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Evaluating climate impacts on geographical accessibility to basic services in rural Colombia[☆]

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A R T I C L E I N F O

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A B S T R A C T

Climate change exacerbates extreme natural hazards such as floods and landslides, potentially affecting large areas worldwide, including urban and rural areas. This research measures the impact of flooding and landslides on accessibility in Colombia, a country facing significant topographical challenges. Many variables exacerbate accessibility challenges, e.g., decades of armed conflict have hindered the development of rural communities. We implement an accessibility measure to assess the impact of natural hazards on the road infrastructure under different return periods using census and crowdsourcing data. In addition, we calculate the effect of climate change yearly. Finally, we evaluate accessibility impacts across vulnerable communities, considering rurality, income, and armed conflict. Results show that 22.32% of the population experiences travel times higher than 1 h to the main town in the baseline scenario, increasing by 32% on average because of floods or landslides in the 100-year return period, disproportionately affecting more rural and low-income communities.

1. Introduction

Natural hazards can impact society in diverse dimensions, such as food security, road infrastructure, and accessibility to services, posing major challenges that must be tackled (Akudugu et al., 2012). Climate change also potentiates the effects of natural events by affecting more people and infrastructure yearly (IPCC, 2023). Besides, vulnerable communities will be disproportionally more affected by climate change despite their contribution less to it (Ahmed and Eklund, 2019; Akudugu et al., 2012; Bündnis Entwicklung Hilft, 2024; Schweikert et al., 2014). For instance, natural hazards like floods or landslides can impact the accessibility of people to essential services by disrupting road networks and infrastructure (Ahmed and Eklund, 2019); meanwhile, agricultural production can be impacted, raising food insecurity, especially among rural communities (Akudugu et al., 2012). Accessibility is the potential of interaction that a person or group of people have through the combination of transport supply and land use development (Geurs and

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van Wee, 2004). However, accessibility in a region is inequity distributed, leading to excluded people from participating in society (Lucas, 2012; Pereira et al., 2017). For instance, the access of rural settlements to health and educational services is lower than that of urban dwellers, which is related to road infrastructure development and the location of facilities (Ahmed and Eklund, 2019; Barrucand et al., 2017; Cardona et al., 2021). Identifying the impact of natural hazards on geographical accessibility is crucial to designing and developing transport policies focused on adaptation to climate change, considering that more significant effects are expected, especially among vulnerable communities and developing countries.

Colombia is ranked fourth in the World Risk Report 2024, which considers exposure and vulnerability to natural hazard events, being the riskiest country in Latin America and the Caribbean (LAC) (Bündnis Entwicklung Hilft, 2024). Flooding, landslides, and earthquakes are the most critical natural hazards that can affect the Colombian population (Barrucand et al., 2017; Bündnis Entwicklung Hilft, 2024). Three mountain ranges of the Andes overpass the country, with two main rivers crossing the country from south to north. The larger population live in the Andes region; consequently, the road infrastructure faces continuous challenges when going through the mountains while at constant risk of landslides. On the other hand, the valleys are prone to floods. This potentially can reduce connectivity among population centres.

Colombia has been affected by more than seven decades of armed conflict (Escobar García et al., 2022; Salazar, 2016), shrinking the country's social and economic development. For instance, the armed conflict produced a large displacement from rural to urban areas, producing high urbanisation rates close to those experienced in developed countries, e.g., the rural population in Colombia is less than 20 % in 2023. In addition, Colombia is the most unequal country in LAC, with a Gini Index of 54.8 in 2022 (World Bank Open Data, 2022); consequently, it has had a historically unequal economic development. Despite the recent peace treaty signed in 2016 between the Colombian government and the most important guerrilla, the Revolutionary Armed Forces of Colombia (FARC) (Escobar García et al., 2023), Colombia is currently facing an increase in violence, reaching first rank in the Armed Conflict Exposure Index (Bündnis Entwicklung Hilft, 2024). This index was calculated in the World Risk Report 2024 to explore the connections between exposure to natural hazards, negative impacts of climate change and exposure to armed conflict. Therefore, establishing the importance of armed conflict, rurality, and income, which can exacerbate the effects of natural events, raised the following questions, which will be answered considering Colombia as a case study:

- How do climate change and extreme natural hazards such as flooding and landslides affect accessibility in a country?
- Who are the most vulnerable community groups in a country to climate change and extreme natural hazards like flooding and landslides?

We will measure the effects of flooding and landslide events on the geographical accessibility of Colombia, taking into account the differences between baseline scenarios (without natural hazard disruptions) and those with natural events. Furthermore, we calculate the adverse effects of climate change by the expected annualised population affected by natural hazards. Furthermore, income, rurality, and armed conflict were used to identify which groups of people can experience larger effects on their accessibility, considering an index inspired by the Palma Ratio.

1.1. Literature review

The impact of natural hazards on communities is related to the type and severity of the events. Those hazards can affect the road infrastructure network, affecting the connectivity of people and the access to essential services during critical events (Ahmed and Eklund, 2019). Research in network vulnerability and resilience focused on identifying critical roads potentially isolating communities when extreme events occur (Jenelius and Mattsson, 2012; Taylor and Susilawati, 2012). This allows for prioritising investments in the road networks to adapt them to natural hazards, increasing their resilience to climate change (Schweikert et al., 2014). For instance, Schweikert et al. (2014) studied the impact of climate change on the road infrastructure of ten countries, considering their materials and identifying the most critical investment areas. They found that developing countries will be more impacted by climate change and natural hazards, increasing the necessity of investment in road networks adapted to those events. In addition, Espinet et al. (2016) studied the Mexican road network with a similar methodology, finding the provinces and areas where the investments should be prioritised to maximise the benefits. Similarly, the Cambodia road network was studied using accessibility analysis to calculate connectivity among cities and find the most affected after flooding events, which impacted 27 % of the population (Espinet Alegre et al., 2020). Another study conducted among 13 important African cities shows that most of the job opportunities are located in areas at risk of flooding, highly impacting the economy of the cities and the accessibility of the population (Rentschler et al., 2019). Studies in road vulnerability and road resilience to natural hazards evidence the importance of investments in adaptation to climate change and natural hazards to reduce the future impact on the road infrastructure and the communities, especially among developing countries, which have a higher opportunity to build new infrastructure adapted to the necessities of the future (Espinet et al., 2016; Schweikert et al., 2014).

Identifying the impacts on accessibility due to natural hazards or network vulnerability is critical to measuring the effects on communities, the economy and the social welfare. Accessibility is the ease of interaction due to a person's combination of transport supply and land use (Geurs and van Wee, 2004). Therefore, measures of accessibility consider the level of service of the transport network and the facilities that people can reach through it, e.g., job opportunities, health services or grocery stores. Several accessibility measures have been developed in the past decades, making LAC a place where diverse research has been conducted, especially regarding transport equity (Geurs and van Wee, 2004; Vecchio et al., 2020). For instance, studies in LAC have found deep inequalities in their urban cities, exacerbated by income level and social background, making it more difficult for specific communities to move around their cities (Oviedo and Dávila, 2016; Tiznado-Aitken et al., 2023; Vecchio et al., 2020). Although many studies have focused on urban cities in LAC, little attention has been paid to rural areas or country-based calculations (Cardona et al., 2021). For example, Gage and Guirlène Calixte (2006) found low accessibility levels to antenatal healthcare due to poor road conditions among Haiti's rural communities based on self-reported questionnaire surveys and in-situ observations. On the other hand, Cardona et al. (2021) identified that rural municipalities in Caldas (Colombia) experience lower accessibility to higher education and healthcare systems, exacerbated by a lower road infrastructure development due to armed conflict. The relationship between accessibility and armed conflict in Colombia was further explored by Escobar García et al. (2023) by considering two case studies in the centre and south of the country. Studies about accessibility in Colombia, intercepted by variables such as rurality and armed conflict, are in their initial steps, having a significant opportunity to develop promising findings. Furthermore, there is scarce evidence of the accessibility levels at the country level with higher resolution data; meanwhile, the impacts of natural hazards are underexplored.

Data availability and reliability are some of the challenges in studies about accessibility and natural hazards, including rural areas. This challenge increases as the size of the case study increases. For instance, the road network information is retrieved from different data sources like government inventories (Espinet Alegre et al., 2020; Espinet et al., 2016; Schweikert et al., 2014) or OpenStreetMap (Moratalla and Uma, 2023; Qiang and Xu, 2020; Rentschler et al., 2019; Wang et al., 2024). Other studies used crowdsourced data from Twitter and Google Maps (Florath et al., 2024). Therefore, results should be analysed carefully, and the data need to be contrasted from several data sources, while studies with more resolution must be conducted.

Finally, several studies have explored the effects of socio-demographic and spatial dimensions that could exacerbate the effects of natural hazards on accessibility. Nevertheless, there is no comprehensive approach to consider variables to deepen intersectionality analysis. Rurality has usually been considered in assessing natural hazards, while income has been extensively considered in transport equity studies in LAC in urban settlements (Cardona et al., 2021; Vecchio et al., 2020). Under this context, this paper aims to analyse climate impacts on accessibility to basic services using geospatial data on accessibility, natural hazards, and climate change. Following a stream of work on the impacts of rural accessibility on human, social and economic development (Espinet Alegre et al., 2020; Mikou et al., 2019), this paper goes a step further by integrating census data and evaluating the impacts of climate disruption on accessibility on poverty, rurality, and armed conflict.

The research article is composed of four more sections. The second section explains the Colombian case study, introducing indicators about armed conflict, rurality and income and the resolution of the data. The third section describes the methodology and the data used. Then, the fourth section shows the study's primary results, followed by the fifth section, which discusses the results with the current knowledge about climate change assessment and accessibility analysis. Finally, we present the conclusions.

2. Case study

Colombia is a country in South America with a population of 50 million inhabitants. It has unique geographical characteristics, and it is crossed by the Andes Mountain range, divided into three parts, crossing the country from the south and almost reaching the Caribbean Sea. 70 % of the Colombian population lives in the Andes region, a vast area prone to landslide events (Barrucand et al., 2017). Furthermore, it has extensive river systems, e.g., the Magdalena and Cauca River Valleys, which are prone to overflooding during heavy rain periods, typical in tropical weather.

Colombia is geopolitically divided into 32 departments and 1101 municipalities. In this article, we will use the province division as a unit of analysis, considered as a middle point between departments and municipalities, managing to capture better the patterns in the rural areas of the territory (Ramírez and de Aguas, 2017). The Province Division was defined by Ramírez and de Aguas (2017) in their work for the Economic Commission for Latin America and the Caribbean (CEPAL in Spanish). A total of 143 provinces were used, and their configuration was updated considering the accessibility calculations conducted for this study (see Appendix A).

Furthermore, we used 7644 Census Tract (Sectores Censales in Spanish) geographically defined by the Department of Administrative of National Statistics (DANE in Spanish) for the Census of Population and Households in 2018 (CNPV in Spanish) (DANE, 2018). Accessibility measures were calculated from Census Tract origins to the province's main town (or "cabecera mayor de la provincia" in Colombia). The main town is considered the most relevant population centre, concentrating on several essential services such as secondary and higher education, health, and justice (Ramírez and de Aguas, 2017).

3. Materials and Methods

The methodology comprises three subsequent stages: baseline accessibility calculations, the impact of flooding and landslide events, transport equity measures and the effect of climate change.

3.1. Baseline accessibility calculations

The location-based accessibility measure considers three main inputs: origin, destination, and impedance function (Geurs and van Wee, 2004). The origin will be the centroid of the census tracts, and the destination will be the centroid of the province's main town. The impedance function considers the willingness to travel between the origin and the destination. In this study, we considered travel time using the transport network. Therefore, we must retrieve the transport network suitable for GIS-shortest path analysis.

The driving transport network was downloaded from OpenStreetMaps API, considering the geographical boundaries of each Province (OpenStreetMap contributors, 2017). We used road link categories to calculate a random categorised sample (n = 10.000) to retrieve speeds from Google Maps Distance Matrix API from six Colombian medium-sized cities (Manizales, Pereira, Bucaramanga, Cúcuta, Cartagena and Ibagué) (Cardona et al., 2021; Wang and Xu, 2011). The real links' lengths and the API's shortest path result were compared to validate the obtained speeds. Finally, the average speed per link category, shown in Table 1, was adopted to input the speeds in the driving network.

The *NetworkX* library from Python was used to calculate the travel time for the shortest paths between Census Tracts centroids and provinces' main town centroids throughout the country (Hagberg et al., 2019). This first approach allowed us to identify disconnected census tracts. Therefore, we refined the OSM transport network by linking disconnected census tracts through driving, maritime or fluvial networks. Google Maps satellite images and information from the Planning National Department (DNP in Spanish) and the Ministry of Transport were checked manually to complement the transport network in QGIS (Espinet and Rozenberg, 2018). The manual check allowed us to identify pedestrian paths that connected census tracks, which we assume a speed of 3.6 kph (Zuluaga et al., 2018). Finally, the maritime and fluvial speed depends on the boat and the water flow. An average speed of 30 kph and 25 kph was defined for ocean and river links.

After completing the transport network, shortest path calculations were conducted, considering travel time as the impedance function. We defined five accessibility categories, considering the travel time from the origin of the census tract to the province's main town (see Table 2) (Espinet Alegre et al., 2020; McCormick et al., 2023). In addition, we defined isolated census tracts considering two criteria. First, it is isolated if the census tract centroid is more than 2 km (Euclidean distance) from the road network. This criterion follows the Sustainable Development Goal (SDG) 9.1 for the Rural Accessibility Index (RAI) guidelines (Mikou et al., 2019). Second, it is isolated if no shortest path exists between the centroid and the province's main town. This is considered the baseline accessibility, which will be affected by flooding and landslide events in the natural hazard impact scenarios.

3.2. *Flooding scenario*

The flooding scenario considered the effects of overflooding on the transport network and its impacts on accessibility levels. The impact was reflected by reducing the operational speed, considering the flood levels, as per the recommendations of Pregnolato et al. (2016) (see Table 3). In addition, the road is closed if the floods exceed the drainage capacity by 25 cm (Espinet and Rozenberg, 2018). We considered flooding projections from the World Bank's climate change portal for 10, 20, 50, 75, and 100-year return periods. The drainage capacity baseline was set considering the drainage capacity per typologies, i.e., tertiary roads are affected from the baseline scenario, secondary roads from the 10-year return period and the primary and trunk roads from the 20-year return period onwards. Finally, the shortest path and accessibility calculations are conducted for each return period.

3.3. *Landslides scenario*

The landslide scenario considered the probability of landslides in the area. We considered an isochronic effect (equation (1) by closing the transport network if they are affected by a landslide using the Global Landslide Hazard Map developed by the World Bank (World Bank, 2021a). We used the 10, 20, 50, 75 and 100-year return periods to determine the landslide effect. Finally, the shortest path and accessibility calculations are conducted for each return period.

$$f(L_i) = \begin{cases} \textit{Road not affected by landslides if} \;\; L_i \geq \dfrac{1}{T_i} \\ \textit{Road closed if} \;\; L_i < \dfrac{1}{T_i} \end{cases} \tag{1}$$

3.4. *Transport equity analysis*

We calculated the Concentration Index (CI) as a transport equity indicator for accessibility in the baseline scenario and those affected by flooding and landslides events. The CI measures how the accessibility inequalities are concentrated on certain groups (Karner et al., 2024). In this research, we calculated CI considering variables of rurality, armed conflict, and income (see Fig. 1). Eq. (2) presents the CI where n is the number of observations, μ is the average accessibility value, a_i is the accessibility for each observation and R_i indicates the proportion status of each observation with respect to the group of analysis (e.g., the income, rurality or armed

Table 1
Operational speed per OSM typology.

Typology	Total length (km)	Speed (kph)
Primary	8239	27.56
Secondary	15 517	22.98
Tertiary	33 258	18.99
Trunk	10 698	42.61
Residential	80 491	13.01
Unclassified	184 852	16.77
Ocean	515	30
River	8995	25
Pedestrian Paths	141	3.6

Table 2
Accessibility levels considering travel time in minutes from the census tract's origin to the province's main town.

Accessibility	Criteria
Very High	Lower than 60 min
High	Between 60 and 120 min
Medium	Between 120 and 180 min
Medium-Low	Between 180 and 240 min
Low	More than 240 min
Isolated	More than 2 km from the origin to the road network
	No path from the origin to the province's main town.

Table 3
Speed affection considering flooding levels.

Category (cm)	Speed reduction
0	0 %
0–5	15 %
5–10	40 %
10–15	60 %
15–20	75 %
20–25	85 %
More than 25	The road is closed

Source: Adapted based on calculations from Pregnolato et al. (2016).

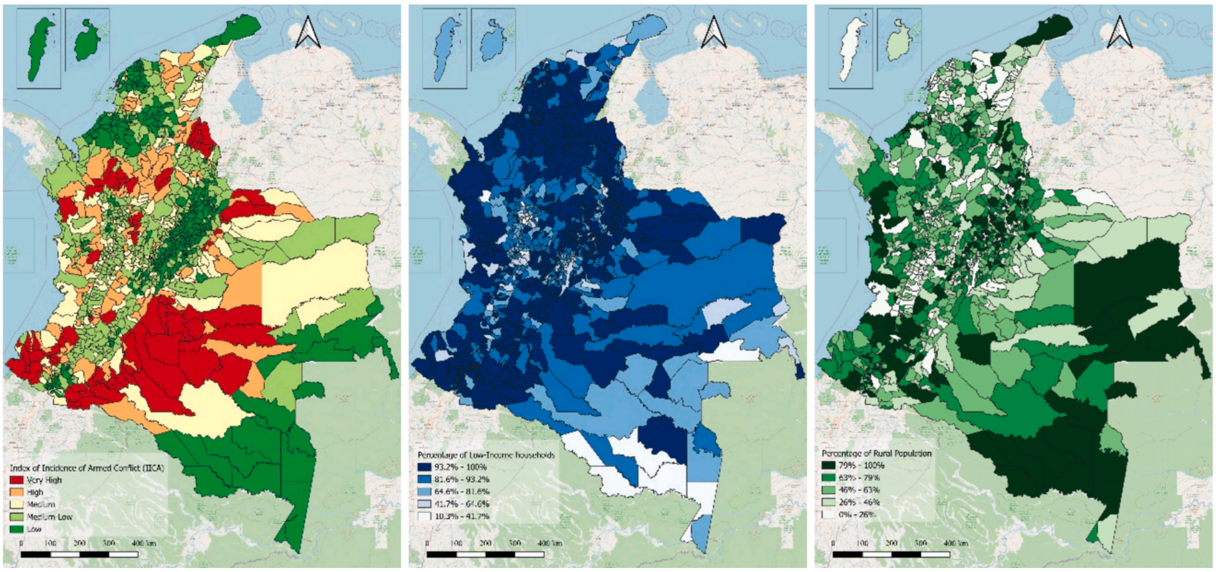

Fig. 1. IICA (left), Income level (Middle), and Rurality (Left) in Colombia.

conflict).

$$CI = \frac{2}{n^{*}\mu}\sum_{i=1}^{n} a_i{}^{*}R_i - 1 \tag{2}$$

The CI calculations consider the cumulative accessibility, which needs to be ordered from lowest to highest values. To do so, we calculate the potential accessibility (see Eq. (3) based on the travel times from census tracts to the province's main town (*TTi*) and a beta parameter of 0.01. This value was found to better explain the travel behaviour in regional areas in Colombia, where travel times are high (Escobar et al., 2020).

$$PA_i = e^{-0.01^{*}TT_i} \tag{3}$$

This article concentrated on rurality, armed conflict, and income to identify how group characteristics affect transport equity (see Fig. 1). Information on rurality and income was retrieved from the National Census at the Census tract level (DANE, 2018). The Census classified each sector as rural or urban. On the other hand, the household income level in Colombia is proxied through the socio-economic strata (SES), divided into six categories from 1 to 6 (Cantillo-García et al., 2019). It was developed to assign subsidies and resources to the people in the most need. Usually, SES 1 and 2 are considered low-income households, SES 3 and 4 medium-income households, and SES 5 and 6 high-income households. Finally, the incidence of armed conflict in the territory is defined through the Index of Incidence of Armed Conflict (IICA, for its acronym in Spanish) developed by the National Department of Development (DNP), considering six variables: armed actions, homicides, kidnapping, anti-personnel mines, forced displacement, and coca cultivation (DNP, 2016). IICA categorised municipalities into five categories: Low, Medium-Low, Medium, High, and Very-High. IICA was calculated in 2014, using data from 2002 to 2013. We calculated the CI for rurality, SES, and IICA, taking into account baseline scenarios and flooding and landslide events at different return periods.

3.5. Risk to the Population: Expected annualised population

We calculated the Expected Annualised Population (EAP), representing the yearly population affected by flooding and landslides based on event probabilities. Accessibility under baseline and natural hazard scenarios at different return periods were compared, considering population as affected when accessibility drops from very-high (< 60 min) (Espinet and Rozenberg, 2018). Equation (4) presents the formulation of EAD using a trapezoidal rule, where D_i is the population affected and T_i the return period of event i. The probability difference $\left(\frac{1}{T_i}-\frac{1}{T_{i+1}}\right)$ weights the average population affected between consecutive events

$$EAP = \frac{1}{2}\sum_{i=1}^{n}\left(\frac{1}{T_i}-\frac{1}{T_{i+1}}\right)^{*}(D_i + D_{i+1}) \tag{4}$$

3.6. Climate change effects

Climate change is expected to increase the probability and intensity of natural hazards such as flooding and landslides. We estimated the EAP affected by flooding and landslide events and taking into account climate change impacts by considering the future return periods for Colombia, centred on 2050 and 2075, and calculated by the World Bank Group (World Bank, 2021b). Representative concentration pathways (RCP) of 4.5 and 8.5 were used in this case. The EAP, including climate change effects, is calculated using Eq. (4) and the future return periods for 10, 20, 50, 75, and 100 years, considering the largest 1-day precipitation for Colombia (Table 4).

Then, we calculated the EPA considering rurality, SES, and IICA, taking into account flooding and landslide events and the broader impacts of climate change. To examine how the flooding and landslide events disproportionally affect different groups, we calculate an index based on the Palma Ratio, which compares the accessibility of the wealthiest group (top 10 % wealthiest) with that of the most vulnerable (bottom 40 %) (Guzman and Oviedo, 2018; Karner et al., 2024). In our research, we estimated the ratio considering the EAP (%); therefore, we compared the ratio between the most vulnerable and the wealthiest, considering an inverse formulation of the Palma Ratio. Similar to section 3.3, we consider rurality, income and armed conflict to estimate this index. In the case of rurality, rural areas are considered more vulnerable than urban ones. In the context of SES, the comparison is made between low and high-income groups. Finally, for IICA, the ratio compares regions with very high IICA as the most vulnerable with those with low IICA.

4. Results

Results are divided into four. First, the accessibility baseline scenario is presented. Second, the accessibility scenarios affected by flooding and landslide events are shown. Third, the effects of climate change are presented. Finally, equity indicators related to rurality, income level and armed conflict are discussed.

4.1. Colombian geographical accessibility: The first gaze

The baseline scenario shows that 77.87 % of the population (37.5 million) have high accessibility, i.e., they can reach a main town in 1 h or less. On the other hand, we found that 52,606 (0.11 %) inhabitants are isolated, i.e., they cannot find a route from their census tracts to the province's main town. The results vary depending on the country's geography; Fig. 2 presents the population per

Table 4
Future return periods considering the Largest 1-day Precipitation for Colombia. Source: Adapted from https://climateknowledgeportal.worldbank.org/country/colombia/extremes.

Scenario	RCP	10-yr	20-yr	50-yr	75-yr*	100-yr
2050	SSP2-4.5	6.88	13.04	30.4	43.96	57.52
(2035–2064)	SSP5-8.5	6.58	5.88	28.03	40.31	52.56
2075	SSP2-4.5	5.58	10.26	22.98	32.475	41.97
(2060–2089)	SSP5-8.5	4.78	8.45	17.94	24.88	31.82

*The 75-yr return period was interpolated between 50-yr and 100-yr return periods.

department experiencing accessibility higher than 60 min or Isolation. The highest values correspond to peripheral areas near the Pacific coast (Chocó with 53.21 %, Putumayo with 52.02 %) and the Orinoco region (Vichada with 73.07 %). On the other hand, the Andean region, in the centre of the country, presents the highest accessibility. For instance, the coffee region traditionally represented by the departments of Caldas, Risaralda, and Quindío exhibits percentages of the population with high accessibility of 83.48 %, 88.17 %, and 95.79 %, respectively. These can be related to their size, considering that they are among the departments with the lowest area. In addition, the capital city, Bogotá, with more than 7 million inhabitants, presents 99.99 % of people with high accessibility, representing the high connectivity of urban areas in the country.

Some variables can exacerbate the accessibility inequity. This article concentrated on rurality, income, and armed conflict. Colombia has 5.2 million people living in rural areas; Fig. 3 shows the large difference in accessibility between rural and urban areas. Remarkably, 92.39 % of the urban population presents very high (less than 60 min) or high (between 60 and 120 min) accessibility compared to 63.6 % in the rural areas. On the other hand, the socioeconomic strata (SES) of the house was used as a proxy of the income level. Table 5 shows the baseline scenario results exhibiting deep inequalities, e.g., 27.07 % and 13.32 % of households in SES 1 and 2 present accessibility higher than 60 min (high to low), compared to 4.45 % of the households in SES3, 1.25 % in SES4 and less than 1 % in the high-income levels (SES 5 and 6). In addition, the largest portion of isolated households (89.55 %) are low-income households (SES1).

Table 6 presents the accessibility considering armed conflict, showing that the population with very high or high IICA experienced higher travel times and therefore, lower accessibility with 63.34 % and 56.01 %, respectively. Interestingly, municipalities with medium–low and low IICA represent 75.28 % of the isolated populations, which could be related to their low connectivity, diminishing the presence of illegal army groups.

Table 7 shows the concentration index of accessibility considering rurality, income and armed conflict. The CI works as a measure of transport equity in the Colombian territory based on travel times to the provincial main towns. The results evidence the transportation inequity towards the most vulnerable groups: rural, low-income, and highly affected populations by armed conflict. Besides, the most critical CI is for rurality, considering a value of 0.798; therefore, the highest accessibility values are disproportionately concentrated in urban areas.

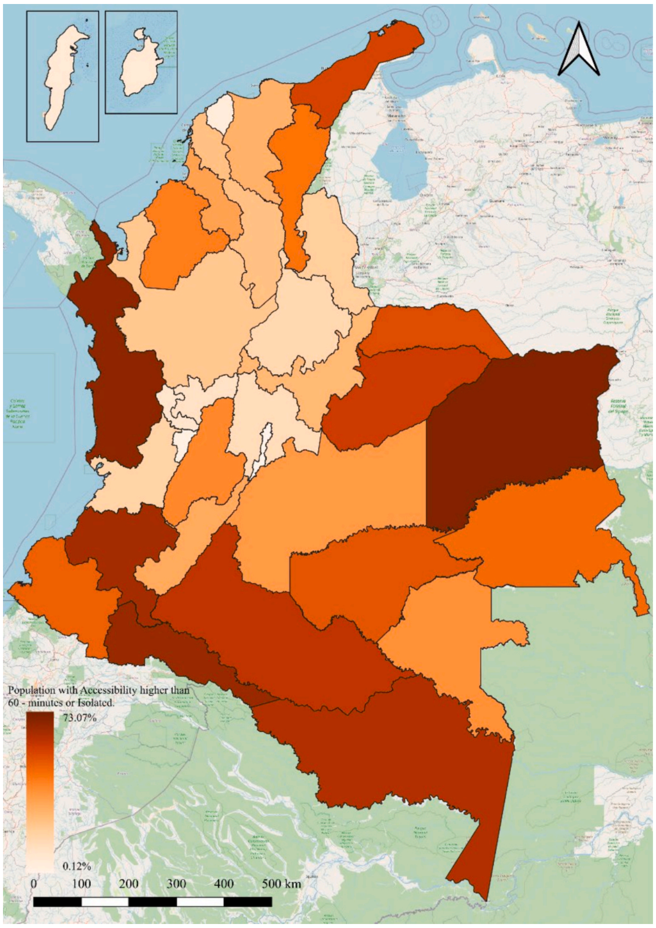

Fig. 2. Percentage of people who experienced Accessibility higher than 60 min or Isolation per department in the baseline scenario.

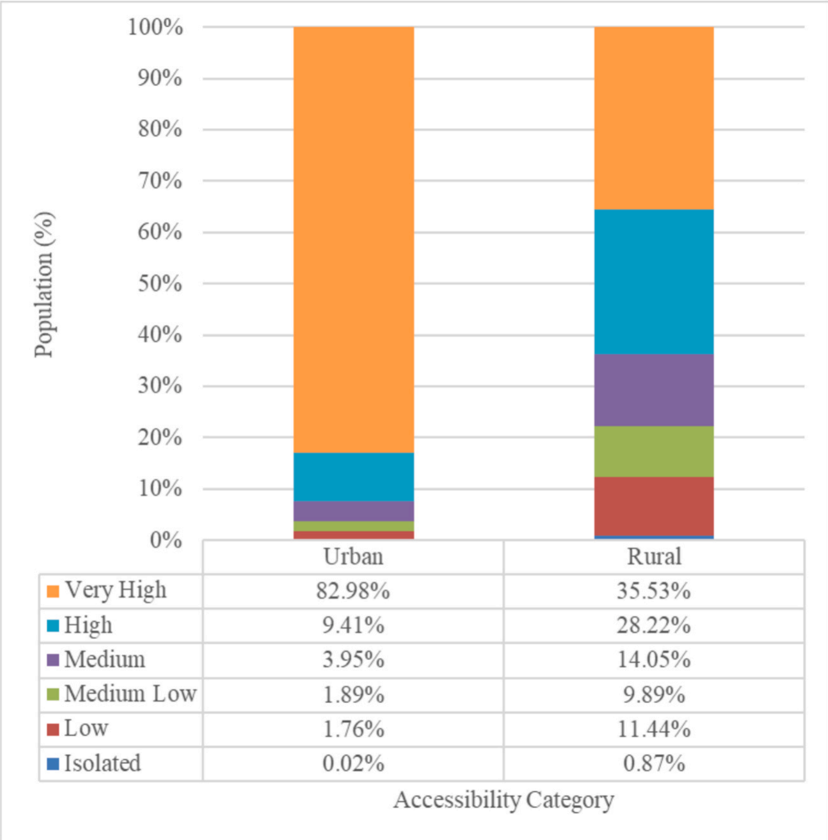

Fig. 3. Accessibility results considering rurality in the baseline scenario.

Table 5
Accessibility in the baseline scenario, considering socioeconomic strata.

Income	Very High	High	Medium	Medium Low	Low	Isolated
SES 1	2539500(72.83 %)	477271(13.69 %)	244099(7 %)	121554(3.49 %)	101015(2.9 %)	3566(0.1023 %)
SES 2	3403632(86.68 %)	342567(8.72 %)	94557(2.41 %)	54991(1.4 %)	31018(0.79 %)	34(0.0009 %)
SES 3	2496426(95.55 %)	83331(3.19 %)	16969(0.65 %)	9902(0.38 %)	6069(0.23 %)	13(0.0005 %)
SES 4	757413(98.75 %)	8575(1.12 %)	506(0.07 %)	392(0.05 %)	128(0.02 %)	1(0.0001 %)
SES 5	293439(99.54 %)	1155(0.39 %)	106(0.04 %)	46(0.02 %)	35(0.01 %)	0(0 %)
SES 6	159840(99.85 %)	156(0.1 %)	46(0.03 %)	24(0.01 %)	17(0.01 %)	0(0 %)
Unclassified	56073(67.35 %)	12058(14.48 %)	6746(8.1 %)	4030(4.84 %)	3982(4.78 %)	368(0.442 %)

Table 6
Accessibility in the baseline scenario, considering armed conflict.

Armed Conflict	Very High	High	Medium	Medium Low	Low	Isolated
Very High	668744(36.35 %)	270083(14.68 %)	334272(18.17 %)	171769(9.34 %)	389191(21.15 %)	5774(0.31 %)
High	1017733(43.89 %)	503361(21.71 %)	381825(16.47 %)	232092(10.01 %)	181427(7.82 %)	2437(0.11 %)
Medium	3008946(65.51 %)	877791(19.11 %)	353903(7.71 %)	131415(2.86 %)	216008(4.7 %)	4793(0.1 %)
Medium Low	16088351(78.58 %)	2633947(12.87 %)	817935(4 %)	574281(2.81 %)	339578(1.66 %)	19264(0.09 %)
Low	16793634(88.23 %)	1232667(6.48 %)	542400(2.85 %)	218042(1.15 %)	225849(1.19 %)	20338(0.11 %)

Table 7
Concentration Index for accessibility, considering rurality, income and armed conflict.

Indicator	Rurality	Income	Armed Conflict
CI	0.798	0.467	0.256

4.2. The impact of flooding and landslides on geographical accessibility

The effects on accessibility of flooding and landslide events across different return periods are shown in Fig. 4. Results show a similar impact on high accessibility, considering that 7.16 % and 7.08 % of the population reduced their accessibility because of flooding and landslides in the 100-year return period scenario. This represents an average increase of 32 % in the population with travel times higher than 1 h. Besides, there was no increase in the number of isolated populations. Nevertheless, there are differences in how flooding and landslides impact the population across return periods. Since floods constantly increase through the return periods, with more people having accessibility higher than 60 min, the pattern of landslides is different. The effects of landslides in the 50-year return period are crucial because they affect 13.57 % of the Colombian territory, reducing the accessibility of nearly 4 million people compared to the baseline. Those results exhibit the high vulnerability of the transport network due to climate events, mainly because of landslides, which seem to have a higher impact because many of the population live in the Andes Mountains; consequently, they are more vulnerable to those events.

The impact of flooding and landslide events will be distributed considering their probability of occurrence. Fig. 5 presents

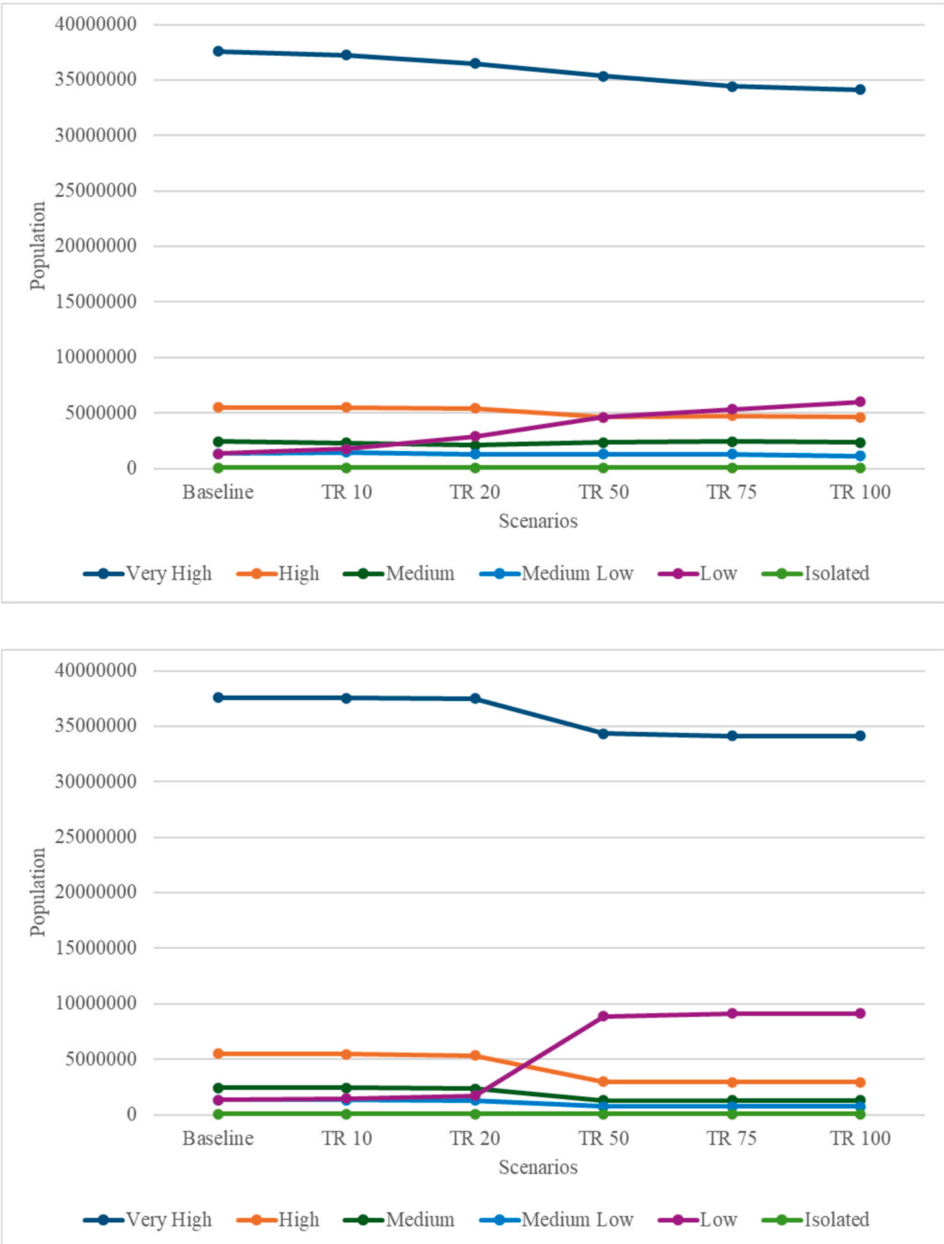

Fig. 4. Population per accessibility category across different return periods considering the impact of flooding (top) and landslide (bottom) events.

Colombia's expected annualised population (EPA) affected by flooding and landslide events, reaching 131,130 and 102,787 inhabitants on average. These values represent the people who reduce their accessibility because of natural hazards, considering a travel time of 60 min as a cut-off. Those values have considerably increased because of climate change. For instance, climate change will increase the EAP by 53.5 % by 2050 and 105.2 % by 2075. The effects of climate change on landslides are similar to those of flooding.

4.3. The effects of natural hazards on accessibility considering rurality, income and armed conflict

Results of the Expected Annual Population affected (EAP) by flooding and landslide events considering rurality, income and armed conflict are presented in Tables 8, 9 and 10. Besides, we present the inverse Palma Ratio, considering the division between the EAP for the most vulnerable populations against the wealthiest. Firstly, a higher percentage of the rural population will be reduced in their accessibility due to flooding or landslide events than urban populations, considering an inverse Palma Ratio of 2.88 and 2.13 for the baseline scenarios of flooding and landslides. Interestingly, flooding (0.65 % in the baseline) tends to disproportionately affect more rural populations than landslides (0.40 % in the baseline).

Table 9 shows the imbalanced impact of flooding and landslide events on accessibility for low-income households (SES 1 and 2) compared to the high-income households (SES 5 and 6). For instance, in the flooding baseline scenario, the EAP for SES 1 and 2 reaches 0.26 % and 0.27 % of the total households, respectively, compared to just 0.04 % and 0.02 % of households in SES 5 and 6. In addition, climate change exacerbates the effects by increasing the EAP, e.g., it doubled the values for the scenario centred in 2075 (2060–2089). Regarding the landslide events, there are similar trends to flooding, with slight changes in the percentages and the inverse Palma Ratio index, which is doubled in the flooding scenarios.

Three remarkable analyses emerge from income and natural hazard impacts. First, the inverse Palma Ratio is much higher than one for both types of natural hazards, indicating a disproportionate impact on low-income households compared to high-income. This trend is similar to rurality, where the vulnerable group is more affected. Second, the index of flooding (8.95 in the baseline) is higher than the landslide value (3.26 in the baseline), suggesting smaller disparities in the effect of this natural hazard between low and high-income households. Third, while landslides tend to affect wealthier groups more than flooding, the index remains greater than one, indicating that low-income households are still disproportionately affected.

Table 10 presents the results of EAP affected by flooding and landslide events, considering the impact of IICA and climate change on accessibility. This shows that most of the territory affected by flooding is located in areas with low or medium–low IICA values. Furthermore, there is a higher percentage of the affected population by floods in the medium–low category (0.32 %) and by landslides in the medium category (0.31 %). In both cases, there is a considerable increase in the EFA because of climate change, with those scenarios centred on 2050 and 2075. Furthermore, the inverse Palma Ratio index is lower than one; therefore, a higher proportion of the population with a low incidence of armed conflict is more impacted by flooding and landslide events than those highly affected (very-high category of IICA). In addition, the index is higher for flooding (0.73 in the baseline) than for landslide events (0.30 in the baseline); therefore, the disparities in the EAP are higher in the landslide events, favouring municipalities with a very high incidence of armed conflict.

5. Discussion

This study found that 22.13 % of the population experiences low levels of accessibility or isolation in the baseline scenario, i.e., they take more than 1 h of travel to reach a main town. Considering that accessibility to services is essential for social and economic development, there is a clear opportunity to improve the connectivity of those communities through infrastructure proactively adapted to natural hazards and climate change events (Schweikert et al., 2014). Low accessibility levels increase with landslides and flood disruptions, spatially concentrated in the country. For instance, in the baseline scenario, the regions most affected are located in the country's peripheries. In contrast, areas with the highest connectivity are located near the Andes mountains, in the country's centre, which will be more affected by landslides. This generates two main actions in terms of accessibility and climate change adaptation. The first one considers the baseline accessibility results, prioritising the investment in areas with current challenges in terms of regional connectivity. The second one considers the regions more affected by the floods and landslides. This case focused on areas with good road infrastructure development where adaptations must be conducted. In both cases, proactive, adaptive measures are crucial to decrease the long-term costs of climate impacts and the raised of transportation equity throught the country and communities.

Our results underscore the compounded effects of rurality, income, and armed conflict on the accessibility and the impacts of natural hazards and climate change, disproportionately affecting socially vulnerable communities. This aligns with studies about rural accessibility and climate change in the Global South, including Africa (Akudugu et al., 2012; Espinet Alegre et al., 2020; Espinet and Rozenberg, 2018; Rentschler et al., 2019), Asia (Ahmed and Eklund, 2019), and Latin America (Barrucand et al., 2017; Chamorro et al., 2020). Moreover, our findings reinforce evidence of the impact of armed conflict on road infrastructure development in Colombia, previously explored in the departments of Caldas and Nariño (Escobar García et al., 2023).

The Concentration Index (CI) considering rurality, income, and armed conflict shows that accessibility disproportionately favoured more urban towns, highly income households and less affected municipalities by armed conflict. The CI is a measure that helps to calculate the distribution of accessibility through different groups, allowing better insights compared to indexes like the Gini Index (Karner et al., 2024). Besides, we used an index inspired by the Palma Ratio to measure how much the vulnerable populations are more affected by natural hazards than the more wealthy groups. Rural communities and low-income households will experience reduced accessibility more due to natural hazards, with floods having a higher effect than landslides. The areas more susceptible to landslides are the Andes region, the most socially, infrastructurally, and economically developed country. Therefore, there is a higher probability

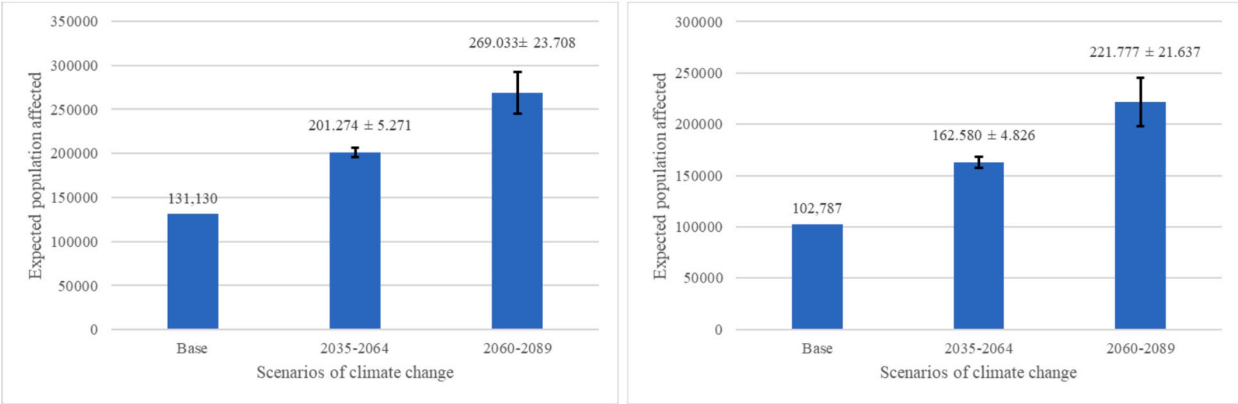

Fig. 5. Expected annual population affected by flooding (left) and landslides (right) events in the baseline and climate change scenarios.

Table 8
Expected annualised population affected by flooding and landslides events considering rurality.

Rurality	Flooding			Landslides		
	Baseline	2035–2064	2060–2099	Baseline	2035–2064	2060–2099
Urban	97,308 (0.23 %)	146066–154105 (0.35 %)	183262–219408 (0.47 %)	81,801 (0.19 %)	125537–133216 (0.30 %)	159262–193686 (0.41 %)
Rural	33,822 (0.65 %)	49937–52441 (0.98 %)	62064–73334 (1.30 %)	20,987 (0.40 %)	32217–34190 (0.64 %)	40878–49727 (0.87 %)
Index	2.88	2.83	2.79	2.13	2.13	2.13

Table 9
Expected annualised households affected by flooding and landslide events considering socioeconomic strata.

SES	Flooding			Landslides		
	Baseline	2035–2064	2060–2089	Baseline	2035–2064	2060–2089
1	10,709 (0.26 %)	15962—16808 (0.39 %)	19946—23748 (0.53 %)	6624 (0.16 %)	10,139 – 10,753 (0.25 %)	12,847 – 15,599 (0.34 %)
2	12,767 (0.27 %)	19219—20293 (0.42 %)	24,151 – 28,977 (0.57 %)	11,914 (0.26 %)	18,305 – 19,430 (0.40 %)	23,236 – 28,279 (0.55 %)
3	5697 (0.18 %)	8648—9152 (0.29 %)	10,917 – 13,180 (0.39 %)	5428 (0.17 %)	8339 – 8851 (0.28 %)	10,584 – 12,879 (0.38 %)
4	504 (0.06 %)	786—838 (0.09 %)	1009—1243 (0.12 %)	914 (0.10 %)	1405 – 1491 (0.16 %)	1784 – 2171 (0.22 %)
5	131 (0.04 %)	206—220 (0.06 %)	265—327 (0.08 %)	180 (0.05 %)	277—294 (0.08 %)	352—429 (0.11 %)
6	30 (0.02 %)	47—50 (0.03 %)	61—76 (0.04 %)	126 (0.07 %)	193—205 (0.10 %)	246 – 299 (0.14 %)
Undetermined	308 (0.31 %)	458—482 (0.47 %)	571 – 679 (0.63 %)	223 (0.23 %)	343—364 (0.36 %)	435 – 530 (0.49 %)
Index	8.95	8.48	8.15	3.26	3.71	3.70

Table 10
Expected annualised population affected by flooding and landslide events considering socioeconomic strata. Percentages are calculated considering their category.

IICA	Flooding			Landslides		
	Base	2035–2064	2070–2099	Base	2035–2064	2070–2099
Very High	3541 (0.19 %)	5408—5287 (0.29 %)	6378—7466 (0.38 %)	1078 (0.06 %)	1656—1758 (0.09 %)	2103—2559 (0.16 %)
High	4116 (0.18 %)	6115—6433 (0.27 %)	7628—9059 (0.36 %)	4175 (0.18 %)	6587—7046 (0.29 %)	8489—10546 (0.41 %)
Medium	8975 (0.20 %)	13711—14538 (0.31 %)	17374—21091 (0.42 %)	13,998 (0.31 %)	21434—22609 (0.48 %)	26984—29822 (0.65 %)
Medium-Low	65,366 (0.32 %)	97680—102924 (0.49 %)	122230—145812 (0.65 %)	45,634 (0.22 %)	69923—74166 (0.35 %)	88626—107650 (0.48 %)
Low	49,132 (0.26 %)	73332—77244 (0.40 %)	91715—109315 (0.53 %)	37,903 (0.20 %)	58245—61828 (0.32 %)	73938—89998 (0.43 %)
NHAEI	0.73	0.73	0.72	0.30	0.28	0.37

for wealthier communities to be impacted there, reducing this ratio. Interestingly, the index for armed conflict results in the opposite direction, meaning municipalities less impacted by armed conflict will have higher impacts because of the flooding and landslide events. This highlights the deep inequalities that produce armed conflict and their lower road infrastructure development among areas with a high incidence of armed conflict (Cardona et al., 2021; Escobar García et al., 2023, 2022).

6. Conclusions

This article is the first approach to calculating geographical accessibility and transport equity in Colombia at the country's level, integrating Census and crowdsourced data. By using a GIS transport network, detailed travel times from census tracts to the province's main town were estimated. Furthermore, the effects of floods and landslides on accessibility levels were identified, allowing the identification of the communities and areas of the country most affected by those natural hazards. The main findings are related to baseline accessibility, where nearly 10 million people are experiencing low accessibility levels, i.e., they take more than 1 h to reach a main municipality. Natural hazard impacts are concentrated in areas with better road infrastructure connectivity, historically located in wealthier areas of the country. The Colombian government can develop the country's connectivity by investing in an infrastructure adapted to climate change among communities in the most need: rural areas, low-income, and those affected by armed conflict.

Using census tracts as the base for accessibility calculations gave a good resolution level since the Census contains insightful information that could be useful to create indicators to evaluate public policy. Similarly, the OpenStreetMap transport network is an excellent approach in areas with scarce data, like rural communities. However, their information needs to be curated and complemented by other sources. In this case, using official information from the government and satellite images helps improve it. Future research should focus on regions like the Pacific, Orinoco, and Amazonas, where data gathering was challenging and baseline accessibility is low because of limited road infrastructure development. In addition, the intersectionality theoretical framework promises to understand deep transport inequalities among vulnerable communities, focusing on indigenous communities and ethnic minorities.

Finally, the study identifies nearly 52 thousand isolated inhabitants, highlighting the importance of developing focused transport solutions for these communities. Isolated populations should be analysed in future studies to understand why they are disconnected from road infrastructure to other areas in the country. Detailed spatial methodologies may be used, e.g., dasymmetric mapping with high-resolution satellite images is promising to identify isolated populations from transportation networks. On the other hand, numerous communities can be reached only by water networks, maritime or fluvial. The government should understand how transport works for those communities and develop terrain connections to other municipalities in the country. For this scenario, community involvement is essential to understand the necessities regarding accessibility and climate change adaptation.

CRediT authorship contribution statement

Santiago Cardona-Urrea: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Juan Manuel Gómez:** Methodology, Formal analysis, Data curation. **Ellin Ivarson:** Validation, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Xavier Espinet-Alegre:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2025.105079.

Data availability

Data will be made available on request.

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