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Exploring Network Analysis for Urban Planning and Disaster Risk Reduction in Informal Settlements:

Cases From Honduras, Jamaica, and Peru

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ABSTRACT

The work explores the use of street network analysis on informal settlements and discusses the potential and limitations of this methodology to advance disaster risk reduction and urban resilience. The urban network analysis tool is used to conduct graph analysis measures on street networks in three informal settlements in the LAC region: Portmore, Jamaica; Tegucigalpa, Honduras; and Lima, Peru. Authors incorporate risk variables identified by these communities and combine them with prospective scenarios in which street networks are strategically intervened to improve performance. Authors also compute one graph index named Reach centrality. Results are presented spatially through thematic maps, and statistically by plotting cumulative distributions. Findings show that centrality measures of settlements' networks helped identify key nodes or roads that may be critical for people's daily life after disasters, and strategic to improve accessibility. The proposed methodology shows potential to inform decisions on urban planning and disaster risk reduction.

KEYWORDS

Cities, Disaster Risk Management, Disasters, Informality, Latin America and the Caribbean, Neighborhood Scale, Urban Development, Urban Informality, Urban Network Analysis

INTRODUCTION

Street Network Analysis for Informal Settlements

With half of the world's population living in cities nowadays, and another two billion people expected to move into urban areas in the next two decades, the pressures of rapid and uncontrolled urbanization can mean that careful urban planning is more difficult today than ever. The United Nations Human Settlements Programme (UN-Habitat) estimates that China will need to build new cities for 350 million people in the next 20 years, and over the same period, 250 million new urban dwellers are

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expected in India and 380 million in Africa (UN-Habitat, 2016). Compliance with urban regulations and zoning are being omitted in complex processes such as those presented by informal settlements, where about 880 million people currently live: 106 million in the Latin America and the Caribbean (LAC) region (UN-Habitat, 2016). It is considered that 70 percent of today's urban growth occurs without the benefit of formal planning processes, and maybe for that reason informal settlements are considered the most common form of urbanization on the planet (Davis, 2006). This also implies that if these trends do not change, the inefficiencies of contemporary cities may become the norm in the future (Daniels, 2011). Such scenario can be hindered also by an accelerated disaster risk creation (DRC) —faster than disaster risk reduction (DRR)—, as root causes and drivers of informal settlements and vulnerability often leave people with no other choice but to occupy hazard-exposed areas (sometimes the only available for the poor) while devoid of basic urban services (Lewis & Kelman, 2012).

Researchers of the City Form Research Group at the MIT School of Architecture & Planning (SA+P) have recently created a new set of simulation tools that offers urban analysts and city planners a better understanding of how the spatial patterns of cities affect people's mobility and accessibility. Improving people's mobility within cities and making city's potentials accessible to all is critical for an equal access to opportunities and urban justice (UN-Habitat, 2003, 2016), as well as for making cities safer and resilient. By using mathematical network analysis methods from graph theories, the Urban Network Analysis (UNA) tool examines urban networks centrality and redundancy, while it offers to policymakers a detailed look at how their decisions would shape different aspects of urban development, such as where traffic is likely to be highest and on which streets local commerce is most likely to flourish (Daniels, 2011). In this sense, this paper aims to explore the gap between formal and informal urbanization processes through the above-mentioned simulation tool, while supporting local governments, and development and community organizations' planning decisions.

This paper bases on the evaluation of the Urban DRR programming carried out in Latin America and the Caribbean by Sarmiento et al. (2018), supported by the United States Agency for International Development's Office of U.S. Foreign Disaster Assistance (USAID/OFDA). The evaluation conducted between 2017 and 2018 focused on the assessment of eight projects funded by USAID which applied the Neighborhood Approach for DRR (NA-DRR) which seek to find practical and workable solutions for DRR in densely populated informal urban settlements in Colombia, Guatemala, Haiti, Honduras, Jamaica, and Peru. Based on the data availability for this study, authors have selected three settlements to analyze each street network and urban accessibility using the UNA tool: José Arturo (J.A.) Duarte in Tegucigalpa, Honduras, Leticia in Lima, Peru, and Naggo Head in Portmore, Jamaica. Particularly, authors conducted a graph centrality measure named Reach centrality. Moreover, to study urban networks and how these can be affected under certain risk scenarios, authors incorporate disaster risk variables identified by these communities such as floods and landslides areas. Likewise, authors also combine such analyses with prospective scenarios in which urban networks are strategically intervened to improve neighbors' mobility.

The purpose of this work is, on the one hand, to offer reflections on the potential use of the UNA tool in characterizing informal settlements, specifically on how do graph centrality measures (i.e., Reach) perform within delimited informal neighborhoods, and on the other hand, to explore how these results can be useful to inform decisions on urban planning and disaster risk reduction in informal and precarious settlements.

Confronting how rigid formal planning processes and state apparatus tend to produce informality is the first step to deal with informal urbanization (Roy, 2005). This also implies to leave behind the idea that informal settlements are unplannable and the opposite to formal, as these were a seemingly natural phenomenon that is external to those studying it and managing it (Mitchell, 2002). Yet, studying the spatial configuration of cities and their associated social, economic, and environmental processes has been generally identified with the analysis of 'formal' urban contexts (Boeing, 2018). Moreover, urban network analyses tend focus on metropolitan and city scales as small sample sizes can limit the representativeness and reliability of findings, and are more common for urban design, public transport, and commercial analyses (Boeing, 2017; Sevtsuk, 2014).

The analysis of urban networks in informal settlements has been generally focused on the interactions of such settlements with the rest of the city, either analyzing the use of resources (Omenya, 2007), access to opportunities (Oviedo Hernandez & Dávila, 2016), or road network connectivity and proximity (Sirueri, 2015). In this respect, it is important to look at network performance and mobility at the neighborhood scale in informal settlements for two reasons. First, the precarious circumstances of these self-organized settlements are not only reflected in the quality of materials and modes of occupancy, but they also on the precariousness of urban services and the built environment (Sarmiento et al., 2018). Second, national and local authorities often do not have pertinent and reliable data on informal settlements to inform decision making in urban planning and disaster risk reduction. On the one hand, intensive disasters like those triggered by earthquakes threat people in informal settlements generally because they lack adequate housing and mitigation measures, sometimes due to the inability of emergency services to access these areas, or simply because safety locations and hazards are not properly identified. On the other hand, extensive disasters —i.e., low-severity, high-frequency hazardous events— can deteriorate urban networks and interrupt daily life, exacerbating poverty, uncontrolled urbanization and environmental degradation (UNISDR, 2011). Likewise, the generalized lack of representative and standardized demographic and spatial information on the conditions of many informal settlements poses another ‘threat’ (Sandoval & Sarmiento, 2018), as insufficient information can lead to inadequate planning decisions and may affect disaster risk management. Hence, this study draws upon existing survey data on residential land use and hazards in the selected neighborhoods, provided by local residents and international NGOs, which it allows authors to construct hazard and prospective scenarios. In this way, the authors combine traditional graph centrality measures with disaster risk variables at the neighborhood scale.

At the methodological level, this study is grounded in the intersection between urban planning and graph theory, complemented by disaster studies. According to Taylor (1998), urban planning refers to a process of design and development of land-use in an urban environment, this includes the physical layout of human settlements and urban services such as air, water, sewage, energy, transportation, among others. As a multidimensional process, urban planning encompasses a multiplicity of actors from a wide range of sectors, from public to private, including non-governmental organizations (NGOs). Urban planning is generally tied to political, economic, and social processes, having people’s welfare as its principal concern. Throughout the history of cities, the process of urban planning has evolved to satisfy people’s needs as well as to reflect the aspirations of different societies. To the extent that cities were expanding, different institutions and legal frameworks such as laws, codes, and a long list of regulations have been created to support the coexistence of different groups of people and activities, and to improve urban life. This entanglement of well-established institutional forms encompasses what Roy (2005, p. 147) considers the “formal order of urbanization”, from where different actors design and develop cities. However, with the accelerated growth and dramatic expansion of cities during the twentieth-first century, especially in the developing world, a not-new and yet contemporary mode of urbanization challenged formal orders: informal settlements. Although informal urbanization should not be realized as the opposite to formal urbanization, this includes processes of urban planning, informality is often considered lying outside of urban planning’s realm of control (Roy, 2005).

In response to social and transport disadvantages, and the insufficiency of public investments in certain urban areas, people in Latin America resort to informal alternatives to address their needs to access transport, employment and housing. According to Porter et al. (2011), there is a strong relationship between formality and informality determined by constant ‘transactions’ in terms of spatial, economic and social linkages that mark the notion of informality as a system that is not external to formal systems, but that is instead a consequence of formal structures, and that is usually strongly related to accepted formal set of rules and settings. Informality in this context will be explored in a wider sense, being interpreted as a logic of organization that reform practices, norms and rules leading to urban transformations (Roy & AlSayyad, 2004). Since 2003, UN-Habitat defines informal settlements as residential areas where 1) inhabitants have no security of tenure vis-à-vis the land or dwellings they inhabit, with modalities ranging from squatting to informal rental housing, 2) the neighborhoods usually lack, or are cut off from, basic services and city infrastructure and 3) the housing may not comply with current planning and building regulations, and is often situated in geographically and environmentally hazardous areas (UN-Habitat, 2015). Slums are the most deprived and excluded form of informal settlements characterized by poverty and large agglomerations of dilapidated housing often located in the most hazardous urban land.

According to Graham and Marvin (2001), patterns of provision of infrastructure and networks of transport and communications tend to produce 'premium networked spaces' for the wealthy while bypassing less-powerful groups (Graham & Marvin, 2001). In this process of production of urban spaces, certain social groups and geographic areas experience "poverty of connections" (Ohnmacht et al., 2009, p. 31), as a result of continuous improvement of connectivity of central areas, while less profitable areas and groups "tend to get increasingly disconnected, bypassed by infrastructure and socio-cultural investment". Such is the case of slums in many cities of the Global South, which, in addition to tenure insecurity, lack formal supply of basic infrastructure and services, public space and green areas, and are constantly subject to eviction, disease and violence (UN-Habitat, 2003, 2015, 2016). As a result, the cycle of segregation and spatial concentration of opportunities is strengthened, increasingly representing a barrier for less slum dwellers to interact with the rest of society. Roy (2005) argues that informality can be interpreted as a state of exception from the formal system of urbanization that can potentially alleviate some of the vulnerabilities of the urban poor. Under this interpretation, the argument of Graham and Marvin (2001) also incorporates the notion of 'resistance strategies' which can encompass parallel networks of urban infrastructures, services and opportunities that become part of the set of nodes and connections that might increase the ability of segregated groups with limited power to extend their influence in space.

In relation to the study of urban networks, graph theory provides valued insights to characterize the key locations and nodes within a network, which is conceptually coherent with notions of splintering urbanism, segregated and high-value nodes. As argued by Ramaswami et al. (2016), such understanding of urban networks can contribute to the development of smart and inter-connected cities, addressing challenges at different scales and dealing with the complexities of the multi-scalar and multi-sectoral nature of urban development. Examples of network analysis of urban infrastructures in different contexts in the Global South have led to new understandings of the role of innovations and forms of governance and coordination in filling gaps in infrastructure networks in unplanned settlements (Criqui, 2015). Moreover, recent research highlights the role of urban networks in the development of communication and cooperation strategies that enable incremental urbanism in deprived urban areas, linking physical densities of the built environment with social and institutional networks that can contribute to further development (Dovey, 2016). Similar techniques include network centrality, or the study of centralities in a network. Centrality measures aim to identify key vertices within a graph (Freeman, 1978), while their applications include solving the problem of stopping epidemic (Michalak et al., 2013), identifying key influencers during elections (Sudhahar et al., 2015), or for analyzing accessibility in urban networks and critical infrastructure (Derrible, 2012; A. Sevtsuk, 2014; Stergiopoulos et al., 2015). As the definition of 'central' varies by context and purpose, there are different dimensions of centrality, some of them include: degree, closeness and betweenness centrality (which is relative to the rest of network), among others. In this paper, the authors concentrate on the study of network centrality at the neighborhood scale, particularly on informal settlements. For this reason, the decision was to utilize only one distinctive measure name Reach centrality. This type of spatial accessibility measure is typically used to estimate the qualities of a location's accessibility that are attributable to street network designs. Moreover, this measure is sensitive to land-use patterns, including densities, as buildings and parcels can be weighted. In the following section, the authors detail the use of this graph measure for the objective of this study.

METHODOLOGY

The three informal settlements —i.e., J.A. Duarte (Honduras), Leticia (Peru), and Naggo Head (Jamaica)— were selected for this study based on the availability of information provided by international NGOs in the context of a performance evaluation carried out by Sarmiento et al. (2018), requested by USAID/OFDA. GOAL Global (Ireland) provided spatial and survey data for the case of J.A. Duarte, an informal settlement in Tegucigalpa, the capital of Honduras. COOPI (Cooperazione Internazionale, Italy) shared information for the case of Leticia in Rímac, a consolidated settlement in Lima, Peru. And Habitat for Humanity (HfH) provided spatial and demographical data for Naggo Head, an informal settlement located in Portmore, a dormitory-city near to Kingston in Jamaica. Figure 1 displays the neighborhood's locations, their land plots or parcel distribution, and street networks. According to the NGOs, street network's data points were collected through GPS devices while hazards' locations were collected by participatory methods such participatory mapping. In addition to these ground control points, the authors utilize low-resolution imageries to control the provided data. Table 1 shows the spatial information of the three selected neighborhoods.

Figure 1. Locations, parcel distributions, and street networks. Source: Authors, 2019.

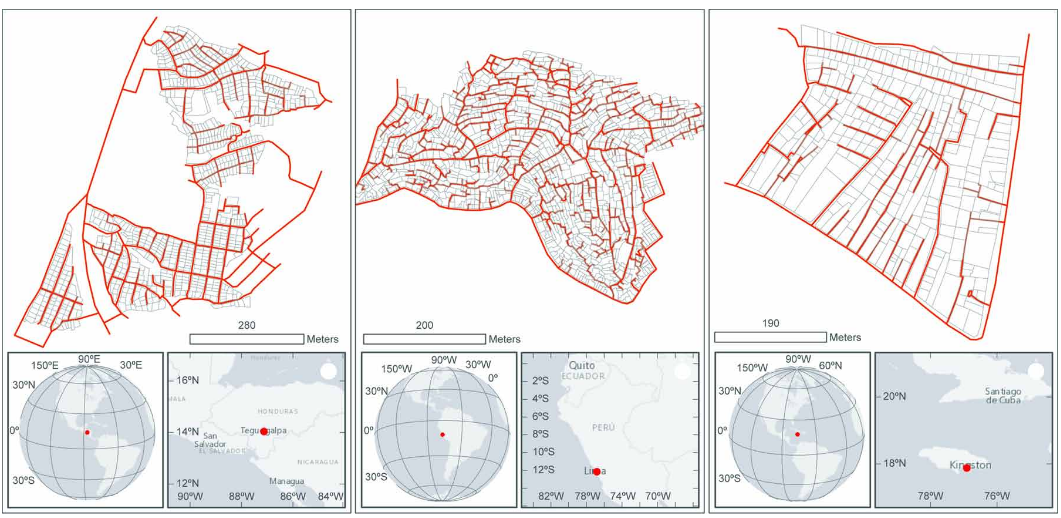


Table 1. Spatial information of the three selected neighborhoods

	Neighborhoods		
	J.A. Duarte	**Leticia**	**Naggo Head**
Network length (meters)	24,944	12,552	8,513
Number of parcels	787	1,151	325
Total area of parcels (Sq. meters)	123,114	101,517	119,571

Source: Authors, 2019

To calculate network centrality in the three selected settlements, ArcGIS 10.3 and the Urban Network Analysis (UNA) toolkit v.1.01 are used. Statistical measures were performed using R language on RStudio v.1.1.453. The UNA tool has been selected because it incorporates three important features that make it suitable for spatial network analysis of informal settlements. First, it accounts for both geometry and topology in the input networks, using either metric distance (e.g., meters) or topological distance (e.g., turns) as impedance factors in the analysis. Second, unlike previous instruments that operate with two network elements (i.e., nodes and edges), the UNA tool includes a third type of network elements that are used as the spatial units of analysis for all measures: buildings or parcels. And third, the UNA tool optionally allow buildings or parcels to be weighted according to their particular characteristics —more voluminous or larger, more populated, or otherwise more important buildings can be specified to have a proportionately stronger effect on the analysis outcomes, yielding more accurate and reliable results to any of the specified measures (Sevtsuk et al., 2013). This study does not utilize weights as particular characteristics of each building and parcel in the selected settlements are missing, or only average data was provided by the NGOs and Sarmiento et al. (2018).

The UNA allows to compute five types of graph analysis measures on spatial networks: Reach; Gravity; Betweenness; Closeness; and Straightness, although the study bases on only one: Reach. This study has excluded other measures because these, especially Gravity and Betweenness, are often used to estimate the potential of passersby at different buildings on the network (Freeman, 1977). Although these measures can be highly useful for network analyses related to commerce and public transportation, we have estimated that they do not necessarily work when we analyze an urban network without public transportation or the weight of buildings and parcels are difficult to estimate, as it is the case in informal settlements. Moreover, Reach centrality measure is typically used to estimate the qualities of a location's accessibility that are attributable to street network designs. For these reasons, this spatial accessibility measure seems to be the most appropriated to conduct a preliminary attempt to characterize informal settlements' street networks, and with that, to plan prospective interventions to improve such accessibility and resilience under disaster scenarios.

Reach centrality (Sevtsuk, 2010) captures how many surrounding plots each parcel reaches within a given Search Radius on the network.[1] The Search Radius defines how far along the network the destinations (D) may be from an origin (O) in order to be included in the analysis, this allows authors to filter in only those O-D pairs for calculations that are within a chosen network radius from each other. The reach centrality, $R^r\left[i\right]$, of a building i, in a graph G describes the number of other parcels in G that are reachable from i at a shortest path distance of at most r. Here, $d\left[i,j\right]$ is the shortest path distance between nodes i and j in G, and S is the cardinality of the set S.

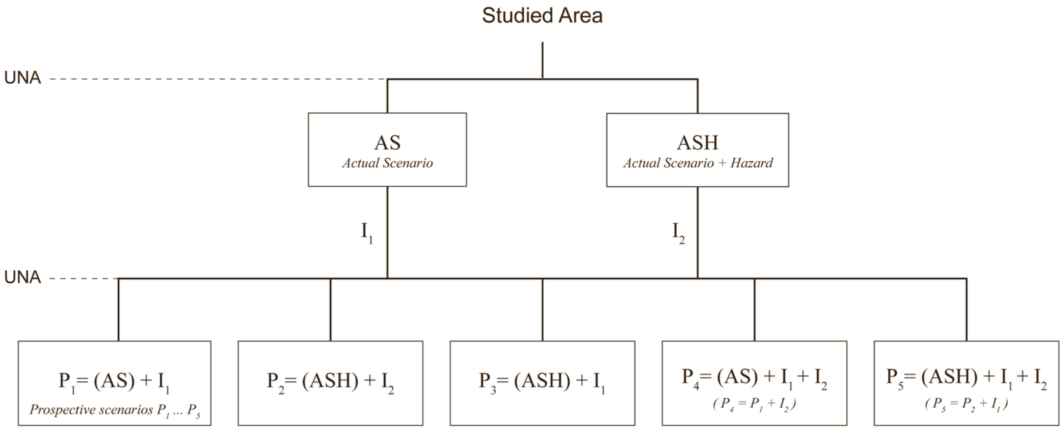
Reach centrality is defined as follows:

$$R^r\left[i\right] = \left\{j \in G - \left\{i\right\} : d\left[i,j\right] \leq r\right\}$$

In order to estimate the potentiality of different urban network performances, Reach centrality measure was carried out according to three different scenarios, one empirical and two hypotheticals:

- Actual scenario (AS) or empirical: reflecting the current network settings based on NGOs assessments and authors field observations between 2017 and 2018. This scenario allowed the study to identify the current neighborhoods' areas with more and less accessibility.
- Actual+Hazard scenario (ASH) or post-disaster: reflecting unavailable or affected sections of an actual network due to hazards. These sections were defined by the NGOs that worked with the communities and by using participatory methods such as community hazard mapping and focus groups. Based on an actual street network (AS), this hazard scenario tends to exacerbate the existing problems in accessibility of each neighborhood while it exposes critical areas for emergency evacuation and first response access.
- Prospective (P) scenarios: reflecting hypothetical road interventions that should provide better access of parcels to the street networks of each neighborhood. Both results from AS and ASH

Figure 2. Method to perform Reach centrality measures



scenarios brought to light critical areas and sections where accessibility was limited or affected by hazards, then, networks are strategically intervened to try to improve neighbors' mobility. These new sections, made through Interventions (I), follow these steps/criteria:

a. Identify up to four groups of parcels with lowest values.
b. Connect areas with lower values to main roads or well-connected areas using shorter distances.
c. Sum of interventions should not exceed the 5 percent of the total network length.

The Figure 2 summarizes the method and settings to perform the analysis, and to replicate it.

In total, there are seven outcomes: AS; ASH, and five Prospective (P) scenarios. All Reach centrality measures are carried out using the UNA tool on ArcGIS and following these pre-determined settings:

- Impedance factor: Metric distance
- Units of analysis: Parcels (the study does not use weights)
- Mode of travel: Walking
- Radius type: Network
- Radius: 600-meter (or ten-minute walking range).

Considering the physical features of the studied settlements in all neighborhoods, 'walking' as main mode of travel was used. Walking has been the primary means of transportation in urban history, and its importance appears to be increasing again in the sustainable metropolis of the twentieth-first century. Most notably for the analysis, walking is the primary mode of travel in neighborhood-scale (Garbrecht, 1978; Zacharias, 2001), while in the field research authors documented a reduced percentage of car ownership in all neighborhoods (Sarmiento et al., 2018). The analysis models walking in a 600-meters network radius (or ten-minute walking), allowed the authors to study the effects of spatial accessibility from a pedestrian point of view. This choice corresponds to Waddell's use of 600 meters (Waddell & Ulfarsson, 2003). As Impedance factor, authors use the metric distance (i.e., length in meters), while for the Search Radius input the Network Radius type (Sevtsuk & Mekonnen, 2012) was selected. Likewise, as all neighborhoods are settled in different topographies authors decided to set the ArcGIS's elevations feature. In this way, z coordinates values are automatically assigned from geometry. Finally, to make centrality measures comparable in different street networks, the results at each scenario are normalized by the range of minimum and maximum values, thus adopting values between 0 and 1.

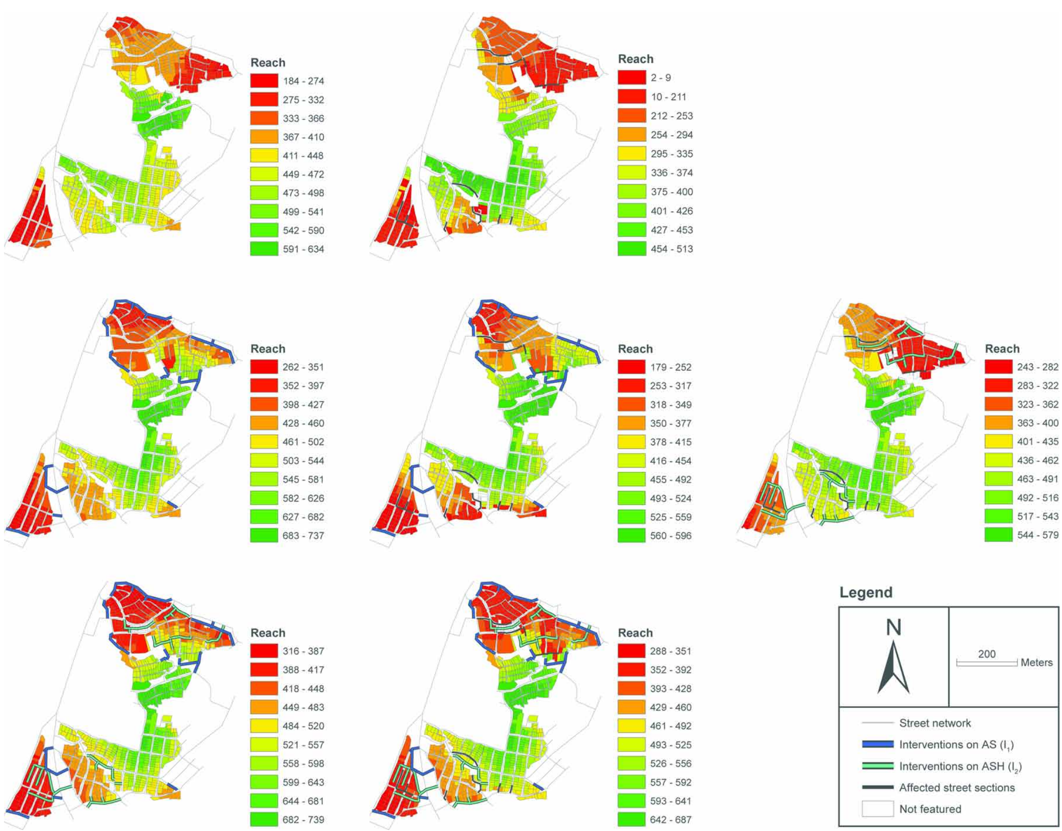
In the next section, centrality measures are investigated over the scenarios of urban street networks ‘spatially’, through the presentation of thematic maps, and ‘statistically’, by plotting their probability distributions —as proposed by Porta et al. (2006), using empirical cumulative distribution functions or ECDFs. At the end this paper, authors dedicate some reflections on the use of the UNA tool in the context of informal settlements and its potential for urban planning and disaster risk reduction. Such reflections emerged during the analysis process and are the result of an academic exchange between authors.

RESULTS

The spatial distribution of network centralities is graphically illustrated by means of GIS supported color-scaled maps in the next figures. The colors represent ten scaled-classes of parcels with different values of centrality, ranging from 0 to the maximum number of parcels in each case. Figure 3 shows the centrality measures for the case of J.A. Duarte (Tegucigalpa), organized according to the proposed seven scenarios.

Looking at the AS and ASH (baselines) maps in the Figure 3, the differences between the two initial scenarios are clearly identified, as well as the two groups of interventions (i.e., I_1 and I_2) reflected on the P_4 and P_5 maps. The P_4 represents how both I_1 and I_2 improve accessibility of J.A. Duarte residents during normal times (baseline AS), and P_5 illustrates how interventions improve

Figure 3. Reach centrality for J.D. Duarte, Tegucigalpa. Source: Authors, 2019.



mobility when hazards affect its street network (baseline ASH). In this particular case, it is possible to observe that interventions improve both AS and ASH street networks, but the effects are more accentuated in P_5. The Reach centrality mean of P_4 increased 10.2 percent from AS, while P_5 improved 22.1 percent with respect to ASH (all results are discussed later). The maximum Reach value is in P_4, 739, indicating that in this scenario a resident can reach as maximum as 739 other neighbors (i.e., parcels) in a 600-meters network radius type. The next Figures 4 and 5 show the results of Reach centrality for Leticia and Naggo Head respectively.

The first difference of Leticia with respect to J.A. Duarte is that its street network is significantly denser and more branched, reflected ultimately in a predominance of high centrality values (green colors). As in the previous case, the interventions (i.e., I_1 and I_2) improve mobility within AS and ASH street networks, being more accentuated in P_5. The Reach centrality mean of P_4 increased 1.2 percent from AS, while P_5 improved 12.3 percent with respect to ASH.

In the case of Naggo Head in Figure 5, the AS and ASH show clearly differentiated areas between well-connected (in green) and poor connected (in red). Here, the effect of interventions I_1 and I_2 on the AS and ASH street networks, respectively, are important. The Reach centrality mean of P_4 increased 22 percent from AS, while P_5 improved 46.5 percent with respect to ASH.

In the Figure 6, authors report the empirical cumulative distribution functions (ECDFs) of Reach centrality obtained for J.A. Duarte, Leticia, and Naggo Head. Scenarios are represented by lines: black for Actual (AS), red for Actual+Hazard (ASH), blue for Prospective 4 (P_4), and green for Prospective 5 (P_5). All values were normalized for comparative reasons. In the ECDF plots, y axis represents the

Figure 4. Reach centrality for Leticia, Lima. Source: Authors, 2019.

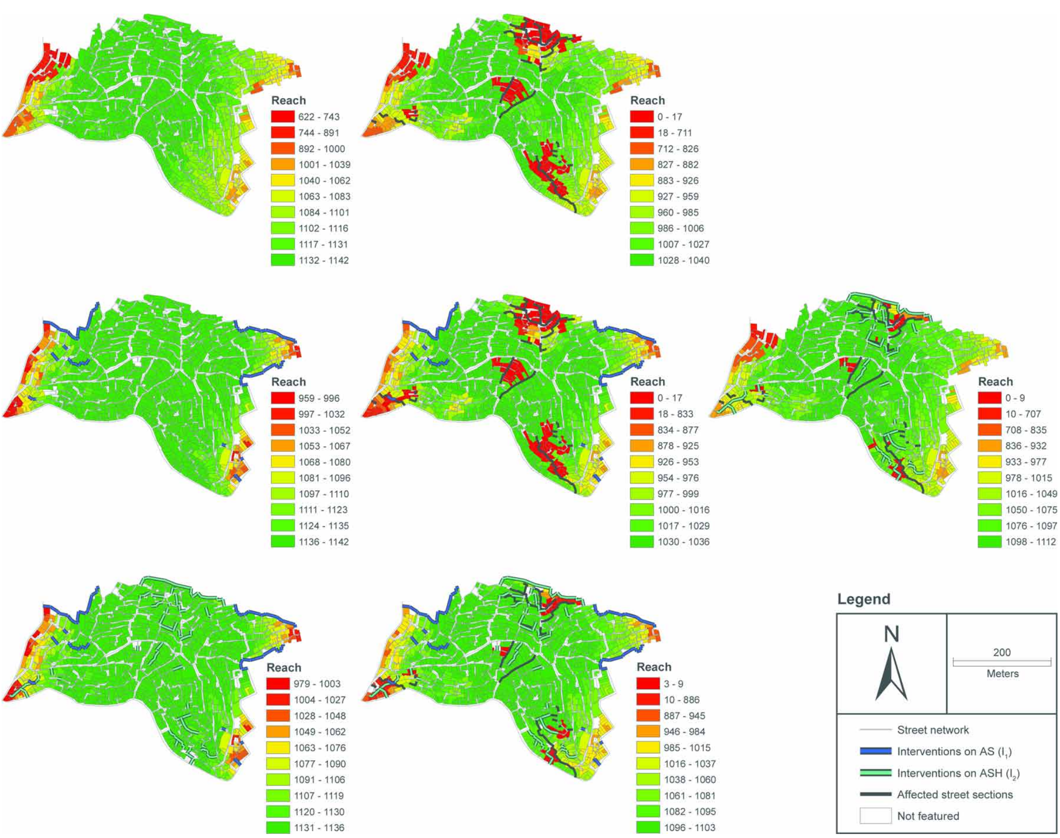
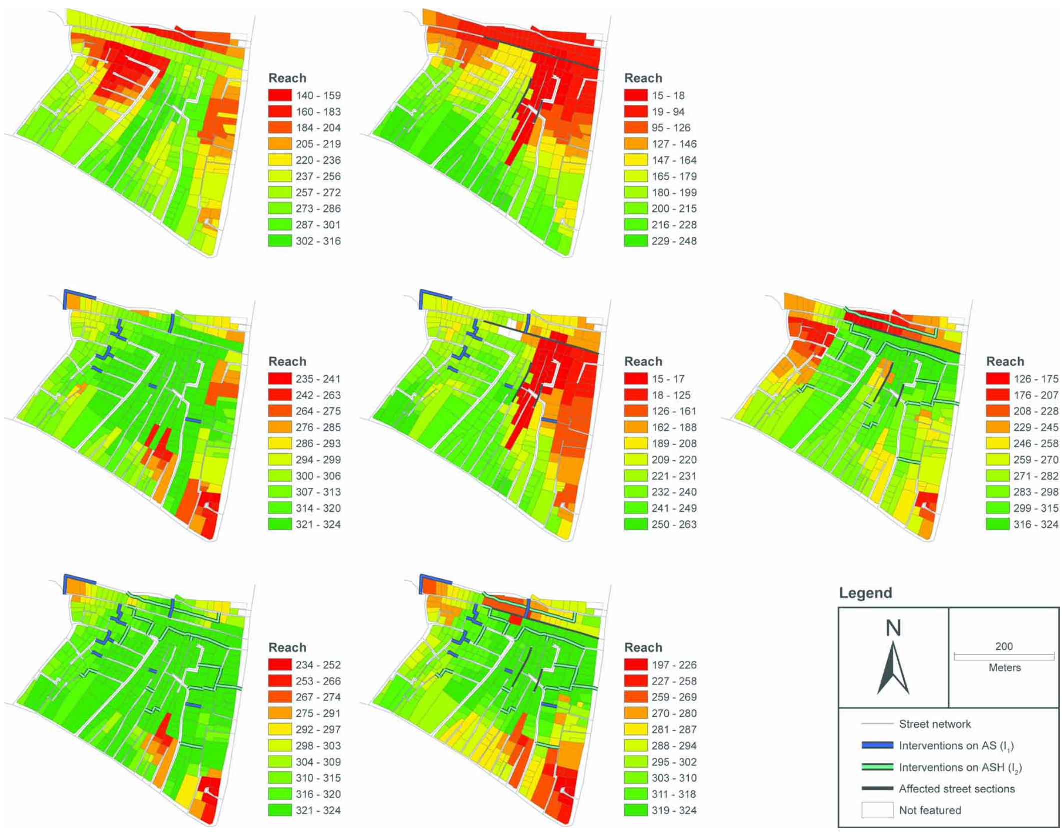


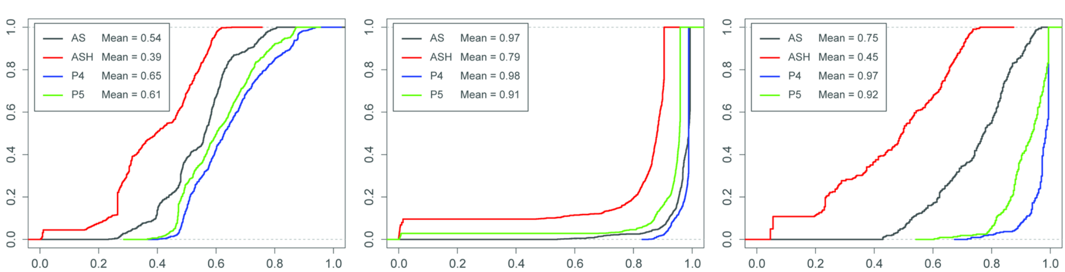
Figure 5. Reach centrality for Naggo Head, Jamaica. Source: Authors, 2019.



cumulated distributions of values normalized on 1, which gives the probability of the distribution or percentile. The x axis represents the normalized values for each Reach centrality index.

Figure 6 shows that under the AS scenario (black lines) Leticia's street network performs better than J.A. Duarte and Naggo Head, with a mean of 0.97, in contrast to 0.54 and 0.75 respectively. In all neighborhoods, affected roads (ASH scenarios, red lines) impact negatively the accessibility from actual scenarios (AS), being the difference more accentuated in the case of Naggo Head (-29.3 percent), and less for J.A. Duarte (-15.2 percent). As described earlier, prospective scenarios P_4 (blue lines) and P_5 (green lines) present important improvements in centrality with respect to AS and ASH scenarios. For instance, Naggo Head has the most significant increases in accessibility (P_5=46.5 percent) after

Figure 6. ECDFs of Reach centrality for J.D. Duarte, Leticia, and Naggo Head. Source: Authors, 2019.



the interventions I_1 and I_2 were applied (see more in Table 2). This implies that interventions allow Naggo Head's residents, on average, to reach over 46.5 percent more neighbors (i.e., parcels) with respect to a previous scenario with the same affected roads (ASH scenario).

The following Table 2 summarizes centrality results. Means, minimum and maximum values, standard deviations, and differences in sample means are provided.

Table 2. Descriptive statistics per neighborhood and scenario

	J.A. Duarte (N=787)					
Scenario	**Mean**	**Min.**	**Max.**	**Std. Deviation**	**Mean (norm.)**	**Difference***
Actual (AS)	427.1	184	634	95.74	0.543	
Actual+Hazard (ASH)	307.9	2	513	118.04	0.392	-15.2%
Prospective 4 (P_4)	507.0	316	739	100.77	0.645	10.2%
Prospective 5 (P_5)	481.7	288	687	96.19	0.613	22.1%
	Leticia (N=1,151)					
Actual (AS)	1110	622	1142	65.56	0.966	
Actual+Hazard (ASH)	906.8	1	1040	285.86	0.789	-17.7%
Prospective 4 (P_4)	1124	979	1136	27.01	0.977	1.2%
Prospective 5 (P_5)	1049	3	1103	183.24	0.912	12.3%
	Naggo Head (N=325)					
Actual (AS)	243.7	140	316	44.53	0.747	
Actual+Hazard (ASH)	148.1	15	248	68.13	0.454	-29.3%
Prospective 4 (P_4)	315.3	234	324	15.02	0.967	22.0%
Prospective 5 (P_5)	299.7	197	324	23.54	0.919	46.5%

Source: Authors, 2019
* Difference in sample means

CONCLUSION

Authors initiated this work with the hypothesis that as informal settlements generally lack the benefits of proper urban design and planning, their self-organized networks would tend to have poor street mobility in terms of pedestrian accessibility. This would be revealed through lower levels of Reach centrality. If one establishes a 'good accessibility' at the threshold of 0.5 level (normalized Reach mean), then the three selected neighborhoods would obtain that label: J.A. Duarte 0.54; Leticia 0.97; and Naggo Head 0.75. Beyond the spatial relationship between the neighborhoods and the rest of the city, this suggests that the 'unplanned' and spontaneous development of these neighborhoods could have followed a certain functionality that allowed them to coherently distribute parcels alongside with a pathway.

The analysis shows that Leticia's street network performs better than the other neighborhoods, with a centrality mean of 0.97, indicating that Leticia residents reach over, on average, more neighbors (i.e., parcels) in a ten-minute walking range than residents of J.A. Duarte and Naggo Head. This could be explained due to Leticia has smaller parcel plots, and a denser and more branched street network. Other reasons for the differences can be associated to the origins and geographical conditions of each neighborhood. For instance, the historical, political, and economic conditions under which these areas were occupied by settlers (i.e., illegal occupation of state vacant land, illegal partitioning or sub-division of private/agricultural land, land-use and zoning changes, among others) or the presence contour lines (elevations) that resulted in a distinctive distribution patterns of parcels. Authors assert that elevations, rivers, surrounding roads and networks can play an important role. In the case of the J.A. Duarte, which is crossed by a channel in the north and a motorway in the south, these conditions have segregated some areas and could have affected J.A. Duarte's centrality calculations.

On the other hand, authors did not include surrounding parcels outside neighborhoods due to the lack of such information, and this may also have also affected calculations. Although authors recognize that confining the analysis to settlements' boundaries could have limited the study's findings, the use of the UNA tool at neighborhood scale has resulted advantageous for approaching network accessibility and urban coherence in informal settlements. For example, centrality analyses helped us to identify key nodes or roads that may be strategic for improving internal mobility (i.e., prospective scenarios). Here the study acknowledges that prospective scenarios were fictitious and subjective because they depend on various technical, economic and social factors for their viability, but this exercise sought to prove that in an ideal scenario, it is possible to improve street network performance and accessibility. Moreover, significant variation of results depending of strategic interventions (i.e., ASH and P scenarios) in the three cases indicates the sensitivity of our approach in terms travel distance in meters, that is our selected Impedance Factor. For instance, differences of centrality sample means in Naggo Head between AS, ASH, and prospective scenarios P_4 and P_5 (see Figure 5) revealed that strategic interventions can produce significant improvements in accessibility. As our approach to measure informal settlements' accessibility aims to provide inputs to urban decision makers based on community/NGOs' information in tandem with a street network analyses, the precision and accuracy of results need to be scrutinized with and after *de facto* interventions. Then, centrality measures can result valuable for urban planners and local governments as they can advance community hazard mappings with prospective interventions. Authorities and planners can clearly identify two type of interventions, one group (I_1) that will work to improve inherent resilience in the short term (i.e., ability of function well during non-crisis times), and another group of interventions (I_2) to address latent risks (based on previously identified hazardous areas) in the long term.

Likewise, identifying key roads and nodes may result critical for people's daily life after disasters, disaster relief planning, and reconstructions. In this sense, authors assert that centrality measures could complement traditional evacuation models which base their calculations on elevations and land-use (Jones et al., 2014; Laghi et al., 2006) or on the performance of roads for predetermined assembly areas (Wood et al., 2016). Although authors also recognize that centrality metrics presented in this work would have benefited more from additional data such as the location of stores, population densities, road types, among others, as this would allow the use of weights, resulting in more accurate results.

In this study, authors conducted different urban centrality analyses aiming to better understand the internal spatial configuration of three neighborhoods, considering that informal settlements tend to be marginalized from formal urban processes of planning and zoning, and are generally ignored by official figures. The analysis allowed the authors to estimate urban accessibility through Reach centrality measures and three type of scenarios, one empirical and two hypotheticals. These metrics provided an overview of street network centrality for J.A. Duarte, Leticia, and Naggo Head, and results were congruent with recent observations on accessibility (Sarmiento et al., 2018). The research considers, however, that one limitation for the success of centrality measures lied largely on the preparative work of surveying marginalized neighborhoods *in situ*. Community mapping and the identification of hazardous areas are extremely important to initiate any street network analysis aiming to determine strategic interventions for risk reduction and resilience. It is worth mentioning here the case of Naggo Head in Portmore, Jamaica, as the international NGO Habitat for Humanity considered a demographic and spatial survey as a basis for a land tenure strategy aiming to link land registration and access to credit, housing improvement, and risk reduction. Considering that mainstream town planning does not recognize informal settlements in the process of provision of public utilities and infrastructure networks unless they have attained 'critical mass' that enables them to exert enough political pressure to have their neighborhood 'legalized' (Bocarejo & Velasquez, 2013). The increase in size and political significance of segregated nodes influences local authorities to provide connections to utilities and build other infrastructure like sewerage, pavements, roads and street lighting. In this context, surveying marginalized settlements is an important, if not fundamental, step toward urban justice, while dimensioning the problematic of urban informality is critical to improve settlements' conditions. The availability of evidence and sound indicators that highlight the social relevance of infrastructure investments in low-income and informal neighborhoods can contribute to increase the social and political relevance of such, otherwise overlooked, settlements. Data about the spatial conditions of the built-environment will serve either for making planning decisions more effective as well as for better disaster risk management. Ultimately, by comparing urban networks at neighborhood scale, this work sought to offer planning alternatives to informal developments that can be used by urban planners and local governments for improving the conditions of established settlements. The UNA tool and the methodology carried out in this work can inform decision making on strategic interventions in the urban networks which can facilitate internal mobility but also provide better performance in cases of disasters, and ultimately increase resilience. In this sense, the novelty of our methodology is that it provides a preliminary and yet insightful analysis of the possibilities (in terms of interventions, feasible or not by local governments and communities) to improve accessibility and disaster resilience, especially considering the endemic lack of 'formal' information that characterize informal settlements, and also the need to address the imbalance between formal and informal spaces.

Authors have identified some avenues for future research on incorporating multi-scalar analysis of neighborhood and city scales together. The city scale analysis would give an idea about the relative 'situation' of a neighborhood within a city, while the neighborhood scale analysis would give an idea of the critical areas that may improve not only the internal mobility but also its integration within the urban system. Another avenue of further research should include Multiple Centrality Assessments (MCA) of neighborhoods (Porta et al., 2010), where other centrality indices such as Closeness and Straightness are included, providing new perspectives on mobility and accessibility, and perhaps more alternatives for strategic interventions.

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ENDNOTES

[1] Due to computational limitations, here authors do not model parcels with multiple connections to a street network, which can play an important role for parcel accessibilities in real-life urban settings.