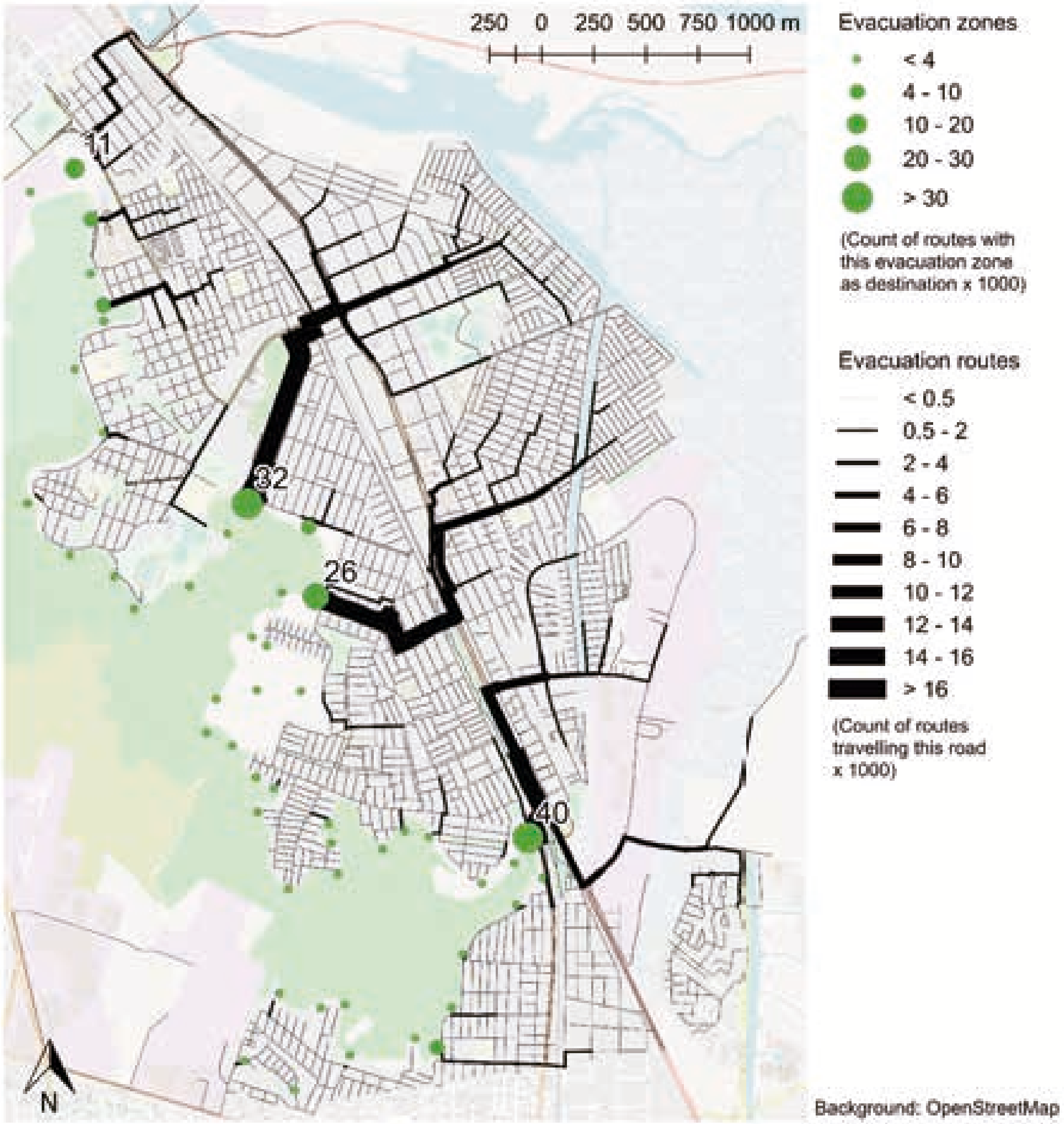

Figure 10: Most used evacuation routes and evacuation zones in Las Salinas.

Figure 10 reveals three main evacuation corridors for the inhabitants of Las Salinas.

DISCUSSION

The results of the case study reveal that irrespective of a lack of official information and the all-clear of a tsunami by responsible authorities in 2010 (Rojas et al., 2014), the majority of the respondents evacuated mostly because of the intensity of the prevenient earthquake. This behaviour may arise out of risk awareness due to past experiences.

However, despite the autonomous response of the affected population, the reported time needed for evacuation in 2010, which was a combination of the time taken for decision-making, actions for preparing the evacuation, and travel to the evacuation zone, was critical, bearing in mind that the first tsunami waves arrived 12-20 minutes after the earthquake in some coastal locations (Vargas et al., 2011). Although the majority decided within 5 minutes whether to evacuate or not, 10.3% indicated to have taken more than 25 minutes for the decision, a time period which might be critical in a hazardous event, in which time for response is limited. The delay in decision-making may be traced back to uncertainty, due to the all-clear of tsunami by responsible authorities (Rojas et al., 2014). This delay is even longer when summing up time needed to prepare for the evacuation, including reuniting family members. Although it did not pose a problem in 2010, because the tsunami took place at night and in vacation time when most of the family members were together, the reunion of the family might become a critical issue in a hypothetical future scenario. The results revealed that the respondents would pick up their children from kindergarten or school, which both increases the time needed for evacuation and might lead to blockages of street sections due to congestion by contraflow, which might even be directed into the hazard-prone area, where many kindergartens and schools are located. Consequently, increasing traffic volume might additionally raise total evacuation time, from leaving the home until the arrival at the evacuation zone, which already took more than 25 minutes in most of the cases in 2010. Besides congestion due to car use as main transport medium, the distance to the evacuation zone posed a critical issue in evacuation time in 2010.

In order to reduce evacuation time due to congestion by car use, a GIS simulation was executed, identifying the shortest possible footpaths to the nearest evacuation zones (Figure 9). The simulation considered walking speeds of different age groups. The results demonstrate that at the east end of the research area, more than 40% of the evacuees of the area, in each speed category, would need more than 15 minutes to evacuate by foot. Consequently, the evacuees would not make it walking to the nearest evacuation zone before the first tsunami waves arrived. In 2010 the first tsunami waves arrived in some coastal locations after a few minutes. Additionally, 9.6% of the area for slow walking speed, including children under 10 years and 7.4% of the area for medium walking speed, would need more than 30 minutes to evacuate to the nearest evacuation zone. Consequently, the preference for use of the car as transport medium in evacuation in the research area becomes understandable. The indicated reasons for car use in the questionnaire, which are velocity, the presence of children and seniors and the distance to the zone, reinforce these findings. Although according to the indications the number of evacuees evacuating by foot would increase in a hypothetical scenario compared to 2010, more than half of the respondents indicate they would evacuate by car. Another reason that favours the evacuation by foot is the accessibility to the evacuation zones, since the roads are in most of the cases muddy footpaths and blocked by fences which could not be passed by car.

Comparing the evacuation route and zone choice in both scenarios (Figure 7), the main road, which crosses Talcahuano from south to north and leads outside of the community, is the primarily road chosen for evacuation. Comparing the roads chosen in the past and the hypothetical future scenario, they do not coincide with the official evacuation routes, which lead up the hills to the yellow framed evacuation zone in Figure 2, even when 22.8% indicate that the recommendation of the evacuation zone by authorities is relevant for future choice. Also, the factor of proximity to the evacuation zone gains in importance in a future scenario, however the majority would evacuate to zones outside the community according to the indications in the map. This may argue for a lack of knowledge of official evacuation routes and zones. On the other hand, knowing that the main reason for route choice is the familiarity with the route, it becomes understandable. Official evacuation routes lead just up to the hills, where no infrastructure for daily needs is located and land use is mostly dedicated as residential area. In contrast, the main road leads outside the community in direction to the next biggest city Concepción, which provides infrastructure for daily needs and workplaces. Expected congestion and blockages influenced the choice to a small degree in 2010; however, the importance of this factor in route choice gains importance in the hypothetical future scenario. Nevertheless, despite the awareness of possible congestion, the respondents indicated the same route in a hypothetical scenario.

Furthermore, as the distance of the evacuation zone was a major factor in transport medium choice, in order to detect if evacuating by foot would be an alternative, the shortest paths for walking out of the inundation zone to the nearest evacuation zone have been simulated. The simulation results show three main evacuation corridors and one minor evacuation corridor (Figure 10). Four major access points to evacuation zones are identified, which serve as a destination for 57% of the shortest evacuation routes. However, it has to be noted that these identified evacuation zones are just empty areas up the hill, which do not provide shelter and are not equipped with essential supplies like beds, food, water and medicine for evacuees. Additionally, if all households would evacuate to these areas, the capacity might be exceeded. Furthermore, the nearest paths which lead to the identified zones are particularly small muddy roads which are not paved and may not satisfy the demand in case of evacuation. Additionally, fences of private estates and the trail rail line along the main road might hinder evacuation to these zones. Examining the results of the shortest paths, those do not coincide with the results in the standardised questionnaires for the hypothetical and past scenario (Figure 7). However, they coincide with the official evacuation routes Figure 2. Furthermore it has to be acknowledged that those evacuation zones will not be reachable for all evacuees in a short time period (see Figure 9).

CONCLUSION AND RECOMMENDATIONS

This research points out three critical issues in evacuation, identified by an analysis of a past and a hypothetical future event, integrating the affected population by means of a standardised questionnaire. These issues, namely evacuation time, distance to the evacuation zone, transport medium choice and congestions in the road network, are underpinned by the results of the GIS simulation.

The research highlights that these critical issues identified depend on one another. Given that the evacuation zones on the hills are, according to the indications in the questionnaire, too far away, the main transport medium in evacuation was and will be the car. This is fortified by the GIS analysis, which illustrates that the evacuation zones are particularly not reachable within a few minutes by foot. Familiarity was the main reason for route choice. Most of the evacuees used and will use the main road, which they use daily, resulting in congestions which increases time needed for evacuation starting from leaving the house to reaching the evacuation zone. Consequently, if the urban environment will not be adapted to the case of evacuation, e.g. build evacuation zones within the research area (see f. e. Ramos, 2016), it is questionable if in a future event, transport medium choice will change. Hence, time delay in evacuation will continue and may even be aggravated by the fact, that if a future event happens on a weekday during the day, a high percentage of the population will first pick up their children from kindergarten and school. Furthermore, the official evacuation zones on the hills, which are also identified in the GIS simulation, modelling the shortest path to the nearest evacuation zone, are not equipped with shelters and supplies like water, food, medicine and beds and are sometimes only reachable by small muddy footpaths with impediments like railroad lines or fences of private estate, which might also be a reason for not using the evacuation routes and zones heading to the hills. Even if evacuating by foot would be promoted, the nearest evacuation zones, identified in the GIS simulation, would not satisfy the capacity needed for the number of evacuees. Further, it has to be considered, that the car also provides a shelter in case of evacuation.

In order to alleviate the critical issues identified, we recommend short- and long-term measures to strengthen DRM at local level. As a short-term measure, raising awareness regarding transport medium and evacuation route and zone choice, we recommend workshops for the affected population, which would be guided by the leaders of the *Juntas de Vecinos* and local authorities responsible for DRM and urban planning. In these workshops the critical issues in evacuation, time delay, transport medium and evacuation route and zone choice should be discussed. At the end of the workshops, every household should be provided with an emergency kit and a family emergency plan, which includes strategies in evacuation. The latter should include where to meet absent family members, and which evacuation route and zone to use. The distribution of evacuation routes and zones within the *Juntas de Vecinos* should alleviate traffic flow in evacuation. These workshops should be repeated once a year, so that changes in the urban environment and human behaviour can be considered. Furthermore, the results of the workshops could be integrated in an online platform of the municipality, in order to be available for daily use to the community. The online platform should be updated by the responsible disaster managers and enriched with data of further municipality departments, such as road construction.

In order to promote evacuation by foot in the long-term, as pointed out in this research, hard measures are needed. The urban environment has to be adapted to the necessities in the case of emergency. Besides the signage of the designated evacuation routes and zones in the workshops with the *Juntas de Vecinos*, the evacuation zones have to be equipped with shelters, which would provide capacity for a certain number of evacuees and provide essential supplies. Additionally, this paper provides (see Figure 10) the nearest footpaths in the research area to the nearest evacuation zones on the hills. However, the accessibility to these zones has to be improved, removing impeding elements like fences. Furthermore, evacuation routes have to be paved and extended if necessary. Further, experts have to be aware of the scarce capacity of the nearest zones identified in this research, as they have to accommodate more than 57% of the households. Consequently, alternative routes and zones have to be provided. If evacuation by foot should be promoted, the long-term measures are indispensable. Those include as well possibilities for vertical evacuation in Las Salinas (see f. e. Ramos, 2016), given that the residents at the east end of the area would not make it walking in case of a near-field tsunami. The same is valid for families with children and seniors.

Additionally, in order to avoid counter-evacuation traffic flow, it is recommendable to relocate kindergartens and schools to evacuation zones. Furthermore, these might provide shelters in case of emergency and consequently have a multifunctional use.

This research highlights the necessity of the combination of a social science approach and GIS simulation, integrating the affected population. As the research showed, the standardised questionnaire provides insight into critical issues in a past event-based and a hypothetical future scenario. The GIS-based simulations integrate on the one hand the results of the questionnaires and provide on the other hand results of the evacuation by foot. Thus, critical issues detected by the questionnaire are faced and underpinned. The combination of the results ensures an effective evacuation planning. Disaster managers and urban planners might benefit from the results. Of course both approaches have limitations. Since the event in 2010 was seven years before the research was executed, the respondents to the questionnaire might not remember every detail of the evacuation. Additionally, the indication for the future scenario is hypothetical, so that the results contain assumptions about future choices. A limitation of the GIS simulation is that the topography of the research area, which might influence walking speed, is not considered.

Future research may consider the advantages of the application of interdisciplinary approaches, but also consider the limitations which are discussed above. The research design applied in this study can be transformed to other Chilean coastal communities, as they face similar problems and share the same social, ecological and political background. In order to apply this approach to other countries and other natural disasters, the specific context has to be considered, and the social science approach, especially the standardised questionnaire, has to be adapted to this context. It would be interesting to integrate further data collected by the standardised questionnaire, like the period of time in which the evacuation started. A (multi-)agent-based system might consider this valuable data and also consider the critical issue of contraflow, fetching the children from kindergarten and school (f.e. Mas et al., 2012).

Evacuation reduces the risk for the affected population during natural disasters, however, the evacuation might be more effective, if time delays and congestions are considered in preparation measures and strategies of DRM. Therefore, it is argued that a more detailed analysis can only be conducted if the strengths of different scientific approaches are combined, analysing human behaviour in the evacuation process as well as investigating the linkages to the road network and the urban environment, which play a crucial role in evacuation.

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