



Application of Weighted Overlay Techniques for the Identification of Areas Threatened by Expansive Soil Formation

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Abstract

This study proposes a methodology to assess the threat of expansive soil formation in Bucaramanga, Colombia, based on three main criteria: geotechnical properties, infiltrated precipitation (I), and temperature. The geotechnical criterion is determined using the Unified Soil Classification System (USCS) and Atterberg limits to assess plasticity and fines content. Infiltrated precipitation (I) is calculated using average monthly rainfall over the past ten years and an infiltration coefficient (C) that includes vegetation cover (kv), slope (kp), and soil texture (kfc). Temperature is considered for its impact on clay formation and adjusted for altitude. 101 soil samples were collected and analyzed, with climatic data from 2012 to 2022 also considered. Geographic Information Systems (GIS) were used to apply interpolation methods (IDW and kriging) to generate thematic maps and identify risk zones. By integrating these key factors, this methodology improves the accuracy of assessing the threat of expansive soil formation, providing a more reliable tool than traditional models. It is adaptable to other regions with similar conditions, offering valuable insights for predicting expansive soils in urban settings. The study highlights how temperature, soil properties, and precipitation infiltration influence risk, making this approach an effective tool for urban planning and risk mitigation, ultimately supporting better land management practices.

Keywords Expansive soils · GIS · Multicriteria decision analysis · Environmental factors

Introduction

Expansive soils contain clay minerals, such as montmorillonite, capable of retaining high amounts of water, which causes them to experience considerable variations in their

volume as their moisture content changes. A part of the territory in Colombia is composed of residual soils that are formed through the weathering of soils of sedimentary origin, which results in the formation of clay soils (Cantillo et al., 2017; Meza, 2012; Ochoa et al., 2021). The analysis of expansive soils is crucial due to the economic losses resulting from damage caused by differential settlement in light structures and infrastructure (Arancibia Galleguillos & Collarte Concha, 2003; Dam Nguyen et al., 2022).

Numerous investigations have focused on detecting the presence of expansive soils (Labib & Nashed, 2013; Li et al., 2023a, 2023b; Sakr et al., 2021; Costantino et al., 2016), but the understanding of the process of their formation is still scarce. Research has studied the chemical composition, mineralogical composition, and reactions involved in swelling mechanisms, such as electrical repulsion of clay particles, osmotic repulsion, and cation hydration (Chang et al., 2022; Henry & Igwe, 2016; Prakash et al., 2009). Other research has studied mechanical properties through tests to evaluate expansion strength, volumetric changes, and correlations with geotechnical parameters (González Rufino & Chávez Alegría, 2021; Huang & Azam, 2020; Z. Li et al., 2023a,

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2023b; Costantino et al., 2016; Yangping et al., 2023). However, the analysis of environmental factors in the formation of expansive soils, as predominant agents in their presence and conformation within a region, has been scarcely investigated. Climatic variables such as precipitation and temperature generate chemical reactions that decompose the parent rock, forming, in some cases, clayey soils (Dam Nguyen et al., 2022; Gracia Romero & Suarez Barrios, 2014; Lew, 2010).

The present research focused on the development of a simple and practical methodology to determine the threat to expansive soil formation from field samples, correlations of geotechnical parameters, meteorological data, and satellite images. This study provides three key aspects: first, it evaluates the threat of expansive soil formation by considering criteria such as precipitation, temperature, vegetation, slopes, and soil texture. Second, integrating this methodology with GIS makes it possible to evaluate large terrains. As a third aspect, it analyzes the variability of the subcriteria with a 504-point mesh using box plots and seven control points.

The article is organized into four sections, as described below: The following section describes the study area along with the characteristics of the data collected. This is followed by the section detailing the entire methodological design process, including the criteria evaluated, their characteristics, and their subsequent processing. Then, the results obtained are presented and discussed. Finally, the last section presents the study's main conclusions, including the research's strongest points.

Study Area

Bucaramanga, Santander, Colombia, is located at 959 m.a.s.l., with an average temperature of 23 °C and an area of 162 km² (Alcaldía Municipal de Bucaramanga, 2013). Figure 1 shows the location of the study area and the 101 soil samples collected in the urban area.

Monthly pluviometric data (2012–2022) were collected from 10 meteorological stations near the study area, managed by IDEAM. Figure 2 shows the multiannual average precipitation. Annual levels ranged from 700 to 1900 mm,

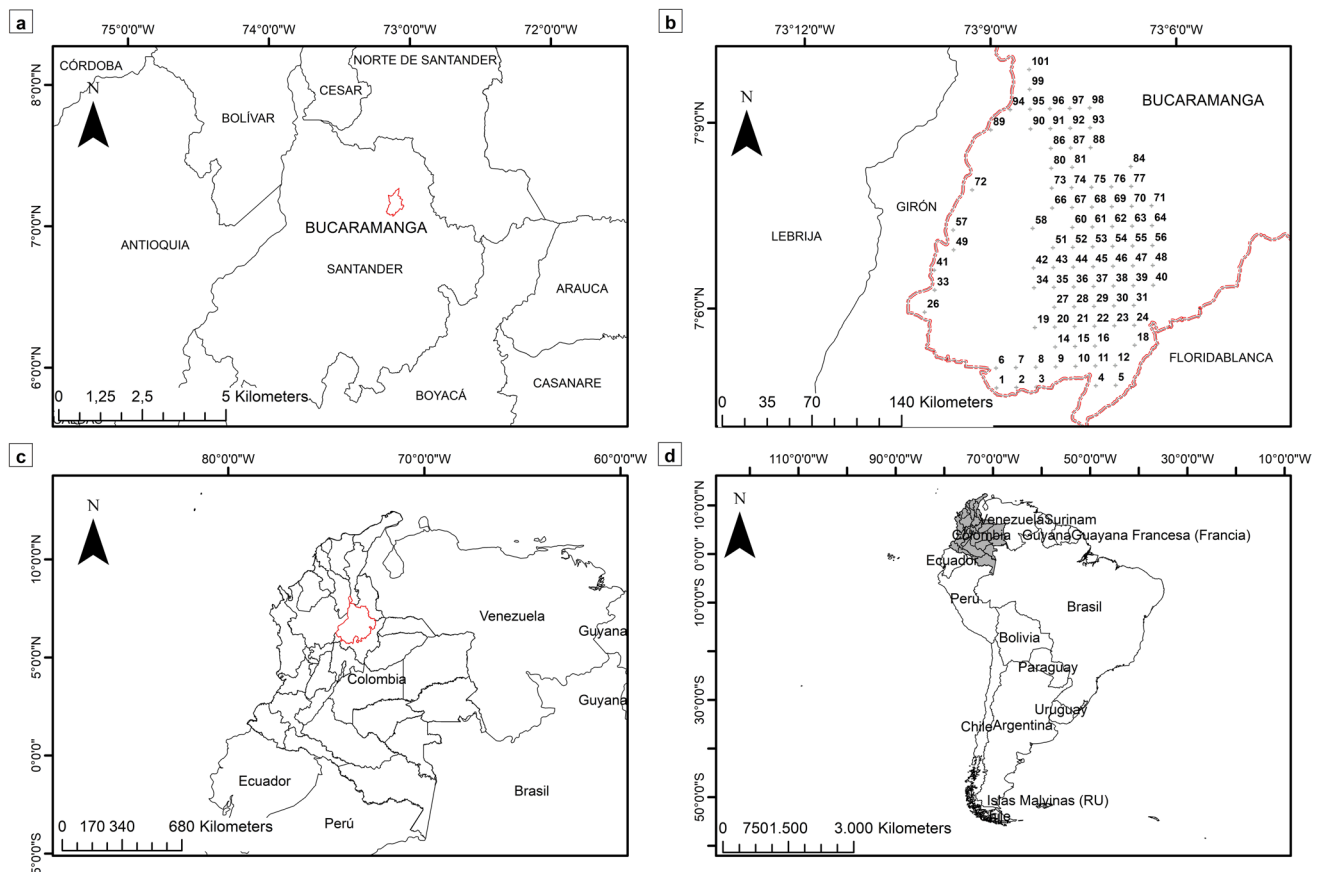
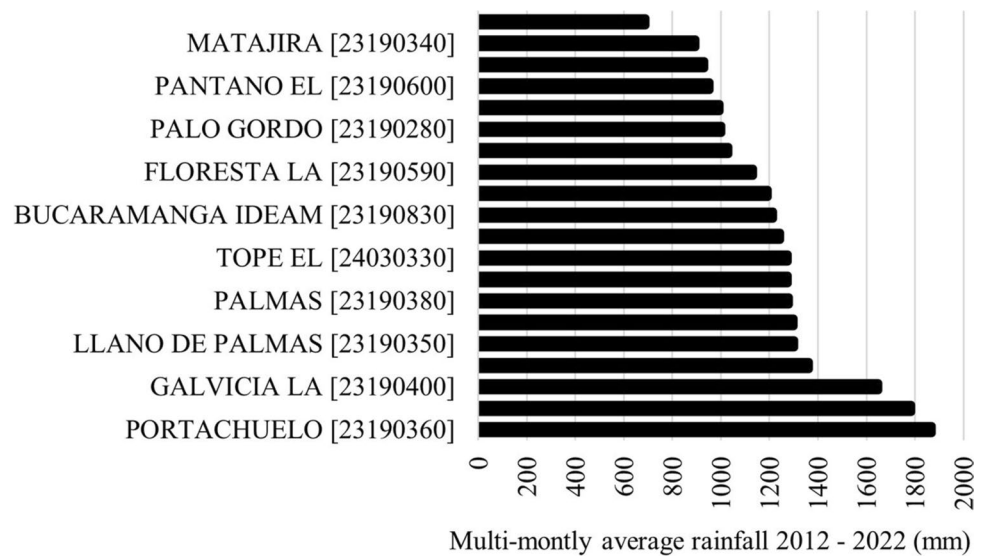


Fig. 1 Location of Bucaramanga city, Santander. **a** Department of Santander, **b** Bucaramanga city, **c** Colombia Country, **d** South America Continent

Fig. 2 Multi-monthly average rainfall from 2012 to 2022 (mm) – adapted (IDEAM, 2022)



coinciding with records from the municipal development plan (Fernando et al., 2020).

The information collected from the study area provided a detailed visualization of land cover, revealing the spatial distribution ranging from natural vegetation to buildings (Rodríguez et al., 2021). Particularly on the eastern slopes, the disorganized replacement of vegetation cover by buildings and crops increases the risk of erosion and landslides (Fernando et al., 2020). Despite these challenges, the city retains extensive areas of forests, grasslands, and parks. According to the Bucaramanga Municipal Mayor's Office (2013), the city is divided into 17 communes, 219 neighborhoods, 36 urban settlements, 29 villages, and 15 rural settlements. In the metropolitan area, 74 parks cover a total of 1000 m².

The city has a rugged topography in a valley surrounded by mountains of the Eastern Andes. Its center is flat, with

slopes between 1 and 5%, while the outlying areas can have slopes of up to 20%. In addition, the presence of streams and rivers influences urban planning and infrastructure (Servicio Geológico Colombiano, 2012).

Data Collection

The study used spatial datasets from different sources to represent topography, land cover, and temperature. Regarding rainfall data, 10 pluviometry stations from the IDEAM (Instituto de Hidrología, Meteorología y Estudios Ambientales), which cover the study area with information from 2012 to 2022, were used to analyze the updated rainfall trend. The compilation of all datasets and data collected is presented in Table 1. On the other hand, for soil classification data, 101 samples were taken in the field (Fig. 1.) from the top 30 cm of the soil profile; the collected samples were

Table 1 Spatial datasets used for the methodology

Datasets/ data collection	Data source
DEM*	ALOS PALSAR 12.5 m DEM* https://search.asf.alaska.edu/#
Rainfall data	Consultation and downloading of hydro-meteorological data http://dhime.ideam.gov.co/atencionciudadano/ A product of IDEAM**
Land use / land cover	Map of land cover. adaptation corine land cover for Colombia republic. https://www.colombiaenmapas.gov.co/?u=76377&t=32&servicio=880
Mean temperature	A product of IDEAM** TerraClimate: monthly climate and climatic water balance for global terrestrial surfaces, University of Idaho https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_TERRACLIMATE A product of GEE*** and the University of California Merced

*DEM, Digital elevation model; **IDEAM, Instituto de Hidrología, Meteorología y Estudios Ambientales;

***GEE, google earth engine

subjected to the following tests: moisture content, particle size determination using granulometry, liquid limit, and plastic limit.

Methodology

Research on expansive soils has advanced significantly in recent years, establishing solid foundations for their characterization. Musso (2014) highlighted the importance of Atterberg limits and montmorillonite as a key mineral in the expansion of these soils, providing a fundamental framework for their evaluation. Subsequently, Asuri and Keshavamurthy (2016) and Prakash et al. (2009) delved into the relationships between plasticity index, soil activity, and cation exchange capacity, essential elements for analyzing the expansive behavior of soils. In the same year, Tahasildar et al. (2017) highlighted the relationship between montmorillonite content and swelling pressure, emphasizing the need to quantify mineralogy to assess expansive behavior accurately.

In recent years, the use of advanced technologies and multidisciplinary approaches has improved the assessment of risks associated with expansive soils. Ahmed et al. (2020) employed GIS tools and spatial interpolation techniques, such as Kriging, to model the variability of soil properties in Sulaimani, Iraq. However, most of these investigations have focused their efforts on the expansion of already formed soils, leaving a significant gap in the specific conditions that favor the initial formation of expansive soils.

Although some studies have considered factors such as precipitation, temperature, and index properties, these have been used primarily to evaluate the expansion of existing soils. Comprehensive approaches from a practical perspective that determine the conditions necessary for the formation of expansive soils, especially in local and urban contexts, have not been developed. This research addresses this gap by integrating climatic and geotechnical data using multi-criteria analysis and tools such as GIS. By identifying the conditions that favor the formation of expansive soils, this study contributes significantly to

territorial planning and geotechnical risk mitigation in vulnerable urban areas.

The study used spatial datasets from different sources to represent topography, land cover, and temperature. Regarding rainfall data, 10 pluviometry stations from the IDEAM (Instituto de Hidrología, Meteorología y Estudios Ambientales), which cover the study area with information from 2012 to 2022, were used to analyze the updated rainfall trend. The compilation of all datasets and data collected is presented in Table 1. On the other hand, for soil classification data, 101 samples were taken in the field (Fig. 1.), and the collected samples were subjected to the following tests: moisture content, particle size determination using granulometry, liquid limit, and plastic limit. The importance of identifying expansive soils is highlighted in the scientific field, but there is little attention to their formation (Asuri & Keshavamurthy, 2016). This study aims to develop a method that evaluates the possibility of expansive soils, considering the type of soil, land cover, temperature, and rainfall as the assessment factors.

In the initial phase of the multi-criteria analysis by superpounding, the foundations for the evaluation were established by identifying key criteria and sub-criteria, as seen in Fig. 3. In the geotechnical criterion, the classification of soils based on particle size, liquid limit, and plasticity index was considered. On the other hand, the rainfall infiltration criterion was calculated by combining the subcriteria of soils (K_{fc}), land cover (K_v), and slope (K_p). Furthermore, temperature was considered an additional criterion, considering the correlations documented in the literature on the relationship between the formation of expansive soils and the temperature gradient. Subsequently, a threat scale was designed based on the correlations collected by the authors. From this scale, the weighted overlay tool was applied to the GIS platform using three main criteria: geotechnics, precipitation, and temperature. As a result, a map was generated that identifies areas with different levels of threat to the formation of expansive soils.

Fig. 3 Methodology for evaluating the threat of expansive soil formation

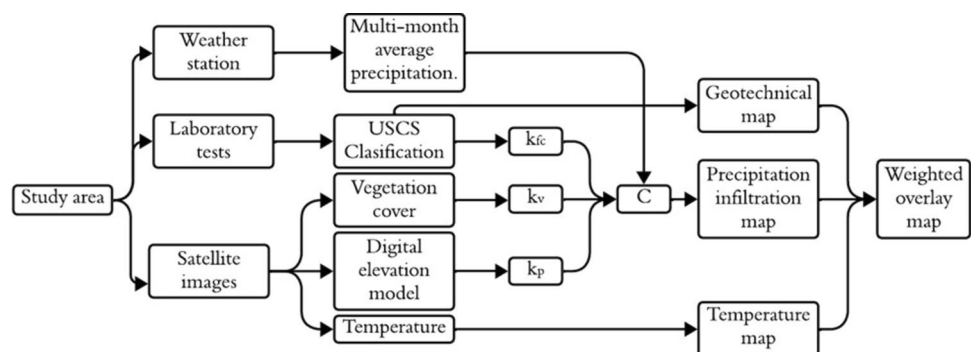


Table 2 Correlations between Atterberg limits and expansion potential in soils

Expansion potential	Liquid limit			Plasticity index			Limit of contraction	
	(Chen, 1956)	(Snethen et al., 1977)	(IS, 1498, 1970)	(Chen, 1988)	(IS, 1498, 1970)	(Holtz & Gibbs, 1956)	(Holtz & Gibbs, 1956)	(Chen, 1988)
Low	< 30	< 50	20–35	0–15	< 12	< 18	> 15	> 12
Medium	30–40	50–60	35–50	10–35	12–23	15–28	7–12	10–12
High	40–60	> 60	50–70	20–35	23–32	25–32	12–16	< 12
Very high	> 60	–	70–90	> 35	> 32	> 32	< 16	–

Table 3 Correlations between activity, percentage of fine particles, and soil expansion potential

Expansion potential	Activity (Asuri & Keshavamurthy, 2016)	Weight % of fine particles		% of edometer expansion		
		(Chen, 1956)	(Chen, 1956)	(H. B. Seed et al., 1962)	(Chen, 1988)	
Low	< 0,75	< 30	< 10	0–1,5	0–15	
Medium	0,75–1,25	30–60	10–20	1,5–5	10–35	
High	> 1,25	60–95	20–30	5–25	20–35	
Very high	–	> 95	> 30	> 25	> 35	

Geotechnical

Clay soils, such as bentonite, kaolinite, illite, and montmorillonite, are characterized by their high expansivity. Over time, empirical correlations have been developed to evaluate this property using indirect methods based on Atterberg limits (Sridharan & Prakash, 1998). A higher clay content and a high plasticity index are associated with a higher expansion potential. Considering the above, Table 2 presents a summary of empirical correlations reported by various authors, along with the corresponding potential level of expansion (IS, 1498, 1970).

Expansive soils, with high activity related to the electrical charge of clay particles, can exchange cations with water and other ions in solution (Asuri & Keshavamurthy, 2016). Clay activity, fine particle content, and plasticity index are closely linked to the ability to retain water and change from solid to plastic state, increasing the soil's swelling potential and plasticity index (Labib & Nashed, 2013), as seen in Table 3.

According to the correlations described above, levels of threat to expansive soil formation were defined by geotechnical criteria on a scale from low to high, as shown in Table 4. To evaluate the level of threat of formation of expansive soils according to geotechnical criteria, the 101 soil samples collected in the urban area of Bucaramanga were analyzed (Fig. 1). The soils were classified according to the USCS, and the Atterberg limits were determined. A table showing each type of soil identified according to the USCS classification and its respective nomenclature is presented in Online Appendix 1. The georeferencing

Table 4 Scale of threat to expansive soil formation by geotechnical

Liquid limit	Plastic limit	Plasticity index	Weight % of fine particles	Threat
0 – 30	0 – 20	0–15	0–30	Low
30 – 40	20 – 30	15–20	30–50	Low medium
40 – 60	30 – 40	20–25	50–70	Medium
60 – 80	40 – 60	25–35	70–90	Medium high
80 – 100	60 – 100	35–100	90–100	High

of the different types of soils in the study area is found in Online Appendix 2.1, where their spatial distribution is visualized respectively in the urban area. An interpolation process was carried out on a GIS platform to generate the spatial distribution of the geotechnical criterion using the IDW and Kriging methods. To evaluate the performance of both methods, the mean absolute error (MAE) and the root mean square error (RMSE) were calculated by comparing the actual values with the predictive ones, presented in Online Appendix 3. Finally, the IDW method was chosen due to its significant error reduction compared to Kriging. This was attributed to the fact that, on several occasions, the distance between points with different classifications was considerably low, allowing the IDW method to preserve the accuracy of predicting the values better (Hassan et al., 2024; Mejía-Parada et al., 2024; Yunusa et al., 2024).

Precipitation Infiltrated and Temperature

Precipitation and temperature are fundamental in soil processes since thermal variations not only cause soil contraction and expansion but also accelerate the decomposition of the parent rock through chemical reactions (Gracia Romero & Suarez Barrios, 2014). In warm and humid environments, water infiltration favors the formation of clay deposits, while this process slows down in cold and dry climates, as observed in Fig. 4 (Bishop et al., 2018; Gutiñas Rodríguez, 2009).

The temperature distribution in the study area was obtained from the TerraClimate database using the Google Earth Engine platform (Table 1). Monthly data for the last 10 years were collected, and the multi-year monthly average was calculated. Moreover, precipitation data (2012–2022) were collected from 10 meteorological stations near Bucaramanga. For some stations, missing data were corrected using the US National Weather Service inverse quadratic distance method (DSI) (Chow et al., 1996; Gallegos-Cedillo et al., 2016), represented in Eq. (1).

$$P_x = \frac{\sum(P_i W_i)}{\sum W_i} \quad (1)$$

where P_x is the missing data from station x , P_i is the existing data corresponding to the same year from the auxiliary station and W_i can be calculated with Eq. (2).

$$W_i = \frac{1}{D_i^2} \quad (2)$$

where D_i is the surrounding distance between the auxiliary station and the x station.

After processing the rainfall data, the multi-year monthly average was calculated and the spatial distribution was generated using a GIS platform. For this analysis, the Kriging interpolation method was chosen for its statistical approach that allows modeling spatial variability and

estimating unknown values based on the statistical properties of existing data (Bojago et al., 2024; Tabatabaei et al., 2025). The above guaranteed a more accurate and reliable representation of precipitation patterns in the study area.

To increase the scale accuracy of the temperature map obtained from the TerraClimate database, the concept of the relationship between elevation and temperature was incorporated. In mountainous tropical areas, temperature is directly affected by terrain elevation. Altitude influences atmospheric pressure and, thus, heat retention. At higher altitudes, atmospheric pressure decreases, resulting in a reduction in temperature. The procedure described by (Fries et al., 2012) was applied to correct for this altitude-based variation. In the development of this methodology, a DEM was used for the study area obtained from ALOS PALSAR. From this, a point cloud was generated, allowing information to be extracted from the temperature and elevation layers. The relationship obtained between these variables is presented in Fig. 5.

Temperature correction employs a simple trend reduction technique to normalize measurements to the reference level. It seeks to use geostatistical interpolation with raw

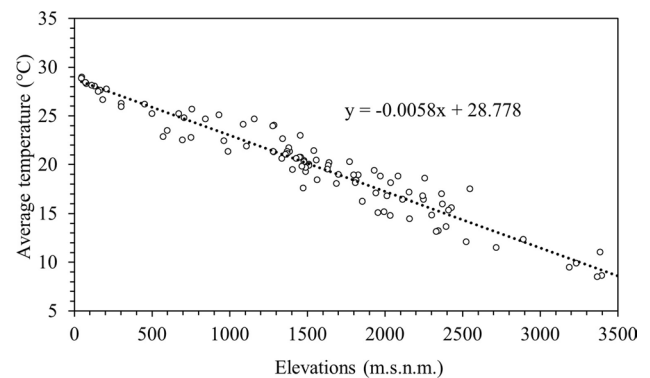
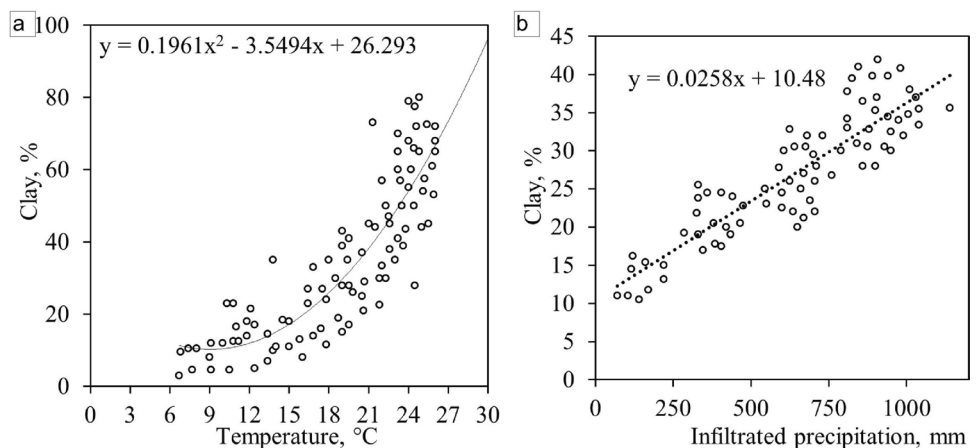


Fig. 5 Relationship between mean annual temperature and elevations of Bucaramanga

Fig. 4 Clay formation with **a** Temperature y , **b** infiltrated precipitation – adapted from (Arancibia Galleguillos & Collarte Concha, 2003; Gutiñas Rodríguez, 2009)



data to obtain high-resolution maps. Initially, the deterministic temperature was calculated using Eq. (3)

$$T_{Det} = T_{Media} + (m \times (Z_{Det} - Z_{DEM})) \quad (3)$$

where Z_{Det} is the mean height of the city, T_{Media} is the mean annual temperature, m is the slope of Fig. 6, y Z_{DEM} is the height of each point.

A raster was generated using kriging to interpolate isotherms in ArcGIS with the deterministic temperature data and then temperature correction was performed using Eq. (4).

$$T_{(x,y)} = T_{Det} + (m \times (Z_{DEM} - Z_{Det})) \quad (4)$$

After adjustment of the data, the temperature in the city varies between 14.8 °C and 24.43 °C. Based on these data and the relationship between clay soil formation and temperature (Fig. 4), a temperature-based scale of threat to expansive soil formation was created. This scale is shown in Table 5 and consists of five levels: low, low medium, medium, medium, medium high and high.

Table 5 Scale of threat to expansive soil formation by temperature

Temperature °C	% Clay	Threat
0–8	0–10	Low
8–18	10–26	Low medium
18–23	26–44	Medium
23–28	44–80	Medium high
31 or more	100	High

Figure 6 presents a summary of the maps resulting from the aforementioned methodology. Figure 6a shows the average temperature map, where a clear relationship between temperature and terrain elevation is evident (Fig. 6b). On the other hand, Fig. 6c illustrates the precipitation map of the study region, prepared from the data collected from the 10 meteorological stations included in the analysis. For a more detailed analysis of criteria, sub-criteria, and threat of expansive soils, 7 monitoring points strategically distributed in the research area were established: one in the north, one in the south, two in the east, two in the west, and one in the center.

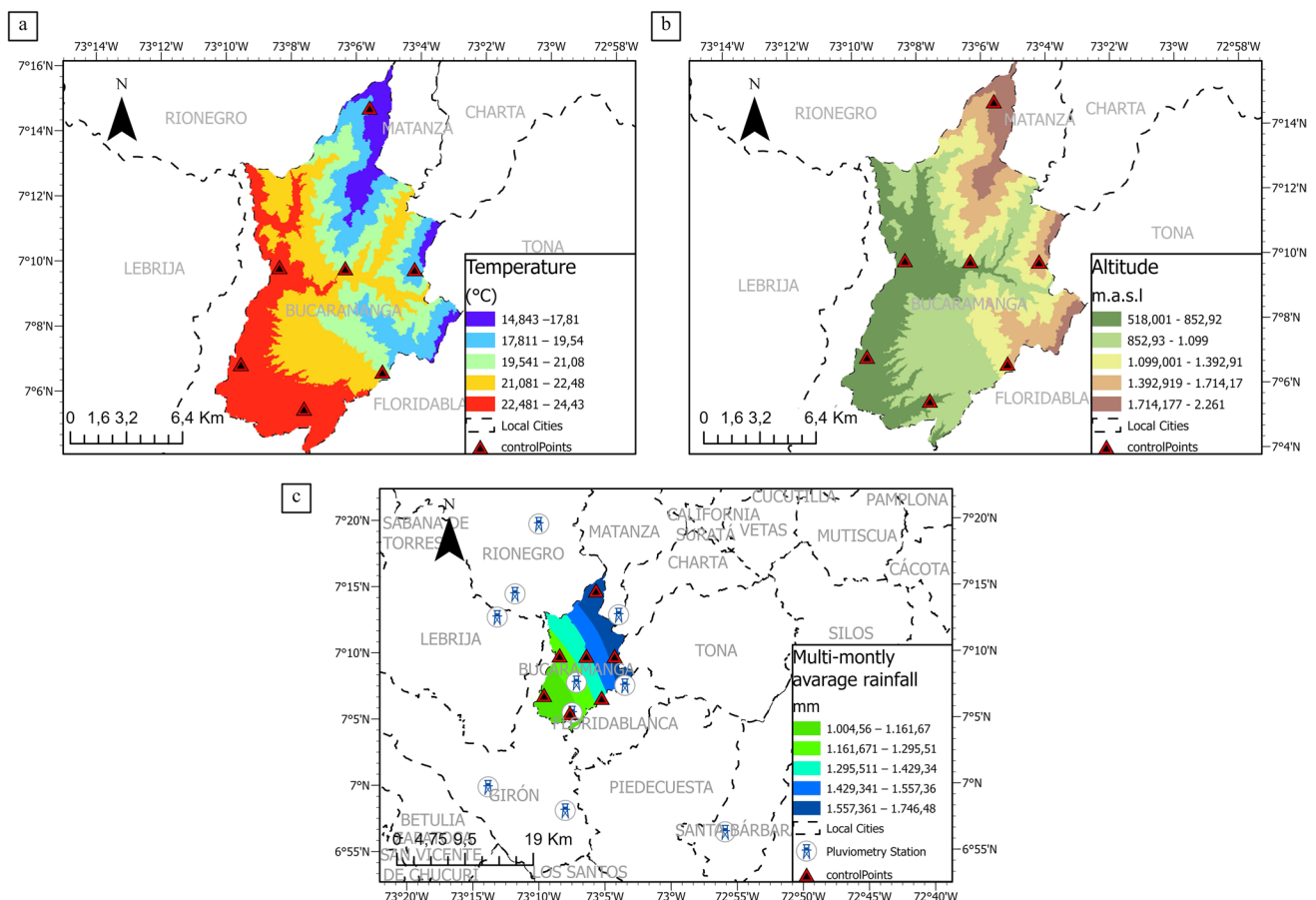


Fig. 6 Climate and geographical patterns of Bucaramanga. **a** Temperature, **b** altitude, **c** multi-monthly average rainfall

Water from precipitation accumulates on the soil surface and percolates through pores and cracks, known as infiltration (Schosinsky & Marcelino, 2007). Multi-annual monthly infiltrated precipitation was estimated using the precipitation map (Fig. 5c) and the RAS 2005 methodology, which considers soil texture, vegetation, slope and rainfall intensity (Arredondo, 1995; RAS, 2005), as seen in Eq. 5.

$$I = 0.88 \times C \times P \quad (5)$$

where P is the monthly multiannual precipitation [mm] and C is the infiltration coefficient [-] to be calculated with Eq. (6).

$$C = (K_v + K_p + K_{fc}) \quad (6)$$

where kfc is the fraction that infiltrates due to soil texture [-], kp is the fraction that infiltrates due to slope effect [-] and kv is the fraction that infiltrates due to vegetation cover effect [-]. The kv subcriteria evaluates the influence of vegetation cover on water infiltration, as detailed in Table 6. Vegetation improves soil porosity, facilitating water flow, while its absence causes compaction and reduces infiltration (Izabá-Ruiz & Morales-Hernández, 2022; Schosinsky & Marcelino, 2007). To calculate the distribution of the Kv subcriteria, a land cover map obtained from IDEAM was used, which was developed using the Corine Land Cover methodology adapted for the conditions of Colombia; this cover map can be found in Online Appendix 2.2. The Kv values were correlated with the coverage map, generating the spatial distribution of Kv, which is presented in Fig. 7a.

The slope subcriteria (Kp) is linked to the infiltration of water into the soil according to topography. In convex relief, water flows to lower areas, decreasing infiltration, while in

concave relief, water accumulates, increasing infiltration. Permeable soils with gentle slopes allow greater infiltration, while less permeable soils with steep slopes result in limited infiltration, with most of the water flowing superficially. These conditions influence the formation of clay soils, especially in low-lying areas (Sanzono, 2019). From the DEM of the study area, the slope map was generated (Online Appendix 2.3), which was subsequently reclassified according to the subcriteria classification specified in Table 7. As a result, the Kp map was obtained, which is presented in Fig. 7b.

The kfc subcriteria evaluates the influence of soil texture on water infiltration, indicating its permeability and capacity to allow flow through the porous medium (Arredondo, 1995). Table 8 presents the kfc values that indicate the capacity of the soil to facilitate or restrict water flow, where impermeable soils, such as rocks or clays, block the passage, and granular soils, such as sands or gravels, allow circulation (Rodríguez & Pérez Álvarez, 2014). As mentioned above, the texture of the soils was determined according to the USCS classification. Subsequently, each point was correlated with the Kfc value indicated in Table 8. Based on these data, an interpolation was performed using the IDW method to generate the spatial distribution of Kfc values in the study area, as shown in Fig. 7c.

Once the subcriteria kv, kfc and kp were established, Eq. (6) and the raster calculator of the GIS software were used to calculate the infiltration coefficient C, which encompasses the variables that regulate water infiltration in the soil, as illustrated in Fig. 7d.

The multi-annual monthly infiltrated precipitation (I) was calculated using Eq. (5), using the GIS platform and considering the sub-criteria Kv, Kp, Kfc, along with the multi-monthly average precipitation. The threat of expansive soil formation was evaluated as a function of monthly multiannual infiltrated precipitation and its relationship with clay soil formation (Fig. 4b). A precipitation threat scale was established in Table 9, with five levels: low, low medium, medium, medium high and high.

Table 6 kv sub criteria – adapted from (Arredondo, 1995; RAS, 2005; Sánchez et al., 2013; Schosinsky & Marcelino, 2007)

Vegetation	K _v [-]
Lakes, lagoons and rivers	0
Marshy meadows	0,05
Sugar cane	0,1
Cultivated pastures	0,1
Cultivated land	0,1
Urban green areas	0,15
Land without forest	0,15
Coniferous forest	0,15
Annual crops	0,15
Grassland cover	0,15
Low shrub vegetation	0,2
Fruit trees	0,2
Urban fabric, commercial areas	0,3
Thorny vegetation	0,3

Results and Discussion

In order to evaluate the threat of expansive soil formation, it is essential to determine the amount of water infiltrating into the soil. With this objective in mind, a grid of 504 points uniformly distributed in the study area was made in the GIS platform (Online Appendix 2.4), making possible to analyze the different factors that affect water infiltration I (Eq. (5)) into the soil. These factors were evaluated using the infiltration precipitation equation, which calculates the amount of water that actually infiltrates into the soil, considering the capacity of the soil to absorb it. The infiltration coefficient

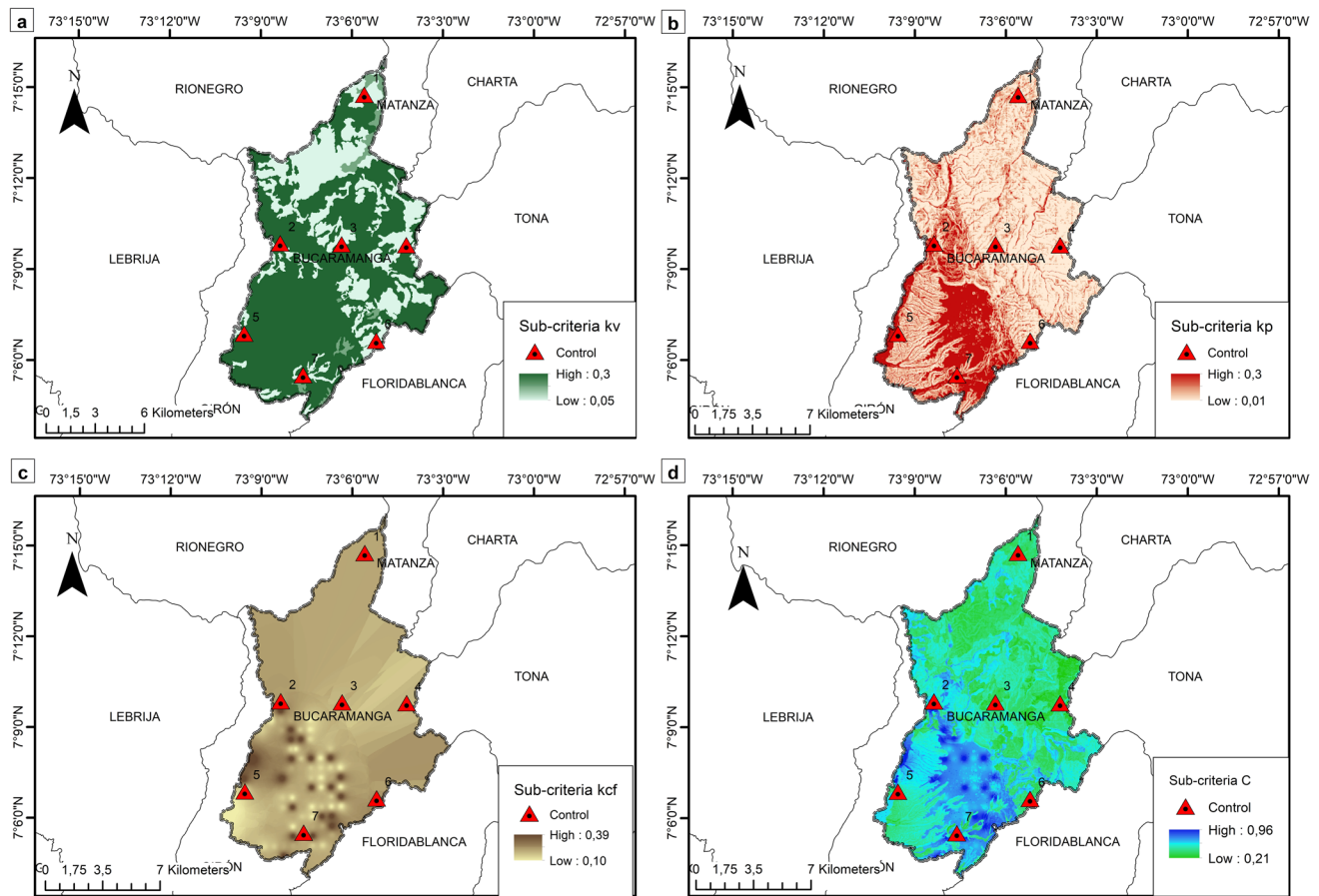


Fig. 7 Soil water infiltration sub-criteria. **a** kv, **b** kp, **c** kfc, and **d** C

Table 7 kp sub criteria – adapted (Arredondo, 1995; RAS, 2005; Sánchez et al., 2013; Schosinsky & Marcelino, 2007)

Slope (%)	K_p [-]
70–100	0,01
50–70	0,05
30–50	0,07
15–30	0,1
1–15	0,15
0,3–1	0,2
0,01–0,3	0,3

Table 8 kfc sub criteria– adapted from (Arredondo, 1995; RAS, 2005; Sánchez et al., 2013; Schosinsky & Marcelino, 2007)

Soil	K_{fc} [-]
High plasticity clays CH, urban areas or compact and impermeable rocks	0,1
Low plasticity clays CL	0,13
High plasticity silts and tectonically faulted zones	0,15
SM silty sands or SC clayey sands	0,2
Sands, gravels, riverbed soils, not very compact soils and areas with many faults	0,4

Table 9 Scale of threat to the formation of expansive soils by infiltrated rainfall

Infiltrated monthly multi annual precipitation (mm)	% Clay	Threat
0–600	10–26	Low
601–1300	26–44	Low medium
1301–2000	44–62	Medium
2001–2694	62–80	Medium high
2695–3470	80–100	High

C (Eq. (6)), which represents this capacity, is calculated by summing three sub-criteria: kv, kp y kfc. The infiltrated precipitation equation has been widely used in studies, including by Schosinsky and Marcelino (2007) to estimate aquifer recharge in Costa Rica, Rodríguez and Pérez Álvarez (2014) evaluate water recharge in Cuba's Guara basin, and Granados (2013) to analyze the Frío River basin in Costa Rica. These studies have shown that the equation is effective for water resources management, as it allows an accurate

estimation of water infiltration and aquifer recharge, essential factors for evaluating the formation of expansive soils.

In the study area, the k_v coefficient showed values fluctuating between 0.05 and 0.3. The lowest 25% of values, around 0.05, correspond to swampy areas in the south of the city, while the 50% closest to the median are in the range of 0.1 to 0.3, reflecting areas of plantations, crops, and urban areas. The median k_v was 0.2, indicating that most of the study area is covered by vegetation, such as shrubs and forests, favoring water infiltration. This behavior agrees with the findings of Patiño-Rojas and Jaramillo (2022), who concluded that vegetation contributes significantly to reducing surface runoff and improving water absorption in the soil.

The coefficient k_p , which represents the influence of the terrain's slope, had a median of 0.08, with values concentrated between 0.05 and 0.1. These values indicate that most of the zones in the study area have moderate slopes, which favor water infiltration. This behavior is consistent with the findings of Salahalden et al. (2024a), who observed that on land with gentle slopes, water has more time to infiltrate the soil and less runoff.

The k_{fc} coefficient, which evaluates the capacity of the soil to allow water infiltration, ranged from 0.14 to 0.27, with a median of 0.21. This indicates that the soils in the area are predominantly silty or sandy, which favors infiltration. These results are consistent with those found by Schosinsky and Marcelino (2007), who observed that sandy soils have a greater infiltration capacity due to their porous structure.

The value of the C coefficient, which reflects the total water infiltration potential of the soil, ranged from 0.27 to 0.81 in the study area, with a median of 0.49. This indicates that most soils have a considerable capacity to absorb water from precipitation, which is in agreement with the findings of Schosinsky and Marcelino (2007), who showed that the combination of vegetation, slope, and soil texture directly influences the amount of water infiltration.

The box-and-whisker plot (Fig. 8) shows that k_v has a narrower range than k_{fc} and k_p , suggesting that vegetation has a more uniform effect on infiltration in the study area. In contrast, the greater scatter observed in k_{fc} and k_p indicates

that water infiltration varies considerably depending on soil texture and terrain slope. Outliers in these two subcriteria suggest that some areas, such as soils with high plasticity clays and regions with very gentle slopes, have very different characteristics from the rest of the area, which could influence water infiltration and the formation of expansive soils.

Table 10 presents the coordinates and key data for the seven randomly selected control points to highlight variability. These points, distributed in diverse geographic locations with notable variations in altitude, latitude, and longitude, reflect a diverse threat of expansive soil formation. This threat is influenced by geotechnical criteria, temperature, precipitation, and the sub-criteria k_v , k_p y k_{fc} . The infiltration capacity, a key factor in this analysis, is highlighted, given that points with high infiltration compensate for the limitations generated by steep slopes. According to the multi-criteria classification, the threat of expansive soil formation varies from low to medium, depending on the conditions of each point. The overlay methodology allows for a comprehensive assessment, identifying critical areas and supporting the implementation of preventive measures.

Temperature emerges as a relevant factor in the formation of expansive soils. High temperatures increase the plasticity of clays, increasing their expansion capacity when saturated. For example, a greater threat of expansive soil formation was observed at control points 2 (23.32 °C) and 7 (23.38 °C). This pattern coincides with the findings of Maheepala et al. (2022), who showed that increasing temperature alters the mineral structure of clay soils, making them more prone to expand. In contrast, point 1, with a lower temperature (17.53 °C) and a high slope (37.79%), presents a low threat, which agrees with Barshad, (1957), who concluded that lower temperatures reduce expansion by limiting soil water retention.

The threat of expansive soil formation is low at points with high water infiltration, such as point 1 (with a coefficient $C=0.65$) and point 4 ($C=0.73$). This is because the high infiltration allows water to drain quickly and not accumulate on the surface, limiting the possibility of expansion, especially in sandy soils. This behavior agrees with the observations of Schosinsky and Marcelino (2007), who suggested that soils with high infiltration capacity are less prone to expansion. However, points 2, 5, and 7, which have a lower infiltration capacity (coefficients of 0.30 and 0.31), present a medium to low hazard due to the accumulation of surface water, which increases the risk of expansion.

Geotechnical factors also significantly influence the expansive behavior of soils. Points with low clay soils (such as point 5, with $C=0.51$) and point 7 (with $C=0.31$) show a higher threat, as clay soils have a higher water-holding capacity, which favors expansion. This behavior is consistent

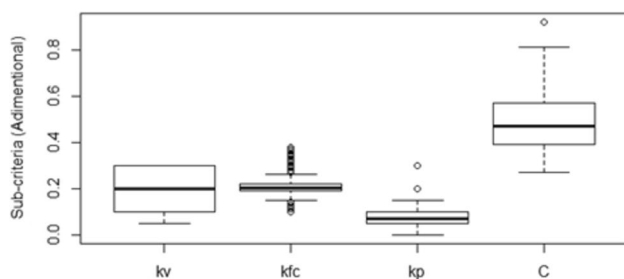


Fig. 8 Distribution of sub-criteria data

Table 10 Control points USCS, slope, temperature, and precipitation

Id	Longitude (°)	Latitude (°)	USCS	Slope (%)	Temperature (°C)	Multi-annual mean precipitation (mm)	kv (–)	kp (–)	kfc (–)	C (–)	Infiltrated precipitation (mm)	Multicriteria
1	-73.093	7.246	SM	37.7918	17.534	1682.78	0.1	0.01	0.20	0.65	964.97	Low
2	-73.139	7.164	SM	9.45653	23.316	1242.15	0.3	0.10	0.20	0.30	331.64	Medium
3	-73.106	7.164	SM	28.2696	20.9104	1411.53	0.2	0.05	0.20	0.38	474.39	Medium-low
4	-73.070	7.163	SM	15.2515	17.6518	1596.77	0.1	0.10	0.18	0.73	1019.75	Low
5	-73.159	7.114	CL	18.3509	23.6265	1057.99	0.1	0.07	0.12	0.51	472.01	Medium-low
6	-73.087	7.111	SM	37.2165	20.5111	1369.95	0.1	0.05	0.23	0.62	742.94	Medium-low
7	-73.127	7.092	ML	3.48483	23.38	1111.02	0.3	0.15	0.17	0.31	307.66	Medium

with that reported by Rodríguez and Pérez Álvarez (2014), who established a direct relationship between fines content and the expansion capacity of soils.

The geotechnical analysis reveals a low threat for expansive soil formation, as the Atterberg limits are low at the control points, indicating low plasticity of the soils (Fig. 9a). Points 6 and 7 are composed of silt and clay of low plasticity, which is consistent with the literature suggesting that silty, low-plasticity soils have a reduced risk of volumetric expansion. This is consistent with research highlighting that soils with a higher proportion of silty sands present a reduced risk of swelling, as discussed in the context of expansive clays in Iraq and Egypt, where low-plasticity clays are observed to have less expansive behavior (Labib & Nashed, 2013; Salahalden et al., 2024b).

Thermal analysis revealed temperatures (Fig. 9b) ranging from 17.53 to 23.62 °C at the monitoring points, reflecting a low to medium threat in the southern zone. Higher temperatures favor evaporation and volume changes in clay soils, which could increase susceptibility to soil expansion, especially in areas where the temperature increases during the summer. This coincides with previous studies associating high temperatures with greater susceptibility to expansive behavior in hot areas. In similar research, such as that carried out in the municipality of Souk Ahras in Algeria, climate change has also been associated with an increase in the susceptibility of clays to shrinkage and expansion due to thermal and humidity variations (Hadji et al., 2014; Herianto et al., 2020).

Regarding precipitation infiltration (Fig. 9c), a large variability in infiltration coefficients was observed between control points, with the first points showing high infiltration (coefficient of 0.65) and points 2 and 7 showing lower infiltration (coefficient of 0.30). These differences are key to the expansive behavior of soils, as soils with higher infiltration capacity tend to have less risk of expansion because moisture is more evenly distributed and not concentrated in the surface layers. Previous research, such as that conducted in the Eastern Plains of Colombia, has shown that high infiltration can increase the susceptibility to soil swelling since the absorption capacity improves the structural stability of silty and clayey soils (Milton Orjuela-Matta et al., 2012).

The multi-criteria analysis (Fig. 9d), combining the geotechnical, temperature, and infiltrated precipitation maps, revealed that 95.3% of the region has a low-medium threat of expansive soil formation; a small percentage (0.24%) has a medium threat. This threat pattern reflects the integration of the different factors. According to the results of the map overlay, low infiltration and moderate temperatures in the northern and central zones explain the low threat, similar to what is observed in other regions such as Toshka, Egypt, where geotechnical characteristics

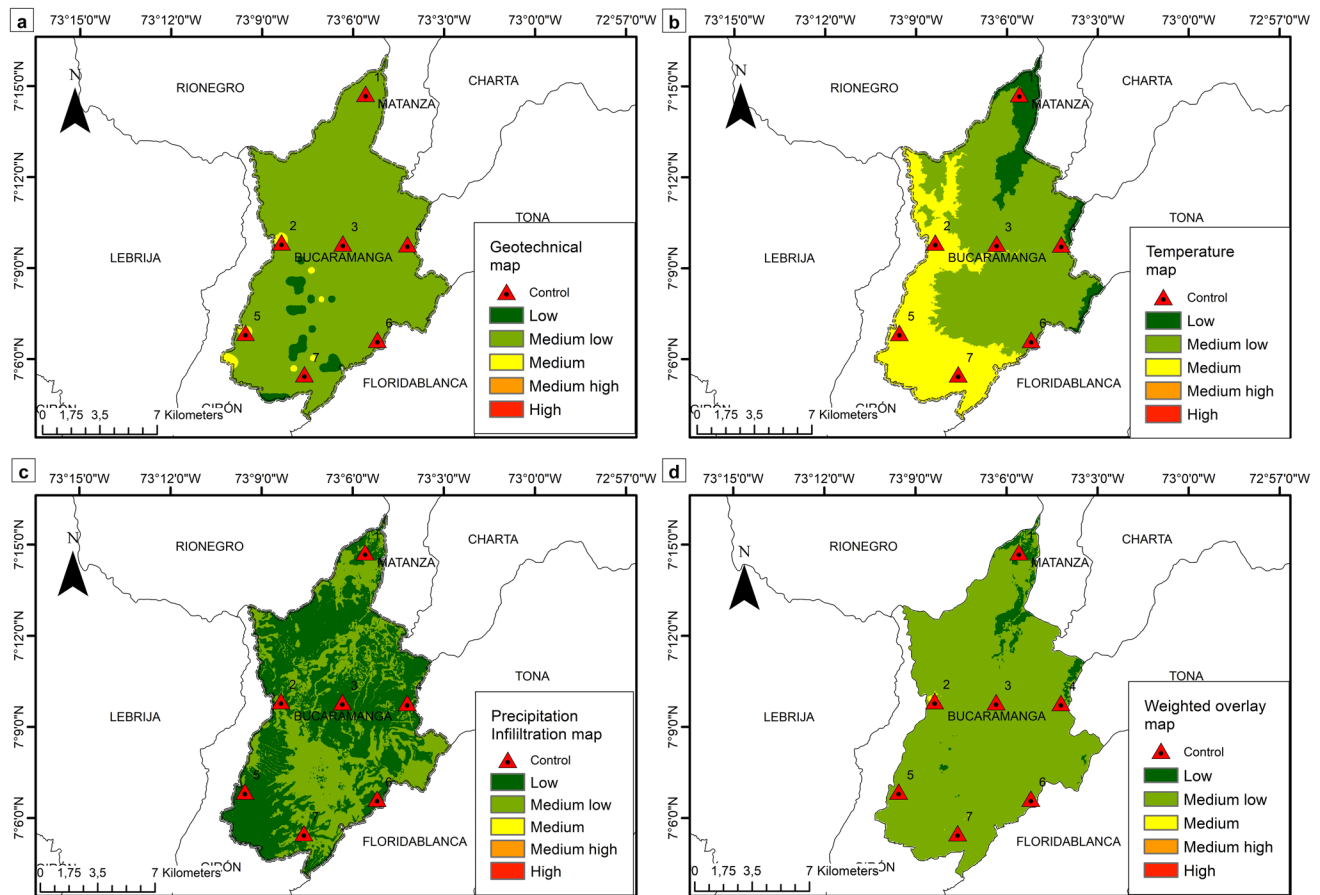


Fig. 9 Threat map for expansive soil formation. **a** Geotechnical, **b** temperature, **c** infiltrated rainfall and **d** multi-criteria

and low infiltration indicate a low risk for soil expansion (Labib & Nashed, 2013). However, in the southern zone, with higher infiltration and higher temperatures, the threat is slightly higher due to more favorable conditions for the swelling of clay soils, as discussed in studies on the behavior of expansive soils in areas with higher thermal and moisture activity (Hadji et al., 2014; Herianto et al., 2020).

Work Limitations

The methodology proposed in this study to evaluate the threat of expansive soil formation has been developed and applied using geotechnical, climatic, and infiltration criteria. Although this approach is sound and has proven helpful in the context of Bucaramanga, it must be recognized that it has been carried out with limited data, which implies certain restrictions when attempting to replicate it in other regions. In particular, the absence of detailed mineralogical analyses means that correlations based on Atterberg limits were used as approximations to characterize the expansive properties of soils. Although these correlations are accepted and applied in similar studies, the lack of direct mineralogical analysis

limits accuracy and could lead to differences if applied to soils with different geological characteristics.

Likewise, the estimation of infiltrated rainfall was based on indirect variables such as vegetation, soil type, and slope, resulting in a practical estimate for the urban area of Bucaramanga but not on direct hydraulic measurements. Although functional within the specific context, this approach may not accurately reflect conditions in other regions where climatic and geological characteristics vary. In addition, although the IDW interpolation method was used because of higher performance in the predictions than the Kriging Method in the geotechnical criteria, this method is not necessary to be accurate in all the cases the decision of which method used must depend on the results, field conditions and the distance between points. Despite these limitations, the applied methodology represents a significant step in assessing the threat of expansive soil formation and is considered a valuable basis for future research. However, since few studies comprehensively address this issue, further research is needed to validate and refine this methodology, especially in diverse geographic and climatic contexts. This will allow a better

understanding and extension of the results obtained, contributing to broader and more accurate implementation in different regions.

Conclusions

This study has developed an effective methodology to evaluate the threat of expansive soil formation in Bucaramanga, Colombia, through the integration of three main criteria: geotechnical, infiltrated rainfall, and temperature, using GIS tools for the generation of thematic maps. The results show that the southern zone presents greater vulnerability due to more significant water infiltration, higher temperatures, and soils with high plasticity indexes. In contrast, the northern and central zones have a reduced risk, given that their geotechnical characteristics do not favor soil expansion.

The geotechnical analysis, based on Atterberg limits and soil classification, revealed that most of the soils in the control points have low plasticity, indicating a reduced risk of expansion. This finding is consistent with previous studies suggesting that soils with higher sand content and lower clay content are less prone to volumetric expansion. Temperature was identified as a determining factor in the formation of expansive soils. Areas above 23 °C showed a higher threat of soil expansive forming, confirming that high temperatures favor evaporation and volumetric changes in clay soils, increasing their susceptibility to expansion. This aligns with previous studies that have associated elevated temperatures with an increased propensity to expansion in clay soils. Regarding precipitation infiltration, it was observed that points with a high infiltration capacity presented a low risk since water was distributed more uniformly in the soil, limiting its accumulation in the surface layers. In contrast, areas with low infiltration showed a higher threat, due to the accumulation of water, which favors soil expansion. This pattern is consistent with research suggesting that soils with high infiltration capacity have a lower risk of expansion.

The integrated multi-criteria analysis, which combines the geotechnical, thermal, and infiltrated precipitation maps, revealed that 95.3% of the region has a low-medium threat. In contrast, a small percentage has a medium hazard. This pattern reflects how the interaction between geotechnical, thermal, and infiltration factors directly influences the threat of expansive soil formation. In particular, areas with low infiltration and moderate temperatures in the north and center explain the low threat. In contrast, the threat increases slightly in the south with higher infiltration and higher temperatures.

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