

Urban morphology as a tool for supporting tsunami rapid resilience: a case study of Talcahuano, Chile.

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Abstract

Tsunamis are infrequent but highly destructive natural phenomena, in which limited time is available to make appropriate response decisions regarding key matters such as evacuation and sheltering. This paper argues that this specific type of 'rapid resilience' to tsunamis can be enhanced by changes in urban morphology, related to street networks and assembly areas. The Chilean city of Talcahuano (severely affected by an earthquake and tsunami in 2010) is examined using a mixed methods approach as the basis for proposed urban design modifications, aimed at improving tsunami evacuation and sheltering in public spaces. The proposal is quantitatively assessed by an agent-based computer model, which shows significant reductions in total times for evacuation. The modifications can also deliver qualitative impacts, providing new liveable public spaces for the city while contributing to maintaining an ongoing tsunami prevention culture.

Keywords

Tsunami, evacuation, urban morphology, agent-based model

Introduction

The consequences and overall impacts of urban disasters can be strongly influenced by populations' responses during the initial phases of emergencies. This is particularly critical in the case of rapid onset disasters such as near-field tsunamis, in which people have only minutes or hours to make appropriate decisions about critical activities such as evacuation and sheltering. Further, these actions often need to be undertaken autonomously by members of the public, due to failures or inadequacies of emergency systems following strong earthquakes. In this context of crisis, a city's morphology can positively influence the community's abilities to rapidly and effectively respond to the disturbance, promoting urban resilience (Allan et al. , 2013).

Existing literature regarding the management of tsunami risks in coastal communities focuses mainly on mitigation actions for possible future events (see for instance Eisner, 2005, Murata et al. , 2010, Preuss, 1988, Shuto, 2005) and assessment of current vulnerabilities (Mas et al. , 2013, Post et al. ,

2009, Taubenböck et al. , 2009). Accordingly, resilience is focused upon recovery *after* the disaster (Adger et al. , 2005, Paton et al. , 2008, Rajkumar et al. , 2008). It is noteworthy that, in their studies of urban morphology influences upon cities' resilience, Allan and Bryant (2011) and Allan et al. (2013) focus analysis upon initial recovery periods after major earthquakes (i.e. days to weeks), finding links between socio-spatial resilience and geophysical attributes at different scales. In these studies, preventive tsunami evacuation is only examined as a part of a broader diagnosis of an urban response during the emergency.

It is argued here that, due to the specificity and critical importance of evacuation in tsunamis, it is necessary to enhance it in three ways. Firstly, by a specific analysis of the response phase, i.e. the initial minutes to hours after the related earthquake. Secondly, by the examination of urban morphology, including interventions through modified design recommendations. Thirdly, quantitative tools can appraise the first two. This threefold approach suggests that urban morphology can enhance a specific type of 'rapid resilience' in tsunami prone coastal urban communities, via capacities to rapidly react and cope with a developing threat, supported by the key activities of evacuation and sheltering.

This paper presents a case study of the Chilean city of Talcahuano, the site of previous tsunamis, the most recent of which struck on February 2010. The paper has four parts. First, background regarding key principles such as resilience, tsunamis, and urban morphology is provided. Second, the city of Talcahuano is introduced as a research context. Third, an intervention framework for the city and a tool for its quantitative analysis, a computer agent-based model, are provided. Finally, the outcomes of the proposal and its implications for tsunami risk reduction and urban planning policies are discussed.

Background: Cities and Disaster Resilience

Resilience is a concept rooted in physics and mathematics, where it was used "to describe the capacity of a material or system to return to equilibrium after a displacement" (Norris et al. , 2008: 127). In ecology a seminal description was provided by Holling (1973: 14): "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables". Since this time, resilience has become

widely used, influencing many different fields such as disaster management, psychology, and ecology (March, 2011).

In disaster management, resilience has been referred as the ability to cope with disasters, by surviving them, minimizing their impacts, and recovering with minor social disruptions (Cutter et al. , 2008). In turn, Twigg (2007) suggests that a disaster-resilient community is characterized by: (a) the capacity to absorb stress through resistance or adaptation; (b) the capacity to maintain basic functions and structures during disasters; and (c) the capacity to recover or “bounce back” after an event. Moreover, resilient communities are complex adaptive systems, capable of self-organization, learning and adaptation, without a significant outside assistance (Adger, Hughes, 2005, Mileti, 1999).

As urbanization gathers pace, it is likely that by 2030 more than 60% of the world's population will live in cities (Bloom and Khanna, 2007). This also means that the main site of many potential disasters has shifted to urban areas (Brown, 2012). Where cities historically sought to provide refuge from nature's menaces, while taking advantage of its resources; this has now shifted whereby many of them are 'hot-spots' for exposure to natural hazards (Joerin and Shaw, 2010). Multiple factors converge to create risks (Satterthwaite, 1987, quoted by Pelling, 2003): population growth, poverty, fast expansion of informal settlements, overcrowding of tenement districts, failure to ensure lifelines, and lack of governance. Hewitt (1995, quoted by Pelling, 2003) argues that cities' dense pattern of urban living contributes to risks: while being only one per cent of the Earth's land area, they concentrate over half of the world's population and most of its physical capital.

Improving resilience to disasters in the urban realm is a critical task in the context of rapid urbanisation. Urban planning can play a central role, via its ability to integrate multi-dimensional aspects affecting disaster risk reduction (March and León, 2013). Planning has inherent capacities: to systematically and comprehensively affect the location and design of urban development, to provide strategic interventions, to embody public participation, and to provide political linkages (Schwab, 1998). Urban planning can also contribute to build citizen awareness of the risks of natural hazards (Burby et al. , 1999).

Despite conceptual consensus about the feasibility of achieving resilience to disasters through urban planning and its impact on city morphology, it has been difficult to translate this into practice (March and León, 2013). In particular, there is limited research on the links between resilience and the design

of urban form, as Allan et al. (2013) argue. Moreover, a review of literature shows that planning-based efforts to increase resilience (or, alternatively, to reduce vulnerability) usually take place in the mid or long term before and after a disaster, i.e. during the mitigation, preparedness, and recovery disaster management phases. Insufficient research has been conducted to understand the importance of urban morphology during response phases, i.e. its role in achieving 'rapid resilience' to disasters.

This lack of knowledge regarding rapid resilience is illustrated in the case of tsunami risk reduction, which focuses on three main areas (Eisner, 2005, Gotoh et al. , 2013, Murata, Imamura, 2010, Preuss, 1988, Shuto and Fujima, 2009): (1) large civil-engineered countermeasures (e.g. breakwaters, seawalls, tsunami gates); (2) urban land use and morphology (e.g. identification of inundation areas, relocation of dwellings and other activities, improved building codes, etc.); and (3) emergency readiness (forecast and warning systems, evacuation preparedness, evacuation simulation, etc.). The first type has been used extensively in Japan, involving considerable technical and economic resources, producing mixed outcomes during the last main disaster, the 2011 Great East Japan Tsunami (Suppasri et al. , 2012). The latter two types (2 and 3 above) currently appear somewhat disconnected. Land use and morphology change requires long-term strategies, not typically addressing population-focussed tsunami-response activities. In turn, emergency readiness activities do not typically engage with ways to modify urban morphology. Rather, the urban realm is usually approached as a relatively fixed context. Some authors such as Di Mauro et al. (2013), González-Riancho Calzada et al. (2013), and Sahal et al. (2013) have recently begun examining the impacts of urban interventions upon the expected tsunami evacuation times. These approaches, however, have focused on overall urban configurations, without addressing the specific design of the urban public space.

For hazards such as tsunami, where timely responses mark the difference between life and death, disconnections in risk reduction approaches are an important focus to improve rapid resilience via key changes to urban morphology. Particular emphasis can be placed upon urban structure, morphology, and public space design as the primary places where people gather, evacuate and shelter during a disaster, including impacts upon other risks such as panic and stampedes (He and Xu, 2012).

Talcahuano

Talcahuano, Chile (36°43'S, 73°07'W) is an industrial port city, 800km south of the nation's capital Santiago, in the Biobío region. Its population in 2012 was approximately 172,000 (INE, 2012). The city is predominantly located on a coastal plain (ground elevation roughly 5 to 10 metres above sea level), but includes several hills of varied size and height (between 50 to 130 metres above sea level). Talcahuano was founded in the 18th century, when the Concepción council decided to move from its former coastal location 10 km inland, after four destructive tsunamis occurred in 1570, 1657, 1730, and 1751. Only the shipping activities remained in Talcahuano, the bay's best mooring point (Benavides et al. , 1998, Mazzei de Grazia and Pacheco, 1985, SHOA, 2013). The founding location, the current site of the CBD, is a narrow 1km strip of land connecting the mainland with the Tumbes peninsula, between Concepción Bay and San Vicente Bay. From this original site, the city progressively extended southeast to become part of the Great Concepción conurbation (total population around 1,000,000). The southwest coast, in turn, became an industrial area. See Figure 1.



Figure 1: Satellite view of Talcahuano. Source: Google Earth (2013).

On the 27th of February 2010, at 3:34am, a M8.8 earthquake hit the central-southern area of Chile. Its epicentre was located 95 km northeast of Talcahuano (USGS, 2010). The earthquake triggered a large tsunami that affected more than 500 km of the Chilean coast. Talcahuano was initially hit at approximately 4:20am by a 3 metre-high wave (Martínez et al. , 2012), and then by two main tsunami waves, at 5:57am and 6:05am, both with an estimated run-up (i.e. the difference between the ground elevation of the point reached by the tsunami, and the sea level) of 10 metres (Ayala and Labrín, 2013). The tsunami seriously damaged large parts of the city's coastal areas (particularly the CBD and Salinas zones), destroying housing, industry, commercial and public spaces areas (PNUD, 2011). Five-metre-high waves swept ships and containers into the city; the naval base, the ASMAR shipyards, and caused devastating impacts upon port infrastructure (Morales, 2010). The Chilean Public Prosecutor's office (2011) established that 21 people died in Talcahuano because of the tsunami. This relatively low number could be largely attributed, in this case, to the long time span between the earthquake and the first damaging wave (approximately 46 minutes), which allowed the majority of the population to safely evacuate to higher areas. The evacuation was autonomously conducted by occupants themselves, because the tsunami-warning national system (SNAM) and related agencies (the Chilean Navy's hydro-oceanographic service, SHOA, and the Chilean Emergency Management Agency, ONEMI) failed to release a timely national warning, due to multiple technical and administrative errors (Carvajal and Soler, 2012, Cavallo, 2013, Ramírez and Aliaga, 2012, Romero et al. , 2010).

Method

To examine the possibilities for improved rapid resilience in an urban form sense, a case study method was employed after the selection of Talcahuano (Stake, 1995, Yin, 2009). The method included five phases: (1) Diagnosis of the city's current tsunami evacuation vulnerability; (2) Literature review to obtain a set of urban design recommendations enhancing tsunami evacuation; (3) Fieldwork study; (4) Development of a ground-based proposal embodying recommendations; and (5) Assessment and synthesising of the proposal.

Diagnosis

Analysis of Talcahuano's tsunami evacuation vulnerability began with identification of the expected floodable area in the event of a feasible close-epicentre earthquake scenario, based on the separate

CITSU Project ('Tsunami Inundation Maps for the Chilean Coast'). This was conducted from 1997 by SHOA, the Chilean Navy's hydro-oceanographic service (SHOA, 2012). It defines expected attributes (extension and flood depth) of probable tsunamis along the Chilean coast, using digital numeric simulations based on historical geophysical information. The most recent tsunami 2013 flood map for Talcahuano was supported by a study on the 1835 earthquake. See Figure 2.

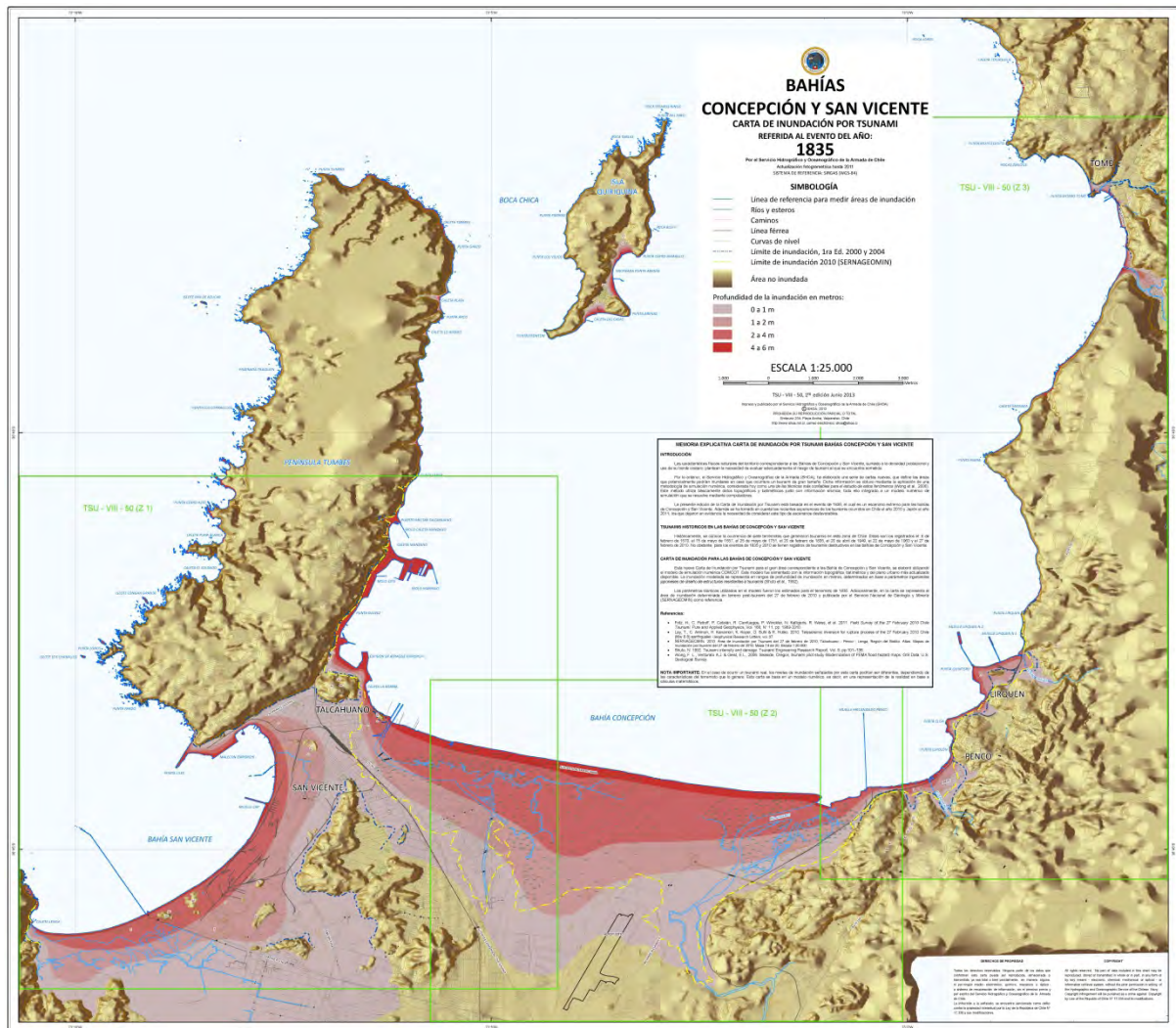


Figure 2: tsunami flood map for Talcahuano. Inundation depths between 1 (light red) and 6 (deep red) metres. Source: SHOA (2013).

A vulnerability analysis was then carried out to identify critical evacuation areas in case of a tsunami. Vulnerability can be defined by two main factors: geophysical and socioeconomic (Birkmann, 2006, Blaikie et al. , 1994, Cutter et al. , 2003, Taubenböck et al. , 2008, UNISDR, 2009). In this case, these factors were combined with the support of ArcGIS® software, using a 'weighted overlay raster-based analysis', i.e. "a technique for applying a common measurement scale of values to diverse and

dissimilar inputs to create an integrated analysis” (ESRI, 2011), where different factors can be assumed as having diverse influences (‘weights’) on the final outcome. For the case of the evacuation vulnerability assessment, the following group of determinants were incorporated, falling into geophysical and social categories (see Table 1).

Vulnerability type	Parameter	Weighting factor (%)	Rationale
Geophysical	Expected pedestrian evacuation time	40	<i>Disadvantageous location is the most critical evacuation factor.</i>
Social	Population density	20	<i>The more the population, the slower the evacuation process</i>
	Population with special needs	5	<i>People with special needs require assistance and have slower evacuation speeds</i>
	Schools	10	<i>Schools operate concentrate vulnerable population, and act as attractors of parents during an emergency</i>
	Child care centres	5	<i>Child care centres operate concentrate vulnerable population, and act as attractors of parents during an emergency</i>
	Health centres	5	<i>These facilities operate as agglomerators of population</i>
	Overnight accommodations	5	
	Worship centres	5	
	Other critical facilities	5	
TOTAL		100	

Table 1: factors for a weighted overlay analysis. Source: the authors.

Table 1 shows the expected pedestrian evacuation time to a safe location outside the floodable area calculated using ArcGIS® ‘cost distance raster-based function’, which calculates accumulated travel cost (in this case, time) from any location to the nearest safe location, according to factors including land use and terrain slope (Laghi and Cavalletti, 2006, Wood and Schmidlein, 2012). In the case of tsunamis, wide consensus exists that pedestrian-based evacuations are preferred over vehicular-based approaches (Johnstone and Lence, 2011, Samant et al. , 2008, Scheer et al. , 2011, UNESCO, 2008, Wood and Schmidlein, 2011). Vehicles are associated with traffic congestion, roads blockages, and impediments due to infrastructure damage, collisions, and threats to pedestrian safety.

The analysis of social parameters were based in census data disaggregated to the block level (in the case of population) and by a set of discrete locations identified from official sources (Chilean Government and Talcahuano Municipality during the second semester of 2012. This allowed identification of nine critical evacuation areas in the case study (Figure 3), providing a basis for developing ground-based design recommendations.

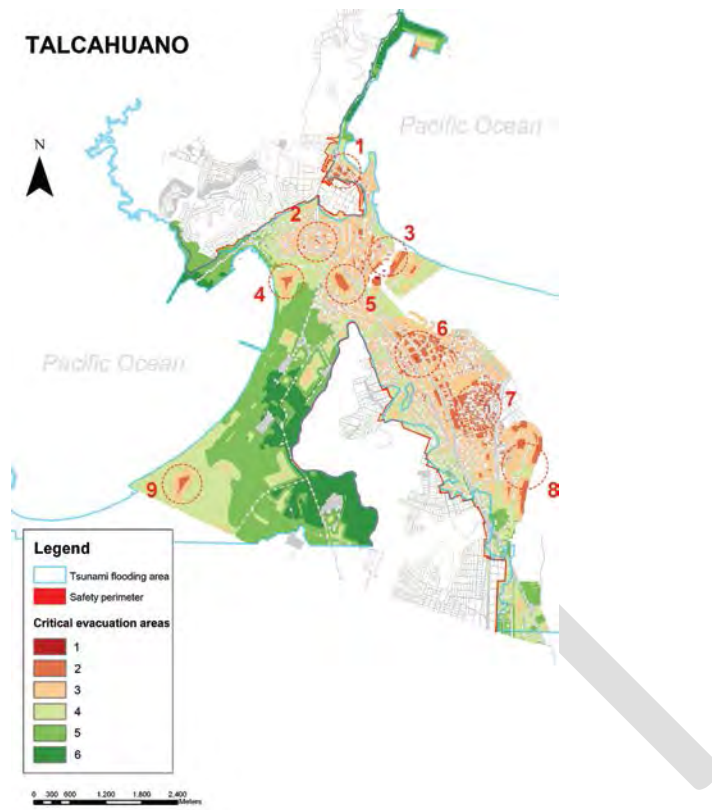


Figure 3: critical evacuation areas in Talcahuano. Source: the authors.

Urban design modifications

The tsunami evacuation vulnerability analysis identified the urban areas where urban morphology modifications will result in the greatest improvements to the population's rapid resilience capacities. Three types of urban design recommendations to support tsunami emergency response exist. Firstly, the creation or enhancement of safe assembly areas, which can be horizontal or vertical (Scheer et al. , 2012, UNESCO, 2008). The former are typically open public spaces with adequate location, accessibility, capacity, and terrain qualities. The latter, in turn, are recommended as a solution for urban areas unable to complete pedestrian evacuation before the estimated arrival of the waves. There are two types of vertical evacuation solution: existing buildings with adequate characteristics (height, capacity, structure); and, new structures such as platforms or evacuation towers (Nakaseko et al. , 2008, Rojahn, 2004).

The second type of tsunami evacuation urban design approach addresses street networks. This provides critical spatial connections between the vulnerable parts of the city and assembly areas to provide three basic requirements of large pedestrian evacuations, according to Ercolano (2008):

accessibility, safety, and mobility. Accordingly, topological and qualitative modifications are suggested. The former relate to changes to network configurations, such as creation of new streets, or the widening or extension of existing ones. The latter, in turn, deal with the enhancement of identified existing routes, by improving their safety-related characteristics (pavements, emergency lighting, access for disabled persons, change to pedestrian usage only, inclusion of tsunami-resistant furniture, etc.) and their capacity to provide wayfinding information to the evacuees (for instance, by including signage and maps, or by increasing the continuity of colours and materials along the routes).

The third and final type of urban design recommendations for tsunami safety relates to management of specific evacuation-hindering features, caused by the wider effects of the associated earthquake. Damaged urban utilities such as fallen electricity lines or large gas leaks have hindered evacuation during previous tsunami emergencies (Preuss et al. , 2001); it is also common that collapsed facades can block escape routes, and that the pavements are damaged or destroyed. Hence, specific evacuation-hindering features must be identified and removed from the designated safety network (i.e. routes and assembly areas).

Fieldwork study

The feasibility, selection and location of the design recommendations identified on the previous phase were assessed during a two-week fieldwork study conducted in Talcahuano in May 2013. The fieldwork occurred in in two components: (1) in-depth interviews with local emergency stakeholders, including the city's main neighbourhood association (see Table 2), and (2) an on-site survey of urban conditions.

Code	Institution	Description
1	Municipality of Talcahuano, CATOE.	The municipality's agency in charge of coordinating the response to all the emergencies located in the Talcahuano area.
2	Municipality of Talcahuano, Risk Management Unit.	The municipality's agency in charge of developing long-term risk reduction strategies, especially for a community-based approach.
3	ONEMI, Biobío state.	The government's agency for emergency management in the Biobío state, responsible for the national system of civil protection.
4	Carabineros de Chile, Talcahuano unit.	The uniformed Chilean police, in charge of guaranteeing the enforcement of the law and the public safety.
5	PDI, Biobío state.	The civil Chilean police, its mission is the enforcement of the law and the criminal investigation.
6	Chilean fire-fighters, Talcahuano unit.	Chilean fire-fighters is a volunteers organization aimed to respond nature or manmade emergencies.
7	Chilean Navy, Talcahuano zone.	In times of peace, the Chilean Navy is in charge of providing administration and security to the sea shore, being responsible for a 80-metres wide land strip that starts in the high tide limit.
8	Talcahuano Health Services, emergency and disasters unit.	The unit is responsible for guaranteeing the continuity of public medical attention during emergency and disaster situations.
9	Chilean Red Cross, Talcahuano unit.	Chilean Red Cross aims to provide support to the enforcement of public health policies, to social welfare, and to risk management and emergency response strategies.
10	Chilean Civil Defence, Talcahuano unit.	The Civil Defence is a public volunteers institution (under de Ministry of Defence) aimed to be actively engaged with the Chilean national system of civil protection. It develops risk reduction and emergency management activities.
11	Union of neighbourhood councils, Talcahuano.	The main neighbours' organization in the city, in charge of coordinating 49 local neighbourhood councils.

Table 2: Institutions Consulted in Talcahuano. Source: the authors.

The interviews provided insights into the city's ongoing tsunami preparations, actual experiences during the 2010 emergency, and improvements to response sought in the future. Three main conclusions were reached. The first is that Talcahuano has built a strong population-based tsunami-response culture, from experiences such as the 1960 event (a 2-meter tsunami provoked by the Valdivia's M9.5 earthquake) and the 2005 'false' tsunami (when a false rumour about approaching waves spread among Talcahuano's inhabitants, provoking huge panic and large spontaneous evacuations). This culture implied that the majority of the population rapidly evacuated following the 27th of February of 2010 earthquake, despite the absence of any kind of governmental warning or guidance (due to the collapse of the public warning system). The second conclusion is that Talcahuano's urban infrastructure was insufficiently prepared to deal with the emergency. Evacuation routes and assembly areas were neither physically prepared nor identified with signage. Communication networks did not work, triggering multiple problems, including lack of information for emergency services and waiting evacuees (which led to some returning home immediately before the tsunami hit the coast). Reticulated services (electricity, water, gas), in turn, failed almost immediately after the earthquake and remained inoperable for days or weeks, depending on the area. In particular, the absence of street lighting seriously hindered the evacuation (the earthquake occurred at 3:34 AM). The third conclusion is that there is a strong need to improve the population's knowledge about hazards, particularly earthquakes and tsunamis, to cope with future emergencies. It is also necessary

to maintain a public focus on this knowledge due to the long term recurrence of tsunamis, in contrast to the usual short attention span of populations after any disaster (Bird and Dominey-Howes, 2006).

Guided by the results of the desk-based tsunami vulnerability analysis and the interviews, the field work also examined the most relevant urban conditions that might affect evacuation processes. As public space is the environment supporting the populations during a tsunami emergency, two of its aspects are crucial: streets and open public spaces. While streets provide a movement network for evacuees, open space in safe areas provides shelter for the evacuees during hours or even days, depending on the extent of the tsunami warning or any resulting damage. The existing street network was surveyed under an evacuation approach, i.e. as a pedestrian connection system between the vulnerable areas in the coast and the safe higher grounds. Emphasis was placed on identifying and analysing well-known feasible evacuation routes that provide the most expedite connections to the safe areas, and which therefore might concentrate larger amounts of evacuees during a tsunami emergency. It has been argued that people's familiarity, knowledge of escaping routes, and perception of the closest destination are key factors for deciding evacuation, and that hence evacuees usually choose the well-known paths instead of the designated ones (Sime and Kimura 1988; Proulx 2001, quoted by Mohareb, 2011). Each feasible route was analysed according to physical characteristics (e.g. lengths, widths, slopes, pavement conditions, existing open spaces, pedestrian-only areas, etc.), its active properties (type of urban district and uses, traffic conditions, day/night activities, etc.), and its evacuation-related capacities (obstacles, drops, bottlenecks, possible falling objects such as electricity wires or facade walls, the availability of tsunami-related information, etc.).

Secondly, the fieldwork survey allowed identification and assessment of sites which had the characteristics that made them appropriate as safe assembly areas in case of a tsunami emergency. These requirements were established drawing on the work of ONEMI (2001), Mück (2008), Samant, Tobin et al. (2008), Taubenböck, Goseberg et al. (2009), Johnstone and Lence (2011), and Scheer, Varela et al. (2012). These include: an appropriate location, accessibility, and certain physical characteristics (area, land cover, slope, capacity to install emergency-relief services such as fresh water, electricity, and communication, etc.). The authors enhanced these criteria according to current efforts aimed to identify public spaces used during the 2010 emergency (Allan, Bryant, 2013, Steccanella, 2012). Finally, 12 open spaces sites were selected as feasible shelter areas in case of a

tsunami evacuation. They are distributed across the north-south axis of the city. Some of them adapt existing urban open spaces (lookouts, parks) whilst others are located in non-built up zones within the city (e.g. hills).

Development of a ground-based proposal

Based on the results of the previous phases, a proposal including a set of urban design recommendations was developed for Talcahuano, aimed at improving the outcome of large pedestrian evacuations in case of a tsunami (see Figure 4).

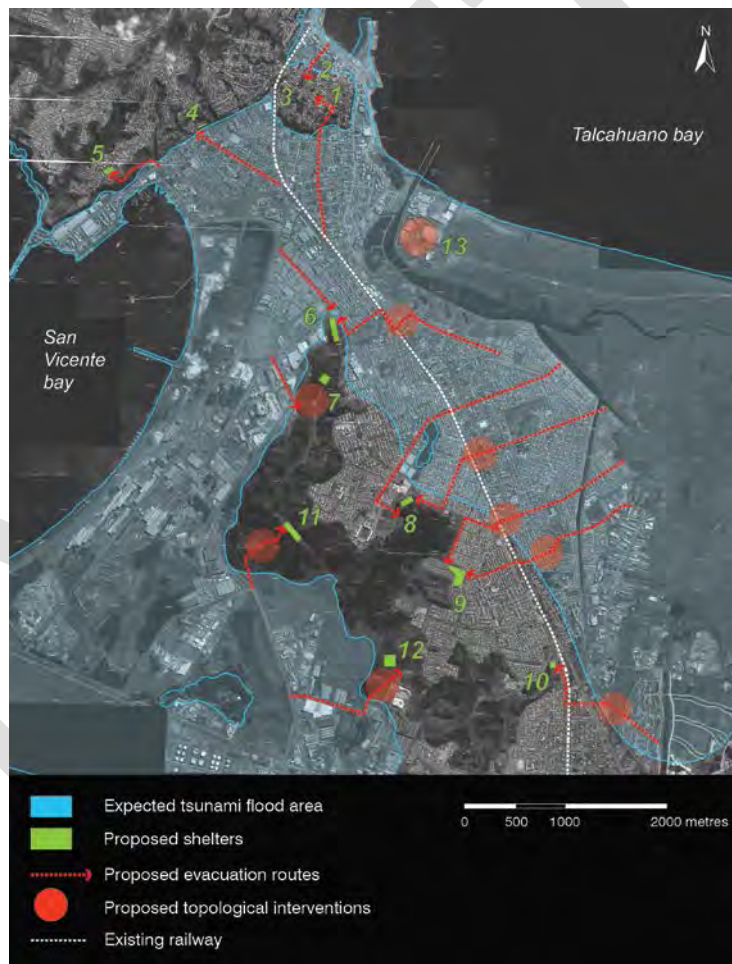


Figure 4: Proposed tsunami-based urban design recommendations for Talcahuano. Source: the authors.

The proposal includes, firstly, the identification of 12 open spaces that might serve as shelter areas during a tsunami emergency, which be used for long periods (for instance, in the case of the 2010

Talcahuano disaster, sea level anomalies were registered for seventeen hours after the earthquake (Barrientos, 2010)). These areas have three main objectives: (1) to provide safe assembly spaces (i.e. above the expected tsunami flood run-up level) during the emergency period; (2) to provide the basic emergency services and utilities, such as first aids, fresh water, electricity, and communication (e.g. wireless phones and internet, radio, etc.); and (3) to become visual vantage points, capable of improving evacuees' wayfinding during night time (by acting as 'beacons' supported by an appropriate emergency illumination) but also adequate to serve as lookouts to constantly assess the ocean behaviour.

It is necessary to underline that these open areas must operate during both emergency and non-emergency times; therefore their main purpose is to provide liveable public spaces that can be permanently used by Talcahuano's dwellers. While some of them (numbers 1, 2, 3, and 9 on Figure 4) are already functioning as public parks, squares or lookouts, the others would require management and modifications to achieve their new role, because they are located on private non-built areas. Shelter 13, in turn, is a special case: in the absence of an appropriate open space, it is proposed as a vertical evacuation point (e.g. tower, platform) whose purpose is to provide safety for the workers from the factories located in the Rocuant Island (see Figure 4). This wholly industrial area is connected to the mainland only by two concrete bridges, which in case of a structural failure during the earthquake would leave those persons in a highly vulnerable situation.

The second part of the proposal addresses the street network. Although the whole network can serve as a pedestrian escape system, desk-based analysis and fieldwork identified 14 routes that are particularly advantageous for efficiently connecting vulnerable areas with safe spaces. Two different types of modifications are suggested: topological and qualitative. Topological modifications are related to changes to the street network's morphological configuration, such as the creation of new streets, or the widening or extension of existing ones. Qualitative modifications seek to enhance the route's evacuation capacities by: (1) improved evacuees' safety (e.g. by additional works such as solar-powered lighting, non-slip materials, guaranteed accessibility for people with special needs, non-sharp and tsunami-resistant furniture elements, pedestrianisation of certain roads, and elimination of specific features such as hanging electrical wires, at-grade gas tanks, intrusive advertising, etc.); and (2) evacuees' wayfinding (i.e. "the process of determining and following a path

or route between an origin and a destination” (Golledge, 1999: 6)); such as tsunami signage (evacuation direction, vulnerability information, etc.) and by modifying features along selected routes. For instance, features such pavements, poles, furniture and facades can be colour coded or themed (see Figure 5). A related outcome could be transformation of selected routes into ‘active memorials’, i.e. everyday places that maintain the memory of tsunami disaster potential.



Figure 5: reference image of qualitative modifications during a night-time evacuation. Source: the authors.

Topological changes are also suggested for eight of the routes (see Figure 4). They are located in the southern area of the city, where dwellings and industries are in particularly risky locations, up to 2 km from safe areas. Routes 7, 11 and 12 that lead to shelters are currently poorly-maintained dirt trails requiring upgrading to become proper evacuation routes, probably including improvement to their current paths. In the case of the routes to shelters 6, 8, 9 and 10, topological changes (extensions and connections) are required to overcome existing physical barriers such as the railway (which currently has only three vehicular crossings and seven narrow pedestrian overpasses), urban blocks, and marshy areas that interrupt the routes’ connectivity to safe grounds.

Assessment of the proposal

Given the multiple competing needs of a city such as Talcahuano, it is important to develop tools to appropriately assess the likely evacuation-related impacts of the proposed changes in urban morphology. While qualitative modifications can be evaluated by matching methods (e.g. focus groups, interviews, etc.), in this paper the analysis focused on quantitative appraisal of the suggested topological modifications, via development and use of an agent-based computer model.

A model is a tool to “gain understanding of and insight into aspects of the real world” (Mas, Adriano, 2013: 286). Agent-based models allow bottom-up, time-based computer modelling where large numbers (maximum hundreds of thousands) of low-level units (agents) are provided with a set of local rules (e.g. interacting between themselves and their environment). The result is an emergent complex system (Chen and Zhan, 2008, Klüpfel, 2003). For evacuation modelling, this procedure allows calculation of the time required to evacuate all agents from an endangered area (Lämmel et al. , 2010).

The model was developed in Agent Analyst (<http://resources.arcgis.com/en/help/agent-analyst/>), an open-source software package integrating the Repast® agent-based modelling platform with the ArcGIS® environment (Johnston, 2013). The model allowed diagnosis of the existing urban tsunami emergency scenario and comparison against the proposed situation with modifications. Three information inputs were used: (i) vulnerable population spatial distribution (agents' starting points) for night-time and daytime scenarios; (ii) the shelter destinations; and (iii) an evacuation route for each evacuee.

The night-time population distribution was obtained from the most recent available population data, the 2002 Chilean Census database (INE, 2002), spatially disaggregated to the block level. The tsunami flooding area from the CITSU project was overlaid with census data. According to this, Talcahuano has 72,675 persons living in tsunami vulnerable zones, approximately 42.4% of inhabitants. Daytime population distribution was determined using census data cross-referenced with land use information regarding places of work and study, and official information about the number of workers and students. Based on commuting related to these activities, there is a population of 69,513 in vulnerable areas during daytime.

The shelter destinations were identified as previously described. For each evacuee's route, the 'shortest path' approach was used to estimate the routes between every evacuee's position (during night-time and daytime) and its closest shelter point; this approach is commonly used in tsunami evacuation models (see for instance Clerveaux et al. , 2008, Di Mauro, Megawati, 2013, Goto et al. , 2012, Sahal, Leone, 2013, Taubenböck, Goseberg, 2009) (in a real context, this route choice could be strengthened by information campaigns, evacuation drills, and signage). The routing calculation was developed outside the model by using the ArcGIS® Network Analyst's 'Closest facility' function.

To run the model, a base free pedestrian speed of 1.4 m/s (5.04 km/h) was used, as suggested by Ando et al. (1988, quoted by Smith, 1995). When every agent 'walked' its route, this base speed was reduced by two types of factors: environmental conditions and density of evacuees. Two environment factors were considered: terrain slope (i.e. steeper gradients lead to slower movement), according to Post et al. (2009); and existing traffic conditions (assumed occupied or abandoned cars reducing available street capacity) according to Mück (2008). These were converted to speed-reduction factors that evacuees encountered (Table 3 and Table 4). Evacuee density, in turn, is inversely proportional to each agent's speed. Ando et al. (1988, quoted by Smith, 1995) provide factors to assess impacts on pedestrian speed from numbers of persons per area unit (see Figure 6). Unlike environmental factors, this is a dynamic value resulting from the interactions of evacuees in space; therefore it has to be assessed for each agent during each of the steps of the model.

Slope (degrees)	Speed conservation (%)
0°	100%
0° - 5°	90%
5° - 15°	80%
15° - 30°	40%
30° - 45°	15%
more than 45°	5%

Table 3: terrain slope and pedestrian speed conservation. Source: adapted from Post et al. (2009).

Road classification					
Width_type	1	1	1	2	2
Traffic volume_type	1	2	3	1	2
Speed Conservation (%)	50%	65%	80%	55%	70%
Width_type	2	3	3	3	4
Traffic volume_type	3	1	2	3	1
Speed Conservation (%)	85%	60%	75%	90%	75%
Width_type	4	4	5	5	5
Traffic volume_type	2	3	1	2	3
Speed Conservation (%)	80%	95%	85%	90%	100%
Legend					
Width	1	One lane small			
	2	One lane wide			
	3	Two lanes small			
	4	Two lanes wide			
	5	Four lanes			
Traffic volume	1	Very much			
	2	Much			
	3	Not much			

Table 4: traffic and pedestrian speed conservation. Source: adapted from Mück (2008).

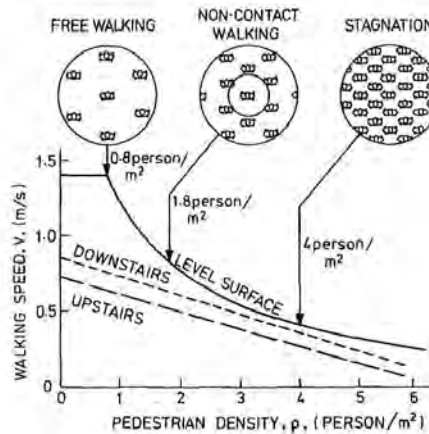


Figure 6: uni-directional walking speed as a function of density. Source: Ando et al. (1988), quoted by Smith (1995).

Processing an evacuation scenario in excess of 70,000 agents is time and computer memory consuming. Accordingly, following Imamura, Muhari et al. (2012) the evacuation area was split into 11 sub-areas, delimited according to the proposed shelters using the 'Closest facility' function (see Figure 7). The sub-areas' simulations were undertaken independently assuming no agent-exchange between areas. For each sub-area, the number of agents varied between night-time and daytime scenarios, according to the previously mentioned population distributions.

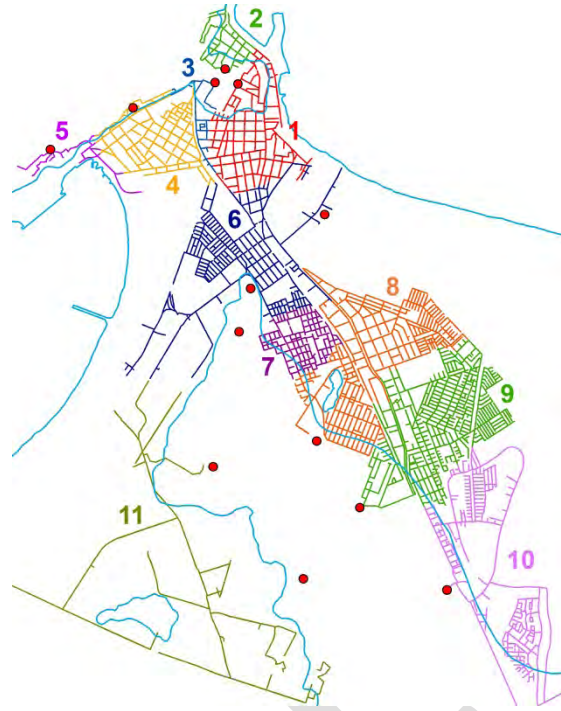


Figure 7: evacuation sub-areas for Talcahuano. Source: the authors.

For each sub-area and time scenario, the model assumed simultaneous departure of all evacuees at time 0. Although not fully realistic (evidence from past tsunami emergencies shows evacuation rates and start times vary from place to place and from tsunami to tsunami (Imamura, Muhari, 2012, Yun and Hamada, 2012)), this is feasible for the assessment purposes of the model. During each step (minute) of the model's run, it recorded the total amount of evacuees that have reached a safe location within each sub-area. Once all agents arrive at their destinations, the model wrote recorded data to a text file (see Figure 8). Table 5, Table 6 and Figure 9 summarize the results of the simulations for the non-modified and modified daytime and night-time scenarios.

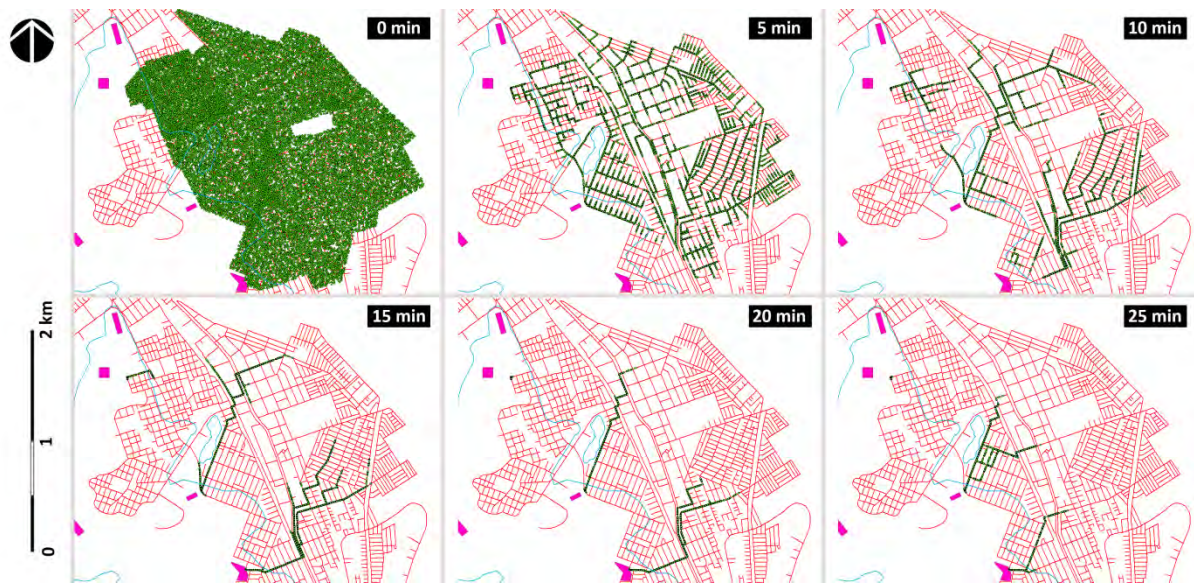


Figure 8: snapshots from the Talcahuano tsunami evacuation model, showing the evacuees, the urban network, the assembly areas, and the expected flooding area. Source: the authors.

Talcahuano		Non-modified evacuation scenarios			
Area	Main land use	Daytime		Night-time	
		Number of evacuees (n)	Total required evacuation time (min)	Number of evacuees (n)	Total required evacuation time (min)
1	Residential - commercial	7627	23	7655	24
2	CBD	1877	19	1003	22
3	Residential - commercial	560	21	880	21
4	Residential - commercial	4535	22	5387	24
5	Port-industrial	1292	27	77	25
6	Residential-industrial	11180	29	11170	27
7	Residential	3697	16	6252	16
8	Residential	10589	38	16655	38
9	Residential	11436	39	15572	39
10	Residential-industrial	6877	37	8019	37
11	Industrial	9844	72	5	17

Table 5: total required evacuation times for Talcahuano, daytime and night-time, non-modified scenarios. Source: the authors.









Talcahuano		Modified evacuation scenarios				Topological interventions	
Area	Main land use	Daytime		Night-time			
		Number of evacuees (n)	Total required evacuation time (min)	Number of evacuees (n)	Total required evacuation time (min)		
6	Residential-industrial	11180	27	11170	21	Vertical evacuation point on Rocuant Island	
						New connection between 'Venecia' and 'Carlos Dittborn' streets	
8	Residential	10589	35	16655	35	Extension of 'Almirante Neft' street	
9	Residential	11436	37	15572	37	Extension of 'Juan Guillermo Sosa' street	
						Extension of 'Las Lilas' street	
10	Residential-industrial	6877	35	8019	35	Extension of 'Calle Seis' street	
						New access road to shelter	
11	Industrial	9844	66	5	17	New access road to shelter	

Table 6: total required evacuation times for Talcahuano, daytime and night-time, topologically modified scenarios. Source: the authors.

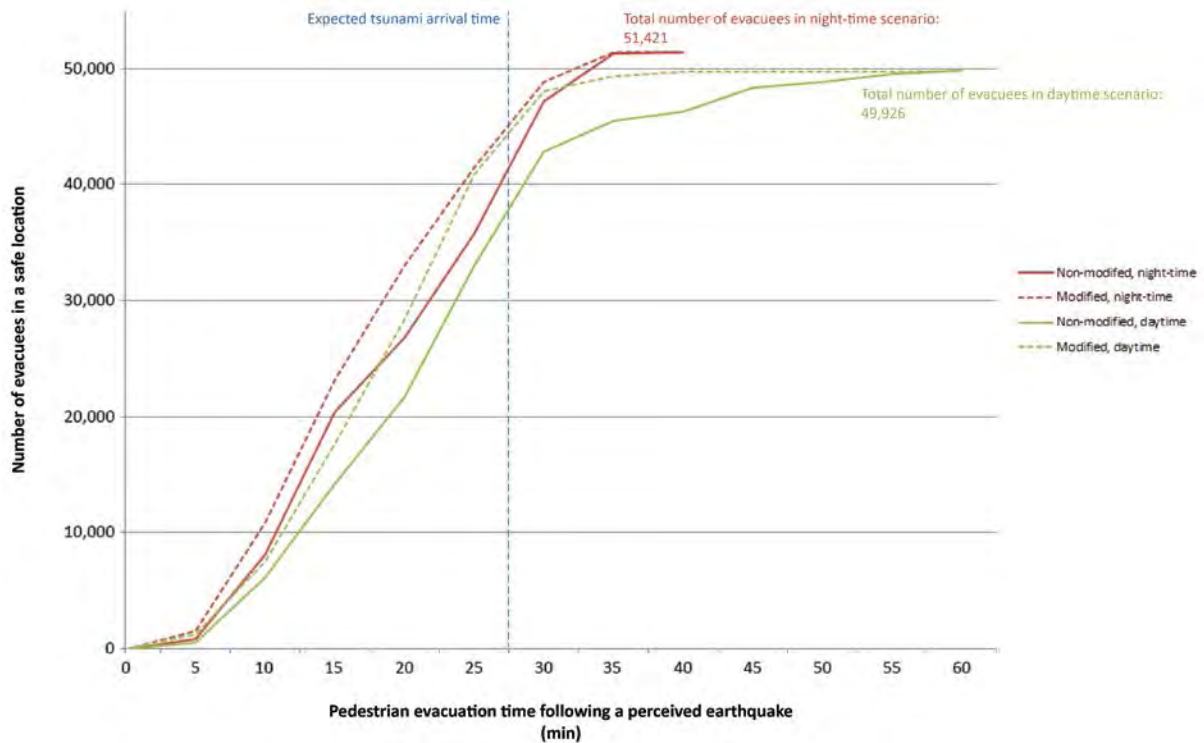


Figure 9: Synthesis of evacuation areas 6 to 11. Number of safe evacuees vs. time in non-modified (continuous lines) and modified (dashed lines) scenarios, for night-time (red) and daytime (blue). Source: the authors.

Discussion

The research results show that Talcahuano's vulnerable areas can be divided (in terms of tsunami evacuation) in two main zones: a relatively safer north zone with lower total evacuation times below 30 minutes; and, a more problematic south zone where complete clearing might take around 40 minutes, including a peak of more than 70 minutes on the south-western industrial area. These results need to be considered against the timing of a tsunami like that modelled in Figure 2 that might hit the coastline approximately 25 to 30 minutes after an earthquake (SHOA, 2000). This research suggested mitigation via particular qualitative and topological modifications in the urban morphology, tested using computer agent-based modelling.

The agent-based model shows that significant improvements to total evacuation times and on safe evacuee numbers could be achieved using specific topological modifications upon the city's urban network. These include changes to key evacuation routes improving connectivity, reducing evacuees' distances to safety. In all examined areas and scenarios (except Area 11 night-time) total modelled required evacuation times were reduced by the modifications. In turn, the number of evacuees being

safe within time before the modelled tsunami, shows noticeable improvement resulting from the topological design recommendations, especially during the middle part of the evacuation (approximately between 10 and 30 minutes after the start). For instance, in the more problematic evacuation areas 6 to 11 during night-time (total number of evacuees: 51,421) at minute 20 there are 32,959 safe evacuees in the modified scenario, in comparison to 26,783 in the non-modified scenario (23.06% improvement). During daytime (total evacuees: 49,926), at minute 20 there are 28,320 safe evacuees in the modified scenario, compared with 21,703 in the non-modified one (30.49% different). See Figure 9.

The model also underlines important quantitative differences between daytime and night-time evacuation scenarios, due to expected differences in population distributions associated with work and educational commuting. Four of the areas analysed (06, 08, 09 and 10) are primarily residential, implying increased night-time populations and corresponding total evacuation times. This information is critical for adequate determination of recommended peak capacities of shelters.

The model's focus is upon assessment and scenario testing, rather than 100% accurate depiction of the tsunami evacuation in Talcahuano. For instance, the 'time 0 simultaneous start' assumption is an optimistic evacuation scenario (even considering that the earthquake itself is the best possible warning). As mentioned above, in reality start times vary between tsunamis and evacuees' characteristics, possibly extending required times for total evacuation. The model also depends upon the quality and accuracy of the base data, including the GIS street network and population information. Triangulation methods, such as fieldwork assessment or cross-referencing with commuting surveys, could help to strengthen accuracy.

Future research might address the specific urban/architecture design of qualitative recommendations for urban networks. In turn, a design research methodology could be developed to support assessment of proposals, involving local neighbours and stakeholders, and including qualitative methods such as interviews and focus groups.

Conclusion

This paper has argued that urban morphology impacts upon a community's specific type of 'rapid resilience', the capacity to rapidly react and cope with a developing threat, by two essential response

activities, evacuation and sheltering. The paper also argues that these capacities can be enhanced by two types of urban modifications: qualitative (enhancement of existing safety and wayfinding characteristics) and topological (i.e. modification of the network's morphology, such as the extension of streets). The approach was examined in the context of a specific type of rapid onset disaster, tsunamis, in a previously affected location, the Chilean city of Talcahuano. To support the analysis, a computer agent-based model was developed.

The results show that the overall evacuation process can be significantly enhanced quantitatively by specific urban modifications. These can be identified, located and designed according to ground-based methods. It was shown that total times for evacuation and rates of safe evacuees "in time" can be improved. Design recommendations can also have important qualitative impacts, providing new liveable public spaces for the city, and creating 'active memorials' that might contribute to maintaining a tsunami prevention culture, a challenge resulting from the long recurrence times of this disaster type.

Finally, it is noted that these design recommendations are part of a theoretical and modelling approach. To be implemented, the modifications would require testing against multiple real-world constraints and competing needs such as funding, traffic implications, engineering requirements, and developing political and social support, among others.

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