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Evaluation of the risk and the evacuation policy in the case of a tsunami in the city of Iquique, Chile

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Abstract The low seismic activity in the north of Chile has caused a significant accumulation of energy throughout the last two centuries. It is estimated that the energy stored could cause an earthquake of magnitude higher than 8.5 M_w. This earthquake poses a threat of tsunami to the coastal zone. The city of Iquique is at great risk due to the high demographic density and the long distances between the coastline and the safety zone. An agent-based simulation model has been developed with the objective of quantifying the answer of Iquique's population under the threat of a tsunami. The model was validated through face validation, sensitivity analysis, and statistical analysis. Two evacuation policies were tested: the current evacuation policy and a policy that combines vertical and horizontal evacuation. The results show that in the diurnal scenario the current evacuation policy does not allow evacuating on time around 40% of Iquique's population and that the risk may be reduced to 33% by incorporating vertical evacuation. This results are based on the time limit established by local authorities that stipulates a time of 20 min to reach the safety zone. Additionally, we consider an analysis of the simulation model combined with a flooding model. Our results show that the number of people at risk because of a tsunami is much lower than the estimates based on the criteria defined by local authorities. Considering an evacuation policy that combines vertical and horizontal evacuation, it is possible to evacuate over 1500 people more than with the current evacuation policy.

Keywords Agent-based models · Tsunami · Vertical evacuation · Validation

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1 Introduction

Chile is a country characterised by a high seismic activity. Earthquakes in Chile are caused by the subduction process of the Nazca Plate under the South American Plate. Frequently, this process releases great amounts of energy, which causes earthquakes of diverse intensities. The possibility of causing a tsunami depends on the magnitude and depth where an earthquake is produced. Since 1562, there have been more than 102 tsunamis registered with an origin close the (Lagos López 2000).

In Table 1 , the earthquakes that have produced tsunamis in Chile, since the twentieth century, are detailed. Recent examples of tsunamis, which have affected the Chilean coasts, took place in the Maule region in 2010, and in the Coquimbo region in 2015. In the former case, there were a total of 521 death tolls, due to the earthquake and subsequent tsunami (Fritz et al. 2011).

Since 1877, there have not been high-intensity earthquakes ($>8.3\ M_s$) in the northern part of Chile, meaning a period of 139 years of accumulation of energy. It is estimated that the earthquakes that have taken place in the area, including the earthquake of April 2014, have not allowed the release of the accumulated energy since 1877 (Schurr et al. 2014). In the same study, Schurr et al. (2014) indicate that the period of recurrence for high-intensity earthquakes in the north of Chile is 111 ± 33 years. Therefore, there is a significant risk of a high-intensity earthquake occurring in the following years. The expected intensity of this earthquake varies in literature. Schurr et al. (2014) affirm that the earthquake should have a magnitude higher than $8.5\ M_s$, while Hayes et al. (2014) consider that the intensity should be close to $9\ M_s$. In both scenarios, the expected magnitude is such that the earthquake may cause a subsequent tsunami, endangering the population of multiple cities.

The case of Iquique is noteworthy for the high demographic density of the city, and for the exposure of the population to the risk of a tsunami. According to the projections of the National Statistical Institute (INE), Iquique has a population of approximately 287,000 people (INE 2012). During the day, the population is concentrated in the city centre and the free trade zone, Iquique's centre of commerce. Both areas are nearby the coastline and at an altitude lower than 20 m above sea level. The National Emergency Management Office (ONEMI) has designated all the areas located at a height higher than 30 m above sea level as a safety zone. Hence, a significant part of the population is exposed to the risk of a

Table 1 List of earthquakes that caused tsunamis in Chile since the twentieth century Source: SHOA (2016)

Year	Epicenter	Magnitude (M_s)
1906	Valparaiso	8.3
1918	Copiapó	7.6
1922	Provincia de Atacama	8.4
1928	Talca y Constitucion	7.9
1943	Illapel	8.1
1960	Valdivia	9.5
1966	Taltal	7.8
1985	Valparaiso	8.0
1995	Antofogasta	8.0
2010	Concepción	8.8
2014	Iquique	8.2
2015	Illapel	8.3

tsunami. Furthermore, the distance between the coastline and the safety zone is greater than 2 km in some areas of the city.

The features of an earthquake have a direct impact on the characteristics of the tsunami that could follow. In this sense, it is impossible to determine a priori the characteristics that a future tsunami may have. Depending on the earthquake, the tsunami may have different direction or time of landfall. Therefore, in order to analyse this problem, case studies are defined according to the different probable scenarios. Cienfuegos et al. (2014) have considered the worst scenario associated to an earthquake of magnitude 9.0 M_w. In their study, they emphasise that the first wave train may reach Iquique's dock in 15 min. An et al. (2014) use another flooding model to simulate the waves produced by Iquique's earthquake in 2014. The result of that study indicates that the arrival time of the tsunami to Iquique is lower than 20 min. Both scenarios contemplate a tsunami that would reach Iquique's coast in a short time and that would endanger its population.

Given the potential risk of a tsunami, ONEMI has established a horizontal evacuation policy that includes only evacuating by foot. Horizontal evacuation consists in a process where people located in areas at risk follow streets and roads to reach the safety zone, in this case 30 m above sea level. Some cities also consider vertical evacuation, which consists in people using tsunami evacuation buildings in order to reach a safe altitude. Vertical evacuation is not recommended in Iquique by local authorities at present.

Furthermore, ONEMI has divided Iquique into 5 areas, with the objective of coordinating the evacuation process, according to the particular need of each area. Zone 1 covers from the northern part of Iquique to Sotomayor Avenue, and includes the industrial quarter and the free trade zone (ZOFRI). These are particularly interesting, since during the day they have a high influx of people and they possess few evacuation routes. Zone 2 covers from Sotomayor Avenue to Libertad Avenue. This zone includes the centre of Iquique, Bellavista Beach, and the dock. Zone 3 is located between Libertad and Tadeo Haenke Avenues. This zone is a residential area, with a significant presence of buildings, and includes the Peninsula sector, a nightlife neighbourhood. Zones 4 and 5 are located to the south of Tadeo Haenke Avenue and are characterised for being residential areas, having a lower influx of people compared to the previous zones, and for having a smaller distance between the coastline and the safety zone. Figure 1 presents the zones, the evacuation routes, and the assembly points established by ONEMI. An evacuation route is a specific street that has to be used by people to move to an assembly point. An assembly point is a designated area within the safety zone, where people should gather in case of evacuation.

Since the tsunami of 2010, the local authority has organised drills in order to evaluate the population's behaviour in an evacuation process under the current evacuation policy. On 8 August 2013, an evacuation drill took place in the Atacama region, the geographical area in which Iquique is located. In Iquique, approximately 76,000 people participated, and the time required to evacuate the city was of 28 min on average (Walker Rousseau 2013). An evacuation drill differs from a real process of evacuation in the perception of risk that affects people. In an evacuation due to an imminent risk, the number of people evacuating should be greater than in a drill, which will generate greater congestion in the evacuation routes. Nowadays, there is no information in order to quantify people's behaviour in a real evacuation process in Iquique.

The lack of knowledge regarding the ability to evacuate the population creates uncertainty and narrows the options for making good policy decisions regarding evacuation strategies. Due to the short time available to evacuate, it is convenient to evaluate the current evacuation policy, the amount of population that is able to evacuate on time, and

Fig. 1 Evacuation routes of Iquique

the alternatives to reduce the risk. A possibility to determine the population's vulnerability is through agent-based models (ABM). This technique enables to study the aggregated performance of a system based on the interactions among agents.

In the present article, a simulation model was conducted in order to evaluate the performance of Iquique's population in a process of evacuation. The model is intended to be a tool for decision-making, regarding evacuation policies in Iquique. Additionally, we have opted for evaluating the use of an alternative evacuation policy that combines vertical and horizontal evacuation, in order to reduce the risk to which the population located near to the coastline is exposed.

The remainder of this paper is organised as follows: Sect. 2 contains a literature review on agent-based simulation models, and of articles about evacuations in case of a tsunami. In Sect. 3, the case of Iquique is described in detail and the simulation model is developed. Section 4 deepens in the validation methodology used, and Sect. 5 presents our results. Finally, the conclusions and discussion derived from the research are presented in Sect. 6.

2 Evacuation models

2.1 Agent-based simulation

ABM[1] is a simulation technique that represents a system as a collection of autonomous entities called agents. Each agent has specific characteristics that distinguish it from other agents. Furthermore, agents posses a set of rules that define their actions. The behaviour of an agent is oriented to objectives. In every instant of the simulation, the agents make decisions on the basis of an objective. These decisions depend on the agents' characteristics, their interactions with other agents, and the environment in which they find themselves. The environment may have diverse characteristics in every point; therefore, it may influence the agents in diverse manners. Time in the agent-based simulation elapses in discrete instants of equal duration. An agent makes a decision in every time unit and acts according to its objective. As the time of the simulation progresses, the system's configuration, and hence, the state of the model, vary.

The great advantage of this simulation method is that it enables to represent decentralised systems, highly heterogeneous, and with active entities. The agent-based models usually consider agents that not only differ in their characteristics, but also in their objectives and in their decision-making rules. These simulation models have been widely used in sociology, economy, and health, among others. Particularly, ABM have been used to study alternatives in order to reduce the inherent risk of certain systems. Examples are the study of building evacuations in case of fire (Meister 2007) or city evacuations. The latter case is addressed in Mysore et al. (2006), who evaluate the evacuation process of the population of New York in the case of a terrorist attack with sarin gas.

2.2 Tsunami evacuation

An evacuation may begin due to multiple factors, such as earthquakes, fire, or terrorist attacks. The nature of the event and the place where it occurs determine the logistics of the evacuation process. In this manner, it is possible to distinguish the evacuation process of a building on fire from a city evacuation, due to a hurricane warning. In the case of fire, the event occurs in a sudden manner, and people must escape through the stairs, probably creating bottlenecks in reduced spaces. In the case of a hurricane, people have probably

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[1] Agent-based models.

been informed of the characteristics of the event, and they have larger spaces to evacuate. Then, in order to simulate correctly an evacuation process in case of a tsunami, it is important to capture the characteristics that distinguish these types of processes.

Mas et al. (2012) define a decision-making structure for agents in evacuations in case of tsunami. In this structure, the first decision that an agent makes is the instant in which it will start to evacuate. That instant is different for every agent, and it is suggested that it should be modelled using a probability distribution. Later, the agent must choose the assembly point where it will evacuate. In the case of knowing the existing assembly points, it is supposed that the agent will choose the closer one; otherwise, he will follow other agents. Then, every agent must identify the evacuation route that it will use. Finally, the agent must regulate the speed depending on internal factors (age and disability, among others), and external factors (congestion in evacuation routes and availability of vehicles, among others).

On their paper, Mas et al. (2012) analyse the case of Arahama, Japan. After the big earthquake of 2011 in Japan (9.0 M_w), the city of Arahama was struck by a tsunami. The aim of the developed model consists in replicating the evacuation process and analyse its performance. An interesting element to analyse is the selection of the evacuation start time. In this case, the start time was modelled through the Rayleigh distribution with the mean uniformly distributed between 7 and 67 min. Then, in every replication of the model, the population had a different mean for the evacuation start time. The limits of the mean were obtained from population surveys and an analysis of revealed preferences.

The evacuation speed selected by each person or group is thoroughly addressed by Goto et al. (2012), in which they consider a tsunami evacuation process in Banda Aceh, Indonesia. In this case, every agent represents a local family. According to information from interviews, the families were classified as fast or slow family, depending on whether the family included children or elderly. Then, the value 5.4 km/h was assigned to the fast group, and 2.7 km/h to the slower one. Furthermore, the possibility of the families evacuating by car or motorcycle was included with a speed of 30 km/h. Regarding the speed reduction factors, the congestion in the evacuation routes has been considered as a determining factor. As the congestion increases in the evacuation routes, the speed decreases according to a concave quadratic function.

The case of Iquique has been previously studied by León and March (2015). They conduct a diagnosis of the urban development of Iquique, and they generate an agent-based model for the city's evacuation. This model was used to evaluate a set of urban modifications on the city, such as changes in the street connections and the construction of buildings for vertical evacuation in the free trade area and the dock. Then, the approach of the study is the analysis of urban planning in Iquique, aiming to improve the responsiveness of the population against a tsunami. The model did not go through a validation process that assures credible results. Our purpose in this paper is to solve issues that were not addressed in the paper of León and March (2015); specifically: the validation of an agent-based model that could enable local authorities to make credible decisions on evacuation policies, a thorough assessment of the current evacuation policy, and to propose changes in the current evacuation policy that enable risk reduction in the short-term.

In Table 2, a summary of specific parameters used in each of the mentioned evacuation studies is included.

Table 2 Cases of evacuations through ABM

Entities	Arahama, Japan (Mas et al. 2012)	Banda Aceh, Indonesia (Goto et al. 2012)	Iquique, Chile (León and March 2015)	La Punta, Perú (Mas et al. 2013)	Padang, Indonesia (Imamura et al. 2012)
	Pedestrians and vehicles	Families and vehicles	Pedestrians	Pedestrians and vehicles	Pedestrians
Number of agents	2271	100,000	Day: 108,881 Night: 83,331	3695	14,352
Expected time of arrival of tsunami	1 h	35 min	20 min	20 min	20 min
% of the population evacuated on time	82%	∼70%	No medido	94%	38%

3 Characteristics of the developed model

The evacuation model was developed in Netlogo (version 5.3.1) and uses GIS data as input to incorporate of street features (length, slope, and width) and location of the population. Each simulation represents the evacuation of the whole population of Iquique and takes around 7.5 min to run in parallel on a procesador 1.80 GHz Intel i5 processor. In this chapter, we present the details of the simulation model.

3.1 Case study

ONEMI has established as a safety area every place located 30 m above sea level. This height is determined based on the flood charts developed by the Chilean Navy's Hydrographic and Oceanographic Service (SHOA) regarding the tsunami that occurred in Iquique in 1877. Furthermore, the local authority has designated evacuation routes and assembly points, where people should evacuate in case of an emergency. The evacuation routes have been defined so that the routes are perpendicular to the coastline, and priority was given to those streets whose direction of transit is heading towards the coast. Hence, in case people use vehicles to evacuate, cars and pedestrians will evacuate on different streets and there will not be any conflict between them.

Regarding the geographical distribution of the population, it has been considered relevant to distinguish two scenarios: a diurnal scenario and a nocturnal scenario. In the diurnal case, the inhabitants of Iquique may be at work, in the commercial area, or in the beach, among others. In this scenario, the free trade area of Iquique (ZOFRI) acquires great importance due to the flow of people that attracts. In the nocturnal case, it has been considered that the population is located in their houses. The location of people in the diurnal scenario has been determined through the Origin-Destiny Survey of the Ministry of Transportation (SECTRA 2010). This survey provides information about the distribution of the population during 5 working days in 41 points of the city. The nocturnal scenario has been modelled with information from the census of 2012. For the particular case of the ZOFRI, it has been decided to model the scenario with maximum influx of people (30,000

during the day Van Blokland et al. 2013). At night, there is no activity in the ZOFRI. No additional scenarios have been considered, for example, distinguishing working days from public holidays, due to the lack of information to generate those scenarios.

The Origin-Destiny Survey establishes the amount of people located at groups of blocks, while the census establishes the amount of people located at each block. Therefore, it is important to notice that there is a difference in the precision of the results obtained for the diurnal and nocturnal scenarios. Due to the unavailability of more precise information, people have been located uniformly within the blocks determined by the survey on the diurnal scenario and by the census on the nocturnal scenario.

The evacuation plan of Iquique only contemplates the evacuation of pedestrians. The city of Iquique is characterised by its relatively narrow streets, a significant number of people located in the tsunami risk area and a great amount of vehicles parked on the streets. Under these circumstances, local authorities have determined that evacuation on vehicles should not be encouraged. Furthermore, the evacuation of pedestrians is considered as the most effective procedure when a quick evacuation is required, and when the massive integration of cars may have a negative impact in the evacuation process (Scheer et al. 2011). Therefore, it is expected that by including cars in the evacuation process congestion will increase, lowering the population evacuation speed. Similarly, the obstruction of streets, due to rubble, or other negative effects of the infrastructure of the city that may result from an earthquake have not been considered.

It has been determined to model the evacuation of zones 1, 2, and 3 of Iquique, since they gather the greater proportion of the population [about 86% of the total population of Iquique (SECTRA 2010)]. Additionally, the distance between the coastline and the safety zone in zones 4 and 5 can be easily covered in time before the arrival of the tsunami (in average the distance is less than 500 m).

According to the evacuation policy established by ONEMI, people have to evacuate in a perpendicular manner to the coastline, following designated evacuation routes. Every route stays within the boundaries of a zone and, thus, there is no flow of people between zones. This assumption relies on: (1) people knowing designated evacuation routes and (2) prioritising evacuation over other activities (e.g. finding family members or gathering personal belongings). The validity of this assumption should be tested on a future study in order to determine whether the inhabitants of Iquique do not cross zone boundaries. For each zone, an independent simulation model has been developed in order to reduce computational costs.

3.2 Resources, entities, and evacuation logic

The evacuation model receives as input geographical information from GIS databases. This information consists in the streets of Iquique, the vertical evacuation buildings, evacuation routes, and designated assembly points. The streets and evacuation routes of Iquique are described on the basis of their width and inclination. Agents use both characteristics in order to regulate their journey throughout the simulation. In the case of the vertical evacuation buildings, according to FEMA (2012) the minimum height required to house refugees in vertical evacuation points corresponds to 3 m above the tsunami run-up. Therefore, only the buildings with space available at a height over 33 m above sea level have been considered. The buildings considered and their respective capacities are detailed in Table 3 and Fig. 2.
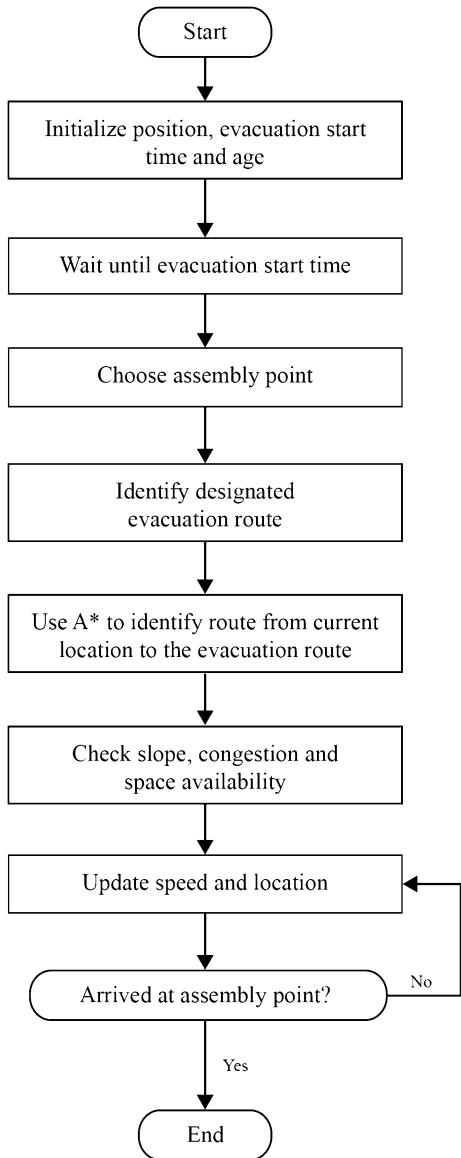
	ID	Address	Capacity (people)
Table 3 Evacuation buildings' capacity	Z1B1	Patricio Lynch 91	450
	Z1B2	Patricio Lynch 60	200
	Z2B1	Esmeralda 528	600
	Z2B2	Arturo Prat Chacón 353	700
	Z2B3	Bolivar 202	400
	Z2B4	San Martín 255	400
	Z2B5	Serrano 145	300
	Z2B6	Costanera 960 Torre A	350
	Z2B7	Costanera 960 Torre B	350
	Z2B8	Esmeralda 340	200
	Z2B9	Arturo Prat 1199	200
	Z2B10	Bernardo O'Higgins 195	700
	Z2B11	Arturo Prat Chacón 1497	300
	Z2B12	Arturo Prat Chacón 430	650
	Z2B13	Manuel Rodriguez 540	350
	Z3B1	Arturo Prat Chacón 889	450
	Z3B2	Amunategui 2130	400
	Z3B3	Amunategui 2090	650
	Z3B4	Arturo Prat 1060	450
	Z3B5	Diego Portales 920	450
	Z3B6	Arturo Prat Chacón 2272 Torre A	1000
	Z3B7	Arturo Prat Chacón 2272 Torre B	1000
	Z3B8	Héroes de la Concepción 2462	550
	Z3B9	Héroes de la Concepción2464	550
	Z3B10	Arturo Prat Chacón 2740	450
	Z3B11	Arturo Prat Chacón 2748	400
	Z3B12	Héroes de la Concepción 2784	700
	Z3B13	Filomena Valenzuela 395	700
	Z3B14	Filomena Valenzuela 770	600
	Z3B15	Pasaje Manuel Matta 2757	1000
		Total	15,050

The modelled entities are the inhabitants of Iquique. Every agent represents one person, who is characterised by its age, geographical position, and the time in which it will start evacuating. The maximum speed of movement is determined according to their age. In the case of children under 10 years old, it has been considered that they will evacuate accompanied by an adult. Additionally, agents have a decision-making structure, which determines the manner in which they will evacuate to the safety zone. In order to model the agents' behaviour, the structure proposed by Mas et al. (2012) has been considered, which has been detailed in Sect. 2.2. Figure 3 summarises the agents decision-making structure. A thorough description of the evacuation logic of the agents will be presented next.

Fig. 2 Vertical evacuation buildings of Iquique

Fig. 3 Agents decision-making
structure

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                    ┌──────────────┐
                    │    Start     │
                    └──────┬───────┘
                           ↓
         ┌─────────────────────────────────┐
         │ Initialize position, evacuation  │
         │       start time and age         │
         └─────────────────┬───────────────┘
                           ↓
         ┌─────────────────────────────────┐
         │  Wait until evacuation start time │
         └─────────────────┬───────────────┘
                           ↓
         ┌─────────────────────────────────┐
         │      Choose assembly point       │
         └─────────────────┬───────────────┘
                           ↓
         ┌─────────────────────────────────┐
         │      Identify designated         │
         │       evacuation route           │
         └─────────────────┬───────────────┘
                           ↓
         ┌─────────────────────────────────┐
         │ Use A* to identify route from     │
         │ current location to the           │
         │ evacuation route                  │
         └─────────────────┬───────────────┘
                           ↓
         ┌─────────────────────────────────┐
         │   Check slope, congestion and     │
         │      space availability           │
         └─────────────────┬───────────────┘
                           ↓
         ┌─────────────────────────────────┐
         │     Update speed and location     │←──┐
         └─────────────────┬───────────────┘   │
                           ↓                     │ No
         ┌─────────────────────────────────┐   │
         │     Arrived at assembly point?   │───┘
         └─────────────────┬───────────────┘
                           ↓ Yes
                    ┌──────────────┐
                    │     End      │
                    └──────────────┘
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3.3 Evacuation start time

The first decision that an agent makes within an evacuation process corresponds to the time when it will start evacuating. This decision is personal and depends both on the risk perception of the individual and the importance that it gives to other activities (finding relatives, gathering belongings, etc.). One approach to model the evacuation start time is to consider that the entire population starts the evacuation process at a determined time. This is the case proposed by Dawson et al. (2011), in which each agent decides whether to start

evacuating or not as soon as local authorities issue a warning. The main problem of this approach is that it does not properly represent the observed behaviour during evacuations.

Since every person chooses to evacuate at different times, it is convenient to model the start time of evacuation of every agent through a probability distribution. Let $F(t)$ a probability function that describes the % of the population that has started the evacuation in the interval $[0, t]$. An accepted approach among researchers is to characterise $F(t)$ through sigmoid curves (Mas et al. 2012). This is because the sigmoid curves enable to represent the general performance of an evacuation process: in the beginning, there is a low percentage of the population that evacuates. As time passes, the participation in the evacuation increases. Finally, as people reach the assembly points, the amount of people evacuating decreases, since the population is finite. Tweedie et al. (1986) suggest the use of the Rayleigh distribution to model evacuations in case of a hurricane, due to the sigmoid shape of its distribution function and domain.

The Rayleigh cumulative function is described by:

$$F(t) = 1 - \exp\left(\frac{-t^2}{2\sigma^2}\right)$$

where σ is a scale parameter that is related to the expected value of the Rayleigh function (μ) throughout the equation:

$$\mu = \int t\,\mathrm{d}F(t)\mathrm{d}t$$
$$= \sigma\sqrt{\frac{\pi}{2}}$$

For the case of Iquique, it has been considered $\mu = 3$ min, due to the following factors:

- Citizen warning system: Iquique has a siren system to warn the population in case it is necessary to evacuate. Once the need to evacuate is confirmed, the sirens are immediately initialised. ONEMI requires 3 min approximately to confirm the need to evacuate.
- Education: Iquique's population is aware of the existing risk of a possible tsunami. The evacuations due to the drill of August 2013, the earthquake of Iquique of April 2014, and the earthquake of Illapel of September 2015 have been useful in order to practice the evacuation dynamics. The local authorities have organised educational campaigns with regard to evacuation, which contributes to improve the response time of people.

3.4 Assembly points and evacuation routes

Our model assumes that all the agents know the evacuation routes and the assembly points established by ONEMI. This assumption is based on the recent experience of evacuations in Iquique, and the results of the drill of August 2013, in which the 92% of the participants showed being aware of the evacuation routes and assembly points (Walker Rousseau 2013).

Once an agent has decided to evacuate, it should choose the assembly point to which it will head. We assume that agents choose the nearest assembly point. Afterwards, agents should decide the evacuation route that leads to the chosen assembly point. The route choice is a key aspect in order to optimise the use of the time available to evacuate. The

	Evacuation routes	Assembly points
Zone 1	5	6
Zone 2	15	39
Zone 3	9	14

current configuration of the evacuation routes and assembly points per zone is detailed in Table 4.

The problem of route choice has been modelled as one of calculating the shortest route in a network. These kinds of problems have been widely studied as graphs, and there are multiple algorithms that enable the calculation of optimum solutions. The whole city of Iquique has been modelled as a graph of 3978 vertices and 4960 edges. In this graph, edges represent the streets of the city and vertices represent street intersections. Since it is necessary to determine the evacuation route for a great number of agents ($\sim$100,000 people), it is important to consider the efficiency when choosing an algorithm to find the shortest route. The algorithm A* has been chosen, because it has a better performance in terms of execution time than other algorithms, among them Dijkstra, when solving the shortest route problem in real streets' networks (Zeng and Church 2009). A* is a heuristic algorithm that operates under the logic of best-first search. In every iteration, this algorithm evaluates the neighbouring nodes and estimates the best route on the basis of the distance travelled from the start node, and an estimation of the route's length that is left to the destination node.

3.5 Speed adjustment

As the simulation progresses, the state of the system varies: agents start to evacuate and evacuation routes become congested. The speed of an individual in an evacuation process has been modelled as a function that depends on 3 factors: physical features of agents, congestion, and slope of the evacuation routes.

The effective evacuation speed of a pedestrian (v_{eff}) is obtained by multiplying the speed that an individual can reach, depending on its physical conditions and on the congestion in the evacuation route (v_c), multiplied by a factor of speed decrease due to inclination (f_{slope}). Then, the effective speed of an agent is attained as:

$$v_{\text{eff}} = v_c \cdot f_{\text{slope}}$$

Regarding physical features, agents have been distinguished by age range. The approximation presented by Goto et al. (2012) has been used in order to model the impact of age and congestion in the evacuation speed of agents. In the case of people between 10 and 65 years old, a speed of evacuation of 1.5 $\frac{m}{s}$ has been considered, while for the case of children under 10 years old and adults older than 65 years old, a speed of 0.75 $\frac{m}{s}$ has been considered. The speed of fast agents remains constant for congestions between 0 $\frac{\text{person}}{m^2}$ and 1 $\frac{\text{person}}{m^2}$ and then decreases for congestions over 1 $\frac{\text{person}}{m^2}$, following a concave quadratic function and reaching its minimum (0 $\frac{m}{s}$) for any congestion over 6 $\frac{\text{person}}{m^2}$. The case of slow agents has been modelled similarly: the evacuation speed remains constant for congestions between 0 $\frac{\text{person}}{m^2}$ and 1.7 $\frac{\text{person}}{m^2}$. Then speed decreases for congestions over 1.7 $\frac{\text{person}}{m^2}$ and reaches a minimum for congestions over 6 $\frac{\text{person}}{m^2}$.

Regarding the impact of the slope, we based our approach on Tobler's law. Tobler's law (1993) establishes that speed can be modelled with an exponential function that considers the slope of the plain. According to Tobler, the walking speed (w_s) in metres per second can be modelled on the basis of the slope ($\frac{dh}{dx}$) through the following formula:

$$w_s\left(\frac{dh}{dx}\right) = 6e^{-3.5\left|\frac{dh}{dx}+0.5\right|}$$

The advantage of this approximation is that it enables to distinguish, in a continuous form, the impact of the inclination on the speed. León and March (2015) consider a different approach to address the impact of the slope on the velocity. On their study, a factor of speed reduction was determined for different slope ranges. For instance, if the slope is between 0 and 5% the velocity is reduced to 90% of its original value. In the case of Iquique, it is not correct to model the impact of slope on velocity considering slope ranges because of the length of evacuation routes (over 2 km in some cases). Since agents have to cover long distances between their initial location and the assembly points, it is convenient to consider the impact that different slopes have on the velocity.

Then, the reducing factor of the speed according to the slope of the plain (f_{slope}) for an inclination $\frac{dh}{dx}$ is calculated as the quotient between the speed according to Tobler's law for an inclination $\frac{dh}{dx}$, and the maximum speed that a person can reach. For the case study analysed, the maximum speed is reached in a plain with no inclination ($\frac{dh}{dx} = 0$). Afterwards, f_{slope} slope is calculated according to:

$$f_{slope}\left(\frac{dh}{dx}\right) = \frac{w_s\left(\frac{dh}{dx}\right)}{w_s(0)}$$

4 Validation

The case study analysed differs from other cases in that the tsunami studied has no occurred yet. The studies detailed in Sect. 2.2 are characterised by trying to replicate an evacuation process that occurred in the past. This presents a great advantage when validating the model, because there is a base case available to compare the obtained results.

Due to the lack of information about evacuation processes in Iquique, it is necessary to use a robust validation methodology, which combines a thorough examination of the models developed with an analysis of the results obtained. Moreover, it is highly recommended to apply an iterative validation methodology in the phase of development of the model. A validation framework has been adopted, which is composed by 3 stages: (1) face validation, (2) sensitivity analysis, and (3) statistical analysis. This methodology is based on the work developed by Klügl (2008) on the validation of agent-based simulation models, and it considers that the work context is characterised by the lack of information about evacuation in Iquique. Face validation consists in a detailed review of the model by subject matter experts. Sensitivity analysis was performed by analysing results over plausible values of the evacuation start time. Finally, statistical analysis was performed by comparing the results of the model and data registered during an evacuation drill in Iquique. The distribution of the population that was considered is detailed in Table 5.

Table 5 Distribution of the simulated population for a validation process	Population
Zone 1	44,557
Zone 2	36,595
Zone 3	18,689
Total	99,841

4.1 Face validation

Face validation consists in a review with experts of the developed model, by way of auditing. Suggested manners to conduct face validation are the animation evaluation of a simulation, the analysis of the obtained results, and the monitoring of an agent's actions. It is important to highlight that the agents' behaviour contains multidisciplinary elements; thus, it is suggested the participation of experts in the relevant areas.

The conceptual model was reviewed with ONEMI's regional director and with researchers of the National Research Centre for the Integrated Management of Natural Disasters (CIGIDEN). The decision-making processes of the agents, the interactions among them and with the environment, and the obtained results have been reviewed. From this review, priority has been given to adapt the model proposed by Mas et al. (2012) to the local reality of Iquique's population. In order to achieve this goal, the observations made of the drill conducted in Iquique 2013, and the videos of the evacuation made after the earthquake of April 2014 were been reviewed. From this analysis, the discussion about the validity of excluding evacuation in vehicles from the model emerged, since observations registered during the drill and videos from the news channels reveal the participation of vehicles during evacuations in Iquique. This dilemma has been solved considering that the results of the developed model present a lower limit for results in a real evacuation process. This is because evacuating by car is considered less effective than evacuating by foot (Scheer et al. 2011).

4.2 Sensitivity analysis

A sensitivity analysis was performed on the average evacuation start time for it is a key parameter of the model. The base case scenario of the simulation of the model corresponds to $\mu = 3$ min. For the present analysis, a pessimistic scenario and an optimistic scenario have been considered. The former considers a delayed response of the population when evacuating. The value of μ used in this case is of 7 min. This value is similar to the one used by Mas et al. (2012). The latter scenario corresponds to an early response of the population. For this scenario $\mu = 1$ min has been considered.

The aim of the sensitivity analysis, beyond the numeric results provided by the model, is to evaluate the coherence between the parameter variations and the emergent patterns. It is expected, a priori, that modifying the value of μ will maintain the general performance of the arrival process, but it will cause variations in the time required by the population to evacuate to the safety zone. In Fig. 4, it can be seen the percentage of the population evacuated, in accordance with the time elapsed once the evacuation process has started, for each of the scenarios mentioned. It can be observed in the graph that when modifying the value of μ, the curve of the evacuation process maintains its shape throughout time, and suffers a horizontal displacement. The fact that the performance of the evacuation process
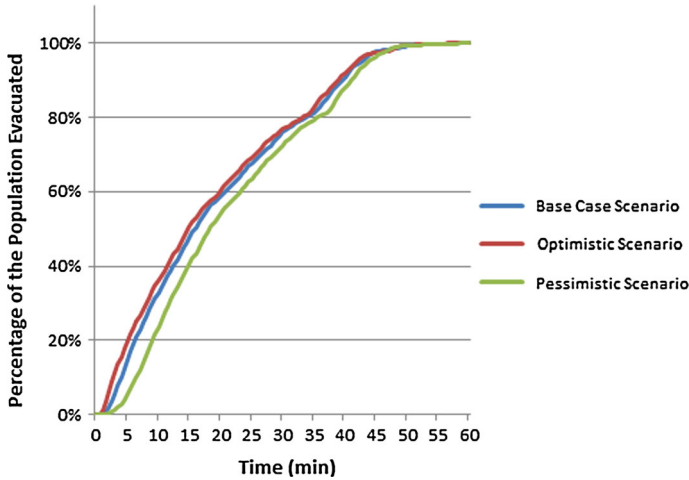
Fig. 4 Sensitivity analysis for μ

is sustained, is coherent with the expectations, because variations in the start time should not have an effect at the macroscopic level, as long as the distribution function of the start time of evacuation and the characteristics of the interaction among the agents remain consistent.

It can be observed in the graph, as well, that from minute 35 on, there is a significant change in the slope. This is due to the massive arrival of people located in the surroundings of the free trade area. The distance between the free trade area and the safety zone is almost 2 km, and in order to reach the safety zone there are essentially 3 evacuation routes, each one with a slope higher than 7%. Moreover, the population simulated in the free trade area is of 30,000 people. Therefore, the change of performance in the process of arrival to the safety zone is coherent with the expectations made before.

Furthermore, the sensitivity regarding μ for each of the simulated zones has been studied. Table 6 shows, for every zone, the percentage of the population that manages to evacuate within the estimated time before the arrival of the tsunami. Based on the results, it can be observed that zones 1 and 3 present a high risk against the threat of a tsunami. In both areas, the amount of people that does not manage to evacuate on time exceeds the 30,000 people in total, even when considering $\mu = 1$. Moreover, it can be observed that zone 1 presents a low sensitivity regarding μ, when compared to the other zones. Then, zone 1 requires an integral solution that goes beyond improving the answer time of the population.

Table 6 Percentage of the population in the safety zone 20 min after the start of the evacuation

μ (min)	Zone 1 (%)	Zone 2 (%)	Zone 3 (%)	Total (%)
1	35.2	89.9	64.0	60.3
3	33.8	87.1	54.5	58.4
7	32.5	80.5	51.0	54.2

4.3 Statistical evaluation

In order to validate the results of the model, the arrival process of the people to the designated assembly points of every zone was analysed. Given the lack of information about the evacuation processes in Iquique, the information registered by CIGIDEN in the drill of August 2013 has been used, in order to validate the results of the model developed. This drill was conducted on Thursday, 8 August 2013 starting at 11:23 hrs. Some people registered the evacuation process at different assembly points in the safety zone. The assembly points registered, which are interesting for the present study, include one assembly point in zone 1, seven in zone 2, and three in zone 3. Every counter registered the amount of people that arrived to the assembly point designated, every 30 s. In total, 12,658 people were registered in the assembly points. From the data registered, a curve of the population arrival was constructed, based on the time. Before comparing the results of the model and the drill, it is important to consider the differences that should be among both of them.

The first significant difference is the amount of people that participated in both events. During the evacuation due to the tsunami risk, it is expected that the population participation is almost complete; while in a drill, the participation is lower due to the absence of risk, and possibly to the willingness of not interrupting the activities that are being conducted. The difference in the number of people participating causes a lower level of congestion in the evacuation routes. This enables the population to evacuate faster in a drill, and it causes less congestion in the bottlenecks. During the drill of 2013, a participation close to 70,000 people is estimated (Walker Rousseau 2013), number considerably lower than the 110,000 people considered in this study.

Another factor that varies is the urgency with which people evacuate. The tsunami risk may cause panic and other emotions that lead people to evacuate at a higher speed in a real case. The effect of this factor is that of a faster initial response on behalf of the population. When increasing the number of people in the evacuation routes, the congestion also increases. This effect is accentuated particularly in reduced spaces with a high flow of people, causing bottlenecks, which results in a lower evacuation speed.

Drill results were compared to the base case scenario ($\mu = 3$ min). Figure 5 presents the arrival process of the population to the assembly points for the drill and for the developed model, according to the time. Initially, both curves present similar results, and as time
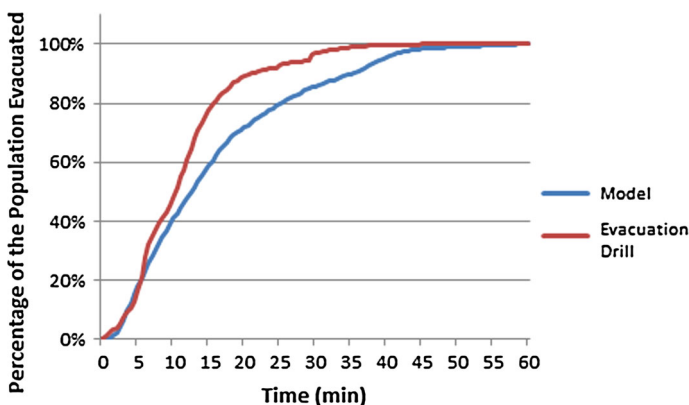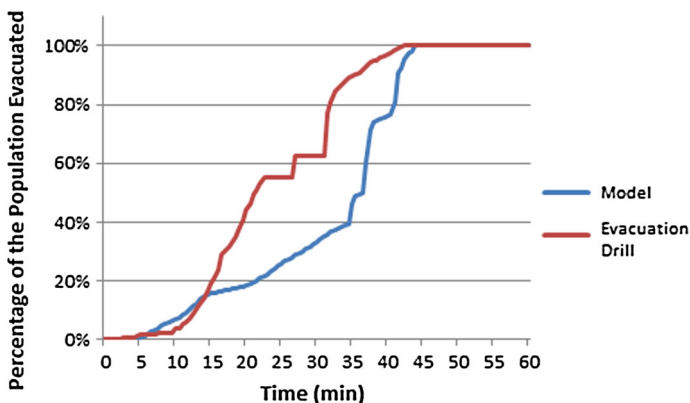

Fig. 5 Arrival of the population to the assembly points of all zones

passes, both curves distance themselves. From minute 6, the model requires more time to evacuate the same percentage of the population. The identified cause for this behaviour is that, as time passes, the evacuation routes become congested and the evacuation speed decreases. This has a greater impact on the model than in the drill, since the amount of people evacuated is higher. Despite the existing differences, the behaviour of the arrival curves is similar in shape. In order to review the similarity of the behaviour between the model and the drill in more detail, an analysis of the arrival at the assembly points was made in each of the simulated zones.

In the case of zone 1, during the drill of 2013 only one assembly point was registered. This assembly point corresponds to the one located in Sotomayor Avenue with Circunvalación Avenue and is one of the two evacuation routes available for the industrial neighbourhood and the free trade area to evacuate. The distance between the assembly point and the free trade area is of 1.8 km. approximately. This situation contrasts with other assembly points in zone 1, whose distance to the evacuation areas is shorter. Therefore, it has been chosen to compare the arrival of people to the assembly point in accordance with the register of the drill and the predictions made by the model. The arrival process to the assembly point mentioned is presented in Fig. 6. In this case, the results provided by the model differ significantly with the register of the drill. It can be observed that the time required to evacuate is considerably higher according to the predictions made by the model. The results distance themselves from minute 15 and reach differences up to 49% in minute 34. An explanation for these differences consists in the case that is being studied. The model contemplates an evacuation from the free trade area in the worst estimated scenario (30,000 people), while the drill was conducted during a day with a smaller flow of people.

Another factor that explains the differences is the simulated population. For the assembly point studied, 7827 people were simulated and the drill registered 1379 people. This factor is even more important in this case, since the assembly point has only one evacuation route (Circunvalación Avenue). People arrive through it and when increasing the congestion, a more accentuated decrease in the speed is caused, in comparison with other cases that have more evacuation routes. Then, it is not possible to compare directly the results of the model with the ones of the drill, because they are two different scenarios. Nonetheless, it can be observed that the model developed presents a worse performance in the evacuation process than in the drill, which is coherent with the greater amount of people simulated in the model.

Fig. 6 Arrival of the population to the assembly point of zone 1

Figure 7 presents the arrival process of the population to the assembly points of zone 2, for the drill of 2013 and for the model developed. The evacuation of 36,596 people was modelled, and in the drill the arrival of 7439 people was registered. The number of assembly points registered in the drill corresponds to 7 out of 14. The curve of arrival of the population predicted by the model is similar to the register of the drill. In general, the value predicted by the model of the population evacuated for a given time is equal or slightly inferior to the value of the drill. Similarly to the previous zones, this difference may be because a greater amount of people was considered in the model, which increases the congestion in the evacuation routes and decreases the speed of people.

An interesting question to explore is why in zone 2, unlike the other zones, the congestion has less impact in the performance of the evacuation. The identified cause is that this zone differs in having more evacuation routes. Subsequently, there is more space available to distribute the population, and the congestion produced in the routes is lower than in other zones. The results of the validation process of the model developed for zone 3 are detailed in Fig. 8. The evacuation of 18,689 people was modelled, and in the drill the arrival of 3840 people was registered. The amount of assembly points registered in the drill
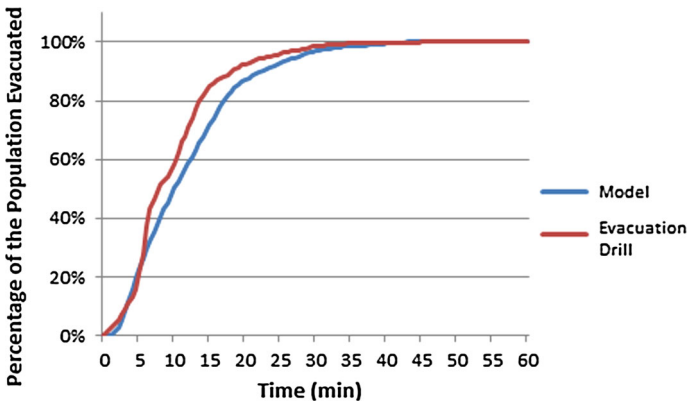

Fig. 7 Arrival of the population to the assembly points of zone 2
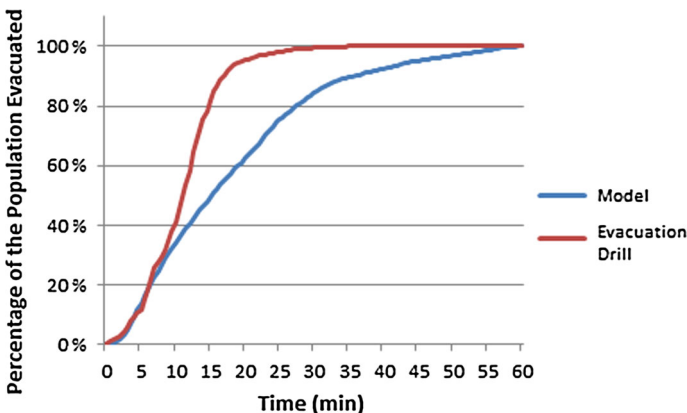

Fig. 8 Arrival of the population to the assembly points of zone 3

corresponds to 3 out of 8. The graph shows that the prediction made by the model is close to the register of the drill, when analysing the first 10 min from the beginning of the evacuation. From minute 10, the curves take distance, reaching the maximum difference at minute 20, approximately.

The reason behind this difference lies in the amount of people who participated in the drill. The model considers a greater amount of people, and zone 3 has a lower amount of evacuation routes. Subsequently, the congestion increases in a more accentuated manner than in other zones, which translates into a lower speed of evacuation. Beyond the differences between the values of the model and the ones of the drill, it can be observed that the difference between both curves is coherent with the expectations a priori.

5 Results

This section covers the results obtained in the diverse scenarios considered (diurnal and nocturnal) and their analyses, for every evacuation policy (horizontal and mixed). A total of 50 replications have been made, amount that guarantees a relative error lower than 1%, and a confidence interval of 99% for the percentage of the population that manages to evacuate within the first 20 min. Each replication considers a different geographical distribution of the population and different evacuation start time for each person.

5.1 Diurnal scenario

The diurnal scenario is characterised by having greater activity in the free trade area, dock, and areas close the beaches. In this scenario, a total of 99,841 people have been simulated, distributed as follows: 44,555 in zone 1, 36,595 in zone 2, and 18,689 in zone 3.

Figure 9 shows the curves of the population's arrival to the assembly points throughout the time for both evacuation policies. It can be inferred from the graph that the mixed evacuation policy enables to significantly improve the performance of the evacuation process in the initial minutes. From minute 35, it can be observed an increase in the slope of both curves, which means an increase in the arrival rate of the population. This is
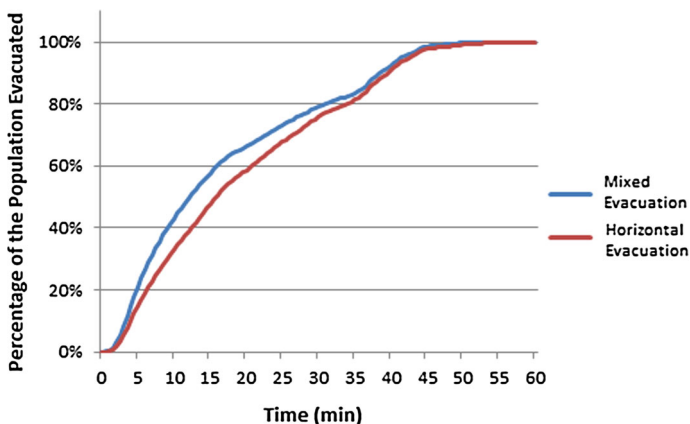
Fig. 9 Arrival of the population to the assembly points in the diurnal scenario

because of the massive arrival of people from the free trade area, case that occurs similarly in both policies.

ONEMI has established a 20-min time limit to evacuate the population to the safety zone, taking into account the estimated arrival time of the tsunami. Table 7 shows the percentage of the population that is able to evacuate in less than 20 min for every zone in Iquique. It is important to note that considering the current evacuation policy, the percentage of the population that manages to evacuate within the first 20 min (limit time according to ONEMI) is of 58.4%. That is to say, almost 41,500 people do not manage to reach the safety zone within the expected time. This result is greatly influenced by the performance of the evacuation in zone 1. This zone has 30,000 people distributed in the free trade area and the industrial neighbourhood, areas whose distance to the safety zone exceeds the 1.5 km.

Another important factor to highlight is the impact of implementing a vertical evacuation policy. The additional percentage of the population that manages to evacuate within the first 10 min, thanks to the mixed evacuation policy, is of 7.9%, which corresponds to 7900 people approximately able to evacuate before because of the mixed evacuation policy.

In the case of zone 1, the performance of the evacuation process of this zone is considerably worse than the global performance of Iquique. Only 33.8% of the population in zone 1 manages to evacuate in less than 20 min. That is to say, nearly 29,500 people cannot evacuate in said time. The implementation of a mixed evacuation policy does not have a greater impact on the performance of the evacuation. After 20 min of evacuating, there is a great difference between both policies close to the 1% of the population from the zone, which corresponds to approximately 450 people more that would be able to evacuate if the mixed evacuation is implemented. The limited impact of a mixed evacuation policy is coherent with the expectations, since in zone 1 there are only 2 buildings available for vertical evacuation, and they are located away from the free trade area. Thus, they are not helpful to evacuate the zone with greater congestion.

Zone 2 presents a significantly better performance than zone 1. Regarding the current evacuation policy, the 87.1% of the population manages to evacuate within the first 20 min. Then, approximately 4700 people are not able to evacuate within that time. The better performance in this zone is due because the population is distributed at a shorter distance from the safety area. Moreover, there are more evacuation routes. This causes a lower congestion in the routes, and the population is able to evacuate faster. Unlike zone 1, zone 2 is characterised by having 13 buildings available for vertical evacuation. The 13 buildings considered are distributed mainly throughout the coastline. This enables the citizens who are away from the safety zone to evacuate in a short time. Therefore, the implementation of a mixed evacuation policy has a positive impact on the evacuation performance. When analysing the performance after the first 20 min, the number of people who do not manage to evacuate is reduced from 4700 with the horizontal policy to 2500

Table 7 Percentage of the population that manages to evacuate in less than 20 min in the diurnal scenario

	Horizontal evacuation (%)	Mixed evacuation (%)
Zone 1	33.8	35.5
Zone 2	87.1	93.2
Zone 3	61.0	87.2
Total	58.4	66.3

with the mixed policy. Then, the use of the available infrastructure to evacuate vertically would become into an important benefit for the population located throughout zone 2.

Zone 3 is characterised by the activity close to the Cavancha Beach, and the commerce of Mall Plaza Iquique. This implies that the population is concentrated in the coastline, at a greater distance from the safety zone. Moreover, zone 3 has more houses and buildings. In total, there are 15 buildings located in the coastline that would enable the evacuation to the places away from the safety zone in less time. Regarding the current evacuation policy, 61% of the population is able to evacuate zone 3 within the first 20 min. This means that approximately 7300 people are not able to evacuate within that time. When evaluating the implementation of a mixed evacuation policy in this zone, it can be observed that 87.2% of the population manages to evacuate to the safety zone on time. This represents an increase of 4900 people approximately who would manage to evacuate on time.

A further analysis has been carried out on the number of inhabitants evacuated and the mean agent evacuation speed for each evacuation route. This analysis considers evacuation routes that would be affected when changing from the current evacuation policy to a mixed evacuation policy, i.e. evacuation routes that are near to a vertical evacuation building; there are 17 such evacuation routes in Iquique, all of them located in zones 1, 2 and 3. Table 8 shows the results for these evacuation routes for the diurnal scenario for both

Table 8 Number of inhabitants evacuated and mean agent speed for evacuation routes that are affected when considering horizontal and vertical evacuation (diurnal scenario)

Evacuation route	Current evacuation policy		Vertical and horizontal evacuation policy	
	Inhabitants evacuated	Mean evacuation speed (km/h)	Inhabitants evacuated	Mean evacuation speed (km/h)
Zone 1				
Sotomayor	3478	3.04	2856	3.17
Zone 2				
Céspedes y González	4181	4.08	3895	4.15
Manuel Rodríguez	1714	4.22	1484	4.38
Vicente Zegers	3190	4.02	2249	4.31
Almirante Latorre	2559	4.22	2405	4.28
Bernardo O'Higgins	1811	4.44	1630	4.50
Esmeralda	2286	4.16	1875	4.17
Thompson	3389	4.23	2646	4.24
San Martín	1654	4.09	1207	4.22
José Joaquín Pérez	1594	4.24	1528	4.24
Zone 3				
Diego Portales	2481	4.11	1565	4.18
Brigadier General Hernán Fuenzalida	8474	2.55	8220	2.56
Las Achiras	1517	4.04	1143	4.03
Libertad	951	3.57	535	3.60
Tadeo Haenke	3219	4.18	1510	4.18
Tomás Bonilla	1722	3.71	1164	3.85
Los Lilenes	1323	3.99	1031	4.00

evacuation policies. In the case of vertical and horizontal evacuation policy the number of inhabitants evacuated for each route is lower than under the current evacuation policy because in the former some people use vertical evacuation buildings, leading to less people using evacuation routes. It is important to notice that it is not possible to compare mean evacuation speed changes between two different evacuation routes because each route has a different width and slope along its length.

As seen in Table 8, adding vertical evacuation to Iquique's current policy not only reduces the amount of people on evacuation routes, but also raises the mean evacuation speed of agents. The most significant differences on evacuation speed are observed at zone 2 on Vicente Zegers (−7%) and Manuel Rodriguez (−4%) streets. Both streets have narrow sections and collect a significant amount of population located near the coastal area. Evacuating people vertically reduces congestion and bottlenecks on these streets, leading to a faster evacuation for agents that evacuate horizontally. Wide streets as Tadeo Haenke and Tomás Bonilla have a greater decrease on the amount of people evacuating (over 30%). However, the decrease on the amount of people evacuating does not have an impact on mean evacuation speed for the congestion is not a limiting factor on these streets.

Finally, there are 2 evacuation routes that exhibit a significantly lower evacuation speed: Sotomayor and Brigadier General Hernán Fuenzalida. In the first case, this is due to narrow sections in that street, while in the second the number of people evacuated is much greater than in other evacuation routes.

5.2 Nocturnal scenario

The nocturnal scenario is characterised by not having activity either in the free trade area or in the industrial neighbourhood, and by presenting a greater demographic concentration in zone 3. Therefore, the focus of study is moved to other risk zones. In this scenario, a total of 80,148 people have been simulated, distributed as follows: 12,364 in zone 1, 34,112 in zone 2, and 33,672 in zone 3.

Figure 10 shows the curves of the population's arrival to the assembly points. The graph indicates that the mixed evacuation policy enables to significantly improve the performance of the evacuation process. When considering a mixed evacuation policy, the
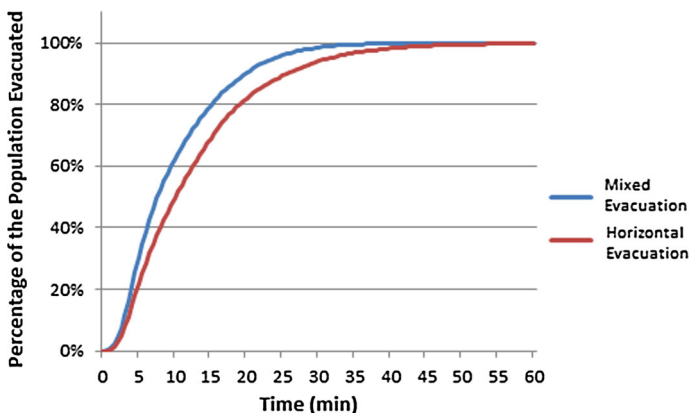

Fig. 10 Arrival of the population to assembly points in the nocturnal scenario

additional percentage of the population that manages to evacuate within the first 20 min is of 7.9%. That is to say, 6300 people are able to evacuate before, considering this policy. As the simulation progresses, the performance of the mixed evacuation policies maintains a better performance than the horizontal evacuation policy. This differs from the diurnal scenario. In the latter, both policies present a similar performance within the last 20 min of the evacuation. In the nocturnal scenario, a different behaviour can be observed, because the segment of the population that manages to evacuate through the vertical evacuation consists of the group of people that require more time to reach the safety zone. Subsequently, the evacuation process regarding the mixed evacuation policy finishes before. Particularly, the evacuation time required to evacuate the whole population of Iquique decreases from 55 to 35 min, when implementing the suggested evacuation policy.

The evacuation process in the nocturnal scenario presents a performance considerably better than in the diurnal scenario. This is mainly due to the absence of activities in the free trade area. The percentage of the population that is able to evacuate within the first 20 min with the horizontal evacuation policy is of 82.4%. This means that nearly 14,200 people are not able to reach the safety zone in said time. This result is greatly influenced by the population located in the coastline of zones 2 and 3. As the vertical evacuation is not allowed, these people must travel long distances to reach the safety zone. The obtained results for every zone and evacuation policy are detailed in Table 9.

In the case of zone 1, the percentage of the population that is able to evacuate within the first 20 min of evacuation is of 87.7%, considering the current evacuation policy. This performance is considerably better than the one observed in the diurnal scenario, which is due to the absence of activities in the free trade area and in the industrial neighbourhood. When considering a mixed evacuation policy, the additional percentage of the population that manages to evacuate within the first 20 min is of 3.85%. That is to say, 436 people are able to evacuate before, considering this policy. The low impact that the change of the evacuation policy has is due to the low vertical evacuation capacity in zone 1 (only 2 buildings).

Zone 2 also presents a considerably better performance in the nocturnal scenario than in the diurnal scenario. The percentage of the population that manages to evacuate within the estimated available time is of 98.8%. That is to say, nearly 400 people are not able to evacuate on time. The implementation of a mixed evacuation policy has a positive impact on the initial minutes of the evacuation process. This is because in zone 2 there are 13 buildings available to evacuate vertically. The additional percentage of the population that manages to evacuate vertically in the first 10 min is of 12.3%. That is to say, 4200 people are able to evacuate before, considering this policy. Therefore, the implementation of a mixed evacuation policy presents a significant improvement with respect to the horizontal evacuation policy, in case the arrival time of the tsunami is lower than 20 min.

Finally, zone 3 presents a worse performance than the previous zones, due to the presence of residential neighbourhoods in the coastline. The distance between the coastline

Table 9 Percentage of the population that manages to evacuate in less than 20 min in the nocturnal scenario

	Horizontal evacuation (%)	Mixed evacuation (%)
Zone 1	87.7	91.5
Zone 2	98.8	99.5
Zone 3	63.5	80.5
Total	82.4	90.3

and the safety zone exceeds the 2 km. in some points, impeding the evacuation of that area in less than 20 min. The percentage of the population that is able to evacuate within the first 20 min with the horizontal evacuation policy is of 63.5%. This means that 12,300 people approximately do not manage to reach the safety zone in said time. Zone 3 has 15 buildings available to evacuate vertically, which means that there is a wide margin of improvement for the evacuation process. The additional percentage of the population that is able to evacuate vertically within the first 20 min is of 17.0%. That is to say, 5700 people manage to evacuate before, when including vertical evacuation. Then, when using the available infrastructure to evacuate vertically, besides the population, the performance of an evacuation process can be significantly improved.

Similarly to the diurnal scenario, the number of inhabitants evacuated and the mean agent evacuation speed were analysed for each evacuation route and each evacuation policy. Table 10 shows the results of 17 out of 26 evacuation routes located in zones 1, 2 and 3, for the nocturnal scenario. In this scenario, the greatest impact on mean evacuation speed is seen in zone 3. Unlike the diurnal scenario, Tomás Bonilla shows the highest increase in mean evacuation speed (6%) when including vertical evacuation. The change on behaviour of this street and zone 3 is due to the greater number of population located at zone 3 in the nocturnal scenario and the availability of few evacuation routes in zone 3,

Table 10 Number of inhabitants evacuated and mean agent speed for evacuation routes that are affected when considering horizontal and vertical evacuation (nocturnal scenario)

Evacuation route	Current evacuation policy		Vertical and horizontal evacuation policy	
	Inhabitants evacuated	Mean agent evacuation speed (km/h)	Inhabitants evacuated	Mean agent evacuation speed (km/h)
Zone 1				
Sotomayor	3120	3.03	2777	3.34
Zone 2				
Céspedes y González	4237	4.22	3944	4.35
Manuel Rodríguez	1664	4.46	1407	4.54
Vicente Zegers	2405	4.31	1864	4.45
Almirante Latorre	2513	4.39	2301	4.40
Bernardo O'Higgins	2925	4.48	2678	4.51
Esmeralda	2564	4.34	2101	4.36
Thompson	3123	4.27	2226	4.31
San Martín	1334	4.27	990	4.31
José Joaquín Pérez	1613	4.37	1481	4.38
Zone 3				
Diego Portales	4461	4.38	3503	4.50
Brigadier General Hernán Fuenzalida	7786	3.79	6623	3.96
Las Achiras	3262	4.28	2896	4.46
Libertad	2249	4.53	1895	4.55
Tadeo Haenke	3742	4.65	2230	4.72
Tomás Bonilla	4486	3.66	4010	3.89
Los Lilenes	2859	4.57	2617	4.60

which leads to congestion on the roads. Evacuation routes in zone 2 shows a less significant change on mean evacuation speed compared to the diurnal scenario. Streets such as Thompson and San Martín have over 25% decrease on the amount of people evacuated and yet the mean evacuation speed decreases only 1% when including vertical evacuation. In this case, the lack of activity on zone 2 coastal area reduces the impact of vertical evacuation on agents' evacuation speed.

A final comment in comparing the diurnal and nocturnal scenarios has to do with a counter-intuitive behaviour in the sense that in some routes the number of inhabitants evacuated increases from one scenario to the other and yet the mean evacuation speed also increases. This is the case of Céspedes y González, Bernardo O'Higgins, Esmeralda, Diego Portales, Las Achiras, Libertad, Tadeo Haenke, Tomas Bonilla, and Los Lilenes. The factors that explain this difference have to do with: age distribution of the population, type of activity on the diurnal and nocturnal scenarios, topology of the evacuation route (width and slope), and distribution of inhabitants along the route (people distributed uniformly along the route or concentrated on the beginning or end of the route). We have examined each of these cases and have found a coherent combination of some of these factors that explain this counter-intuitive behaviour. For example, the Tadeo Haenke route exhibits a greater proportion of middle age population (less population of kids and old people) during the nocturnal scenario, leading to a greater evacuation speed.

5.3 Flooding model

Our evacuation model only evaluates the evacuation process of the population of Iquique, and it considers neither the arrival of the tsunami nor the interaction between the tsunami waves and the people. Now, we would like to consider explicitly the effect of a tsunami. In doing so, we would like to take advantage of the flooding model developed by Cienfuegos et al. (2014) for the city of Iquique.

This study considers an earthquake of magnitude 9.0 M_w, and uses the tsunami propagation model STOC. The model generates time series that indicate the height of the flooding in any point in a determined time. The time series are generated in raster format with grids of 5×5 m. CIGIDEN has provided the time series for zone 1 and zone 2, with information every 5 s. Figure 11 shows the flood height in Iquique's dock throughout time. It can be observed that the first wave train arrives in approximately 15 min to the dock, and reaches a height of 5 m.

According to Dawson et al. (2011) flooding heights that exceed the 25 cm are capable of dragging people and provoking accidents. This height has been considered as a threshold in order to have a conservative estimate of the people that are not able to evacuate on time. We have combined our agent-based simulation model with Cienfuegos' flooding model. As the evacuation simulation evolves, we identify at each time point how many people are reached by a tsunami wave of height of 25 cm or more. These are the number of people affected by the tsunami.

Table 11 presents the results of the simulation model and the flooding model. It can be observed that the number of those affected is considerably smaller than expected, according to the results exposed previously in Tables 7 and 9. This is because the first wave train simulated has an arrival time to the coast close to 15 min, and its run-up does not reach 15 m above sea level. The second wave train arrives after 30 min from the beginning of the evacuation, which is why the population has enough time to evacuate. Subsequently, the simulated scenario differs from the scenario considered by the local authority and that determines the results obtained before.
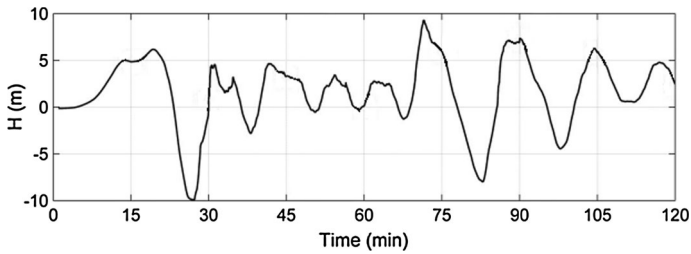
Fig. 11 Flooding height simulated in Iquique's dock. *Source*: Cienfuegos et al. (2014)

Table 11 Amount of people reached by the tsunami

Scenario	Model	Evacuation policy	Number of affected people	Percentage of the simulated affected population (%)
Diurnal	Zone 1	Horizontal	6503	14.6
		Mixed	6147	13.8
	Zone 2	Horizontal	2289	6.3
		Mixed	837	2.3
Nocturnal	Zone 1	Horizontal	1468	11.9
		Mixed	1062	8.6
	Zone 2	Horizontal	2003	5.9
		Mixed	898	2.6

In the diurnal scenario under the current evacuation policy, a total of 6503 people in zone 1 and 2228 in zone 2 (8792 people) affected by the tsunami are registered, while in the nocturnal scenario the number of affected people is reduced to 3472. The difference between both scenarios is coherent with the greater commercial activity in the coastline that can be observed during the day. The most affected zone is zone 1. This is mainly due to the great concentration of people in the industrial neighbourhood and in the surroundings of the free trade area.

The implementation of a mixed evacuation policy enables to evacuate a greater amount of people before the tsunami arrival. In the diurnal scenario, 1808 additional people are not reached by the wave in case a mixed evacuation policy is implemented, while in the nocturnal scenario this number is of 1511 people. The impact of a mixed evacuation policy should be even greater in zone 3, since there is a significant amount of people located near the coastline, and there are more buildings available to evacuate vertically. Therefore, modifying the current evacuation policy to a policy that includes the use of the available infrastructure to evacuate vertically may help to reduce the amount of people affected by the tsunami in Iquique.

6 Conclusions

In this work, the process of evacuation in case of a tsunami in the city of Iquique was analysed. A city evacuation is complex, and involves the interactions among people and the interaction with the environment they inhabit. They main challenge of simulating the

evacuation of a city is to represent in the correct manner the behaviour of the study population. The agent-based modelling enables to define performance structures oriented to objectives and incorporating the effect of the interaction among agents and the environment where they live. This is highly important, since every simulated place presents unique features that define the evacuation process of the population. The main difficulty of Iquique's case consists in the short time in which the tsunami is expected to arrive.

An important limitation when validating the simulation model is the availability of information or the capacity to generate it. In the addressed case, there is little information registered and it is not possible to conduct evacuations in order to generate data to validate. This is because of the high cost that means stopping commercial and industrial activity, and the impossibility to recreate the human psychological conditions that occur when there is en evacuation due to a tsunami. The information registered in drills organised by the local authorities has been considered in order to validate the developed model. Nonetheless, it is convenient to study ways of improving the information availability in order to validate models of this type.

The evacuation process of Iquique was simulated under the current evacuation policy. It was obtained, as a result, that in the diurnal scenario 58.4% of the population manages to evacuate to the safety zone within the first 20 min, while in the nocturnal scenario the percentage increases to 82.4%. There are critical points in the city that have a high demographic density, and which are located at a great distance from the safety zone. This makes more difficult the evacuation within the expected time of the tsunami arrival. Such is the case for the free trade area and the dock.

Given the short time before the tsunami arrival, it is important that the population starts to evacuate as soon as possible. A sensitivity analysis has been conducted for the average start time of evacuation, aiming to evaluate the impact on the performance in the evacuation process. From this analysis, it can be concluded that reducing the start time of evacuation has a minor impact on the percentage of people that manages to evacuate within the expected time. This means that in order to improve significantly the evacuation process of the population, it is necessary to find solutions different to reducing the response time.

An option to reduce the evacuation time required by the population is using the infrastructure available to vertically evacuate the people that are away from the safety area. This would help to evacuate mainly people located close to the coastline of Iquique. The implementation of a policy that includes horizontal and vertical evacuation has been evaluated through the developed model. When analysing this mixed evacuation policy, it can be observed that the number of additional people that manages to evacuate within the first 20 min in the diurnal scenario is 7800, while in the nocturnal scenario it is 6400. The greater impact is observed in zone 3 of Iquique, because of the high concentration of people in the coastline and the great number of buildings available to evacuate vertically.

The greater risk under the current evacuation policy can be observed in zone 1 in the diurnal scenario. Only 33.8% of the population in zone 1 is able to evacuate within the first 20 min of evacuation (see Table 7). There are few buildings available in this zone to evacuate vertically. Moreover, reducing the start time of evacuation enables to improve the performance of the evacuation, marginally. Therefore, it is necessary to design a solution that enables to reduce the existing risk in the zone.

The construction of infrastructure to evacuate vertically may be an unsuitable option for zone 1. This is because the number of people that would have to be evacuated vertically is too high, which would create congestion and bottlenecks. Furthermore, the cost of building infrastructure with space for such amount of people at a safe height is too high. An option to mitigate the risk in zone 1 is to build a seawall that contains or delays the arrival of the

tsunami to land. Jager et al. (2015) determine that the minimum height required for a seawall to contain the tsunami in the worst-case scenario would be of 1.7 m. The higher points of the coastline in zone 1 are located at a height of 4.5 m approximately above sea level, and installing a seawall there would completely contain the tsunami in the worst-case scenario. In total, 29,500 additional people could evacuate to the safety zone.

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