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Urban adaptation planning and climate-related disasters: An integrated assessment of public infrastructure serving as temporary shelter during river floods in Colombia

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ABSTRACT

Emergency reports prove that extreme weather events are overcoming disaster management systems in vulnerable cities. While a number of studies focus on comprehensive and long-term coping strategies to deal with disasters, only few have addressed the challenge of temporary shelter in acute crisis intervention. Experiences in developing countries have shown that local governments have improvised emergency accommodation in sport halls, schools, and similar infrastructure identified as Collective Centres. The aim of this paper is hence to develop and apply an integrated assessment of public infrastructure serving as temporary shelter in case of extreme weather events. We chose the case study of Chía in Colombia in 2011, where erratic rainfalls and river floods led to property loss and damages and the designation of collective centres. We propose a Collective-Centre Suitability Index to evaluate the appropriateness of public infrastructure to serve as transitional shelter through a ranking-based assessment of (i) compliance of humanitarian shelter standards; (ii) the analysis of geographical risks; and (iii) the accessibility of selected infrastructure. Results for the case study suggested compliance of minimum transitional shelter standards on most of assessed locations and infrastructure. Scenarios of flood-risk recurrence intervals indicated higher exposure from the urbanized area along the Frío River. Suitability of Collective Centres near the Frío River was comparably higher than the evaluated shelter near the Bogotá River. The proposed assessment offers a flexible screening tool for transitional shelter and local adaptation planning considering urban changing settings.

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1. Introduction

Rising and extensive impacts on urban systems associated with climate-related disasters are particularly noticeable in the past 30 to 40 years [35,54]. Losses of human lives and

property are increasing, especially in vulnerable cities where different challenges coincide: limited insurance coverage [26], inappropriate planning practices [7], rapid urbanisation following population growth and migration [4,16,27] leading to land scarcity and informal settlements [2,44,66]. Decision-makers are asked to increase their efforts in the implementation of early adaptation measures and disaster management plans to recover from climate-related disasters and to deal with the impacts from present and future climate variability [36]. One of the priorities of local authorities when

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confronting the increased number of climate-related disasters entails the provision of safe transitional shelter to the affected population [1].

The challenges of shelter management in times of increasing extreme weather events and the growing number of people living in vulnerable settlements have been highlighted by earlier studies [56,58]. Residents who are forced to leave their property temporarily or permanently as a result of natural disasters triggered by environmental degradation have been identified in the disaster research literature as environmentally displaced people [19] or climate refugees with a reference to the global climate change debates [18]. In the following we refer to environmentally displaced people to stress the acute nature of disaster events that are not only limited to climate-induced causes but also to other environmental and human stimuli [5,48].

Among the types of emergency accommodation to be arranged in case of a disaster, both transitional shelter and permanent housing solutions have to be provided accordingly on each stage of an emergency as recommended for example by the IFRC Shelter Kit [31] and the Shelter Centre [58]. Most often, transitional settlements are the ones that are relied upon directly after the disaster. According to Corsellis et al. [14] one can differentiate transitional shelters into non-grouped shelter (e.g. host families, rural self-settlement, urban self-settlement) and grouped shelter (e.g. self-organized camps, collective centres, planned camps). Collective Centres (ColCs), specifically, are frequently used by local authorities who rely on existing infrastructure such as sports halls, schools and community centres [64]. They have been defined as “pre-existing buildings and structures used for the collective and communal settlement of the displaced population in the event of conflict or natural disasters” [10,58]. One advantage of ColCs is the lower operational and financial costs when properly managed. This is because as a grouped settlement, ColCs facilitate evacuees registration and reduce humanitarian operational costs compared to shelter solutions spread over large areas [14]. Moreover, ColCs allow a comprehensive adaptation and emergency preparedness when planned at an early stage on the disaster management cycle [77]. Finally and perhaps most importantly, they offer accommodation when preferable and durable long-lasting shelter solutions are not immediately at hand because of limited financial, operational and institutional capacities at local level [51].

While ColCs are frequently used, the criteria to select adequate infrastructure is based most of the time on an adhoc and improvised selection by local authorities, who are frequently short on resources and time to undertake a comprehensive assessment. This situation is evident in official and international humanitarian reports, e.g. following the flooding in Chía, Colombia [12], the Guatemala Floods [32], or the Syrian refugees [72]. Initial selection criteria have been defined by the International Federation of the Red Cross Red Crescent Societies, the Sphere Project on minimum humanitarian standards and the Camp Coordination/Camp Management (CCCM) Cluster. These criteria cover a wide range of physical conditions such as sanitation and water, living space, thermal comfort, etc. [31], to organisational arrangements to procure order and

safety inside ColCs [21,64] to other requirements on external and institutional settings such as ownership and the legal use of facilities [10]. Bangladesh has for instance substantial experience in planning dual-purpose infrastructure, e.g. elevated shelters/schools at disaster-prone coastal areas, to procure safe conditions and mitigate loss and damage from cyclones and other hydrometeorological hazards [38]. In Melbourne, Australia, the Central Business District Emergency Relief Centres have been established [45] due to the regional economic importance of this city and its proneness to heat waves and floods. Likewise, major investments have been made in United States as a result of the Federal Emergency Management Agency (FEMA) directives for selecting temporary refugee areas in buildings, as well as for designing ‘public and community safe rooms’ against different hazards [20].

While these approaches try to address the specific demands in their settings, a suitability assessment of ColCs that identifies and integrates different suitability factors in collaboration with stakeholders and local knowledge is not available to the knowledge of the authors. The aim of this paper is hence to fill this gap and to address the following research question: How can different factors be integrated in one collective center assessment index to evaluate the suitability of existing public infrastructure to be used as temporary shelter in fluvial flood-prone municipalities? We develop and apply the assessment in close collaboration with stakeholders from the municipality of Chía, Colombia. Our findings offer an assessment that goes in line with existing international shelter standards (i.e. UNHCR, Oxfam, Sphere, and IFRC) and augment these by additional geographical criteria. More specifically, the combination of different suitability factors in the proposed assessment will be of benefit for stakeholders to apply a first screening analysis for possible transitional shelters in the context of their disaster management strategies. In addition, we think our study adds to the discussion about assessment studies that are developed in a participative approach together with stakeholder’s local knowledge.

Our paper is hence structured as follows: In the first part, the introduction sets a conceptual framework, our research problem and a brief state of the art on transitional shelters in environmental and climate-related disasters. In the second part we introduce the case study and explain the methods applied to develop the suitability assessment tool. The third and fourth sections explain our findings and discussion, respectively on the proposed suitability analysis of ColCs in Chía. Final conclusions and policy recommendations are given in the last part of the paper.

2. Case study and research methods

2.1. The study area of Chía

We designated the municipality of Chía in Colombia as a case study for our research because it experienced substantial property damage and temporary displacement of residents resulting from river floods during the national erratic rainfalls in 2011. Furthermore, local authorities and

disaster management officials were willing to participate and cooperate in the research process. In addition, they complied with disaster management directives at local (Local Committee for Disaster Management – CLOPAD) and regional level (Regional Committee for Disaster Management – CREPAD).

Chía is an urbanized municipality located in the department of Cundinamarca in Colombia, 31 km to the north of the district capital, Bogotá. It has an estimated population of 111,998 inhabitants [15]. It is often called a “dormitory city” due to the high number of its inhabitants commuting daily to their workplace in the capital city. Population in Chía has rapidly increased in recent decades, as it grew from 1,585 habitants in 1938 to 47,180 in 1993. Likewise, rural population of the municipality decreased steadily, dropping from 80.4% in 1938 to 9.2% in 1993 [76]. The population is dominated by middle income families and workers who commute daily to Bogotá [46,60]. Almost one-third of the population is younger than 15 years [60]. Correspondingly, a higher number of high-income properties (e.g. two- and three-store houses, villas and enclosed housing projects) are evident as more middle and high-income families move into this municipality [46].

From Chía’s total area (79 km²), 17 km² is defined as urban or built-up area at present [63]. With economic and population growth and the higher costs of property in Bogotá and in neighbouring municipalities, urbanisation has rapidly followed in the last years exhibiting a dispersed and irregular pattern, thus encouraging land conversion from agricultural to commercial and housing (Vargas 2006). In 60s to 70s, recreational and agricultural land uses were arranged in flood-prone areas along the Bogotá and the Frío River [63]. Recently, Ramírez-Daza [53] referred to political turmoil as a result of conflict of public and private interests aiming to change the Land Use Plan to convert protected areas for housing projects [17]. Moreover, investments from local and regional environmental authorities have been undertaken to create natural buffered areas (e.g. parks and pathways) on the urban fringe and near watersheds to limit urban expansion in flood-prone zones [11].

Our study area is located on the Cundiboyacense high plateau region rising to an average altitude of 2600 m above sea level on the Andes Northeast mountain ranges, commonly known as the *Cordillera Oriental*. Chía has a subtropical temperate highland climate with annual temperatures ranging 10–16 °C. The dry and rainy seasons alternate frequently during the year, of which December, January, February and March are the driest months. During the rainy months the temperature has fewer variations between 9 °C and 20 °C. June, July and August are the months with higher variations on temperature [8,9,22].

Enclosed to the west and east by the mountain systems of La Valvanera and el Peñon respectively, the municipality’s main catchment drainage system is composed by the Bogotá River to the east and its tributary the Frío River to the west side of the main urban area as shown in Fig. 1. The urban centre is located in between both rivers, making it vulnerable to river floods. Since 1970s until today built-up areas have extended on the western urban fringe, thus taking over a large part of the natural drainage system. The National Authority for Disaster Risk Management or UNGRD has insisted to formulate and update Local Contingency and Emergency Plans - PLECs (i.e. Planes Locales de Emergencias y Contingencias) after the national erratic rainfalls in 2010 and 2011. In this document, municipalities need to assess available resources and disaster scenarios to respond to the risk of natural and man-made disasters ([71]).

Chía has experienced severe flooding in the west and east of the urban fringe as registered by CAR [8] and SP-Chía [63]. In 2006, residents from 800 houses close to the Frío River had already experienced temporary displacement due to floods [74]. River flooding accounting for the highest amount of property damage ever registered in the municipality took place between April and May in 2011. This emergency was explained by deficiencies on run-off and waste water infrastructure, a 100-year recurrence interval of erratic rainfalls, and exceeding values on the water table of the aquifer system on the Frío River and Bogotá River [12,28]. Accessibility gained higher relevance during this emergency in view of blocked roads and the significant number of residents commuting daily to Bogotá. Extensive

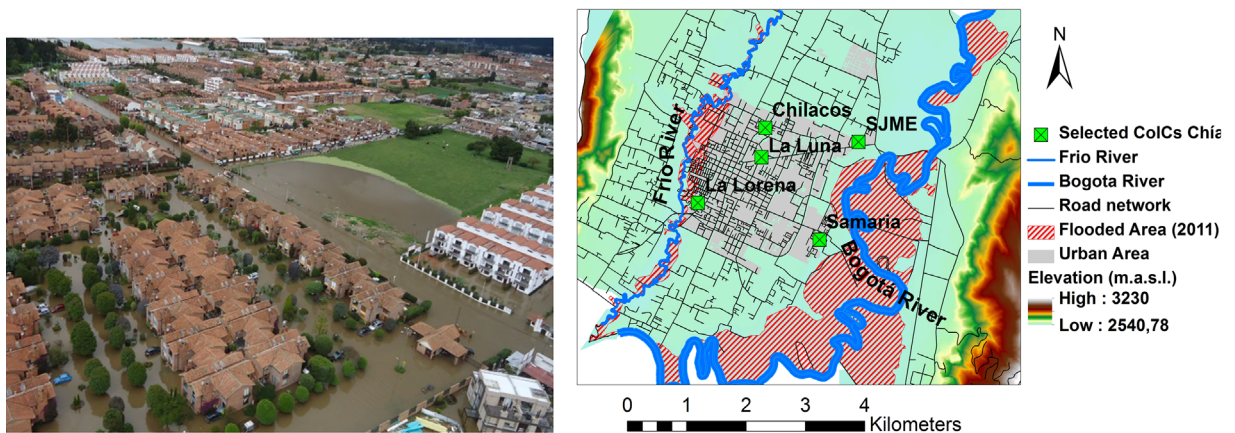


Fig. 1. Left image [63]: Chía’s 2011 flooding on the northwest of the urban area beside the Frío River. Right image (own source): location of assessed CoICs (green squares) over the urban area. The red striped-layer shows the flood extent in 2011.

damages on properties along the Frío River basin were reported: 8.58% (1,455 of 16,952) of urban plots in the municipality were flooded and 3 out of 6 flooded areas had to be evacuated [63]. Despite the large flooded areas on the catchment of Bogotá River (895 ha), flooded property was comparatively smaller with 92 housing units that were flooded compared to 1247 near the Frío River. The Planning Office explained this as a consequence of the enforcement of land use regulations to avoid new construction projects on the greater floodplains of the Bogotá River. Official national reports estimated 4189 affected people or approximately 1416 families in Chía during the river flood peak period between April and May 2011 [59]. According to local authorities, most of the affected population found shelter arranged with relatives or in other dispersed settlements by their own means. Nevertheless, the municipality pre-assigned two buildings (i.e. Chilaco's Community Centre and La Lunita School) to host affected population for a short-term while the flood water receded [12]. To enhance local disaster response and recovery, the Planning Office agreed to exchange La Lunita School with La Lorena Sport Centre in the southwest and selected three additional buildings in the city centre and the eastern urban area serving flood-prone zones along the Bogotá River (La Luna Sports Hall, the SJME School and The Samaria School) (i.e. map on the right in Fig. 1).

2.2. An integrated assessment of collective centres

We follow the concept of an integrated assessment with our suitability analysis in two ways: First, an assessment is integrated when it considers different areas of knowledge and capacities from practitioners and risk analysts to evaluate the vulnerability and risk factors in a situation or system [37]. Through this interdisciplinary dialogue between scholars and decision-makers, this kind of analysis offers technical and case-oriented information for policy and disaster risk management [25]. Second, in the disaster response cycle, stages of the emergency are not taken as independent or sequential processes (Asghar et al., [3]). Instead, a Collective Centre assessment needs to be flexible enough to plan for complementary shelter strategies during disaster preparedness, response, recovery, rehabilitation and the overlapping of these stages (e.g.

a common situation while planning for receding times of river floods) [14]. Most integrated assessments demand involving decision-makers in the process of analysis and problem solving. According to Borda [6] and Whyte et al. [78] in social research, scientific findings benefit greatly if stakeholders take an active role in the research process, thus allowing them to become agents of change within their own problematic. This approach is known as Participatory Action Research (PAR) which we followed in its four stages (see Fig. 2).

We selected this approach because we believe that first, this is a much applied topic with only few studies about it that needs in-depth local knowledge and second, that only a close collaboration with the stakeholders may foster future application of such a tool to then evaluate it. We started with the stage of **diagnosis**, where members of the planning and disaster prevention offices at the municipal administration identified key factors which limited crisis management and rehabilitation of the affected population during the 2011 river floods in Chía. This exercise allowed studying worst case scenarios on flooded property based on the official emergency reports [12] and on a regional modelling of climate variability delivered by the Regional Environmental Agency of Cundinamarca [50]. This last study, despite being limited to one General Circulation Model (GCM), served to identify possible moderate and severe changes on temperature, precipitation and thus on the hydrological system in the region.

We then prioritized risk factors on fluvial flood evacuees (i.e. environmentally displaced people) to identify most relevant suitability variables for ColCs and then pre-selected Collective Centres from the available public infrastructure (stage of **action planning**). Third, in **action taking**, we developed a Collective Centre Suitability Index (CCSI), thus integrating the three prioritized suitability analyses. Finally, figuring out a weighting and ranking of such factors was necessary to **evaluate** the prospective infrastructure within perceived and measurable changing conditions of exposure and vulnerability. Moreover on the last stage, community and institutional **learning** is projected once the preliminary results of the CCSI are delivered and revised with local authorities to determine policy implications on transitional shelter and disaster response (e.g. updating of Emergency and Contingency Plans).

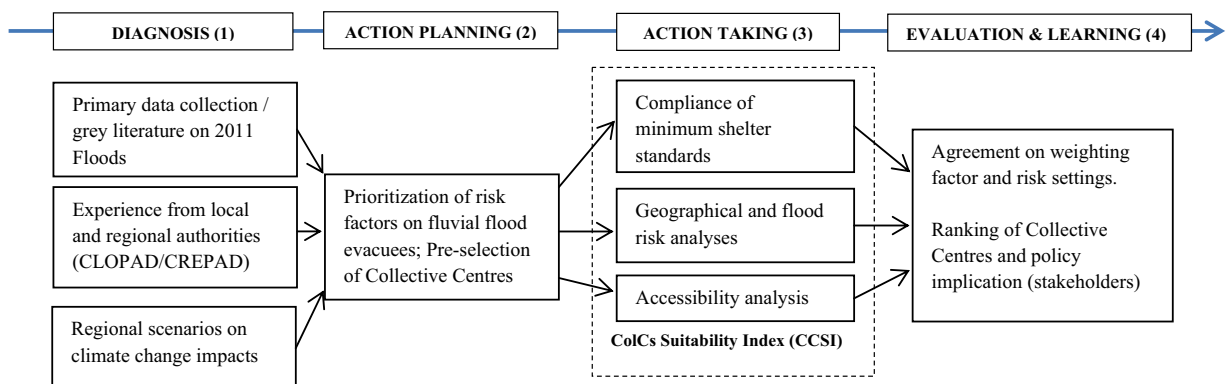


Fig. 2. Stages to an assessment of public infrastructure for transitional shelter during fluvial floods in Chía.

2.3. Developing the suitability assessment

2.3.1. From the prioritisation of risk factors to the suitability of ColCs

Through semi-structured interviews and focus group discussions with local authorities from the planning and disaster prevention offices, we identified factors which characterized the risk to evacuees during the river floods of 2011 (adapted from IFRC [29]). This information was then categorized into one or both of: 1) vulnerability, meaning the inability to withstand and recover from similar or worse floods in the future and 2) exposure, describing the local environmental settings which made it evident that they were highly prone to similar climate-related disasters. The planning and disaster risk management officials denoted vulnerability of environmentally displaced people or EDPs, due to the difficulty of procuring safe shelter immediately during and after the crisis. In addition, accessibility and transport conditions were very limited towards the capital and from flooded units to humanitarian services. Capacities on disaster respondents and the community's coping capacity were also identified but more on the recovery stage to bring living conditions back to normal. Rural to urban migration and a higher number of formal and informal settlements in flood-prone areas had equally increased exposure to future erratic rainfalls and flooding. Respondents identified rapid urbanisation and degradation of watersheds and river basins as well as blocked roads connecting to neighbouring municipalities as factors increasing both vulnerability and exposure to fluvial flood risk. Based on this risk analysis and on the available resources to improve identified weaknesses, three major suitability factors for Collective Centres were defined by researchers and respondents: (i) the capacity and appropriateness of infrastructure to offer adequate transitional shelter during fluvial floods; (ii) the safety on the location and geographical settings in relation to geographical and flood risk and; (iii) the accessibility to prospective ColCs and from these to humanitarian aid provided by neighbouring municipalities (clustering of sub-regional humanitarian capacities). In addition, compliance with disaster prevention national and municipal legal framework and guidelines [61,70] at local and regional level had to be ensured.

2.3.2. The collective-centre suitability index (CCSI)

Applicable methods to identify the current state of the prioritized factors were assessed and selected to develop a simple ranking analysis of prospective ColCs as an aggregation of the mentioned suitability factors. These methods constitute the basis of the Collective Centre Suitability Index (CCSI) and preliminary ranking assessment for transitional shelter.

Compliance of minimum shelter standards: As recommended by the Federation of Red Cross Red Crescent Societies [31], the Sphere Project on Humanitarian Standards [64], UNHCR [10] and by national and local authorities [70], the fulfilment of three minimum shelter standards is needed. External settings as the first standard foresees on surrounding requirements of the shelter, such as procuring for security and public order, access to vital public services, closure agreements, and general well-being of sheltered and host

communities. The collective centre strategic planning is the second standard, in which property rights and uses of the infrastructure are confirmed and supplementary measures are delivered as well to allow safe conditions, reengagement on daily activities from displaced families and early recovery. Finally, minimum conditions of the infrastructure have to be defined (i.e. thermal comfort, water and sanitation, covered living space $\sim 3.5 \text{ m}^2$, etc.) (see e.g. Corsellis et al. [14]) as well as shelter's capacity of an estimated population based on the previously flooded housing units and registered environmentally displaced people living within flood-prone areas [64].

Geographical and flood risk analysis: Humanitarian agencies equally request the infrastructure's location and environmental settings to be safe. For the case of Chía, this meant ColCs preferably avoided slopes gradients of 30° or higher to prevent risks of landslides/mudslides due to soil saturation during erratic rainfalls and these were located outside flood-prone areas of recurrence intervals of river gauges experienced during the 2011 floods (i.e. 100-year return period). In addition, scenarios of 1000 and 30,000-year return intervals of floods were integrated into the flood maps and watershed analyses, as well as the soil type maps from CAR [9] and IGAC [33]. We used basic analyses from the ArcMap 10 [®] Hydrologist extension to visualize and create awareness on built-up areas near or even within watersheds and runoff areas as well as on higher lacustrine and fluvial soils (we included exposed housing units at the urban-rural fringe near Bogotá River). Afterwards, we validated the ColCs surface slope gradient to check on the risk of landslides according to Sphere standards on humanitarian assistance (i.e. equal or higher than 30°). Lastly, the ColCs had to be located outside the forecasted flood-prone areas for flood recurrence interval scenarios that were developed using ArcMap 10 [®] 3D Analyst with a 3 m resolution DTM (Ultracam) and a soil type vector map. Despite the impossibility to establish a standard on safe distance of shelters from fluvial flood-prone areas, according to humanitarian shelter practices [64] and researchers [68], 100 m on a 100-year- and 50 m on a 1000-year-flood return periods were considered as minimum distances to mitigate public health risks from flood-water. The reason to this is that in previous related emergencies in Chía, flood-water has mixed with sewage water until receding phase.

Accessibility analysis: A least cost algorithm on the digitalized transport network allowed us to estimate the shortest time and distance a pedestrian takes from previously flooded units to assessed ColCs. In addition, we calculated the average and fastest time to reach non-flooded regional roads so as to identify among which nearby municipalities the clustering of humanitarian services was feasible despite blocked or flooded roads. Thresholds on reaching prospective ColCs from each flooded housing unit in 2011 were agreed with local authorities at 1.5 km in distance and 23 min as best time for a pedestrian to reach transitional shelter. ArcGIS [®] 10 – Network Analyst served to build the network grid and to run the impedance analyses, which determined the amount of resistance or cost required to traverse a path in the road network, or to move from the 2011 flooded units to prospective ColCs.

The Collective Centre Suitability Index (CCSI) for fluvial flood risk integrated these three factors and assessed the suitability (SCCy[hz]) of a prospective building (y) to be used as shelter during a particular hazard [hz]. Local stakeholders and risk analysts can modify and adapt the influences of the suitability factors by using a weighting factor (Δr) according to local urban and environmental settings:

$$CCSIy[hz] = \Delta r (CSy + ASAtty + Accy + ANod)$$

where

- **CCSIy[hz]** = Suitability index for Collective Centre at building (y) for a specific hazard (i.e. fluvial flood risk).
- **Δr** = Weighting factor on perceived risks agreed among technical staff and local authorities for each assessed suitability factor, for the particular settings of the location and climate-related hazards.
- **CSy** = Rating on compliance of minimum humanitarian shelter standards at building (y).
- **ASAtty** = Rating on adequate geospatial attributes from building (y) in relation to risk source and hazards (i.e. slope, soil type, hydrography and flood recurrence scenarios).
- **Accy** = (Inwards) Least cost accessibility rating from housing units at risk to Collective Centre at building (y).
- **ANod** = (Outwards) Least cost accessibility rating from building (y) to a functional regional node or exit road.

The developed index allows municipalities to identify which infrastructure serves best as transitional shelter by: complying with minimum shelter standards to procure safety from displaced people, minimizing the building's vulnerability to be affected by the risk source under different flood risk recurrence interval scenarios (i.e. fluvial floods), and by ensuring accessibility from and towards the selected CoC. In the following section, we apply and calculate the CCSI for the case study of Chía.

2.3.3. Suitability analysis of collective centres in Chía

To apply the Suitability index for collective centres in Chía we first assessed the necessary data in close cooperation with the local municipalities. We used aerial photography

and a 3 m resolution airborne Ultracam-collected Digital Terrain Model (DTM) provided by the Planning Office from the Municipality of Chía and a soil type vector map from the Environmental Regional Agency of Cundinamarca (CAR) (see Table 1). We minimized errors from the high resolution DTM while analysing the watershed and adjacent urban features, by using ArcGIS 10[®] - Hydrology functions to fill sinks and to enhance hydrological attributes [52]. We verified on secondary data, bio-geomorphological proxies studied by Van der Hammen et al. [75] to validate classification of lacustrine soil type and to enhance maps for discussion of results. ArcGIS[®] 10-3D Analyst and Spatial Analyst were used to build such scenarios based on flood maps and watershed analyses. All datasets were projected in the same reference system using Transverse Mercator.

Geographical and spatial settings of exposed urban areas and risks resulting from river floods required separate analyses of the CoCs of the Bogotá River and the Frío River. Three CoCs (i.e. Chilacos Community Centre, La Luna Sports Hall and La Lorena Sport Centre) were identified to serve the eastern side of the urban centre which is more vulnerable due to population density, exposed housing units and proximity to the Frío River catchment area. On the west side the SJME School and Samaria School were pre-selected as collective shelter serving exposed areas close to the Bogotá River.

The sum of all weighting factors equals to 1.0 in order to have a standardized index and rating. Stakeholder and risk analysts agreed on the distribution of the weighting factor by assigning higher or lower weights on suitability factors considering relevance to recovery and risk in a given time of year (i.e. rainy season) and location, as well as on previously experienced river floods. Results of suitability factors are equally standardized after determining thresholds that are based on the grey literature and stakeholders' expert knowledge. They were rated based on a four scale value, ranging from 0 (low), going from minor (0.33) to major (0.66) as intermediate values, until reaching highest full suitability value (1) (Table 2).

Coming to an agreement with stakeholders on perceived spatial-temporal changes on vulnerability and exposure to construct a weighting factor (Δr) can be a

Table 1
Data and geodata used in the study considering each CoC suitability factor.

CoC suitability factor	Data/Geodata used	Specifications	Source
Compliance of minimum shelter standards	Infrastructure designs, plans and characterization of buildings. Minimum shelter standards.	Building specifications and design. Collection at site on areas, water and sanitation supplies (2012).	Planning office municipality of Chía. Public infrastructure Office. Sphere [64] and CCCM standards (2010).
Geographical and flood risk analyses	Digital Terrain Model (DTM). Aerial Photography (Chía). GPS collected 2011 flood peak. Maps of urban infrastructure (roads, public infrastructure and land use plans and maps). Soil type vector map.	3 m resolution DTM (2009). 1 m resolution (2009) Ultracam. Polygon shapefile (2011). Points, lines and polygons shapefiles (2005/10). Soil Type (2007) – CAR/IGAC.	IGAC/Planning Office (Chía). Regional Environmental Agency (Corporación Autónoma Regional de Cundinamarca - CAR).
Accessibility analysis (inwards/outwards)	Municipal road network (Chía). Cadastral map (housing units).	Polylines (2012). Cadastral Map from Chía (2005). Intersections from municipal, regional and national roads (2010).	GPS/Geodata Vendor. Planning Office (Chía).

Table 2

Proposed weightings and ranges to estimate the CCSI according to agreed perceived risk settings. D=distance (m), SG=Slope gradient ($^{\circ}$), SFlc/SFlt=Inwards least cost-distance/time (km/min), CES=Outwards cost-distance (km).

CoLc suitability factors (Chía)	Weighting factor ($\Delta r_T = 1.0$)	Scores and ranking range			
		Low (0)	Minor (0.33)	Major (0.66)	Full value (1)
STANDARDS ON SHELTER CONDITIONS					
Compliance of Shelter Standards	(Priority value) 0.25	Does not comply	Complies with major resources	Complies with minor resources	Fully complies
GEOGRAPHICAL AND FLOOD RISK ANALYSIS					
Slope gradient	0.05	$> 30^{\circ}$	$\geq 20^{\circ}$ and $\leq 30^{\circ}$	$\geq 10^{\circ}$ and $< 20^{\circ}$	$< 10^{\circ}$
D \times 100:Distance from risk source (based on 100-year risk scenario)	0.25	≤ 100 m	101 m to 200 m	201 m to 250 m	> 250 m
D \times 1000:Distance from risk source (based on 1000-years risk scenario)	0.15	≤ 50 m	51 m to 100 m	101 m to 200 m	> 200 m
ACCESSIBILITY ANALYSIS					
Accessibility (inwards) % from exposed houses reaching CoLcs. (distance-cost: SFlc and time-cost: SFlt)	0.20	SFlc > 3 km SFlt > 45 min	2–3 km 30–45 min	1.5 km–2 km 23–30 min	< 1.5 km < 23 min
CES: Accessibility (outwards) from CoLc to D \times 100 non-flooded regional/national road	0.10	CES > 3 km	1–3 km	0.5–1 km	< 0.5 km
Total / Max. Score	1.0	0	0.33	0.66	1.0

challenging task. There are a number of methods which may facilitate this exercise from a cause-effect approach, such as risk flowcharts [43] and quantitative fault tree analysis [67]. To agree with the local stakeholders on perceived spatial-temporal changes on vulnerability and exposure to construct a weighting factor, the Vester matrix [13] and the environmentally significant behaviour analysis from [65] were chosen in this case study.

In the urban centre from Chía, slope analysis and landslide risk were not that relevant, as elevation in the focused study area was ranging from 2543 m to 2555 m and distance to hills and mountains was significant. Despite the latter, this suitability factor was preserved for later use in the CCSI as the planning team identified higher geological risks in the rural area, thus implying the weighting factor would need another weighting arrangement within the same municipality. From the total weighting factor (1.0), only 0.05 was assigned as the maximum value regarding safety on slope gradient. In spite of relevance, the assigned weight on CoLcs accessibility (0.10) to regional and national roads to cluster emergency services with adjacent municipalities was also not highly prioritized in view of registered blocked or flooded roads towards the capital during previous emergencies. Highest weight (0.25) was given to the distance of the studied collective centre in relation to the risk source based on a 100-year flood risk return period (Dx100) and to compliance of shelter standards.

Accessibility or least cost-distance (Sflc) and time (Sflt) analyses from 2011 flooded housing units to the prospective CoLc was highly valued (0.20). The remaining weighting factor (0.15) was assigned to the distance scenarios of the CoLc and a 1000-year flood risk scenario modelled with the DTM and the soil type map. CoLc suitability factors which are critical need to be defined as priority values to minimize life-threatening hazards. In our case, compliance of shelter minimum standards was a prioritized factor which automatically discarded a collective shelter when it did not offer minimum conditions.

3. Results

We received the results for the suitability of the selected CoLcs as shown in Table 3. La Luna Sports Hall gave the highest CCSI (0.97) on the suitability analysis, followed by the SJME High School (0.78). The community centre of Chilacos had to be discarded because it did not comply with minimum shelter standards. La Lorena Sport Centre and Samaria School both yielded a medium suitability of about 0.5. In the following section, results on each one of the three suitability factors are explained in more detail.

3.1. Results on CoLcs minimum shelter standards

Chilacos CoLc had to be automatically discarded considering its insufficient conditions of the infrastructure and covered living space compared to the number of flooded properties in 2011 (i.e. 60 units or an average of 180 people) in a 1 km predefined range (see Table 4). Samaria and SJME Schools have a restricted use as it may interrupt education services during long lasting floods, water receding and recovery phase. This situation could trigger social conflicts with nearby families, students, teachers and other staff as daily users of these buildings. Inversely, La Luna Sport Hall complies significantly with most of the standards, although it may still require further assessment on water and sanitation as well as on thermal comfort. Finally, deficiencies on the collection and sewer systems may pose a risk of drainage backflow flooding and water contamination close to the CoLcs of La Lorena Sport Centre and the SJME School.

3.2. Geographical and flood risk analyses in Chía

The geographical analysis showed, as expected, that the slope gradient had full suitability value (1) on all assessed infrastructure, considering that no CoLc was laying on slopes higher than 30° on a 1 km radius, which means risk of






Table 3

Collective centre suitability indices for the 5 selected public infrastructure sites. On each cell find the computed suitability factor (score multiplied by its weighting factor) and in parenthesis the score and measured (~) values.

Ratings from CoIC suitability factors (Chía)	Weighting factor (Δr $T=1.0$)	Chilacos	La Lorena	La Luna	Samaria	SJMEs
		Frío river catchment area			Bogotá river catchment area	
STANDARDS ON SHELTER CONDITIONS						
Compliance of shelter standards	Critical (0.25)	Discarded (0~Non-compliance)	0.08 (0.33~ minimum compliance)	0.25 (1~ high compliance)	0.08 (0.33~ minimum compliance)	0.17 (0.66~ medium compliance)
GEOGRAPHICAL AND FLOOD RISK ANALYSIS						
Slope gradient	0.05	0.05 (1~0.1°)	0.05 (1~2.3°)	0.05 (1~0.02°)	0.05 (1~1.5°)	0.05 (1~0.5°)
Distance from risk source (based on 100-years flood scenario)	0.25	0.25 (1~707 m)	0.083 (0.33~126 m)	0.25 (1~872 m)	0.17 (0.66~235 m)	0.25 (1~315 m)
Distance from risk source (based on 1000-years flood scenario)	0.15	0.15 (1~617 m)	0.05 (0.33~71 m)	0.15 (1~800 m)	0.10 (0.66~185 m)	0.15 (1~290 m)
ACCESSIBILITY ANALYSIS						
Accessibility (inwards) % of exposed housing units reaching CoICs based on threshold (23 min./1.5 km)	0.20	0.13 (0.66~53%)	0.20 (1~64%)	0.20 (1~75.9%)	0.07 (0.33~6%)	0.07 (0.33~3.3%)
CES: accessibility (outwards) from CoIC to D \times 100 non-flooded regional/national road	0.10	0.10 (1~80 m)	0.03 (0.33~2037 m)	0.07 (0.66~721 m)	0.03 (0.33~1963 m)	0.10 (1~0 m)
CCSI/Total:	1.0	Discarded	0.499	0.966	0.496	0.781

Table 4

Compliance of humanitarian standards of selected CoICs (based on [32,10]; UNGRD, 2012).

Collective centres	Visual description [23]	CoIC type/use of infrastructure	External settings	Collective centre strategic planning	Conditions of the infrastructure
Chilacos		Community centre. Short-term transitional shelter.	Access to public services not compromised.	Adequate use and property rights. Central location.	Does not comply; insufficient covered living space.
La Lorena		Sport centre and community centre. Short-term transitional shelter.	Sanitation risk due to the probability of waste water backflow.	Adequate use and property rights.	Complies partially if complemented with modular shelter alternatives.
La Luna		Sport hall and cultural centre. Short- to medium-term transitional shelter.	Access to public services not compromised.	Adequate use and property rights.	Complies.
Samaria		High school. Short-term transitional shelter if no interruption to education services.	Neighbours may disagree. May compromise water and sanitation due to underground water.	Interrupts education services and community daily activities. Relatively close to road network.	Complies partially if complemented with modular shelter alternatives.
SJMEs		High school. Short-term transitional shelter if no interruption to education services.	Neighbours may disagree. Need to verify water and sanitation.	Interrupts education services and community daily activities. Relatively close to road network.	Complies partially if complemented with modular shelter alternatives.

landslides are unlikely to happen on these locations. In contrast to this, the flood risk analysis revealed that the distance from Samaria and La Lorena to flood scenarios of 100 years was less than 200 m (see Fig. 3a). Chilacos, SJME School and La Luna Sports Hall, however, greatly exceeded the distance threshold (100 m for a 100-year flood risk scenario and 50 m for a 1000-year flood risk return scenarios).

Concerning the soil properties, slopes and foothills of the mountains as well as the flat areas contain silt and clay sediments of the Neocene and Quaternary age [8]. Geomorphological and biological research of the high plateau region carried out by Torres et al. [69] and Van der Hammen et al. [75], suggest a complex hydrography and

possible interconnectivity of aquifers, rivers, and wetlands as well as seasonal fluvial floods throughout the natural and anthropogenic drainage process that took place from the Palaeogene age until today. Particularly in the urbanized area on the western side of the city, areas contain higher concentrations of lacustrine and fluvial sediments and moderate permeability compared to those at higher level in the city centre [9,33]. Since 1970s until today built-up areas have extended on the western urban fringe, thus taking over a large part of the natural drainage system as seen on the watershed analysis and soil type maps along the Frío River (Fig. 3a). These areas contain higher concentrations of lacustrine and fluvial sediments (labelled as

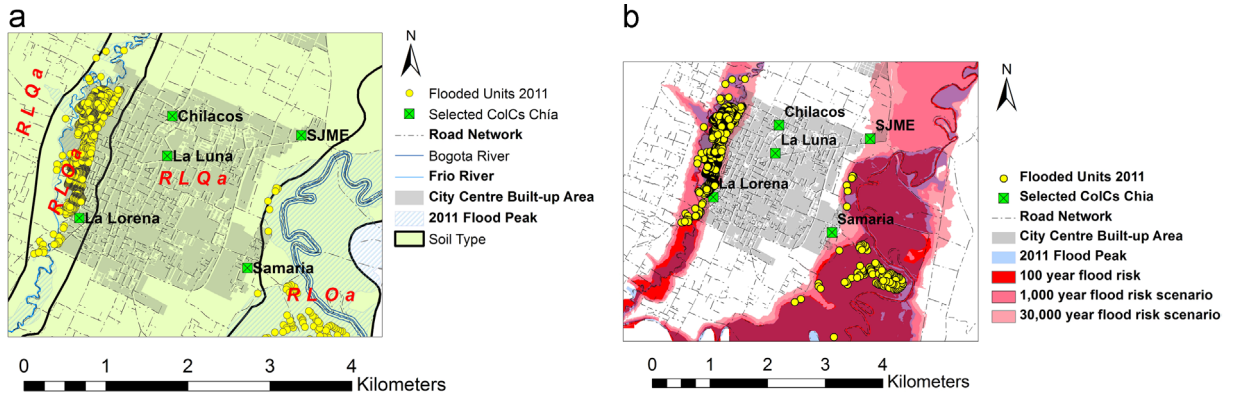


Fig. 3. Correlation of soil type, 2011 flood-peak, and 2011 flooded units (a). The right map (b) depicts overlaid Chía's 100-/1000-/30,000-flood risk scenarios when assessing ColCs vulnerability.

RLOa) and moderate permeability compared to those at higher level in the city centre (labelled as RLQa) [9,33]. We denoted complete correlation between RLOa soil type and digitized flooded units during the 2011 emergency (1330 out of 1339 or 99.33%).

Sanitation conditions could be compromised due to high water tables and inappropriately combined sewer and rain runoff collection systems near SJME, Samaria and La Lorena (distance from Samaria and La Lorena to flood scenarios of a 100 years was less than 250 m). This was mentioned as well on emergency reports [12] and verified while examining the 100 and 1,000 year flood recurrence scenarios (Fig. 3b). Chilacos, SJME School and La Luna Sports Hall greatly exceed the maximum distance threshold (100 m for 100-year flood risk scenario and 50 m for a 1,000-year flood risk return scenarios).

3.3. Inwards/outwards accessibility analysis

The least-cost accessibility from exposed housing units to ColCs (inwards) gave lower values for La Luna near the catchment area of the Frio River. This means residents living in 947 (75.9%) out of 1247 flooded units on the west side would take less than 23 min (pedestrian time) or 1.5 km to reach this ColC. Alternatively, applying the same impedance threshold to La Lorena and Chilacos resulted in 798 (64%) and 662 (53%) served flood-prone units, respectively.

Only three flooded units exceeded the defined impedance threshold for this catchment area. Results on the Bogotá River catchment area indicated a very limited accessibility from flooded units to the pre-assigned ColCs. Considering the same least-cost time and distance impedance threshold, only 11 (6%) out of 184 flooded units would reach Samaria. This value further drops to 6 (3.3%) for SJME School. Even increasing the impedance thresholds to 2 km (30 min or less pedestrian-time), the latter would only have one additional served flooded unit whereas the former would increase by two.

Four out of nine exits from the city centre or road network nodes were still functional (i.e. north and north-east) while considering impedance values and flooded roads in 2011 as a mobility restriction (outwards) in our

network analysis. In order of accessibility, ColCs closer to most functional road exits on the northern area of the municipality were: Chilacos (80 m), La Luna (721 m), SJME (1733 m), La Lorena (2037 m) and Samaria (2924 m). We evaluated also distances to the second most functional exit to cluster aid with neighbouring municipalities (i.e. Bogotá, Cajicá, Zipaquirá and Tenjo): SJME (0 m), La Luna (1397 m), Chilacos (1436 m), Samaria (1963 m) and La Lorena (2884 m). Full values on the CCSI for this factor were therefore assigned to Chilacos and SJME School (0.10). A major value (0.066) was given to La Luna and least values for clustering emergency services (e.g. outwards accessibility analysis) were assigned to Samaria and La Lorena (0.033).

4. Discussion

Our findings reveal that the developed Collective Centre Suitability Index applied for the case study of Chía allows a first assessment of public infrastructure to be used as a transitional collective shelter in case of an acute flooding or environmental disaster. We show that the CCSI can provide a transparent information and ranking of the selected five prospective collective centres in Chía, while using the 2011 River Floods as a 100-year return period baseline [12]. We therefore augment existing studies that have focused on flood coping and management strategies in general [37,49], conditions and impacts of resettlements in case of a disaster or crisis [47,67] or climate-induced migration analysis [5].

This analysis goes in line with other studies undertaken in Thailand [34], Guatemala [32] and Bangladesh [38] that are working towards this direction by building dual-purpose social infrastructure [38,39], through the classification of long-term and short-term collective centres [32], or with the implementation of a nation-wide strategy to organize communities and adapt buildings which serve vulnerable regions. In addition to these studies, the Collective Centre Suitability Index (CCSI) offers a transparent, adaptable, and systematic assessment for disaster management and may be of large benefit for local and regional decisions-makers. The proposed choice of suitability factors, criteria and weightings was made in

collaboration of Chía's municipal planning and disaster prevention officials and supported with evidence from previous related emergencies from 2006 and 2011 [12,63,74]. It is therefore a locally adapted index that is limited to a set of vulnerability and exposure criteria, however, due to its participative approach, it may be transferred and tested in other locations and in diverse disaster management contexts. The CCSI may be updated by integrating additional factors, by modifying the thresholds or the weighting factor according to different location-specific and dynamically changing urban settings [37]. For instance, mobility [57], property rights [2], or cultural values [25] may influence preferences on the selection and use of ColCs [10]. Additional criteria could support middle-sized cities which are strongly dependent from nearby larger urban settlements [62], thus the need to highlight continuous access to neighbouring municipalities particularly during rehabilitation and recovery of sheltered families. While we are aware of these possible extensions we are now certain that beyond the minimum shelter standards being frequently accepted and accounted for by international agencies (i.e. UNHCR, Sphere, IFRC), geographical settings and the accessibility of prospective ColCs need to be further considered.

We hence go in line with Corsellis et al. [14], IFRC [31] and Sphere [64] who call for such an analysis, however, to the knowledge of the authors, a respective method similar to our index has not been proposed before. We know also that temporary emergency accommodation is only one possibility of shelter of many others [58] and that ColCs are only one strategy from many to design and integrate according to the particular settings of vulnerable municipalities and hazards [73]. However, the proposed multi-criteria assessment of suitability of collective centres requires the necessary geographical and physical data (i.e. design, construction plans, etc.) of available infrastructure to be used as collective shelter, their current condition to procure for minimum standards and the institutional and legal mechanisms to facilitate humanitarian operations [70]. In other vulnerable regions, particularly in low-income municipalities from countries affected by climate variability and extreme events (e.g. Thailand, Guatemala, El Salvador or Colombia), this may be a major challenge to overcome in the future if irregular urban expansion, environmental degradation and climate change set over time an undesirable atmosphere to humanitarian operations and disaster risk management [25,32,37]. Limitations to our analysis and on case study of Chía, relate considerably with the politics of decision-making and information management during emergency response and recovery. For instance, a wider analysis in other vulnerable municipalities close to Chía was not possible due to the restrictions to information, capacities and insufficient political interest from authorities to participate in the project. Information on humanitarian operations and recovery decisions was indeed asymmetrical [24], thus limiting regional strategies to disaster risk reduction.

The question of how to evaluate the effectiveness of the proposed ColCs suitability assessment is a difficult one considering limited research for this particular subject. There are additional limitations to our case study in Chía,

such as the restriction on the assessment of only five prospective buildings to be used as collective shelter in a particular geographical setting vulnerable to fluvial floods. We addressed these limitations through working on the adaptable connotation of the multi-criteria assessment tool, and by involving key stakeholders from the planning and the local disaster risk management committee in the updating of emergency shelter and contingency plans.

5. Conclusions

Identified and prioritized risk factors led to the construction and measurement of an integrated Collective Centre suitability analysis. Our study showed that considering environmental and geographical changing settings positively complements traditional transitional shelter assessment methods (e.g. Sphere standards, IFRC Shelter Kit, Oxfam transitional shelter standards). A participatory action research process [6,78] demonstrated to be an appropriate method to formulate with relevant stakeholders (i.e. Chía's municipal planning and disaster prevention officials) a flexible and multi-criteria shelter assessment tool that adds to the rehabilitation and recovery dimension of environmentally displaced people, thus being in line with related research [14,40,47] and recommended practices from federal and international aid agencies [21,30,72]. We applied the Collective Centre Suitability Index (CCSI) to five locations in Chía using the 2011 River Floods as a 100-year return period baseline [12].

Three key findings and policy recommendations were derived from our analysis. First, hydrological and geographical settings of prospective ColCs were used to assess the risk of environmentally displaced people. Conventional shelter assessment methods [14,31,64] support this idea, but may fall short to allow for integrated analyses on natural and man-made changes and on the environmental factors that increase exposure or vulnerability. The CCSI aims to reduce this knowledge gap, but still requires a level of expertise to, e.g. agree on the weighting of risk factors or to include additional suitability criteria of collective shelters depending on the region and conditions. Second, while Local Emergency and Contingency Plans (PLECs) need to be updated in Colombia following a legal and institutional change from responding to disasters [41] to managing the risk of disasters [42], national and regional emergency authorities may request mayors to include a detailed inventory and specifications on the assessment of prospective emergency shelter, thus complying with recent national guidelines [70].

Finally, challenges remain in finding sustainable and cost-effective mechanisms to further assess applicable shelter solutions during extreme weather events. Hence, the importance of complementing methods and capacities from risk analysts, residents and local authorities in a permanent co-learning process [55]. We think here lies the key point and knowledge gap of urban adaptation planning and disaster risk reduction: to offer an analysis and framework linking the particular settings of urban development (e.g. growth, social inequalities, cultural and physical fragmentation, etc.) with future shelter and humanitarian needs considering the uncertainties of climate and environmental change.

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