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The contribution of tsunami evacuation analysis to evacuation planning in Chile: Applying a multi-perspective research design

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ABSTRACT

Research on evacuation behavior in natural disasters provides a valuable contribution in the development of effective short- and long-term strategies in disaster risk management (DRM). Many studies address evacuation simulation utilizing mathematical modeling approaches or GIS-based simulation. In this contribution, we perform a detailed analysis of an entire evacuation process from the decision to evacuate right up to the arrival at a safe zone. We apply a progressive research design in the community of Talcahuano, Chile by means of linking a social science approach, deploying standardized questionnaires for the tsunami affected population, and a GIS-based simulation. The questionnaire analyzes evacuation behavior in both an event-based historical scenario and a hypothetical future scenario. Results reveal three critical issues: evacuation time, distance to the evacuation zone, and method of transportation. In particular, the excessive use of cars has resulted in congestion of street sections in past evacuations, and will most probably also pose a problem in a future evacuation event. As evacuation by foot is generally recommended by DRM, the results are extended by a GIS-based modeling simulating evacuation by foot. Combining the findings of both approaches allows for added value, providing more comprehensive insights into evacuation planning. Future research may take advantage of this multi-perspective research design, and integrate social science findings in a more detailed manner. Making use of invaluable local knowledge and past experience of the affected population in evacuation planning is likely to help decrease the magnitude of a disaster, and, ultimately, save lives.

1. Introduction

Tsunamis triggered by a preceding earthquake are classified as low-probability events. Events like the Indian Ocean Earthquake and Tsunami 2004, the Maule Earthquake and Tsunami in Chile 2010, and the 2011 Tohoku Earthquake and Tsunami illustrate how huge their impact on human life and infrastructure can be [1–3]. Reminders of the tsunami in the Indian Ocean in 2004 demonstrate the destructive potential of tsunamis and their spatial impact far beyond international borders. During this event, some 230,000 people lost their lives. The city of Banda Aceh, Indonesia, which was one of the closest to the epicenter, suffered the greatest number of fatalities and missing persons. One of the attributing factors for the number of fatalities in the affected countries in 2004, apart from the short time lapse between the earthquake and the arrival of the first tsunami waves, was notably the lack of knowledge and awareness of the population. Put simply, the fact that no evacuation took place in a timely manner, proved fatal [4]. Indigenous communities, however, experienced a lower fatality rate, as they self-evacuated following their experience of the preceding earthquake [5]. Another reason for the high fatality rate among non-indigenous communities was a lack of early warning due to intergovernmental and interinstitutional communication failures among the affected countries [6]. Further issues were the particularly flat terrain, and the missing evacuation infrastructure [6–8].

Considering the evacuation of the Maule Earthquake and Tsunami in Chile in February 2010, a very similar set of failures also led to disaster.

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During the night of February 27th, an 8.8 Mw earthquake struck central Chile, triggering a tsunami, which affected 800 km of the coastline [3]. The first tsunami waves arrived 12 min later in some coastal locations [9]. Failures in communication between the responsible institutions in combination with a poorly designed evacuation infrastructure were identified as the central weaknesses in disaster risk management (DRM) [10–12]. According to the Chilean government, more than 12.8 million people were affected socio-economically, and 521 people were killed [13]. The relatively low number of deaths might be ascribed to awareness of tsunami among the population. Most of the affected population evacuated autonomously after the intense earthquake without official support [14,15].

The previous examples highlight that in addition to the awareness of the population [14–16], well-organized and rapid evacuation is crucial to save lives in rapid-onset disasters [17–19]. During tsunami events, it is essential that the affected population is able to perform evacuation autonomously, without official guidance. This is particularly important as failures in road infrastructure and the breakdown of communication systems as a possible result of a preceding earthquake might hinder institutions responsible for DRM and emergency services in their support [10,18,20]. As human behavior has been identified as a key issue to minimize the impact of natural hazards, the details of human behavior in evacuation processes need to be looked at and meticulously analyzed (c.f. [17]).

Previous studies have identified various factors, which influence the fatality rate in tsunami events, and which are important for evacuation research. These factors can be placed into four categories and be divided into physical and social characteristics [21–23]:

(1) Characteristics of the tsunami (e.g. arrival time and inundation depth),
(2) Characteristics of the terrain (e.g. slope and land elevation),
(3) Characteristics of tsunami mitigation measures (e.g. evacuation routes and zones, and DRM),
(4) Personal characteristics (e.g. awareness of tsunami and knowledge of evacuation routes and zones, mental and physical ability).

Categories 1, 2 and 3 are often considered in evacuation research focusing on modeling approaches, especially GIS-based approaches and agent-based modeling (ABM) [24–26]. Personal characteristics are frequently considered with regards to evacuation speed (see e.g. Ref. [27]), and are mainly based only on estimations (e.g. Ref. [26]), as stated also by Lindell & Prater (2007) [28]. Only a few modeling approaches integrate empirical data obtained by questionnaires (e.g. Ref. [23]). Estimation, often without consideration of specific local conditions, might lead to inadequate results for evacuation behavior regarding evacuation time and route choice. Social science research (e.g. Refs. [29–31] provides valuable results on personal characteristics (4) concluded from an event-based analysis of human behavior. The involvement of the affected population, taking advantage of their unique local knowledge and their experience, might provide scientists with additional results, which go beyond scientific theories, as shown by many studies in the field of Community Based Disaster Risk Management [32,33]. Consequently, apart from the need to combine different scientific perspectives, the integration of the local population in data collection helps to model human behavior in evacuation more accurately [17,34,35].

In order to create the basis for effective short- and long-term evacuation planning, we apply both a standardized questionnaire and a GIS-based modeling approach in a multi-perspective research design. The research was performed in the community of Talcahuano, Chile, with a focus on the Maule Earthquake and Tsunami in 2010 and on a hypothetical future tsunami event. Some of the results were taken up by Kubisch et al. (2019) [17] with a different focus.

The main objectives of the present study are as follows:

- To give a brief introduction to relevant evacuation research so far,
- To demonstrate the contribution of a detailed evacuation analysis to evacuation planning,
- To point out the value of the integration of knowledge and experience of the local population in form of a case study,
- To demonstrate the added value of a social science approach in combination with a GIS- based modeling approach for evacuation planning,
- To focus on a different socio-cultural background as compared to previous studies, of which few analyze evacuation in South America,
- Based on the results, to give recommendations for short- and long-term measures for evacuation planning and thus, ultimately, contribute to saving lives in a possible future event.

The following section 2 gives insight into the research area, and considers evacuation problems in past tsunami events in Chile. Section 3 reviews recent evacuation research, and presents modeling approaches as well as social science approaches in this field. In section 4, the research design and methods are explained. Section 5 is dedicated to the results. Section 6 is the discussion, and, based on the results, also provides recommendations for both short- and long-term measures. Section 7 concludes the study.

2. The research area: the community of Talcahuano, Chile

The high seismicity of Chile was demonstrated with the Maule Earthquake and Tsunami in February 2010 [36]. The reason why Chile is continuously stricken by earthquakes of lower and higher magnitude is that it is located at the plate boundaries of two highly active tectonic plates: the oceanic Nazca Plate and the continental South American Plate. Consequently, Chile is one of the countries most prone to earthquake and tsunamis worldwide [37–39].

In the earthquake and tsunami event in 2010, the two most populated areas in Chile were also the most affected ones, the metropolitan region of Santiago de Chile and the conurbation of Concepción-Talcahuano within the central region of Bio-Bío [13,40,41]. Fig. 1 shows the tsunami risk area of Talcahuano, based on a simulation by the University of Bío-Bío after the tsunami in 2010 [42]. Due to the low ground elevation of the terrain between 5 and 10 m above sea level, and run-up heights up to 8 m, an area of 11.04 km^2 up to 1 km inland was affected by four registered tsunami waves [12,43]. The first wave arrived at approximately 3:30 a.m. local time in Talcahuano, and the fourth and strongest wave about 3 h later. In total, 18.1% of the inhabitants of the community were affected, and, according to the national institute of statistics, 9137 houses were destroyed by the earthquake and tsunami [12,44,45].

The first tsunami wave has been reported as arriving some 12–20 min after the earthquake, with the second following 30–45 min later [9], the relatively low number of deaths might be ascribed to awareness among the population. As already mentioned, most of the affected population evacuated autonomously after the intense earthquake without official support, and despite the ONEMI (Oficina Nacional de Emergencia del Ministerio del Interior y Seguridad Pública), issuing a tsunami 'all clear' [10,11]. The ONEMI reaches from national to regional level, but at the local level there are no ONEMI offices. According to Rojas et al. [11], the tsunami all clear gave rise to a lack of trust in the authorities responsible for DRM, and approximately 87% of the respondents indicated they would not to be willing to follow the advice of DRM in a future event.

During this event and in subsequent natural-hazard events only a small percentage of the population left the area on foot, the significant majority made their escape in private vehicles. This resulted in congestion on the roads and many accidents which, in turn, hindered the speed of the evacuation [17,20,46–48].

Before the event in 2010, no officially marked evacuation routes and zones existed. Even nine years after the event, the evacuation

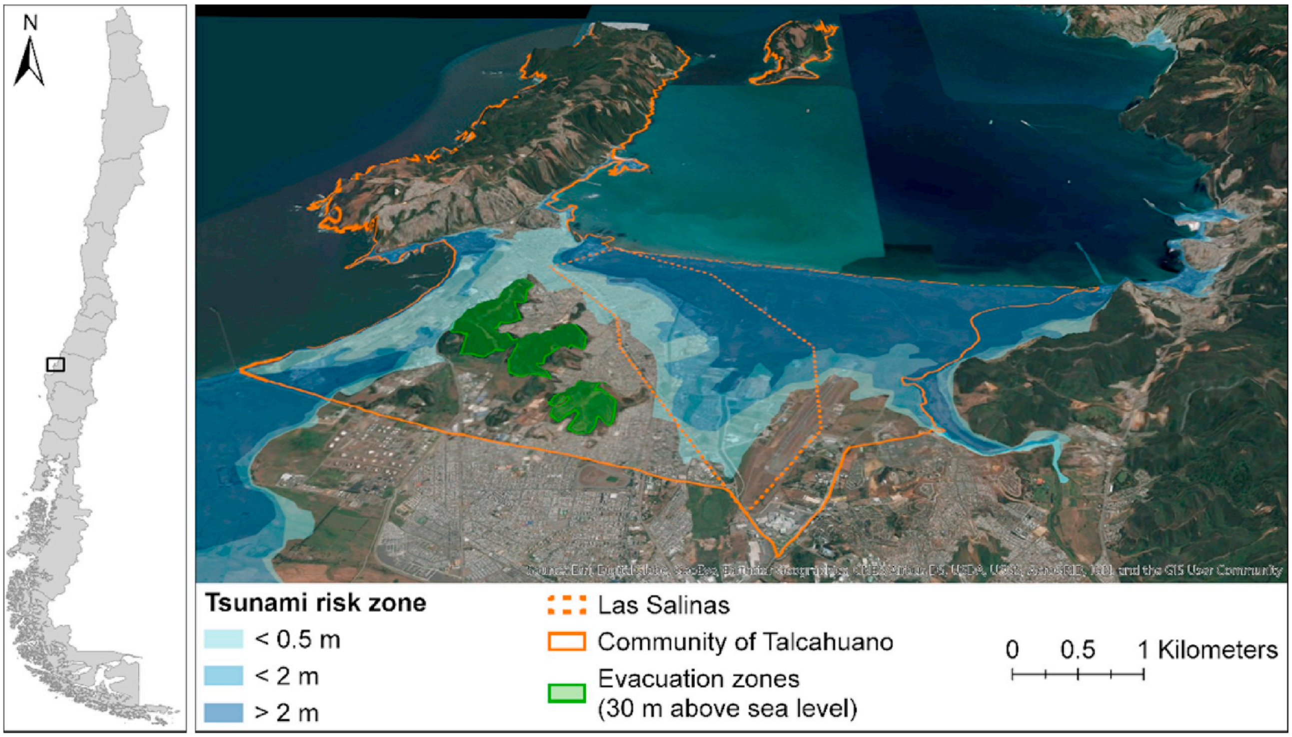

Fig. 1. Map of Chile (left hand side), the community of Talcahuano, including the research area of Las Salinas (orange frame) and the tsunami risk area (right hand side).

infrastructure is poorly designed. Officially designated evacuation zones (Fig. 2, green framed area) are mostly open landscapes at ca. 30 m above sea level without any shelters or helpful equipment. Official evacuation routes are shown in white in Fig. 2 [49].

3. Brief introduction into evacuation research

The tsunami events that have taken place in the recent past (Indian Ocean 2004, Chile 2010, Japan 2011) demonstrate the importance of evacuation planning and its fundamental contribution to an effective DRM. Modeling approaches simulating tsunami events have contributed to the understanding of this natural phenomenon [50]. However, recent natural disasters have shown the importance of integrating social factors, which strongly influence the consequences of a disaster. Thus, social sciences contributions leading to a more holistic picture of evacuation research should be intensified [17–19,26,34].

GIS-based evacuation research focuses mostly on evacuation time simulation, and simulations of the shortest path to the nearest evacuation zone. These approaches are easy to implement, and do provide valuable results, like route optimization by foot or evacuation time. Consequently, they contribute to evacuation planning, especially, evacuation route planning. Péroche et al. [25], for example, simulated the accessibility of evacuation zones, which are reachable within 15 min walking distance, using the shortest-path analysis (for further description see section 4.2). A detailed analysis of evacuation time and optimal evacuation routes as well as a tsunami vulnerability assessment in El Salvador, Central America was given by González-Riancho et al. [51]. They used the closest-facility analysis (network analyst, ArcGIS 10.1). Freire et al. [52] applied a cost-weighted distance approach in order to obtain the fastest evacuation route from any given location to an evacuation zone. In addition to the time needed for traveling these roads, they analyzed the exposure of people in a day-time and night-time scenario for the city of Lisboa, Portugal.

Recent advances to integrating event-based social science findings as model parameters are agent-based modeling (ABM) approaches. ABM also includes survey results as input parameters. Revealed-preference surveys and stated-preference surveys are considered. The former are based on actual travel or evacuee behavior based on experience, while the latter refer to hypothetical future behavior [34,53]. Further ABM approaches based on estimation about evacuee behavior or the origin of empirical input data are not mentioned [28]. In agent-based approaches, each individual is part of a system and is considered to be an autonomous decision-making unit in modeling evacuation. Each of these units follows special rules, like choosing the shortest path to evacuate, and can behave in various manners. The development of a macro description of the system, based on an emerging evacuation, results from the interacting units [26,34,54]. Therefore, interactions of units, for example, a community's behavior in evacuation, can be visualized, and resulting problems of these interactions, like congestions in the road network or casualties, can be detected [34]. Model parameters integrated in the simulation are, in particular, evacuation timing, route preference, speed and shelter demand. Some models considered car use, while others model pedestrians' behavior [26,54]. As time is critical in evacuation, some models were based on the assumption that all units evacuate at the same time [55,56], and others considered the evacuation of smaller groups at different points in time [57,58]. Determining timing in evacuation, further approaches included psychological characteristics from surveys, and every unit was considered individually, which might be an obstacle to simulating big populations [59,60]. Others, like Lindell and Prater derived evacuation starting time from sigmoid curves, which describe the populations' behavior [28].

Earliest works on social science research as well a large part of social science research today have been locally limited to the United States and have remained focused on hurricane evacuation behavior (e.g. Refs. [61–64]. Kang et al. [63], for example, compared respondents' evacuation expectations with their actual behavior two years after Hurricane Lili had struck the USA. Variables investigated were, amongst others, information sources, transport medium, evacuation preparation time and shelter type. Sadri et al. [61] investigated transport medium choice in a hypothetical Hurricane 4 Scenario in the USA. In recent research, a

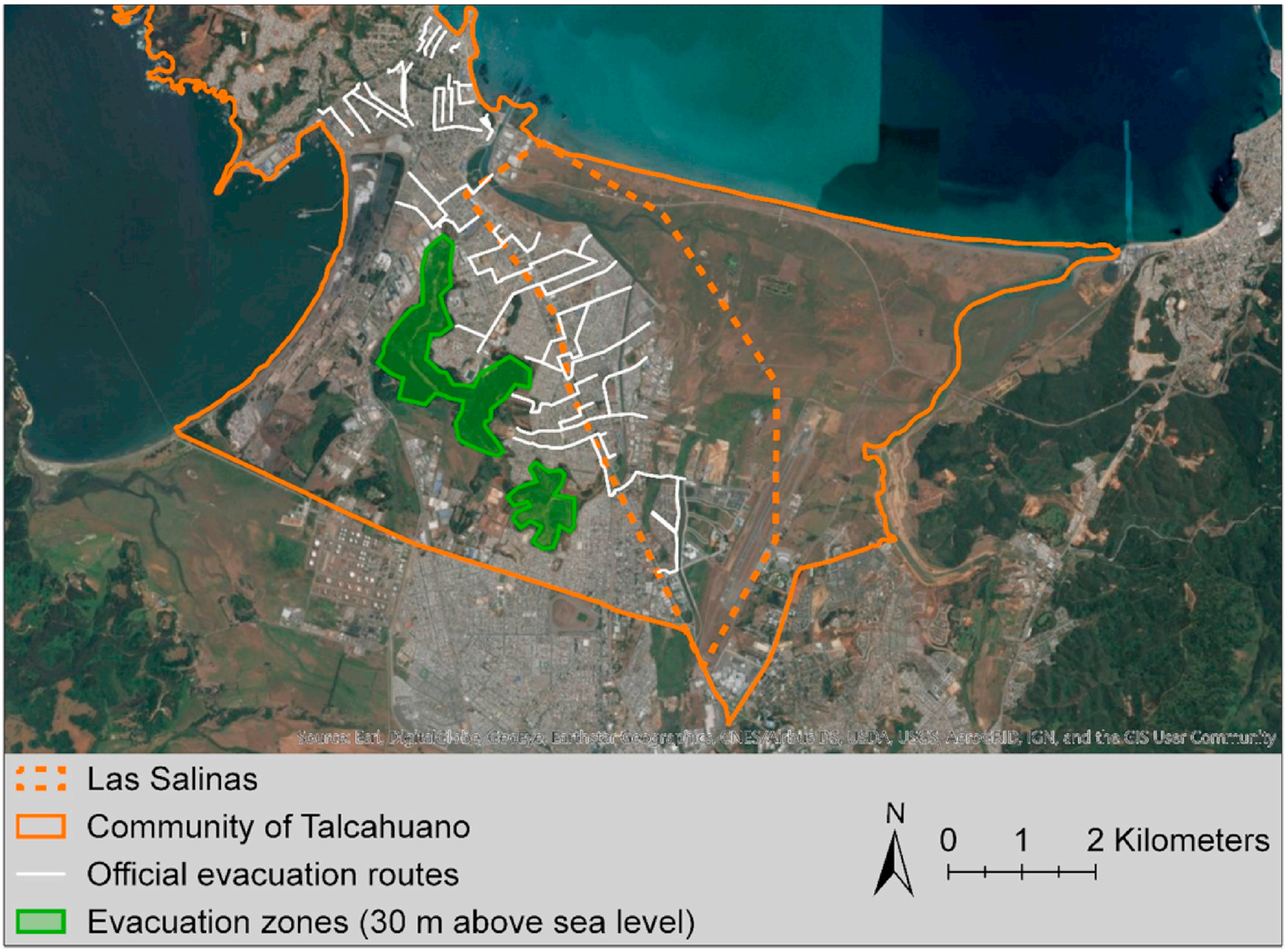

Fig. 2. Official signed evacuation routes and zones in the research area based on data from Ref. [49]).

shift to further natural disasters and other cultural backgrounds is noticed. Apatu et al. [29] and Lindell et al. [65], for example, examined the households' response to the earthquake and tsunami in American Samoa 2009. While Apatu et al. [29] focused on households' characteristics which initiate or impede evacuation, Lindell et al. [65] investigated situational variables using the Protective Action Decision Model (PADM) [66], which determines factors triggering evacuation. The PADM gave a main contribution to evacuation decision-making and behavioral response to natural hazards. The PADM analyzes the whole decision-making process and indentifies factors like environmental, social and informative cues which initiate this process, and eventually lead to evacuation [66]. A timely response comparison to a hypothetical tsunami event in Thailand in the provinces of Phuket and Phang-nga was analyzed by Charnkol & Tanaboriboon [67]. A detailed analysis of the evacuation process in the Great East Japan Earthquake, focusing on the city of Natori, was given by Murakami et al. [30]. At household level, a questionnaire was distributed, asking for reasons to start evacuation, destination of evacuation and traffic conditions, among others. The people who did not evacuate were included and asked for their reasons. The researchers also asked about preparedness actions and awareness trainings before the event [30]. However, the report lacks an accurate indication of the exact amount of time needed for evacuation. Further literature reviewing the tsunami risk in Japan, focus on the fatality rate and influencing factors in the context of evacuation [21–23].

Both modeling approaches and social science approaches contribute to the advances in evacuation research and provide valuable results as a basis for evacuation planning. However, as stated in this paper and acknowledged by further research (e.g. Refs. [26,28]), there is a need to consider the evacuation process more holistically, benefiting from the findings of different research perspectives as shown in the following sections (c.f. [17]).

4. Research design and applied methods

This paper now refers to a case study carried out in the community of Talcahuano, Chile. As the district of Las Salinas was highly affected by the tsunami in 2010, the research concentrates on this residential area in particular. The main focus lies on integrating the experience of the affected population of the Maule Earthquake and Tsunami 2010 and their assumption how they would evacuate in a hypothetical future event, into the research by means of a questionnaire. The integration of direct information given by the population should provide a more holistic picture of the evacuation process and its underlying problems. The GIS simulation provided more results for the evacuation analysis, and the combination of both approaches resulted in more valuable research results, and turned out to deliver added value to answering the overall research questions.

A progressive research design allows for this multi-method approach. The research phases were conducted step by step, and the results and conclusions of previous steps were partly integrated into subsequent ones. In total, we carried out three main steps:

(1) Social science data collection and evaluation by means of standardized questionnaire, providing information about:
   a. experience of the affected population in the evacuation in 2010,

b. possible behavior in a hypothetical future event,
(2) GIS-based simulation, providing information about:
a. the shortest path to the nearest evacuation zone by foot,
b. the time needed for evacuation by foot (time was calculated for different age groups),
(3) Recommendations for short- and long-term measures of disaster risk planning based on the synthesis of the results of the questionnaire and the GIS-based simulation.

4.1. The survey process – analysis of evacuation behavior

We assumed that evacuation takes place at household level. Past evacuation studies confirm this (e.g. Ref. [28]. Consequently, the standardized questionnaire (see Appendix 1) was applied at the household level. The household sizes of the surveyed households are shown in the result section.

The Municipality of Talcahuano and the leader of the *Juntas de Vecinos* supported us in the distribution of the questionnaire in the respective *Juntas de Vecinos* groups in order to reach the community level and trust among the local population. The *Juntas de Vecinos* are neighborhood associations which meet occasionally to discuss relevant issues within the community. As such they play an important role in Chile, as, on the one hand, they provide the possibility of citizens' participation and communication [10], while on the other hand, they provide a platform to identify and communicate local needs to the municipality and the national government [68].

The spatial distribution of the *Juntas de Vecinos* within Las Salinas permitted the even distribution of the questionnaires. In total, we surveyed 136 households ($n = 136$). In order to calculate the sample size, we identified the area affected by the tsunami flood in 2010 on Las Salinas Area in Talcahuano. The population located in that area is $N = 25.093$ inhabitants (corresponding to 7.779 households). We assume that half of the population evacuated, this, statistically, gives us maximum variability. Consequently, we calculated with a probability of $p = 0,5$ and a 95% confidence level ($z = 1,96$). A margin of error of 10% was selected ($e = 0,10$). The subsequent formula to calculate the sample size is derived from Montgomery et al. [69].

$$n = \frac{\frac{z^2 * p(1-p)}{e^2}}{1 + \frac{z^2 * p(1-p)}{e^2 N}}$$

$Where: n = sample\ size; N = population\ size; p = probability; z = level\ of\ confidence;$

$e = tolerated\ margin\ of\ error.$

The calculation of the sample size based on the household results in N = 95 surveys. However, due to a suspected low response rate we sent out more questionnaires in order to ensure we reached that number. Finally, we obtained N = 136 answers to our survey. The questionnaire was subdivided into eight parts: (1) socio-economic data; (2) general experience with tsunami and its impacts; (3&4) factors influencing the decision of evacuation and data about the evacuation in 2010; (5) target location of evacuation in 2010; (6) evacuation route and zone choice in 2010, and reason for the choice, identification of obstacles in the evacuation routes; (7) future evacuation route and zone choice, and reasons for the choice; (8) data about the evaluation of disaster risk management at local and national level. Parts (6) and (7) included maps (see Appendix 1), in which the respondents had to mark their past and hypothetical evacuation route and zone choice.

The questions were mostly closed and with multiple choice answers. The respondents could tick "I did not evacuate", if they had not evacuated or not been in the community during the event. The questionnaire language was Spanish. The evaluation was done utilizing IBM SPSS Statistics 24. The results of the maps of parts (6) and (7) were visualized with QGIS.

4.2. GIS-based simulation – identification of shortest evacuation routes and time

We used OpenStreetMap (OSM) road network data for the GIS-based simulation [70] (cf. [17]). OSM is crowd-sourced and provides free use under an open license. Due to regional variation in the quality of OSM data, we carried out a manual analysis of the road network data for the research area. The analysis resulted in a sufficiently high accuracy and completeness of the data.

GIS was both used to visualize the data of the maps of parts (6) and (7) of the questionnaire, and to simulate the shortest routes to the nearest evacuation zone. Additionally, a time simulation of the evacuation for different walking speeds was conducted.

We identified 50 access points or routes to the evacuation zones on Google Maps satellite data. The high resolution of the data permitted us to visually identify the points. The results show that most of the access points to the evacuation zones are small, unpaved footpaths, which might even be in bad condition during the rainy season. Few access points were paved roads. The access points to the evacuation zones are herewith called evacuation zone access points (EZAP).

For the simulation of evacuation by foot, we categorized different walking speed classes. The walking speed of pedestrians is dependent on multiple factors like age, disability, gender, road conditions and group size [71]. Walking speed in disaster scenarios is even more unpredictable. We used the classification developed during a simulated tsunami evacuation in Padang, Indonesia by Yosritzal et al. [27]. They observed different walking speeds for various age groups. In this study, we applied three different walking speed categories identified in their study: Slow (1.35 m/s) for children under 10 years old, medium (1.4 m/s) for elderly persons older than 60 years, and fast (1.51 m/s) for adults between 20 and 60 years. The age group between 11 and 19 years was not included in Yosritzal et al. [27]. We assume that this group is very diverse regarding its walking speed, so that adolescents in this age group might be included both in the slow walking category, and in the medium and fast category. The fact that, in the past, evacuation mostly took place on the household level (i.e. people in one household evacuated together), also has to be considered in the categorization of walking speed [28]. This means that for many households with children and elderly persons, the slow and medium walking speeds are more likely. We did not consider the slope of the terrain as a factor also influencing the walking speed.

Data on the exact location of households surveyed in Talcahuano was not available. In order to obtain the starting points for the calculation of the shortest path to the evacuation zones, we created a 10 m × 10 m grid over the research area. The centroids of the grid cells were determined as starting points for the evacuation routes. Only centroids that are closer than 200 m to a road were considered for the simulation. About 180.000 starting points in the area were detected. For the next stage, we calculated the shortest walking path via the OSM road network to the closest road to an EZAP from every grid cell. We applied the Dijkstra Algorithm [72] to calculate the shortest path. The distances from the centroid and from the EZAP to the nearest road, respectively, were added to the shortest path distance. In addition, we calculated how many times each road in the network is travelled in our simulated scenario. For every EZAP, we evaluated how many starting points it is the closest. This calculation is intended to highlight the importance of each road for the evacuation of the community.

We used the open-source object-relational database PostgreSQL (v. 9.3) and its extension PostGIS (v. 2.3) for the simulation. pgRouting (v. 2.4) provides geospatial routing and other network analysis functionality. We illustrated the results with the GIS software QGIS (v. 2.18).

5. Results

This section combines the results of the standardized questionnaire and the GIS-based simulation. To provide a better overview, the findings are presented in the order of an evacuation process, from the decision to evacuate up to the arrival at an evacuation zone. Within the subsequent phases:

(1) Decision of evacuation and factors influencing the decision,
(2) Time needed for evacuation and reasons for time needed,
(3) Transport medium choice and reasons for the choice,
(4) Evacuation route choice and reasons for the choice,
(5) Target location choice and reasons for the choice,
(6) Combination of the results of the questionnaire and the GIS-based simulation,

The results of the event-based past scenario and the hypothetical future scenario are presented. N = 136 households were surveyed. Regarding the event-based past scenario, 72.1% of the respondents indicated to have evacuated, whereas 22.8% decided against an evacuation or have not been within the community, when the first tsunami waves arrived. 5.1% did not answer the question.

In total 65.4% of the respondents were female, 34.6% were male. The average household size was three people (32.4%), followed by four (26.5%), and only a minority of households consisted of five (10.3%) or more members (5.8%). The distribution of age categories within participating households can be gathered from Fig. 8.

Asking the respondents ***How do you evaluate the risk of tsunami as threat to your life and to your family?,*** more than two thirds of the respondents evaluated their awareness of tsunami risk as very high (Fig. 3). None of the respondents evaluated her or his awareness as low or very low. Moreover, 89% of the respondents acknowledged that their house was located inside the tsunami hazard zone. 79.4% indicated that they felt prepared for a future earthquake and tsunami event, whereas only 11% confirmed not knowing what to do in a future event.

(1) decision of evacuation and factors influencing the decision

In order to know which factors influenced the surveyed households in their decision to evacuate, we asked ***Which factors did you consider in the decision for evacuation?*** *(multiple answers possible)*. The main factors were environmental cues (75%) for the decision to evacuate like the intensity of the prevenient earthquake (58.8%) and the withdrawal of the sea (16.2%). Another factor was the evacuation infrastructure, emphasizing the distance to the evacuation zone (23.5%). Personal and family characteristics (20.5%) like the reunion of family members before evacuation and the presence of children and elderly people and their health status also played a role in the decision to evacuate, as did the availability of a transport medium (19.1%), and cues of the social environment (14.7%) (evacuation of family and neighbors). Information by responsible authorities played a subordinated role (7.3%) (Table 1). Regarding the question ***Why did you decide against an evacuation?*** *(multiple answers possible)*, the main reasons were the evaluation of their house being outside of the tsunami hazard zone (5.1%), and the lack of information (3.7%). 2.9% decided against an evacuation as they did not have a car available. 2.9% expected blockages and congestion in the streets, and were afraid of robbery (2.9%) when leaving their house unattended.

(2) time needed for evacuation and reasons for time needed

Answering the question ***How much time did you need to take the decision to evacuate or not?,*** 30.9% of the respondents said they needed up to 5 min, another 21.3% decided within 10 min, while 10.3% took more than 25 min for the decision whether to evacuate or not (Fig. 4).

Further, we asked the respondents ***Which activities did you do before the evacuation?*** *(multiple answers possible)*. 33.1% of the respondents indicated to have collected equipment essential for survival. Another 27.2% tried to bring together all family members, while 19.9% just tried to communicate with other family members. 14.7% of the respondents tried to exchange information with their neighbors. Only 8.1% tried to receive information from responsible authorities.

We also asked the respondents **Did you evacuate with the whole family?,** 59.6% responded affirmatively. Thereupon, we asked ***What would you do in a future event, if your family could not be united?*** *(multiple answers possible)*. The main answer to this question was the evacuation with the family members present (71.3%). Another 27.2% of the respondents would gather together all family members before

Table 1
Factors (in %) influencing the decision to evacuate in 2010.

variable	evacuation in 2010 in %
cues of the natural environment	75.0
cues of the social environment	14.7
information by authorities	7.3
evacuation infrastructure	23.5
transport medium	19.1
personal/family characteristics	20.5

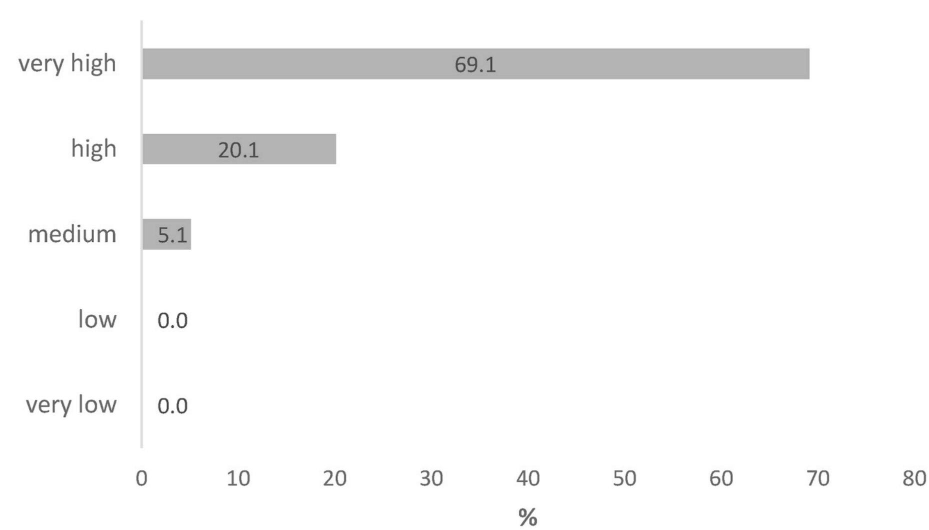

Fig. 3. Evaluation of awareness of tsunami risk.

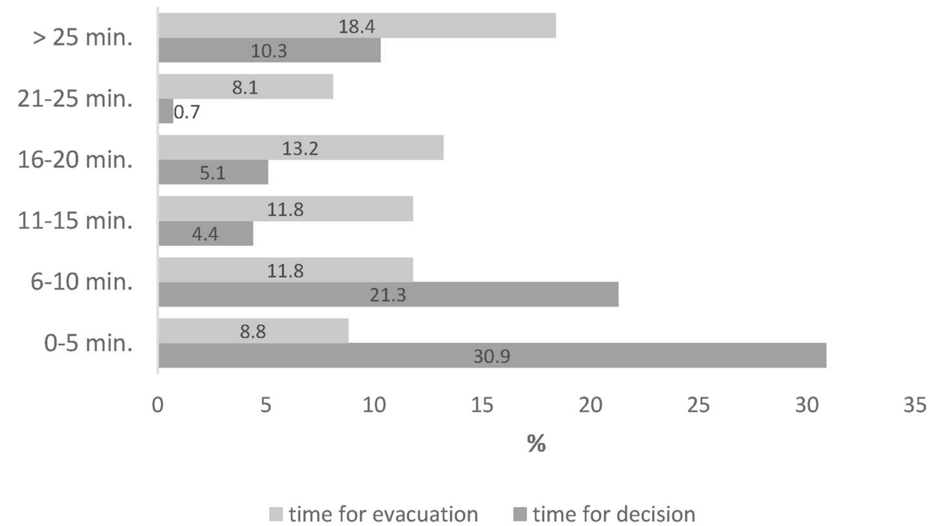

Fig. 4. Time needed for making the evacuation decision and for the actual evacuation in the tsunami event of 2010 (adopted from Ref. [17]).

actually evacuating and would pick up their children from kindergarten or school.

In a further question, we asked the evacuees ***How much time did you take from leaving your house up to the arrival at an evacuation zone?,*** 18.4% of the respondents indicated that they took more than 25 min to reach an evacuation zone, and 13.2% took up to 20 min. Only a small number of the respondents (8.8%) indicated to have taken as little as 5 min (Fig. 4). Further, we asked the respondents ***Why did you need the indicated time for the evacuation?*** *(multiple answers possible)*. The principal reasons indicated were blockages in the road network (47.1%), followed by the distance to the evacuation zone (22.8%). To the question ***Which obstacles did you identify on your way to the evacuation zone?*** *(multiple answers possible)*, the respondents indicated the following types: Congestion (39.7%), people in the street (38.3%), parked cars (21.3%), and debris as a result of the preceding earthquake (14.7%) [17].

(3) transport medium choice and reasons for the choice,

Moreover, we asked ***Which transport medium did you choose for your evacuation in 2010?*** The primary answer was a private vehicle (52.2%), only 17.6% evacuated by foot (Fig. 5). Further, we raised the question of ***Why did you decide on this transport medium for evacuation?*** *(multiple answers possible)*. The main reason was speed (26.5%), followed by the presence of children and elderly adults (24.3%). The distance to the evacuation zone (20.6%) and the possibility to spend overnight inside the car (18.4%) were also indicated. Only a minority of the respondents (10.3%) expected blockages and congestion in the road network, so they chose to evacuate by walking [17].

Asking the respondents ***Which transport medium would you choose in a future event?,*** 46.3% indicated they would evacuate by car, while almost the same number of people (43.4%) would evacuate walking. A correlation analysis demonstrated that those who took a car in the past event are more likely to choose a car in a future scenario (medium correlation: Cramer V = 0.490, level of significance p = 0.000).

(4) evacuation route choice and reasons for the choice,

The next graphic (Fig. 6) visualizes the evacuation routes and zones chosen by the respondents in 2010 (left hand side) and the ones they

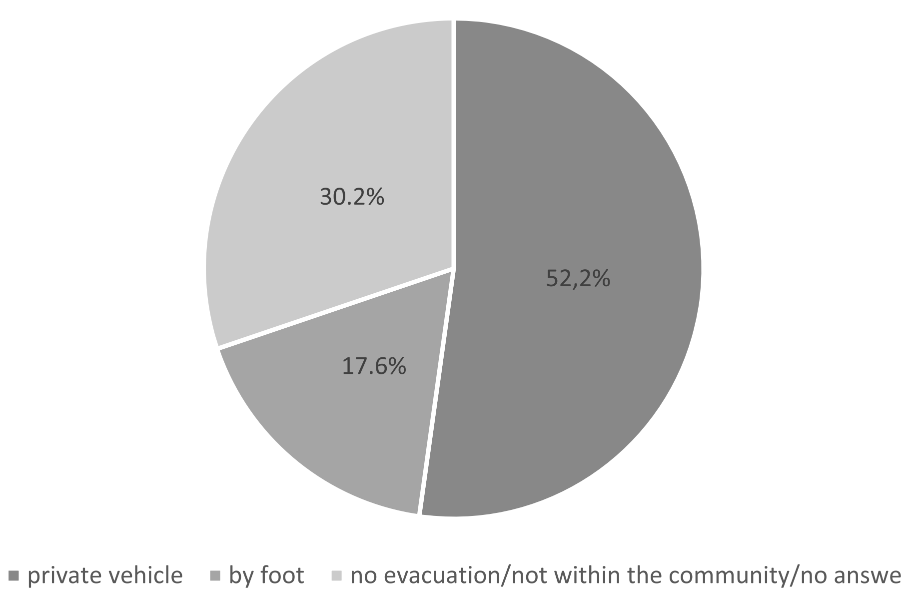

Fig. 5. Transport medium choice in 2010.

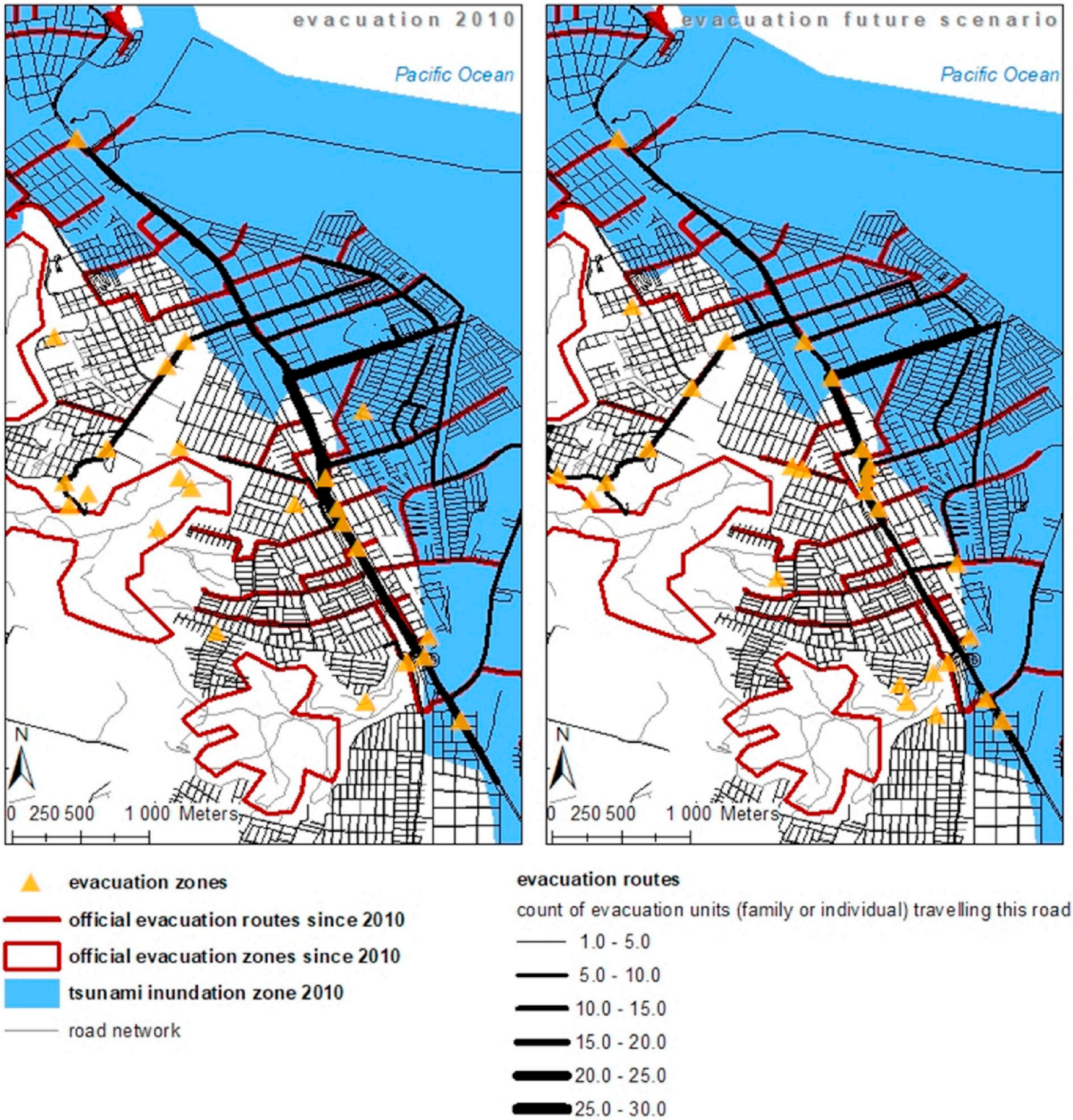

Fig. 6. Evacuation routes and zones chosen in 2010 (left), and in a hypothetical future event (right).

would choose in a hypothetical future event (right hand side). The respondents indicated these evacuation routes and zones in the maps (see Appendix 1) that were part of the questionnaire. The thickness of the street highlights the number of evacuees who used it in 2010 or will use it in a future event [17].

The comparison of the historical and future scenarios shows almost identical results. Many of the respondents tried to evacuate via the main road and did not use the safe zones up the hills in 2010, thus not coinciding with the official signed evacuation routes. The same is true for the future scenario. It also shows that some of the target locations for evacuation were and still are located within the tsunami hazard zone along the main street.

Furthermore, we asked the evacuees ***What was the reason for your route choice?*** *(multiple answers possible)*. The major indication was familiarity with the route (42.6%), followed by the evaluated safety of the route (17.6%), or the shortest distance to the evacuation zone (11.8%). Estimated congestion and blockages (9.6%) played a subordinate role. Regarding a hypothetical future event, we asked the respondents ***What is the reason for your future route choice?*** *(multiple answers possible)*. Familiarity with the route (58.1%) is also the main reason in a future event. The distance to the evacuation zone (30.9%) and the estimation

Table 2
Reasons for the choice of the evacuation route in 2010 and a hypothetical future event.

variable	evacuation in 2010 in %	hypothetical evacuation in %
familiarity	42,6	58,1
security	17,6	20,6
distance	11,8	30,9
blockages and congestions	9,6	22,8

of route security (20.6%) become more relevant in future choice, as does congestion and blockages (22.8%) (cf.Table 2).

(5) Target location and reasons for the choice

Regarding the question ***What was your evacuation destination in 2010?,*** the main indication was the nearby hills (53.6%). A minority indicated that they went to family or neighbors (13.7%). Others indicated to have left Talcahuano via the main road in the direction of distant cities. When we asked ***Why did you choose this evacuation zone?*** *(multiple answers possible)*, mainly the proximity to the house (26.5%) and the accessibility to the zone (25.7%) were the reasons indicated. To the question ***What evacuation zone would you choose in a future event?***, the respondents indicated the evacuation zones in Fig. 6. Further, we asked for ***Why would you choose this zone?*** *(multiple answers possible)*. Reasons given were the estimation of security of the zone (30.9%), the proximity to the house (30.1%), and evacuation zones recommended by authorities (22.1%). Also, accessibility to the zone (16.2%) would play a role in the choice. Recommendation by friends and family members, and overcrowdedness were indicated by 11%, respectively, as reasons for evacuation zone choice. The facilities at the evacuation zone like shelters, for example, are rarely critical for the choice (2.9%) [17].

(6) Combining the results of the questionnaire and the GIS-based simulation,

In order to figure out which footpaths would be the shortest to the nearest evacuation zone access points (EZAP) up the hills, we performed a shortest path simulation (see Fig. 7). All in all, 192.249 shortest

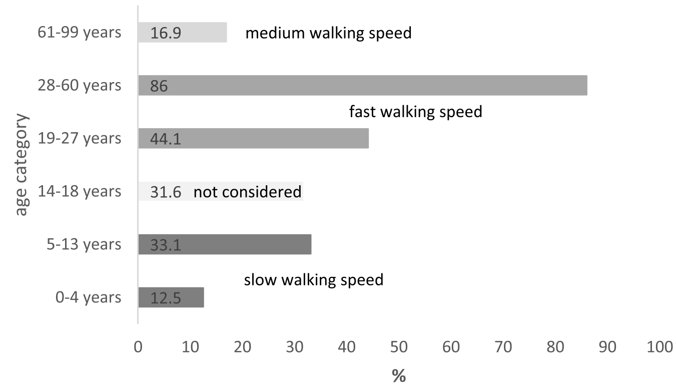

Fig. 8. Walking speed distribution among age categories identified in the questionnaire. The different grey tones consider the age categories of speed distribution according to Ref. [27]. Notice that the category of the slow walking speed 5–13 years and 61–99 is not exactly the same used by Ref. [27]. The categorization of the light grey bar is not considered by Ref. [27].

evacuation paths were calculated. The figure shows three main evacuation corridors leading up to the four most often used EZAP, which are the nearest EZAP for 57% of the area. Comparing the shortest paths in Fig. 7 with the official evacuation routes in the right graph for fast walking speed, it becomes clear that the shortest paths to the nearest evacuation zone differ from the official signed evacuation routes. Neither do the evacuation routes indicated by the respondents in the questionnaire (Fig. 6) coincide with the shortest paths, neither for the historical scenario nor for the hypothetical future scenario.

Moreover, Fig. 7 shows the simulation of a possible evacuation by

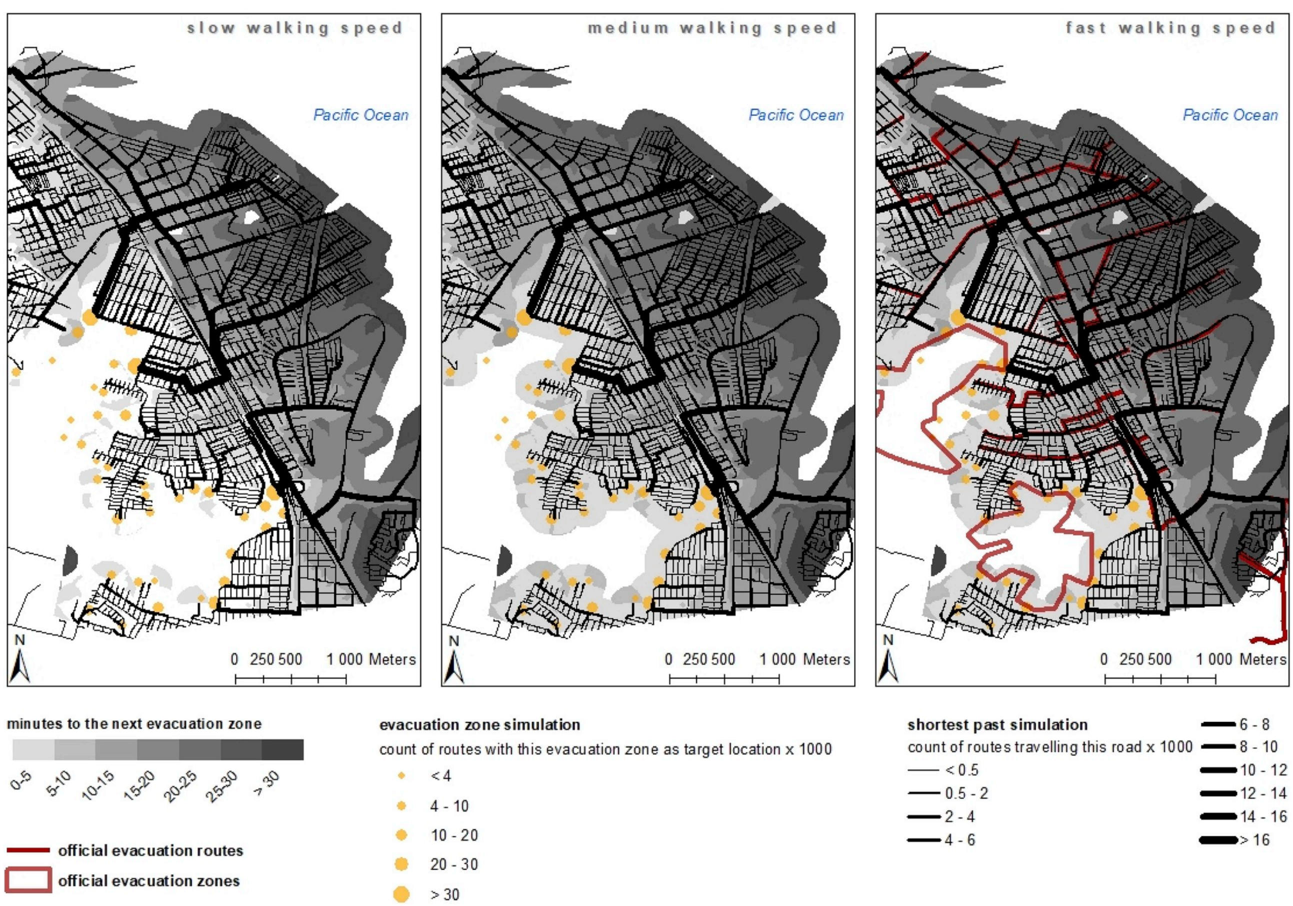

Fig. 7. Shortest past simulation and walking speed estimation for slow, medium and fast walking speed during an evacuation.

foot for different walking speeds. The simulation should indicate if the identified evacuation zones are reachable for the evacuees within an adequate time. The three walking speeds revealed in the study by Yosritzal et al. (2018) [27] were applied. The simulated area of Las Salinas is 19.2 km^2. The results show that for a slow walking speed, 46.5% of the area needs an evacuation time which exceeds 15 min. The percentage of the area, which needs an evacuation time more than 15 min decreases insignificantly for a medium (45.5%) and a fast walking speed (43.3%). 9.6% at slow speed, 7.4% at medium speed, and 4.2% at fast speed need more than 30 min (red marked area) to evacuate by foot. These results are based on the assumption that the evacuees follow the shortest path to the nearest evacuation zone as shown in this figure [17].

In the following, we bring the walking speed categories by Yosritzal et al. [27] in line with the results of the questionnaire. For this, we categorize the distribution of the age groups within the households (Fig. 8) according to the walking speeds used in the GIS-analysis (see Fig. 7). Notice that the age categorization in the questionnaire is different from the age distribution by Yosritzal et al. [27]. Consequently, the age categorization differs slightly among both classifications.

The distribution shows, that 12.5% of the respondents belong to the slow walking speed group. Further, the group of 5–13 years old (33.1%) can be accounted to the slow walking speed group. Consider that in the study of Yosritzal et al. [27] under ten year old belong to the slow walking speed group and that the age category from 10 to 20 years is not considered by Ref. [27]. 16.9% of the respondents belong to the group with medium walking speed, according to the questionnaire and the categorization of [27]. The majority of household members belong to the fast walking speed group.

6. Discussion and recommendations

Linking the results of the questionnaire for the past event-based and the hypothetical future scenario of evacuation behavior with the results of the GIS-based analyses, it becomes evident that the social science approach, integrating the knowledge and experience of the local population, provides additional and valuable resources for evacuation planning. These results could not have been identified and delivered by a modeling approach alone. By means of the questionnaire, integrating the experience of the population, it not only became evident that familiarity with the evacuation route was the main reason for its choice. It also became evident why the evacuees had needed so much time and why the car had been the main transport medium in evacuation in 2010. The questionnaire also revealed a further risk factor in a future event. The respondents indicated that they would first reunite their family, before starting the evacuation. Three critical issues have been detected to be relevant for both past and future events, namely (1) evacuation time, (2) distance to the evacuation zone, and (3) car use.

The majority of the respondents evacuated autonomously, despite of the missing alert. The reason for autonomous evacuation was mainly the intensity of the previous earthquake followed by characteristics of the infrastructure (e.g. distance to the evacuation zone). Personal and family characteristics like the health status of family members and the presence of children and elderly persons played another important role in the decision to evacuate. The consideration of environmental cues as main factor of evacuation can be traced back to the awareness of tsunami risk (see Fig. 3). The majority of the respondents were aware of living in the tsunami hazard zone. Generally, awareness of tsunamis has increased in many countries such as Japan, USA, Indonesia, particularly in the aftermath of the Indian Ocean Tsunami 2004 [73–75]. In addition, the Chileans already had experienced destructive earthquakes and tsunamis in the past, and are constantly faced by the risk due to the seismicity of the country [9]. The same can be said of resident's willingness to evacuate [74,75], especially residents who have lived at the coast for many years are used to the risk (see also [5]). This is confirmed by the fact, that most of the fatalities in Chile in 2010 were tourists, who did not know the area [76]. This was also the case in further natural disasters [74]. Nonetheless, resident's awareness must not be confused with adequate preparedness [73,75]. Simulation research clearly shows that the degree of social groups preparedness influences fatality [77]. Even though residents are increasingly aware and willing to evacuate, the cooperation between public authorities and residents needs to be improved by non-structural measures. Residents need and expect reliable public warning and evacuation signals [74,78]. This was not the case in 2010 in Chile. Official evacuation routes and zones did not exist and there was no efficient warning system at local level [11]. Even today, despite advancements in DRM triggered by the Indian Ocean Tsunami 2004, DRM in many countries is in need of improvement [73,79]. This is also true for DRM at local level in Chile [10,46].

Generally, preparedness in terms of better coordinating resident's responses needs to be improved by means of public interventions, such as information campaigns and safety drills. Even though the majority of the respondents of the questionnaire indicated that they feel prepared for a future earthquake and tsunami event, preparedness in Chile has to be improved [73,80]. This is vitally necessary because the use of cars poses an additional risk in terms of evacuation, as does the fact that evacuation is initiated at household level. The questionnaire also demonstrated that many Chileans will search out their children at kindergarten and school in a future event. The majority of kindergartens and schools within the research area are located in the tsunami hazard zone, which might lead to a contraflow situation and even hinder evacuation. As the 2010 event took place on a weekend at night during vacation time, the families were already together.

Information campaigns are valuable tools to raise awareness among those who did not evacuate in the past. A lack of awareness was the main reason for those who did not evacuate in 2010. They perceived their house to be outside of the tsunami hazard zone. Further reason for not evacuating was a lack of information from public authorities, which also underlines the need of reliable public warning systems and evacuation signals at local level [74,78].

The majority of those who evacuated decided to evacuate within a few minutes, which might be traced back to awareness, due to direct or indirect experience (the majority evacuated due to the preceding earthquake). However, as revealed in the questionnaire and confirmed by the GIS-based simulation, evacuation time was and will be critical in a future event, if there are no profound changes in the evacuee's behavior, in evacuation route and zone planning at local level. The reported time needed for evacuation in the past event may exceed the time between an earthquake and the arrival of the first tsunami waves in a future event. The time was composed of the time needed for decision-making, actions conducted to prepare the evacuation and the time needed from leaving the house up to the arrival at the evacuation zone. Although in the past event, the majority decided to evacuate rapidly, one tenth of the respondents indicated they needed more than 25 min, which might have been due to uncertainty about whether a tsunami would take place or not and the lack of warning and contradictory information from public authorities [11]. Adding the time for preparing for the evacuation to the time needed from leaving the home up to the arrival at an evacuation zone, took most of the respondents involved in the past event more than 25 min. This delay has to be considered as being critical, bearing in mind that the first tsunami waves arrived after just 12 min in some locations in 2010 [81]. Reasons for time delay were mostly congestion on evacuation routes and the distance to the evacuation zones. The former may even be aggravated in the future, if children have to be picked up first from kindergarten or school. The GIS-based simulation confirmed the criticality of evacuation time. The results revealed that at a slow walking speed, 46.5% of the evacuees would need more than 15 min to reach the evacuation zones. As in Chile and as shown in many past natural disasters, evacuation takes place at household level [28], consequently the time for slow walking speed might prevail, as the average household size comprises between three and four people, including small children and elderly family members. In our research the majority of the families consisted at least of one family member belonging to the slow walking speed group (c.f. Fig. 8). The inhabitants of the east end of the research area, near the Pacific Ocean, would need even more than 30 min when evacuating on foot (red marked area Fig. 7).

Further, obstacles in the street resulting from a preceding earthquake, might additionally raise evacuation time, as does car use. Moreover, the calculation in the GIS-based simulation is based on the assumption that the evacuees will choose the shortest route to the nearest evacuation zone. However, the evacuees might not know the shortest route, as they mostly use the routes with which they are more familiar. This is shown by comparing the shortest path simulation (Fig. 7) with the evacuation routes indicated by the respondents of the questionnaire (Fig. 6). Both for the historical scenario and the future scenario, the respondents indicated to use the routes they were the most familiar with, which in many cases was the main road. However, the shortest paths calculated in the GIS simulation lead up the hills to the officially signed evacuation zones. Using the most familiar route for evacuation is also shown in previous studies [82,83].

Due to the distance to the evacuation zones, identified in the GIS simulation, car use becomes understandable. Further reasons for car use, revealed through the questionnaire were speed and the presence of children and elderly persons. Even if the results of the questionnaire show that car use decreases insignificantly in a hypothetical future event, a correlation analysis revealed that most of the evacuees will would use the same transport method they used in the past in a future event. A reason which favors evacuation by foot is the accessibility of the evacuation zones. As visible in the analysis of the Google Maps satellite data and the field work, the roads which lead to the evacuation zones are mostly footpaths and blocked by fences which could not be passed by vehicles. This might be another reason why not all evacuees in 2010 used the official evacuation zones, instead taking the principal road, which crosses Talcahuano from south to north and leads outside the community (see Fig. 6). This route was also indicated for a future scenario. A further reason for not using the evacuation zones up in the hills might be that those are mainly empty spaces without any infrastructure, or shelters. In the past scenario, expected congestions and blockages influenced route and zone choice only to a minor degree. In a hypothetical future scenario, this factor gains in importance. Nevertheless, even if the respondents seem to be aware of possible congestion, they might still choose the same route and the car as their method of transport in a hypothetical future scenario.

Utilizing the GIS-based simulation we wanted to analyze the shortest footpaths to the nearest evacuation zones. We found three main evacuation corridors, which lead up into the hills and serve as the shortest routes for 57% of the evacuees in the research area. The shortest paths analyzed, differ from the official signed evacuation route shown in Fig. 7. This finding is a major critical fact. If the evacuees used the currently official signed evacuation route, they would not be using the shortest path to the nearest evacuation zone. However, if all evacuees use the shortest paths detected, this might exceed road network capacity. Overcrowding and congestion would therefore again negatively affect evacuation time. A critic on the GIS-based simulation we deployed, is that it does not consider the slope of the terrain. The slope however, might additionally increase evacuation time by foot, using the official evacuation routes and zones, which lead up the hill.

Combining both approaches, the social science approach and the GIS-based simulation, the results show that the critical issues detected are interrelated. As the nearest evacuation zones up into the hills are not reachable in the required time by foot due to the distance, the evacuees used and will continue to use the car as transport medium. The use of cars leads to congestion and blockages in the road network and consequently results in increasing evacuation time. Additionally, the official evacuation zones do not provide any evacuation infrastructure, like shelters and essential supplies for survival, and are hardly accessible by car. This means that the main evacuation route by car is in the direction of Concepción, which is outside the small town's limits. If there are no changes in DRM, the critical issues might negatively affect a future evacuation.

Without integrating the knowledge and experience of the local population in the data collection the modeling approach alone would have only detected the need for improvement in DRM regarding adequate evacuation route and zone installation. Even if the evacuation routes and zones are signed adequately and easily accessible in a short time by foot, there are further reasons like e.g. the familiarity of route choice and picking up children at kindergarten and school, which influence route and choice of transport and consequently evacuation time. These factors would not have been detected using a modeling approach alone. The questionnaire therefore provided valuable results. However, the questionnaire also has limitations. For example, the event in 2010, was seven years ago, it is highly possible that the respondents might not remember every fact of their evacuation. Further, the indications for the future scenario is based on assumptions, while the questions within the questionnaire are limited and predetermine the response options of the local community. Further concerns of the local community regarding evacuation are not considered. Thus consideration should be made to going beyond standardized questionnaires and integrating the community in a more holistic manner in DRM, similar to approaches along the lines of Community-based Disaster Risk Management [33].

6.1. Recommendations for short- and long-term measures for disaster risk management

In order to mitigate the critical issues of evacuation time, distance to the evacuation zone and car use, and to establish the limitations of the data collection methods, we recommend both short- and long-term measures to improve DRM at the local level. The recommendations are already given partially in Ref. [17].

Alongside the general increased awareness and willingness to evacuate worldwide, as also revealed in this study in order to strengthen preparedness, there is a need of cooperation between public authorities responsible for DRM at local level and residents [74,84]. An optimal preparedness can only be achieved by systematic long-term strategies [73,79], such strategies must include land use policies and planning [78,84], because the congestion of evacuation routes, not only in this research, but also in other countries worldwide during natural disasters continues to be a problem [78]. However, short-term measures are also necessary – most notably awareness building regarding choice of transport.

As a short-term measure, we recommend workshops for the inhabitants of the *Juntas de Vecinos*, which are guided by community leaders and responsible authorities for DRM. Due to the structure of DRM in Chile, the administrative centralization and the incidents in the past (all-clear of tsunami), workshops with the affected population seem to be an adequate strategy for awareness-building. The workshops not only build on overcoming the lack of trust in authorities responsible for DRM and the lack of transparency of DRM strategies [11], but also help to build a Community-Based Disaster Risk Management scheme at local level, which considers the experience and knowledge of the local population and might lead to a more sustainable DRM by participation of the population [85,86]. During the workshops, the critical issues should be addressed. Together with the affected population, strategies to alleviate the issues should be explored. These strategies should include an evacuation plan for every household, composed of suggestions as to where to meet absent family members, which transport medium to use and which evacuation route and zone to choose. Furthermore, every family should have at their disposal an emergency kit, which includes daily requirements, blankets and medicine. The emergency kit prepared in advance should decrease preparation time. The even distribution of evacuation routes and zones within the *Juntas de Vecinos* should reduce congestion during evacuation. These workshops should take place at least once a year, and consequently changes in the urban environment and human preferences might be considered. Additionally, the results of the workshops should be available for community members on an online platform, as well as on maps in the municipality and the buildings of the *Juntas de Vecinos*. These mediums should be updated continuously by responsible authorities.

However, as pointed out in this research, there is a need for significant changes in the evacuation infrastructure in the long term. Visible and intuitive signposting of evacuation routes and zones should not only be regularly maintained but routinely adapted to meet an emergency situation. Evacuation routes have to be expanded in order to be able to cope with the capacity needed in the case of emergency. Furthermore, impeding obstacles have to be removed from the evacuation routes and it should be ensured that possible debris from a previous earthquake does not hinder evacuation on these routes. Furthermore, the evacuation routes have to be illuminated adequately (e.g. Ref. [20]). Official evacuation zones should be accessible and shelters should be provided, to meet the number of evacuees. These shelters should provide essential supplies (water and food), blankets and medicine.

In order to address the issue of parents picking up their children from kindergarten and school during a disaster, the collaboration between schools, disaster managers and parents is needed. Joint evacuation plans should be constructed, which are known by all relevant persons (students, teacher and parents etc.) and which indicate the safe zone were parents will meet their children. This is similar to the concept of *tendenko*, which became famous following the Tohoku Earthquake and Tsunami 2011. The concept of *tendenko* implies that each person should evacuate individually, having confidence that other family members do the same [74]. This would avoid contraflow. However, we recommend in the long term, that kindergartens and schools, as well as hospitals should be relocated in safe zones. In the case of disaster, these buildings could serve as shelters. The multifunctional use of these buildings would therefore alleviate two problems: The lack of shelters and contraflow during evacuation. Furthermore, if evacuation by foot is to be promoted, there is a need for vertical shelters within the research area for residents living at the east end of the area and families with children and elderly people [46]). Consequently, as mentioned before, an optimal preparedness can only be achieved by focusing on long-term strategies [73,78,79,84]. The long-term measures in planning, establishing and designating adequate evacuation routes and zones are also important especially when taking into account that in Chile in 2010 as well as in many other disasters worldwide, most of the fatalities were non-residents, namely tourists, who did not know the area [74,76].

The findings of this research, either of the questionnaire or the GIS-based simulation, can provide a basis for evacuation route designation and evacuation zone installation. These findings can be integrated in the workshops. However, as already mentioned, the capacity of routes and the accessibility to the zones has to be improved.

7. Conclusion

Due to the persistent lack of preparedness, tsunami hazards continue to be higher than necessary [73,79]. This is particularly true for Chile, where the lack of governmental preparation is pronounced and consequently, resident's response in the Maule Earthquake and Tsunami 2010 were suboptimal (for instance, use of the car for evacuation, resulting in congestion) [75]. As speedy evacuation is the most important strategy to save lives, especially, in rapid-onset disasters like tsunamis [18,19], evacuation research is a most important research field.

This research introduces and promotes the application of social science approaches in combination with modeling approaches in a progressive research design. By means of the application of different scientific methods, a multi-facetted problem like evacuation can be addressed more holistically. Additional and valuable results for evacuation planning, which cannot be identified by a single approach alone, can be achieved by combining different methods, as demonstrated in this study. The main value of this study however, lies in the integration of the knowledge and experience of the local population, the population at risk, in form of a case study. However, it should be also emphasized, that the combination of standardized questionnaires and a GIS-based simulation, as in this study, are also limited in their informative value. Research designs, which involve the local population in a more holistically manner in DRM, in the identification of risk and vulnerabilities and evacuation planning in their community like this is the case in CBDRM (e.g. Refs. [32,33,85]) might go beyond the limitations of the applied methods and provide even more insight into the evacuation process. A proposal with regards to how to integrate a CBDRM approach in the research design deployed in this study is shown in the recommendations section. Evaluating the value of the latter should be part of future research.

The research design is transferable to other regions; however, the questionnaire has to be modified to each local context. As evacuation time and the use of cars are major problems in many natural disasters, the methods and recommendations given here can be applied to other countries. In highly centralized countries like Chile with a lack of evacuation planning at local level, participation of the population in form of Community Based Disaster Risk Management might be a successful means towards alleviating these critical issues.

This research demonstrates that a detailed analysis of evacuation behavior applying a multi-perspective research design produces important results for risk disaster management. As the behavior of the affected population during a natural disaster can be decisive in lowering fatality rates, evacuation research should draw greater input from the knowledge and experience of the affected population, and also help raise their awareness, and thus change their evacuation behavior in future events. Ultimately, evacuation must never be reduced to just representing a scientific issue, but it is literally a matter of life and death for hundreds of millions of people around the world.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2019.101462.

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