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Potential of hazard mapping as a tool for facing COVID-19 transmission: the geo-COVID cartographic platform

Potencialidad de la cartografía de peligrosidad como instrumento de lucha frente a la trasmisión de la COVID-19: plataforma cartográfica geo-COVID

María Jesús Perles Roselló

mjperles@uma.es

Juan Francisco Sortino Barrionuevo

francis.sortino@uma.es

Francisco José Cantarero Prados

fjcantarero@uma.es

Hugo Castro Noblejas

hugocastro@uma.es

Ana Laura De la Fuente Roselló

anadelafuente@uma.es

José María Orellana-Macías

jmariaorellana@gmail.com

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Sergio Reyes Corredera

sergioreyes@uma.es

Jesús Miranda Páez

jmpaez@uma.es

Matías Mérida Rodriguez

mmerida@uma.es

University of Málaga (Spain)

Abstract

The present research analyses the epidemiological bases, the methodology approach and the utility of the Geo-Covid Cartographic Platform to face COVID-19 transmission at an intra-urban scale. Geo-Covid is based on the study of the main drawbacks and limitations of the current risk maps, and the proposed hazard mapping methodology is presented as an alternative approach with a high spatial-temporal accuracy. It is based on 1) the map of neighborhood active focuses of contagion, which are classified according to several hazard indexes, 2) the map of highly-transited areas by potential asymptomatic positives cases and 3) the map of Points of Maximum Risk of contagion. In order to test the effectiveness of the proposed methodology for mapping COVID-19 hazard and risk, it has been applied to Málaga City (Spain) during several stages of the epidemic in the city (2020 and 2021). The neighborhood focus of contagion is proposed as the basic spatial unit for the epidemiological diagnosis and the implementation of mitigation and control measures. After the analysis, it has been concluded that the proposed methodology, and thus, the maps included in the Geo-Covid Cartographic Platform allow a realistic and rigorous analysis of the spatial distribution of the epidemic in real-time.

Key words: COVID-19 mapping; neighbourhood contagion focus; decision-making.

Resumen

El artículo recoge los fundamentos epidemiológicos, la metodología y las utilidades de la plataforma cartográfica Geo-Covid para la lucha frente a la trasmisión de la Covid-19 a nivel intraurbano. Tras un análisis de las principales carencias en el ámbito de la cartografía de riesgo a nivel vecinal, y de los fallos que inducen a un diagnóstico erróneo del patrón de trasmisión en la ciudad, se propone como complemento y alternativa una cartografía de peligrosidad de máximo detalle espacial y temporal, que se basa en el Mapa de Focos de contagio vecinal activos, gradado según distintos indicadores de peligrosidad. El catálogo cartográfico de peligrosidad de Geo-Covid se complementa con el Mapa de áreas de máximo tránsito de potenciales positivos asintomáticos, así como el de Puntos de máximo riesgo de contagio. La metodología cartográfica propuesta se aplica a distintos momentos de afección de la pandemia a la ciudad de Málaga (2020 y 2021). Se concluye que la plataforma cartográfica propuesta en el artículo (Geo-Covid) permite un análisis realista y riguroso de la distribución espacial natural de la epidemia en tiempo real. El foco de contagio vecinal se propone como unidad básica para el diagnóstico epidemiológico y la acción contra el contagio.

Palabras clave: cartografía de Covid-19; focos de contagio vecinal; apoyo a la decisión.

1 Introduction and state of art

The experience obtained and the analyses carried out during the successive COVID-19 waves across the world have shown that the contagion distribution pattern is not homogeneous in the territory, nor at a regional or intra-urban scale. The development of maps of contagion based on data gathered on spatio-temporal basis from municipalities, provinces, regions and countries have multiplied. These types of maps are guiding documents for informative purposes, although they are also being used as supporting information during the decision-making process for implementing perimetral lockdowns. However, the number of researches that have focused on the characterisation and delimitation of the unequal spatial distribution of contagion at a detailed scale (i.e. intra-urban scale) is low (Lall & Wahba, 2020). Several authors, such as De Cos, Castillo, & Cantarero (2020) highlight the importance of using a multi-scale approach for enabling effective prevention strategies. The authors define this approach as geo-prevention. Rosenkrantz, Schuurman, Bell & Amram (2021) also states that it is essential to include an accurate spatial approach to the analyses of the pandemic, as well as to improve the quality of the cartographic methodologies when representing epidemiologic analyses. Therefore, it seems necessary to carry out studies analysing the spatial pattern of contagion at an intra-urban scale, which is the environment where social contact is more intense. In light of this thought, Chang, Pierson, Koh, Gerardin, Redbird, Grusky & Leskovec (2021) emphasise the need of adapting the control measures to the heterogeneous distribution of the transmission in urban areas after they track intra-urban movements and preferential areas of contagion in ten of the largest cities in the US.

The use of maps as a basis and a key support tool for the decision-making process during epidemics has its origin in the nineteenth century. In recent decades, the use of cartography for medical research, and epidemiological analysis had a great boost thanks to the powerful tools for spatial analysis included in Geographic Information Systems (GIS) softwares. The adaptability and advantages that GIS have for spatial analysis has strengthen the strategies and methodologies developed by Health Geography (Lai et al., 2009; Olaya, 2016, Shaw & McGuire, 2017), and by Epidemiology (Jacquez, 2000; Pfeiffer et al., 2008; Lawson et al., 2016; Redondo-Bravo et al., 2018), regarding to the characterization and management of epidemics.

In the last months, since the beginning of the spreading of the pandemic across the world, numerous researches focused on the spatial analysis of COVID-19 have been carried out. Most of them have been based on Geographic Information Technologies (GITs). GITs, especially GIS, have been usually utilised for mapping risk components, such us vulnerability or hazard. Not in vain, one of the most common researches is the mapping of people vulnerability to the disease and to contagion (DeCapprio et al., 2020; Lakhani, 2020; Jordan et al., 2020). On the other hand, other authors have assessed explanatory factors of contagion and hazard maps. Franch-Pardo et al. (2020) distinguish between thematic areas, such as spatio-temporal analysis, health geography, identification of environmental variables, data mining, and web mapping. Other lines of research analyse the possible explanatory factors related to the spatial distribution of the disease, including human factors, such as population movements, as well as natural factors, as climatic and atmospheric characteristics (Sajadi et al., 2020; O'Reilly et al., 2020). From a methodological point of view, researches carried out by Zhou et al. (2020), Kamel & Geraghty (2020) or Desjardins et al. (2020) combine big data analysis and spatio-temporal statistics, with the aim of detecting and visualizing big focuses.

One of the most relevant aspects of COVID-19 researches is the scale of analysis. The published works are framed into different scales, although the most common is a low-detailed scale (i.e. regional, national or global). Some examples were the studies published by Adekunle, Onanuga, Akinola, & Ogunbanjo (2020) for Africa, Shaw, Kim, & Hua (2020) for Eastern Asia and, at a national level, all the descriptions and epidemic projections for the US provided by Mollaloet al. (2020), and by Xie et al. (2020) and Gross et al. (2020) for China. Also on a national scale, Niu et al. (2020) assessed the role in the transmission of the disease of inter-urban population movements in China, while Hamidi et al. (2020) identified a higher correlation between COVID-19 incidence rate and a high intra-urban mobility, than between COVID-19 incidence rate and a high urban population density in the US. At an urban scale, most of the researches were focused on the analysis of urban factors that may be influencing the incidence level of the disease. This line of research is followed by the studies published by Whittle & Díaz-Artiles (2020) and Borjas (2020) in New York City (USA), Buzai (2020) in Buenos Aires and Luján (Argentina), Elías-Cuartas et al. (2020) in Medellín and Cali (Colombia), and Suárez et al. (2020) in México D.F. (México). Also at an urban scale, some researches highlight the relationship between COVID-19 transmission and the socioeconomic vulnerability of the population, such as the study published by Bamweyana et al. (2020) in the Kampala metropolitan area (Uganda).

However, the number of researches that reach a more detailed level of the COVID-19 spatial analysis is significantly lower (i.e. intra-urban scale). The intra-urban level is a complex environment in which many deficiencies in data are observed, thus, the analysis of the spatial pattern of transmission and the observation of contagion within urban areas are not currently possible in many cities. The obstacles for accessing to personal information about cases, and the poor quality of the data, given its confidential nature, are the reasons behind the lack of researches at that scale. Nevertheless, the spatial analysis of the epidemic at intra-urban scales is important for modelling the spatio-temporal pattern of contagion. Hooper (2020) stated some of the social factors influencing the spread of the disease in urban environments, and other studies in the matter can be referenced, such as Chadi & Mousannif (2020) in Casablanca, the study carried out by Gibson & Rush (2020) about the suburbs of Cape Town (South-Africa), or the work developed by Desai (2020), focused in mega-cities as London and New York. Finally, Chang et al. (2021) analysed the relation between the mobility of the population and the contagion in some of the main cities (and metropolitan areas) in the US.

In Spain, there are several researches currently in progress at intra-urban scale, but their results are still preliminary or, in most of the cases, unpublished. One of these researches is carried out by Gutiérrez Puebla and García Palomares, who use data from mobile phones for analysing population journeys within Madrid, in line with similar researches carried out by Oliver et al. (2020) in Valencia. Andrés, Herrero and Martínez (2021) analyse the drawbacks associated to the inadequate selection of spatial unit for the decision-making process in Castilla-León, especially when the selected unit does not represent the real pattern of contagion. Other researches also use the intra-urban scale for analysing the vulnerability of the population to the epidemic in Zaragoza (Zúñiga Antón et al., 2020), and Málaga (Marín Cots & Palomares Pastor, 2020).

The present study follows a line of research already initiated by some published works (Perles et al., 2020; Perles et al., 2021). Other ongoing researches that follow the same line of research, and which should be mentioned are the study carried out by Miramontes & Balsa (2021) in Galicia (Spain), or the work recently published by De Cost et al. (2020), framed in Cantabria. All these researches are based on the urban analysis at the maximum spatio-temporal level of detail, this is, address information from the medical records of the infected people in real-time.

Once the main lines of research in the analysis of the COVID-19 transmission spatio-temporal pattern at different scales have been reviewed, and the current background has been set, some weaknesses in the data analysis and a lack of accuracy of some results at intra-urban scale have been observed. Likewise, it has been detected that a significant part of the published and public maps developed by researches, public administrations and health authorities related to the epidemiological management, have significant conceptual and methodological drawbacks in relation to the spatio-statistical use of data. Consequently, confusing or incomprehensible results and maps are obtained, which usually lead to misinterpretation and incorrect conclusions about the spatio-temporal pattern of transmission. Overall, the most common drawbacks and limitations observed are described below:

- Their main source of information and analysis is the number of cases gathered by administrative units (e.g. cadastral parcel, municipalities, etc.), which result in a spatio-temporal accumulation of cases that usually does not represent the natural spatio-temporal pattern of transmission. As a consequence, in this type of maps, there is an underlying trend to attenuate the real incidence rate of the most affected areas, since it is calculated as the average value of areas with very different rates and the high values are masked by areas with low or null rates. In many cases, the representativeness of the estimated incidence rate at the selected administrative unit is practically null.
- From a cartographic point of view, they represent the distribution of the disease by using heat maps whose thresholds between density intervals are arbitrary or randomly selected, since they do not follow epidemiological criteria. When applying this methodology, the obtained maps are not suitable for identifying and delimit the simultaneous accumulation of active cases in neighbourhoods, which can be considered the basic spatial unit of transmission. In this line, Perles et al. (2021) have analysed the spatial pattern of contagion in Málaga City on a weekly basis during the four waves that have affected the city. The authors have observed a defined spatial pattern in the focuses (areas where cases are simultaneously accumulated), which have specific parameters regarding to their morphometric characteristics and to the linear distance between cases. If the correct criteria are considered, these parameters can be used for detecting and preventing new focuses.

- They use the total number of cases for periods longer than 14 days, so in the spatial analysis, they mix cases that have not been simultaneous. The consequence of using this methodology is that the most densely populated areas of the city accumulate the highest number of cases. Following this approach, some studies go further in the analysis and try to relate the risk of contagion to some indicators of poverty and to the socio-economic level of each urban sector. However, it is necessary to highlight that the population density may be a confusing variable, leading to misinterpretation of the results and, thus, to the assumption of wrong conclusions. Based on the direct spatial correlation between a high number of cases and a high population density, as well as an invert correlation between the socio-economic level and the population density, many authors deduce a simplistic causal relationship between high transmission rates and poverty. However, this hypothesis is refuted when analysing areas with low socio-economic levels and low population densities, which not necessarily have high transmission rates, or when areas with high economic level and high population rates (less frequent) have a high number of cases.

Therefore, the researchers' malpractice and the use of spatial analysis methodologies that lack of spatio-temporal consistency when developing COVID-19 maps has direct consequences: the misleading of the explanatory reasons of transmission, and the loss of efficiency of the control measures addressed to prevent transmission, since they are not adapted to reality (e.g. perimetral lockdowns of some areas, specific disinfection measures, etc.). The implementation of generic and homogeneous measures for preventing transmission in urban sectors with different characteristics and contagion rates significantly decreases the efficiency of those measures.

In Spain, Autonomous Communities, provinces and municipalities are the most common administrative divisions selected for implementing perimetral lockdowns and shutdowns. Theoretically, the aim of those shutdowns is to isolate areas of the country with different contagion rates by avoiding the mobility of the potential asymptomatic from areas with high contagion rates, to areas with low contagion rates. However, the reality is that those administrative divisions do not necessarily separate areas with different contagion rates. In addition, an administrative spatial unit can include areas with different contagion rates, in which mobility is not restricted (e.g. municipalities). Therefore, since mobility and social contact is not restricted in the areas of the municipality where contagion rates are high, contagion can spread without control across the municipality and reach areas where the contagion rates were low. Consequently, these types of measures are not efficient for stopping contagion at a municipal scale, and they produce confusion, distrust and fatigue in the population affected by restrictions.

With the aim of facing this issue, authors as Rosenkrantz et al. (2021) insist on the importance of using a rigorous spatial approach to analyse the evolution of the epidemic and urge to improve the quality of the methodologies for mapping all the epidemic analyses. The line of thought about the influence of the spatial unit over the quality and the accuracy of the results when carrying out epidemiological analyses has been previously developed by health geography authors, such as Openshaw & Taylor (1981), Moore & Carpenter (1999), Arsenault et al. (2013) or De Cos et al. (2020).

Given the current state of art, the Geo-Covid Cartographic Platform have two main purposes: (1) to create realistic and spatially accurate COVID-19 transmission hazard maps, for delimiting the natural spatial pattern of contagion, and (2) to reinforce the usefulness of the analysis and the hazard maps, as well as their role as a complementary tool for the COVID-19 transmission control and management. The resulting maps identify spatial units ad hoc, such as the neighbourhood focus of contagion, proposed by the authors in previous researches (Perles et al., 2020; Perles et al., 2021), which are used as the basic unit of spatial analysis.

The present research aims to address three main objectives, (1) the description of the cartographic catalogue available in the Geo-Covid Cartographic Platform, (2) the explanation of all the conceptual and methodological basics in which each map and hazard index is based, and (3) the utility of each hazard index for facing the epidemic. Additionally, in order to test the efficiency of the hazard indexes and the maps, the research includes some examples obtained from the Geo-Covid Cartographic Platform after the application of the proposed methodology to Málaga City at different epidemiological stages. With the aim of being representative of the range of characteristics of each wave, those examples include maps of the first (March 2020), the second (November 2020) and the third wave (January-February 2021).

The Geo-Covid Cartographic Platform has been developed in the frame of a research project geared to the creation of a cartographic catalogue. The project was funded by the Instituto de Salud Carlos III (Spanish Ministry of Science and Innovation). The results of the project have been provided to the provincial health authorities (Regional Hospital of Málaga), and to local authorities (Málaga City Council). Thus, the cartographic platform has served as an instrument for supporting the decision-making process.

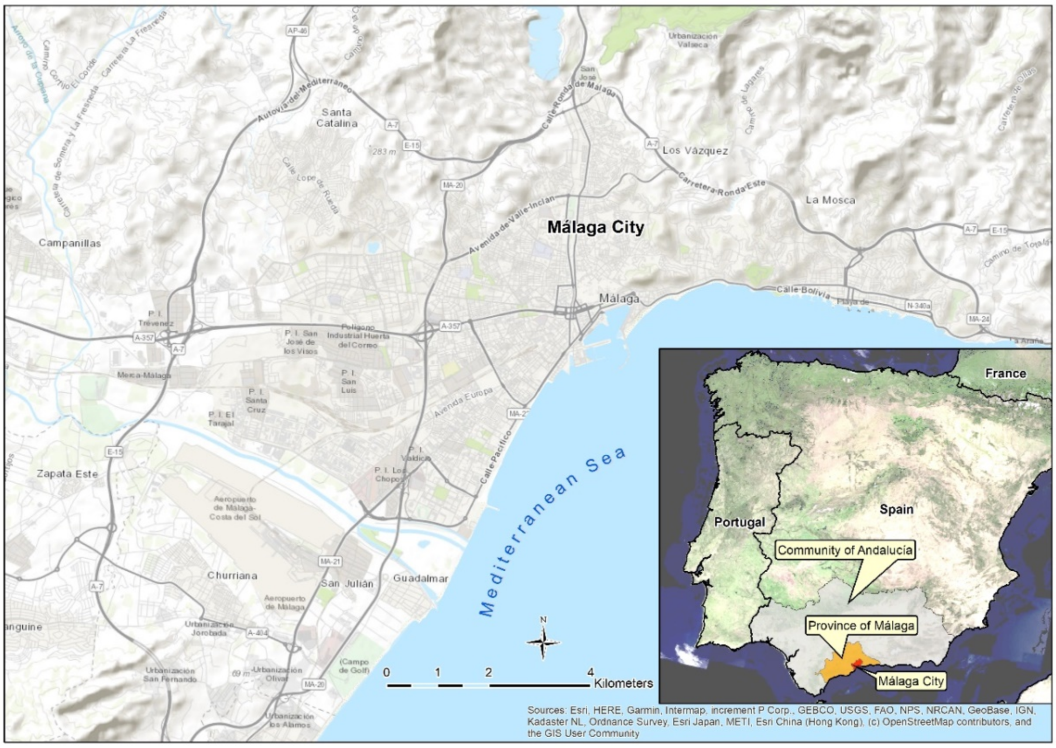
2 Study area

The spatial framework of the present research is Málaga City (Spain). Málaga has been chosen as the observation and study area for the application of the proposed methodology in several stages of the epidemic. Málaga City is located in Andalucía, at the southern boundary of Spain (Figure 1). It is the sixth most populated city of the country, with 574,000 inhabitants, and its metropolitan area reaches 912,191 inhabitants (INE, 2020). The city extends continuously all over the coastal plain, forming an urban area of about 40 km^2.

Generally, the city is economically linked to tourism, the services and the construction industry. The industrial activities, which were very important during the nineteenth century and the beginning of the twentieth century, are currently moderately developed. In relation to communications, the city is well connected nationally and internationally by road, train, air and maritime transport. Not in vain, Málaga's International Airport is the third biggest Spain mainland airport, following Madrid and Barcelona, and the fourth in Spain, following Palma de Mallorca, with an annual traffic of around 20 million passengers. The tourism has grown quickly in the last decades and Málaga is currently a very dynamic city, strongly linked to services and nationally and internationally well-connected. All these characteristics help to explain that during the first months of the pandemic, the city was the most affected area in Andalucía by COVID-19.

The structure and morphology of the urban core of Málaga is not homogeneous. The city includes a wide range of urban typologies and patterns of urban growth, which makes Málaga a perfect candidate for analysing the contagion pattern and the potential intra-city differences. Overall, the eastern area, mostly composed by single-family homes in residential zones, can be distinguished from the western and northern areas, which are densely populated and consist of multi-family buildings (Figure 2).

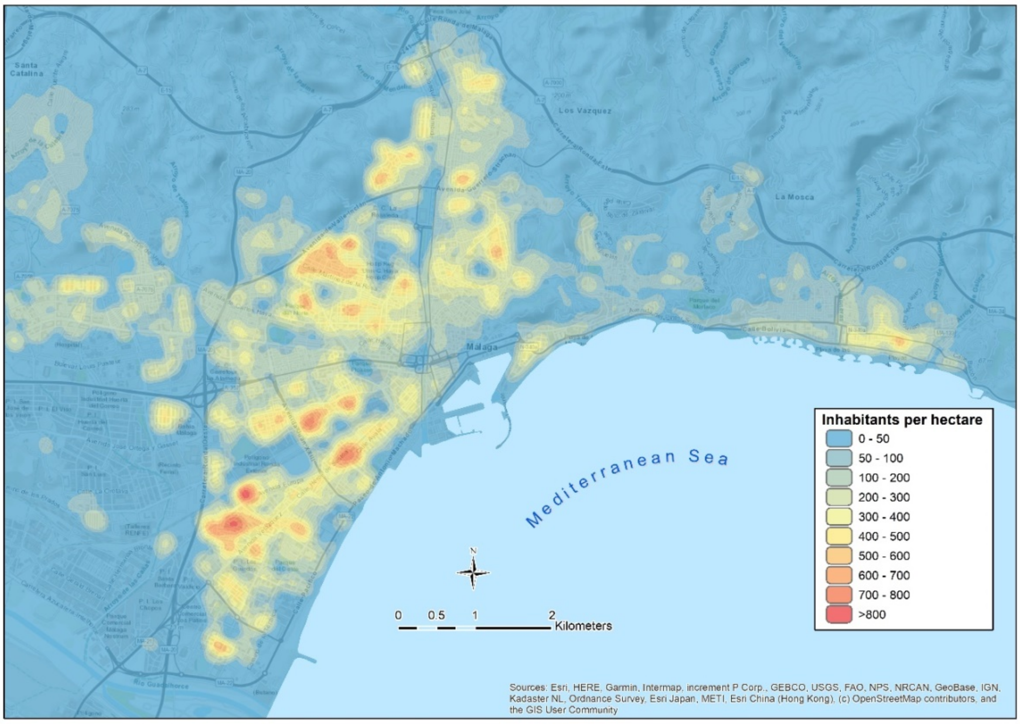
Figure 1. Location and spatial characteristics of the study area



Source: authors' own elaboration based on data provided

by the Spatial Reference Data of Andalucia (DERA)

Figure 2. Population density map



Source: authors' own elaboration based on data provided

by the Spanish Statistical Office and the Spanish Cadastre

3 Conceptual basis, sources and materials

The present research addresses the COVID-19 contagion pattern and the structure of the Geo-Covid Cartographic Platform. The conceptual framework is based on the Risk General Equation, which defines risk as the product of the spatial concurrence of hazard, vulnerability and exposure elements.

$$\text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability}$$

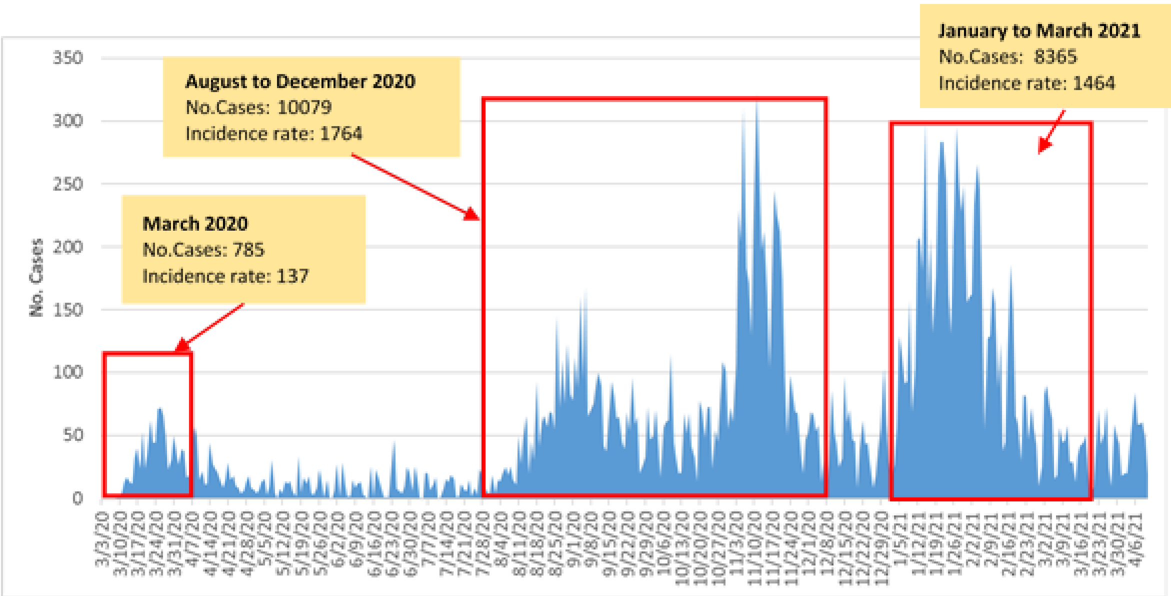
The Risk General Equation proposed in this study is based on the concepts mentioned by UNISDR (2009), and used in other works by Ayala and Olcina (2002) or by Lavell (2000). Other authors propose some modifications of this equation, in which risk is calculated as the product of hazard, vulnerability and exposure, and then divided by the fight capacity against hazard. Therefore, this factor is considered to act in inverse proportion to risk. In this study, the selection of the equation has been based on the view that there are no criteria related to fight capacity against hazard that can be spatially distinguished within urban areas, so it would be considered as a constant.

From this conceptual model, considering the epidemic as a risk with a spatial and territorial nature, a cartographic platform has been developed with the aim of supporting the decision-making process. The platform included spatial information at a very detailed scale, directed to spatially diagnose the stage of the epidemic, which would help the decision-makers in order to solve the social issues related to it (Perles et al., 2020). Considering this framework, the present work is specifically focused on the analysis and the development of hazard maps of the contagion focuses. Thus, factors as the amount of people exposed to contagion, people vulnerability to the disease or people vulnerability to socioeconomic consequences of the epidemic are not considered.

The basic source of information used for the cartographic catalogue is the anonymised data from the medical records of the infected people. The selected data were the address and the reported date of contagion. Once the personal records were anonymised, the date of contagion was associated to the address, which was converted into geographical coordinates in order to know the cadastral parcel and its precise location on a map. Since both the reported date of contagion and the address came from the medical record of the patient, the records were anonymised for scientific purposes. The use of those data for scientific purposes was authorized by local health authorities, with the consent of the Ethics Committee of the Regional Hospital of Málaga, in the frame of the R&D Project entitled Development of COVID-19 transmission hazard maps in urban areas aimed at the application of anti-propagation measures at a detailed scale (COV20/00587). The use of the data complied with the Spanish Data Protection Law (Organic Law 3/2018) and the European Regulation (EU 2016/679 of the European Parliament and of the Council of 27 April 2016).

In the present work, some representative maps of the Geo-Covid cartographic catalogue have been selected as examples. Those maps show confirmed cases in some areas of Málaga during the first and the third wave of the pandemic in Spain (March 2020 and January-February 2021, respectively). Figure 3 shows all the data used in the analyses, including the selected study periods and the incidence rate of each wave detected in the city.

Figure 3. Temporal evolution of cases and period selected
for the analysis during the first, the second and the third wave



Source: authors' own elaboration based on data provided
by the Regional Hospital of Málaga (Andalusian Health Service)

The demographic and dwelling variables considered in the analysis as well as the maps are based on the data obtained from the Spanish National Statistics Institute (INE, Instituto Nacional de Estadística, from its Spanish acronym), and the Spanish Cadastre. The most detailed spatial scale of the data is urban section and cadastral parcel, respectively. These data have been complemented with information obtained from the Andalucía Street Map, and the Public Bus Company (EMT, Empresa Municipal de Transporte, from its Spanish acronym), in order to assess the flux of passengers in the public urban buses.

The functioning and updating of the Geo-Covid Cartographic Platform is carried out by means of spatial and statistical analysis tools from a Geographic Information System. The selected softwares for this study were ArcGIs Pro and ArcMap 10.3, developed by ESRI. The results and all the maps have been periodically provided to the local authorities (Málaga City Council, Málaga Civil Protection and Regional Hospital of Málaga) via the ArcGIS Online platform, developed by ESRI.

4 Methods

The COVID-19 transmission hazard maps in urban areas proposed in the Geo-Covid Cartographic Platform are based on the consideration of a specific spatial unit, the neighbourhood contagion focus, which is defined as "the basic spatial unit that represents the natural distribution of the contagion in intra-urban areas. It delimits spaces with differentiated epidemiological diagnosis and different needs." (Perles et al., 2021, p.21). The criteria considered for the proposed methodology of the present work are supported by a series of findings and results obtained by the authors in previous researches, in which the following aspects have been analysed and proved:

- Distribution of COVID-19 contagion in urban areas has a non-randomized spatial distribution, with an unequal density and higher concentration rates around areas with accumulation of cases. These areas of accumulation are the basic units of contagion.
- From the analysis of the distance between the closest cases in different pandemic stages and waves, it can be deduced that the areas with accumulation of cases have some recurrent morphometric characteristics, which allow us to describe and characterize a specific distribution pattern. Thanks to this method, it has been possible to identify the basic unit of transmission, the neighbourhood contagion focus, which is defined as the area where more than 5 simultaneous cases are reported in a 200 m buffer (Perles et al., 2021). From this distance on, the pattern of infection scatters, and the probability of infection by neighbours is reduced.
- There is a way of COVID-19 contagion based on social events (e.g. work meetings, social meetings, etc.) that can be identified as outbreaks. They are detected by health authorities by means of tracking. This via of transmission has an essentially random spatial and temporal distribution. Together with the outbreaks as a way of transmission, the simultaneous accumulation of cases in neighbourhoods has been verified. Thus, it should be considered a common origin (neighbourhood focus). The continuation and persistence of the focuses in the same area, or in nearby areas, during the following weeks proves that the contagion has its

origin in the neighbourhood. In addition, this hypothesis is also supported by the fact that most of the new infected during a period comes from focuses that were active in previous weeks.

- The categorization of the morphometric characteristics of the areas that accumulate simultaneous neighbourhood cases (neighbourhood focuses) allows using the distance in order to detect and predict focuses. The mapping of focus in real-time and in biweekly periods also allows to identify the areas of the city where neighbourhood focuses can be declared. These focuses would remain actives at least during one week after they were identified. The early detection of focuses permits to activate or intensify mitigation and prevention measures ad hoc in those areas, as well as the tracking and monitoring of the people living within the focus (e.g. massive screening or mobility restrictions). The early detection of the active neighbourhood focuses, when the transmission rate is still low and easily controllable, could be a powerful tool for the containment of contagion not only in the neighbourhood and its surroundings, but also in the rest of the city, since the transmission is stopped from its roots.

The maps provided in the Geo-Covid Cartographic Platform aim to identify, in real-time, the areas of the city where the possibility of contagion is higher. The objective is to preferentially apply control measures in those areas, as well as to improve the effectiveness of measures addressed to avoid contagion. To do so, the method is based on the assumption that in an urban context, the most hazardous areas would be the following:

- Surroundings of active neighbourhood focuses, in which, there is a high concentration of asymptomatic cases that share spaces and places with the rest of the neighbours in the surroundings of their homes, especially in crowded indoor places (e.g. supermarkets, restaurants, gyms, etc.) located within the neighbourhood. These crowded places can be considered as Points of Maximum Risk.
- Areas with high concentration of asymptomatic cases that use public transports (usually for working purposes). These asymptomatic people spread the disease from the initial area to other sectors of the city. Given that asymptomatic cases use the public transports, the places and areas in this category mainly include buses, trains, metro lines and stops in the active neighbourhood focuses and their surroundings.
- Public transport lines that connect active focuses. These lines can enhance a spatial pattern of contagion around public transport axis (i.e. mainly people that live close to a certain transport line and are users of that line).

- Workplaces that gather a significant amount of infected and asymptomatic people. In this category are included all the workplaces that gather workers indoor, especially hospitals and health centres. The surroundings of these places (e.g. public transport stops, restaurants, shops, etc.) can also be considered as hazardous places. These places propitiate the concentration of workers, infected people, patients, and relatives indoor, so they are especially susceptible to contagion, since people share the same places. The level of hazard of these places has been progressively reduced thank to the vaccination of health workers and patients.
- Routes followed by infected people before they were identified by trackers.

With the aim of including all the aforementioned scenarios in the analysis, two different spatial units have been distinguished for mapping contagion hazard: the neighbourhood focus of contagion, and the heavily-transited public areas by potential infected. Both spatial units include additional information about the location of Points of Maximum Risk in the area.

All the proposed maps available in the Geo-Covid Cartographic Platform are based on the address of infected people recorded by health authorities in real-time. For the original data processing, a data geo-codification tool available in ArcGIS Online has been used. From the address information recorded in the infected people database, supplied by health authorities, the anonymized address has been georeferenced by this data geo-codification tool. Further details about the methods, the tools, and the mathematical approach used for the creation of each map are explained below.

4.1 Development of the map of the neighbourhood focuses and micro-focuses of contagion

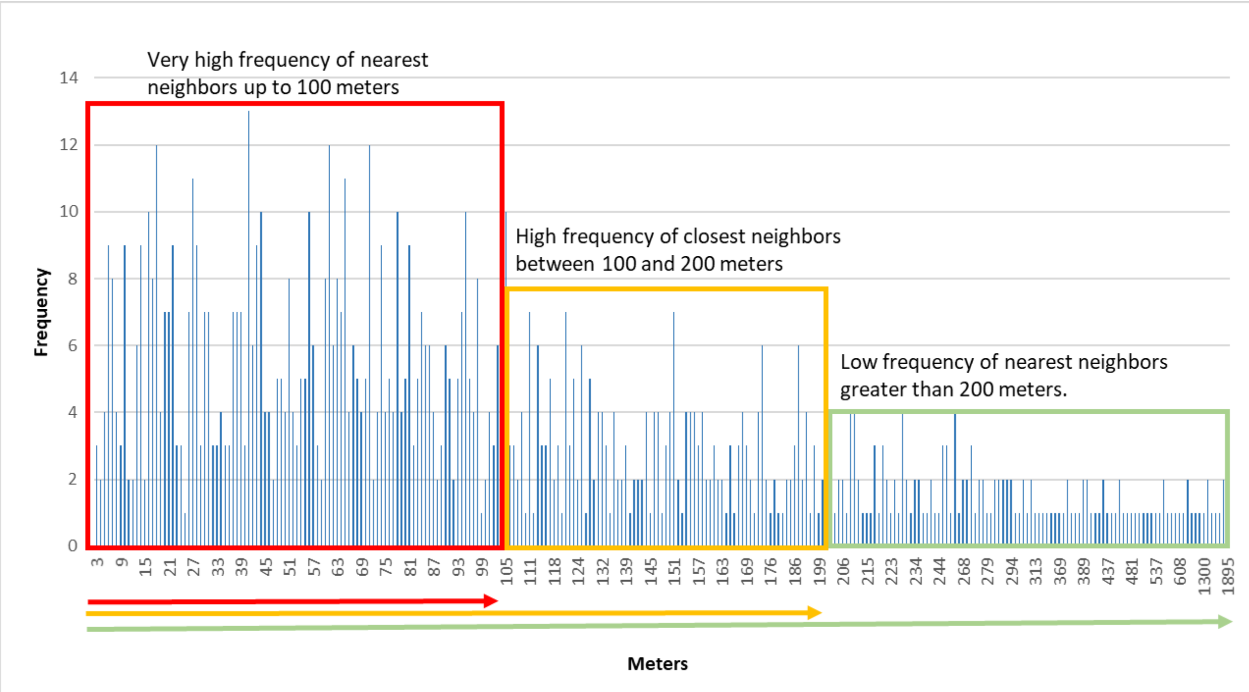
The neighbourhood focus of contagion is the basic spatial unit considered, since it represents the natural distribution of contagion in intra-urban areas. The neighbourhood focus of contagion also delimits areas with different epidemiological characteristics and needs, where the action measures have to be implemented. For the identification and mapping of such neighbourhood focus of contagion, the criteria proposed by Perles et al. (2021) have been considered. To do so, the steps followed are summarized below:

- Geolocation of the address of confirmed cases.
- Data cluster analysis with monitored criteria (Find Point Clusters tool, available in ArcGIS Pro (ESRI), and DBSCAN statistic method). The aim was to create groups of more than 5 cases within a 200 m radius. For the delimitation of micro-focuses, a 100 m radius between cases

was set. The distance between cases when delimiting focuses and micro-focuses is based on the observation and empirical measurement of the morphometry and characteristic parameters of the spatial distribution pattern of contagion. After using the Average Nearest Neighbor tool (ArcGIS Pro 2.6.) and the calculation of the R Index, the most frequent distance between nearest infected was obtained, and a frequency histogram was plotted (see Figure 4). The frequency distribution allowed observing that in the accumulation of cases, the average distance between infected was 100 m, and, in a second level, it was close to 200 m between cases. From this distance on, the contagion distribution pattern is scattered.

- Creation of a 50 m buffer zone around the peripheral cases of each focus by using the Buffer tool, available in ArcGIS Pro (ESRI).

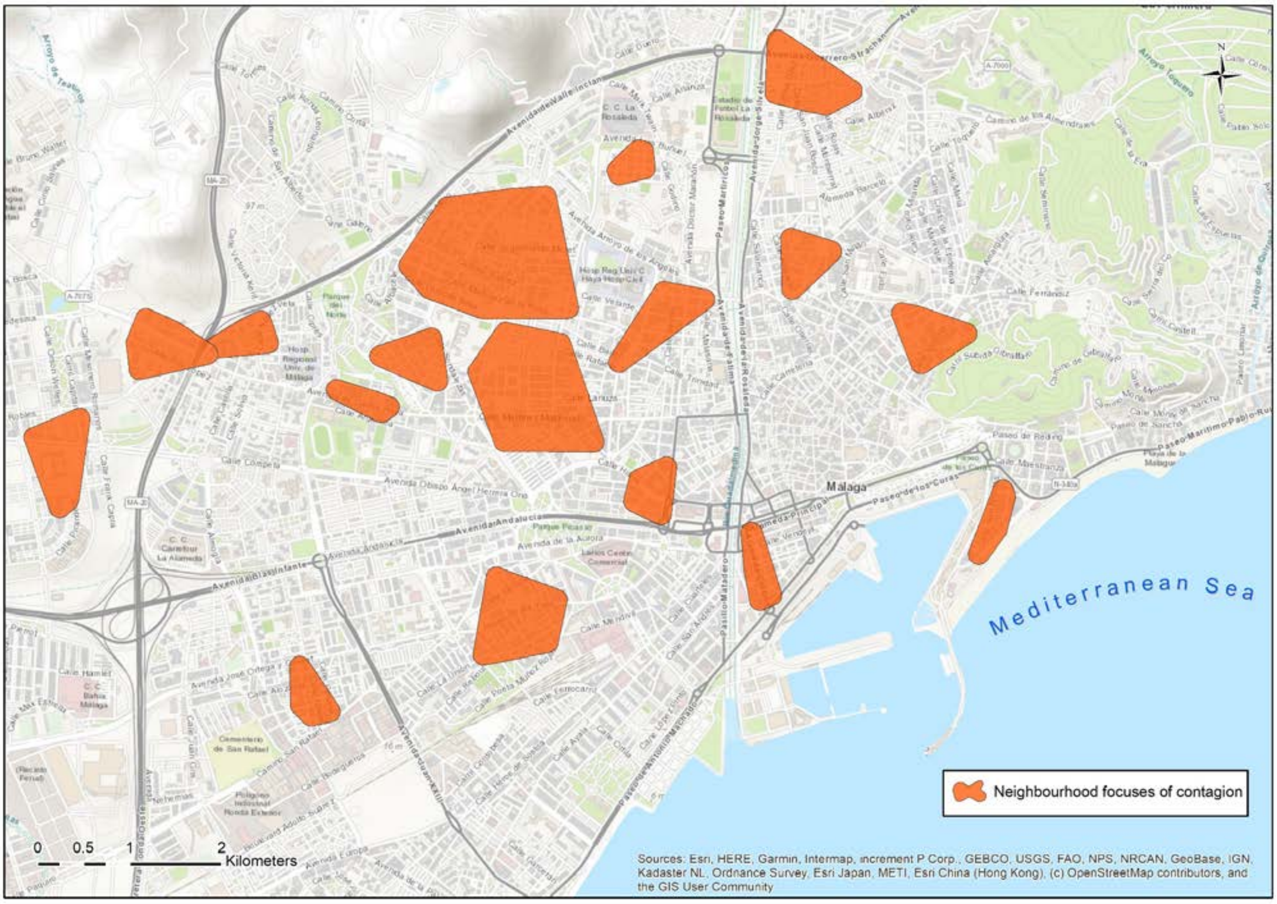
Figure 4. Frequency histogram of the mean distances observed between cases (the nearest neighbour)



Note: Calculation and delimitation of the area covered by each neighbourhood focus of contagion by using the Minimum Bounding Geometry tool, available in ArcGIS Pro (ESRI).

Source: retrieved from Perles et al. (2021)

Figure 5. Neighbourhood focuses of contagion



Source: authors' own elaboration based on data provided
by the Regional Hospital of Málaga (Andalusian Health Service)

4.2 Development of the map of heavily-transited public areas by potential infected

The map of heavily-transited areas by potential infected identifies in which sectors of the city the risk of contagion is higher in public areas, due to the spatial concurrence of a greater amount of potential asymptomatic cases with a higher population density.

In this map, two groups with a high potential of transmission are distinguished:

- Asymptomatic infected people in the early stages of the disease; this is, previous to their isolation (positive cases).
- People that live nearby infected people (e.g., relatives, neighbours) that have been physically in contact with a confirmed positive (personal contact or sharing common spaces). They are also potential positive and asymptomatic cases.

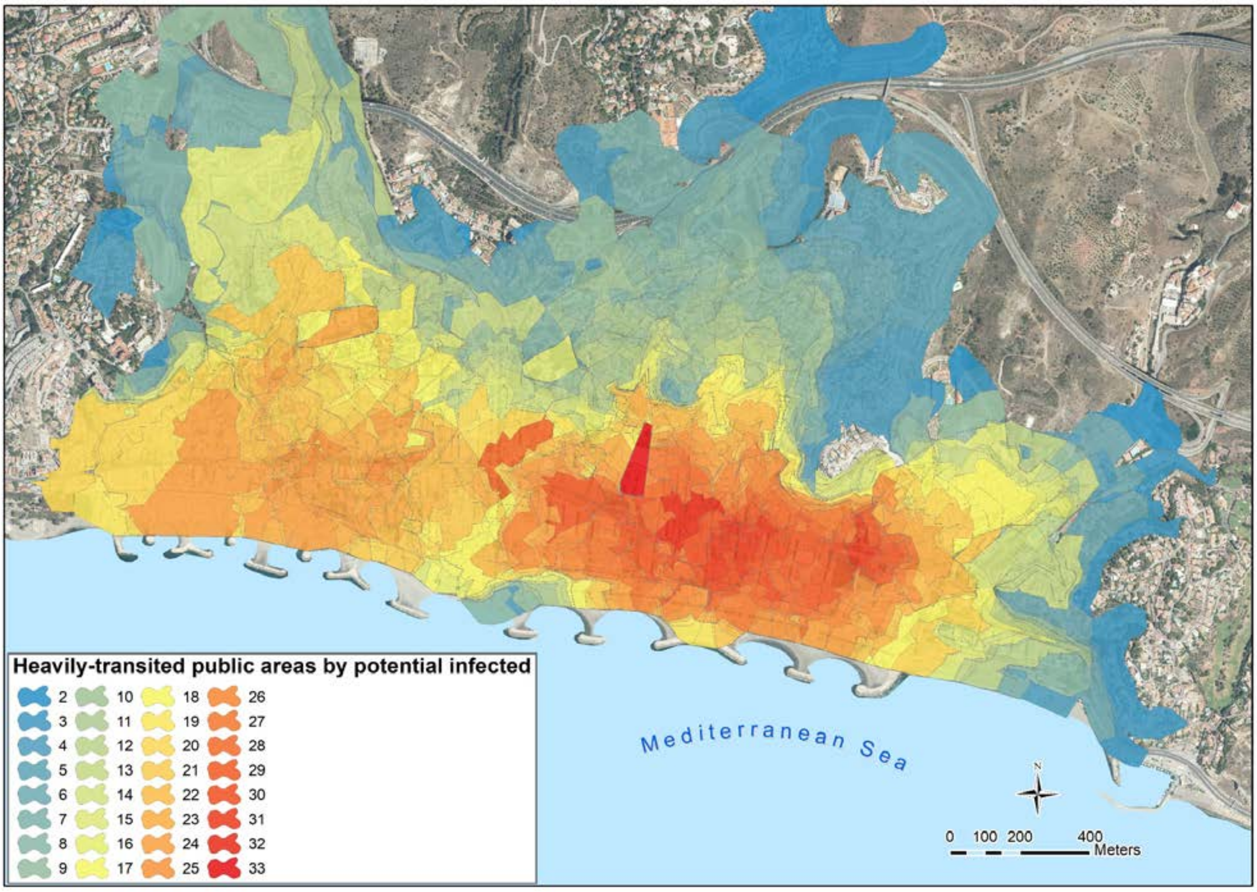
There is a high probability that people from both groups (infected people in the early stages of the disease and potential asymptomatic people close to an infected person) circulate around their homes for daily tasks (e.g. grocery shopping, take the dog for a walk, use of public transport for working, etc.). It can be estimated that the mean time of these activities is about 10 minutes. If the walking speed of the infected is around 4 km/h, which is a standard walking speed, the likely transit area around the home of each infected can be delimited within a 600 m radius.

From the separation of these two groups, the steps to create the heavily-transited areas map are the following:

- Delimitation of the likely transit area for each infected person based on the location of its home by carrying out a network analysis around that location. For each infected person, a transit area has been delimited, considering travel time at 4 km/h, which allowed obtaining a polygon showing the potential mobility zone of each infected person in the surroundings of its home.
- Once the likely transited area has been defined for each infected person, they have to be spatially overlapped. The overlapping index is calculated (i.e. number of transit areas overlapping).
- Classification of the transit areas based on accumulation intervals, which represents the hazard of transmission. The thresholds of the intervals have been defined by the natural interval methods, which is based on the mean and the standard deviation of the data during the selected period. The heavily-transited areas by potential infected people map is obtained.
- As optional complementary information for the analysis, the assessment of the risk of contagion for each transit area can be calculated. To do so, the hazard of transmission already calculated can be related to the amount of people susceptible to be infected in each area. The population exposed have been inferred from the population density estimated in each building, which has been obtained from the alphanumeric database of the Spanish Cadastre and INE database. Based on the residential surface per building, expressed in meters, and on the number of inhabitants per census section, the occupation rate per census section has been calculated. This rate relates the number of people and the total residential surface of each census section. Finally, the occupation rate has been multiplied by the sum of the residential surface of each building, and the result is the estimated number of people per building, which can be used for calculating the population density of each building.

Figure 6 shows the heavily-transited areas by potential infected people for the period 16-29 November 2020.

Figure 6. Heavily-transited areas by potential infected



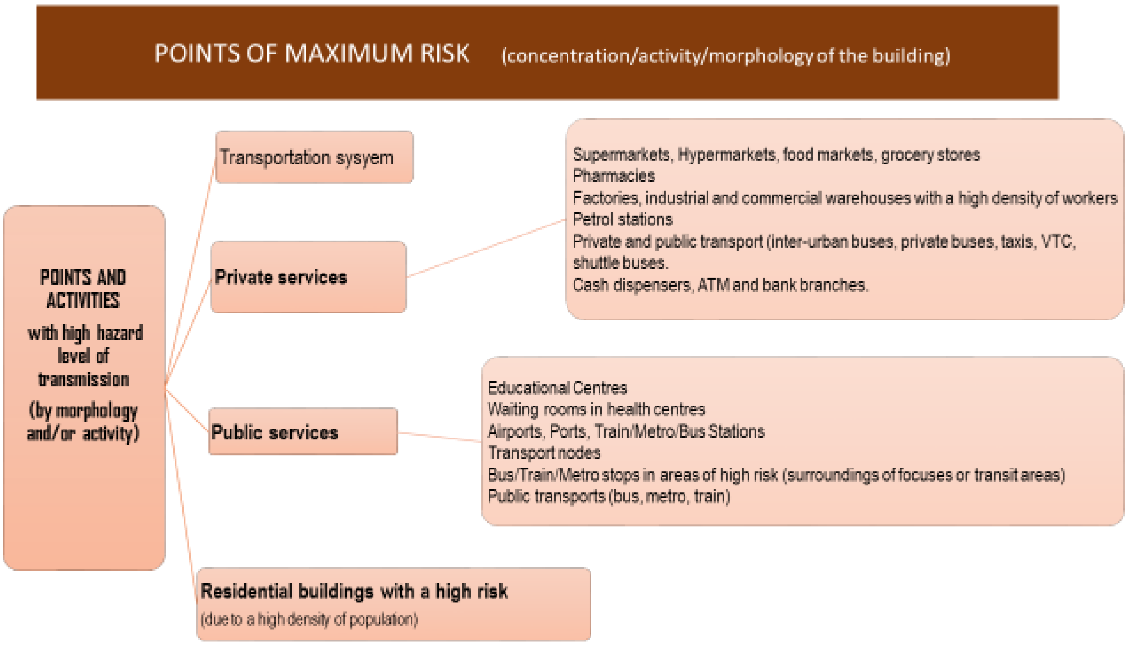
Source: authors' own elaboration based on data provided
by the Regional Hospital of Málaga (Andalusian Health Service)

4.3 Identification of the Points of Maximum Risk

The Points of Maximum Risk of contagion are those places of the city where the presence of the people enhances crowding and social contact. In these places, the contact can be direct or indirect, and they are operative even during lockdowns and shutdowns. Figure 7 lists the places in Málaga that have been identified as Points of Maximum Risk within the city in the present research, which have been included in the Geo-Covid Cartographic Platform with the aim of supporting the risk control process. The Points of Maximum Risk of contagion can be added as complementary information not only in the neighbourhood focus of contagion maps, but also in the map of heavily-transited areas by potential infected people.

In the results section, Figure 15 and Figure 16 display how the Points of Maximum Risk can be added to the heavily-transited areas by potential asymptomatic people in order to specify where the probability of crowding is higher, and thus, so it is the probability of contagion.

Figure 7. Points and activities considered as Points of Maximum Risk



Source: authors' own elaboration

4.4 Calculation of hazard indexes per focus and development of hazard maps

The focus of contagion hazard (or the heavily-transited areas hazard) can be estimated by several epidemiologic parameters that characterise the spatio-temporal pattern of contagion. Those parameters use indexes to calculate the potential harmfulness of the focuses in each area. Some indicators, such us the number of confirmed cases within a focus, can be used to estimate the total amount of people that could be infected, whereas the percentage of cases, the contagion rate per 100,000 inhabitants, or the density of cases can infer the hazard of contagion in relative terms. On the other hand, other parameters such as the contagion speed within the focus or the temporal clustering of cases give information about the transmission temporal behavior.

In this research, it has to be highlighted that the hazard indexes for each focus have been calculated based on the number of cases reported in an area, and on the total population of the area affected by an active focus. Therefore, population within the focuses have not been estimated nor averaged from biggest spatial units, which means that the accuracy of the data is high.

In order to obtain those data, it has been necessary to acquire data from the Spanish Cadastre (ATOM file format), and to use infer calculation for determining the number of inhabitants in each dwelling or cadastral parcel. From this source of information, the following hazard indexes have been calculated for each focus.

- Number of cases per focus. It calculates the number of cases reported in each focus. This index shows the potential of contagion of the focuses in absolute terms. When the number of reported cases is high, it is usually correlated with a high population density within the focus.
- Density of cases per focus. It calculates the total number of cases per hectare in an active focus. This is a representative index that can be used to know the proximity of positives between them.
- Percentage of cases per focus. This index shows the portion of people infected in relation to the total estimated population in the focus, so it can be considered an indicator of the relative hazard of the focus and of the level of transmission within the focus, regardless of the number of cases. This index is useful for detecting those focuses in which a high number of cases is not correlated with a high population density, which lead to think about more complex and less common explanatory factors.
- Contagion speed per focus. It calculates the speed at which the disease spreads within a focus on a selected temporal basis (e.g., daily, weekly, biweekly, monthly, etc.)
- Temporal clustering of cases. It estimates the time lag between the first and the last infected within the focus. The temporal clustering of cases, together with the spatial proximity within the focus, can show if the contagions have a common origin, which could be a social event or a heavily-transited place within a neighbourhood.
- Incidence rate within the focus (new positives rate per 100,000 inhabitants on a daily or biweekly basis). The rate of contagion per 100,000 inhabitants have been estimated and mapped both on a daily and a biweekly basis. This index shows the potential of transmission within the focus. The analysis of the trend (increasing or decreasing trend) is a good indicator of the stage of the epidemic within the focus, and of the expected rate of transmission (i.e. linear, exponential, etc.)

The intervals classification of the aforementioned hazard indexes, when they have been mapped, has been established based on data at a local scale. This is, the intervals of each variable and index represent the specific hazard level for our study area (e.g. maximum, minimum and mean values, data distribution, standard deviation, etc.). The proposed methodology for establishing thresholds and creating intervals is preferred for obtaining more comprehensible and realistic maps of each variable based on local data, but it has to be highlighted that the intervals and, thus, the hazard levels, are exclusively representative of the study area, and they cannot be extrapolated to other areas. However, the method is adaptable so it can be applied to other zones, which will have their own hazard intervals. The intervals have been calculated based on a statistic approach (mean plus/less standard deviation), and the outliers have been previously removed following Equation 1.

- Removing outliers
    - o IQR =Interquartile Range (Q3-Q1) Equation 1
    - o Where Q1 and Q3 are the value of the first and the third quartile.
- Outliers:
    - o q<Q1-3*IQR
    - o q>Q3+3*IQR
        - ▪ Where q is the threshold to detect outliers

Establishing thresholds for data classification

Interval classification	Hazard level
$\times - \sigma < a < \times$	Low
$\times < a < \times + \sigma$	Moderate
$\times + \sigma < a < \times + 2\sigma$	High
$a > \times + 2\sigma$	Very high

Where σ is the standard deviation and $\times$ is the mean.

Currently, it is not possible to create those intervals at a lower scale, with a wide range of spatial pattern and characteristics, since the casuistry of the variables and the information about their behaviour are not available. That level of diagnosis and analysis could be reached in following stages of the research, once a comparative analysis of the values and trends of each variable and index have been carried out for Andalucía or Spain. In any case, it is important to highlight that in order to compare hazard, vulnerability and risk data and maps, it is necessary to use comparable methodological criteria. The resulting maps obtained in the present research for each hazard index are shown and described in the Results section (Figures 11-14).

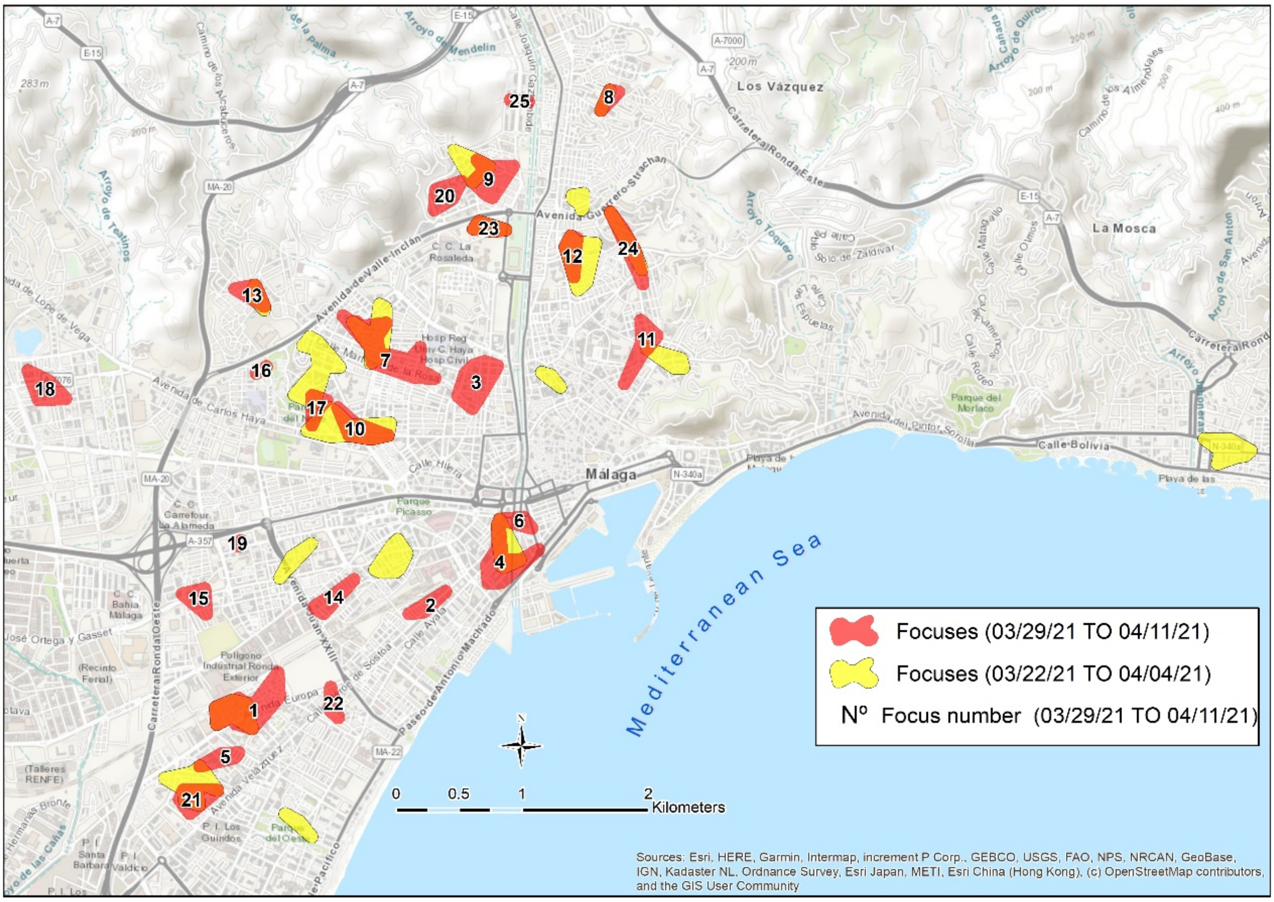
5 Results

5.1 Focuses and micro-focuses of contagion

The most relevant map obtained by the proposed methodology and available in the Geo-Covid Cartographic Platform is the one that identifies and delimits the focuses and micro-focuses of contagion for a selected period (Figures 8 and 9). The mapping of focuses supplies real-time snapshot, which allows observing the distribution and the evolution of the pandemic during the increasing and decreasing stages of contagion.

Figure 8 is a diachronic map that shows the spatio-temporal evolution of contagion during two consecutive 14-days periods. The map clearly shows how the distribution of contagion in the study area during both study periods is not homogeneous, since some sectors and neighbourhoods have incidence rates significantly higher (4025 cases per 100,000 inhabitants) than the mean value calculated for the whole city (115 cases per 100,000 inhabitants). The sequence of maps of contagion in consecutive periods allow to observe the spatio-temporal evolution of some focuses, which after one week, tend to remain in the same area or/and to spread to nearby areas.

Figure 8. Map of the neighbourhood focuses of contagion
in two consecutive periods (March-April 2021)

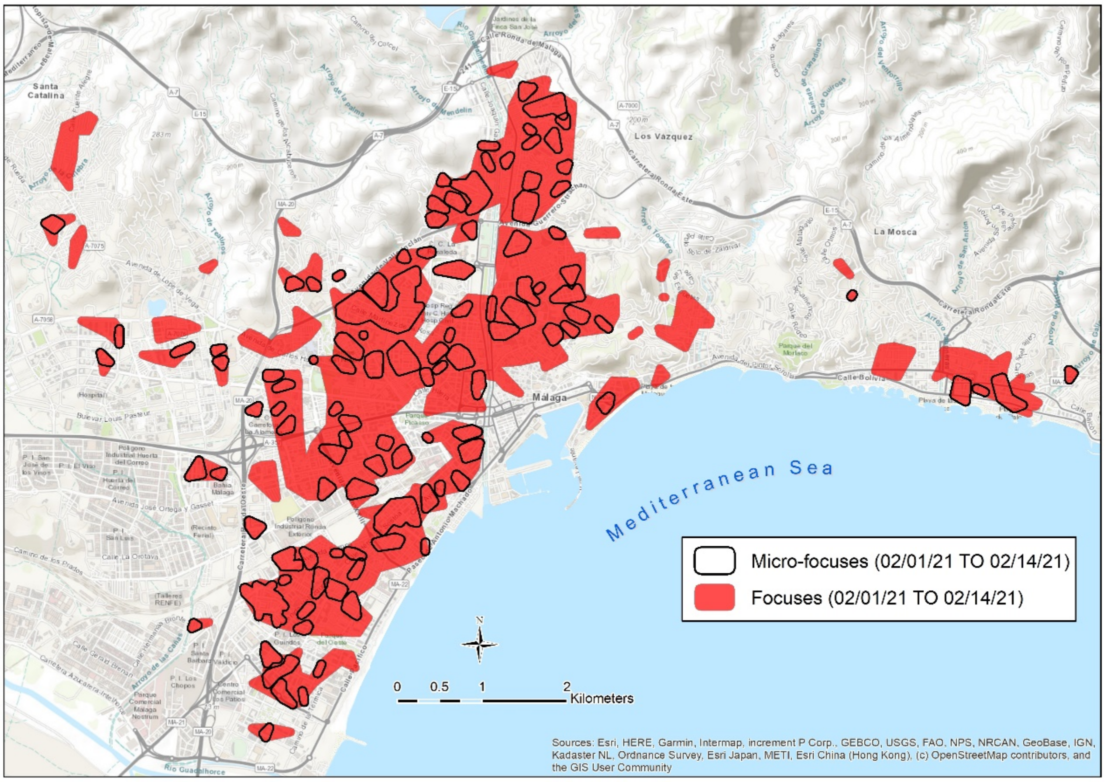


Source: authors' own elaboration based on data provided
by the Regional Hospital of Málaga (Andalusian Health Service)

In Figure 9, the map displays the location and shape of the focuses during a very expansive stage of the pandemic, so there are a lot of focuses all over the city and the pattern of contagion is shifting from gathered to scattered. In that stage of the pandemic it is important to distinguish between areas that can be considered as focuses (more than 5 infected within a 200 m radius), and micro-focuses (more than 5 infected within a 100 m radius).

Both in Figures 8 and 9 show a spatial relationship between the urban areas with more focuses and the most populated areas of the city. This hypothesis, which relates a greater incidence rate and a higher population density, will be nuanced in following sections, when analysing several hazard indicators of the focuses of contagion.

Figure 9. Map of the neighbourhood focuses and micro-focuses of contagion. Period January-February 2021)



Source: authors' own elaboration based on data provided by the Regional Hospital of Málaga (Andalusian Health Service)

5.2 Distribution and delimitation of the focuses within the city and comparative hazard analysis

The maps that show the location of the focuses in Málaga, as well as the results of some of the hazard indexes calculated for each focus, are displayed in several figures (Figure 11-Figure 14), whereas the comparison of the values of the hazard indexes is shown in Figure 10. All the neighbourhood focuses of contagion hazard maps represent the early stages of the first wave in Spain (March 2020), this is, an expansive stage of the epidemic.

Table 1. Hazard indexes of the focuses detected
during the early stage of the first wave (March 2020)

No. cluster	Number of cases	Density of cases /ha	Percentage of cases	Temporal clustering of cases (days)	Contagion rate	Incidence rate in 14 days/100,000 Inhabitants (03/01/2020 to 03/14/2020)	Incidence rate in 14 days/100,000 Inhabitants (03/15/2020 to 03/28/2020)
1	5	1.0	0.28	10	0.5	166	111
2	7	0.8	0.24	12	0.6	35	208
3	27	0.6	0.12	29	0.9	23	78
4	15	0.5	0.13	22	0.7	27	90
5	5	1.6	0.44	16	0.3	177	266
6	10	5.8	15.38	2	5.0	15385	00
7	5	0.7	0.22	14	0.4	87	131
8	12	0.8	0.16	24	0.5	81	68
9	7	0.7	0.16	18	0.4	22	112
10	6	0.8	1.14	15	0.4	189	947
11	5	0.9	0.20	6	0.8	159	40
12	12	2.2	0.86	9	1.3	787	72
13	7	8.5		2	3.5		
14	8	0.7	0.30	13	0.6	150	150
15	5	0.8	0.38	6	0.8	153	229
16	7	0.7	0.39	13	0.5		386
17	5	1.4	0.40	20	0.3	79	238
18	9	0.7	0.27	18	0.5	150	90
19	7	1.0	0.16	21	0.3	115	00
20	7	1.7	0.38	24	0.3	108	217
21	6	1.1	0.42	25	0.2	70	349
22	7	1.1	0.69	12	0.6	491	196

Classification of variables	Low	Moderate	High	Very High

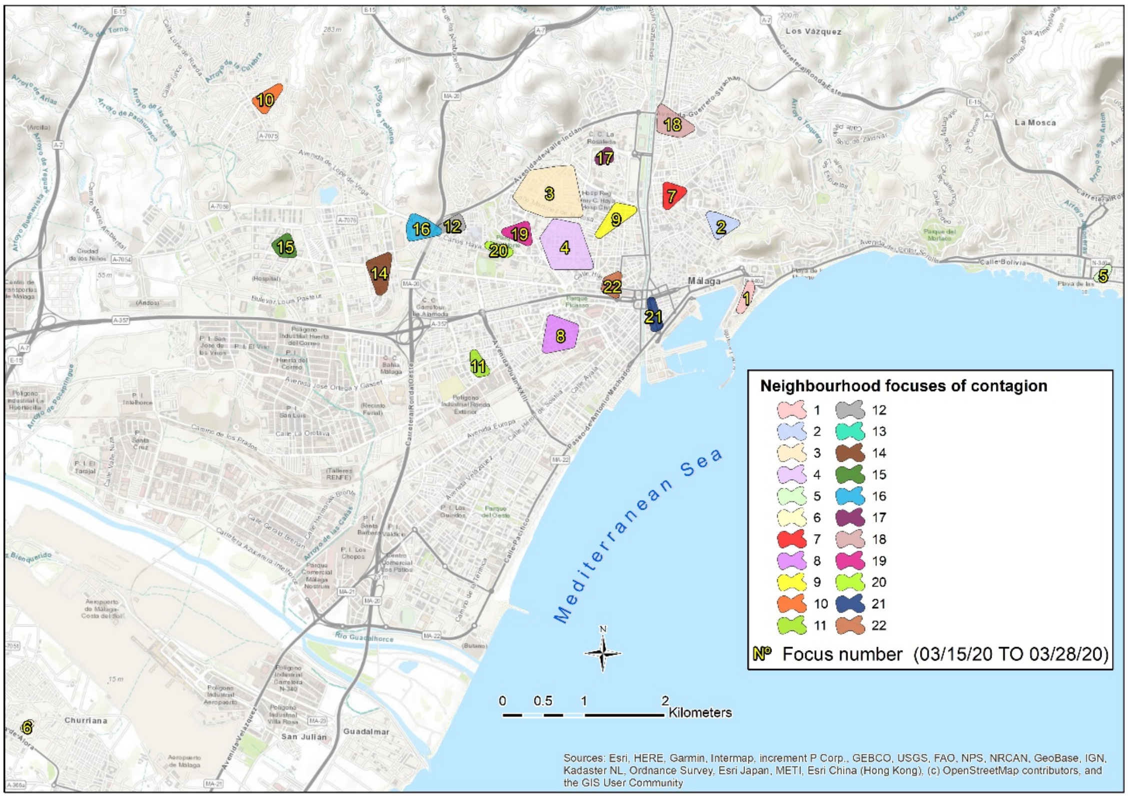
Source: authors' own elaboration based on data provided
by the Regional Hospital of Málaga (Andalusian Health Service)

Overall, it can be observed a higher concentration of focuses in the western and north-western sectors of Málaga City (see map in Figure 11). This concentration is especially high in the area delimited by Carlos Haya Avenue—Martínez Maldonado Street (South), Guadalmedina River (East), and Valle Inclán Avenue (North and West).

The distribution of infected people has a low density in the historical centre of the city, and the pattern of contagion is scattered (any focus was detected in the area). The current main role of the historical centre of the city as an area devoted to services enhance an urban model in which the concentration of touristic accommodations, shops, offices and restaurants is very high, but the amount of people that live in the area is low. This fact may explain the low number of confirmed cases in the area. However, in the surroundings of the city centre, which are traditional residential areas, 5 focuses where detected: Focus 21 (Alameda de Colón) at SW, Focus 22

(Compositor Lemberg/Hilera) at W, Focus 1 (Malagueta) at E, Focus 2 (Victoria/Lagunillas) at NE, and Focus 7 (Capuchinos/Molinillo) at N. All those focuses have a low number of cases, but the distance between the infected people is low, and thus, the contagion density is high (Figure 12). This is especially remarkable in Focus 1 (Malagueta), Focus 21 (Alameda de Colón) and Focus 22 (Compositor Lember/Hilera). In the latter focus, the percentage of cases, and the contagion speed are also very high (Figure 13). In relation to the contagion speed, it is high (0.5-1 infected/day) both in Focus 22 and in Focus 2 (Figure 14).

Figure 11. Distribution of the focuses in Málaga during the first wave (March 2020)



Source: authors' own elaboration based on data provided
by the Regional Hospital of Málaga (Andalusian Health Service)

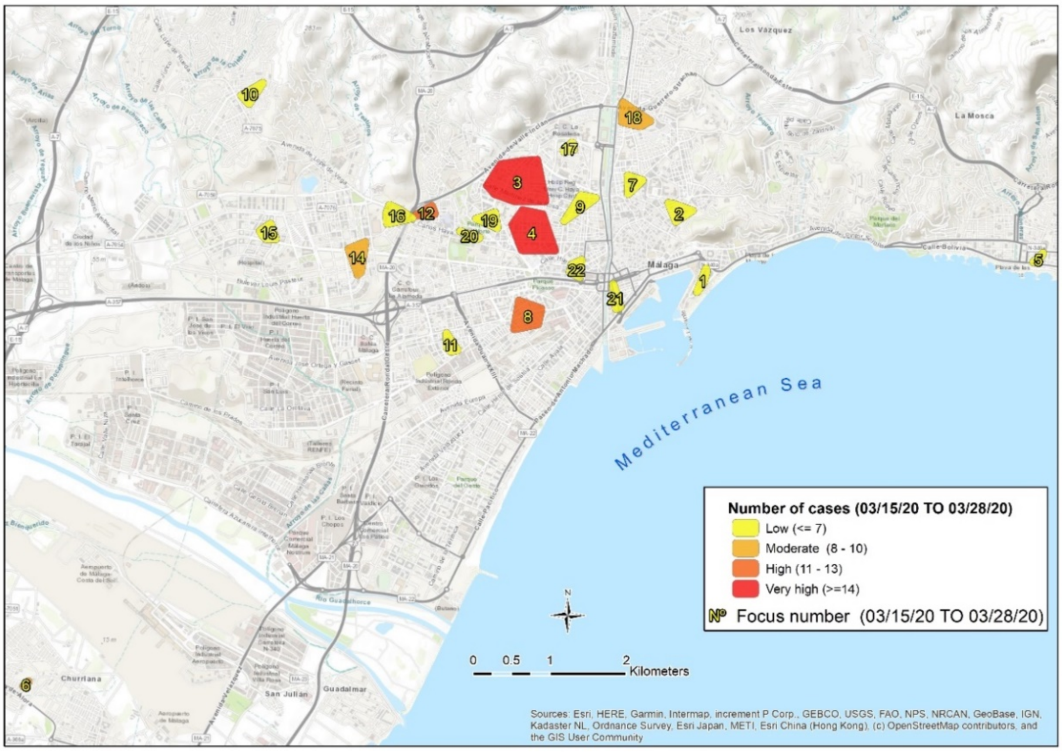
Regarding to the existence of focuses of contagion at the western part of the city, Focus 8 (La Unión/Los Tilos) and Focus 11 (Camino San Rafael-Ortega y Gasset Avenue) are the most relevant. Focus 8 is important due to the high number of cases, whereas the most important characteristic of Focus 11 was the high contagion speed. Surprisingly, the western part of the city, developed around the Málaga-Cádiz road, has a scattered pattern of contagion, despite the high population density of the area, and any other focus was observed during the aforementioned study period in that sector of the city.

On the other hand, the area with a higher concentration of focuses in the city is the north-western sector, to the north of the Carlos Haya Avenue-Martínez Maldonado Street axis. In this sector, it should be highlighted Focus 3 (Suárez/Miraflores de los Ángeles) and Focus 4 (Martínez Maldonado/Eugenio Gross) due to their great spatial extent and the number of cases reported. The number of cases in these focuses reaches critical levels, and the contagion speed is high. However, the density of cases and the percentage of cases are moderate and low, respectively, so it can be considered that both focuses are associated to the high population density of the area.

Focus 12 (NW Regional Hospital) and Focus 20 (Parque del Norte-Carlos Haya) are also remarkable at the north-western sector of the city, due to the critical and very high density of cases reported, respectively. In both focuses, a very high percentage of cases is also observed. The existence of both focuses can be influenced by the proximity to the Regional Hospital. Additionally, the contagion speed is very high in Focus 12 (1-1.3 positive cases/day). In this focus, the very high values in several hazard indexes may be explained by the presence of a retirement home (8 out of 12 cases within the focus belong to the retirement home). Other focuses of this sector, such as Focus 20 (Parque del Norte-Carlos Haya) and Focus 17 (La Roca), have also a high contagion speed.

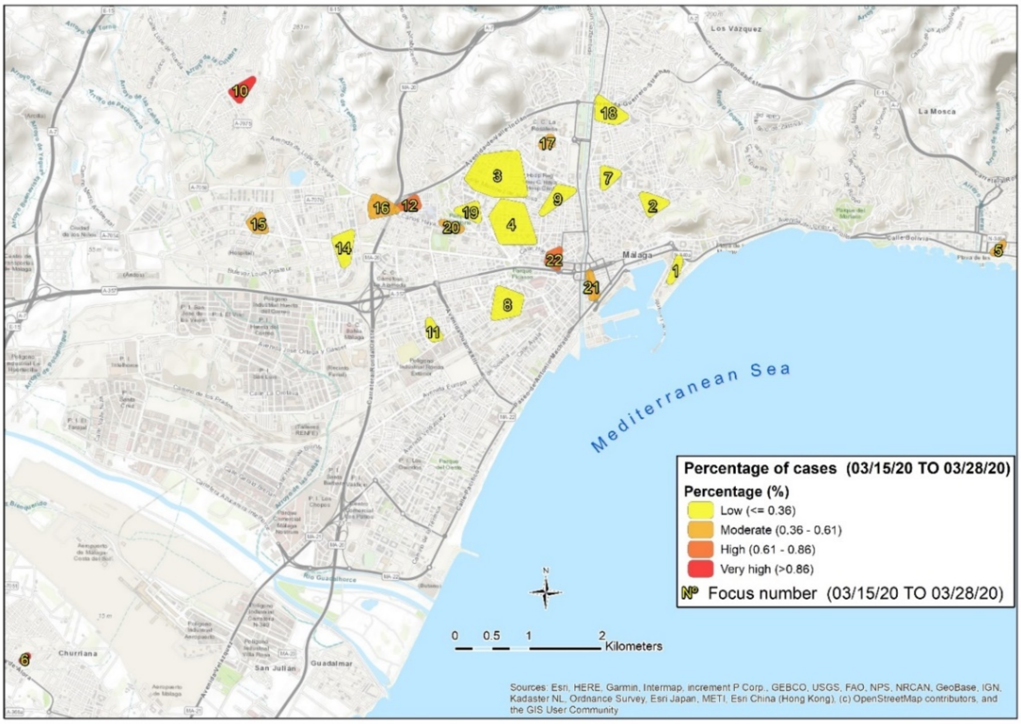
On the western outskirts of the city, other focuses can be also highlighted. Focus 14 (Mayarme Street), Focus 15 (Plutarco Avenue-North) and Focus 10 (Puerto de la Torre). Focuses 14 and 15 are located next to the university campus, in a residential area where many students use to live. Most of those students live with other students, so the high percentage of cases may be originated because of them. In the case of Focus 10, in Puerto de la Torre, the percentage of cases reached critical values, despite the urban model of the area is composed by single-family houses, which complicates contagion between neighbours, and there are not retirement homes or health centers that may explain such high values.

Figure 12. Number of cases per focus



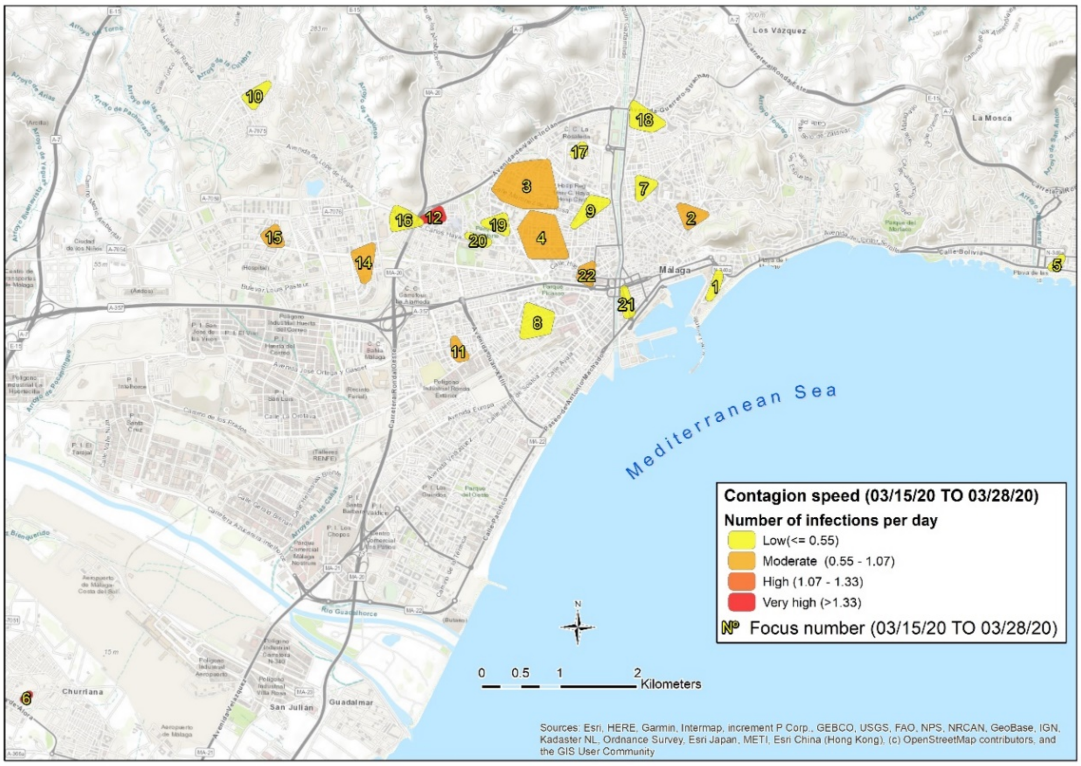
Source: authors' own elaboration based on data provided by the Regional Hospital of Málaga (Andalusian Health Service)

Figure 13. Percentage of cases per focus



Source: authors' own elaboration based on data provided by the Regional Hospital of Málaga (Andalusian Health Service)

Figure 14. Contagion speed per focus



Source: authors' own elaboration based on data provided
by the Regional Hospital of Málaga (Andalusian Health Service)

5.3 Map of the heavily-transited areas by potential asymptomatic people weighted by the population density

Figure 15 and Figure 16 display examples obtained from the map of the heavily-transited areas by infected people weighted by the population density, so that map indicates and delimits public and open areas of the city where the probability of contagion is higher.

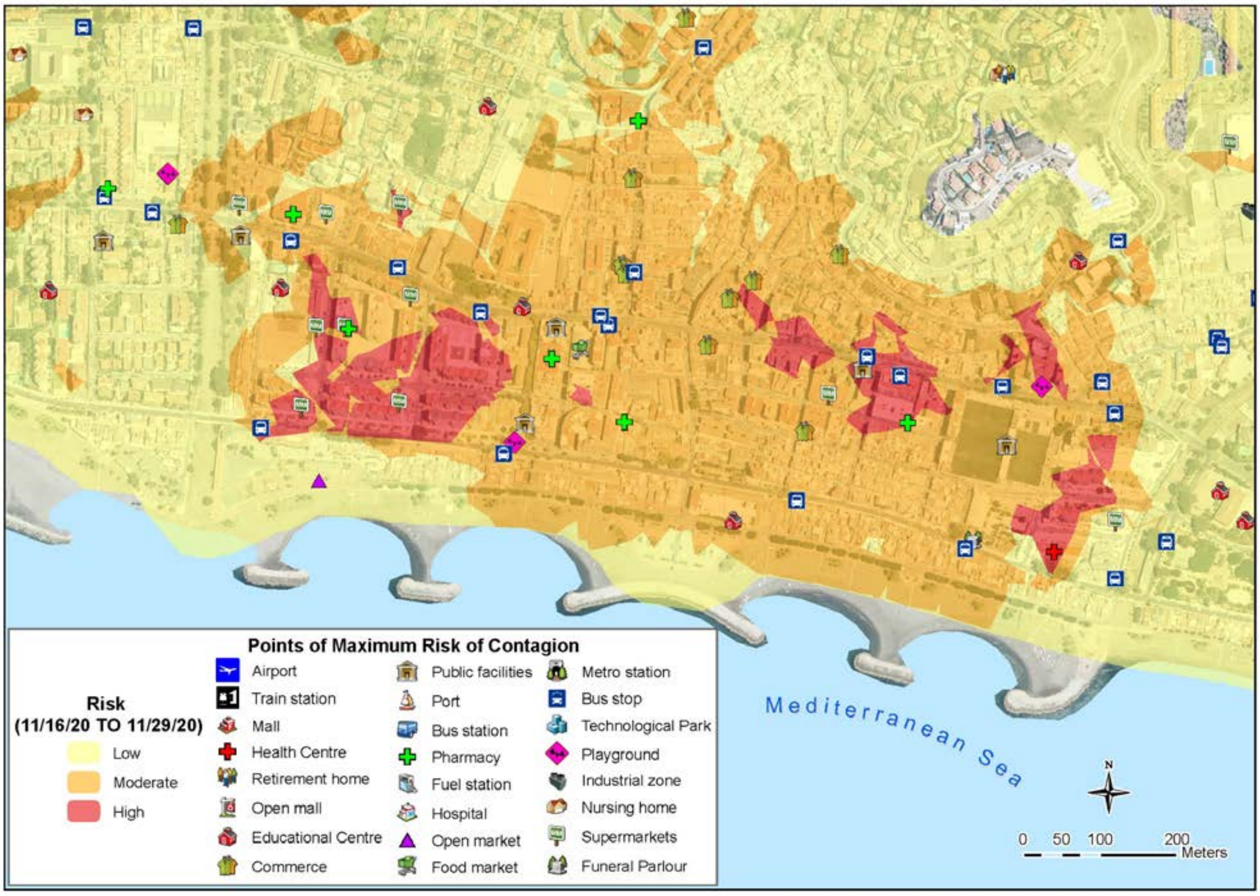
As it can be observed in Figure 15, which is focused on El Palo district, the highest values are reached in a residential area called Echevarría, which is composed by tall multi-family buildings (6-8 floors) and shops and restaurants on the ground floors. To the east, other two areas are classified in the high hazard level next to the N-340 road, which acts as the transport axis of this part of the city. Finally, a fourth area in the surroundings of the health centre and the cemetery, with the same urban typology than the above-mentioned Echevarría residential area, also reaches the high hazard level.

In the case of the second example displayed (Figure 16), it is focused on the central-north sector of the city. In that area, the blocks with higher risk of contagion are mostly located west of Cristo de la Epidemia Street. Those blocks are tall multi-family buildings (6-8 floors), with bars and shops on the ground floors. In the map it is also observed how small blocks of high risk have been developed along some of the main transport axis of the area: Cristo de la Epidemia Street and Alameda de Capuchinos. The spatial extent of the high-risk areas grows in the confluence of those streets in Fuente Olletas Square and Capuchinos Square.

5.4 Points of Maximum Risk Map

Figures 15 and 16 are good examples of the addition to the map of high risks of contagion, punctual information about the buildings and facilities within the study area that may be problematic from an epidemiological point of view (e.g., transmission rate, risk of contagion, etc.). In some areas, the spatial concurrence of points of high risk and the existence of active focuses may indicate that the risk of contagion in the area is related to those points' activities.

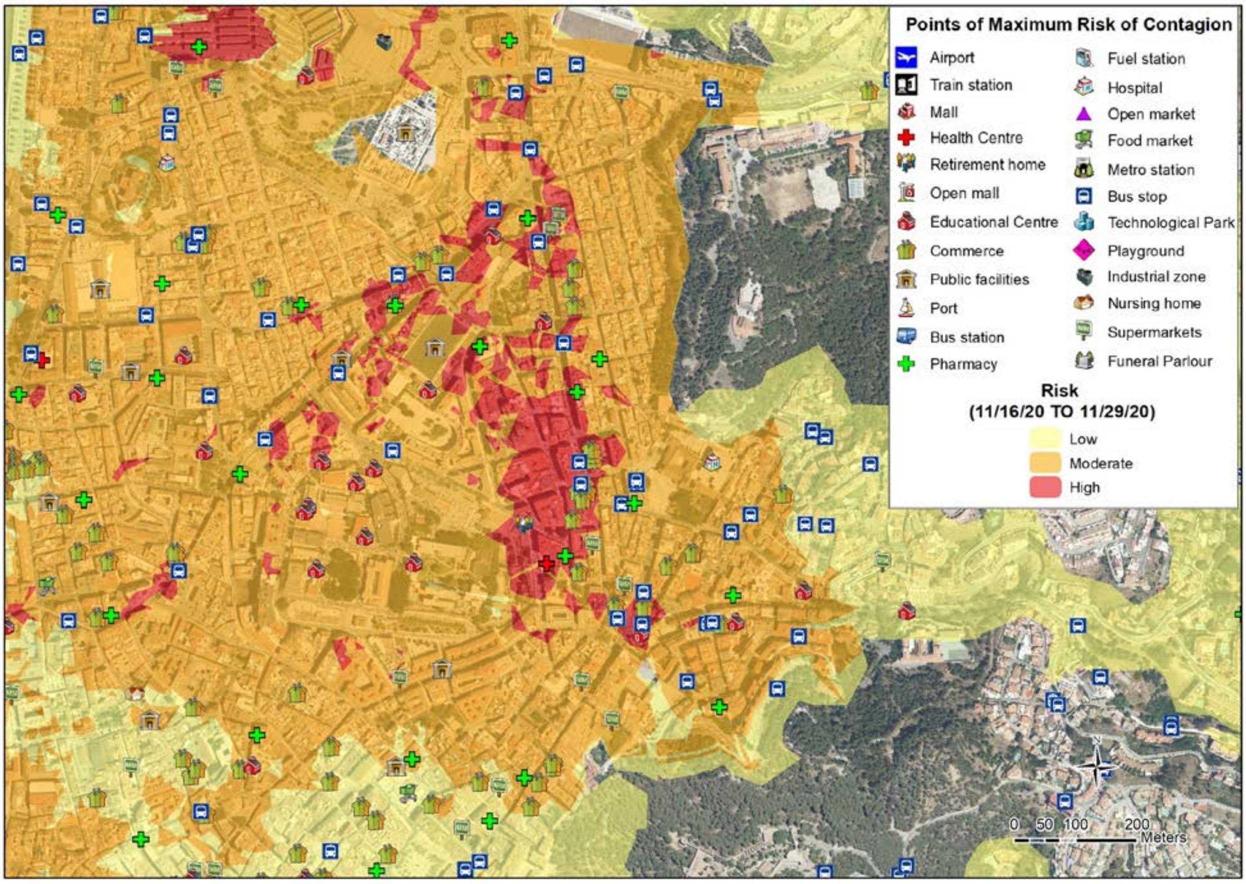
Figure 15. Map of areas and Points of Maximum Risk of Contagion. Example 1: El Palo



Source: authors' own elaboration based on data provided
by the Regional Hospital of Málaga (Andalusian Health Service)

When mapping the Points of Maximum Risk in the areas analysed and showed in Figures 15 and 16, it can be observed that in El Palo sector, the area of maximum risk of contagion overlaps the local health centre and the local cemetery, so it is recommended to reinforce vigilance and informative measures in those places. Additionally, in the Echevarría residential area, and in the surroundings of Cristo de la Epidemia Street, in the central-north sector, not only the supermarkets but also the shops and restaurants are high risk areas, so supervision has to be also strengthened here. Likewise, in both areas, the urban typology eases the risk of contagion in common areas of residential buildings with commercial activities on the ground floor, due to the transit of people (e.g. lifts, entrance halls, etc.). These residential buildings must be highlighted as points of maximum risk due to the concentration of people and activities.

Figure 16. Map of areas and Points of Maximum Risk of Contagion.
Example 2: Central-North Sector



Source: authors' own elaboration based on data provided
by the Regional Hospital of Málaga (Andalusian Health Service)

The underlying model explaining the development of maximum risk areas around some of the main road axis in El Palo and in the central-north sector (Salvador Allende Avenue and Capuchinos Avenue, respectively) may relate a higher risk of contagion with the feasible transmission of the disease in public transports, which can act as vectors of contagion along their route. Following this approach, and based on the distribution of the maximum risk areas, bus stops have to be considered as points of maximum risk. In the light of the distribution of the maximum risk areas, it is recommended to increase the frequency of buses and to reduce the number of passengers in lines that cross maximum risk areas or active focuses.

6 Discussion

The maps of focuses and micro-focuses of contagion, as well as its spatio-temporal evolution in weeks (Figures 8 and 9) allow observing how the spatial distribution pattern of contagion in Málaga during the study periods is heterogeneous, including sectors where infected are scattered and areas that are prone to accumulate cases. The limit between both patterns, this is, the delimitation of focuses, is established around 200 m between the nearest infected. Although the scale of the present research is not frequent in other researches, the same patterns have been observed in researches carried out by de Cos et al. (2020, 2021). Those authors, based on similar microdata, observed a spatial accumulation pattern in urban areas as Santander and Torrelavega. Other works at urban scales as those carried out by Lall & Wahba (2020) and Chang et al. (2021), also coincide in showing the unequal accumulation of infected in urban areas, although these studies are based on data from artificial spatial units (e.g. census section, health district, regular polygons, etc.).

According to the spatial variability of the incidence rate in urban areas, and the low spatial representativeness of average values in this parameter, it may be concluded the need of using detailed spatial-temporal criteria in order to know the evolution of contagion and to apply effective control measures. The most common spatial units used to this purpose (e.g., municipalities, health districts, etc.) may mask different contagion patterns. In addition, the implementation of generic and homogeneous measures against contagion in urban areas with different incidence rates and characteristics of contagion not only enhances lack of protection in areas with high incidence rate, but also overconfidence and annoyance in areas with low incidence rate and strict restrictions during a long time.

The use of the neighbourhood focus of contagion as the basic epidemiologic unit provides the advantage of showing the natural pattern of contagion, without artificial spatial biases. Some authors have focused on the correlation between spatial distribution of contagion and geographical information (De Cost et al., 2020; Díaz-Olalla et al., 2021, García et al., 2021; García-Morata et al., 2022). The focuses of contagion maps may be enriched with those data, since they can aggregate and contain information from others common units, such as the census section.

Regarding the likely connection between focuses and the identification of potential paths of contagion within the city, when analysing the distribution of the focuses, an organization along heavily-transited roads used by public transports can be observed. This is the case of the focuses around Martínez Maldonado Street- Carlos Haya Avenue, which connect focuses 4, 12, 16, 20, and even Focus 10, in Puerto de la Torre. All these focuses are connected by several bus lines (e.g. line 8, line 15, line 18, line 21, line 23, line 38, line 62 and line N4). Following this approach, bus lines 4, 14, 19, 20, 22 and 64 connect Focus 8 and Focus 11, so they can act as areas of transmission and accumulation of potential asymptomatics from both focuses. Therefore, if this hypothesis is taken into account, the bus lines should be places in which the prevention measures (i.e. social distancing and disinfection) have to be strictly obeyed.

In relation to the possibility of the development of new focuses in areas surrounding hospitals or health centres, it has been already mentioned a likely connection between Focus 12 and Focus 16 with the Regional Hospital, since the percentage of cases in those focuses are too high based on the population density of the areas. This could also be the reason behind the delimitation of Focus 9, in the surroundings of the Civil Hospital. However, in this case, the connection is weak, and the percentage of cases is the same that in other areas with the same population density than the focus.

6.1 Usefulness of the proposed maps

According to the analysis of the hazard indexes in Málaga City, it can be concluded that the proposed maps that have been included in the present research are useful for the following tasks:

- Based on the hazard indexes calculated for each focus, it is feasible to identify and delimit the location of the focuses in the city, its natural extent (avoiding the use of larger administrative units that lead to data misinterpretation), its spatio-temporal evolution, and its hazard classification. The location and the accurate spatial delimitation allow to delve into the study of the underlying territorial and urban model of the area where the focuses are active, and to discover the reasons behind each focus.
- From the information about the focuses it is possible to delineate the routes and areas of the city highly-transited by potential positive and asymptomatic cases, as well as their most frequent intra-urban movements. This information allows to accurately mapping areas and

points where the implementation of specific measures have been addressed to prevent the spread of the disease (e.g. extra disinfection and air circulation in crowded places).

- The precise location of buildings and points in the urban area where the probability of contagion is higher because of the type of activity or service they are devoted for (e.g. health centres), or due to the accumulation of people (e.g. supermarkets, bus/train/metro lines, building with a high number of people).
- The suggestion of specific mitigation measures for each area classified in the high hazard level based on the territorial model of the area and the spatial pattern of contagion in that area during a certain period.
- The identification of preferential areas for massive scanning of the population that live within them, especially during expansive stages of the epidemic, when the transmission is high. The identification in real-time of the areas with a high number of potential asymptomatic people may allow the social tracking of the disease within the affected area, and the subsequent immobilisation of asymptomatic cases. This strategy is complementary to the common approach to detect and immobilise asymptomatic people, which is focused on the tracking of outbreaks originated in social meetings and workplaces.
- The early detection of upturns in the contagion of some areas that are especially hazardous. The aim is to impose lockdown in some sectors, as well as to narrow the tracking of contagions.
- The planning of the cities and urban areas management during the epidemic. In order to avoid reactivation of the transmission chain, the management and the uplifting of lockdowns and mobility restrictions (both in urban areas and municipalities) must be based on accurate spatial criteria. The Geo-Covid Cartographic Platform allows to regulate the mobility of the population when de-escalating lockdowns in a systematic and data-based way.

7 Conclusions

The mapping of focuses of contagion implemented in Málaga has shown that the distribution of contagion in urban areas is not randomized. The pattern is characterized by the accumulation of cases with specific morphometric characteristics that remain immutable both during increasing and decreasing stages of contagion. The neighbourhood focuses of contagion and the heavily-transited areas by potential infected are dynamic spatial units, and a direct relation between the existence of focuses of contagion and higher population density is also observes. However, this relation is not evident in the opposite direction, since focuses with high incidence rate and very high contagion speed are observed in areas with low population density.

Based on the applications of the maps of focuses of contagion, it may be concluded that the Geo-Covid Cartographic Platform is a useful and explanatory tool, which allows a better understanding of the epidemic transmission pattern, as well as to improve the implementation of prevention and mitigation measures in focuses. The Geo-Covid Cartographic Platform supplies a spatial approach to the management of the COVID-19 crisis, which could be the key for improving the effectiveness of the measures addressed to prevent contagion. The accurate understanding of the spatial pattern that enhances the intensification of contagion in an area is essential for identifying the origin of contagion and for the effective implementation of control and prevention measures in each area. This approach is supported by authors such as De Cos et al. (2020) and it is named as geo-prevention.

Moreover, the mapping of neighbourhood focuses of contagion proposed in the present research is a tool that allows to solve the drawbacks and limitations of other methods and maps of infected people that use administrative divisions as the basic unit of analysis. The neighbourhood focus of contagion has proven to be a rigorous and trustful unit of spatial diagnosis, which represents the evolution of contagions in the city, as well as the tracking of those contagions.

Overall, the proposed maps allow to implement more effective measures for pandemic control and management. They also allow to delimit the areas in which the intervention for stopping the transmission is essential, to detect the areas where prevention measures have to be implemented or intensified, and to determine the optimal areas in which massive scanning of the population must be done for prevention. From an epidemiological point of view, the maps are useful for identifying the sectors of the city that are likely to accumulate a higher concentration of potential asymptomatics infected (A), as well as for classifying the population of each sector in groups, in order to apply the HEIR (SEIR: Susceptibles, Expuestos, Infectados, Recuperados, from its Spanish Acronym) model: Healthy, Exposed, Infected, Recovered.

The proposed hazard indexes allow to distinguish all the hazard nuances in each focus, with the aim of describing several urban hazard models. In the selected study area, two models of spatial distribution can be observed: mainly scattered in the coastal belt of the city, and gathered in focuses in other sectors, especially at the north-western part.

Regarding to the explanatory factors of the distribution of infected people in the urban area, it could be deduced a multi-factorial model, despite of the influence of the population density over the number of cases and the contagion density. Some factors, such as the urban typology, the proximity to hospitals and health centres, the socioeconomic characteristics of the population (e.g. university students), and the type of daily intra-urban movements of the population may be explanatory parameters of the spatial pattern of contagion, so further analyses are needed in the following stages of the research.

The accuracy of the data requested to identify and map focuses of contagion is not only a guarantee of precision, but also a limitation when implementing and replicating the method in other areas. On the one hand, some health authorities have not developed detailed records of contagion during the pandemic, whereas others have not been prone to provide those records. This fact has limited the implementation of studies at the same scale than the present research, which has restricted the comparison of hypothesis and the discussion of results. The confirmation of our hypothesis in non-urban areas is also a potential future line of research.

The use of addresses as the reference location of a potential source of contagion is also a limitation when developing a general explanatory model of transmission, since the estimated mobility of infected people is restricted to the surroundings of their homes. In order to overcome this limitation, we are currently working on a model that includes addresses of infected people and shopping records. The focuses of contagion can be used as the basis of a dynamic model based on the confluence-transmission concept. This concept relates active focuses with the maximum incidence rate in a certain date, and the spread of contagion ten days later, especially in the neighbourhoods of the city whose inhabitants have been in the focus. The preliminary results show the coherence of this model of transmission in recent studies carried out by Khatib et al. (2021) and Llanes et al. (2021).

Given its dynamic and adaptable nature, the Geo-Covid Cartographic Platform is a very useful tool for supporting the decision-making process. The platform allows to use accurate and updated information for fulfilling epidemiological and management challenges that arise during each stage of the epidemic both from health and socioeconomic points of view.

The application of the proposed methodology for hazard analysis and mapping in other study areas would permit to compare results from different cities, with alternative spatial characteristics, and it would also allow to obtain comparable maps of the evolution of the epidemic in several study areas.

Therefore, the Geo-Covid Cartographic Platform is a strong input for the decision-making process, and it enables to significantly improve the efficiency of the risk of contagion management. Its versatility and applicability for solving specific aims, as well as its adaptable nature for facing new challenges (e.g. influence of the vaccination pattern), and its utility in several epidemic stages and waves (not only against COVID-19 pandemic, but also against other epidemic with similar characteristics of transmission), turn it into a great forward-looking tool.

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