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A GIS-base exploration of the relationships between open space systems and urban form for the adaptive capacity of cities after an earthquake: The cases of two Chilean cities

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A B S T R A C T

In human environments subjected to natural hazards, places such as plazas, parks and free areas can, after a catastrophe, be places for refuge which can satisfy survival needs and support adaptation. The relationships of such an open space system and the urban form, are explored in this study by focussing on the spatial context of two Chilean cities affected by earthquakes. Data was collected in interviews with people from emergency organisations using the Projecting Mapping Technique, and subjected to Content and Geographic Information System analyses to identify the type, utility and distribution of the open space system for earthquake recovery. The objective was to evaluate, by means of different spatial indexes, the extent the open space system of these cities impact on measures associated with urban resilience, namely *overlap in governance* and *diversity*. Findings suggest that the regularity of the grid and city density affect the adaptive capacity of cities, hence, resilience. Findings also shed light on a methodological approach, including participatory and geographical data, through which these resilient aspects can be explored and evaluated in other human environments prone to earthquakes.

Introduction

Based on the continuous increment of human and infrastructure loss after natural and man-made catastrophes, one of the priority measures requested by the Hyogo Framework for Action 2005–2015 in 2005 is to ensure resilience, or the capacity of a system to adapt to unexpected changes, rather than resisting, without losing its basic structure, functions and identity (Walker & Salt, 2006). The theory of ecological resilience poses the idea that a resilient system evolves in an adaptive cycle that includes a release, reorganisation, exploitation and conservation phase (Resilience Alliance, 2010). The phase of reorganisation begins after the destruction, caused by the energy released during a catastrophe (i.e. an earthquake). Similarly, in the disaster cycle discussed by Blanco et al. (2009) the reorganisation stage is known as the response period, or the time after the disaster when actions are taken to minimize damage. Particularly in the urban context, resilience "signifies how planning should be prepared for innovative transformation" (Davoudi et al., 2012, p. 311), which may be explored by looking at the city structure during the reorganisation period of the adaptive cycle: indeed, the reorganisation phase provides a window for exploring the adaptive capacity of the system leading to renewal (Resilience Alliance, 2010), by including the new information acquired during the response period, and in turn, increasing resilience.

Although recent works suggest a large variety of indicators to measure resilience in the physical, economic, social and environmental dimensions (e.g. Ainuddin & Routray, 2012; Blanco et al., 2009; Hutter, Kuhlicke, Glade, & Felgentreff, 2013; Zhou, Wang, Wan, & Jia, 2010), this is an ongoing task. The outcomes depend on the different scales and methodological approaches of the research (Zhou et al., 2010) and the period of the adaptive cycle which is being explored (Resilience Alliance, 2010). Hence, further context-specific studies are needed in different urban settings to capture the specific information that contributes to create more resilient communities. Work developed under this topic underlies a very limited but influential area of study focused on the attributes

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of the open space system and urban form for resilience (Allan & Bryant, 2011; Ishikawa, 2002). This approach is supported by the idea that alternative sites in human settlements are part of a dormant network of streets, squares and parks, among other open areas, which in times of crisis can be prepared to adapt to uncertainty (ISDR, 2005), and provide temporal refuge, information, goods and medical care, among other survival needs.

This paper contributes to this topic by exploring relationships of the open space system (OSS) and the urban form (UF) and by focussing on the spatial context of two South American cities during the reorganisation phase after an earthquake. The objectives are: (1) to identify the OSS that plays a role for adaptation after an earthquake; (2) to explore casual relationships between UF and the spatial distribution of sites and uses of the OSS during the response period; (3) and to contrast attributes of the UF of both cities (i.e. size) that enhance or impede adaptation.

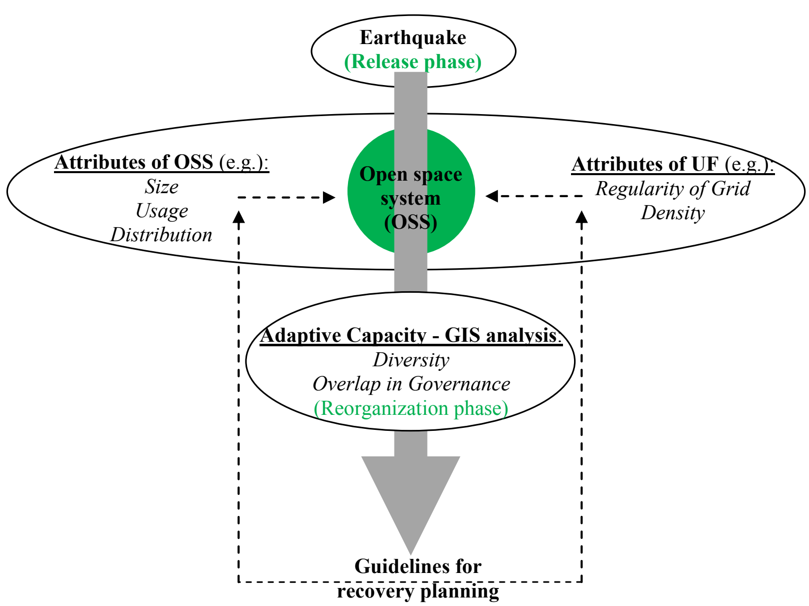
The conceptual model of study of Fig. 1 illustrates the scope of this research, which is focused on the spatial relationships by GIS between the attributes of the OSS, (e.g. distribution, size and usage) and the attributes of the UF (e.g. regularity of the grid and density). These relationships are explored using the *diversity* and *overlap in governance* measures, which are discussed in the next section, that can be influenced by the distribution of the open space network that is used by the community to adapt to disaster during the reorganization phase. The outcomes can inform the extent the system can adapt to disaster with respect to the measures under study, and provide guidelines for improving the attributes of OSS and UF that enhance resilience. These findings can inform about recovery planning and urban system models that improve city adaptability to disaster.

Background

The distribution and characteristics of the open space network have contributed to adaptability of the community (Allan & Bryant, 2011; Ishikawa, 2002). These aspects comprise a set of resilience attributes that have been addressed as measures for urban resilience (Allan & Bryant, 2011; Walker & Salt, 2006).

One measure that has received greater attention in research, in the Japanese context in particular, is the *diversity* of the OSS. It refers to the need of multifunctionality of the open space network (Ahern, 2011). A diverse system offers a wider range of options, or redundancies, to cope with disaster. In the OSS of cities, *diversity* has been evaluated by measuring urban density, a variable which at the same time influences the abundance/scarcity of useful open space (Jacobs, 1993). *Diversity* has been observed in cities with spatial heterogeneity (McGrath et al., 2007). For example, Ishimoto (2000) explored the potential value of the open space in 24 cities finding that *diversity* varies with respect to the size of the open space and percentage of open space, or urban density. He found that 50%–60% of open space observed in middle-sized cities is useful in cases where fires spread after earthquakes. Besides, the size of the open space affects *diversity*. A balance between large and smaller areas (with the smaller units under 1,000 m^2), which provide leisure as well as shelter and are connected to evacuation routes, are recommended (AUHS, 1997). Tachikawa (1997) also studied urban density effects on the multifunctionality of the OSS. He looked at the utility of parks and schools located in the inland area, for the reclaimed land area of Hanshin. He found that as the reclaimed land became denser over time, the inland was more useful. Likewise, as density increases in the city centre, refuge is found on the periphery, where low density areas provide higher flexibility of use of the open space during a crisis.

Another measure which can be influenced by the characteristics of the OSS during the reorganisation period is the *overlap in governance*, which refers to the 'set of capacities' and the efficiency of institutions (Hutter et al., 2013). *Overlap in governance* increases response diversity and flexibility (Gaudreau & Gibson, 2010; Ostrom, 1999) and can reduce the disadvantage of societies in



Note: This model represents the scope of this study. The attributes of the open space and urban form, determine the characteristics of the open space system used by the community in times of crisis. In turn, it influences the *diversity* and *overlap in governance* measures. Then, the understanding of the interaction between the different attributes of the OSS, *diversity* and *overlap in governance*, can provide guidelines for recovery planning by informing about urban system models that enhance city adaptability to disaster.

Fig. 1. Conceptual Model of Study.

disaster prone environments by improving urban resilience. Good governance is particularly important in developing countries (Dunford & Li, 2011) where it can address the needs of poorer communities. Since it has been associated with the redundancy of the governance structure (Walker & Salt, 2006), it is possible to pose the idea that the more the open spaces are within the reach of a variety of institutions, the greater the adaptive capacity of the system during the reorganisation period. In this case, if one organisation fails, others can take its role: besides, areas with different geographical scope can be managed by different organisations at different scales. Indeed, urban resilience occurs when a set of central government and non-government institutions have the capacity to perform equally at different levels when disaster comes (Allan & Bryant, 2011; Godschalk, 2003). Hence, the extent the open space network used for adaptation is well distributed and served after disaster can influence adaptability. With respect to the UF that more effectively facilitates *overlap in governance*, recent studies suggest that a modular urban system, with several units and a polycentric structure may be better served by institutions in times of crisis (Allan & Bryant, 2011).

Methodology

A comparative study approach (Yin, 2004) was taken to explore the extent different UFs of two Chilean cities (Concepción and Valdivia) relate to the attributes of the OSS and affect *diversity* and *overlap in governance*. In short, the set of open spaces used after an earthquake were identified by interviewing professionals from government and non-government organisations engaged in emergency situations. Data was subjected to content analysis to identify the uses associated with the open space network. Afterwards, GIS analysis was undertaken to explore how well the system performs in terms of *overlap in governance* (The Directional Distribution index) and *diversity* (Balance Index and Kernel Density).

Cities of study

The research was conducted in the cities of Valdivia (39°48′51″ S, 73°14′45″ W) and Concepción (36°49′37″ S, 73°02′59″ W) (Fig. 2). Concepción has a population of 212,003 inhabitants and occupies 221 km^2 with a population density of 956.69 per km^2. Valdivia has a population of 140,559 inhabitants, which doubles in size during the summer due to Valdivia's touristic attractions, and occupies an area of 1005 km^2. Both cities have undergone extensive changes during the last century due to urban expansion processes and the effects of earthquakes (e.g. 9.5 Mw in the 1960 Valdivia earthquake; 8.8 Mw in the 2010 Concepción earthquake). A wide range of literature explains their evolution, destruction, reconstruction and relationship with the geographical context in which they are embedded (e.g. Guarda, 2001; Pérez & Salinas, 2007). Valdivia and Concepción have similarities and differences. Both are located next to rivers, surrounded by hills and were founded on the basis of the Spanish grid with a main square that characterises the city centre until today. However, Concepción's city centre is mostly placed on flat land while Valdivias' is located on a more irregular topography with heights ranging from 0 to 30 m above sea level. Both locations have various hills toward the periphery. Besides, urban development has been different for these cities. While the sprawl of the regular urban grid in Concepción has diminished the extension of urban wetlands and hills, incrementing city density, the planning process in Valdivia has been more sensitive to its natural surrounding (Guarda, 2001) and the sprawl of the city has been concentrated along the Picarte Avenue, a wide street that connects the city centre with the wetland area at the south.

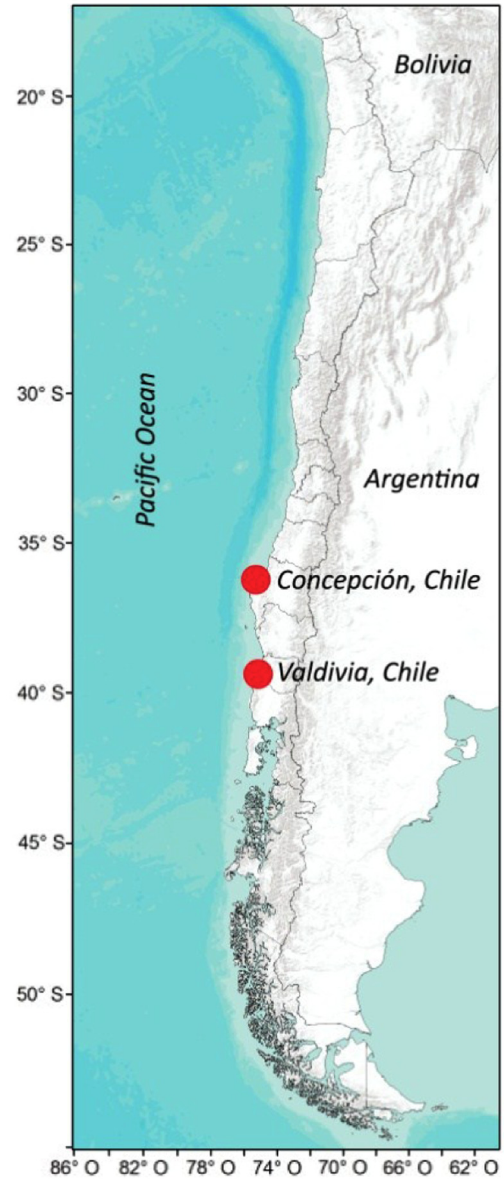


Fig. 2. Location of Valdivia and Concepción in Chile.

Data collection and preliminary analysis

Participants and projective mapping technique

To identify the network of open spaces useful for earthquake recovery, professionals from government and non-government organisations (NGO) were asked to participate in an interview. A total of 14 organisations involved in emergency and recovery procedures after disaster were identified in each city. The sample of participants involved in emergency procedures was prepared based on personal communications with the directors of each institution. A total of 89 people were identified in Valdivia and 84 in Concepción. From this population it was possible to interview 88 (98.87%) and 73 (86.88%) professionals in Valdivia and Concepción respectively (Table 1). Participants were interviewed using the Projective Mapping Technique as used by Green (2005), which consists in showing the participant a map of the cities under study and asking them to identify areas according to their own expertise. Participants were asked individually to identify places which have been useful for earthquake recovery according to their experience.

With this information, it was possible to identify the sites which can be served by each organisation and the frequency of mention. Participants were also asked to provide information on the utility of sites in times of crisis, and to describe their qualities for emergency situations after an earthquake. Each open space was verified on site and then assigned an identifier (ID). Afterwards, sites were grouped by types of open space such as streets, plazas and parks, among others, according to the General Law on Urbanism and Construction of Chile, and used in subsequent GIS analysis.

Content analysis

The utility of sites was subjected to content analysis by following procedures suggested by Weber (1985) to reduce the number of uses described by the professionals to a manageable number. First, words with the same meaning were grouped together to avoid redundancy; second, this new group of data was clustered by uses and organized in descending order by frequency; finally, most frequently mentioned uses were selected for the GIS analysis. This procedure was undertaken by two researchers separately, to assure validity of the results.

GIS analysis and data

Data processing

The outcomes of the projective mapping techniques and content analysis were coded into different matrices ($m \times n$) prepared to code frequency of types of open spaces ($ID \times Type$), utility of open space ($ID \times Use$), size of open space ($ID \times Size\ m^2$) and descriptions of sites ($ID \times Descriptors$). The number 1 was used each time a place, use or descriptor was mentioned by each participant, otherwise, the number 0 was assigned. With respect to the open space size, these were classified into 5 categories, using as a baseline the studies by the Government of Tokyo (2013), Ishimoto (2000) and Ishikawa (2002). Category 1 includes small open spaces of less than 1000 m^2; category 2 (1000–5000 m^2) and 3 (5000–10,000 m^2) include areas up to 1ha and mostly useful for evacuation. In addition, categories 2 and 3 correspond to half and 1 block of the traditional urban grid in Chilean cities. Categories 4 (10,000–100,000 m^2) and 5 (over 100,000 m^2) include open spaces which might be useful for temporal shelter and to supply other demands that arise after an earthquake, such as the provision of services. To further explore the population holding capacity of these sites, the square metre per person was calculated in accordance with Chou, Ou, Cheng, and Lee (2013) and recommendations by The Sphere Project (2004). These indicate that each person requires 4 m^2 of temporal shelter space and 45 m^2 for camp sites which include long term emergency accommodation and various services. The Neighbourhood Unit (NU) was used as the unit of analysis. To develop the spatial analysis, vectorial features and census data were utilised and processed by tools of ArcGIS software. These were provided by the regional governments and municipalities of Valdivia and Concepción and by the National Institute of Statistics. The information was processed using a UTM WGS 84 Zone 18 South parameters of projection including the data collected during the interviews (See Table 2).

Table 2
Maps used during the spatial analysis.

Information	Shapefile typology	Source
Urban limit	Line	Regional Government/Municipality
Urban grid	Line	Regional Government/Municipality
Built infrastructure	Polygon	Regional Government/Municipality
Hydrologic System	Polygon	Regional Government/Municipality
Neighbourhood Units	Polygon	Municipality/Own elaboration
Location of Emergency Organisations under study	Point	Own elaboration
Urban density	Polygon	Own elaboration
Open Space system for earthquake recovery	Polygon/Point	Own elaboration

Spatial index

Three types of spatial index in GIS environment were used: Directional distribution (standard deviational ellipse), Kernel Density and Balance Indexes. These are applied and designed to measure and evaluate the attributes of the open space and their contribution to urban resilience.

Directional distribution index (standard deviational ellipse). This spatial index was used to measure the extent of the

Table 1
Distribution of participants and sample representativeness.

Organisations	Interviews					
	Concepción			Valdivia		
	Expected	Undertaken		Expected	Undertaken	
	Percentage	Percentage	Count	Percentage	Percentage	Count
A. Government Organisations						
ONEMI (O)	3.57	3.57	3	3.37	3.37	3
Regional Government (GR)	3.57	0	0	2.25	1.12	1
Local Government (G)	4.76	4.76	4	2.25	1.12	1
Municipality (M)	3.57	3.57	3	3.37	4.49	4
Army (E)	3.57	3.57	3	3.37	5.62	5
Police Force (C)	11.9	11.9	10	21.35	21.35	19
Civil Defence (D)	3.57	1.19	1	5.62	5.62	5
Firefighters (B)	35.71	34.52	29	26.97	26.97	24
B. Non-Government Organisations (ONG)						
Bío Bío Radio (R)	3.57	3.57	3	3.37	4.49	4
House of Christ (H)	3.57	2.38	2	3.37	3.37	3
Red Cross (CR)	4.76	4.76	4	4.49	4.49	4
A Roof for Chile (UT)	3.57	0	0	5.62	5.62	5
Community Union (UC)	10.71	10.71	9	11.24	11.24	10
Trascender (T)	3.57	2.38	2	3.37	0	0
Total (%)	100	86.88	73	100	98.87	88

Note: (0) indicates cases in which it was not possible to undertake an interview during the time data was collected.

performance of organisations in the cities, or *overlap in governance*. This technique originates from the ecological study of the extension of animal habitats and consists in obtaining a bivariate confidence interval corresponding to the coordinates X and Y. These define the major and minor axes of an ellipse with the smallest possible area. Then the standard distance (Euclidian) is calculated between the centre locations X and Y of sites mentioned by the emergency organisations. Such a structure is represented in a map that shows the realm of sites mentioned by each emergency organisation which takes the form of an ellipse. Each standard deviational ellipse is a summary of data dispersion of a point structure.

In this study, the ellipse is used as a measure of the area of influence of institutions post-earthquake and is given by equation (1).

$$\mathrm{SDE}_X = \sqrt{\frac{\sum_{i=1}^{n}(xi-\overline{X})^2}{n}} \quad \mathrm{SDE}_y = \sqrt{\frac{\sum_{i=1}^{n}(yi-\overline{Y})^2}{n}} \tag{1}$$

Where xi and yi are the coordinates for feature i, $\{\overline{x},\overline{y}\}$ represents the mean centre for the features, and n is equal to the total number of features.

The angle of rotation is calculated as:

$$\tan\theta = \frac{A+B}{C} \quad A = \left(\sum_{i=1}^{n}\overline{xi}^2 - \sum_{i=1}^{n}\overline{yi}^2\right) \quad C = 2\sum_{i=1}^{n}\overline{xiyi} \tag{2}$$

Where $\overline{xi}$ and $\overline{yi}$ are the deviations of the xy-coordinates from the mean centre.

The standard deviations for the x-axis and y-axis are:

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n}\left(\overline{xi}\cos\theta - \overline{yi}\sin\theta\right)^2}{n}} \qquad \sigma_y = \sqrt{\frac{\sum_{i=1}^{n}\left(\overline{xi}\sin\theta - \overline{yi}\cos\theta\right)^2}{n}} \tag{3}$$

The matrix prepared to elaborate the standard deviational ellipses includes the frequency of mention of a site by each organisation, with an individual ellipse being made for each emergency organisation. Subsequently, the centroid was calculated for each site in order to obtain a structure of data points with its respective identifier (ID). The size of the ellipses depends on the number of the standard deviations. In this case, a standard deviation of 1 was used, covering 65% of the open spaces. In addition, a standard deviation of 2 was used in Valdivia covering 95% of the data in order to obtain a more representative view of the following organisations: ONEMI (National Emergency Organisation), Regional Government, Local Government, The Army, Firefighters and A Roof for Chile.

Kernel Density. Kernel Density was used to explore the most used areas and their multifunctionality. The application of this technique shows where points are concentrated. It refers to how a phenomenon is spread across the landscape based on the quantity of a variable, for example population, that is measured at each point. It is also based on the spatial relationship of the points. Usually, it is applied to social phenomenon in crime and health studies (Dai, Zhang, Lynch, Miller, & Shakir, 2013; Valdivia & Castro, 2013). This index explores the spatial variations in event intensity. Specifically, it calculates the uses associated with the open space, in an area around those places (the city). It is based on the quadratic kernel function. A conceptual definition is given by Bailey and Gatrell (1995): if s represents a general location in a network R, and $s^1 \ldots s^n$ are the locations of the n observed events, then the intensity, $\lambda\,(s)$ in s is defined by equation (4), where k is the chosen kernel function, which is symmetric with respect to its origin. The parameter τ is the bandwidth, which defines the radius of a disk centred at s, within which the points contribute to $\lambda\,(s)$.

$$\lambda_\tau(s) = \frac{1}{\delta_\tau(s)}\sum_{i=1}^{n}\frac{1}{\tau^2}k\left(\frac{s-s_i}{\tau}\right) \tag{4}$$

This parameter defines the “smoothing” (continuous transformation) in function of the intensity. Frequency weighting based interaction influences the intensity $\lambda\,(s)$. The calculation was made by using data concentration with respect to the frequency of mention of site according to a specific use for each city (ID $\times$ Use). The matrices used for this case include the frequency of mention of open spaces according to a specific use. These were attached to the layer of points derived from the centroids of each open space, and subsequently used to elaborate a map of density by means of the Kernel Density tool.

In summary, this index shows the density of open spaces mentioned by institutions, around each output raster cell per 1 km^2, represented in five ranges for the two cities (natural breaks classification). The pixel size used was 25 $\times$ 25 m, including a spherical surface type and a radius between 100 and 200 m. The results are illustrated in maps which indicate the urban nodes with more intensity of use. The Kernel Density values are differentiated according to the shade and intensity of a particular colour: the more points located in the area, the greater are the resulting kernel raster values.

Balance Index and open space diversity. Basically, this is the Balance Index proposed by Cervero and Duncan (2003) to compare the land-use diversity dimensions of built environments with mobility conditions. Here it is used to show the balance between built and unbuilt areas, with the aim of exploring the *diversity* of OSSs with respect to urban density (Ishimoto, 2000; Tachikawa, 1997). This index shows the potential *diversity* value of sites in equilibrium with the distribution of the open space. When the value of this index is high, there is less density and a higher percentage of unbuilt area, and the system is potentially more diverse. In contrast, when the value of this index is low, the system is denser and potentially less diverse. The Neighbourhood Unit (NU) was used as unit of analysis.

Specifically, the index used here measures the degree of density of a NU simply by analysing the ratio of square metres of available inbuilt area. It is used by applying the equation (5).

$$\mathrm{DI} = \frac{\sum \mathrm{m}^2\ \text{unbuilt} - \text{up area}}{\sum \mathrm{m}^2\ \text{built} - \text{up area}} \tag{5}$$

The “Urban Grid”, “Built Infrastructure” and “OSS for earthquake recovery” spatial data (shapefiles) were used for this analysis. Technically, this index involves a simple geoprocessing analysis to overlap urban land-use polygons. It computes a geometric division between open spaces and built-up areas per spatial unit (NU). The indicator is expressed as a dimensionless unit. But *diversity* of the system may also depend on the proportion of open space (urban density) and on the variety of size of open space by unit of analysis (Ishimoto, 2000). We explored this by relating the Balance Index value and size variety value of open spaces (1–5 according to the categories described in Section 2.3.2) within NUs with similar density. A unit of analysis with high index value and high variety value is then more diverse.

Results

Site types of the OSS

The data obtained during the projective mapping technique was analysed finding a total of N = 198 open spaces for Valdivia and

$N = 149$ for Concepción. Results of the content analysis suggest seven typologies of open spaces. The most frequently mentioned open spaces are: "green areas" (C = 28.19%; V = 30.61%), such as parks, green strips, plazas, recreation parks; "free areas" (C = 27.52%; V = 28.57%), including football grounds, parking lots and free lands; and the "street network" (C = 18.79%; V = 20.92%) formed by avenues, streets, walkways, passages and roundabouts. "Hills", "water bodies" (lagoons, wetlands and rivers), "courtyards" (including front yards and backyards) and "sites with built infrastructure" (such as aerial, military, aquatic and urban infrastructure) were less frequently mentioned (Fig. 3).

Following the same process of analysis, the predominant uses are for providing "services" (C = 30.61; V = 36.52), including medical attendance, goods and cooking facilities, and for "gathering" (C = 27.52%; V = 24.79%) such as for meeting, finding information and for commemoration. The use of the open space for "temporal housing" (C = 16.25; V = 11.42), such as in tents, and as "water resources" (C = 15.45; V = 10.49), either from a natural source or from water tanks, was also associated with various sites and in both cities (Fig. 4).

Table 3 shows the distribution of use of the open space by type of open space. Pearson correlation coefficients indicate several associations between these aspects. For Valdivia, a positive correlation was found between "free areas" and "temporal housing" ($r = 0.268$) and "debris and waste" ($r = 0.434$). "Green areas" are also positively correlated with "gathering" ($r = 0.318$), "water resources" ($r = 0.263$) and "services" ($r = 0.185$). "Hills" are positively correlated with "evacuation" ($r = 0.200$) and "permanent housing" ($r = 0.244$), and the "street network" shows a strong positive correlation with "evacuation" ($r = 0.754$). Similarly, in Concepción, the "street network" is positively correlated with "evacuation" ($r = 0.615$). Unlike Valdivia, "free areas" are positively correlated with "services" ($r = 0.266$) and "green areas" with "temporal housing" ($r = 0.318$). In this case a positive correlation was also found between "water bodies" and "water resources" ($r = 0.264$) and between "sites with built infrastructure" and "debris and waste" ($r = 0.220$).

Further analysis with regard to the population capacity of the open spaces (Fig. 5) indicates that in Concepción and Valdivia, a 91.83% and 95.84% of NUs respectively, include open spaces that, all together, meet the minimum standard space required per person after disaster (4 m^2). However, when open spaces are grouped by use, it is possible to observe an average percentage of NUs in Concepción (59.19%) and a high percentage of NUs in Valdivia (79.17%) with sites that provide at least 4 m^2 per person for shelter, or the use associated with the "temporal housing" category of this study. There is also a low percentage of NUs in Concepción and Valdivia with sites that provide a minimum of 45 m^2 per person for camps, which can be associated with the "permanent housing" (Concepción = 6.12%; Valdivia = 25.00%) and "services" (Concepción = 8.16; Valdivia = 25.00%) categories in this study.

Concentration of uses

The application of Kernel Density Index provides more specific information about the concentration of open spaces in the city (Fig. 6). These maps illustrate the levels of land use intensification of open spaces for each of the seven uses identified, including a summary map. In Valdivia, open spaces are localised according to a linear spatial distribution with a minimum and maximum average density of 12.24 and 129.21 open spaces per km^2. Instead, in Concepción, open spaces are distributed with a relatively homogeneous spatial pattern, concentric to the city centre and with a minimum and maximum average density of 8.55 and 122.31 open spaces per km^2.

Dispersion of open spaces and overlap in governance

The analysis of the dispersion of sites suggests differences in Valdivia and Concepción (Table 4; Fig. 7). In the case of Concepcion, the ellipses are visually concentrated around the city centre with an average size of 14.68 km^2, and show a slight tendency to spread to the north of the city. The ONEMI ellipse has the largest amplitude with an area of 38.44 km^2 and extends further north and south at an angle of 143.60, surpassing the city limits. In contrast, the ellipse of Trascender covers the lower area of 5.16 km^2, around the city centre. Instead, in Valdivia the results show three overlapping systems of governance and a trend of expansion towards the periphery with an average size of 89.25 km^2. The first system includes the ellipses of the Community Union, Radio Bio Bio and the Red Cross around the city centre, with sizes ranging from 6.20 to 12.30 km^2 and angles from 114.18 to 137.53. The second system is constituted by the Municipality, Police, Civil Defence and the Home of Christ with surfaces of 21.60, 33.10, 40.36 and 39.96 km^2, and angles of 77.52, 79.76, 79.41 and 74.52, respectively. The third system is composed of the Local Government, Firefighters, the Army, Regional Government, the Roof for Chile and ONEMI with surfaces larger than 150 km^2 and angles over 67. Similar to Concepción, the ellipse with less coverage space is the ellipse of the Red Cross, with 6.20 km^2, while the ellipse of ONEMI has more coverage space with 171.10 km^2. This ellipse extends to the far east and west city limits with an angle of 68.65.

Balance Index and open space diversity

In both cities there is a tendency to have denser NUs in the city centre with average values of 0.44 for Concepción and 4.12 for Valdivia, which fall in density towards the periphery with 2.35 and

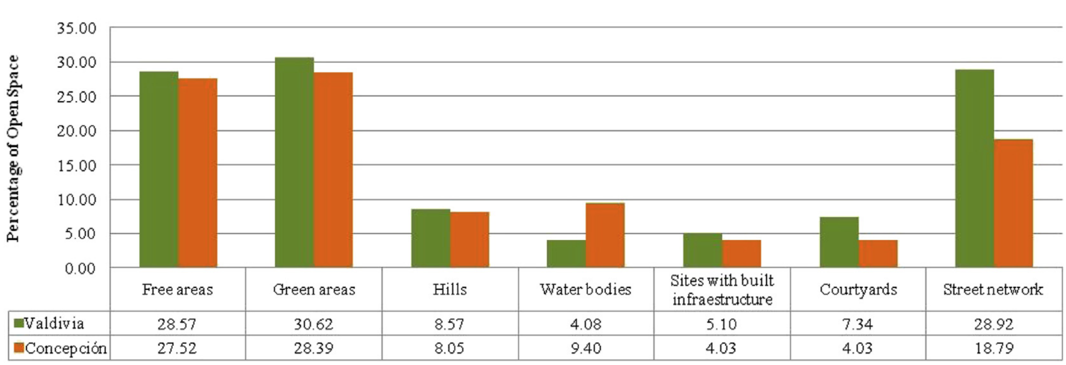


Fig. 3. Type of open space and frequency of mention.

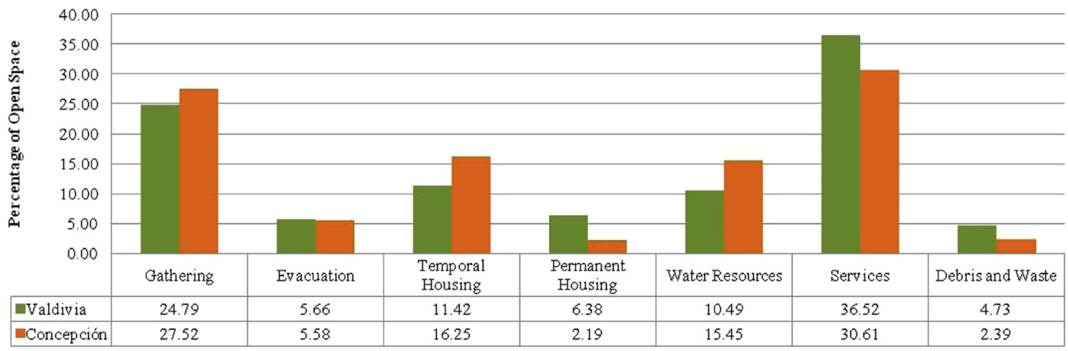


Fig. 4. Use of the open space and frequency of mention.

Table 3
Percentage of use of the open space distributed by type of open space.

CITY	Type/Use	Gathering	Evacuation	Temporal housing	Permanent housing	Water resources	Services	Debris and waste
Valdivia	Free areas	26.13	0.00	41.46	37.50	29.73	31.53	55.56
	Green areas	43.24	5.88	35.37	35.00	45.95	37.84	26.98
	Hills	4.50	9.80	7.32	12.50	0.00	3.60	0.00
	Water bodies	4.50	0.00	6.10	10.00	6.76	4.50	4.76
	Sites with built infrastructure	8.11	9.80	3.66	2.50	5.41	5.41	6.35
	Courtyards	4.50	0.00	4.88	2.50	4.05	9.91	3.17
	Street network	9.01	74.51	1.22	0.00	8.11	7.21	3.17
	Total (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Concepcion	Free areas	33.33	0.00	30.12	18.18	30.77	40.58	42.42
	Green areas	30.11	3.57	40.96	45.45	30.77	36.23	36.36
	Hills	9.68	42.86	12.05	18.18	6.41	2.90	0.00
	Water bodies	8.60	0.00	8.43	9.09	16.67	7.25	0.00
	Sites with built infrastructure	1.08	0.00	1.20	9.09	2.56	7.25	12.12
	Courtyards	2.15	0.00	3.61	0.00	0.00	2.90	3.03
	Street network	15.05	53.57	3.61	0.00	12.82	2.90	6.06
	Total (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00

80.85, respectively. Regardless, the Balance Index values obtained in both cities indicate that Concepción has an overall higher density of built space than Valdivia. A 55.63% of Concepción NUs have a high density with values between 0 and 1.0, while only a 3.57% of Valdivia's units present these indices. In this case, 32.14% of NUs present indices between 2.5 and 5.0, and the 57.14% show indices above 5.0 (Fig. 8), which represent low density. Furthermore, there is a tendency to find more useful space toward the periphery of Concepción, unlike in Valdivia. A total of 34.51% of urban sites are located in peripheral NUs of Concepción. Here, it is possible to find sites on the hilly areas and in areas around large urban infrastructure, such as the regional stadium. On the contrary, in Valdivia, 37.70% of the useful open spaces are concentrated in the city centre - where the city is denser – in the historic district and nearby parks.

With respect to the distribution of site sizes, these are slightly different in both cities. Category 1 ($0 \geq 1.000$ m^2) includes the smaller sites with similar percentages in both cities (C = 10.00%; V = 10.13%). This category is more represented by "courtyards" and "free areas" in Concepcion and by "courtyards" and "green areas" in Valdivia. Category 2 (1000 and 5000 m^2), represented by "green areas" in both cases, and category 3 (5000 and 10,000 m^2), represented by "free areas" in Concepcion and "green areas" in Valdivia, also show similar percentages in both cities (C = 25.83; V = 24.05) (C = 19.17; V = 22.15). Category 4 (10,000 and 100,000 m^2) shows a higher percentage of open space in Valdivia (C = 28.33; V = 34.18)

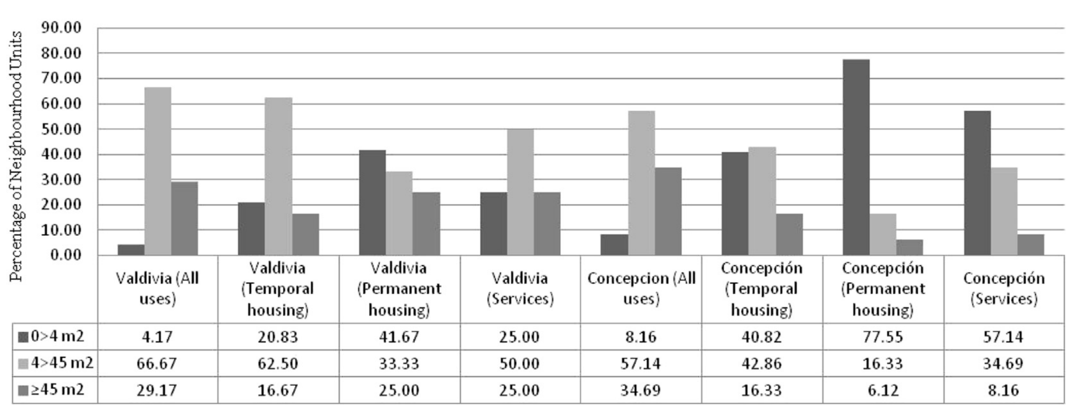


Fig. 5. Population capacity of the open spaces for different uses by Neighbourhood Units.

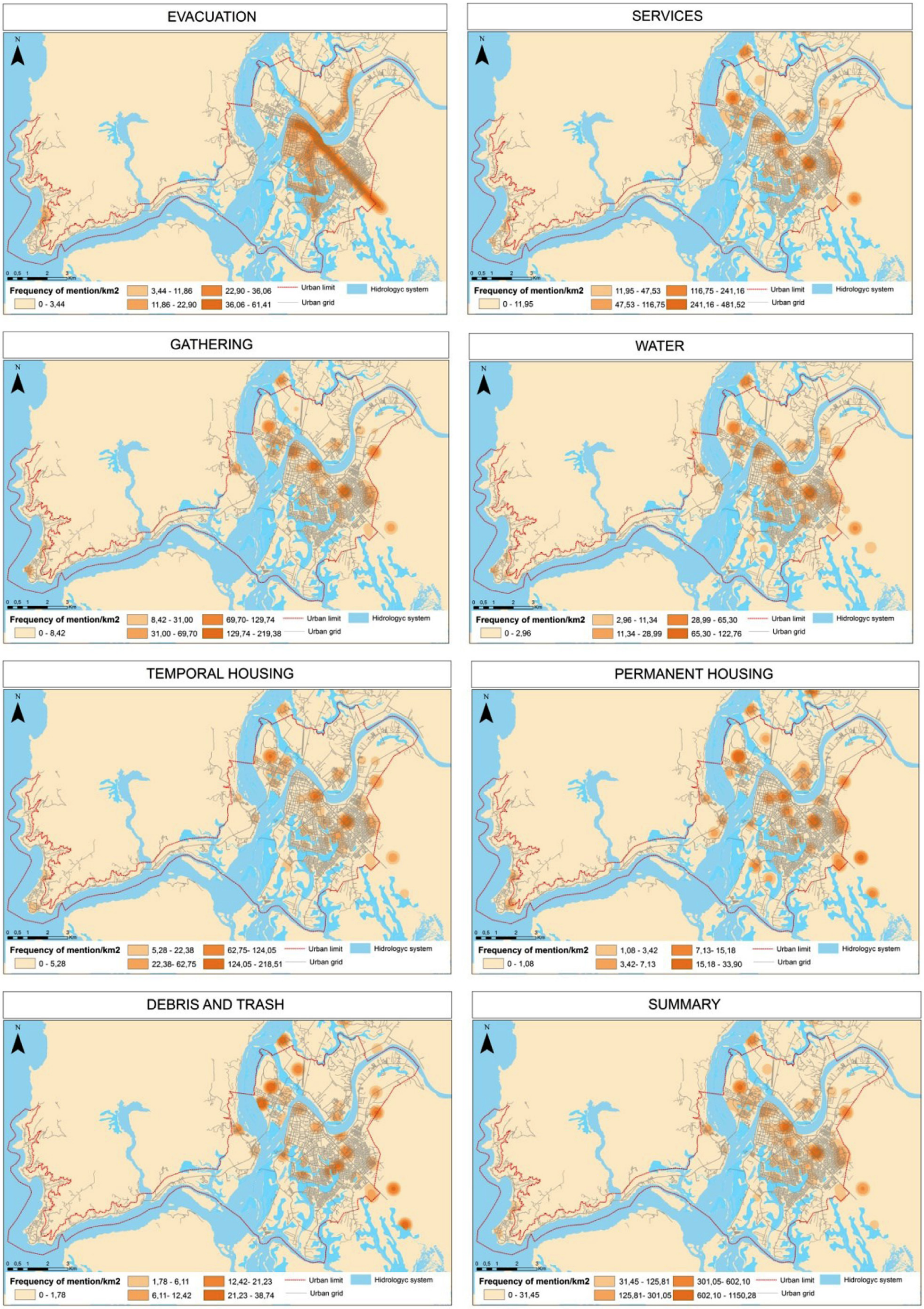


Fig. 6. Example of the Kernel Density maps of Valdivia. Colour intensity indicates concentration of use. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Area of influence of the standard deviation ellipses.

Emergency organisations	Concepción		Valdivia	
	Rotation	Area (km^2)	Rotation	Area (km^2)
ONEMI	143.60	38.44	68.65	171.10
Regional Government	–	–	83.03	183.71
Local Government	2.06	14.05	67.02	151.11
Army	32.50	6.64	69.86	196.75
Civil Defence	92.15	13.04	79.41	40.36
Municipality	65.06	12.72	77.52	21.60
Police	39.69	16.56	79.76	33.10
Firefighters	176.15	18.17	72.23	187.82
Roof for Chile	–	–	72.26	200.77
Home of Christ	56.29	5.37	74.52	39.96
Red Cross	45.24	10.45	128.04	6.20
Community Union	102.92	13.46	137.53	9.92
Trascender	54.31	5.16	–	–
Radio Bio Bio	155.23	22.14	114.18	12.30
Mean value	80	14.68	87	89.25

and category 5 (100,000 m^2) which includes the larger open spaces has a higher percentage in Concepción (C = 16.67; V = 9.49). Both of these categories are mostly represented by “free areas” and “hills” in both cities (Fig. 9).

Discussion

OSS and Urban Grid

The structure of the OSS, in regard to its types and uses, is very similar between cities and to what has been reported in previous studies (Ishikawa, 2002; Ishimoto, 2000). For Concepción and Valdivia, there is a set of seven types of open spaces useful for seven types of different uses in times of crisis. Most used areas are “free areas”, “green areas” and the “street network” and the most frequent uses are for “services” and “gathering”. Further correlation analysis shows that in both cities, “hills” and the “street network” are associated with “evacuation”, also observed in the case of the 1909 earthquake in San Francisco discussed by Allan and Bryant (2011). In their study, they informed that wide streets, large parks, and hills were fundamental for evacuation as well as for social interaction, gathering and finding information.

It is also interesting to observe that “water resources” and “permanent housing” are associated with different types of open spaces in both cities. While in Concepción “water resources” relate to “water bodies”, in Valdivia they relate to “green areas”. A similar situation to Concepción was observed after the Hanshin-kan 1995 earthquake in Kobe, where people gathered near streams, used as recreational sites under normal conditions, and as a source of water after the earthquake. This behaviour influenced the planning and design interventions in the city, by incrementing the number of streams in public streets for improving earthquake recovery (Ishikawa, 2002). It is possible that in Concepción, access to water is also associated with the urban lagoons because they are frequently used by people as they have pathways, urban furniture and managed vegetation. The opposite situation occurs in Valdivia, where most of the urban wetlands lack of recreational facilities. Consequently, people do not visit these sites: hence, this may explain why water is provided in “green areas” most frequently used by the community.

However, the use of sites also depends on their distribution and size, which varies according to the UF and density that can have an impact on the adaptive capacity. The interpretation of the results about NUs density and site size is illustrated in Figs. 10 and 11. The histograms show the balance between large and small sites in NUs grouped by similar Balance Index values. In both cities, the NU with higher index values, or lower densities, have a tendency to have more size diversity of open space. For example, the NUs of Concepción with values between 2.5 and 5.0 comprise a 0.61, 0.61, 0.28, 1.0 and 1.0 average amount of open spaces for categories from 1 to 5 respectively. The trend is similar for Valdivia, where a more balanced distribution of site sizes is observed in the NUs of higher values (5.0–10.0 and >10.0), and the smaller sites are concentrated in the denser NUs located in the city centre. Indeed, Fig. 11 shows that in Concepción, the mean site number tends to increase toward the less dense NUs in the periphery, or those with higher index values. Instead, in Valdivia, sites are additionally concentrated in the city centre where the city is denser.

Tachikawa (1997) observed that there is a strong relationship between the centre and the periphery which can contribute to adaptation and that also seems to be the case in this study. Since a diverse size of sites is needed to host different uses, there is a dependent condition between the city centre and the periphery as suggested by Tachikawa (1997), as one can serve the other one in times of crises. In this study, such dependency is conditioned by urban density which can influence the multifunctionality of the OSS in terms of its size. Indeed, the current Disaster Mitigation Plan in Japan includes five different open spaces for six different functions after an earthquake. These vary from 500 m^2 for neighbourhood evacuation sites to those over 50 ha for wide regional disaster mitigation centres (Government of Tokyo, 2013). In this regard, assuring ease of access between the centre and the periphery, and between NUs with strong differences in urban density, can add to the adaptive capacity of cities.

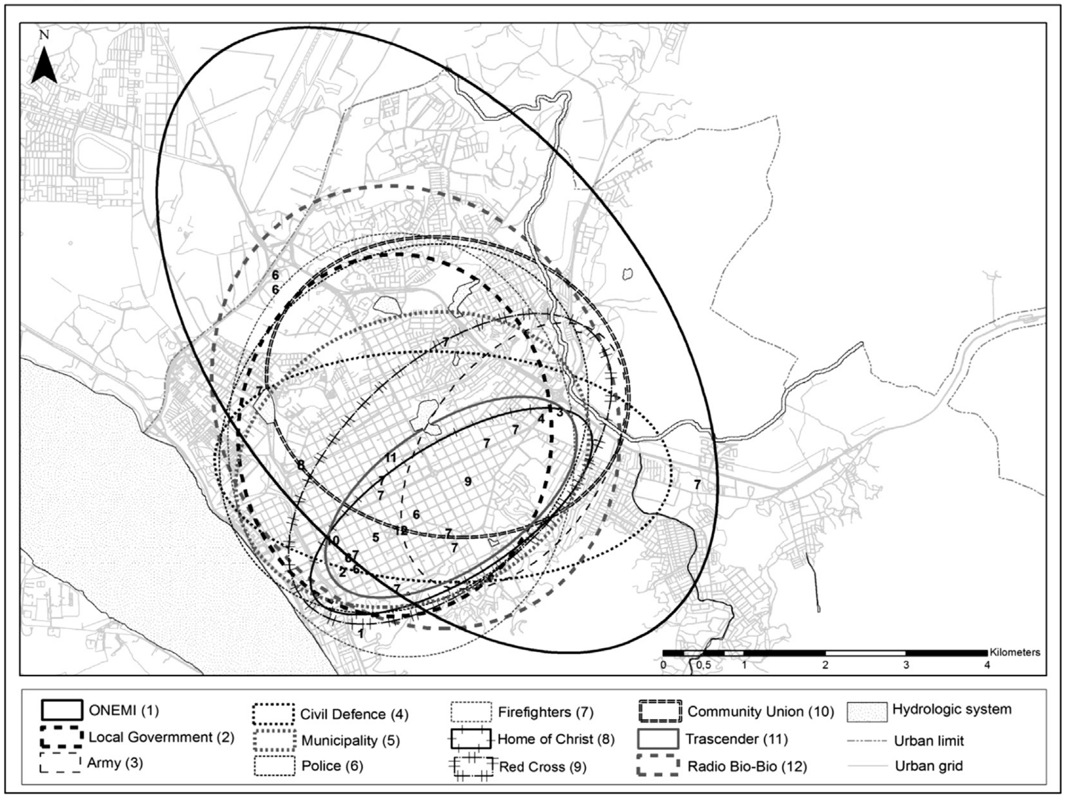
OSS and diversity

The *diversity* in the distribution of the OSS has been addressed as a resilience aspect that has an impact on the adaptive capacity of cities after disaster (Jacobs, 1993; McGrath et al., 2007). This is an important finding to consider because the application of the Kernel Density index shows that the distribution of the OSS varies between Valdivia and Concepción.

Fig. 12 a. shows that in Concepción, there are nine nodes of greatest intensity of use with a homogeneous distribution in the city. Some of them relate to specific historical places and geographical attributes (Nodes 1, 2, 3 and 4), others are in association with the hydrologic system (Nodes 5, 6, 7, 8), while another (Node 9) is placed in a strategic area, in an infrastructure and transport node. In contrast, nodes in Valdivia illustrated in Fig. 12 b, are mostly concentrated along Picarte Avenue, one of the oldest and wider streets in the city, which runs from the city centre to the south exit. The nodes include historic areas (Nodes 1) parks with water facilities (Node 2 and 7), hills on the periphery (Nodes 4, 5 and 6), and key infrastructure and transport sites along Picarte Avenue (Node 3).

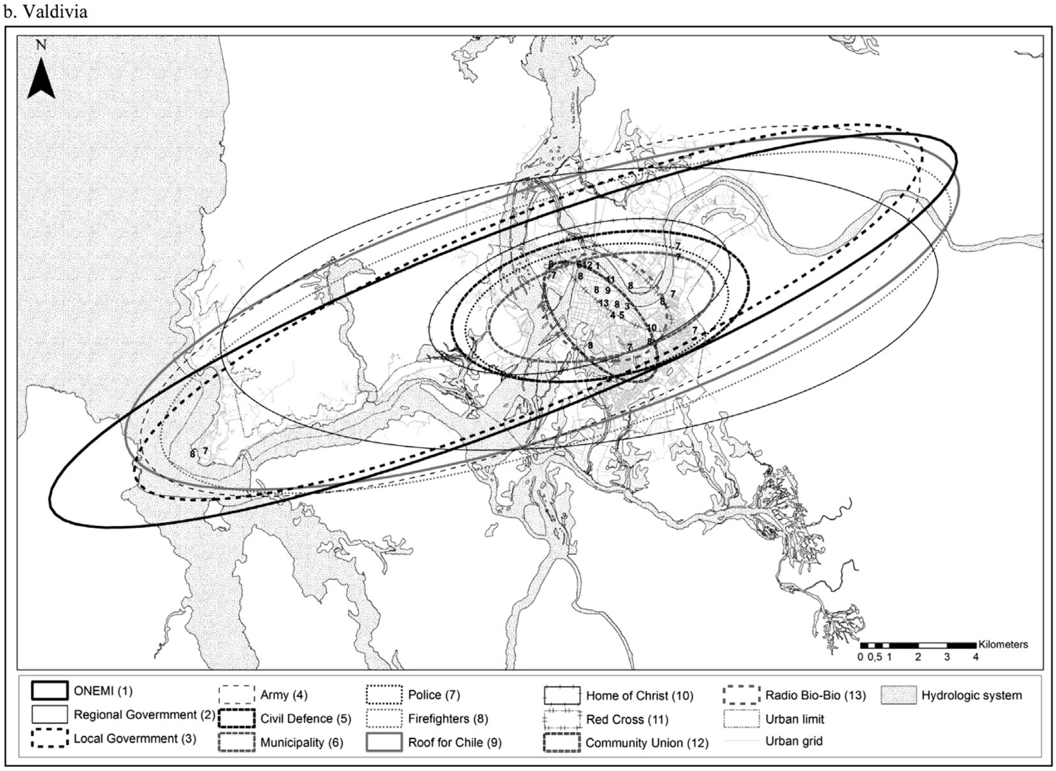
The comparison of these results with other studies is interesting to discuss because they can suggest which city shows more adaptive capacity in respect to spatial heterogeneity and UF. Allan and Bryant (2011) observed that during the aftermath of the 1910 earthquake in San Francisco, the set of widest streets of the city helped to connect people from the harbour to the highest areas, enabling safe evacuation from the fires. This also may be the case for Valdivia, because most of the nodes are placed along the main avenue, where the population gathers and circulates. However, Picarte was the only street observed with these attributes in Valdivia. As pointed out by Walker and Salt (2006), redundancy and *diversity* of the parts of the system are required for this to be considered as resilient. If Picarte fails, then the entire system fails, because no similar street can replace Picarte for the accessibility to

a. Concepción



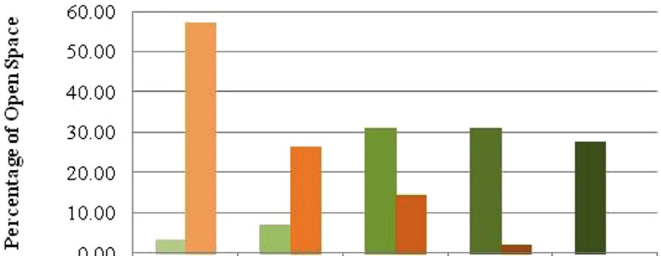
Note: The location of organizations refers to the number in parenthesis.

b. Valdivia



Note: The location of organizations refers to the number in parenthesis.

Fig. 7. Standard deviational ellipse results showing the Overlap in Governance in Concepción and Valdivia.



	0.0 - 1.0	1.0 - 2.5	2.5 - 5.0	5.0 - 10.0	> 10.0
Valdivia	3.45	6.90	31.03	31.03	27.59
Concepción	57.14	26.53	14.29	2.04	0.00

Fig. 8. Distribution of amount of Neighbourhood Units by Balance Index.

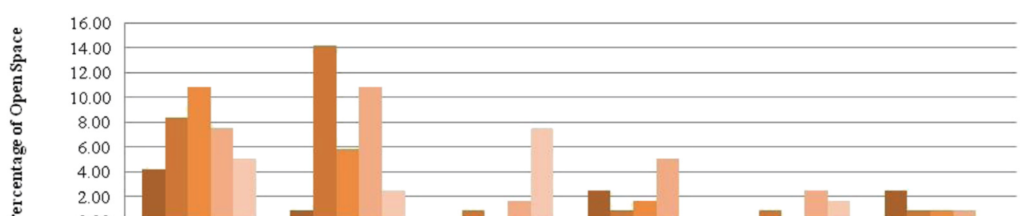
different sites and uses. The linear pattern of concentration observed in Valdivia may not contribute to adaptation to the extent it did for San Francisco, where having a set of wide streets with these attributes was fundamental for urban resilience. Accordingly, Concepción, with a more dispersed concentration of the OSS which is distributed on a regular street grid that eases accessibility, shows a more adaptive capacity than Valdivia.

Nonetheless, if the population holding capacity of the open space system is insufficient, this can complicate community recovery, regardless of the dispersed distribution of the OSS. Fig. 5 shows that the OSS in both cities provides the capacity to give shelter to the entire population; however, there are NUs without enough open space for assisting their community, particularly with respect to temporal and permanent housing and services (Fig. 5). It is possible that after an earthquake, the number of people requiring relocation is less than the entire population. It is also possible that several NUs can host people from different districts. But the damage caused by earthquakes is unpredictable, and people usually prefer to stay close to their house and neighbourhood after disaster. For this reason, Chou et al. (2013) recommend that government organizations should estimate the number of displaced people after disaster based on different earthquake magnitudes and building structures, and by this means, take decisions whether or not to allocate additional infrastructure in districts with insufficient shelter capacity. This recommendation should be taken into consideration by the local government of Valdivia and Concepción and in addition, emergency plans should clearly state the size, use and holding capacity of sites used for earthquake recovery.

Overlap in governance and urban growth

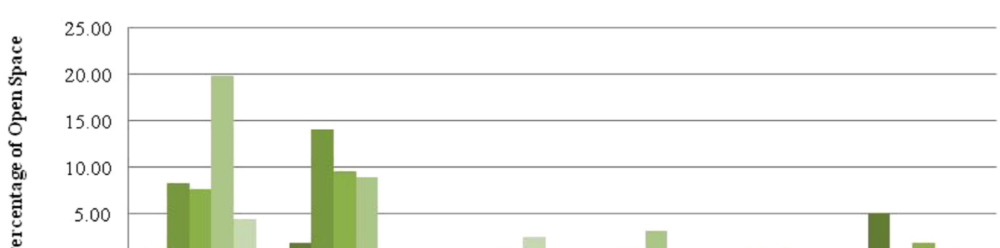
The results of the Directional Distribution indicator are interesting to interpret because the resulting area of the ellipses is an indicator of the spread of open spaces with respect to the urban centre. If the size of this area extends, it could be interpreted as spatial awareness of useful space for urban resilience. Therefore, the points in space and the angle of the main axis of

a. Concepción



	Free areas	Green areas	Hills	Water bodies	Sites with infraestructure	Courtyards
0≥1.000 m2	4.17	0.83	0.00	2.50	0.00	2.50
1.000≥5.000 m2	8.33	14.17	0.83	0.83	0.83	0.83
5.000≥10.000 m2	10.83	5.83	0.00	1.67	0.00	0.83
10.000≥100.000 m2	7.50	10.83	1.67	5.00	2.50	0.83
>100.000 m2	5.00	2.50	7.50	0.00	1.67	0.00

b. Valdivia



	Free areas	Green areas	Hills	Water bodies	Sites with infraestructure	Courtyards
0≥1.000 m2	1.28	1.92	0.00	0.64	0.64	5.13
1.000≥5.000 m2	8.33	14.10	0.00	0.00	1.28	0.00
5.000≥10.000 m2	7.69	9.62	0.64	1.28	1.28	1.92
10.000≥100.000 m2	19.87	8.97	1.28	3.21	0.64	1.28
>100.000 m2	4.49	0.64	2.56	0.64	0.64	0.00

Fig. 9. Type of open space distributed by size category.

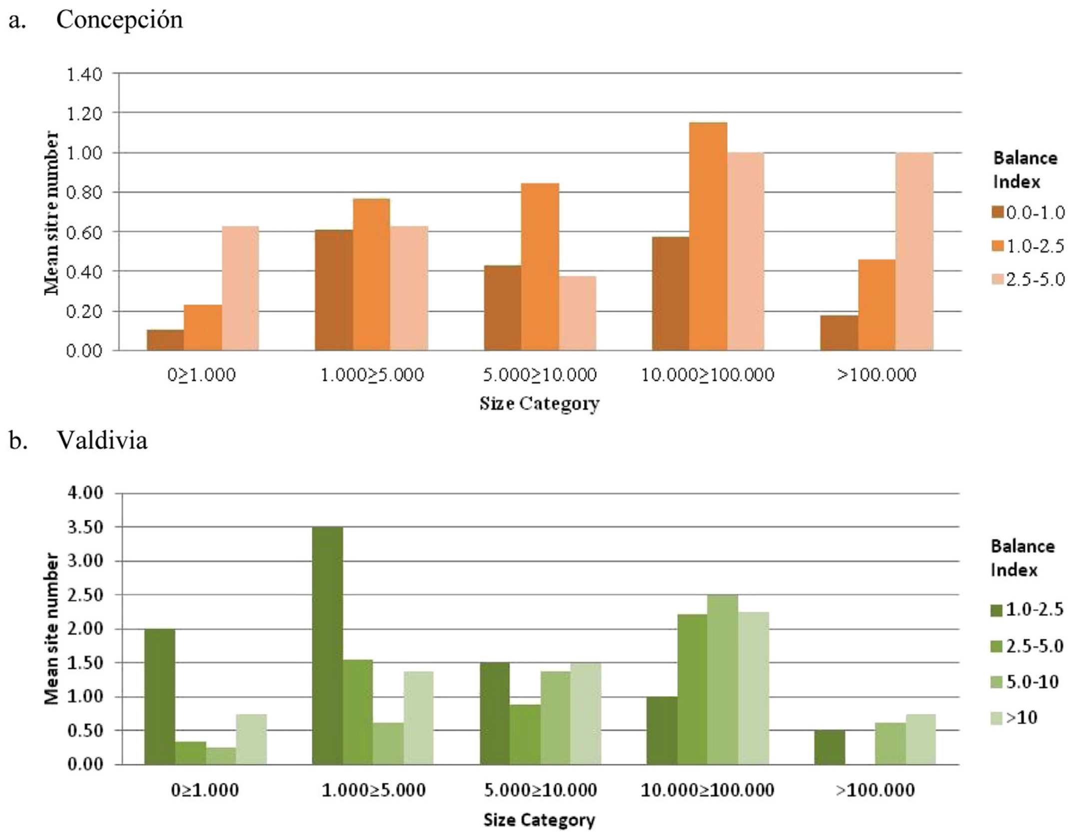


Fig. 10. Mean site number by size category for Concepción and Valdivia.

the ellipse can be interpreted as indicators of the geographic orientation of the OSS useful for urban resilience. This can be observed in the city of Concepción, where the ellipses overlay the city centre and areas of the periphery. Most ellipses in this case are similar in size and have a tendency to a circular form. The only ellipse which shows a larger variation is the ellipse of the ONEMI. This is an expected result because the ONEMI coordinates the overall emergency situations in Chile and is also a regional organisation.

Besides, the increment of the distance among sites together with the loss of proximity to the city centre reflects a more deficient model for connecting the urban space and the dependence of the transportation networks, which might be interrupted during the aftermath of an emergency. This is the case for the city of Valdivia. Three sets of ellipses were identified in this case and these vary in size according to the geographical attributes of the territory. The first set of ellipses overlay the central area of the city and includes institutions which, although they play a role in the city during emergency periods, are not exclusively for that purpose (The Community Union, Radio Bio Bio and the Red Cross). These may not be as thoroughly prepared to reach larger areas of the territory after an earthquake. The second set (The Municipality, Police, Civil Defence and the Home of Christ) overlay the central district and areas across the river in all directions. These organisations are more prepared for emergency procedures and also have a better knowledge of the city districts. The third set is formed by

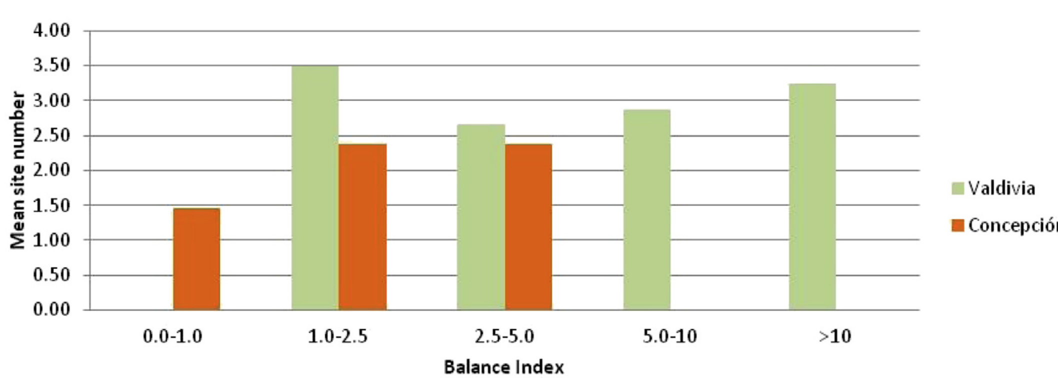
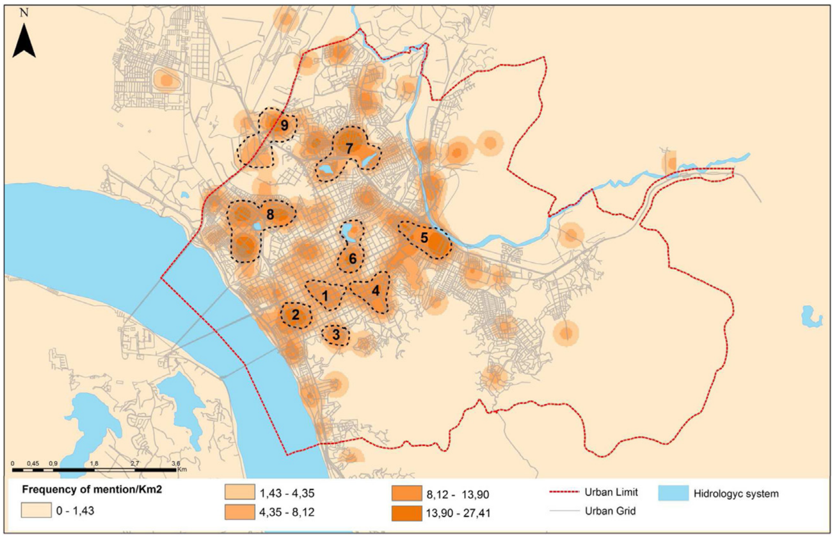


Fig. 11. Mean site number by Balance Index.

a. Concepción. Nodes are circled with a dash line: (1) the main square in the city center; (2) sites around España Square and the Bio Bio River; (3) Park Ecuador next to the Caracol hill; (4) and the University of Concepción; (5) the Army next to the Andalién River; (6) the Tres Pascualas wetland next to the city center; (7) Lo Galindo and Lo Mendez wetlands; (8) the Redonda wetland; (9) and a Shopping Center.



b. Valdivia. Nodes are circled with a dash line: (1) the main square; (2) Harnecker Park and Regional Stadium; (3) the Felix Gallardo Stadium; (4) Llancahue Hills; (5) Collico Hills; (6) Cabo Blanco Hills; (7) and Saval Park.

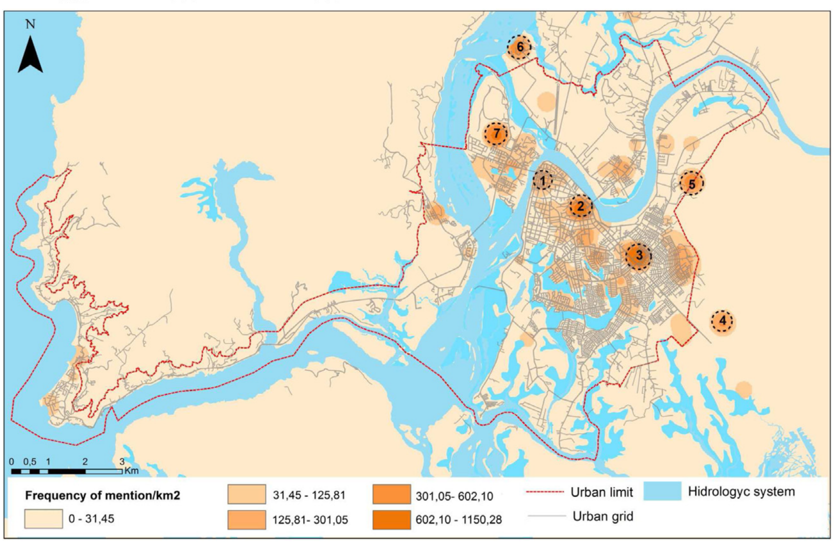


Fig. 12. Summary maps of the concentration of uses according to the Kernel Density Index results.

institutions that work at a regional level (Firefighters, the Army, Regional Government, the Roof for Chile and ONEMI) and reaches areas of the periphery.

The three ellipse system found in Valdivia is different to the more uniform system observed in Concepción, regardless of the heterogeneous distribution of organisations in both cities. Resilience theory suggests that the more *overlap in governance* there is in a system, the more resilient is the system (Walker & Salt, 2006), and this is the case for Concepción. In this case, the set of capacities of the institutions can be increased by their overlap in the city (Hutter et al., 2013), assuring good governance, which in turn can contribute to resilience (Dunford & Li, 2011). It is also possible to suggest that the continuous extension of the regular grid in the flat territory of Concepción, which has less topographic variation and interruptions than in Valdivia, facilitates accessibility, and hence, this contributes to *overlap in governance*. The city of Valdivia has the same number and type of institutions as Concepción, but it is placed on different sides of a wide river (250 m on average) and inbetween hills, geographic aspects that characterise a more fragmented UF, and in turn, may limit the performance of some organisations in times of crisis.

Nevertheless, overlap in governance in the case of Concepción could turn into chaos if there is a lack of coordination among the organisations. For example, different institutions could assist and provide resources in the same area at the same time, and by this, help in other areas of the city will be delayed. Or, in another case, the redundancy of information provided by different institutions could create doubts in the community, in terms of who is in charge, and they would be unsure of whom to contact for further assistance. These problems can be overcome by including in emergency plans, the areas of influence of the different organisations in times of crisis, determining which institutions take others' roles in cases where one of the institutions fails. Emergency evacuation protocols that include the community as well as the organisations engaged in disaster response can also be of great help if these include more realistic experience, such as when organisations are not available because their infrastructure is damaged or because the transport network is blocked.

Further considerations

The findings presented in this paper can be useful for informing the development of the emergency plans of the cities under study. Nowadays, neither Valdivia nor Concepción have an emergency plan. Current government response to earthquake effects is more focused on mitigation than on recovery, which is a trend also found in other contexts (Blanco et al., 2009). Since 2001, the ONEMI have provided to Mayors and to Civil Defence and Emergency Directors a guiding document that will allow addressing vulnerability factors associated with the threat only of a tsunami (ONEMI, 2001). This document is not mandatory; therefore, the local government should take the decision whether or not to undertake this challenge. The document includes a methodology that involves (1) an historic analysis of risk, (2) empirical research on site, (3) identification of priorities, (4) mapping the area with social and physical aspects, and (5) planning for emergency response. The study presented here contributes particularly to part (2) of the methodology and provides useful information for part (5). The fact that in this study a total of 154 and 198 open areas useful for earthquake response were found, provides a baseline on which to develop the plans for Concepción and Valdivia with a focus on the role of the OSS for earthquake recovery. Particularly for Valdivia, where the heterogeneous distribution of the OSS and the low overlap of organisations on the territory contribute to recovery to a lesser extent, the findings suggest planning directions that should be taken into consideration, such as to homogenize the allocation of open spaces within the city, particularly by including more useful areas toward the south periphery. Also, more wide streets are needed which can diversify the street network for evacuation and for adding redundancy of organisations to the system.

These findings can be also discussed in the context of the emergency period after a disaster. Although this is not the focus of this paper, an effective and fast emergency response following an earthquake is critical, particularly for saving lives (ISDR, 2005). The attributes of the UF and OSS discussed in this study can improve the level of readiness to respond to an emergency. A redundant street network, including key wider streets, can ease accessibility within the city, and this can reduce the time frame in which organisations reach highly devastated areas, where most people are probably trapped under the rubble after a disaster. Similarly, a homogeneous distribution and heterogeneous size of open spaces can provide the adequate area to implement alternative sites for field hospitals, which can also reduce the time for severely injured people to receive appropriate medical attention.

These insights bring relevance to the importance of studying the movement of people after disaster in future research. Fig. 12 shows that in Concepción and in Valdivia, there are nodes placed in strategic areas of the city, where open spaces, built infrastructure and transport nodes meet (nodes 9 and 3 in Concepción and Valdivia, respectively). In particular, exploring the association between seismic events and transportation networks is important due to the role of transport after a major disturbance. For example, rescue procedures can be facilitated by the connectivity between city areas after disaster, and an efficient network capacity can accommodate traffic flows despite damage and traffic congestion. Besides, the loss of built environment next to the network, such as residential and industrial buildings among other network components, can delay disaster response, because network-related loss increases the travel time and cost (Pitilakis, 2011).

Indeed, deeper studies that explore relationships between the distribution of open areas used for refuge, transport modes and time of evacuation, can provide further insights for improving evacuation plans after disaster. As an example, a survey on evacuation behaviour in Japan (Cabinet Office Government of Japan, 2011), shows that 57% out of 857 respondents used cars for evacuation, and about 1/3 of them were caught in a traffic jam. For this reason, The Ministry of Land, Infrastructure, Transport and Tourism (MLITT, 2012) conducted a questionnaire survey on evacuation routes (transport network) and shelter (open space network) and found that the average evacuation time was 9.8 min, 15.9 min, 15.1 min for walking, bicycling, and car driving respectively, with an average distance of 434 m, 1573 m and 2209 m for walking, bicycling, and car driving, correspondingly (MLITT, 2012). This report suggests a clear association between time of evacuation, transport modes and the location of the open space system for refuge, which should be further explored in other contexts of study in the future. Assuring the proximity of useful open spaces for recovery to the street network is relevant for an efficient level of response, as long as the network is fully operating, diversified and interrelated with the OSS.

Conclusions

The adaptive capacity of cities in the aftermath of an earthquake has been explored in this study with a focus on the role of the OSS during the reorganisation period. The extent such a system is *diverse* and that organisations perform with *overlap in governance* were found to vary with respect to distribution and size of sites and concentration of uses. Considering the objectives of this study, aimed at exploring relationships between OSS and UF in two South American cities, it was revealed that the regularity of the grid and city density affects the adaptive capacity of cities, hence, resilience. A city with a predominant regular grid, such as the case in Concepción, provides a more heterogeneous distribution of the most useful open space system, assuring *diversity* as well as *overlap in governance*. This suggests a strong resilience system. Besides, a city characterised by less urban density, as is observed in most of Valdivia, apart from the city centre, provides larger variety of sites in terms of size, which is also fundamental for resilience. However, the extent of the fragmented land in Valdivia, its strong linear pattern, and insufficient space per person for particular uses, neither contributes to the *diversity* of the system in terms of concentration of uses, nor to a better governance performance.

These findings are of particular interest for the planning of human settlements which are prone to earthquakes. It may not be possible to reduce significantly the damage to infrastructure, but a balanced OSS, easy to access and with redundancy of parts and site-sizes, can help to adapt to and cope with the unexpected changes that occur after a catastrophe. These findings are also of relevance in the context of developing cities that are undergoing a strong densification process in order to control and reduce urban sprawl, which may reduce the number, size and wide distribution of the OSS and in turn, its resilience capacity over time. The role of OSS of cities during the reorganisation period is particularly interesting for these types of situations where open space is under threat.

The ongoing exploration of relationships between the OSSs and the UF of cities, such as those undertaken in this study, is suggested to capture spatial indicators that can assure resilience in urban environment over time. This is recommended to establish a baseline for the study of resilience in cities undergoing unexpected change. Further studies should be developed in different cities, with different UFs and different geographical contexts.

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